DISSERTATION

Intelligent Distributed Control of Power Flow using FACTS Devices for Congestion Management

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Dedicated to

My Mother, Bibi Jan; for their continuous support, encouragement, love and care which helped me to be the person I am today.

My brother, Naeem Ullah and Sisters Rani Alamgir and Mahjabeen Hanif Khan; Thank you all for their continuous love and prayers.

My wife, Fatima Aqel Afridi, and my sweat daughter Tazakka Ikram; Thank you for your support and love all along the way.

Abstract

The steady growth of electricity demand combined with the large-scale integration of distributed, fluctuating generations constitutes a challenge for system operators' transmission capacity. Due to liberalization, more market participants are trying to participate in the energy market. TSOs want to get all market participants to trade in the energy market to increase competition and reduce costs. However, they must also ensure the safety and reliability of the power system, as the transmission networks would be congested due to the large power transfer. In deregulated market congestion, the violation of physical, operational, and policy restrictions in network operation is associated with one or more devices. Various congestion management methods are applied to relieve the congested elements by managing the power in the transmission and distribution networks. Flexible Alternating Current Transmission System (FACTS) devices are used effectively for congestion management to dynamically control line reactance, bus voltage magnitude, and phase angle to improve controllability and flexibility of the system.

The work of this dissertation is divided into two phases. The first phase is the planning phase, in which an algorithm is developed for analysing the power grid for the maximum improvement of the transmission capability by placing FACTS devices in suitable places. Two types of FACTS devices are contemplated, series devices are used to relieve overloaded lines, whereas shunt devices are used to improve bus voltages. Various IEEE test systems that dominate either the thermal limits or the voltage limits, are analysed. The positions of FACTS devices are determined based on the sensitivity indices that are critical in violating constraints on increasing power transfer. In order to examine the power grids to their maximum capacity and to identify the critical locations for constraints violation, two case studies with different combinations of sources and sinks are used. The first case study determines the total transmission capacity of the network between all generators and consumers in the power network. In the second case study, the power transfer capacity is determined between different combinations of source and sink areas. The systems in both case studies are also analysed with (n-1) contingency. The sizes of the FACTS devices at the proposed locations are estimated based on the improvement in the constraints, which eventually increased the respective transmission capability of the power grid.

The second phase of this dissertation deals with the operation and control of FACTS devices in the energy system. A Distributed Coordinated Control System (DCCS) is being developed based on the Multi Agent System (MAS) to improve performance and control multiple FACTS devices. This helps to overcome network congestion by relieving overloaded lines and improving voltages on violating buses. The conflicting effects of multiple devices that may affect the system performance are resolved through coordination. Each FACTS device has an area of influence in which it can effectively influence other devices. However, all such devices for each FACTS are grouped as positive or negative affected devices. Agents are proposed with these devices to share their status information. In this way, the controlling agents, which are defined only for FACTS devices, can retrieve all status information of the surrounding devices. The controlling agents evaluate the status information of these devices and determine the required FACTS parameters for example, to control the current flow of the respective line or the reactive power injection on a particular bus *etc.,*. In order to avoid contradictory effects, the controlling agents also assess the mutual effects between the FACTS devices and the corresponding elements of their influential areas in setting the FACTS parameters. Dynamic load profiles of 24 hours are used which lead network operation to congestion in IEEE test networks. The proposed FACTS devices in these networks, as specified in the first phase, are subjected to dynamic loading to resolve the

congestion. The performance of the power system with the specified FACTS devices is evaluated and validated by the results of these IEEE test networks.

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1 INTRODUCTION

1.1 Motivation and Objectives

1.1.1 Power System Up gradation

The electric power system is a man-made largest system, which connect thousands of electricity generating units to millions of residential, commercial and industrial consumers through millions miles of transmission, distribution lines covering large geographical areas of a country or even a continent. It composed of main four physical interacting parts: energy production or generation, high voltage transmission, low voltage distribution, and energy consumption or load. The electric grid is thus not just the interconnection of generators and loads in the physical transmission and distribution networks but also associated with operational, regulatory, and governance structures. The other intelligible elements are the operational systems that is important for the protection and control of the physical elements, and the last is the regulatory and governance structures of the system. In almost of the industries of the world, federal policy are substantially reformed to reflect the open market realities. The European Union and many other countries have adopted a comprehensive new structures of competitive wholesale and retail electricity markets [1] and others are also following the same. In the vertical structure of power systems, large amounts of power at high voltages are transmitted from remote generation stations and distributed at lower voltage levels to millions of various consumers. Large amount of power are produced in large power plants of thermal, hydro and nuclear energy *etc.*, which located far away from load centers. The national grid is responsible to ensure secure supplies to the consumers, which is centrally controlled with essential supervisory systems. Liberalization of energy market refers to the reduction of restrictive regulatory framework for private power companies and imply deregulation. Ideally the liberalized energy market is supposed to work within a set of regulatory framework, overseen by a regulator without the external political influence of choosing plant size and fuel. This will result a competition among the participant in the energy market which would cause reduction in the energy cost and improvements in efficiency. Many electricity systems around the world are currently in transition towards more deregulated and competitive markets. The electricity is become the commodity of free trade, among various power supplying entities based on diverse array of co-generation of heat and power (CHP), renewable energy resources of wind and solar, small hydro plants and small generating plants of wood fuel or combustible waste products *etc.* The European electricity system is undergoing transition towards reducing emission of greenhouse gas (GHG) by increasing the share of renewable electricity sources especially wind and solar. The electricity demand is increasing due to the use of electric vehicles in transport sector and the electric heat pumps for heating and cooling. Most of the countries are developing their system to increase the generation capacity at their distribution level and trying to achieved the objective of 45% share of renewable electricity in 2030.

The transmission networks play a key role in encouraging the competition among generators and providing the consumers access to remote generations. The networks are run by transmission system operators (TSO), which facilitate various players to interact each other in the internal energy market. In Europe 43 different TSOs from 36 countries form the European Network of Transmission System Operators for electricity (ENSTO-E) which organize long term development plans and participate in defining network codes. Each member share their objective of setting up the internal energy market and ensure its optimum functioning in support of the European aim of energy and climate agenda. No common rules are imposed and the tariff disparities are not affecting the competition. Transmission grids are operated on a sub-national or national level. There are interconnection across the national borders to export electricity to others [2]. The increasing interests in the last decades towards small distributed energy sources, impact the system with technological innovations and changing economic, environment and regulation in distribution network. These sources are best suited for local loads but from the system operator point of view, these could also be an alternative source for ancillary services. These sources can improve the robustness of the system to tolerate against the natural disaster by reducing the dependency upon immediate restoration of the grid system. But some technical issues are there due to these generators in distribution network. In excess production from local loads, the power flow is reversed from local grid towards higher voltage grid which effect the conventional automatic voltage control scheme and the protective relaying systems, which are design for unidirectional current. The transmission grid has to provide reliable and low cost electricity, which is abandoned by large flows over the interconnection lines due to excess production and eventually curtailed these types of sources.

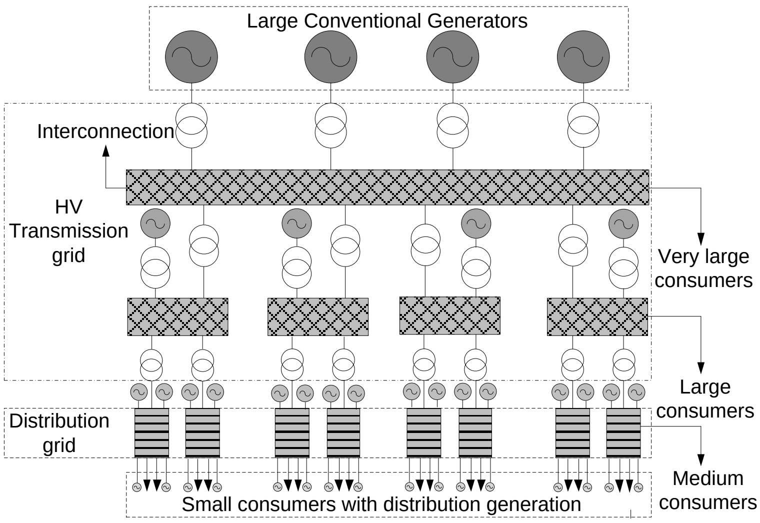


Figure 1.1: Conventional power system structure with expected distributed generation

1.1.2 Transmission System Limitations

The transmission network is the backbone of every power system to transport bulk electrical energy safely to remote consumers. Bulk electrical energy from large power plants is step up to high voltage transmission grid and transported over large geographical area to various load centers. High voltage transmission grids are mostly of meshed structure in AC system, which allow bidirectional electricity flows. Some DC transmission lines are also added within interconnection of two utilities or to connect far away electricity production where AC line are not feasible. The electric power is then step down at substations to lower voltage levels and distribution grids set up the safe delivery to the end consumers. Distribution substations connect the transmission system to primary distribution systems at medium voltage. The primary distribution lines transfer power to secondary distribution substations and larger industrial customers which are directly connected. The secondary distribution lines supply the power to end consumers.

In last century the expansion of electric grid is to supply electrical energy from all the conventional generators to the consumers. But due to the increasing integration of renewable energy resources and small scaled distribution generators the grid experienced a large number of generation at distribution levels as shown in the Figure 1.1. This may cause voltage instability, bidirectional power flows and eventually stressing the line capacity. The large scaled Renewable Power Plants (RPP), connected to transmission network [3], could also stressed the lines even more in excess production hours. Current transmission level RPPs are mainly located onshore and connected at 132 kV voltage level of the transmission grid [4].

The capacity of transmission lines are limited by various primary factors. One of the factor is voltage level, the capacity of high voltage transmission line is high as illustrated by Surge Impedance Loading (SIL). The Characteristic/ Surge impedance of a loss less line is define as :

$$Z_S = \sqrt{\frac{X_L}{Y_C}} \tag{1.1}$$

Where X_L is series impedance and Y_C is the shunt admittance per unit.

So the SIL is defined as the maximum power delivered over a transmission line to a purely resistive load equal to the surge impedance at the receiving end with no net reactive power to or out of the line, it is expressed as:

$$SIL = \frac{\left|V_{R(L-L)}\right|^2}{Z_S} = \frac{\left|V_{R(L-L)}\right|^2}{\sqrt{\frac{X_L}{Y_C}}} \tag{1.2}$$

Where $V_{R(L-L)}$ is the voltage at receiving end node which is equal to the sending end voltage and there is flat voltage profile along the transmission line. Generally 10% of voltage drop is used as the voltage quality threshold. Other major limiting constraints of a transmission capacity are:

- Thermal Constraint
- Voltage Stability
- Transient Stability

The thermal constraint of a line is related to line losses which rise the temperature, that eventually causes expansion in the line and resulted sag in conductors between the two supports.

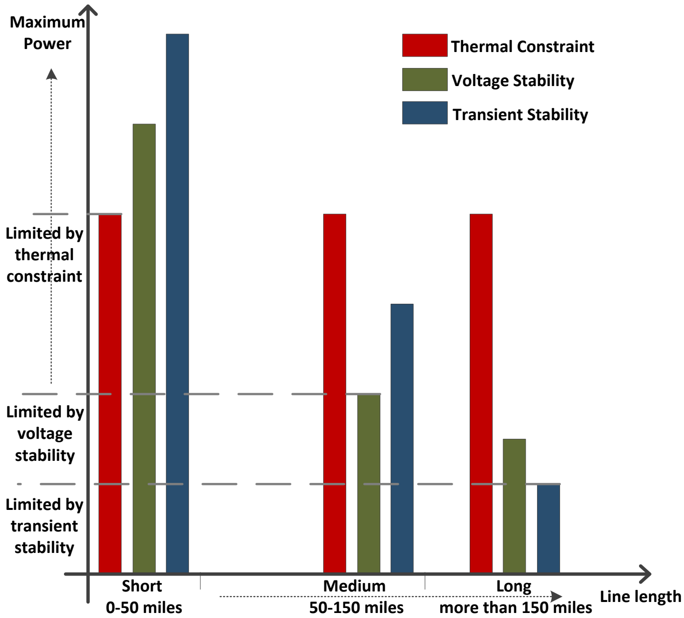


Figure 1.2: Constraints for Transmission Capability

At the thermal constraint the conductors sag down sufficiently to reach the minimum acceptable ground clearance value. The other two constraints are related to stability and are interrelated, that one type usually causes the other. The stability is determined by operators by performing an extensive contingency analysis. Voltage stability refers to the ability of a power system to maintain the voltage levels within the acceptable range after a disturbance occurred. And transient stability refers to the ability of the system to maintain the bus voltage angles within the safe margin, in a transient power increase due to a sudden lost of generator or transmission line. The typical limiting factors of the power transfer for short, medium, and long lines are illustrated in Figure 1.2.

The thermal constraint is similar for all short, medium and long transmission lines because it depends on the material property of a line. The stability limits are different for different line lengths as shown in Figure 1.2. For short transmission lines of length less than 50 miles, the thermal constraint is dominant in limiting the power transfer over the line. The power transfer on the transmission line of medium length is constrained by voltage stability, while long transmission lines of length more than 150 miles are limited by transient stability [1]. The electricity follow the Kirchhoff circuit laws according to the characteristics of the circuit and thus large electric current flow through the smaller impedance parallel path. Due to the meshed structure, the electric power follow multiple paths from one location to other in transmission grid, and may be cross jurisdictional boundaries in interconnected system. Consequently some paths get congested due to the unscheduled flows, which adversely affect the dispatch of least cost generation in the region. So more transmission capacity is necessary for the power transfer to be increased in future.

1.1.3 Transmission Congestion and Management

Transmission congestion occurs when the transmission capacity is insufficient to securely serve all the simultaneous requested transactions within a region. The system operators manage the transactions among the market participants but considering the system security and reliability at high priority. Thus various congestion management methods are employed along with some other objectives. The security constraints that limiting the power transfer capacity of a line as explained before, necessitate the operator to change the generator schedules away from the most efficient dispatch. The generation patterns are fairly stable in traditional vertical environment and the financial implications of re-dispatch can easily be distributed among the participants, due to the direct control. This become more challenging in open access environment where generating companies competing and the patterns of generations and flows could alter exorbitantly in small time periods due to the market forces. Therefore, it more necessitate the methods of congestion management for ensuring the system security. However, this has a direct financial implications over some market players in competitive environment in case of re-dispatch occurred. The nature of congestion problem is different in different countries depending on the deregulation model being employed. The implementation of congestion management methods are influenced by network typologies, density factors, some political ideologies and the overall design of market. Anyhow, the method employed for congestion management should be market efficient and robust in strategic manipulation by market entities, while ensuring system security. It should equally treated all the participants and shouldn't gain any benefits from congestion occurrence. The congestion management methods are mainly grouped in two major classes *i.e.*, market based congestion management methods and non market methods as described in Figure 1.3.

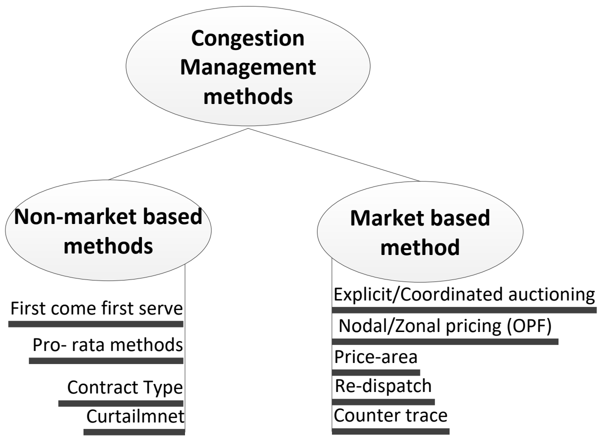


Figure 1.3: Congestion management methods

The non-market methods of congestion management are based on some predefined set of rules like first come first serve, pro-rata and on the type of contract, long or short and irrespective of the ability of the players for the transmission capacity. In first come first serve method, the bilateral contracts are awarded if enough capacity is available for the respective transaction and the participants book their transaction with the system operator. And similarly for the next coming transaction the system operator updates the available transfer capacity (ATC). Market based methods look into economic efficiency in allocating the transmission capacity based on the ATC information. The explicit auctioning and coordinated auctioning, split the market into energy market and transmission capacity market. The coordinated auctioning resolve the problems associated with explicit auctioning method to account the effects of loop flows in the network. These methods are used commonly in Europe with a central auctioneer which manages the capacity allocation at all borders in the Internal European Market (IEM). In nodal pricing and zonal pricing method Optimal Power Flow (OPF) problem is modeled including economical and technical specifications, like generators cost functions, demand elasticity, generation limits and line power flow limits, to maximize social welfare. One of the outcomes of the optimization problem is nodal price for each node or aggregated zone to reduce the complexity. There is no need for explicit auctions for transmission capacity, participants only submit their bids for energy injection and take-off.

In some systems, only few lines are frequent congested compare to other lines, so the concept of inter zonal and intra zonal congestion management methods are used which are further simplified by price area congestion management scheme. In this method, the power network is splited into geographical bid areas with limited capacities of exchange. The system is divide into areas on the predicted congestion bottlenecks and bidders of spot markets have to submit separate bids for their own price area. But the market will settle at one price, if there is no congestion and different prices for each areas in case of congestion. The capacity alleviation methods are in place to relieve the congestion even after ex-ante capacity allocation in day ahead stage or fixing the operation schedule. Due to the unscheduled interchanges the system operators use these methods to ensure the security in real time operation. In re-dispatch method the generations are curtailed or increased without market based incentives to relieve the congestion. Counter trading method is not to command and control only but the system operator will buy and sell electricity at prices determined by a bidding process. The curtailment method is the last option to ensure reliability even losing the economic benefits[5]. The whole process of the entire congestion management is described in Figure.1.4. The system operator determine the ATC between different regions and continuously updating for the transactions commitments. Because the operator needs the information of transfer capacity in settling the day-ahead or spot market. There could be a separate transmission capacity reservation market or integrated in the coordinated market. Next step is the congestion forecast, as there may violation in real time of the transmission capacity, even after capacity allocation. So congestion alleviation methods are applied to relieve real time congestion.

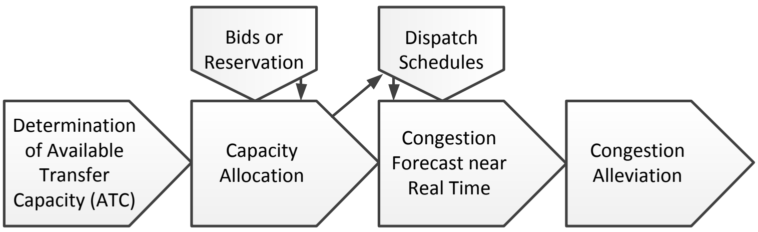


Figure 1.4: Congestion management process

The network congestion leads to market inefficiency, as the most cost-effective generation resources are being halted from serving the load. The difference in social welfare between a perfect market and a real market is a measure of the efficiency of the real market. It may also cause the market power as the power sellers in certain region could raise their profits by strategic bidding, which ultimately results in market inefficiency. The system operators would have to share additional workload of commercial settlements arising of the network constraints which caused congestion.

Flexible Alternative Current Transmission System (FACTS) devices have been used to increase the transmission loading capability of the system. These devices provide flexibility to the transmission system by controlling the line flows, improve the utilization of existing transmission assets without jeopardizing the stability. FACTS improve the transmission capability by 20-30% in stability limited system [6]. So more consumers can be facilitated with comparatively lower investment and the implementation time of transmission reinforcement by constructing new transmission routes are long enough. In most of the literature different optimization tools are implemented to find optimal placement and ratings for various FACTS devices in managing congestion. For their reactive power compensation characteristics, FACTS devices provide more flexibility to the system in controlling power flow, resolving transfer capability and system stability problems. Therefore an extensive literature has been already published for the use of FACTS devices in a variety of method for increasing transmission capacity and mitigating congestion [7]. Multi-objective functions are being optimized, which give interesting results for the respective cases with proposed FACTS devices and their locations. So to explore the opportunities that any electrical network can offer in terms of the maximum capabilities of transporting power from all the sources to all the consumers dully fulfill the stability and reliability constraints, is needed. Furthermore to investigate the critical locations and constraints that cause the capabilities limitations and also finding feasible locations to improve the capabilities.

This study would give an idea of extending the capability of the current power networks by using FACTS devices, incorporating the future load growth and the generation which probably be the renewable generation. So that the low cost, reliable and clean energy could be provided with high power quality to most of the consumers and minimize the transmission congestion to the possible extent.

1.1.4 Summarized Motivational Remarks

The contribution in electricity production by renewable energy sources (RES) is growing rapidly in all over the world. The large integration of these sources can seriously impact on network operation, power flows fluctuations and line overloading due to unscheduled power flows and insufficient control. The power grids are required to upgrade their physical structure as well their controlability and flexibility to handle volatile situation threatening the power quality and system reliability. And the current transmission networks would be incapable in maintaining the essential system security in fulfilling the transmission commitments without congestion, sacrificing the economic benefits. The transmission planners have to think for network extension or any profound potential alternatives. The economical, political and environmental hindrances for transmission reinforcement favoring the FACTS utilization for their potential features. The FACTS are placed in the system for various power system issues and different optimization algorithms are proposed for FACTS placement in literature. So in order to make the transmission network more flexible and controllable, it could not be only placing one or two FACTS devices in the network, but instead more devices are required for this purpose. A variety of FACTS devices could provide an extensive features that any network need to have at various locations, that could enhance its performance even for the integration of large intermittent energy sources in future. Therefore, a thorough investigation is required to analyze the power networks for its requirements in transmitting the power from sources to loads and locate suitable sites for FACTS placement to fulfill those requirements.

The motivation of the study is the concern of the transmission capability enhancement by using multiple FACTS devices and their control strategy to improve the utilization of transmission assets and improve system reliability and stability. The transmission congestion appeared to be happened due to insufficient transfer capability of violating thermal lines capacity or voltage stability. For this purpose the planning of the network operators need to be modify with the use of various FACTS devices that would enhance the transmission capability. Instead of using optimal locations and sizes rather analyzing the network based on electrical characteristics and constraints improvement. Therefore, critical locations which are mostly limiting the power transfer capability of the network would be focused for FACTS placement. So a method is need to be developed which could identify such critical or weak locations, where the respective FACTS devices are placed that could enhance the power network capability. To develop a control strategy for such multiple FACTS devices, because each device could influence certain area in its surroundings. And there could be many elements which are influenced by multiple FACTS devices and in case of contradicting effects could deteriorate the respective control. So coordination should be developed while controlling the FACTS devices so that the mutual contradicting effects could be minimized on the mutual influenced network elements.

1.2 Problem Statement and Solutions

Currently the power grids are already facing transmission bottlenecks which cause congestion and this will be expected more in future due to the steady growth in power demand. The power transactions among buyers and sellers are only implementable if there is enough transfer capability of the network. The congestion management methods are effectively managing the power transmission capability among market participants to ensure system stability and reliability in the expected contingency or market settlement. These methods allocate the scarce transmission capacity, by rescheduling the generators and eventually affecting the market efficiency and social welfare. To enhance the transfer capability of the transmission network by improving the voltage stability and provide power flow controlling features to the transmission system using FACTS devices according to the network requirement instead of network reinforcement. Thus increased the utilization of existing network capacity closer to its thermal loading in comparatively less investment and time.

In literature FACTS devices are optimally placed mostly to enhance the transfer capability of the network[7], minimizing the line losses, and reduce transmission congestion. But the investigation of critical constraints and the locations in the network, which are more prone to violation for respective constraints are still uncovered. Based on the electrical characteristics of the transmission lines in grid topology, some locations are more critical for constraints violation. And that can't be identified by optimal solutions, which are more focused on optimal parameters settings of power flow. This is because, these solutions ascertain the power system variables like the power flow over the lines and power injections at buses so that the constraints are set within the limits. The electrical characteristics of the lines constitute the distribution of power flows over the network elements according to the Kirchhoff law's. And thus, larger power would flow on the least impedance paths in multi parallel paths connecting source and sink. The lines of such characteristics would reach their capacity limit earlier, and become critical in limiting transfer capability. Similarly the electrical distances of the consumer nodes from the source nodes would establish the voltage magnitude at respective nodes. Those nodes which are electrically far from the generator nodes could be more susceptible to load variation and would reach the lower voltage limit and turn into the limiting elements for transfer capability. The method used in this work, focused on such locations for FACTS placement which are critical and improve the respective constraints violation with suitable FACTS placement.

The optimum solutions are more advantageous in power system operation to lead optimal power flow, by specifying the parameter values of the system elements to consummate the necessary system stability for transfer capability. For planning a broader vision is contemplated, in which not only looking to current elements of the system but also other possible opportunities could be probed to improve the transfer capability along with system performance. Therefore more extensive analysis is needed to estimate the maximum transfer capability and limiting areas in the network. This can't be done optimally, rather the power flow solutions with increased power transfer in order to violate the respective constraints. Such locations needs to be identified in terms of the affected constraints, which could influence significantly the overall transfer capability. These locations could be subjected to various FACTS devices based on their types to improve the respective constraints. The method adopted in this work proposed an extensive analysis in planning phase to estimate the transfer capability for normal and contingency cases.

Various sensitivity indices like real power loss and real power flow sensitivity indices are used in literature for FACTS placement to increase transfer capability, which are suitable for loss minimization and line flow reduction but again the critical locations might not be selected. Thus the transfer capability are still limited by critical locations or could improve slightly to current system conditions only. In the proposed methods the sensitivity indices are used to identify the locations based on electrical characteristics which are more prone to violation. The other problem of finding the critical locations using repeated power flow (RPF) method is that, it could be limited to only one or two locations which violate the constraints. Thus further increase in power transfer is being stopped and other critical locations can't be identified. This problem is resolved in the proposed method by identifying large set of locations and the violating constraints are improved at most critical locations which provide further increase in power transfer. The respective constraints are improved on critical locations with suitable FACTS characteristics which enhance the transfer capability even more, until there is no possibility of further enhancement.

The optimal sizing and placement of FACTS devices give better solutions for normal system, containing bilateral or multi-lateral transactions, or even formulated for some specific congestion problem scenarios with closed boundaries. And the network elements behavior for other power transfer cases with possible contingency might not be optimized. This problem is addressed in this work, by considering the possible cases of power transfer between the areas either the contribution in load and generation of all the areas or the power exchange between any two areas. Thus the final identified critical locations are the combination of each individual case. So the locations and sizes of the FACTS devices will contribute for all the power transfer cases among the areas in normal case and $n-1$ contingency cases. And the congestion can be mitigated with the achieved enhancement in transfer capability. The location selection based on PI and L-index sensitivity factors have the advantages to faster the identification of critical locations in line overloading and voltage stability limit violation respectively. And the FACTS placement at these locations will not only help in enhancing the transfer capability but also could help in power flow and voltage stability problem. L-index is also advantageous in finding the effective area of the FACTS devices, used for their coordinating control strategy.

In summary, this work identify the issue related to congestion due the steady growth in electricity demand and the expected integration of renewable generation. The role of FACTS devices in mitigating the congestion by controlling the power flows over the lines and voltage stability at the buses and consequently enhanced the power transfer capability of the overall network. In this study series and shunt FACTS devices are used at different lines and buses, which are critical for system stability and reliability. So the FACTS devices are placed with the objective to enhance power transfer capability for managing the congestion. Thus a high computational efforts is required in the planning phase to identify critical lines and buses for series and shunt FACTS devices using different power transfer cases among the areas. The optimal parameters are being opened to other specific power system problems for FACTS devices at specified locations, but this is not covered in this study. Transmission congestion is focus in this work and the control strategy that utilize FACTS devices for alleviating the transmission congestion by improving the system stability and reliability. Thus the method can be used to motivate the system operator to invest in FACTS placement and can defer the new transmission investment to some extent to the future projected load and generation growth. So it can be justified with the achieved results of network analysis for FACTS placement to improve the system stability and reliability and can make the network capable of integrating more loads and generation like renewable resources and ultimately help in reducing electricity cost.

1.3 Methodology and Contribution

The primary goal of power network expansion is, to reach their native electricity demands and connecting generating plant far from load centers, or interconnecting to other networks for reliability and economical efficiency. The transfer capability of the network is limited mainly by the thermal line limits, voltage or stability limits. The real cause of the limiting network transfer capability is required to explore (*i.e.*, bus voltage violation or exceeding line capacity limits) with the violating constraints locations. For this purpose an extensive computational efforts are required as it could not be done by optimization as this is not an optimization problem. The transmission capability of a network is unique for certain sources and sinks and the critical locations for certain transfer capability could be different. So it is very difficult to establish the transfer capability of certain power network as a final value based on one set of combination of sources and sinks and based on this the critical locations considered for the overall network. So an algorithm is developed for detail analysis of the network based on different cases that are mostly involved in transaction. The critical locations are identified based on the respective constraints violation and the characteristic of suitable FACTS devices are utilized for the enhancement of transfer capability. The enhancement of transfer capability is very beneficial for managing network congestion which improve the power system performance. Although this is true that the transmission congestion can't be completely avoided but can be minimized to some extend by enhancing the network transfer capability.

FACTS devices are available in variety of types as connected in power system and thus provide different features. The Series FACTS devices *e.g.*, TCSC and SSSC, having direct influence over the line impedance X and thus control the real power of transmission lines. Shunt FACTS devices, like SVC and STATCOM, can regulate bus voltage by controlling the reactive power injection. Similarly the combined features of series and shunt are available in UPFCs which can control all power flow parameters *e.g.*, voltage, impedance, and phase angle, whereas TCPST modify the magnitude and phase angle of the series injected voltage to the transmission line. In literature the parameters of these devices are optimized to enhance the transfer capability on already selected locations. But in this study the suitable locations for series and shunt FACTS devices are instead selected based on network analysis using various combination of sources and sinks. The sensitivity indices are initially used for locations selection but critical among these locations are utilized in extensive computational analysis for transfer capability enhancement. The system with FACTS devices at the specified positions are then subjected to congestion situation and coordinated control strategy based on multi agents system (MAS) is developed for FACTS devices control. The FACTS utilization is proposed for congestion alleviation by controlling the power flows and bus voltages *etc.* The parameter settings of respective FACTS devices at proposed locations are adjusted by controlling agents. The controlling agents intelligently decide the actions based on the requirements of the elements in the surrounding influential area of each device and also resolve the mutual contradicting effects and the transmission congestion is relieved by controlling the power flow and bus voltages. The power system is operated in such system conditions that lead to transmission congestion. The methodology of the work is summarized as under along with the justifications and contribution.

Network Analysis for Critical Locations An algorithm is developed for the determination of power transfer capability of a network using AC power flow method based on the iterative increase on power transfer between sources and sinks. The line thermal capacity and bus voltage stability limits are two main constraints considered to limit the transfer capability of the network. The power transfer is incremented due to the progressive load demand at the load buses, supplied by the generator buses in various cases until any constraint is violated. The locations *i.e.*, lines or buses with their respective parameters of power flow and voltage magnitude respectively are observed which could be violated the secure operating limits at certain demand values. Such critical locations of the network for respective power transfer are utilized for enhancement. Thus different sources and sinks are selected for power transfer and the critical elements are identified for each case and the system is checked for $n-1$ contingency cases to identify any other violating elements. The analysis is simple but computationally very extensive which will help in planning various locations suitable for FACTS devices. Sensitivity factors of real power flow performance index PI and voltage stability $L-index$ for lines and buses helped in finding the critical locations even more faster. The critical elements determine either the case is voltage dominant or thermal capacity dominant, so that the corresponding FACTS types are used. The method identify the most suitable location based on the practical AC power analysis with 100% accuracy without the assumptions.

FACTS Placement and Transfer Capability Enhancement The respective individual series or shunt FACTS devices are specified for line or bus location respectively for constraints improvement. In the proposed analysis the characteristics of respective FACTS devices are used to vary the power system parameters like line reactance and bus admittance for further power transfer enhancement. Thus the power transfer is further increased due to which other possible critical locations could be found and then constraints improvement at such locations could further enhanced until there is no further enhancement. The total transfer capability (TTC) in each source and sink combinations are finalized with respective FACTS devices and sizes. The sizes of the FACTS devices are determined based on the improvement in the respective constraints violation. The series FACTS devices are determined in terms of the percent variation in line impedance either increase or decreased for varying respective power flow. While the shunt FACTS devices are calculated in term of reactive power injections based on shunt admittance to improve the voltage of respective buses. Only two types of FACTS devices series and shunt are proposed in this work.

Distributed Coordinated Control System A distributed coordinated control strategy is proposed for these multiple FACTS devices which are placed at different locations in the network. The aim of the control system is to control the power flow of the lines in influential area of series FACTS devices and relieve the overloading lines. And improve the voltage magnitudes of violating buses in the influential area of shunt FACTS devices by controlling the reactive power. Coordination control is developed based on the multi agent system (MAS) which exchange the state information of the elements in influential area based on which controlling agents decided the control actions. Each element is equipped with agents to measure the respective state information and exchange with other agent while control agents decide the control actions for FACTS devices. Thus the power can be redirected from overloaded lines to other paths of comparatively less loading lines and similarly the voltage magnitudes of bus locations in the influential area are improved by providing the reactive power. The mutual influences of multi FACTS devices are efficiently resolved by coordination among the neighboring elements and the inter contradicting effects among the devices could be minimized. Finally, the coordinated actions of the FACTS devices enable the efficient network utilization, relieving congestion with enhanced transmission capacity and improve system performance. Therefore it is expected that the methodological steps of the planning phase for the FACTS placement and the coordinated control of FACTS devices in operational phase will provide a better system performance in real time operations.

1.4 Organization of Thesis

The thesis is organized as follows:

- **Chapter 2: Power Transfer Capability**
  This chapter provide a literature survey about different methods and algorithms used for power transfer capability determination and its enhancement due to the use of various FACTS devices. The significance of the power transfer capability in the energy market, their limiting factors and the steps for its determination are briefly discussed. Then various methods, which covered in different researches for calculation of power transfer capability are over viewed. A brief introduction of FACTS devices is given, proceed with their advantages in power system and an overview of the classification is presented. Then the characteristics of various FACTS devices are explained, which are used for power transfer capability enhancement in literature. Various optimization algorithms used in literature for different FACTS devices placement in power system to enhance transfer capability are covered. And the proposed solution and contribution of the work is discussed in the end.

- **Chapter 3: Power Network Analysis For Transmission Capability**
  This chapter presented the analytical method developed to identify locations for multiple FACTS devices that could enhance the transfer capability of the power network. The proposed modified RPF algorithm is discussed in detail, which is developed for the total transfer capability determination of the network. The formulation of total transfer capability in terms of AC power flow equations, is presented including the sensitivity indices of PI and $Lindex$. The formulation of PI sensitivity factor for multiple critical lines identification and voltage stability $L - index$ are described for identifying critical buses. The FACTS models are presented in terms of power system parameters for both series and shunt FACTS devices with respective limits. The complete illustration of the power network analysis method is explained with flowchart and methodological steps. In the end of the chapter the defined study cases are stated, which encompass the network analysis for all possible inter-area transfers to fully explore the probable critical locations.

- **Chapter 4: Distributed Coordinated Control System**
  The efficient utilization of transmission capability by control actions of multiple FACTS devices in power network for mitigating congestion in less constrained system operation is explained in this chapter. To achieved suitable parameters of FACTS devices in controlling the power flows, a coordinated distributed control system is presented. The control strategy

developed for FACTS devices to mitigate transmission congestion is discussed. Multiple series and shunt FACTS devices as specified in the proposed analysis method are modeled with some realistic sizes. A coordinated control system based on multi agent system is described. The structure of multi agent system, is illustrated, which is defined for different power system elements, for information collection with neighbors in the influential area and shared with the control agents for deciding control actions. The control agents are actually autonomous agents, decide the control actions for FACTS devices to counter the respective changes in the power system. The need of coordinated control is stated for multi FACTS devices deployed in power networks. The sensitivity functions, defined for controlling agents on the basis of which coordination is established, to decide the control actions for FACTS devices to resolve the congestion in the network. In the last, a dynamic load profiles are discussed which are used to validate the performance of the coordinated control of FACTS devices in mitigating congestion.

- **Chapter 5: Results and Discussion for Transfer Capability**
  The first part of the work is related to the planning phase, that is to identify locations for FACTS devices to enhance transfer capability of the network. The results of the proposed analysis method implemented on various standard IEEE networks *i.e.*, 30, 39, 57, 118 and 300 bus systems are discussed in this chapter. The analysis is based on two case studies, which is used to identify different critical locations for the power transfer among different sources and consumers. The first study case analyzed the power networks for the overall system power transfer, subjected to equal contribution of all generators and loads, irrespective of the area. The respective variation in power flow and bus voltages are shown in plots. The FACTS devices placement according to the defined method are displayed with plots and discussed in detailed. The total transfer capability and powers contribution of all sources and consumers are shown in tables. The violating buses and lines in normal and contingency cases are also displayed in tables and explained. In the second study case, the inter-area power transfers among the areas, are considered. The power networks are analyzed for the power transfer, subjected from source area to sink area for identification of critical locations. The FACTS devices are provided at respective locations for enhancing the power transfer capability. Transfer capability of each areas combination is tabulated along with respective violations in normal and contingency cases. The results of all the test networks are discussed for each study case. The presented results are steady state improvement in total transfer capability and the corresponding variation in power flow and bus voltage both in normal and contingency cases.

- **Chapter 6: Results and Discussion of Coordination Control System**
  This chapter discussed the results of the second part of the work *i.e.*, operational phase. All the analyzed IEEE test networks 30, 39, 57, 118 and 300 buses are supplied with realistic FACTS models at the proposed locations, and the system is tested for different congestion scenarios. The power system operation is run for a 24 hours of dynamic load profiles in which the system is congested with line capacity and voltage stability limits violation. Two load profiles are basically chosen for feasible network operation. The results of the congestion of the systems with and without FACTS devices are shown in various plots of power flows and bus voltage magnitudes. The dynamic voltage profile and power flow for operating 24 hours of load profiles in normal case are shown with improved constraints and mitigate the congestion, are discussed with correspondence plots. The number of violating lines and buses at each load value in contingency cases are given in bar plots.

- **Chapter 7: Conclusion and Future Recommendations**
  The conclusion of the work is stated in this chapter. The contribution and summary of the work is briefly discussed. In the last the future recommendation and suggestions of the work are also proposed.

1.5 List of Publications

The following research papers are published during the course of PhD work.

Article:

- U.Ikram, W. Gawlik, and P. Palensky,“Analysis of Power Network for Line Reactance Variation to Improve Total Transmission Capacity” Special Issue Electric Power Systems Research 2017. *Energies*, Energies 2016, 9(11), 936; doi: 10.3390/ en9110936, 10 November 2016

Conference Proceedings:

- M. Shahzad, I. Ullah, P. Palensky, and W. Gawlik, “Analytical approach for simultaneous optimal sizing and placement of multiple distributed generators in primary distribution networks,” in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, pp. 2554–2559, 2014.

2 POWER TRANSFER CAPABILITY CALCULATION AND ENHANCEMENT

2.1 Introduction

The transmission network is the backbone of power system, interconnecting large geographical area, which transfer reliable and economic electrical energy in large amount to even far located customers. Bulk power transportation is possible at high voltage for negligible line losses over long distances. The transmission system are expanding, interconnecting other surrounding networks for security, reliability and system restoration purposes in vertical integrated system which become a market need in deregulated era. Thus, inter-area tie lines provide access to cheap generations in market. The paradigm of grid integration in deregulated market structure, shifted to large geographical areas for optimal utilization of resources. Therefore, it becomes more essential for system operator to determine the power transfer capability of the network in order to efficiently allocate it to the market participants, ensuring security and reliability of the system. Power transfer capability of the network shows the power transfers in between the areas without compromising system security. This information is very important for planning and operation in the bulk power market. So the system bottlenecks can be known to operators while implementing the power transfers. So repeated estimates are required to reduce the risk of expected line overloads, equipment damage, or blackouts *etc.*, occurrence. Therefore, in deregulated market structure, the hourly value of available transfer capability (ATC) is supposed to be placed on open access same time information system(OASIS) website, by the ISO for the market players, to reserve the necessary transmission service for their transactions.

This chapter introduces the literature survey about different methods and algorithms used for power transfer capability determination. Starting from the definition of power transfer capability and the constraints which limits the power transfer capability of power system. Various suggested methods in literature for calculating power transfer capability, will be explained. Then the use of various FACTS devices in power transfer capability enhancement will be briefed. And later on methods used to place the FACTS devices in the network for this purpose.

Transfer capability of transmission system, is the ability of interconnected electric systems to transfer power from one area to another area over all transmission lines between those areas under specified system conditions with affecting reliability of the system [8]. The area could be an individual electric system, a region, or a portion of any of system. Transfer capability is directional quantity and it is not the same in the opposite direction. The transfer capability is different from capacity because it depends not only on the transmission capacity of the transmission lines but also depends on the generations, customer demands and the system conditions. In transmission, the capacity usually refers to the thermal rating of a particular transmission element. It is the ability of a transmission line to transfer electric power, operated in the interconnected system. Similarly transmission capability between two areas is not the aggregated transmission capacities of lines connecting these two areas rather less than the aggregated capacities of those lines. The transfer capability is generally determined using computer simulations of the interconnected power system based on specific set of operating conditions. These off-line simulations are performed well before the system approach to that operational state. The snapshots of the simulation based on the projections of different factors, are used to analyze the network performance and the available transfer capability. The factors usually looked in these simulations are projected demands from base case, generation dispatch, configuration of the system, base schedule transfers and contingency cases. The transfer capability of the network vary as the system conditions are changing in real time therefore the transfer capability is required to periodically calculated and updated for power system operation. Similarly the actual value of transfer capability can often be different from these off-line studies due to network conditions. So more uncertainty is expected in far future projected simulations. Anyhow, the transfer capabilities based on these simulation studies are generally viewed as reasonable indicators of actual network capability.

The power transfer capability of a transmission system is limited by the physical and electrical characteristics of the systems by one or more of the following factors:

- Thermal Limits: The maximum amount of electrical current that a transmission line or electrical facility can conduct over a specified time period before it sustains permanent damage by overheating or before it violates public safety requirements.
- Voltage Limits: The bus voltages of the power system must be within the acceptable range of minimum and maximum limits. The minimum voltage limits allow the maximum amount of electric power that can be transferred without causing any damage to the system or customer facilities. A widespread collapse of system voltage can result in a blackout of portions or all of the interconnected network.
- Stability Limits: The transmission system must be capable of maintaining stability after the transient or dynamic disturbances. The generators begin oscillating relative to each other after the transient disturbance occur, which may cause fluctuations in the system frequency, line loadings, and system voltages. The oscillations are diminished as the systems attain a stable new operating condition, otherwise, the system become unstable and the generators lose synchronism. The results of generator instability may damage equipment and cause uncontrolled, widespread interruption of electric supply to customers.

Total Transfer Capability (TTC) is the maximum amount of electric power that can be reliably and securely transferred from one location to another or across particular paths or interfaces. The steps for TTC determination are as under:

- Base system conditions are defined for the specific period, with customer demands, generation dispatch, system configuration, and the scheduled transfers.
- Contingency cases of generations and transmission system throughout the network are evaluated in order to determine the most restrictive facility outages case in analyzing transfer

capability. The evaluated contingency cases are following the same planning criteria or guides for the system. The evaluation process consist of variety of system operating conditions because the most critical contingency cases and their limiting system elements are different.

- The power transfer capability is limited by the physical and electrical characteristics of the systems as discussed before. The thermal, voltage, and stability constraints are identified as the most restrictive limitations for the critical contingencies.

The TTC is defined as:

$$TTC = Min(\text{Thermal Limit, Voltage Limit, Stability Limit}) \tag{2.1}$$

- The electric power transfer in transmission network causes parallel path flows occur due to structure interconnected system. So this can increase the transmission burdens on other nearby transmission elements which are not part of this transaction. Thus the determinations of transfer capability must consider the limits of the overall interconnected network. Because the parallel path flows may limit the transmission facilities of the systems other than the transacting systems and thus limiting transfer capability.

- Non simultaneous transfers capability are inter-area transfers independent and non-concurrent with other area transfers while the simultaneous transfer capability are concurrent with other multiple transfers. In simultaneous transfer capability, there are inter-dependencies among the concurrent area transfers which is neglected in non simultaneous capability. Therefore simultaneous transfer capability may be lower than the sum of the individual non-simultaneous transfer capabilities.

Available Transfer Capability (ATC), is the amount of transfer capability of transmission network available for further commercial activity over the already running transfer commitment. The value of ATC is very important in balancing both technical and commercial issues. In ATC calculations the effect of instantaneous power flow conditions on the entire interconnected transmission network is considered. Similarly the uncertainty in the system conditions are also accommodated with required flexibility for secure operation in interconnected network. Therefore two types of transmission capability margins are considered in ATC determination *i.e.*, Transmission Reliability Margin(TRM) and Capacity Benefit Margin(CBM). TRM defined the amount of transfer capability reserved for ensuring the reliability in the interconnected transmission network. TRM deals with the inherent uncertainty in system conditions and the need for operating flexibility to ensure reliable system operation. CBM is the amount of transfer capability reserved by load serving entities to ensure the reliability of generation in the interconnected system. The CBM is locally applied than TRM, which is more of a network margin. So mathematically the ATC can be defined as:

$$ATC = TTC - TRM - \text{Existing Transmission Comitments(including CBM)} \tag{2.2}$$

2.2 Methods for Transmission Capability Calculation

There are many methods proposed to calculate the transfer capability of the transmission network in literature. These methods are generally categorize in following different types:

2.2.1 Deterministic Methods

The deterministic methods are based on the mathematical modeling of TTC/ATC based on AC power flow equations, which are computationally solved using Newton Raphson method. The following three methods are mostly used.

- Continuation Power Flow(CPF) Method: The continuation power is used to find a continuous power flow solutions for a given load change scenario. In this method the power flow solution curve is traced through the nose point without numerical difficulty [9]. The problem of singularity in the Jacobian of power flow equations is avoided by reformulating with the load parameter. Consequently a set of solutions of power flow is obtained from a base case up to the critical point in a single program run. Predictor-corrector scheme is employed to find a solution path of augmented power flow equations with load parameter. Starting from a known solution, a tangent predictor is used to estimate another solution corresponding to a new load parameter value. The corrector based on modified Newton Raphson technique is used to correct the estimated power flow solution [10] and [11]. The advantage of CPF is the elimination of ill-conditioning so the complete P-V and V-Q curves to calculate voltage stability margins but the complexity in implementation.
- Repeated Power Flow(RPF) Method: RPF method is also a very simple mathematical based method, used for calculation of transfer capability of power networks [11]. In this method, the system load and power generation is increased with a specified rate until any of the defined operating limits are violated. The conventional power flow equations are solved using Newton-Raphson Method at each succession of points in the direction of specified transfer in RPF. The advantage of this method over other is its implementation simplicity with control parameters and provide P-V and V-Q curve for voltage stability study
- Optimal Power Flow(OPF) Method: In optimal power flow method of calculating the transfer capability, the reactive power flow, and voltage limits as well as the line flow effect are determined for full AC power flow equations in security constrained optimal power flow (SCOPF) and transfer-based security constrained optimal power flow method (TSCOPF). The objective function is mathematically formulated with respective equality and inequality constraints. Various optimization approaches [11] and [12] are used to maximize the total supplied generation power and load demand at specified buses. There might be a convergence problems due to many variable and equations for large scale power network [9]. Heuristic optimization algorithms like genetic algorithm(GA)are used in computing ATC between two specific areas of power network [13].

2.2.2 Sensitivity Based Methods

The deterministic methods are AC power flow methods and therefore these are better in accuracy but require more computational time. Power flow sensitivity based methods are fast methods for determining transfer capability and also well proven in literature. This method is mainly based on the network linear sensitivity factors which are derived from DC load flow approach. The factors relate the the variation in line flows due the changes in generation in the specified network configuration. These factors are basically three types, Power Transfer Distribution Factors (PTDF), Line Outage Distribution Factors (LODF), Generator Outage Distribution Factors (GODF). These factors are already used in security analysis as fast power flow calculation in offline contingency analysis [14]. In [15] a probabilistic composite system evaluation program (PROCOSE) was developed for computing the ATC based on DC power flow model. A non-iterative method calculate single and multiple ATC of transmission systems. Multi-transactions case in ATC calculation is formulated using PTDF in [16]. The accuracy of DC load flow approach is poor due to the assumptions especially for high X/R ratio and the voltage profile is not always flat[17]. The power flow sensitivity methods are another fast methods which are more accurate than DC load flow approach [18] and [19]. In [20], [21] and [22] AC PTDF based approach has been proposed in determination of ATC for multi-transaction using sensitivity based approaches. Another fast method of ATC determination by incorporating reactive power flow for linear ATC determination in [23],[24]. Similarly cubic-spline interpolation techniques are used for fast evaluation of ATC in [25],[26].

2.2.3 Artificial Intelligence (AI) Techniques

In recent years artificial neural networks (ANN) has achieved considerable attention in solving various power system problems like unit commitment, economic dispatch, security assessment, load forecasting etc.,[27]. ANN with suitable hidden layers consist of neurons that are capable to represent any type of non-linear functions. Through a sets of inputs and targets data, ANN learns complex functions through appropriate algorithm for training[28]. In [29] the model of ANN is developed for calculating transfer capability based on optimal power flow method. In this paper, multi-layer feed forward neural network is used to calculate the ATC between two specific areas in the network. To reduce the computation burden in real time execution of ATC, different Artificial Intelligence techniques and Adaptive Neuro Fuzzy Inference System(ANFIS) are used in [28]. In [30] neural network based method for ATC determination in a competitive electricity market is proposed, having both bilateral and multilateral transactions. An ANN model is developed for multi-area ATC based on ACPTDF formulation in [21]. Neural network based approach for fast and accurate estimation of system ATC (SATC) considering a suitable TRM, under distributed computing environment in [31]. A radial basis function neural network based method has been proposed in [32] to determine ATC in electricity markets, having bilateral as well as multilateral transactions.

2.3 Flexible AC Transmission System (FACTS) Devices

Transmission network facilitate the power system in efficient transportation of energy supply to various load centers with high reliability. The transmission grids carry the electric energy to diversely located load centers. In modern age the power systems are highly interconnected to exploit the load diversity, sharing energy reserves, improving the economic gain and increase the competition in the deregulated environment. But on the other hand the security is more threatened in power system interconnection for the chance of disturbances propagation, initiated in one area and spread over to the entire system and may cause major blackouts of cascaded outages.

Generally there is no provision of power flow control over the transmission line in AC power network. The transmission lines are mostly equipped with circuit breakers to protect from various faults with limited number of open and close operations at a time. But the control of power over the transmission line could not be possible using circuit breakers. Inherently the power over the transmission line is determined by the power injected at the two ends [33]. Suppose two areas, each with its own generation and local load, interconnected through a line as shown in Figure 2.1.

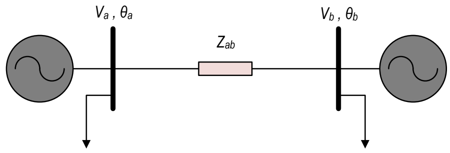


Figure 2.1: Transmission line connecting two areas

The power flow (P) on the line is determined by the the generation load mismatch in each individual areas which can be calculated based on the equivalent circuit shown in Figure 2.1 as follows:

$$S_a = P_a + jQ_a = V_a(\frac{V_a - V_b}{Z_{ab}})^* \tag{2.3}$$

where Z_{ab} is the series line impedance, V_a and V_b are the regulated voltages at two areas, the net difference of available generation at both area determines the flow of power in the line. The voltage magnitudes, line impedance are assumed to be constant then the power flow between the areas will be based on difference of the bus angles. Normally in large power systems more than one line connecting to an area and thus form a meshed network. This improves the system reliability, as the power from generators to loads follow multiple paths, so tripping of one line does not stop the power supply to the load. The power flows in the lines are determined by Kirchhoff Voltage Law (KVL) and thus increasing/decreasing the power flow in one line will also affect the flow of power in some other lines. In general, it can be stated that the power flows in individual lines are determined by KVL and do not follow the requirements of the contracts (between energy producers and customers). It means, the power flow between two nodes cannot be ensured to follow a predetermined path.

In recent years, greater demands have been placed on the transmission network, and these demands will continue to increase because of the increasing number of non utility generators and heightened competition among utilities themselves. Added to this, the problems of financial, political and environmental in acquiring new rights of ways. Increased demands on transmission, long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply. The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability. It must be stressed, however, that for many of the capacity expansion needs, upgrading or up rating and voltage stability of existing lines and corridors will be necessary.

According to IEEE Flexible AC Transmission System (FACTS) are the alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. Electric Power Research Institute (EPRI) has conducted a study to maintain the flexibility and stability of power systems by using electronic power controllers in late 1980. Which was later presented at IEEE meetings, forums, and workshops, and in international conference organized by EPRI in 1990 [34]. This concept was later on clearly discussed by Hingorani [35]. FACTS devices control the power flow over the transmission network according to the commands of the control center.

2.3.1 Advantages of FACTS Devices

FACTS devices are developed to improve the performance of the long distance AC transmission lines. The technology is evolved and the application is extended to other power system issues of power flow, voltage stability and power oscillations. And there are excellent experiences of their used in different parts of the world. The FACTS devices are getting more mature with high power ratings and reliable in operation. Various FACTS devices are applied in shunt connection, in series connection or the combination of both in large interconnected systems for their controlling capabilities. There are various advantages that can be achieved using FACTS devices in electrical transmission systems, which are as follows:

* FACTS devices give a greater control to the power flow.
* To operate near the thermal limits of the transmission lines at safe load levels is made possible due to FACTS devices.
* FACTS devices enhance the capacity of power transmission line.
* FACTS devices also enhance the stability limits of power system which increase the system security.
* FACTS devices are effectively used for damping the oscillations in power system.
* They provide the flexibility to the transmission and distribution.
* Using FACTS devices, transmission assets utilization can be improved.
* Fast FACTS controllers increased the transient stability of the power grid.
* Various FACTS devices have improved the reliability of power system.
* FACTS devices contribute in environmental benefits by better utilization of existing transmission assets.
* FACTS devices are environmentally friendly.
* Congestion in transmission can be resolved using FACTS devices.

FACTS devices are broadly categorized in two generations as shown in Figure 2.2.

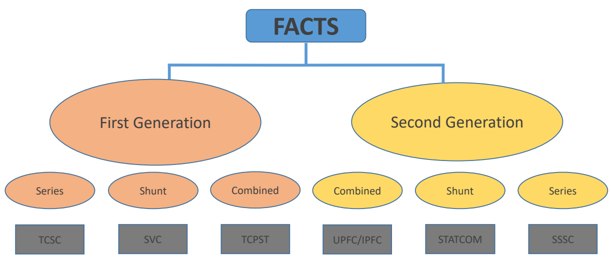


Figure 2.2: FACTS Devices Types

2.3.2 First Generation FACTS Devices

These FACTS devices are based on the real circuit elements of variable impedance using traditional power electronic switches like thyristor for switching the inductors and capacitors and tap switched quadrature transformer. The FACTS devices of this generation are made of the following basic thyristor controlled components.

Thyristor Controlled Reactor (TCR): A thyristor valve in series with an inductor, to provide an effective variable reactance by partial conduction control of the thyristor valve.

Thyristor Switched Capacitors (TSC): A thyristor valve in series with a fixed capacitor, to give varied capacitive reactance in stepwise by full or zeros conduction operation of the thyristor valve.

The FACTS devices belong from this generation are

Thyristor Controlled Series Capacitor(TCSC)

Thyristor Controlled Phase Shifting Transformer (TCPST)

Static Var Compensator (SVC)

2.3.3 Second Generation FACTS Devices

These are voltage source converter (VSC) based FACTS devices that employs self commutated DC converters with AC converters, which produce the reactive power internally for transmission line compensation without reactors or capacitors. VSC consist of semiconductor devices with high frequency switching such as gate-commutated thyristors, gate turn-off thyristors (GTO), Integrated Gate Bipolar Transistor (IGBT), MOS Turn-off Thyristor (MTO), and Integrated Gate Commutated Thyristors (IGCT). These devices provide reactive power compensation or phase shifting to control the transmission line impedance, bus voltage and angle. Also using these devices the real and reactive power flow over the line can be controlled [36]. The devices belongs to this category are:

Static Synchronous Series Compensator (SSSC)

Static Synchronous Compensator (STATCOM)

Unified Power Flow Controller (UPFC)

Interline Power Flow Controller (IPFC)

The FACTS devices can be classified based on their connection in the power network as

Shunt connected devices

Series connected devices

Combined series-shunt devices

Combined series-series devices

2.4 FACTS Devices Used for TTC Enhancement

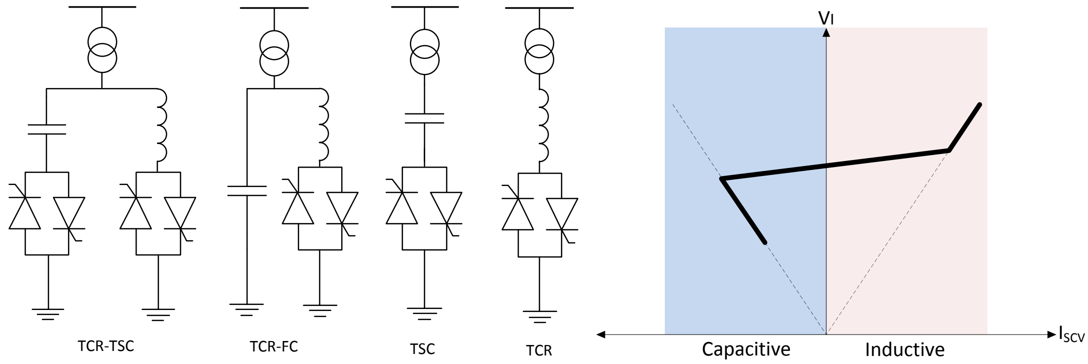
For increasing the transmission capability, power flow and bus voltage magnitude or phase angle in an interconnected system are required to be controlled. It is also very important to look at the effective stability progress when using the features of transmission lines for an economical solution. Flexible AC transmission systems(FACTS) devices can meet these requirements, which can be used to control bus voltages, line impedance, and phase angle in the transmission network, so that can be operated near their thermal capacity limit and increase the transmission capability. Many researchers have investigated various methods to use the features of FACTS devices in enhancing the transmission capability [7],[37]. In this section, the six mostly used FACTS devices are described along with their effects in improving transfer capability.

2.4.1 Shunt FACTS Devices

These devices are used for shunt compensation, which may of variable impedance, variable source or the combination of both in shunt connection to the power system. This device reactive power compensation in a transmission system which could increase the transmittable power, improve the steady-state transmission characteristics as well as the dynamic voltage control to increase transient stability and power oscillation damping.

2.4.1.1 Static Var Compensator (SVC)

This is a shunt compensation device, which is commercially used to improve power quality and installed for the first time in 1972 by GE [38]. Due to the considerable reactive power load variation in each hour, the voltage magnitude is depressed or even in worst case collapse. SVC has been used in more than 100 locations in world to continuously provide reactive compensation for controlling dynamic voltage oscillations in various system conditions for improving power system stability [33]. Using SVC at multiple suitable location in the network can increase the transmission capability by smoothing the voltage profile for different operating conditions. The SVC can be configured using different thyristor controlled components of TCR and TSC with fixed capacitor (FC) in series or parallel along with step up transformer for connecting to transmission system. The practical thyristor valve consist of many series connected thyristors in the SVC building while the reactor, capacitor and transformer are kept outside of the building. A triggering control system triggered the respective polarity thyristors to provide the reactance or capacitance. Different combination of these components are connected in series and parallel with each other or with high voltage AC fixed capacitors as shown in Figure 2.3(a) providing the reactive power compensation both in capacitive and inductive domain as shown in Figure 2.3(b). SVC was used for improving system reliability, dynamic stability, and power transmission capability of transmission line. In [39] the transmission capability is increased with effectively improved the bus voltage under fault conditions. In [40] the power system is analysed by using the SVC in two typical buses, which increased the power transfer capability of the line and improve the bus voltage. A feasibility study on using SVC for voltage control and the transfer capability enhancment of the transmission system in south east Romania is performed in [41]. A static SVC model is implemented in power flow analysis and control(PFAC). The static and dynamic analyses shown the improvement in voltage levels, which leads a better utilization of the transmission grid and the dynamic performances of the power system.



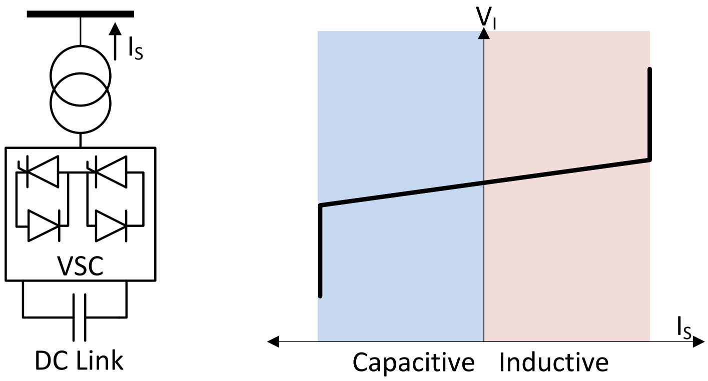
(a) Various SVC models (b) SVC characteristic curve

Figure 2.3: Static Var Compensator SVC

There is a steady increase of SVCs worldwide and recently installed in Chile, Canada, Finland, South Africa and USA *etc.*. In Europe, most of the installation of SVCs are found in the UK, the latest installed SVC in Finland. Installations of SVCs in Europe would be increase, especially for growing penetration of RES. The latest developments is of relocatability in South Africa and the UK [42]. Thus help in fully exploit their potential according to the changed needs in the power system with compact structure which could be easily relocated within a qaurter year of interval.

2.4.1.2 Static Synchronous Compensator (STATCOM)

STATCOM is an advanced Var compensation which based on VSC instead of controllable reactor and switched capacitor. It is a faster response modular and easily interfaced with capacitor, or other real power sources. STATCOM can provide variable reactive power similar to synchronous condenser but with better dynamics and lower operation and maintenance cost. The AC output of the VSC is controlled for the required reactive current flow for any AC bus voltage DC capacitor voltage is automatically adjusted as required by the converter. STATCOM can also used to absorb system harmonics. STATCOM can have an active power source like a battery, flywheel, superconducting magnet, DC storage capacitor etc.,[35] at the DC side for the required injected current as given in Figure 2.4(a). The reactive power exchange between the converter and the AC system is similar to that of the control of rotating synchronous machine. The converter generates reactive power(capacitive) if the AC system voltage is decreased down the output voltage generated by the converter and current flow from converter toward AC system. If the AC system voltage magnitude is above the produced output voltage, the converter absorbs reactive power (inductive) from the AC system and current flow is from AC system to the converter. There will be no reactive power exchange if the voltage of the AC system and the converter are equal. In the Figure 2.4(b), the maximum current is independent of the voltage as compare to SVC. It means STATCOM can provide its full capability even in sever contingency. STATCOM does not require passive elements like inductors and capacitors. STATCOM's are used in transmission and distribution network for better power quality and stability [43]. STATCOM can also provides dynamic voltage support in transmission and distribution network [33]. STATCOM perform better and provide more flexibility then SVC. STATCOM is used to increase the transfer capability of the network [44]. The STATCOMs installed worldwide is limited and few devices deployed in the china, Japan, USA, and the only application in Europe is in UK.



(a) STATCOM models (b) STATCOM characteristic curve

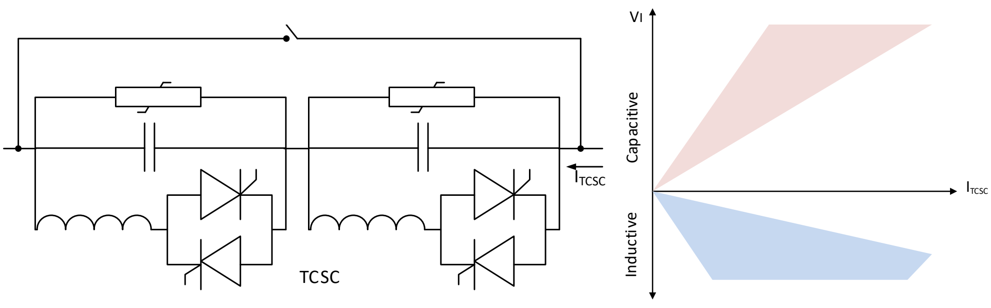
Figure 2.4: Static Synchronous Compensator STATCOM

2.4.2 Series FACTS Devices

These FACTS devices provide series compensation to transmission lines by controlling the impedance of the line and increase the transmittable power. The series compensator also acts as a series connected controlled voltage source in the transmission line, to control its current which is in quadrature with the voltage. Series FACTS devices are used to achieve full utilization of the transmission assets, controlling power flow, improve the stability and effectively damp the power oscillation.

2.4.2.1 Thyristor Controlled Series Compensator (TCSC)

TCSC is a series thyristor controlled compensation device. It is the second most commonly used FACTS device in different parts of the world. The basic objective of its use is to reduce the electrical length of the transmission line and has great potential to increase the transmission capability through the line. The automatic thyristor control are integrated in the TCSC. It also increase the stability margin of the transmission system and being effective in damping sub synchronous resonance(SSR) and power oscillation [35]. The thyristor control make it possible to connect series capacitor for variable series compensation in long transmission lines. A basic TCSC module consists of a TCR in parallel with fixed capacitor but actually more than one series connected modules are used as for desired voltage ratings. A single line diagram of TCSC is shown in the Figure 2.5(a). All the power components are located on an isolated platform while the control and other auxiliary parts are located on the ground [45]. TCSC is a mature technology available for application in AC lines of voltage up to 500 kV. The controls algorithms operate the thyristor valve to provide variable reactance in both inductive and capacitive region by adjusting the delay angle of the thyristors as shown in Figure 2.5(b). TCSC was used by the Western Area Power Administration (WAPA) at the Kayenta substation in 1992. It has increased the power transfer on the 230-kV line by 100 MW and located in the mid-point of the line. A complete modular TCSC was installed and operated by the Bonneville Power Administration (BPA) in 1993 at the Slatt substation.

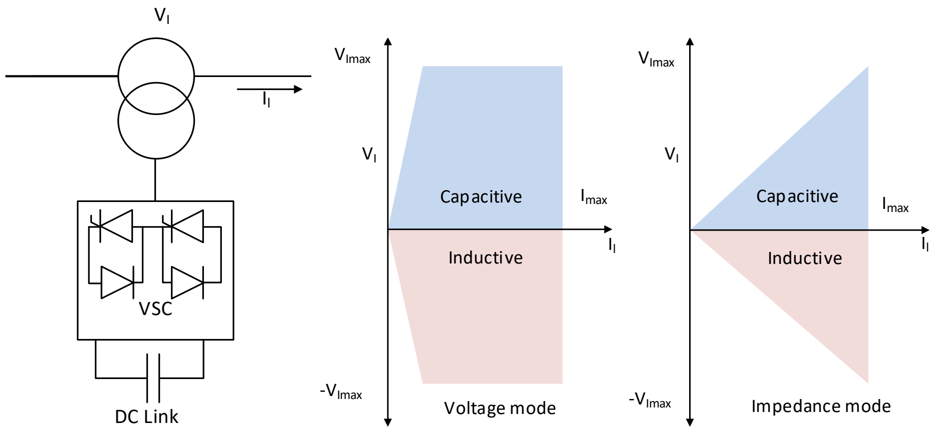


(a) TCSC model (b) TCSC characteristic curve

Figure 2.5: Thyristor Controlled Series Compensator TCSC

2.4.2.2 Static Synchronous Series Compensator (SSSC)

SSSC is an advanced controlled series compensator based on voltage source converter. SSSC injects synchronous inductive and capacitive voltage of variable magnitude in quadrature with the line current for power flow control [46]. SSSC is connected through a transformer in series with a transmission line. SSSC can transfer both active and reactive power within the power system network. SSSC use its own DC capacitor to control active and reactive power of transmission line and to regulate bus voltage, instead of drawing reactive power from the transmission system. The configuration of an SSSC is as shown in Figure 2.6(a). It consist of a DC link source, a VSC and coupling transformer. It is looking to be simple but actually it is complicated because of the mounting platform and protection for semiconductors like IGBT. The characteristic of SSSC in both voltage and impedance mode are shown in Figure 2.6(b). SSSC control the voltage phase



(a) SSSC model (b) SSSC characteristic curve

Figure 2.6: Static Synchronous Series Compensator SSSC

angle with respect to line current and exchange active power with the AC system. So SSSC can simultaneously effect reactive and resistive components of the line impedance. The SSSC has a natural immunity to resonance, in the capacitive compensation, the voltage drop across output inductive impedance of the SSSC due to the leakage inductance of series transformer, is balanced at fundamental frequency. So there would be an effective output inductive impedance at all frequencies except the fundamental operating frequency. And the SSSC would naturally not initiate subsynchronous system oscillation as in series resonant circuit the inductive line impedance form with capacitor. Also due to fast response SSSC would be very effective subsynchronous oscillations damping[42]. SSSC is used to enhance power transfer along with the required active and reactive power flow through a transmission line [47].

2.4.3 Combined FACTS Devices

These FACTS are connected in shunt as well as in series combination and thus are capable in providing both shunt and series compensation as required. The respective combination could provide the reactive power compensation and voltage control like shunt devices as well as could enhance the active and reactive power flow control, power oscillation damping and both transient and dynamic stability, like series devices.

2.4.3.1 Thyristor Controlled Phase Shifting Transformer(TCPST)

Phase shifting transformers have been used for controlling power flows of transmission lines in steady state since 1930. Thyristor controlled PST are called Static Phase Shifting Transformers (SPST) or Thyristor Controlled Phase Angle Regulator (TCPAR). TCPST modify the phase angle of bus voltages and the magnitude of series injected variable voltage to enhance power flow. TCPST can provide the power oscillation damping and control frequency by adjusting the phase angle [48]. It can also improve the transient stability by speeding the phase angle shift [33]. The TCPST basic structure is given in Figure 2.7. Due to the cost of transformer, TCPST is less popular than other FACTS like SVC and TCSC.

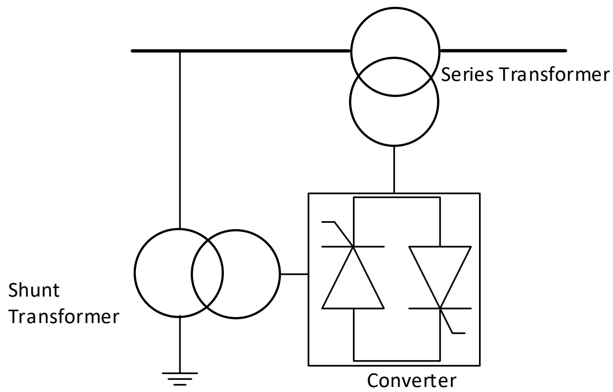


Figure 2.7: Thyristor Controlled Shifting Transformer TCPST

2.4.3.2 Unified Power Flow Controller (UPFC)

UPFC is a versatile advanced FACTS devices which combine the shunt and series compensation. The concept was proposed by Gyugyi in 1991. The UPFC provide multifunctional flexibility to solve many problems in transmission system. The UPFC can simultaneous control all the power system parameters like active power flow, reactive power flow, and bus voltage magnitude and phase angles. It consist of shunt and series transformer connected through two voltage source converters to a common DC capacitor. The DC part of the two converters let the active power to be exchanged between the shunt and series transformer to control the phase shift of series voltage. The configuration set up is given in Figure 2.8. Due to the protection for voltage source converter UPFC getting expensive which limit its applicability. There are some other configurations like Interline Power Flow Controller (IPFC), which is connected between two transmission lines to control the power flow. Grid Power Flow Controller (GPFC) is another configuration which combine three or more shunt and series converters to extend the controlling capability of the device. The UPFC combines the features of a STATCOM and SSSC. It could be operated as a series impedance while only series parts is utilized and become a static VAR source while only shunt part is operated.

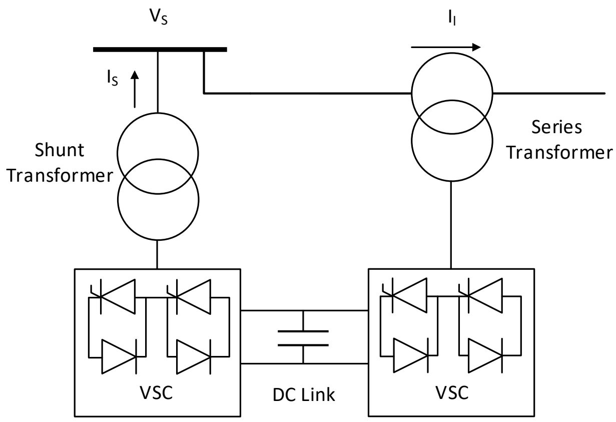


Figure 2.8: Unified Power Flow Controller UPFC models

Currently there are three UPFC implemented worldwide in the USA, and South Korea. The joint effort of the EPRI and Westinghouse, it is being installed for the first time in 1998. Similarly New York Power Authority and the EPRI have jointly developed in the form of convertible static compensator project. The third UPFC installation is carried out by Korea Electric Power Corporation (KEPCO) of 80 MVA at 154 kV [42]. UPFC is used for increasing ATC in [49] with different power flow patterns. In [50] UPFC is used to overcome the damping of real and reactive power and power fluctuation problem in convention control scheme. The PTC is increased by installing UPFC, reducing the fault current magnitude and oscillation in excitation voltage. UPFC was compared with the Sen Transformer (ST) in [51] for enhancing ATC using optimal power flow based approach in multi and bilateral transactions for intact and contingency cases.

2.4.4 Overview of Optimization Techniques for FACTS Placement

Many researches are being done based on optimal placement of multiple FACTS devices. A short overview is given in this section.

2.4.4.1 Particle Swarm Optimization (PSO)

Particle swarm optimization [52] was proposed for multi-objective optimization to minimize power loss and maximize TTC with system constraints [53]. The power transfer capability of power transactions between source and sink areas is enhanced. The optimal types, locations, and parameter settings of UPFC, TCSC, SVC are used in the study. In [37] single area and multi-area

ATC are analysed using TCSC, SVC and UPFC in single device and multi type three similar and different device combinations. PSO is employed for the optimal settings of the FACTS devices.

2.4.4.2 Genetic Algorithm(GA) Real Genetic Algorithm (RGA)

ATC is boosted using TCSC for bilateral and multilateral transaction in [54] using GA and PSO for optimal setting of TCSC. Real code genetic algorithm (RGA) is used to optimized the locations and controlling parameters of TCSC and SVC in deregulated environment[55] and[56]. By installing SVC voltage profile is improved as a result ATC enhanced. Similarly TCSC also proved the ATC improvement both in thermal dominant case and voltage dominant case. RGA Analytical hierarchy process (AHP) and fuzzy sets are implemented in [57] to determine the optimum locations and parameters of TCSC to increase ATC. The proposed methodology is implemented using repeated power flow procedure.

2.4.4.3 Bees Algorithm (BA)

Optimal locations, types and parameters of SVC, TCSC and TCPST are find based on bees algorithm to maximize ATC in a deregulated power system [58]. The proposed algorithm effectively maximized the ATC.

2.4.4.4 Multi Optimization Algorithms)

Hybrid tabu search and simulated annealing (TSSA) are proposed to optimized number and allocation of FACTS devices for power transfer capability enhancement in [59]. Optimal power flow (OPF) technique is used in power transfer capability calculation. In [60] various optimization algorithms like PSO, differential evolution(DE)and composite differential evolution(CoDE) algorithms are compared in optimizing the location and control of FACTS devices for loadability enhancement. Three FACTS devices TCSC, SVC and TCPST are used. Similarly multi type FACTS devices of SSSC, STATCOM and UPFC are optimally sized and located simultaneously through the harmony search algorithm (HSA). A multi objective function consists of increasing the TTC, decreasing line congestion, and minimizing losses are formulated for the optimization problem. Transient stability is improved based on UPFC utilization in [61] and enhance ATC using an OPF method. The ATC is calculated for both transient and steady-state stability constraints. The size of UPFC is optimized based on OPF formulation. The installation of UPFC in system with parallel lines is discussed in [62] , where large impedance lines are supposed for UPFC due to the comparatively higher losses to increase the total PTC. The Newton-Raphson load flow method is used for ATC calculation in [63], which is enhanced by suitable allocation of UPFC and the results are verified by continuous power flow method. A dynamic model of UPFC is developed for power transfer capability enhancement through the transmission in [64]. the shunt and series controller of UPFC are developed based on fuzzy logic.

2.5 Proposed Solution

Instead of placing the FACTS devices optimally in the system for respective problem formulation, a generalized method is proposed, in which the electrical power network can be analyzed for the maximum power transfer capability with essential system security and stability. The power transfer can be increased to the maximum accommodation of load and generations in the system. The main objective of the analysis is to identify the critical locations based on system security or stability violation that limit the transfer capability of the network. These locations are proposed for suitable FACTS devices and the maximum sizes at these locations are determined based on the improvement of the system violating constraints with further rise in power transfer. The proposed method will not only help in planning phase to provide the information of critical locations and their sequential occurrence, but could also be helpful in finding the optimal parameters settings for system operation with a wide span of system conditions. So the strategy adopted in the proposed method is the selection of not only the critical positions appeared in determining the power transfer capability, but a set of other suitable locations as well.

The electrical characteristics of the transmission lines in grid topology ascertain the power flows and the electric distances of load buses from the source bus determine the voltages of the buses. So to identify locations on the basis of such characteristics is very helpful to short list the critical locations. And these locations could be engaged in violating the constraints of line thermal capacity and voltage stability and give chance to congestion. So in other words it is said that these locations are limiting the power transfer capability of the network. It is therefore, proposed in this work to identify such locations for FACTS devices to extend the capability by improving the constraints. And that can't be identified by optimal solutions, which are more focused on optimal parameters settings of power flow. This is because, these solutions ascertain the power system variables like the power flow over the lines and power injections at buses so that the constraints are set within the limits. The electrical characteristics of the lines constitute the distribution of power flows over the network elements according to the Kirchhoff law's. And thus, larger power would flow on the least impedance paths in multi parallel paths connecting source and sink. The lines of such characteristics would reach their capacity limit, and become critical in limiting transfer capability. Similarly the electrical distances of the consumer nodes from the source nodes would establish the voltage magnitude. Those nodes which are electrically far from the generators nodes could be more susceptible to load variation and would reach the lower voltage limit and turns into the limiting element for transfer capability. The method used in this work, focused on such locations for FACTS placement which are critical and improve the respective constraints violation with suitable FACTS placement.

The optimum solutions are more advantageous in power system operation to lead optimal power flow, by specifying the parameter values of the system elements to comply the necessary system stability for transfer capability. In planning phase a broader vision is contemplated, in which not only looking to current elements of the system but also other possible opportunities could be probed to improve the transfer capability along with system performance. Therefore more extensive analysis is needed to estimate the maximum transfer capability and limiting areas in the network. This can't be done optimally, rather the power flow solutions with increased power transfer in order to violate the respective constraints. Such locations needs to be identified in terms of the affected constraints, which could influence significantly the overall transfer capability. These locations could be subjected to various FACTS devices based on their types to improve the respected constraints. The method adopted in this work proposed an extensive analysis in planning phase to estimate the transfer capability for normal and contingency cases. Various sensitivity indices like real power loss and real power flow sensitivity indices are used in literature for FACTS placement to increase transfer capability, which are suitable for loss minimization and line flow reduction but again the critical locations might not be selected. Thus the transfer capability are still limited by critical locations or could improve slightly to current system conditions only. In the proposed methods the sensitivity indices are used to identify the locations based on electrical characteristics which are more prone to violation. The other problem of finding the critical locations using repeated power flow is that, it could be limited to only one or two locations which violate the constraints. Thus further increase in power transfer is being stopped and other critical locations can't be identified. This problem is resolved in the proposed method by identifying more locations while further power transfer is increased when the violating constraints are improved. The use of suitable FACTS devices characteristics at critical locations and enhance the transfer capability even more. The optimal sizing and placement of FACTS devices give better solutions for normal system, containing bilateral or multi-lateral transactions, or even formulated for some specific congestion problem scenarios with closed boundaries. And the network elements behavior for other power transfer cases with possible contingency might not be optimized. This problem is addressed in this work, by considering the possible cases of power transfer between the areas either the contribution in load and generation of all the areas or the power exchange between any two areas. Thus the final identified critical locations are the combination of each individual case. So the locations and sizes of the FACTS devices will contribute for all the power transfer cases among the areas in normal case and $n-1$ contingency cases. And the congestion can be mitigated with the achieved enhancement in transfer capability. The location selection based on PI and $L-index$ have the advantages to faster the identification of critical locations in line overloading and voltage stability limit violation respectively. And the FACTS placement at these locations will not only help in enhancing the transfer capability but also could help in solving power flow and voltage stability problem. The used of $L-index$ is also advantageous in finding the effective area of the FACTS devices, used for their coordinating control strategy.

In summary, this work identify the issue related to congestion due the steady growth in electricity demand and the expected integration of renewable generation. The role of FACTS devices in mitigating the congestion by controlling the power flows over the lines and voltage stability at buses, which also enhanced the power transfer capability of the network. In this study both series and shunt FACTS devices are used at different lines and buses, which are critical for system stability and reliability. Transmission congestion is caused due the scarcity of power transfer capability of the network. So the FACTS devices are placed with the objective to enhance power transfer capability. Thus a high computational efforts is done in the planning phase to identify critical lines and buses for series and shunt FACTS devices using different power transfer cases among the areas. The optimal parameters are being opened to other specific power system problems, only to develop the method for optimal parameters of the specified FACTS locations. Transmission congestion is focused in this work and coordinating control strategy is proposed for FACTS devices to vary the respective parameters so that the transmission congestion could be minimized and improve the system stability and reliability. Thus the method can be used to motivate the system operator to invest in FACTS placement and can defer the new transmission investment to some extent to the future projected load and generation growth. So it can be justified with the achieved results of network analysis for FACTS placement and can make the network capable of integrating more loads and generation like RES and ultimately help in reducing electricity cost.

2.6 Contributions of the Work

The primary goal of power network expansion is, to reach their native electricity demands and connecting generating plant far from load centers, or interconnecting to other networks for reliability and economical efficiency. As the load centers are growing along with the rising integration of RES, the transmission capacity must be increase to reduce the transmission bottlenecks, which cause network congestion. A variety of FACTS devices can be used for their attractive features of controlling power system parameters. The transfer capability of the network is limited mainly by the thermal line limits, voltage and stability limits. Therefore to find the root cause of limiting transfer capacity and the location in the network, which can be resolved by using FACTS devices. This needs a detail analysis of the network to plan suitable types, locations and sizes of the FACTS devices. Although the transmission congestion can't be completely avoided but minimized to some extend by enhancing the transfer capability of the power network and improve the performance.

FACTS devices are available in variety of types as connected in power system and thus provide different features. The Series FACTS devices *e.g.*, TCSC and SSSC, Shunt FACTS devices, like SVC and STATCOM and the combined features of series and shunt are available in UPFCs which can control all power flow parameters *e.g.*, voltage, impedance, and phase angle. The parameters of these devices are optimized to enhance the transfer capability, which are covered in literature. To investigate the critical locations in the network for limiting transfer capability of the network is done in this work. Based on the extensive computational analysis multiple locations are identified and suitable FACTS are placed to enhance the transfer capability of the network. Later the problem of transmission congestion is dealt in a coordinated control strategy of proposed multi agents defined for FACTS devices. The FACTS utilization is mainly focused in this work for congestion alleviation with enhance transfer capability, the power system operation is validated in such system conditions. The methodology of the work is summarized as under along with the justifications and contribution.

Network Analysis In the determination of power transfer capability of a network using AC power flow method, each node and branch are equally participating by varying the respective power system variable values. As the line thermal capacity and bus voltage stability limits are two main constraints which limit the value for transfer capability of the network. The power transfer is increase by injecting more power at generator buses and taken off from the load buses, until any constraint is violated. The location of constraints violation, either line or bus are supposed to be the critical line or bus of the network for respective power transfer. Thus different sources and sinks are selected for power transfer and the critical elements are identified for each source and sink combination and the system is checked for n-1 contingency cases to identify any other violating elements. The analysis is simple but computationally very extensive, which will help in planning various locations, suitable for FACTS devices. In this way the most critical locations which cause congestion by limiting the further increase in the power transfer, is identified. Based on the locations, respective individual FACTS device either series or shunt are specified for line or bus respectively. If any two locations line and bus are connected then the combined series-shunt devices will be a better option. In the proposed analysis the FACTS placement are opened for sizing and even over estimated, this is because the main purpose is the investigation of critical locations identifications, estimating the maximum possible capability enhancement and the computation of FACTS sizes for improvement. The type of critical element specify the network, either it is voltage dominant or thermal capacity dominant, that help in constraints improvement. This method identify the most suitable location based on the practical AC power analysis with 100% accuracy without the assumptions. The Sensitivity factors of PI and L-index for for lines and buses helped in short listing the critical locations.

FACTS Sizes Calculation The sizes for respective FACTS devices at the identified locations are based on the improvement in respective constraints and the possible enhancement in the transmission capability. This is also an iterative method in which the sizes of the FACTS devices will be gradually enlarged based on the improvement in the respective constraints violation. The sizes of other sensitivity based selected critical elements, will be found if there is further possibility in transfer capability enhancement. The sizes of series FACTS devices are calculated in terms of the percent variation in line impedance either increase or decreased for varying respective power flow. While the sizes of shunt FACTS devices are calculated in term of reactive power injections to improve the voltage of respective buses. The determination of separate sizes of series and shunt FACTS devices at this stage is due to assess the requirements which can help later in optimizing the real settings of respective FACTS devices at specified locations. The transfer capability enhancement of different sources and sinks are checked for contingency.

Coordinated Control System A distributed coordinated control strategy is proposed for these multiple FACTS devices which are placed at different locations in the network. The aim of the control system is to reduce the overloading of the critical lines and voltages violation of critical buses in coordination control strategy. The power can be redirected to other paths of comparatively less loading and the reactive power injected is varied to improve the voltage of violating buses. The influence of closely located multi FACTS devices are efficiently coordinated by exchanging information among the neighboring elements. The sensitivity and loadability functions are defined for control agents, so that inter contradicting effects among the control devices could be minimized in controlling the power flow or bus voltage. Finally, the coordinated actions of the FACTS devices enable the efficient network utilization, relieving congestion with enhanced transmission capacity and improve system performance. Therefore it is expected that the methodological steps of the planning phase for the FACTS placement and the coordinated control in operational phase will provide a better system performance in real time operations.

3 POWER NETWORK ANALYSIS FOR TRANSMISSION CAPABILITY

3.1 Introduction

This chapter explains the analytical methods finding locations for multiple FACTS devices which can enhance the transfer capability of the power network and improve the voltage affected in weak buses. In previous chapter a brief overview of various FACTS devices used in enhancing the transmission capability of the networks and various approaches for FACTS placement. The respective merits and demerits of different approaches are also explain. The choice of selecting FACTS devices is kept open unlike the already used approaches. The power network of different topology and characteristics are proposed to analysed based on the characteristic parameters of the power network to be affected by FACTS devices. Instead of going to extensive computational burdens of check all the power network elements for the respective analysis, the proposed methods are used to select the elements. The sizes for FACTS are also iteratively computed based on the maximum compensation offered by the devices in improving the respective limiting constrains. Therefore it is expected that the analysis could provide a basis for selecting and sizing of any type of FACTS use.

The analysis of the power network is done mainly for two ways in TTC calculations. One is the analysis of overall system transfer capability with all simultaneous transactions between all sources and demands. The power transfer is increased by changing the power demand in the all nodes with loads and the generation power is increased in all source nodes for corresponding power demand and system losses. In second analysis the power transfer is increased between any two areas with one area become the consumer/demand area, only load power is increased in it. The generation power is increased in the supplier area according to the power demand in consumer area and the losses. The line locations for series FACTS are selected based on the sensitivity of PI index. If any line flow is violating its rated capacity with increased power transfer, the reactances of the overload line and the selected lines are varied based on the line capacity utilization factor of these lines until the the violation is removed. The respective power injections due to the changed reactance values.

The second aspect of the method is the bus voltage improvement in enhancing the power transfer. Some power networks are bus voltage limited in transfer power determination. The bus locations are selected based on the voltage stability $L - index$ used for stability assessment in order to improve the bus voltages. For the increasing power transfer the bus voltages are affected mostly at load buses. Shunt devices are proposed to be placed on these selected bus locations. When more than 8% of the buses are violating the lower limit, the reactive power injections at the selected buses are increased so that the violating buses are reduced than 8%. The 8% is just selected as the stopping criteria.

The general algorithm for FACTS placement on critical locations is presented. In this section, the problem of total transfer capability is formulated using ac power flow with equations along with all constraints of equality and non-equality. The sensitivity factors of real power flow performance index and voltage stability index of $L - index$ is presented which are used to short list the critical locations for both series and shunt FACTS devices placement. The repeated power flow algorithm is used to achieve the maximum transfer capability with above stopping criteria and with the power system constraints. The proposed algorithm is also presented using flowchart and shown in this section.

3.2 System Modeling for Power Transfer Capability

TTC is the largest power transfer value which causes no line thermal limit or voltage stability limit violation, with and without contingency. For TTC computation between any two areas, it is supposed that the remaining system conditions will unchanged. There should be no variation in load and generations in all other connected areas, because the TTC value is effected with changing system conditions. Several methods for TTC computation have been suggested in the literature [65]. The power transfer is the sum of all real powers flows on the lines connecting these two areas. The power flow for the base case is run to determined base case transfer, then power transfer is increased until there is any constraint violation. There are many assumptions taken for calculating power transfer capability. The main assumptions used in this study are as follows:

- The base case is at the stable operating conditions satisfying the constrains.
- The loads and generations variation are also steady state points with no transient stability violation.
- Bus voltage limits are maintained.

The analysis of power system for planning and operation is done by the solution of power flow equations. This solution is used to determine the magnitudes and phase angle of each bus voltage along with the active and reactive power injection at each bus. Similarly the active and reactive power flow over each line. The Newton-Raphson method is used in solving the power flow equations for voltage magnitude and phase angle, given real and reactive power injections, which can be used for transfer capability calculation. The mathematical formulation is given as follows:

Suppose the complex power injected at bus i is given as

$$\begin{aligned} S_i &= V_i I_i^* = P_i + jQ_i, i = 1, 2, ...n \\ &= |V_i| \textstyle\sum_{j=1}^{n_b} |V_j||Y_{ij}|[cos(\delta_i - \delta_j - \theta_{ij}) + jsin(\delta_i - \delta_j - \theta_{ij})] \end{aligned} \tag{3.1}$$

The active and reactive power injections are separated as:

$$\begin{cases} P_i = |V_i| \sum_{j=1}^{n_b} |V_j||Y_j|[cos(\delta_i - \delta_j)cos(\theta_{ij}) + sin(\delta_i - \delta_j)sin(\theta_{ij})] \\ \quad = |V_i| \sum_{j=1}^{n_b} |V_j|[G_{ij}cos(\delta_i - \delta_j) + B_{ij}sin(\delta_i - \delta_j)] \\ Q_i = |V_i| \sum_{j=1}^{n_b} |V_j||Y_j|[sin(\delta_i - \delta_j)cos(\theta_{ij}) - cos(\delta_i - \delta_j)sin(\theta_{ij})] \\ \quad = |V_i| \sum_{j=1}^{n_b} |V_j|[G_{ij}cos(\delta_i - \delta_j) - B_{ij}sin(\delta_i - \delta_j)] \end{cases} \tag{3.2}$$

The power flows on line connecting bus i to j as shown in the Figure (pi transmission model) is given as:

$$\begin{array}{c} P_{ij} = \left|V_i^2\right| G_{ij} - |V_i| \, |V_j|[G_{ij}cos(\delta_{ij}) + B_{ij}sin(\delta_{ij})] \\ Q_{ij} = -\left|V_i^2\right| (B_{ij} + B_{sh}) - |V_i| \, |V_j|[G_{ij}sin(\delta_{ij}) - B_{ij}cos(\delta_{ij})] \end{array} \tag{3.3}$$

The equality constraints are the power balancing at each bus given as follows:

$$\begin{cases} P_{Gi} - P_{Di} - \sum_{j=1}^{n_b} |V_i||V_j|(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}) = 0 \\ Q_{Gi} - Q_{Di} - \sum_{j=1}^{n_b} |V_i||V_j|(G_{ij}sin\delta_{ij} - B_{ij}cos\delta_{ij}) = 0 \end{cases} \tag{3.4}$$

The inequality constraints are:

$$\begin{array}{c} P_{Gi-min} \leq P_{Gi} \leq P_{Gi-max} \\ Q_{Gi-min} \leq Q_{Gi} \leq Q_{Gi-max} \\ |V_i|_{min} \leq |V_i| \leq |V_j|_{max} \\ S_{ij} \leq S_{ij-max} \end{array} . \tag{3.5}$$

In the power flow equations, the generation and demand are increased as:

$$\begin{array}{c} P_{Gi} = P_{Gi}^o(1 + \lambda K_{Gi}) \\ P_{Di} = P_{Di}^o(1 + \lambda K_{Di}) \\ Q_{Di} = Q_{Di}^o(1 + \lambda K_{Di}) \end{array} . \tag{3.6}$$

Where,

λ : Scalar parameter representing the increase in load or generation of the buses

P_{Gi}, Q_{Gi} : Real and reactive power generation at bus i,

P_{Di}, Q_{Di} : Real and reactive loads at bus i

$|V_i|$, $|V_j|$: Voltage magnitude at bus i and bus j

$\delta_{ij} = \delta_i$ - δ_j : The voltage phase angle difference between bus i and bus j

$G_{ij} = \frac{r_{ij}}{(r_{ij}^2 + x_{ij}^2)}$ and $B_{ij} = \frac{-x_{ij}}{(r_{ij}^2 + x_{ij}^2)}$: The real and imaginary parts of the $ijth$ element of the bus admittance matrix

n_b : Total number of buses.

$|V_i|_{min}$, $|V_i|_{max}$: Lower and upper limit of the voltage magnitude at bus i

S_{ij}: Apparent power flow in $line_{ij}$

S_{ij-max} : Thermal limit of $line_{ij}$

P_{Gi}^o : Initial active power generated at bus i in the source area.

P_{Di}^o, Q_{Di}^o : Initial real and reactive power demand at bus i in the sink area.

K_{Gi}, K_{Di} : Constants used to indicate the change rate in the generation and load as λ alters.

3.2.1 Repeated Power Flow Algorithm

The repeated power flow (RPF) method for its simplicity in implementations and suitable for large scale power, is therefore chosen for TTC determination. The RPF [11] method is preferred for TTC determination due to the following advantages as given below:

- RPF can provide the stability voltage curve of $P-V$ and $V-Q$.
- The control variables adjustment is relatively easy in RPF.
- The RPF is easier in implementation than CPF and the convergence time is also reduced.

In this method the system loads and generations are increased with a specified rate λ as given in equation 3.5 and it will continue until anyone of the operating constraints given in 3.4 related to TTC is violated. The objective is to increase the load to the maximum scaler parameter λ_{max} with no constraints violation. The power flow equations of base case, which is the initial system conditions, and then increasing the transfer. After each increase, another load flow is done and the security constraints tested. The computational procedure of this approach is as follows::

- Solved a base case
- Select the power transfer direction
- Increase the generations and loads for the selected power transfer
- Increase the transfer rate λ for successful transfer
- Check the limiting constraints
- Repeat until any constraints violation

The flow chart of this method is given in Figure.

TTC is calculated as follows:

$$TTC = \sum_{i=Demands} P_{Di}(\lambda_{max}) - \sum_{i=Demands} P_{Di}^{o} \tag{3.7}$$

Where,

$\sum_{i=Demands} P_{Di}(\lambda)$ is the total load for $\lambda = \lambda_{max}$

$\sum_{i=Demands} P_{Di}^{o}$ is the total load for $\lambda = 0$.

The RPF algorithm is modified in this study for selecting locations and sizes of FACTS devices in order to increase the transfer capability of the network. There are many methods applied in literature for FACTS placement in the network in improving TTC [7].

3.2.2 Sensitivity Indices

There are a variety of computational tools employed in transmission expansion planning. These analysis tools include ranking algorithms which identify the additions of alternatives. The ranking of alternatives is usually done on the basis of sensitivity analysis of the system performance index to variations in the system element capacities [66]. This can help in identifying the bottlenecks and assessing the possible improvements. The most performance indices in transmission systems are related to line overloading, bus voltage limit violation. In this study the two sensitivity factors are used to identify locations for FACTS devices. Real power performance index (PI) is employed for the measurement of line overloads in terms of real power flow. The sensitivity factor of real power performance index (PI) with respect to the line impedance variation is used to identify the line suitable for series FACTS. There are various voltage stability indices, used in literature for voltage stability analysis. The $L - index$ voltage stability [67] is used for identifying the weak buses which are supposed to be the locations for shunt FACTS devices.

3.2.2.1 Real Power Flow Performance Index (PI)

The real power performance index (PI) index is used to measure the severity of loading power system in normal and contingency cases. It is define as:

$$PI = \sum_{m=1}^{n_l} \frac{w_l}{2z} \left(\frac{P_{lm}}{P_{lm}^{max}} \right)^{2z} \tag{3.8}$$

Where

P_{lm}: Real power flow on line m^{th}

P_{lm}^{max}: Rated real power of line m

z: The specified exponent $z = 2$

w_m: A real non-negative weighting factor, which show the relative importance of the lines

n_l : Total number of lines in the network

The PI formula contains all the line flows, which are normalized by their thermal limits. The PI value indicates the loading severity of the system for the given system state. The smaller value shows that all the lines flows are under the capacity limits and there is no over loading. The higher value indicates the chance of line overloading. The only shortcoming is that based on PI value the discrimination between one large violation and many small violation cases can't be done. So choosing $z > 1$ means to use high order performance indices, could avoid it to some extent. In this study the exponent value is taken to be 2, as proposed in [68].

PI sensitivity Factor: The sensitivity of the PI w.r.t the line reactance is given as:

$$b_k = \left.\frac{\delta PI}{\delta x_k}\right|_{x_k=0} = \sum_{m=1}^{n_l} w_l P_{lm}^3 \left(\frac{1}{P_{lm}^{max}} \right)^4 \frac{\delta P_{lm}}{\delta x_k} \tag{3.9}$$

The real power flow P_{lm} on m^{th}line can be described in terms of real power injection at the two opposite end buses of the line

$$P_{lm} = \begin{cases} \sum_{n=1,n\neq s}^{n_b} S_{mn}P_n & \text{for} \quad m \neq k \\ \sum_{n=1,n\neq s}^{n_b} S_{mn}P_n + P_j & \text{for} \quad m = k \end{cases} \tag{3.10}$$

Where, s is the slack bus index, S_{mn} is the mn^{th} element of $[S]$ matrix (given in Appendix .1) which relates line flow with bus injections, n_b is the number of buses, k is the line selected for FACTS device between bus i to bus j, so P_j is additional flow due to FACTS towards bus j. So differentiating 3.10 w.r.t x_k.

$$\frac{\partial P_{lm}}{\partial x_k} = \begin{cases} \left(S_{mi}\frac{\partial P_i}{\partial x_k} + S_{mj}\frac{\partial P_j}{\partial x_k}\right) & \text{for} \quad m \neq k \\ \left(S_{mi}\frac{\partial P_i}{\partial x_k} + S_{mj}\frac{\partial P_j}{\partial x_k}\right) + \frac{\partial P_{lm}}{\partial x_k} & \text{for} \quad m = k \end{cases} \tag{3.11}$$

The power injection at buses i and j connected by a line with FACTS

$$\begin{aligned} P_i &= \left|V_i^2\right| \Delta G_{ij} - |V_i|\,|V_j|[\Delta G_{ij}cos(\delta_{ij}) + \Delta B_{ij}sin(\delta_{ij})] \\ P_j &= \left|V_j^2\right| \Delta G_{ij} - |V_i|\,|V_j|[\Delta G_{ij}cos(\delta_{ij}) - \Delta B_{ij}sin(\delta_{ij})] \\ Q_i &= -\left|V_i^2\right| \Delta B_{ij} - |V_i|\,|V_j|[\Delta G_{ij}sin(\delta_{ij}) - \Delta B_{ij}cos(\delta_{ij})] \\ Q_j &= -\left|V_j^2\right| \Delta B_{ij} + |V_i|\,|V_j|[\Delta G_{ij}sin(\delta_{ij}) + \Delta B_{ij}cos(\delta_{ij})] \end{aligned} \tag{3.12}$$

Where, $\Delta G_{ij} = -\frac{r_{ij}x_k(2x_{ij}+x_k)}{(r_{ij}^2+x_{ij}^2)(r_{ij}^2+(x_{ij}+x_k)^2)}$ and $\Delta B_{ij} = \frac{-x_k(r_{ij}^2-x_{ij}^2+x_{ij}x_k)}{(r_{ij}^2+x_{ij}^2)(r_{ij}^2+(x_{ij}+x_k)^2)}$

$$\begin{aligned} \frac{\partial P_i}{\partial x_k} &= \left|V_i^2\right|\left(\frac{\partial \Delta G_{ij}}{\partial x_k}\right) - |V_i|\,|V_j|[\left(\frac{\partial \Delta G_{ij}}{\partial x_k}\right)cos(\delta_{ij}) + \left(\frac{\partial \Delta B_{ij}}{\partial x_k}\right)sin(\delta_{ij})] \\ &= 2G_{ij}B_{ij}|V_i^2| - |V_i||V_j|\left(2G_{ij}B_{ij}cos(\delta_{ij}) + \left(B_{ij}^2 - G_{ij}^2\right)sind(\delta_{ij})\right) \\ \frac{\partial P_j}{\partial x_k} &= \left|V_j^2\right|\left(\frac{\partial \Delta G_{ij}}{\partial x_k}\right) - |V_i|\,|V_j|[\left(\frac{\partial \Delta G_{ij}}{\partial x_k}\right)cos(\delta_{ij}) - \left(\frac{\partial \Delta B_{ij}}{\partial x_k}\right)sin(\delta_{ij})] \\ &= 2G_{ij}B_{ij}|V_i^2| - |V_i||V_j|\left(2G_{ij}B_{ij}cos(\delta_{ij}) - \left(B_{ij}^2 - G_{ij}^2\right)sind(\delta_{ij})\right) \end{aligned} \tag{3.13}$$

$\frac{\partial \Delta G_{ij}}{\partial x_k}\Big|_{x_k=0} = \frac{-2r_{ij}x_{ij}}{(r_{ij}^2+x_{ij}^2)^2} = 2G_{ij}B_{ij}$ and $\frac{\partial \Delta B_{ij}}{\partial x_k}\Big|_{x_k=0} = \frac{x_{ij}^2-r_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} = B_{ij}^2 - G_{ij}^2$ Suppose $2G_{ij}B_{ij} = a$, $B_{ij}^2 - G_{ij}^2 = b$

$$\begin{aligned} \frac{\partial P_i}{\partial x_k} &= a|V_i^2| - |V_i||V_j|\left(acos(\delta_{ij}) + bsin(\delta_{ij})\right) \\ \frac{\partial P_j}{\partial x_k} &= a|V_i^2| - |V_i||V_j|\left(acos(\delta_{ij}) - bsind(\delta_{ij})\right) \end{aligned} \tag{3.14}$$

Substituting 3.12 and 3.14 in 3.11

$$b_k = \frac{\partial P_{lm}}{\partial x_k} = \begin{cases} S_{mi}\left(a|V_i^2| - |V_i||V_j|(acos(\delta_{ij}) + bsin(\delta_{ij})\right) & \\ \quad +S_{mj}\left(a|V_i^2| - |V_i||V_j|(acos(\delta_{ij}) - bsin(\delta_{ij})\right) & \text{for} \quad m \neq k \\ S_{mi}\left(a|V_i^2| - |V_i||V_j|(acos(\delta_{ij}) + bsin(\delta_{ij})\right) & \\ \quad +(S_{mj}+1)\left(a|V_i^2| - |V_i||V_j|(acos(\delta_{ij}) - bsin(\delta_{ij})\right) & \text{for} \quad m = k \end{cases} \tag{3.15}$$

3.2.2.2 Voltage Stability Index L-Index

Voltage stability Indices are used to assess the power system stability for changing the system parameters. These indices are important for operator to check the system stability intuitively and take the required measures accordingly. $L-index$ is one of the stability index proposed by Kessel in [67] based on solution of power flow. $L-index$ can be determined by hybrid representation of transmission system separating the consumer or PQ buses and generator or PV buses. The mathematical formulation of $L - index$ is given as follows: Suppose the transmission system shown in Figure 3.1

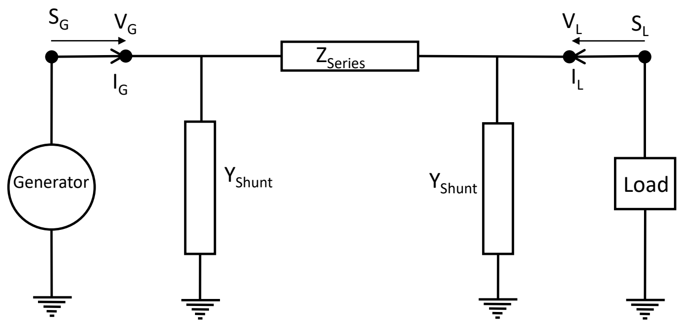


Figure 3.1: Transmission line model

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = |Y| \begin{bmatrix} V_L \\ V_G \end{bmatrix} = \begin{bmatrix} |Y_{LL}| & |Y_{LG}| \\ |Y_{GL}| & |Y_{GG}| \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{3.16}$$

Rearranging the 3.16 for $\begin{bmatrix} V_L \\ I_G \end{bmatrix}$,

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & -F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{3.17}$$

Where, V_L,I_L: Voltage and current vectors for PQ buses

V_G,I_G: Voltage and current vectors for PV buses

The H matrix is constructed from the Y matrix by partial inversion of V_L unknown vector with the I_L currents vector of respective PQ buses. $Z_{LL} = Y_{LL}^{-1}$,$F_{LG} = Y_{LL}^{-1}Y_{LG}$, $K_{GL} = Y_{GL}Y_{LL}^{-1}$.

For any load bus j, $j\epsilon\alpha_L$ an equation for V_j

$$\begin{aligned} V_j &= \textstyle\sum_{i\epsilon\alpha_L} Z_{ji}I_i + \sum_{i\epsilon\alpha_G} F_{ji}V_i \\ \Rightarrow V_j^2 - \textstyle\sum_{i\epsilon\alpha_G} F_{ji}V_iV_j^* &= \frac{S_j^+}{Y_{jj}^*} \\ S_j^+ &= S_j + \left(\textstyle\sum_{i\epsilon\alpha_L, i\neq j} \frac{Z_{ji}^*}{Z_{jj}^*}\frac{S_i}{V_i}V_j\right) \end{aligned} \tag{3.18}$$

For any load bus j, L is defined as:

$$L_j = \left|1 - \frac{\sum_{j\epsilon\alpha_G} F_{ji}V_i}{V_j}\right| = \left|\frac{S_j^+}{Y_{jj}^*V_j^2}\right| \tag{3.19}$$

For stability $L_j < 1$ and must not be violated for any j load bus. A global system indicator L describe the stability of the complete system

$$L = \max_{i\epsilon\alpha_L}(L_j) = \max_{j\epsilon\alpha_L}\left|1 - \frac{\sum_{j\epsilon\alpha_G} F_{ji}V_i}{V_j}\right| \tag{3.20}$$

The global L index is a quantitative estimation of actual system state far from the stability limit and L_j of individual node determine the weak buses which are going to collapse.

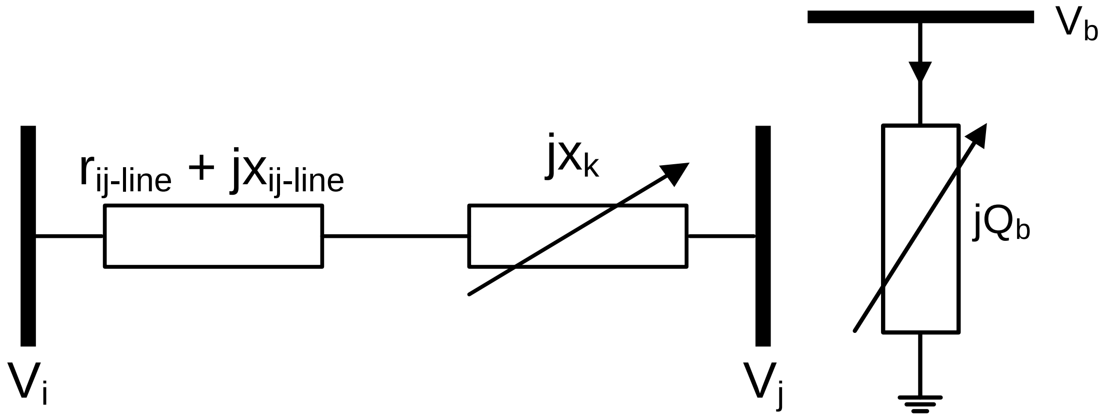
3.2.3 Proposed FACTS Modeling

Two power system parameters are focused in modeling both series and shunt FACTS devices. The series impedance of line is effective parameter in controlling the line flows and reactive power injection at buses for controlling the voltage in enhancing TTC of the network.

Series FACTS: Series FACTS are used for controlling the line flows and shunt FACTS are used for bus voltage improvement. To decrease or increase the line flows, series FACTS devices will increase or decrease the effective impedance of respective lines by adding inductive or capacitive reactance correspondingly. Therefore series FACTS devices are modeled as variable reactance, which is defined as:

$$x_{ij} = x_{ij-line} + x_k, \quad X_{ij-min} \leq x_k \leq X_{ij-max} \tag{3.21}$$

where, x_{ij}: net reactance of $line_{ij}$, $x_{ij-line}$: the original reactance of $line_{ij}$, x_k: reactance of Series FACTS, X_{ij-min}: lower limit (capacitive reactance), X_{ij-max}: upper limit (inductive reactance). Assume the series FACTS device like TCSC as shown in Figure 3.2(a) is connected between bus_i and bus_j with a varying reactance of x_k, the active and reactive power injections at bus_i and bus_j due to series FACTS device are given in equation 3.12. The TTC is limited by some line flows which can be improved by diverting the power flow from high loaded lines to the less loaded lines from varying their reactances.



(a) Series FACTS device (b) Shunt FACTS device

Figure 3.2: FACTS devices models

Shunt FACTS: The second limiting factor of TTC is the voltage of weak buses, especially the voltage of load buses dropped below the lower operating limit for increasing demands. The Voltage of such buses can be improved by injecting suitable amount of reactive power. Shunt FACTS devices have been used as reactive power compensators. Hence, along with some other benefits shunt FACTS devices are used in this work for improving the voltage of violating buses. These devices are basically a var source which reactive power output is adjusted to control the bus voltage. The simplify model is a variable susceptance connected to bus b to control the bus voltage V_b by varying injecting the reactive power Q_b as shown in Figure 3.2(b). This is given as follows:

$$\begin{aligned} Q_b &= -V_b^2 B_b, \quad Q_{b-min} \leq Q_b \leq Q_{b-min} \\ P_b &= P_{load} \end{aligned} \tag{3.22}$$

where, P_b and Q_b: Reactive Power at bus b, V_b: Voltage at bus b, B_b: Susceptance at bus b, B_{b-min} and B_{b-max}: lower limit and upper limit.

3.3 Power Transfer Capability Enhancement

The total transmission capacity enhancement is carried out by improving the limiting factors. Two dominant limiting factors, thermal line capacity and bus voltage limits are improved using FACTS models as explained before. The RPF is modified by analyzing the transmission network with varying the controlling parameters of power system used for FACTS devices. The power transfer is increased in each iteration and the constraints are evaluated. In case of line capacity violation, locations are selected for series FACTS devices and then the reactances of selected lines are varied so that the line flows are within their capacities. Similarly in case of violation in bus voltages, locations are selected for shunt FACTS devices, where reactive power is varied to improve the voltages of violated buses. The procedure of TTC enhancement based on line flow control and bus voltage improvement is given in the following steps:

1. Select any meshed power network as test systems and define criteria for PI sensitivity index.
2. Solve the power flow for (Normal or any contingency case with $\lambda = 0$) and select lines based on PI sensitivity factors.
3. Start RPF of specified increasing rate of power transfer for specified source and sink.
4. Solve the power flow with updated power transfer and check the line loading
5. Identify the overloaded lines (having 80% or above capacity utilization) and less loaded lines(having below 50% of capacity utilization).
6. Update the reactance of the selected lines, until all the lines having capacity utilization below 80%.
7. Check the voltage constraint and identify the weak buses based on $L - Index$
8. Update the reactive power injection at weak buses until the specified criteria is satisfied.
9. Check the constraints and go to the next step if violation occurred, otherwise continue the RPF increment.
10. Decrease the power transfer until no constraint is violated, Calculate the TTC for the specified source/sink transfer

The proposed procedure of TTC enhancement is shown in 3.3. The first two steps is for finding a feasible base case data in normal or some contingency cases and the calculations of sensitivity indices for the selected test network and case. Then the rest is similar as RPF with two additional loop shown by bright solid lines. These two loops are activated on the respective constraint violation and change the respective parameters to bring the system within the security constraint limits in each iteration. For stopping criteria if the constraints could not be bring within their limits using these additional loop, the power transfer is reduced so that there's no any violation. The TTC is then calculated for the test network and cases.

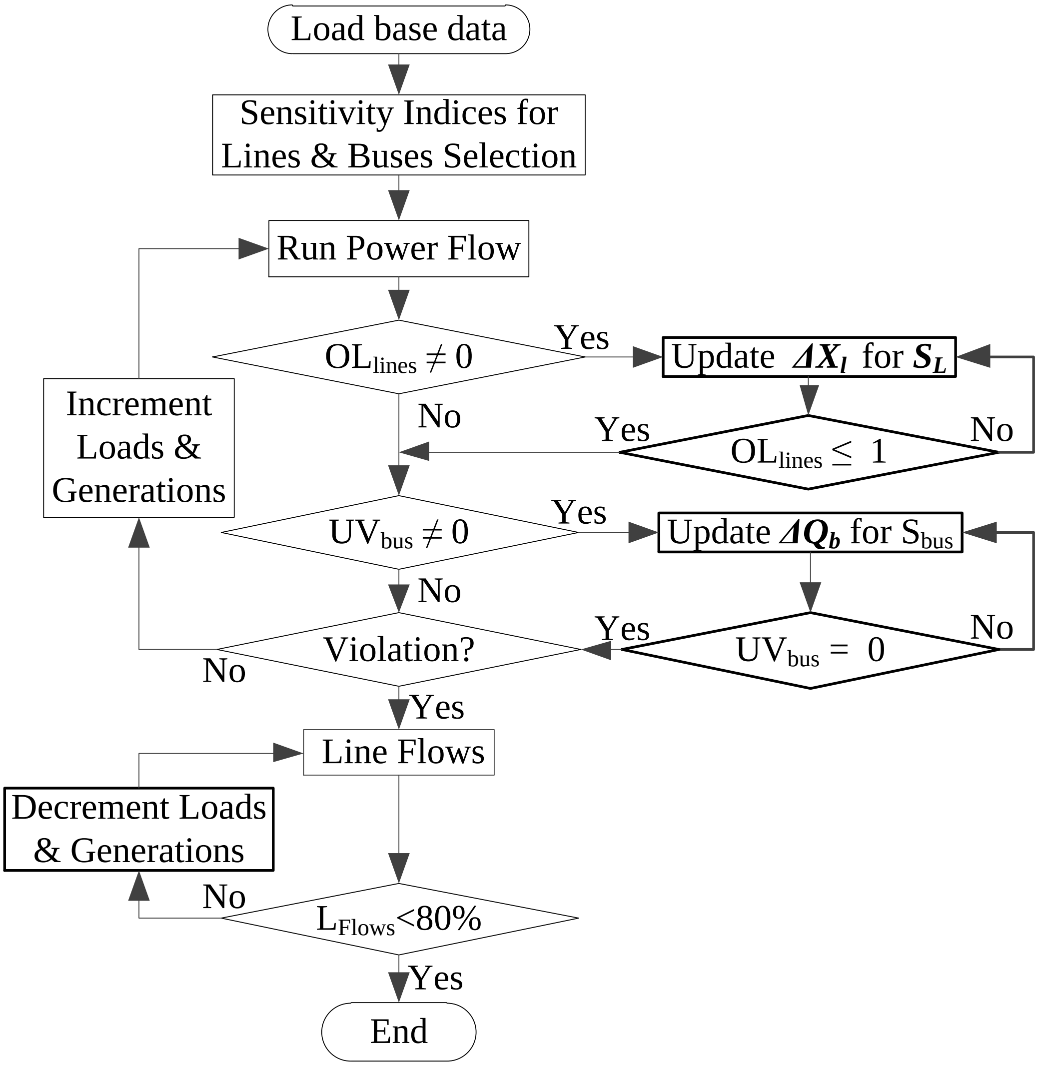


Figure 3.3: Flowchart of Modified RFP for *TTC* Enhancement

3.3.1 Criteria For Series FACTS Devices

To analyse the power network for series FACTS by varying the reactance of each is long and tedious as most of the lines have no reasonable impact on power flow. So it is supposed to selected those lines which have more impact on the power flow. So the PI sensitivity index as given in 3.15 is used for selecting locations for series FACTS devices. The lines having most negative PI sensitivity factors are selected for series FACTS. For increasing power transfer in each RPF iteration, the the reactance of the selected lines are changed based on the line utilization capacity. The lines having higher than 80% of utilization capacity are termed as OL_{lines} overload line, so the power over these lines are reduced by increasing reactance of these lines. Similarly the reactances of the selected lines having less than 50% of utilization capacity, are reduced so that the excessive power follow these paths. After finalizing TTC value the selected number of lines are reduces with changed reactances and the combination of lines are chosen which give maximum TTC.

3.3.2 Criteria For Shunt FACTS Devices

The shunt FACTS are initially supposed for bus voltage improvement in enhancing TTC. In order to place shunt FACTS at suitable locations, L-index values are used. As it is observed that when the thermal capacity is large enough for the line flows, the voltage of some load buses get reduced down from the lower limits and thus limit the TTC. So in such case shunt FACTS devices are proposed to improve the voltages of such locations. So It is required to find the distances of all load buses from the generation buses, because those buses are more likely to be affected which are far from all the generation buses. In $L - Index$ formula in 3.19, F_{ji} matrix relate load buses and generations buses, defined as $F = -Y_{LL}^{-1} Y_{LG}$, where Y_{LL} is the susceptance matrix between load buses and Y_{LG} is the susceptance matrix between load buses and generation buses. So F_{LG} matrix gives the electrical distance of each load bus to all the generation buses. The $L - Index$ is computed for the base case and also computed in the later RPF iterations. The $L - Index$ value of each bus is compare with the maximum value of $L - Index$ in the base case, so the buses are selected which exceed the maximum base case $L - Index$ value. Then when the 8% of the total number of buses are violating the voltage limits, reactive power injections of shunt FACTS devices are changed on those selected bus locations which voltages are dropped down from lower limit. The stopping criteria are defined to be the 8% of total violated buses or any violating line.

3.4 Defined Case Studies

Various power networks are tested to investigate the impact of the proposed method of multiple FACTS devices placement for improving the total transmission capacity. Simulations are done in MATLAB environment using matpower 5.0. To thoroughly analyze the power network for transfer capability and identify the critical buses and lines that limiting the transfer capability, two case studies are constructed. To improve the respective limiting factors, critical buses and lines are identified and FACTS devices are employed on these violating locations to enhance the transfer capability of the network. Various IEEE standard test networks of different sizes are used for results validation and implementations. RPF algorithm based on AC power flow equations is simulated in matpower 5.0 in MATLAB. For simulation, the base power value is supposed to be 100 MVA and the bus voltage range from 0.94 p.u to 1.10 p.u. is considered. The details of these case studies are given in this section.

3.4.1 Overall System Transmission Capability

The purpose of the case study is to identify the locations of the limiting factor for the overall system transfer capability as shown in 3.4. This study case investigate the total power transfer of a network for the whole network sources and consumers. This focuses mainly on the individual line flow and bus voltage effected in contributing the power transferred from all sources to all sinks or consumers in each area power exchange. The limiting locations which hindered the power transfer from further increase. FACTS devices are placed based on the proposed sensitivity indices and the sizes are computed to improve the limiting factors of power transfer capability of all area simultaneously.

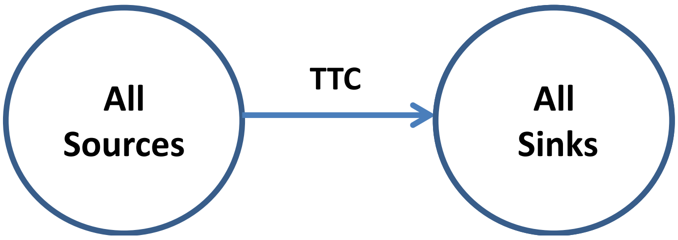


Figure 3.4: Total Transfer Capability of overall system

3.4.2 Inter-area Transmission Capability

This case study focused on the individual inter-area transfer capability between the different area in a network as shown in 3.5. For simplicity of computing data the power network is divided into three area and thus six different source sink combinations of power transfer being made. In this case study the power transfer in each area combination is handled individually *i.e.*, only the specified source sink areas are contributing in power transfer and rest of the system is unchanged. Thus for the power transfer of each area combination is evaluated and the locations of limiting factors are identified. Similarly FACTS devices are placed and sizes are computed with proposed methodology to enhance the respective power transfer capability for each source sink area combinations. In the end all the selected locations and the respective FACTS sizes are finalized.

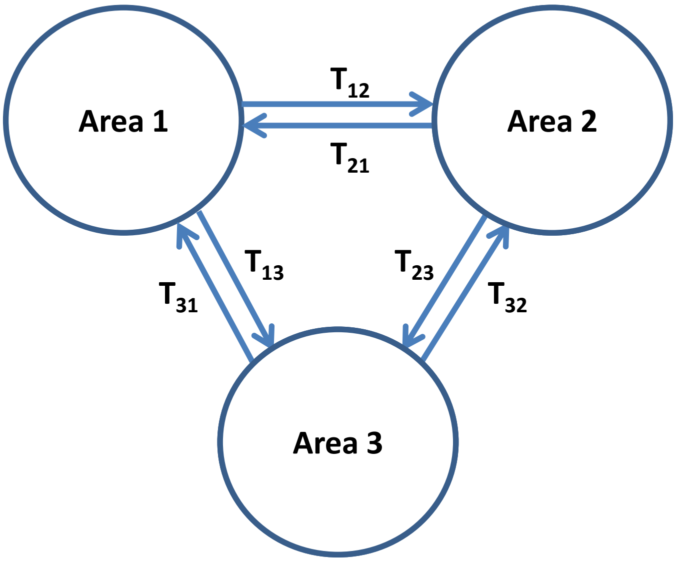


Figure 3.5: Total Transfer Capability between Areas

4 DISTRIBUTED COORDINATED CONTROL SYSTEM

4.1 Introduction

This chapter explain the control structure designed for power flow control and voltage stability improvement using FACTS devices for congestion relieving. As it is already discussed in previous chapter that multiple FACTS devices are suggested at various locations based on the analysis of power network for power transfer capability enhancement. In this chapter the control of these multiple FACTS devices are discussed. In case of multiple FACTS devices, appropriate controllers settings become more important because of the mutual influences may have negative impacts. Typically optimal power flow (OPF) method is being used to control and optimize the operation of a power system. The considered power system is formulated as an optimization problem to find the optimal settings of the controllable devices with respective objective function to the subjected constraints. This is a centralized approach which use the available power system model and the control settings are determined for controllers. This will minimize the contradicting effects of these multiple FACTS devices. However, for large power systems, the availability of accurate overall system model is very cumbersome and also the optimization solution of the available system model would be intractable. Similarly large power system spans several regions of different countries having their own control centers, so the central control would be not feasible. The distributed control would be of course a more realistic option for practical multi regional interconnected system. But this has it own drawbacks of mutual contradicting effects which could reduce the performance. Therefore, coordinated distributed control structure could help in solving the problems by minimizing the contradicting effects in determining the control parameters settings for each controller. A distributed coordinated control system is proposed for these multiple FACTS devices instead of centralized controlled. This chapter aims to improve the steady state voltage deviations from their reference values and relieving the congestion by diverting power flow from overloaded lines using FACTS devices in a dynamic synthetic load profile data of 24 hours. The structure of Multi Agent System (MAS) is discussed which is used for coordinating the distributed control of multi FACTS devices. Each FACTS device is supposed to be controlled by an autonomous agent, which suggest the control actions for FACTS devices based on the information exchanged among the agents of the elements in its surrounding influential area.

Finally, the defined scenarios are described, which are used to validate the proposed control methods for FACTS devices and compared with base case without FACTS and the case of congestion management. A 24 hours load profile is used which affect the voltage profile for all buses and the power flows over the lines. The system behaviour in three cases are checked for the dynamic variation of load at each load buses in normal form without any contingencies. Similarly the inter-area line outage contingency cases are used to study the behavior of the system in terms of number of voltage violating buses and number of overloading lines.

4.2 Multi Agent System

Multi Agent Systems(MAS) is a very interesting approach in the fields of Distributed Artificial Intelligence (DAI)for the analysis, design, and implementation of distributed open system. MAS composed of multiple interacting computing elements, known as agents. There is no universally accepted definition of agents, however some basic characteristics of agent are defined in literature [69]. But there are other features related to specific areas, such as mobility, communication ability, rationality *etc.* However, it could be a hardware and software system that have the following features:

- Autonomous: An agent has the intrinsic computing capability of behaviour control mechanism without the direct human intervention or other agents. It can decide itself the respective actions to achieve its objectives.
- Reactivity: An agent has the capability to perceives its environment which could a physical system, human, or other related agents and react according to the relevant events and the instantaneous changes occurred in the environment.
- Proactiveness: The agent must have the goal driven capability. Its behaviour of taking actions towards its targets achievement or can initiate its own targets and tend to achieve it.
- Socialability: The agent has the capability to cooperate, coordinate and compete with other agents, abiding the social rule of the agent group, and utilize the information and knowledge of other agents through certain communication language.

The agents could have some other features as well in some special application *i.e.*, adaptivity, mobility, rationality*etc.* The difference of agents characteristics is due the application systems and the software requirement designed for agents. So different agents have different behavior flexibility. In some application real time responses to events is needed so a higher reactivity of agent is required in the system. the systems required autonomous and intelligent behavior of agents, that focused proactivity for agents. Similarly the behaviour of reactivity and socialability without proactivity, or proactivity and socialability without reactivity. The autonomous, intelligent, human oriented and cooperative attributes of MAS make it more interesting in solving the problems of large and complex systems. These system could be make flexible and extendible by system reconfiguration and integration through common agent communication by handling distributed sources of data and expertise. The computational efficiency could be improve by concurrent computation of data processing or decision making stages. Similarly MAS has the ability to tolerate uncertainties that could improve robustness and reliability of the system, as the redundant use of agents could help in the case of any component failures. The modularity of MAS flexibly organize and reuse agents that could help in maintaining system by resolving the local abnormalities and restrict them to be propagated to other modules. The common standard of interoperability between different multi agent systems, that is regarded by The Foundation for Intelligent Physical Agents(FIPA)[70]. It provides a reference model for agent management in the form of a framework for the creation, registration, location, communication, migration and retirement *etc.*, of different developed agents to be interoperated.

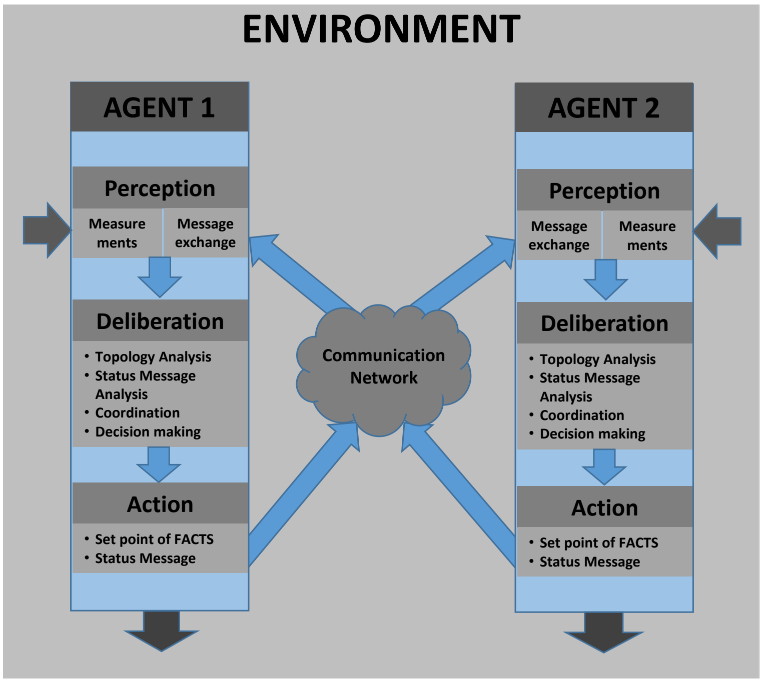


Figure 4.1: Operation and interaction of Multi Agent System

MAS operates in three phases, perception, deliberation, and action [71] as depicted in the Figure 4.1 of MAS operation and agents interactions. The perception phase is related to the collection of environmental information through direct measurements and via communication with other agents for current or the future expected situation. The deliberation is the internal logical intelligent phase which deals with the decision making through reasoning based on the perceived data from the environment. The action is the final phase which influence the environment either altering the system parameters[72], decided in deliberation phase or send the respective information to other agent through communication. Thus the interaction of agents, exchanging their information in perception and action phases, see Figure 4.1.

The potential benefits of MAS application in power system can be achieved using two approaches *i.e.*, simulation and real. In the simulation approach, the agents represent the complex behavior of the power system elements predicted in future. This approach might be used for long time categories of power system *i.e.*, planning, market and management based on the predicted data to estimate the future in the perception phase. Offline decision making is conducted in deliberation phase associated with far future and non physical actions are conducted as software actions in action phase. The real approach, might be applied to the short time categories of power system *i.e.*, operation, control, monitoring and protection. The real task of each agents are presented such as the real data from the monitoring system of the current situation, gathered in perception phase and online decision making is conducted in deliberation and non-physical hardware actions are being taken.

4.2.1 Structure of MAS for FACTS Control

The power flow control of FACTS in a multi area network, MAS based coordinated control system is proposed in this work. Different FACTS devices are deployed in the networks with the objective of improving the transfer capability of the network, which can help in managing the transmission capability in congestion situation. So different agents are proposed which can be differentiated as controlling agents and non controlling agents. Controlling agents correspond to the FACTS devices which directly control the power system parameters to achieve the respective situation. While the non controlling agents correspond to non controllable conventional elements. These agents gathered the states and other related informations of the respective elements and shared with controlling agents. Thus agents are modelled as autonomous, communicative entities of the behaviour described in Fig 4.1.

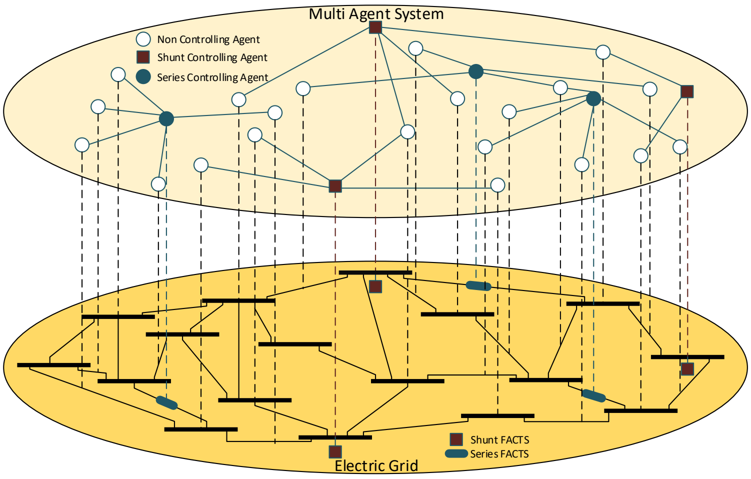


Figure 4.2: Proposed Structure of Multi Agent System

All the agents in the perception phase collect the data through direct local measurements and also the states of other related network elements via information exchange with other agents. The data received in the perception phase is evaluated in deliberation phase. The non controlling agents evaluate the collected data of the environment to analyse the network elements and the current network topology status in the surroundings. Thus adding its own informations and share with other agents so that the controlling agents gets the complete network data in the influential area. The controlling agents have some additional tasks to do in this phase. Each FACTS device has some influential area, which may be common with more than one FACTS devices. So the controlling agents evaluate the received data to decide the control objectives for the respective FACTS in coordinated with neighbouring FACTS devices. The coordination is made possible by exchanging the information with each other through communication. Thus the decision of control action is made not only based on the requirement of the elements in the area, but also taking care of the impacts of other FACTS devices in the area. It would reduce the contradicting actions among the nearly located FACTS devices in controlling the power system parameters. The non controlling agents exchange the state information message resulted from deliberation to neighboring agents about the respective network elements, while the controlling agents would also updated the set points resulted from the coordinated decision for each respective FACTS device and exchange these data with neighbors. The structure of the proposed MAS for electrical grid is depicted in Figure 4.2. The controlling agents shown with coloured square and circles for both series and shunt FACTS devices respectively. The non controlling agents are represented by white circles which are supposed to be deployed on the network elements in the influential area of the FACTS devices. The state informations of the electrical elements in the influential area are sent to the agents of direct connected elements and similarly the information of controlling agents are exchanged through common non controlling agents to the controlling agents. In the proposed MAS structure it can be seen that the number of non controlling agents are limited to only the elements in the influential area of FACTS devices which are more important than others. The MAS approach facilitate the collection of topological information of the scattered network elements and exchanged with distributed controlling devices. This is managed initially by finding the influential area of each controlling devices, and the network elements in the influential area are equipped with agents to participate in communication. The data of the respective elements along with the direct connected neighbors are exchanged regularly to update the states information of the devices. The controlling devices react to the change in the system, which is updated through the state information messages exchanged by the devices in respective influential areas of FACTS devices.

4.2.2 Influential Area of FACTS Devices

Various FACTS devices have been used in power system for different purposes based on their capabilities of controlling various power system parameters. In this thesis FACTS utilization is limited to only series and shunt devices. Both proposed FACTS devices are used mainly for power flow control, reactive power flow reduction and voltage magnitude and phase angle improvement to confined in the defined security limits.

4.2.2.1 For Series FACTS Devices

The series FACTS device has more influence over the power flow of lines in the network. The effected lines in the network by each FACTS device are series and parallel connected lines to the FACTS carrying lines, see Figure 4.3.

All the direct connected lines to the FACTS carrying lines would be highly affected and this effect is gradually decreasing to the next connected lines. So, therefore such lines are considered in the influential area for series FACTS. Then there are two types of affected lines by series FACTS devices *i.e.*, series connected and parallel connected lines. The power flow of series connected lines are directly proportional while the parallel lines flows are inversely proportional with series FACTS devices. controlled but with a less sensitivity and so on to other same connecting lines. Thus the direct connected lines and next connected lines are selected which grouped as influential area. The power network shown in Figure 4.3, where the series FACTS device is placed on $line_{5-10}$. It can be seen that four lines $line_{9-5}$, $line_{8-5}$, $line_{5-6}$ and $line_{10-12}$ are directly connected to the FACTS carrying line. Thus the lines $line_{9-5}$ and $line_{10-12}$ are connected in series, while lines $line_{5-6}$ and $line_{6-12}$ make a parallel path to the line having series FACTS device. Similarly the lines $line_{12-8}$ and $line_{8-5}$ make a loop with the series FACTS carrying line. So all these lines are selected in the influential area for series FACTS devices. All these lines are supposed to equipped with agents to share the information of these lines and all other connected lines to controlling agents via non controlling agents. Thus each control agent would have enough data to visualize the network in its surrounding to take the corresponding actions. Thus there are basically two groups of elements regarding the control of series FACTS devices *IncGroup* and

DecGroup. *IncGroup* consist of elements which power flows are directly related to power flows of FACTS carrying lines *i.e.*, increasing and decreasing accordingly and all the series connected lines belongs to such group. The *DecGroup* consist of elements which power flows are reciprocally related, *i.e.*, increasing and decreasing inversely and all the parallel lines belong to this group. The topological structure of the available lines will make the series and parallel lines with these series FACTS devices and thus *IncGroup* and *DecGroup* are updated accordingly.

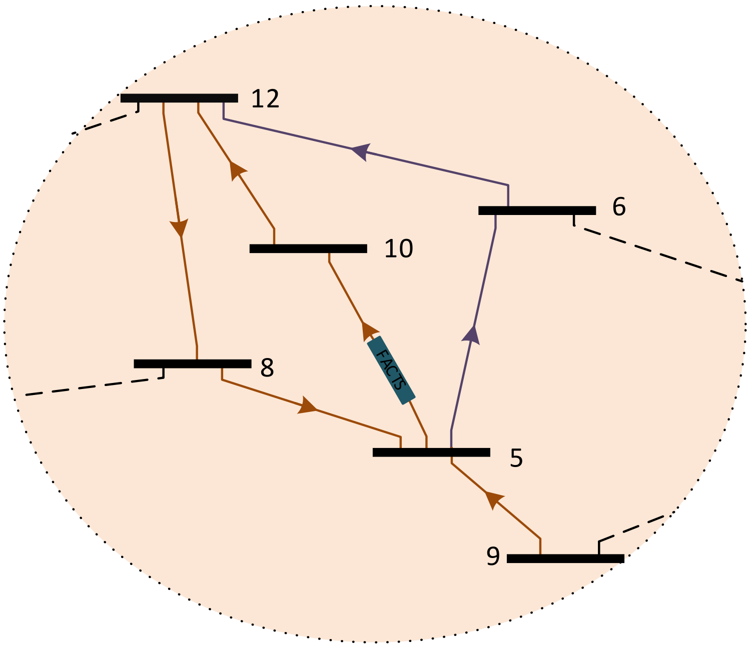


Figure 4.3: Influential Area of Series FACTS Devices

4.2.2.2 For Shunt FACTS Devices

The second proposed FACTS devices are shunt connected and their affects are more over the bus voltage magnitude and phase angle, reactive power compensation, power quality improvement of huge consumers *etc*. The influential area of these FACTS devices are ascertained based on the direct connected buses with shunt installed FACTS buses and other connected buses with these buses as shown in Figure 4.4 and further based on the electrical distance.

The electrical distance can be determined by using L-index formulation as given in 3.17, here it is used for PQ buses only and the buses with shunt FACTS devices are considered as PV buses. Thus it can be represented as given in 4.1.

$$\begin{bmatrix} V_F \\ I_L \end{bmatrix} = \begin{bmatrix} Z_{FF} & -F_{FL} \\ K_{LF} & Y_{LL} \end{bmatrix} \begin{bmatrix} I_F \\ V_L \end{bmatrix} \tag{4.1}$$

Where, V_L,I_L: Voltage and current vectors for PQ buses without FACTS.

V_F,I_F: Voltage and current vectors for the buses with FACTS. And the electrical distance of each shunt FACTS bus to other PQ buses is given as in 4.2.

$$R_{FL} = 1 - real(F_{FL}) \tag{4.2}$$

Where, R_{FL}: The nF X nL matrix which consist of the resistance of the elements connecting each FACTS device with other PQ buses. nF: Number of PQ buses with FACTS devices. nL: Number of PQ buses without FACTS devices.

The buses which have minimum electrical distance from shunt FACTS buses are also considered in the influential area, defined in 4.3.

$$R_{min} = \min_{i\epsilon\alpha_F}(R_{FL}(i)) \tag{4.3}$$

Where, R_{min}: An array of all the PQ buses $i\epsilon\alpha_F$ where shunt FACTS devices installed.

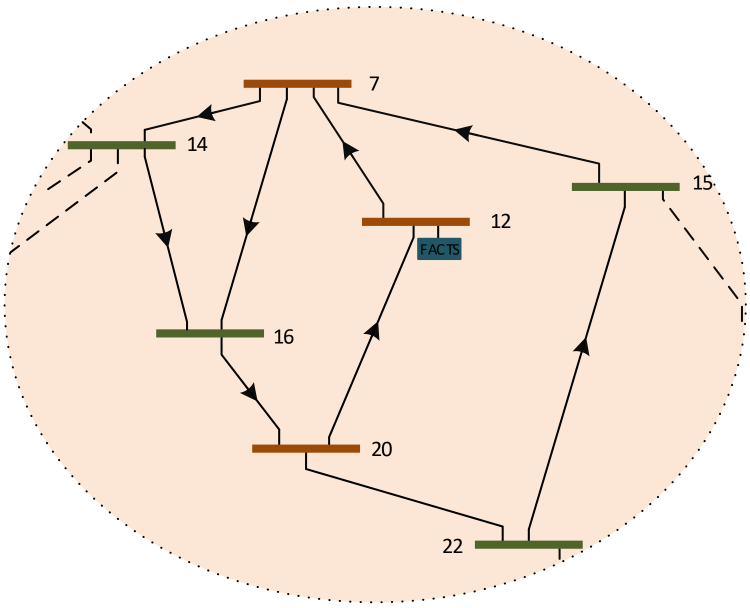


Figure 4.4: Influential Area of Shunt FACTS Devices

Thus the buses of influential area of each shunt device are equipped with non controlling agents to share their information with each other and eventually with controlling agents. The above influential area can be explained by Figure 4.4, where a shunt FACTS device is placed at bus_{12}. Thus the direct connected buses to shunt FACTS connected bus are bus_7 and bus_{20}. The bus_7 is further connected to bus_{14}, bus_{15} and bus_{16}, while bus_{20} is further connected to bus_{16} and bus_{22}. So the influential area of shunt FACTS at bus_{12} is shown in the Figure 4.4. The most prior bus in the influential area is selected based on minimum electrical distance *i.e.*, bus_7. Thus the control of shunt FACTS will look the magnitude and phase angle of buses to be in the security limit. So over voltage and under voltage buses need different control strategy and the control agent will decide optimum action to handle both type of situations.

4.3 Agent Communication

The required data for both utilized types of FACTS devices are provided by agent based approach, which facilitate the distributed provision of updated topological information and power demand status. Thus the state information of the system elements rapidly updated in case of a major change in the system topology like disconnection of lines *etc.* Or the violating operating condition of the system based on the consumers demand. The controllers react subsequently according to the new system state, so that all the elements are within their secure operating limits. Therefore, the state information among the agents would be exchanged regularly to keep the control agents updated about the system status. Each agent adds the information of its respective device in the $AgentMessage$ and forward to all neighboring agents which haven't yet sent the $AgentMessage$ to this agent. It is important that if all the neighboring agents sent the $AgentMessage$ then only the most prior agent defined for each agent is left for sending the message. The priority of agents is based on the closeness to the control agent to avoid replication. Thus the message passing among the agents is reduced in communication network, while considering the importance of direct connected elements to each FACTS device. Which have the required enough data of other devices to guide the controlling agents in specifying the control objectives for respective FACTS device. The $AgentMessage$ of line elements consist of following information:

1 Line % loading

2 Power flow direction through the line

3 Line impedance

4 Neighbouring lines status

5 Received $AgentMessage$ with time stamp

The $AgentMessage$ of nodes contains the following information:

1 Power demand and supply at the node

2 Magnitude and phase angle of node voltage

3 Shunt admittance at the node

4 Impedances of connected branches

5 Received $AgentMessage$ with time stamp

The state info messages are exchanged in a predefined time interval in which all the agents share their data in the influential area and ultimately with controlling agents. The controlling agents analyse the received $AgentMessage$ to find the status in the influential area and evaluate the data to decide the control strategy for the respective FACTS devices, according to the system conditions. The approximated network for each FACTS device is determined from the available elements and ignore the elements which data is not available. The network topology of the influential area is analysed in the surroundings by control agent based on the received $AgentMessage$ for each FACTS device. The control action of each FACTS device is decided according to the parameters of all direct connected elements. Then based on the parameters of next connected elements *i.e.*, that are connected to the direct connected elements. And extension of control actions would be based on installed capability of FACTS devices.

The impedances of all the elements in the influential area are provided to the controlling agents through $AgentMessage$. An admittance matrix Y_{inf} of available lines is formed for series FACTS device based on the buses connecting these lines by control agent. The first two rows and columns of the Y_{inf} matrix consist of all the buses that are directly connected to the lines carrying series FACTS devices and then more rows and columns are added, that consist the buses which are more close to these lines. In case of major change in the network topology like the outage of certain line the parameter of disconnected elements are not considered.

$$Y_{inf} = \begin{bmatrix} Y_{11} & Y_{12} & . & . & . & Y_{1n} \\ Y_{21} & Y_{22} & . & . & . & Y_{2n} \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ Y_{n1} & Y_{n2} & . & . & . & Y_{nn} \end{bmatrix} \tag{4.4}$$

Similarly the Y_{inf} matrix for shunt FACTS devices is formed as the first row and column consist of all adjacent buses to shunt FACTS installed buses. And then other connected buses are added in rest of the rows and columns. The Y_{inf} matrix is very important not only provide information of the available elements in the influential area but also help in finding the sensitivity of line flows and bus voltages. The structure of the Y_{inf} matrix provide also the information to design the control strategy for FACTS devices.

4.4 Sensitivity Function

The control agent of each series FACTS device collect the data from *AgentMessage* of available lines in its influential area and update the group of transmission lines corresponding to *IncGroup* and *DecGroup* based on direction and loading of the respective lines as explained before. The power flow of series connected lines are affected corresponding to the power flow variation of control line if there is only one line connected to those nodes. While the determination of power flow variation of all other lines with multiple series and parallel connected lines are complicated and can only be determined based on the sensitivity. Which is the ratio of active power flow change $\Delta P(l)$ of line l with the change in power flow of control line f having series FACTS device $\Delta P(f)$, given in 4.5.

$$SenFnP(l,f) = \frac{\Delta P(l)}{\Delta P(f)} \tag{4.5}$$

The change in active power flow is approximated by DC load flow analysis as given in equation 4.6. Thus the change in power injection due to the series FACTS device settings is calculated as:

$$\begin{aligned} \Delta P &= B_{inf} \Delta\theta \\ \Delta\theta &= B_{inv} \Delta P \end{aligned} \tag{4.6}$$

B_{inv} is the inverse of influential area susceptance matrix B_{inf} and $\Delta\theta$ is the nodal voltage phase angle. So the change in phase angle of nodes i and j due to the power injection at two buses of the series FACTS of line f can be determined as in equation 4.7.

$$\begin{aligned} \Delta\theta_i &= B_{inv-ij} \Delta P_i \\ \Delta\theta_j &= B_{inv-ji} \Delta P_j \end{aligned} \tag{4.7}$$

The sensitivity of line l between nodes s and r can be calculated for a $p.u$ change in power flow of control line f.

$$SenFnP(l,f) = \frac{1}{X_l} (\Delta\theta_s - \Delta\theta_r) \tag{4.8}$$

The direction and amount of power flow of each lines will specify the line to be in *IncGroup* or *DecGroup*. As the loadings of lines of *InGroup* and *DecGroup* will increase and decrease corresponding to the loading increase in control line and vice versa. Therefore, the control agent will consider the lines loading, their sensitivity while adjusting the settings of series FACTS devices.

Similarly to determine the variation of nodal voltage magnitude for reactive power injection by shunt FACTS devices. The fast decoupled power flow method [73] is used instead of the DC power flow method which is only better in MW flows of lines and give no indication of voltage magnitudes and MVA flows. The sensitivity $\frac{\Delta V_k}{\Delta Q_i}$ of voltage magnitude for all the buses in the influential area for respective change in reactive power of shunt FACTS device.

$$\begin{aligned} \frac{\Delta Q_i}{|V_i|} &= -B_{inf-ik}\Delta|V_k| \\ \frac{\Delta|V_k|}{\Delta Q_i} &= -\frac{B_{inv-ik}}{|V_i|} \end{aligned} \tag{4.9}$$

So the voltage sensitivity of any bus k for the $p.u$ change of reactive power injection by shunt FACTS devices at bus i is given as:

$$SenFnQ(i,k) = -\frac{B_{inv-ik}}{|V_i|} \tag{4.10}$$

4.5 Need for Coordination

In the distributed control system each FACTS device affectively control the elements in its influential area as explained before. But this is not enough for the nerly situated FACTS devices simultaneously affected many elements. Such common elements could be deteriorated in operation due to the inappropriate FACTS settings. The Figure 4.5 depicted such situation where many lines and buses are affected by more than one FACTS devices. The Series FACTS devices like TCSC, SSSC *etc.*, affect mainly the active power flows and bus voltage angles whereas the shunt FACTS devices like SVC, STATCOM *etc.*, influence mainly the reactive power flows and bus voltage magnitudes in their respective locations. The influential impact of series FACTS devices can be further extend to power flow of the adjacent lines while the impact of shunt FACTS devices encompass the voltage magnitude of adjacent buses. In Figure 4.5 an example of three series FACTS devices at $line_{1-2}$, $line_{4-5}$ and $line_{15-16}$ and three shunt FACTS devices at bus_1, bus_3 and bus_9 are used in an electrical network. The influential area of each FACTS device is shown. It can be seen that there is a line $line_{2-4}$, which is under the influence of two neighbour series FACTS device on $line_{1-2}$ and $line_{4-5}$. The series FACTS device located at $line_{15-16}$ is far away from other series FACTS devices and obviously not affecting any lines, instead has only a shunt FACTS device at bus_9 in its vicinity, so could affect the buses combined with that shunt device. The bus_{15} and the $line_{9-15}$ are simultaneously influenced by these two FACTS devices. The bus_2 is simultaneously affected by both shunt FACTS at bus_1 and bus_3 and bus_8 is influenced by shunt FACTS at bus_1 and bus_9. Similarly there are other lines and buses, influenced by series and shunt FACTS devices simultaneously as shown in the Figure 4.5. Therefore, the simultaneous effects of multiple FACTS devices on their surroundings can't be ignored in adjusting the set points for FACTS devices. The lines and buses which are under the influence of multiple FACTS devices could be deteriorated in such operation. As an example the $line_{2-4}$ is in between the two series FACTS devices at $line_{1-2}$ and $line_{4-5}$ could be overloaded if both the series FACTS are trying to increase power flow or cancelling the effects of each other in case of opposite control objectives. In centralized control system the optimal settings of FACTS devices can resolved the problem by adjusting the optimal settings of FACTS devices based on the optimization algorithms. But in distributed control system independent control settings of each FACTS devices devices couldn't resolve the problem. So in order to resolve the issue, the FACTS devices settings could be adjusted by coordinating among multiple FACTS devices using multi agent system.

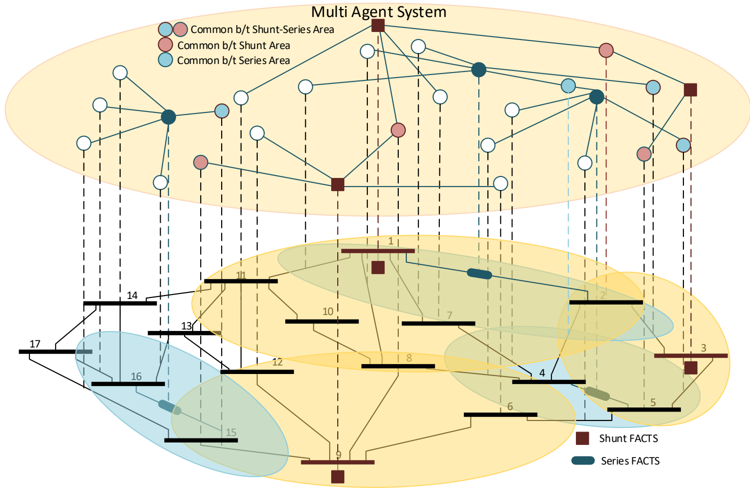


Figure 4.5: Coordination for common elements between influential area of FACTS Devices

4.6 Coordinated Control System

The purpose of the coordinated control system for multiple FACTS devices is to improve the security constraints of power system that causing network congestion. As explained before the series FACTS devices respond to relieve the overloading lines while shunt FACTS devices improve the bus voltage magnitude of violating buses.

The control agents would set the control actions based on the loading and sensitivity of the elements in the influential area. When one element is controlled by FACTS devices, other elements in the influential area could be also affected. The control agents estimate such effects and considered it in deciding the control settings of FACTS devices. The most sensitive elements are the adjacent elements to the FACTS devices, which are more susceptible to the change in FACTS settings. The control agents make use of sensitivity analysis based on DC power flow method of the power network in the influential area independently and approximate the expected effects. Which resulted in the range of control efforts for improving the violating elements and minimize the adverse effects on other elements in the area. The coordination control strategy aims to rectify the possible conflicting effects of multiple FACTS devices in the system. For this purpose, the control settings of the FACTS devices are decided initially based on local area requirements and later coordinated with neighbouring FACTS devices. Each control agent also send $AgentMessage$ to share its suggested control settings and sensitivity of all the elements in its surroundings. Thus the agents of common elements receive the control settings of all the control agents along with their sensitivity. Then these agents added their loading information to $AgentMassage$ and sent to all the control agents as depicted in Figure 4.5. All the control agents have now complete data to decide the final control objective for respective FACTS devices.

The overall effects of contributing FACTS devices to common elements can be determined as given in equation 4.11 and 4.12.

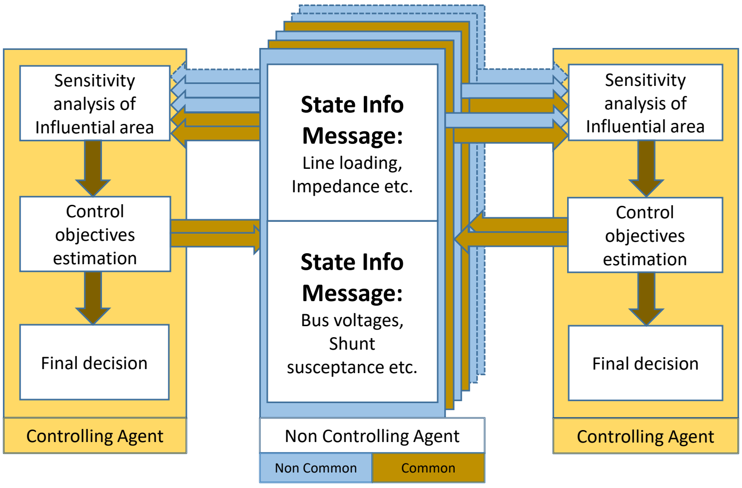


Figure 4.6: Coordination control of FACTS Devices

The total real power variation of common line l among α_f number of FACTS devices.

$$\Delta P(l) = \sum_{i \epsilon \alpha_f} SenFnP(l,i)\Delta P(i) \tag{4.11}$$

Similarly the net voltage magnitude variation of common bus i is given in 4.12.

$$\Delta V(i) = \sum_{k \epsilon \alpha_f} SenFnP(i,k)\Delta V(k) \tag{4.12}$$

The coordination control system would respond by providing the respective control actions for the FACTS devices in case of the critical situation happen in power system. The controlling agents would identify the elements by continuously processing the $AgentMessage$, received from non controlling agents. The critical situation define for line loading is 80% of its rated capacity and 0.94- 1.06 p.u for the bus voltage in this work. Series FACTS devices react to the critical lines and shunt FACTS devices correspond to critical buses. The is no change in control action, if the parameters of all the elements are within the defined range. The control action would be change according to the following situation happened:

1) If a line violation occurred, the concerned control agent of series FACTS device identify the group to which it belongs *i.e*, *IncGroup* or *DecGroup* and suggest a range of control objectives based on the elements of influential area. The suggested control settings are sent to common elements if exist, otherwise the suggested would be decided as final control settings.

2) The control agent of shunt FACTS devices search the violating buses in the influential area and determined the required compensation both individual and cumulative in case of single or multiple neighbouring FACTS devices respectively.

3) The control setting would be suggested for most critical lines among multiple violating line in any influential area. If there are multiple lines of loading 80%, 85% and 90%, then the control setting would be suggested based on the line of highest *i.e*, of 90% loading.

4) If the common elements are seems to be violated due to the individual suggested control objectives of each participating FACTS devices, then the individual suggested control settings are reduced in coordination with each other.

5) In any individual area of FACTS device there is no change in the control settings when no violation occurred or the lines of both groups *IncGroup* and *DecGroup* reach the critical loading at the same time. In such situation which is very rare to be happened, the change of control setting would reduce the loading of one and could increase the other of opposite group.

The parameters of common elements are settled in their security limits due to the coordination among the control agents. The remaining amount of the parameters to the rated value is determined for the current loading situation of common elements and control setting is decided by each control agent. The sensitivity factors and the current difference of parameter from its rated value are given in equations 4.13 and 4.14. The estimated contribution of each FACTS device is calculated using the net difference of the parameter and the sensitivity of each FACTS device. Thus the respective control parameter is determined to decide the final control settings of each FACTS device.

The net remaining loading $\Delta P_L(l)$ of common line l is used to determine the control parameter of line i with series FACTS device.

$$\begin{aligned} \Delta P_L(l) &= P_{lim}(l) - P(l) \\ \Delta P(i) &= \frac{SenFnP(l,i)}{\sum_{k\epsilon\alpha_f} SenFnP(l,i)} \Delta P_L(l) \end{aligned} \tag{4.13}$$

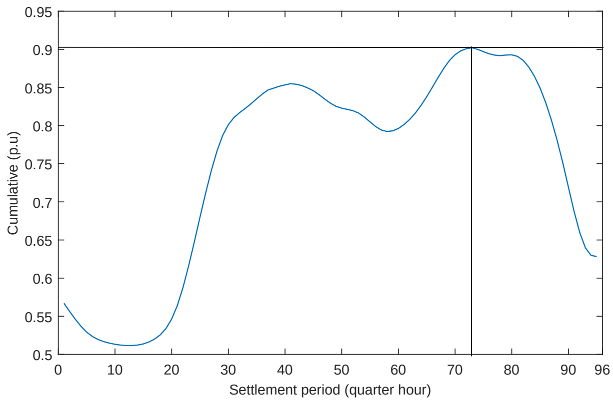
Similarly the amount of voltage $\Delta V_B(i)$ to reach the minimum operating voltage limit of common bus i is used to estimate the controlling voltage $\Delta V(k)$ of bus k with shunt FACTS device.

$$\begin{aligned} \Delta V_B(i) &= V_{min}(i) - V(i) \\ \Delta V(k) &= \frac{SenFnQ(i,k)}{\sum_{k\epsilon\alpha_f} SenFnQ(i,k)} \Delta V_B(i) \end{aligned} \tag{4.14}$$

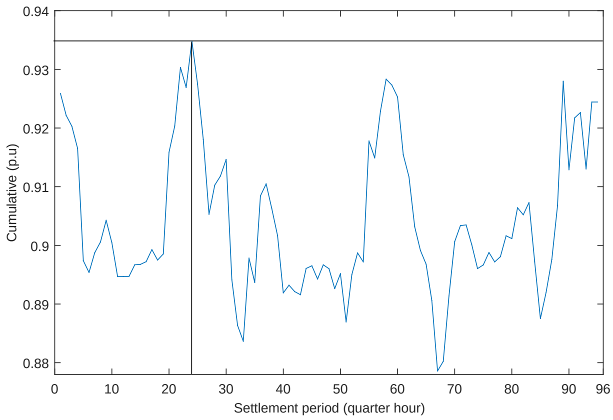
The centralised control is also integrated in the proposed distributed coordinated control system with a high priority. This would be utilized by control center to optimally set the control objectives for the FACTS devices based on overall system evaluation in order to conduct certain power transaction. The control agents would follow such objective but also considering the local requirements. This means the control objective would be adjusted according to requirement of local influential area and coordination among the control agents. The control objectives could be only suggested to only the maximum installed capacity of FACTS devices.

4.6.1 Dynamic Load Profiles

The distributed coordination control of multiple FACTS devices is evaluated by critical situation using dynamic load profiles. The dynamic states of the power system elements based on the dynamic load are updated at regular interval to the defined agents in Multi Agents System, simulated in MATLAB using matpower 5.0.



(a) Dynamic Load Profile 1



(b) Dynamic Load Profile 2

Figure 4.7: Dynamic Load Profiles

Two synthetic dynamic load profiles are used as given in Figure 6.1. The load profile 1 shows the cumulative load variation over the 24 hours with quarter hour step. In the first 6 hours the load is below 60% of the total installed load and remain above in rest of the 18 hours. The load is varying smoothly and the maximum peak of the load is achieved at 16th hour, and then dropping down to the end. This load profile would represent the load demand in different time slots of the day and the behavior of the power network is studied. Similarly the performance of the control strategy in resolving the critical situation is studied. The load profile 2 is also for 24 hours of time with the same quarter hour of step size, the variation of load is more rapidly but varying in between 88-94% of the total installed load. This load profile is used to study the power system operation in more dynamic situation and the compensation of the proposed MAS based control of FACTS devices. The steady state operation of the power system is studied using these load profiles which created the congestion scenarios of line overloading and bus voltage violation. Five IEEE test networks *i.e.*, 30, 39, 57, 118 and 300 bus systems are subjected to conduct this study and the operation of power system with distributed coordinated control of FACTS devices is evaluated. The FACTS devices are placed at the defined locations as proposed in chapter 3, based on the network analysis. The steady state of the elements are simulated for each 15 min of dynamic load and the required control action is provide by MAS. The defined deployed agents follow the dynamic states of the elements and shared the data among the agents to improve the violating conditions.

4.6.2 Congestion Management with and without FACTS Devices

The operational constraints of the transmission network become active during the load variation of the applied load profiles. The steady state operation of the power system with 15 minutes of time step for loading at each load buses is simulated. The lines flows and bus voltages are determined using Newton Raphson power flow method. The main focused constraints are line capacity limit and steady state voltage limits *etc.* The electric network is subjected to system without FACTS devices and the congestion is managed by generation rescheduling method. In this work the power injections and consumption are decided by the operator among the areas, so that no constraint is violated. The line loading is managed by increasing the power injection at the sending or source area, while the power demand of the receiving area is equivalently injected locally. Similarly the bus voltage violation is improved by the power injection in the area corresponding to minimum or maximum bus voltage limit.

The MAS system is activated to control the FACTS devices to improve the violating constraints and manage the congestion without rescheduling the generations. The control objectives are adjusted in case of violation for the corresponding FACTS devices based on the coordination among the agents in each loading step of the load profiles. The power flow are diverted from the overloading lines to other neighboring line with available line capacity. The reactive power are injected in order to improve the bus voltage magnitudes of the violating buses. $N-1$ contingency conditions are also applied to evaluate the system operation in both with congestion management and distributed coordination control of FACTS devices. The operation of both systems in inter-area lines and generators outages contingency cases. The results of the IEEE test networks for normal and contingency cases are discussed in chapter 6.

5 RESULTS AND DISCUSSION OF TRANSFER CAPABILITY ENHANCEMENT

5.1 Introduction

The FACTS technology open new opportunities for transmission planner for controlling power and enhance the usable capacity of transmission network. The current control of a line can provide a large potential of increasing the capacity of existing transmission network. The ability of FACTS devices to control the related parameters of series impedance, shunt impedance, current, voltage and phase angle *etc.*, that govern the operation of transmission system. A proper chosen FACTS device can overcome the specific limitations of designated transmission line or a corridor. There are various methods based on which FACTS are optimally placed to control line current, bus voltage and damping oscillations for improving transmission capability, power system stability and reliability. The capability of transmission network is limited due to thermal, dielectric and stability limits and the used of FACTS devices are efficient in overcoming these limitations.

The enhancement in transmission capability is focused for FACTS utilization along with additional advantages of improvement in bus voltages and line capacity utilization. The power network of various IEEE test systems are analyzed for transmission capability enhancement using static increase of demand in planning phase by using basic parameter of FACTS devices. The locations are selected based on sensitivity indices for both series and shunt FACTS devices as explained in previous chapter 3. Two study cases are consider to check the total transmission capability of the network for transactions among different areas. Similarly the possibility in transmission capability enhancement is investigated using different FACTS devices. The sizes of FACTS on proposed locations are computed iteratively for possible improvement in the said constraints of voltage stability and line capacity utilization. The proposed sizes of FACTS devices are also checked for contingency cases of line and generator outages. The results achieved from the proposed method are quite enough to attract the attention of system operator. The quantitative way to justify the usefulness and applicability of the proposed methods are given in this chapter.

The results of line flows, bus voltages and proposed series and shunt FACTS devices are given for static increase in demand and supply. Each electric network is being stressed by increasing the power transfer between supplier and consumer to the maximum value where after the constraints are going to be violated. Then the critical areas are identified in terms of overloading lines and voltage violating buses. Different groups suppliers and consumers based on areas are made to identify critical locations for all the possible transactions.

The improvement achieved in total transmission capability (TTC) using FACTS devices for each network are shown in comparison to the system without FACTS and Base case. The TTC is mainly limited by line thermal capacity and voltage stability. So the strategy is adopted to extend the capability by improving the respective constraints using FACTS devices. Two sensitivity indices defined in chapter 4, are use to select multiple locations for both series and shunt FACTS devices.

5.2 Study Cases

In chapter 3 the study cases are defined, which described different conditions to analyze the power networks. The transfer capability of power network is strongly affected by all the interconnected lines and buses. Therefore, some assumptions are being made before determining the transfer capability of power network. The objective of the defined study cases is to explore all the possible locations which may become critical during the enhancement of the transfer capability. Thus the increment of load at one location definitely affect other transaction as well. So in one study case all the connected load demands of the test network are simultaneously upgraded. That means the network capability is determined for all the upgraded transactions among the loads and generations. This will analyze the effects of all the raised demands in the network and identify the locations critical for transfer capability. This is not enough because, all the loads are not all the time increased, sometime there is a large transaction between any two areas of the network. As the electricity trading is mostly among different interconnected areas which exchange power depending on their demand requirements. So the other study case is about such conditions where the individual transaction between any two areas are raised to the maximum capability. And the critical locations are identified for each individual upgraded transactions. These study cases are utilized to explore the critical locations in the network and analyze the network for further enhancement in the transfer capability using FACTS devices. Five IEEE power networks 30, 39, 57, 118 and 300 buses are tested for transfer capability enhancement and the results are shown with achieved enhancement with FACTS devices over the proposed locations.

5.3 Study Case I: Overall Total Transmission Capability

This study case focused on the capability of the network with simultaneous rise in all the possible transactions among the loads and generations. This study case would help in analyzing the network for the combined effects of all the transactions. And the identification of critical locations is done, based on the analysis of the system using AC power flow method. The power transactions are supposed from all the available suppliers to all the connected consumers simultaneously. All the nodes with generators are supposed to be suppliers and the consumers are the nodes with loads. The loads are incremented statically with an amount of power which give rise to the the power transfer among the supplier and consumers of the power network. Thus the power transfer is increased to the level beyond which there is no network capability available to allow the further transactions. In this study case it is aimed to explore all the possible critical locations in the network due to the effects of all the transactions and these are not supposed to a certain area only but considering overall network. The purpose of this static growth is investigate the locations in the network which restrict the transfer capability. The capability of the network is computed for 10% of total number of buses violation and any single line exceeding 80% of its rated line capacity. Further the network is analyzed by varying the circuit parameters based on FACTS devices to enhance the network transfer capability. The proposed FACTS locations are based on sensitivity indices and violation of the parameters. Finally the constraints parameters are improved by varying the FACTS parameters.

5.3.1 IEEE 30 Bus System

The smallest network selected for analysis of TTC computation and enhancement using FACTS is IEEE 30 bus system. The data of the network utilised in this work is taken from [74] and given in Appendix .2. There are 30 number of buses, in which 6 buses consist of generators and 24 buses carrying loads. A total of 41 lines connecting the buses as shown in Figure 5.1.

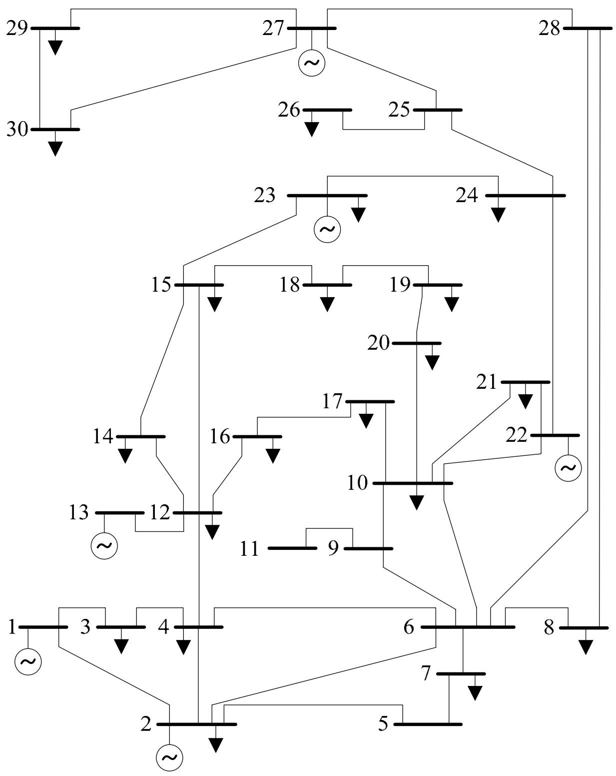


Figure 5.1: IEEE 30 bus system

After analyzing the generation and load data of all three systems are given in Table 5.1. The network has the capability to compensate 32.69% of active load demand with 32.76% of more reactive demand in the system, which is supplied by 33.57% of more active power supply and 43.63% of reactive power supply in the network with only two lines exceeding 80% of the line capacity. And the losses in the network are increased by 95% of the losses in the base case. On the other hand using FACTS devices, the capability of the network is a slightly increased and thus the active load demand is increased by 35.12% with 32.66% of the reactive load demand. This has also raised the losses by more than 89% of the losses in the system with base case data.

Table 5.1: Load and Generation of IEEE 30 Bus System

Cases	Area	Base Case P(MW)	Base Case Q(Mvar)	Max.w.o.FACTS P(MW)	Max.w.o.FACTS Q(Mvar)	Max.w.FACTS P(MW)	Max.w.FACTS Q(Mvar)
Generation	A1	86.94	31.00	111.77	44.99	113.45	37.51
	A2	56.20	19.30	77.40	27.47	78.93	27.80
	A3	48.50	50.11	66.80	71.77	68.12	70.43
% increase				33.57	43.63	**35.93**	**35.18**
Load	A1	84.50	56.40	108.19	72.89	109.90	72.99
	A2	56.20	25.80	76.19	34.93	77.64	34.10
	A3	48.50	25.00	66.80	34.43	68.12	35.11
% increase				32.76	32.69	**35.12**	**32.66**
Losses		2.44	8.99	4.79	17.25	4.64	26.93

Table 5.2: TTC values of overall system for IEEE 30 bus system

Cases	w.o FACTS			w. FACTS		
Area	A1	A2	A3	A1	A2	A3
TTC	23.69	19.99	18.30	25.4	21.44	19.62

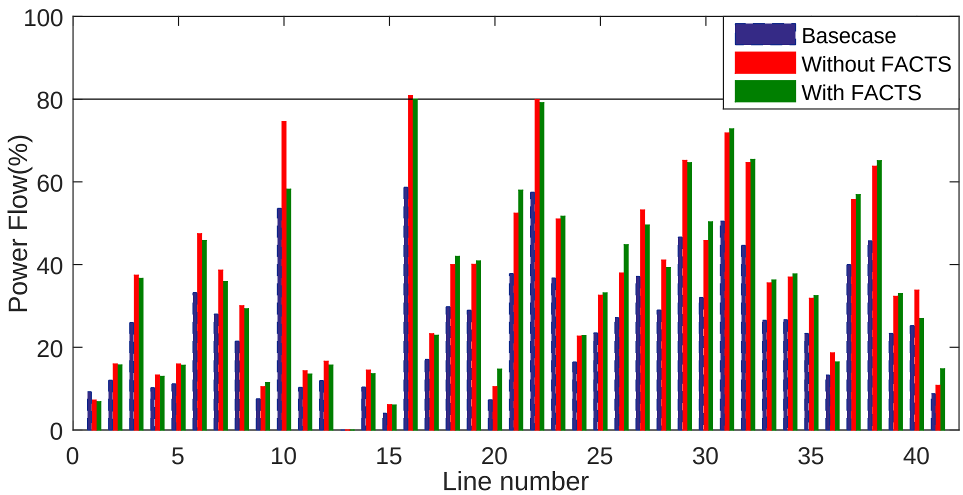
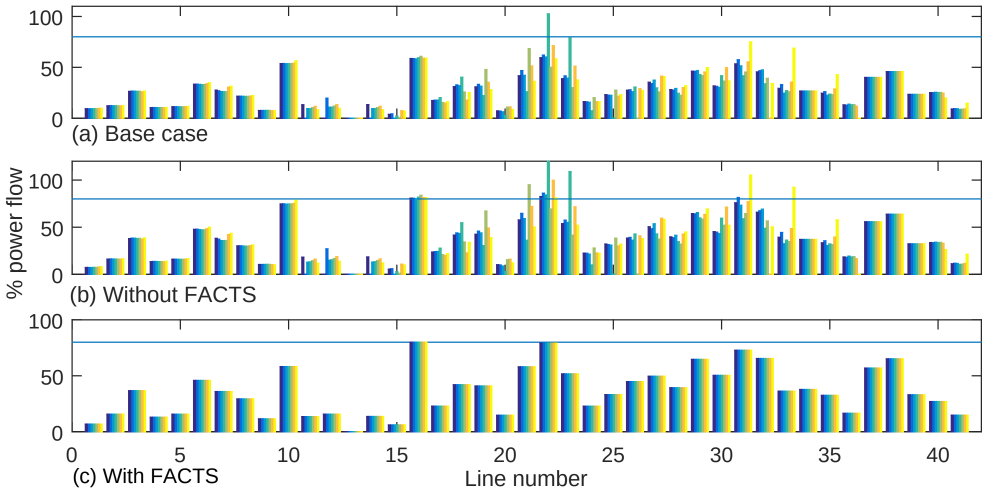
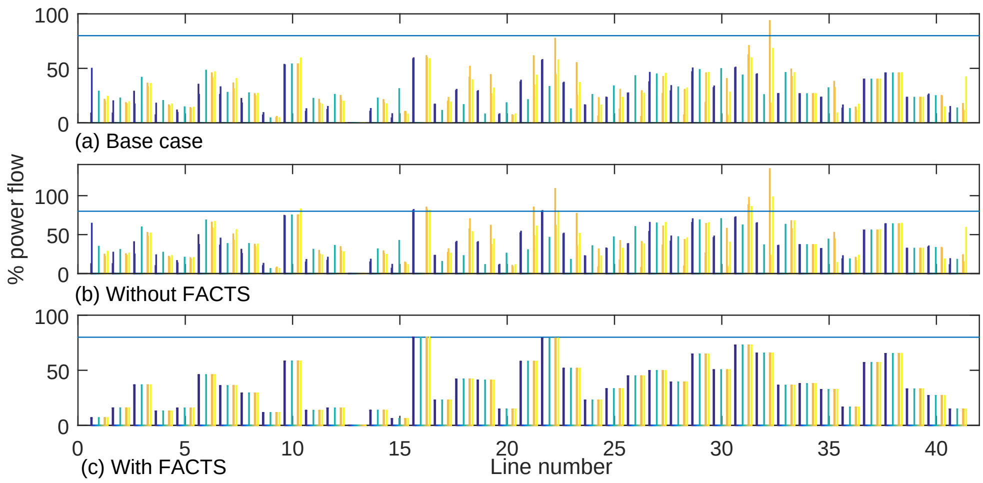


Figure 5.2: Power Flow on lines in IEEE 30 bus system

The network is supposed to be divided into three areas and the TTC values of each area is calculated for the systems with and without FACTS devices, which are given in Table 5.2. It can be seen that the TTC values are increased by 7.21% in each area using FACTS devices as the loads are equally increased at each area. The corresponding effects of the increased load demands over other parameters of the network are shown in terms on line flows and bus voltage magnitudes. The line flows of all three systems are shown in Figure 5.2 in normal case. The system with base case data has the line flows well below 80% of their capacities, shown by blue bars. The system of data with increased demand but without FACTS devices are shown by red bars, where two lines L_{12-13} and L_{15-18} have the power flows exceeded the specified limit and restrict the TTC of the network. The power flows of each line for the system with increased demand and FACTS devices are shown by green bars. It can be seen that the power flows of all the lines are within their 80% of capacity and the power of the exceeding lines L_{12-13} and L_{15-18} are reduced and transferred to other lines in the network. Thus the capability of the network is improved which appeared to incorporate the further increased in demand. Thus the exceeding lines are selected for FACTS devices and shown in 5.4 with change in impedance. The analysis of the systems are



(a) Line outage contingency case



(b) Generation outage contingency case

Figure 5.3: Power flow of contingency cases in IEEE 30 bus system

also extended to contingency cases of lines and generations outages. The power flow of the lines for the inter-area line outage and generators outage cases are shown in Figure 5.3. It can be seen that all the line flows in the base case are within the supposed line capacity limit except in L_{10-20} outage case. The system with increased demand and without FACTS devices has violating lines in all of the line outage contingency cases. The lines *i.e.*, L_{12-13}, L_{16-17}, L_{15-18}, L_{18-19}, L_{22-24} and L_{24-25} can be seen have more than 80% of the line capacity limit. In generation outages, only one line flows *i.e.*, L_{32} is violating the limit in base case. While more than one line *i.e.*,

L_{12-13}, L_{16-17}, L_{15-18}, L_{22-24} and L_{23-24} are violating in the system without FACTS devices.

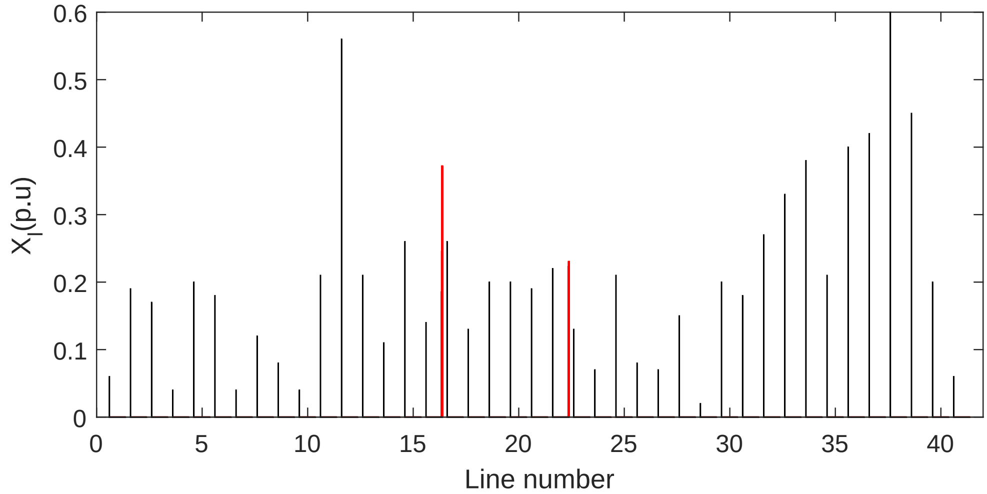


Figure 5.4: Reactance of series FACTS in IEEE 30 bus system

The system with FACTS devices has better line flows with increased demands as compared to the system without FACTS, depicted in the Figure 5.3. It can be seen that the lines flows are raised up due to the increased in power transfer but are well maintained under the specified limit and only few lines reached the limit. And line outage of any line doesn't affect the line flows, because the line flow are well distributed among the lines due to FACTS parameters settings. Similarly in generator outages only two lines L_{16} and L_{22} have reach the line capacity and other line flows are under the line capacity limit. Here also the power flow distribution is nicely performed by the change in line impedance using FACTS devices that no line exceed the limit.

Based on the proposed algorithm two locations *i.e.*, L_{10-20} and L_{10-17} are selected for series FACTS devices in this network. The proposed impedance of the selected lines *i.e.*, L_{16} and L_{22} to achieve the lines flow improvement are shown in Figure 5.4 at L_{16} and L_{22}. Which shows that the most critical lines are selected for series FACTS placement that resulted the respective improvement in power flow. Similarly it can be observed that the line L_{16} is more critical so more impedance change is needed which suggest large FACTS device should be placed.

The magnitude of bus voltages in all three systems with base case data, without FACTS and with FACTS are shown in Figure 5.5. All the buses have normal voltage magnitude in base case. it means there is no voltage violation. The system without FACTS has drop in bus voltage magnitudes in all load buses and only the magnitude of bus_8 reached the lower voltage limit but still within the secure operating limit. It means the system is not much affected by the achieved increased demand. Where as the system with FACTS devices has got more increase in demand but there is no bus where voltage magnitude drop down the lower limit and the voltage magnitudes of the buses are better compare to the system without FACTS. The FACTS devices has increased the capability of the system of adding more demand in the system. Three bus locations are selected for shunt FACTS devices *i.e.*, Bus_8, Bus_{18} and Bus_{19} based on the proposed algorithm. The sizes in terms of reactive power injection of the FACTS devices are shown in Figure 5.6. It can be seen that the voltages are improve in many buses by the FACTS devices. The reactive power injection at Bus_8 is more compare to Bus_{18} and Bus_{19} because it can be seen more critical in the system without FACTS. So the shunt FACTS at this location is more beneficial, at one hand it could improve the voltage magnitude of the critical bus in enhancing the transfer capability but on the other hand it can help in controlling the bus voltage magnitude in the surroundings.

Now to examine the bus voltages in contingency cases look Figure 5.7. There are three buses Bus_{17}, Bus_{19} and Bus_{20} where bus voltage are violated down in one or two line outages of base case system. The number of these buses are increased to five buses Bus_{16}, Bus_{17}, Bus_{18}, Bus_{19} and Bus_{20} in the system without FACTS. Similarly in generator outages there are seven buses Bus_{19}, Bus_{20}, Bus_{21}, Bus_{22}, Bus_{26}, Bus_{29} and Bus_{30}, which are violating in one of the case for base case system. The system without FACTS devices the violating buses are increased to seventeen buses that are violating in one or more generator outages. The details of the violating buses for respective line and generator outages are given in Table 5.3.

The system with proposed FACTS devices has also better bus voltages in line and generator outages as depicted in Figure 5.7. That shows that there is comparatively less effect on the bus voltages in the system in any outage case until unless the whole system is collapse, which is not happened in this network. It means if the critical locations is selected for FACTS placement it could improve the system performance both in normal and contingency cases as given in Table 5.3.

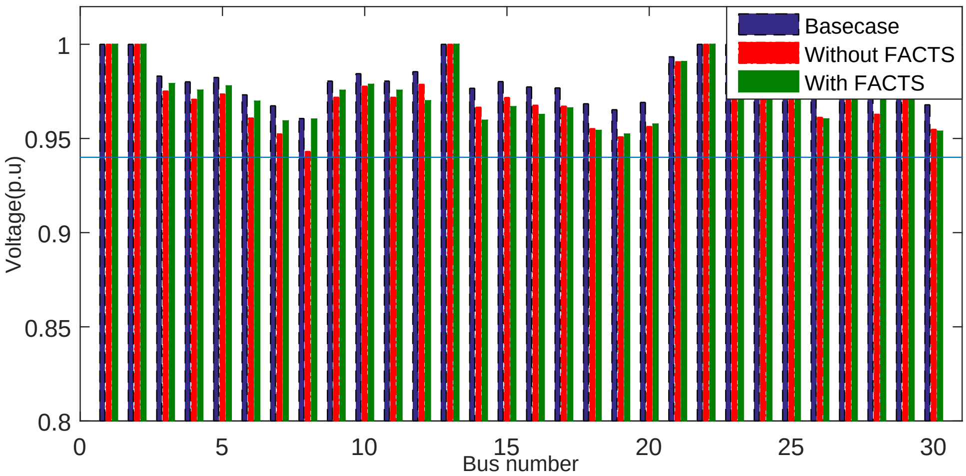


Figure 5.5: Voltage magnitude of buses in IEEE 30 bus system

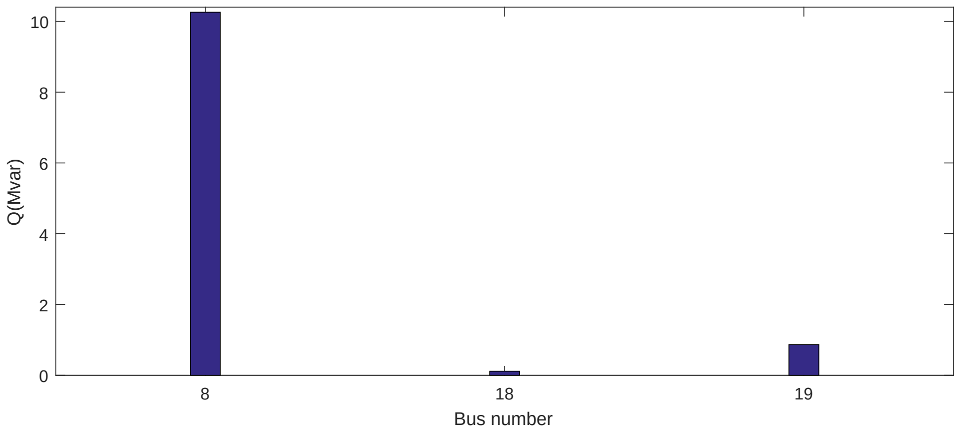
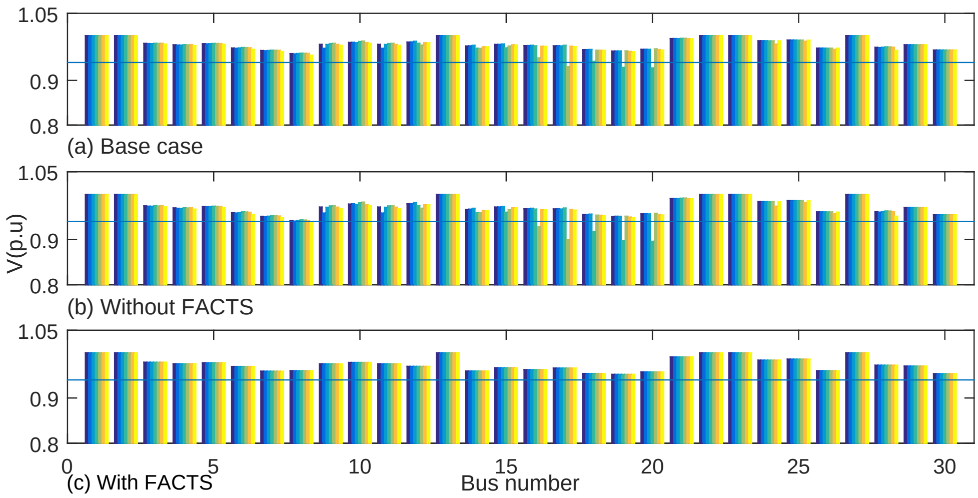
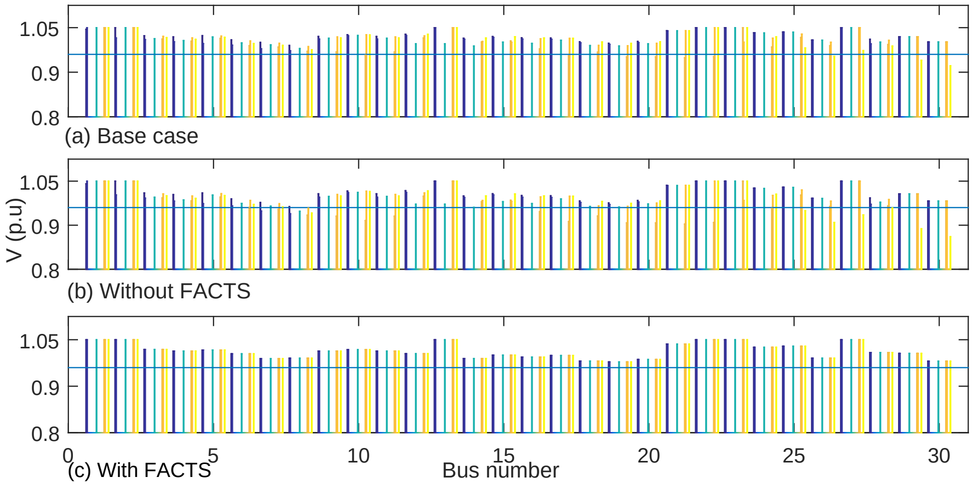


Figure 5.6: FACTS injection in IEEE 30 bus system



(a) Line outage contingency case



(b) Generation outage contingency case

Figure 5.7: Bus voltages of contingency cases in IEEE 30 bus system

Table 5.3: Violation in contingency cases of case study I for IEEE 30 bus system

Cases	**Base Case**		**w.o.FACTS**		**w.FACTS**	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
L_{6-10},L_{4-12},L_{23-24}	0	0	0	2	0	0
L_{9-10}	0	0	0	3	0	0
L_{10-20}	2	1	3	3	0	0
L_{10-17}	1	0	2	2	0	0
	0	0	0	2	0	0
L_{28-27}	0	0	1	4	0	0
G_1	0	0	0	1	0	0
G_2	0	0	2	2	0	0
G_{13}	0	0	1	0	0	0
G_{22}	6	1	13	5	0	0
G_{23}	0	0	1	2	0	0
G_{27}	3	0	7	5	0	0

5.3.2 IEEE 39 Bus System

The second IEEE small network used for TTC computation analysis and enhancement is 39 bus network. This network is known to be the general representative of New England 345 KV system, but it is not an exact or complete model. The data of the network is same as in case data used in *matpower*5.0 and most used for power system stability studies as given in Appendix .2. There are 10 generators and 19 loads on the buses as shown in the Figure 5.8, which are connected by 46 lines. The base case data is not changed, while the load are increased in the systems without FACTS and with FACTS based on the analysis purposes.

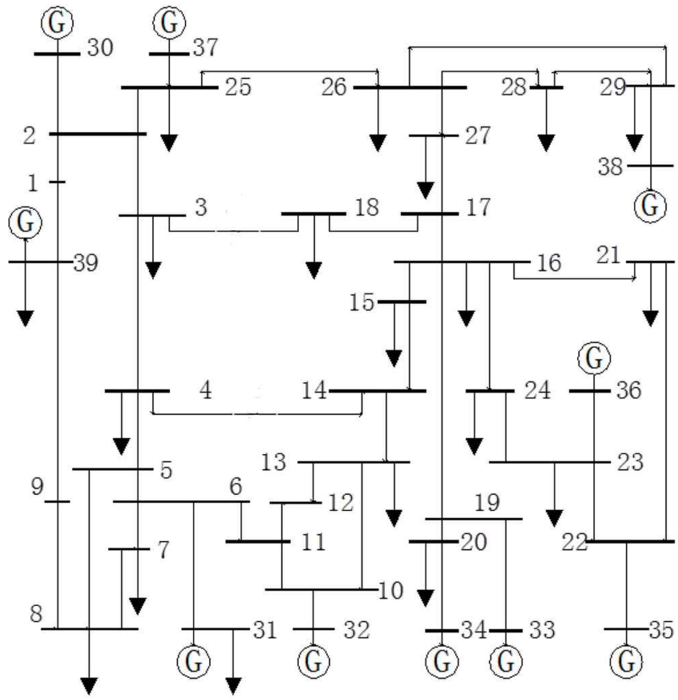


Figure 5.8: IEEE 39 bus system

Table 5.4: Load and Generation of IEEE 39 Bus System

Cases	Area	Base Case P(MW)	Base Case Q(Mvar)	Max.w.o.FACTS P(MW)	Max.w.o.FACTS Q(Mvar)	Max.w.FACTS P(MW)	Max.w.FACTS Q(Mvar)
Generation	A1	2327.87	507.01	2399	550.12	2408.1	573.27
	A2	790.0	160.39	834.8	187.71	840.4	202.86
	A3	3180.0	607.54	3360.3	702.29	3382.8	748.89
% increase				4.7	13	**5.3**	**20**
Load	A1	2384.03	720.60	2456.1	747.03	2465.1	750.32
	A2	1221.6	216.3	1290.9	228.57	1299.5	230.10
	A3	2648.6	450.2	2798.8	475.73	2817.5	478.92
% increase				4.7	4.63	**5.24**	**5.21**
Losses		43.64	1000.59	48.31	1094.53	49.13	1166.29

The total load connected in the base case is 6254.2 MW and 1387.1 MVar in all three areas, which is being raised in both the systems with and without FACTS devices. The system is analyzed for TTC computation and enhancement and the resulted load generation data are shown in Table 5.4. It can be seen that a total of only 4.7% load and generation are increased for the system without using FACTS devices from the base case data. While using FACTS devices the load is increased by only 5.3% of the base case data. With corresponding increase in line flows, 10.69% and 12.58% losses are increased in both without and with FACTS devices respectively.

Table 5.5: TTC values of overall system for IEEE 39 bus system

Cases	**w.o.FACTS**			**w.FACTS**		
Area	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
TTC	72.07	69.28	150.21	81.06	77.92	168.94

The achieved TTC for both systems without FACTS devices and using FACTS devices are shown in Table 5.5. For this network the TTC value can be improved to only 12% using FACTS devices. The TTC of the network is limited by line overloading as the power flow of lines reached the specified line capacity. By using series FACTS device, the improvement in TTC of the network is achieved to the mentioned value, which could not be further possible although a large size of the series FACTS devices is proposed. It means the capability of the network for the given conditions of the network topology could not be further enhanced. It is further investigated that there is one critical line which is violating for each step of the power transfer increase. This critical line is L_{16-19} which reach the proposed capacity limit and the power flow of the line could not be diverted to any other line to reduce the line loading by changing the line impedance. It can be seen in the network topology of the network in Figure 5.8, there is only path *i.e.*, L_{16-19} available to connect four buses Bus_{19}, Bus_{20}, Bus_{33} and Bus_{34} to rest of the network. In which two buses Bus_{33} and Bus_{34} have generators which could be only dispatched through this path. Either there should be another line to connect these generators to other buses in the network or increase the line capacity by installing new line with larger capacity.

So it means without the new transmission reinforcement which could provide alternative paths for connecting the above mentioned buses, TTC couldn't be improved further.

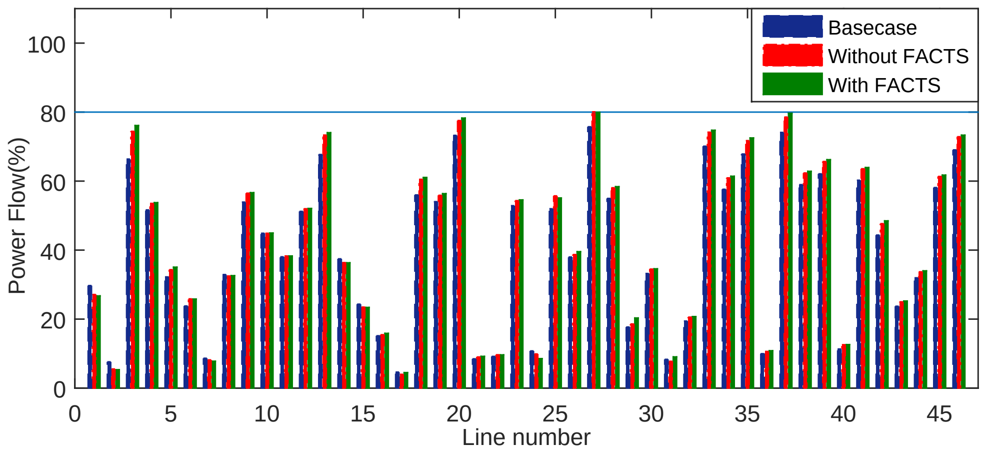


Figure 5.9: Power Flow on lines in IEEE 39 bus system

Anyhow, after the analysis of the network, the lines flows of all three systems are shown in Figure 5.9, where the L_{27} in the Figure is basically the L_{16-19}, that reached the specified capacity earlier for the system without FACTS. Based on the proposed algorithm, this is the only line which is selected for series FACTS placement for respective TTC enhancement. It can be seen that the power flow of the line is maintained at the specified limit although the load is being increased, but due to the critical situation as explained before there is no further enhancement possible and the TTC is limited to only 13%. The corresponding impedance variation of the line in the Figure 5.10 also shows that a large impedance would be required at this very line L_{16-19} to provide such TTC enhancement.

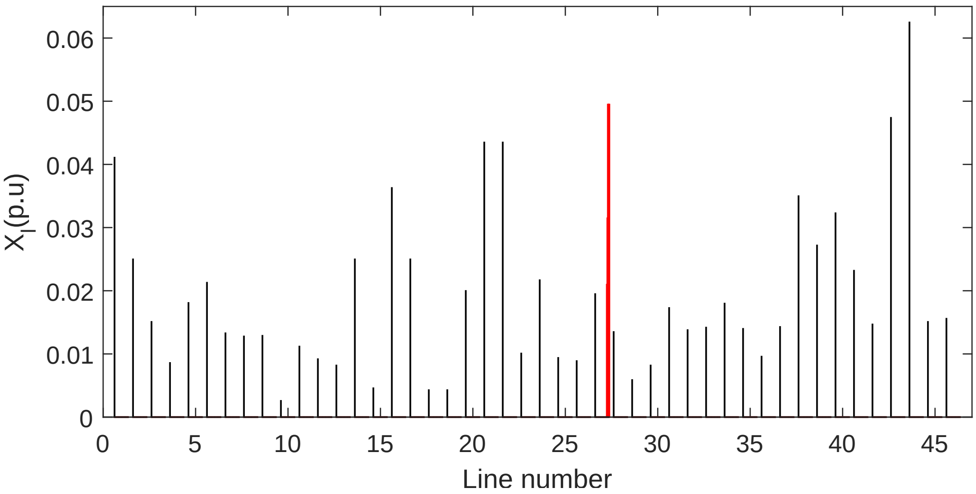


Figure 5.10: Reactance of lines in IEEE 39 bus system

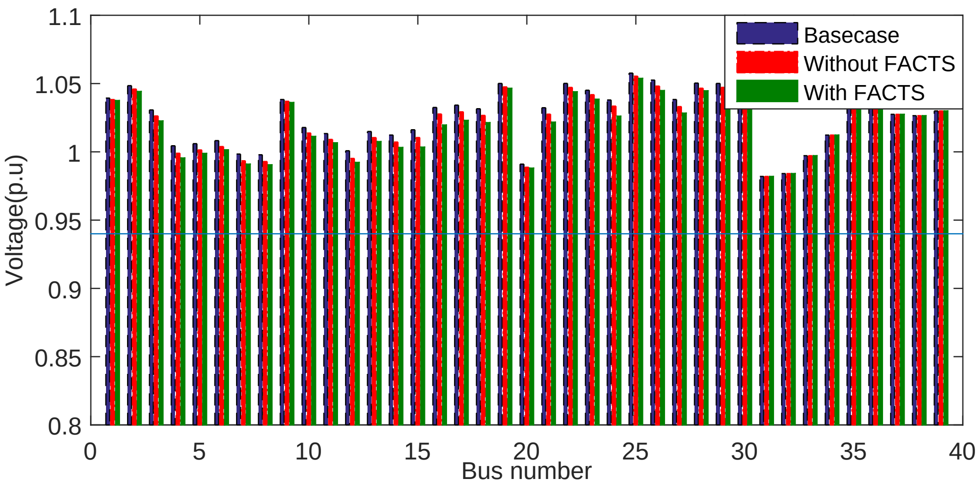


Figure 5.11: Voltage magnitude of buses in IEEE 39 bus system

As in this study case equal contribution of all the generators are supposed for the respective rise in demand to estimate TTC of the network. The critical line violation has stopped the demand increase of the overall network. The line flows of the network for the three systems in contingency cases are also analyzed and the violation in power flow as well as bus voltage are given in the Table 5.21. For the base case system there is not too much violation in power flow, only three lines are violating in one of line outage case. In the generator outage case of the base case system, there are comparatively more lines violated in some cases. Obviously for the system without FACTS, more lines are violated due to the rise in line flows. Thus in each line outage case, more than one line is violated more than the base case in each outage case. Now the system with FACTS is fairly better for both line or generator outage cases and maintained within the specified limits.

The bus voltages for all three systems are not affected in normal case as shown in Figure 5.11. It means that the TTC of the network is only limited due to the line capacity. It can be seen the voltage magnitude at all buses are within the specified limits, only affected slightly due to the increased demand at load buses. Therefore, no FACTS device is required suggested by the algorithm in normal case for this network.

Now in the contingency cases, it can be seen for the base case system, no bus is violated in line outage. While, a single bus is violated in generator outage cases of G_{31}, G_{32}, G_{34} and in G_{39} outage there are eight violating buses. For the system with increased demand have a couple of violating buses in generator outage and more G_{39} outage as given in Table 5.6. Where as for the system with FACTS device this is no violating buses in any outage case of line or generator.

Table 5.6: Violation in contingency cases of case study I for IEEE 39 bus system

Cases	**Base Case**		**w.o.FACTS**		**w.FACTS**	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
L_{1-39}	0	0	0	2	0	0
L_{3-4},L_{14-15},L_{26-28}	0	0	0	1	0	0
L_{16-17}	0	3	0	4	0	0
L_{26-29}	0	1	0	2	0	0
G_{30}	0	0	0	1	0	0
G_{31}	1	5	1	7	0	0
G_{32}	1	0	1	2	0	0
G_{33}	0	3	0	3	0	0
G_{34}	1	2	2	3	0	0
G_{35},G_{36}	0	3	0	4	0	0
G_{37}	0	0	0	4	0	0
G_{38}	0	8	0	11	0	0
G_{39}	8	4	29	26	0	0

5.3.3 IEEE 57 Bus System

The IEEE 57 Bus system represents a portion of the electric power system in Midwestern US. The single line diagram of network is shown in Figure 5.12. There are 7 generators, 36 loads and 80 lines in the network. The test case data of the network used in *matpower*5.0 is used with slight modification as given in Appendix .2. The network is divided into three different areas and analyzed for the TTC computation and enhancement. The load and generation data of the network after the analysis for the system with base case data, without FACTS devices and with FACTS devices are given in Table 5.7.

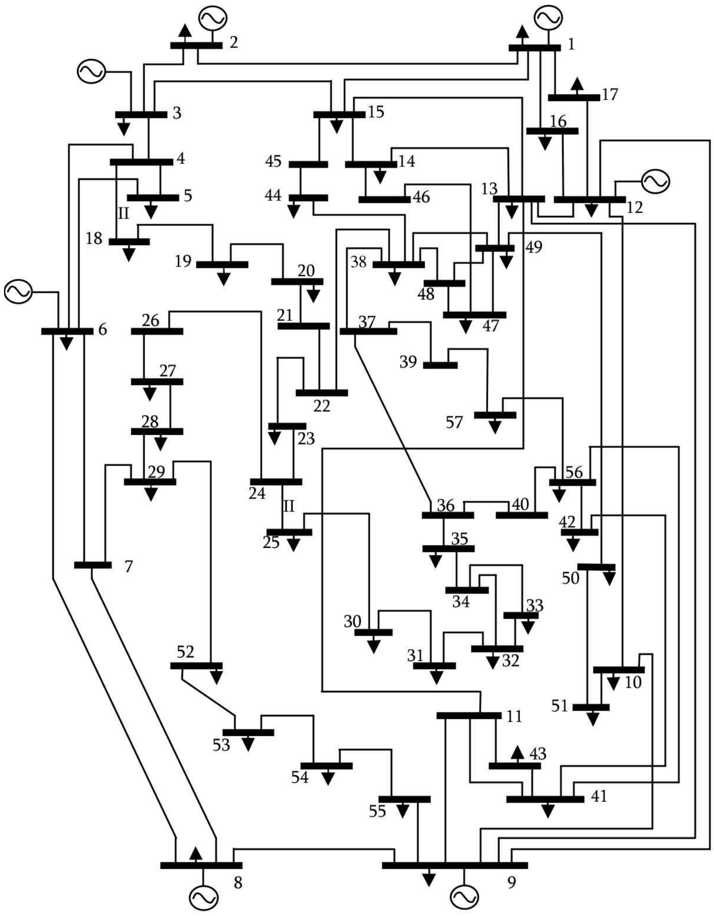


Figure 5.12: IEEE 57 bus system

Table 5.7: Load and Generation of IEEE 57 Bus System

Cases	Area	Base Case		Without FACTS		With FACTS	
		P(MW)	Q(Mvar)	P(MW)	Q(Mvar)	P(MW)	Q(Mvar)
Generation	**A1**	40	-0.7885	43.7154	3.9795	48.5397	7.615
	A2	450	64.388	491.7979	70.2802	546.0711	94.1541
	A3	788.6638	257.4805	782.961	262.1858	777.5551	268.419
% increase				3.1	4.8	**7.3**	**15.3**
Load	**A1**	214.4	135.8	223.2612	138.1035	234.7671	141.0946
	A2	414.9	109.7	428.266	115.431	445.6214	118.3234
	A3	621.5	90.9	639.1016	95.5349	661.9566	101.5532
% increase				3.1	3.6	**7.3**	**7.3**
Losses		27.864	121.67	27.846	123.77	29.293	150.45

Table 5.8: TTC values of overall system for IEEE 57 bus system

Cases	**Without FACTS**			**With FACTS**		
Area	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
TTC	8.86	13.37	18	20	30.72	40

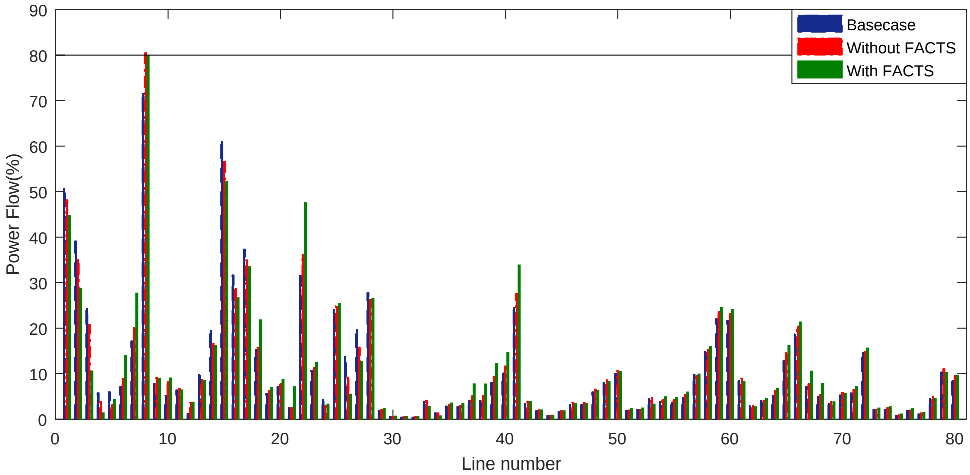


Figure 5.13: Power Flow on lines in IEEE 57 bus system

In the base case data of the network a total load of 1250.8 MW and 336.4 MVar is connected in all three areas of the network. The total load is increased by 3.1% of the base case load data for the system without FACTS devices, which decreased the line losses by 0.018%. Where as the load is increase by 3.1% when FACTS devices are used with line losses increased by 5.1%. The overall TTC values computed for the system without FACTS devices are given in Tables 5.8. It can be seen that using FACTS devices in the network, the TTC values for all three areas are increased by 129.9%.

The power flow of all the lines for the systems of base case, without FACTS and with FACTS devices are shown in Figure 5.13. Which shows that the power flow of line are well below their line capacity and reached only to the maximum of 2.5% of the capacity. So it means the TTC for the network is not restricted by the line capacity limit. In the base case the maximum power flow of line is below 2% at L_{8-9}, which is raised to only 2% for the system without FACTS and further raised to 2.4% using FACTS devices. The analysis of the network based on the utilised data, no series FACTS device is proposed for TTC enhancement. It means the respective TTC enhancement is due to the shunt FACTS devices which are supposed to be placed at critical bus locations.

The bus voltage magnitudes for three systems are shown in Figure 5.14, where it can seen that there is only one bus *i.e.*, Bus_{31}, which is below the lower voltage limit of 0.94. While by increasing the load demand and without using FACTS devices six other buses *i.e.*, Bus_{26}, Bus_{30}, Bus_{32}, Bus_{33}, Bus_{34} and Bus_{57} along with Bus_{31}, have voltage magnitudes dropped down the lower voltage limit and considered to be violated. The stopping criteria for increasing demand in the algorithm is the violation of a single line or 10% of violating buses.

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Figure 5.14. It can be seen that the voltage magnitudes at buses Bus_{31}, Bus_{32}, Bus_{33} and Bus_{34} are well below the limit for the system without FACTS, which is improved by using FACTS devices at buses Bus_{31} and Bus_{33}. Thus the violating number of buses are also reduced with increased TTC using FACTS devices. The proposed sizes for the shunt FACTS devices at selected locations are depicted in Figure 5.15 for respective improvement. The voltage magnitudes of the respective buses as well as the neighboring buses *i.e.*, Bus_{25}, Bus_{30}, Bus_{32} and Bus_{34} are improved.

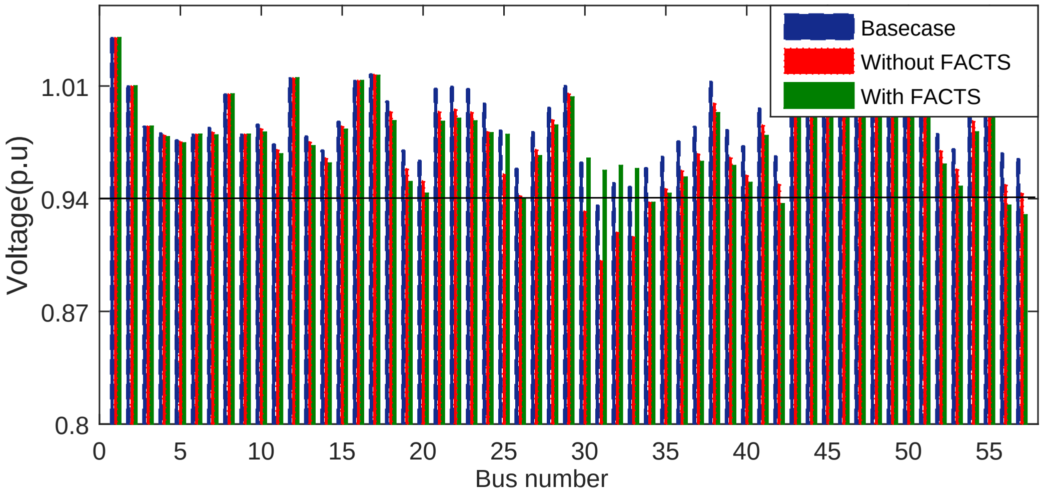


Figure 5.14: Voltage magnitude of buses in IEEE 57 bus system

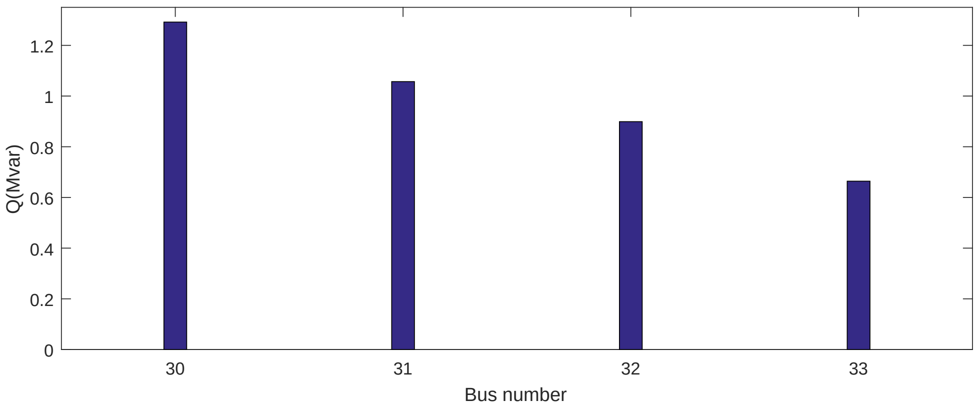


Figure 5.15: Reactive power injection of FACTS in IEEE 57 bus system

In the contingency cases the analyzed data for three systems are given in Table 5.9. There is no line violation for any system in the network due to large line capacity of each line according to the data. In the same way for the achieved TTC value in both line and generator outage cases, different number of buses are violating for each system. The system with base case data has different number of violated buses in each line or generator outage except L_{40-56}. While in three lines L_{27-28}, L_{36-37} and L_{37-38} outages and two generators G_8 and G_{12} outages, there are more than 10% of violated buses. The system with increased demand, the violated buses are increased to more than 10% in each contingency case. Whereas, using FACTS devices for the achieved TTC, the violated buses are reduced to less than 10% in each of contingency case. But all the systems in three generators G_2,G_6 and G_9 outage cases have all the buses violated and even FACTS devices couldn't improve the system.

Table 5.9: Violation in contingency cases of case study I for IEEE 57 bus system

Cases	Base Case		Without FACTS		With FACTS	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
L_{1-2}, L_{6-7}, L_{6-85}	1	0	3	1	0	0
L_{9-12}, L_{9-13}, L_{13-15}	1	0	3	1	0	0
L_{1-15}	3	0	8	1	0	0
L_{10-12}, L_{11-13}, L_{23-24}	1	0	4	1	0	0
L_{14-15}, L_{38-44}, L_{56-41}	1	0	5	1	0	0
L_{24-26}	4	0	6	1	0	0
L_{27-28}	9	0	12	1	0	0
L_{36-37}	12	0	13	1	0	0
L_{37-38}	15	0	16	1	0	0
L_{37-39}	3	0	6	1	0	0
L_{22-38}	5	0	11	0	0	0
L_{49-50}	1	0	5	1	0	0
L_{40-56}	0	0	6	1	0	0
L_{56-42}	1	0	3	1	0	0
G_1	2	1	5	2	0	0
G_3	1	0	3	0	0	0
G_8	6	4	11	4	0	0
G_{12}	20	2	22	2	0	0
G_2, G_6, G_9	57	0	57	0	57	0

5.3.4 IEEE 118 Bus System

This is one of the large electric network selected for the analysis. This test network is also a portion of American Electric Power System in Midwestern US. The network single diagram is shown in Figure 5.16. The data of the network is same from the test case data in *matpower*5.0 with slight modifications as given in Appendix .2. There are 54 generation nodes and 64 load nodes based on the *matpower*5.0 with 186 branches connecting the load and generation nodes. The network is divided in three areas for analysis purposes.

In the base case system a total of 4242 MW and 1438 MVar load is connected. After the analysis of the network without using FACTS devices the system has got an increase of 24.7% in load as given in Table 5.10, which correspondingly increase the generation by 29.1%. Thus the losses are increased more than 150% of the losses in base case system due to large line flows. By using FACTS devices the system load is further raised by 27.5% and generation is 32.9 % compared to base case system. The losses of course are increased by more than 200% because there is enough line capacity available according to the data for line flows. Thus the TTC of this network is enhanced using FACTS by 6% compare to the system without FACTS and shown in Table 5.11.

The power flow of three systems are shown in Figure 5.17. There is enough line capacity of each branch in this network based on the data. So in the base case system the maximum power flow is only reached to 5% of the line capacity.

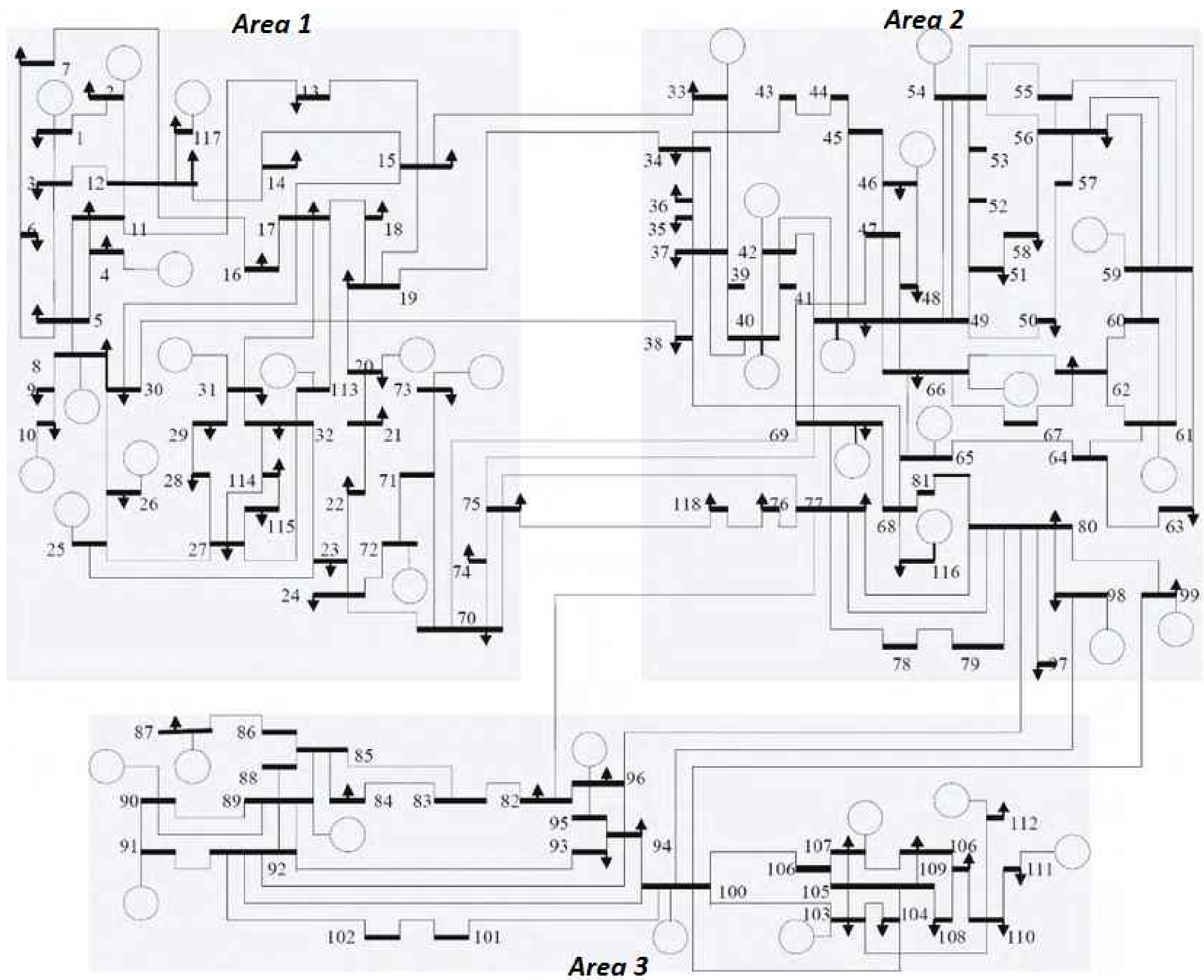


Figure 5.16: IEEE 118 bus system

Table 5.10: Load and Generation of IEEE 118 Bus System

Cases	Area	Base Case P(MW)	Base Case Q(Mvar)	Without FACTS P(MW)	Without FACTS Q(Mvar)	With FACTS P(MW)	With FACTS Q(Mvar)
Generation	**A1**	1076	202.9682	1,861	748	1,951	714.2
	A2	586	209.9167	1,014	336.9	1,063	118.7
	A3	2712.9	382.799	2,771	1,557	2,803	1,304
% increase				29.1	232.0	**32.9**	**168.5**
Load	**A1**	927	335	1,177	417	1,205	371
	A2	1342	438	1,662	529	1,698	462
	A3	1973	665	2,450	876	2,504	794
% increase				24.7	26.6	**27.5**	**13.1**
Losses		132.863	783.79	358.109	2226.82	408.741	2623.1

With increased load the power flow is also increased and the maximum power flow reached 8% of its line capacity. The power flow is increased to the maximum of 24% of its capacity in the system using FACTS. It can be seen that all the lines have power flow within their capacity limits and the TTC is not limited due to line flow, so no series FACTS device for this network is needed.

Table 5.11: TTC values of overall system for IEEE 118 bus system

Cases	Without FACTS			With FACTS		
Area	A1	A2	A3	A1	A2	A3
TTC	262.07	335.63 500.38	276.69	354.35	528	

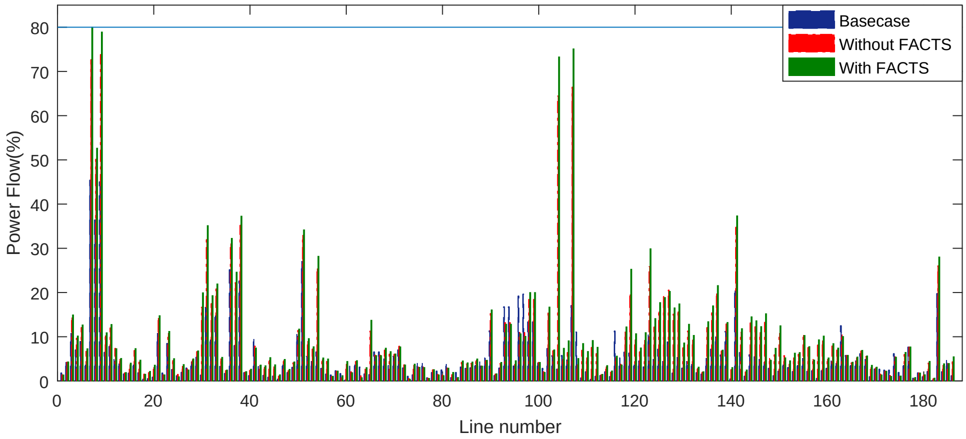


Figure 5.17: Power Flow on lines in IEEE 118 bus system

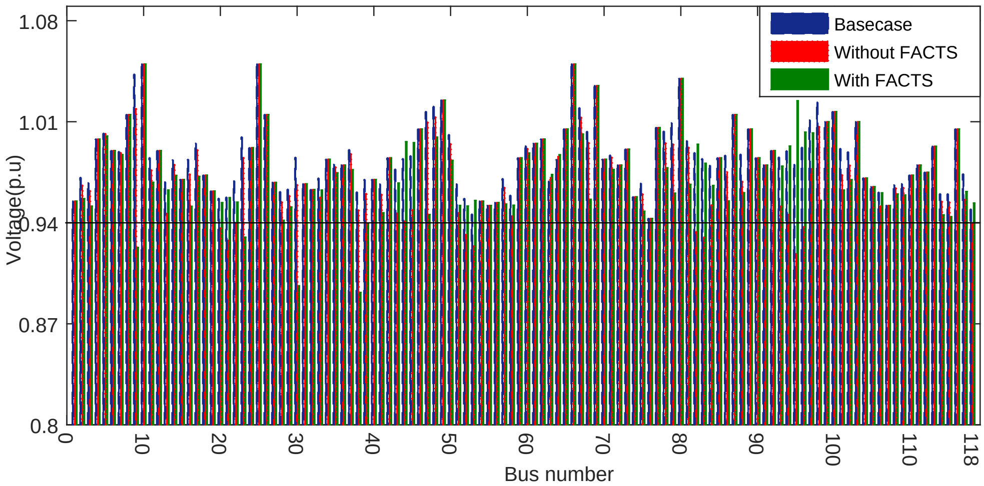


Figure 5.18: Voltage magnitude of buses in IEEE 118 bus system

If the voltage magnitude of the buses are examined for the three systems which are shown in Figure 5.18, then it become clear that the TTC of the network is limited due to the bus voltage violation. For the base case system all the buses have voltage magnitudes within the specified limits. The demand is raised by 24.7% but violated ten buses in the system without FACTS. While using FACTS devices the voltages are improved and increased the demand further to 27.5%, and improved the voltage magnitudes of violated buses as shown in Figure 5.18.

There are 23 bus locations selected for shunt FACTS devices as shown in Figure 5.19 based on the proposed method in this study case. The bus voltages are improved in the violating buses and also improve the capability of the network based on the proposed location and sizes. But other five buses *i.e.*, Bus_9, Bus_{24}, Bus_{30}, Bus_{38} and Bus_{40} are being violated the lower bus voltage limit due to further load increased. These buses are not selected as do not fulfill the proposed selection criteria.

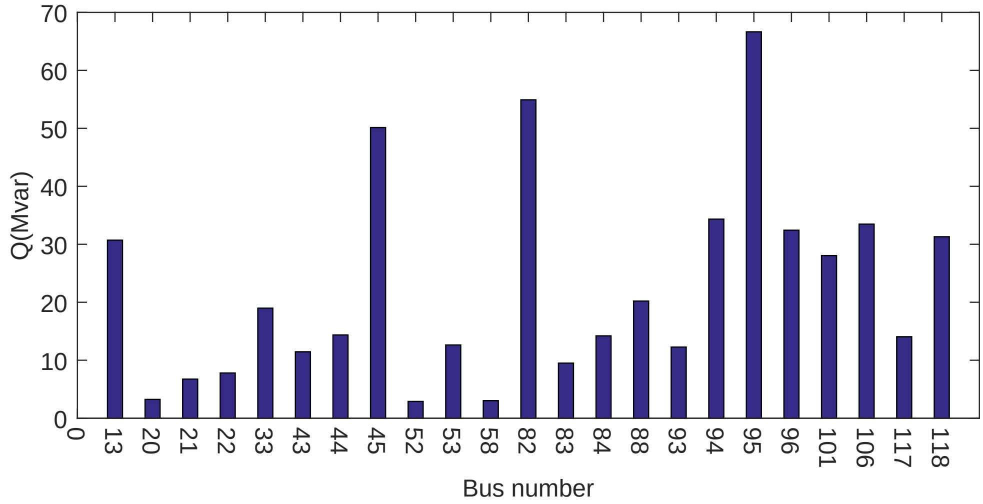


Figure 5.19: Reactive power injection of FACTS in IEEE 118 bus system

Table 5.12: Violation in line contingency cases of case study I for IEEE 118 bus system

Cases	**Base Case**		**Without FACTS**		**With FACTS**	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
L_{15-33}	0	0	6	0	0	0
L_{19-34}, L_{30-38}, L_{69-75}	0	0	4	0	0	0
L_{69-70}	0	0	7	0	0	0
L_{75-77},L_{77-82},L_{80-96}	0	0	4	0	0	0
L_{96-97},L_{98-100},L_{99-100}	0	0	4	0	0	0

Table 5.13: Violation in generation contingency cases of case study I for IEEE 118 bus system

Cases	**Base Case**		**Without FACTS**		**With FACTS**	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
G_{10}	1	0	8	0	0	0
G_{12},G_{49}	0	0	6	0	0	0
G_{25},G_{26}	0	0	5	0	0	0
G_{31}	0	0	5	0	0	0
G_{46},G_{54}, G_{54}, G_{61}, G_{65},G_{66}	0	0	4	0	0	0
G_{80}, G_{87}, G_{89}, G_{100}	0	0	4	0	0	0
G_{69}	0	0	12	0	0	0
G_{103}, G_{111}	0	0	3	0	0	0

The line flow and bus voltage of the systems in the contingency cases are analyzed and the violation lines are given in Table 5.12 and buses and buses in Table 5.13. The base case system is quite better in both line outage and generator outage cases and there is no line or bus voltage violation, only one bus is violated in only generator G_{10} outage. In the system with increased load demands, there is no violating line but has various bus violation in each line and generator outage cases. The system with FACTS devices has also the violating buses in each line and generator contingency cases and no line violation.

5.3.5 IEEE 300 Bus System

This test system was developed by the IEEE Test Systems Task Force under the direction of Mike Adibi in 1993 as given in Appendix .2. There are 69 buses with generators and 231 other buses in which 197 buses have loads and 411 branches interconnect all the buses. The single line diagram of IEEE 300 bus network is shown in 5.20. The analyzed data of loads and generations for three systems in this study case is given in Table 5.14. For the analysis network is divided into 3 different areas. The base case system has a total connected load of 23525.8 MW and 7787.9 MVar. The load is increased by 5.0% in order to compute the network TTC of the system without FACTS devices. In the system with FACTS devices the load is increased by 12.4%. Similarly the losses for the system without FACTS is raised by 16.11% and 74.86% for the system with FACTS devices. Thus TTC is enhanced using FACTS devices in all three areas as shown in Table 5.15. The TTC in this study case for the network is increased by 146.67%. To study the effects of demand increased in TTC computation the power flow of the three systems are shown in Figure 5.21. It can be seen that in the base case system the maximum power flow is 67% of the capacity over the line $L_{7130-130}$. The power flow at the same line $L_{7130-130}$ is reached at 75% of line capacity in the system without FACTS while it is reached to 80% for the system with FACTS devices.

Table 5.14: Load and Generation of IEEE 300 Bus System

Cases	Area	Base Case		Without FACTS		With FACTS	
		P(MW)	Q(Mvar)	P(MW)	Q(Mvar)	P(MW)	Q(Mvar)
Generation	**A1**	8721.9	2657.1	8,848	3,242	9,176	4,772
	A2	8509	3048.9	9,135	3,517	10,053	3,332
	A3	6704.4	2277.7	7,198	2,616	7,921	2,791
% increase				5.2	17.4	**13.4**	**36.5**
Load	**A1**	6554.5	1553.3	6938	1,644	7499	1,750
	A2	9688.1	3163.5	10,141	3,323	10,805	3,534
	A3	7283.2	3071.1	7627	3,211	8132	3,364
% increase				5.0	5.0	**12.4**	**11.0**
Losses		408.316	5504.18	474.101	6452.18	713.979	8526.77

Table 5.15: TTC values of overall system for IEEE 300 bus system

Cases	Without FACTS			With FACTS		
Area	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
TTC	395.31	467.18	354.93	945	1116.8	848.4

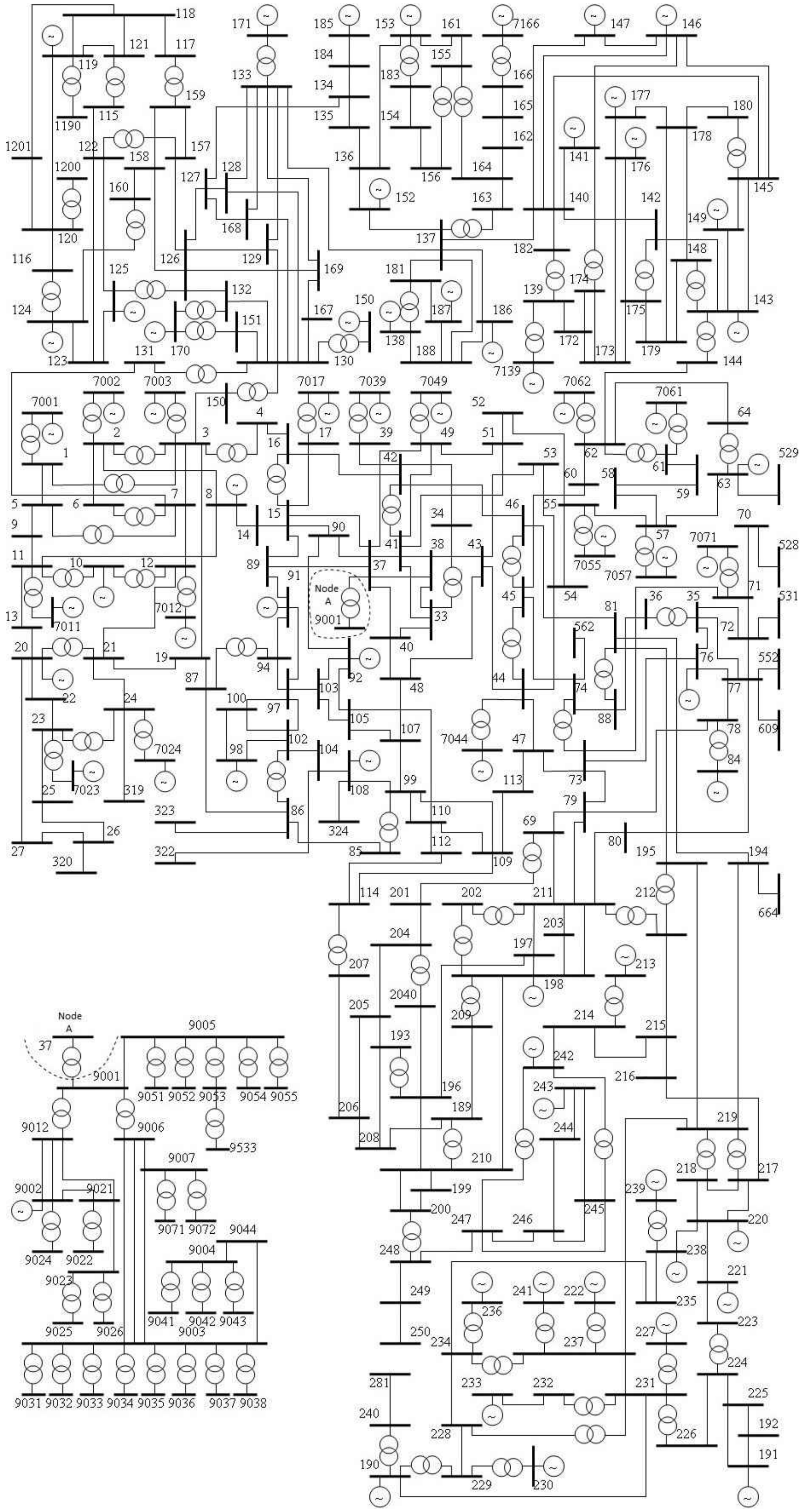


Figure 5.20: IEEE 300 bus system

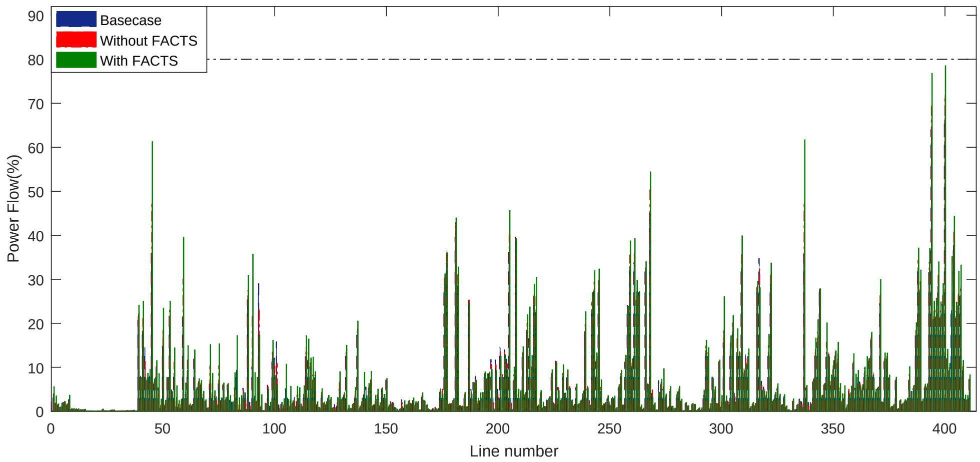
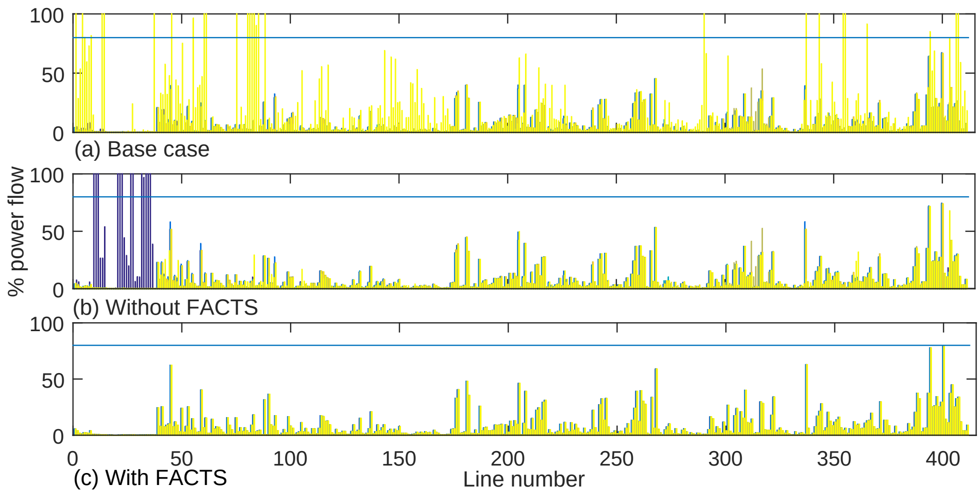
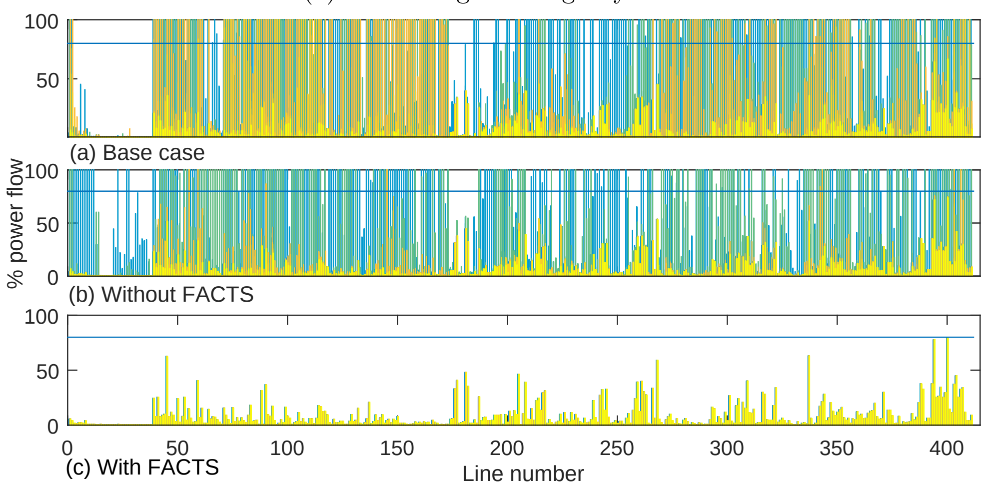


Figure 5.21: Power Flow on lines in IEEE 300 bus system



(a) Line outage contingency case



(b) Generation outage contingency case

Figure 5.22: Power flow of contingency cases in IEEE 300 bus system

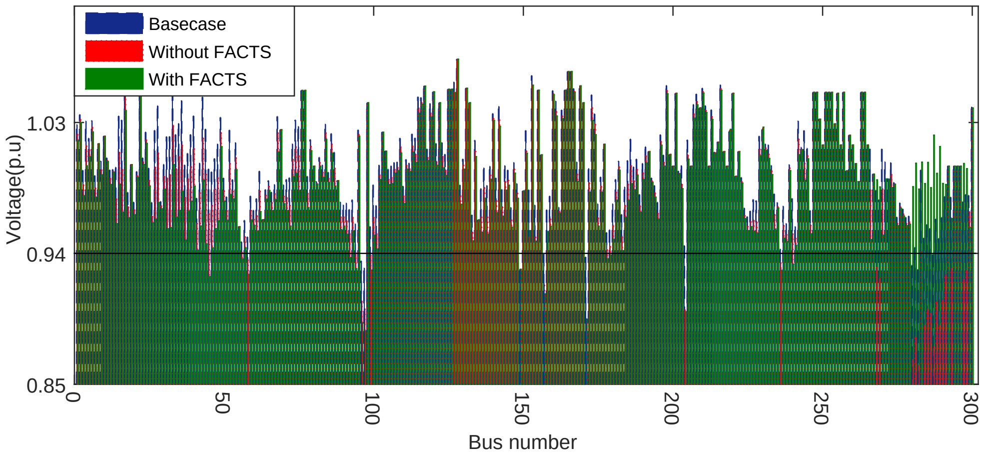
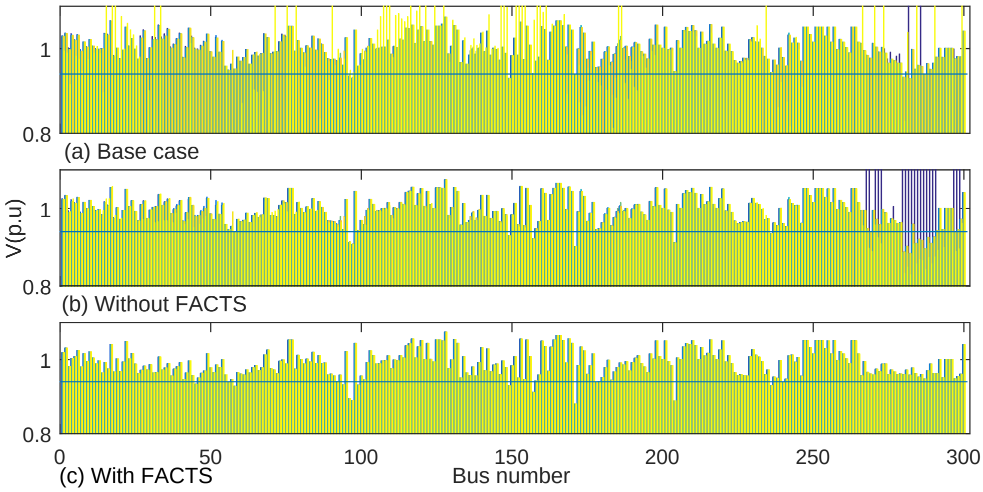
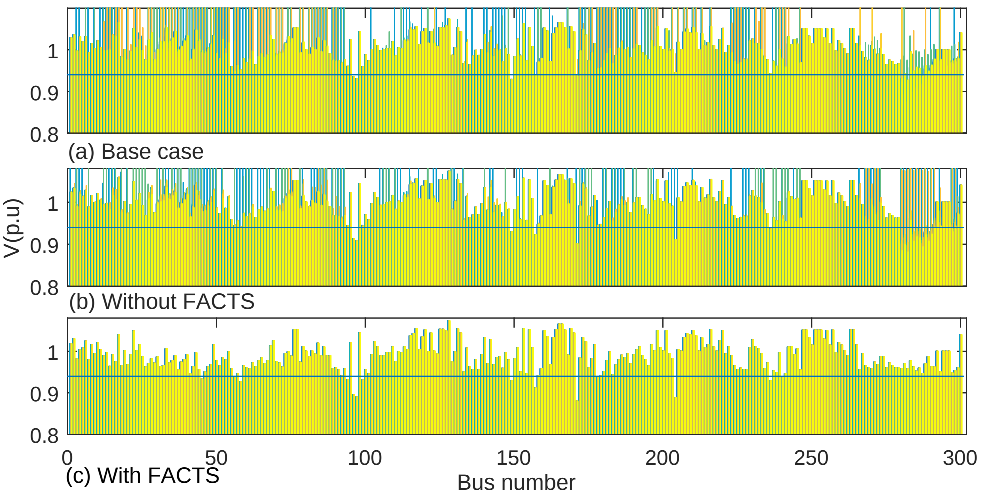


Figure 5.23: Voltage magnitude of buses in IEEE 300 bus system



(a) Line outage contingency case



(b) Generation outage contingency case

Figure 5.24: Bus voltages of contingency cases in IEEE 300 bus system

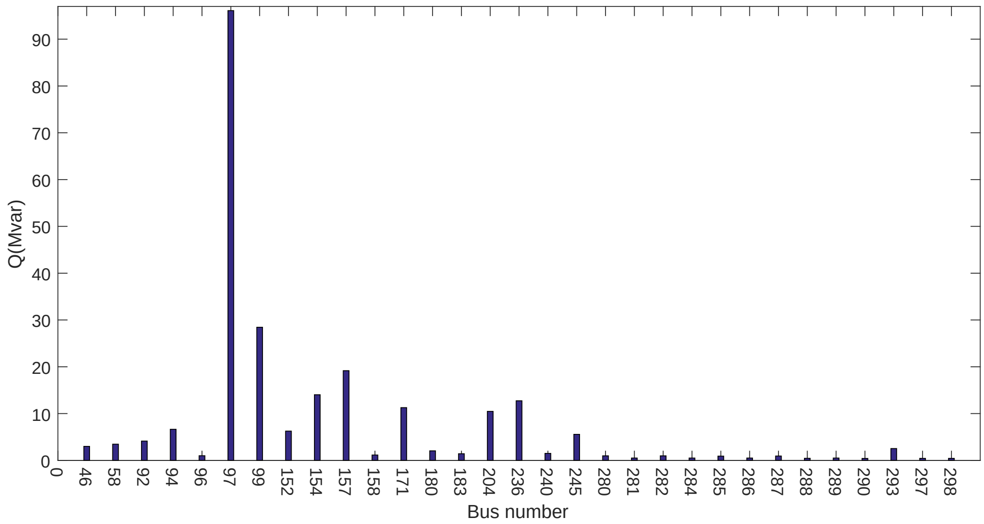


Figure 5.25: Reactive power injection of FACTS in IEEE 300 bus system

In the contingency cases the power flow for three systems can be seen in Figure 5.22. In line outage contingency cases, the base case and the system with projected load but without FACTS have violated lines, while using FACTS devices the power flow of lines are restricted to 80% of the capacity for the achieved TTC. Similarly in generator outage contingency cases, the base case and the system without FACTS devices have violating lines but the power flow of all the lines can be restricted using FACTS devices. The details of the corresponding line outage cases are given in Table **??**. It can be seen that the only line $L_{263-109}$ outage case there are 28 number of lines which violated the specified capacity in the base case system. The system without FACTS devices has 13 number of violated lines in the for the line L_{31-266} and no line is violated for the system with FACTS devices.

There are large number of violating lines for base case system in generators G_{98} and G_{170}, G_{249} and G_{263} outage cases and one violating line in each of four generators G_{165},G_{166},G_{169} and G_{252} outage cases. For the system without FACTS there is line violation in only one line L_{31-266} outage case and large number of violating lines in two generators G_{98} and G_{170}.

The system with FACTS has a better performance in contingency cases for line flow as no line violation occurred in line or generator outage. But all the lines have power flow well below the line capacity, so no series FACTS devices is supposed by the algorithm. Only shunt devices are proposed which improve the line flows as well.

Now the bus voltage magnitudes can be examined for the enhanced TTC values in Figure 5.23. In the base case system most the bus locations have voltages within their respective limits, it means there is no voltage problem in reference system recognised by the blue bars. The system with increased demand have voltage problem for respective TTC value as many bus locations from Bus_{270} to Bus_{290} in the Figure 5.23 have voltage magnitude below the lower voltage limit, represented by red bars. Which shows that these bus locations could suffer lower voltage problem if the demand is increased. Now the system with FACTS devices at the proposed locations given in Figure 5.23, have improve the voltage magnitude at the bus locations where the voltage magnitude is below the lower limits in the system without FACTS.

Thus the demand is further increased as given in TTC enhancement but there are some other bus locations which violate the voltage limits and could be improved by the proposed FACTS devices. And the system have got TTC enhancement with comparatively less violating buses to the system with no FACTS devices. These locations are not selected for FACTS devices based on the proposed criteria, which limit the TTC to the achieved values.

Similarly the voltage magnitudes of buses for three systems in the contingency cases are also analyzed and shown in Figure 5.24. The base case system can be seen with violating buses in line and generator outage cases, where over voltage problem occurred at most of the violating buses. For the system with increased load demand has both over voltage and under voltage problems. It can be seen that the system with FACTS devices have violated buses in both line and generator outage cases but there is no over voltage problem. The details of violating buses in line outages contingency case are also given in Table 5.16, which shows all the line outage cases have lower voltage violating buses but only two lines L_{31-266} and $L_{263-109}$ outage cases have also over voltage violating buses for the base system. For the system with increased demand has comparatively more lower voltage violating buses in all cases and only in lines L_{31-266} outage case over voltage violating buses. The system with FACTS are restricted to 15 violating buses in all line outage cases.

The details of violating buses in generator outage cases are given in Table 5.17. It can be seen that in generator outage cases, the three proposed systems of the network have violating buses, where base case and system with increased demand have different violating buses in each case, while the system with FACTS has restricted the violating buses to only 15 number of buses and that is due to the stopping criteria of the algorithm. In generators outage cases of G_{98} and G_{170} have both lower voltage and over voltage violating buses for the base case system and system with increased demand while the G_{249} and ,G_{263} outage cases have lower and over voltage violating buses for the base case only and other systems have only lower voltage violating buses. G_{263} outage cases has more than 100 violating buses. The system without FACTS has also violating buses more than 200 buses in two generator G_{98} and G_{170} outage cases. The system with FACTS has only 15 number of violating buses in each generator outage case, where the voltage magnitude of the bus locations only dropped down from the lower limit voltage.

Table 5.16: Violation in line outage contingency cases of case study I for IEEE 300 bus system

Cases	Base Case		Without FACTS		With FACTS	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
L_{31-266}	19	1	15	0	5	0
L_{3-129}, L_{7-110}, L_{54-123}	8	0	15	0	5	0
L_{57-190}, L_{94-101}	9	0	17	0	5	0
L_{66-190}, L_{67-190}, L_{68-173}	8	0	15	0	5	0
L_{68-174}, L_{89-93}, $L_{169-210}$	8	0	15	0	5	0
L_{91-93}	8	0	16	0	5	0
$L_{169-219}$	10	0	17	0	5	0
$L_{208-169}$, L_{100-94}	8	0	15	0	5	0
L_{180-57}	11	0	20	0	5	0
$L_{263-109}$	157	163	38	1	5	0

Table 5.17: Violation in generator outage contingency cases of case study I for IEEE 300 bus system

Cases	**Base Case**		**Without FACTS**		**With FACTS**	
Outages	**Buses**	**Lines**	**Buses**	**Lines**	**Buses**	**Lines**
G_{69}	22	0	22	0	5	0
G_{76},G_{199}	9	0	15	0	5	0
G_{77}, G_{261}	15	0	17	0	5	0
G_{80},G_{125},G_{128}, G_{156}	8	0	14	0	5	0
G_{88}	14	0	23	0	5	0
G_{98}	218	358	209	257	5	0
G_{103}	14	0	19	0	5	0
G_{120}	11	0	14	0	5	0
G_{122}	26	0	19	0	5	0
G_{131}	12	0	13	0	5	0
G_{132}, G_{149}, G_{155}, G_{164}	9	0	13	0	5	0
G_{165}	6	1	37	1	5	0
G_{166}	40	1	37	1	5	0
G_{169}	25	0	18	0	5	0
G_{170}	204	237	215	238	5	0
G_{177}	48	0	43	0	5	0
G_{192}	13	0	16	0	5	0
G_{200}	22	0	18	0	5	0
G_{201},G_{206}, G_{209}, G_{212}	16	0	17	0	5	0
G_{215}, G_{218}, G_{220}	36	0	27	0	5	0
G_{217}, G_{221}, G_{222}, G_{251}	12	0	18	0	5	0
G_{247}	15	0	13	0	5	0
G_{248}	21	0	14	0	5	0
G_{249}	159	151	29	0	5	0
G_{252}	56	1	34	0	5	0
G_{254}	13	0	13	0	5	0
G_{255}	21	0	17	0	5	0
G_{259}	11	0	17	0	5	0
G_{260}	19	0	20	0	5	0
G_{262}	14	0	21	0	5	0
G_{263}	108	28	38	1	5	0
G_{264}	28	0	21	0	5	0
G_{265}	17	0	13	0	5	0

5.4 Case Study II: Inter-area Total Transmission Capability

The previous study case cover the whole transmission network for simultaneous demand increased in all the loads, which are provided by all generators and then analysed the network to identify various locations for FACTS devices. Thus the network transfer capability is determined for the load growth at all load locations in respective network. And the network transfer capability enhancement is analysed for the identified FACTS locations. Which could not be useful for the power transactions between any specific two areas. because there might be other locations which would restrict the power transfer. Therefore, this study case is proposed for the investigation of the locations that limit the transmission capability of individual pair of areas in the network. In the study case the transmission capability between any two areas is determined and then the critical locations are identified which could limit the TTC values between any two areas. Then multiple suitable locations for FACTS devices are selected for each inter-area TTC enhancement.

The same IEEE test network are used fro analysis purpose in this study case. As discussed before each test network is divided into 3 areas and thus six different area combinations are found for analysis. For the analysis purpose one area is supposed to be the supplier that it would be only supply the respective power, while the second area would be the consumer, where only demand would be increased. So the supplier is restricted to change only the generation corresponding to the respective change in only demand at the load buses of consumer. Thus for each test network the analysis is being done and inter-area TTC is determined with corresponding enhancement using TTC at identified locations based on the algorithm. The results of all the test networks IEEE 30, 39, 57, 118 and 300 bus system are discussed in detailed.

5.4.1 IEEE 30 Bus System

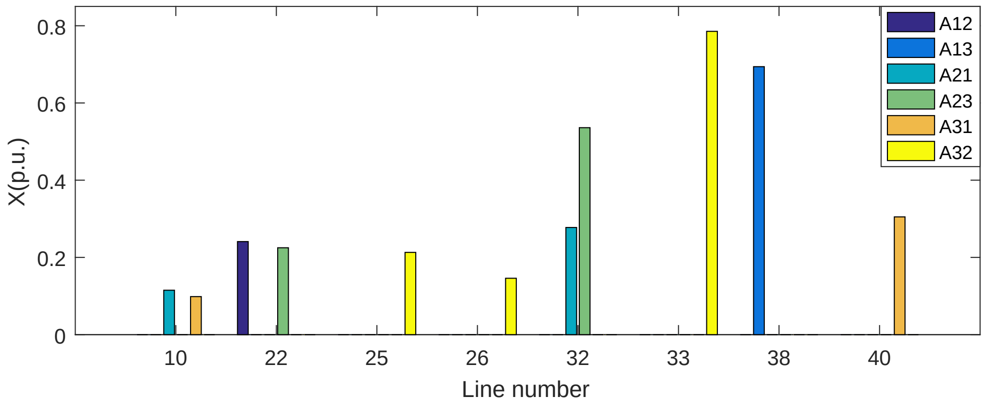
In each areas of the network has two buses with generators and also there are 11,10 and 9 number of load buses in $area_1$, $area_2$ and $area_3$ respectively. In the base case the connected load in $area_1$ is 84.5 MW with generation of 86.94 MW, in $area_2$ 56.2 MW load is connected with 56.2 MW generation and in $area_3$, the load is 48.5 MW and generation of 48.5 MW. The network is analysed for the capability computation of the systems between the areas. The demand is increased in the consumer area above the base case demand value until the constraints violation. Thus the critical locations for each area combination are identified and further enhanced by FACTS devices at the selected locations based on criteria of proposed algorithm. The TTC values of the systems with and without FACTS devices are given in Table 5.18. It can be seen the enhancement of inter-area TTC values of each supplier-consumer area combinations is due to the various FACTS locations for each combination.

Table 5.18: Inter-area TTC values for IEEE 30 bus system.

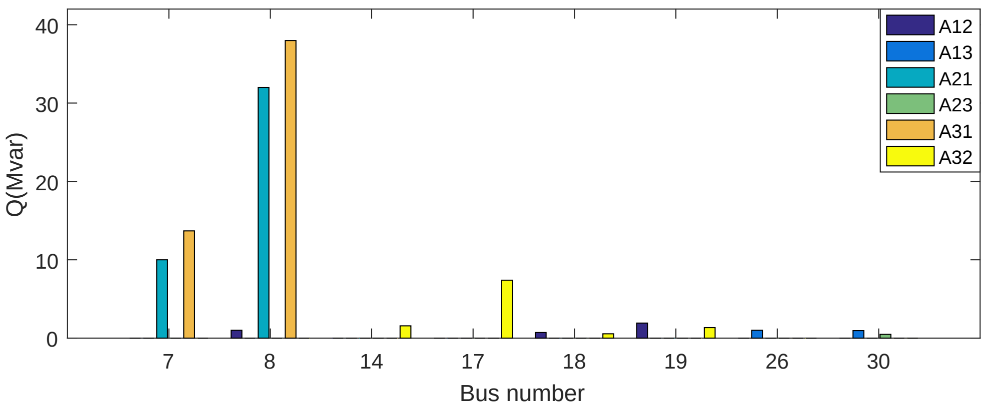
Cases	A12	A13	A21	A23	A31	A32
Without FACTS	43	35	30.44	19	32.32	38.45
With FACTS	61	41.4	94.43	34.68	89.82	74.77
% increase	43	18	210	83	178	94

A total eight locations for series FACTS and similar number of locations for shunt FACTS are being selected. The locations and sizes of the proposed FACTS devices are shown in Figure 5.26. The TTC of supplier consumer combination of $area_1$ and $area_2$ is enhanced by 43% with one series FACTS device on L_{15-18} and three shunt FACTS devices at Bus_8, Bus_{18} and Bus_{19}. More than 200% of TTC is increased by two series FACTS on L_{27-29} and L_{27-30} and two shunt FACTS devices at Bus_{26} and Bus_{30} for the combination of $area_1$ and $area_3$. And the combination of $area_2$ and $area_3$ has got the TTC enhancement by 83% using four series FACTS on lines L_{15-18}, L_{23-24}, L_{27-39} and L_{27-30} and two shunt FACTS devices at Bus_{26} and Bus_{30}. Similarly in the converse combination of $area_2$ and $area_1$ has the TTC enhanced by more than 200% with two series FACTS on L_{6-8} and L_{23-24} and two shunt at Bus_7 and Bus_8. In $area_3$ and $area_1$

combination, 188% TTC is enhanced by two series FACTS on L_{6-8} and L_{8-28} and same number of shunt FACTS at Bus_7 and Bus_8. In the last combination at $area_3$ and $area_2$ 94% of TTC is enhanced by four series FACTS on L_{15-18}, L_{10-20}, L_{10-17} and L_{24-25} along with five shunt FACTS at Bus_{14} and Bus_{16}, Bus_{17}, Bus_{18} and Bus_{19}. It can be seen in the Figure 5.26 that there are five series FACTS locations *i.e.*, L_{6-8}, L_{15-18}, L_{23-24}, L_{27-29} and L_{27-30}, which are selected in more than one area combinations while other four L_{10-20}, L_{10-17}, L_{24-25} and L_{8-28} belong to the specific area combination. Similarly six shunt FACTS locations *i.e.*, Bus_7, Bus_8, Bus_{18}, Bus_{19} and Bus_{30} are selected in more than one area combinations, while three *i.e.*, Bus_{14}, Bus_{16} and Bus_{17} selected in $area_3$ and $area_2$ combination only.



(a) Reactance of selected locations for series FACTS



(b) Reactive power injection of selected locations for shunt FACTS

Figure 5.26: Proposed FACTS size and location for inter-area TTC of IEEE 30 bus system

The violated buses and lines in each area supplier and consumer combination are tabulated in Table 5.19 for both normal and contingency cases. In normal case of the system without FACTS, each area combination of the system has one violating line and no violating buses except in the combination of $area_1$ and $area_2$ only one bus is violated. While in the normal case of the system with FACTS there is also no violated line for any combination but only one bus is violated in $area_3$ and $area_1$ combination. In the contingency cases of line and generator outages, there are different number of lines and buses violation in each area combination. But the system with FACTS devices in any of the contingency cases has neither line or bus violation except in $area_3$ and $area_1$ combination there is only one violated bus in all the line and generator outage contingency cases same as in normal case.

Table 5.19: Violation in Inter-area TTC for IEEE 30 bus system.

Cases	Outages	A12		A13		A21		A23		A31		A32	
		B	L	B	L	B	L	B	L	B	L	B	L
	Normal	3	0	1	1	3	1	3	1	3	1	3	1
	L_{6-10}	3	1	1	1	1	1	0	1	2	1	3	1
	L_{9-10}	3	1	1	3	2	1	0	1	2	1	3	1
	L_{4-12}	3	0	1	1	2	1	0	1	2	1	3	1
	L_{10-20}	5	2	4	2	2	2	3	1	4	2	5	3
	L_{10-17}	5	2	2	1	4	2	1	0	3	1	5	2
w.o	L_{23-24}	3	1	2	3	1	2	0	1	1	1	3	0
FACTS	L_{28-27}	4	0	1	2	2	2	0	0	2	4	3	3
	G_1	1	0	0	1	0	1	0	1	0	1	0	1
	G_2	6	0	3	1	5	1	1	1	5	1	5	1
	G_{13}	9	1	2	1	2	1	0	0	2	1	9	2
	G_{22}	15	2	16	4	14	3	13	2	14	3	14	4
	G_{23}	6	1	2	2	2	1	0	1	2	1	5	2
	G_{27}	9	0	7	3	8	2	6	2	9	1	8	0
w.	**Normal**	0	0	0	0	0	0	0	0	1	0	0	0
FACTS	**All cases**	0	0	0	0	0	0	0	0	1	0	0	0

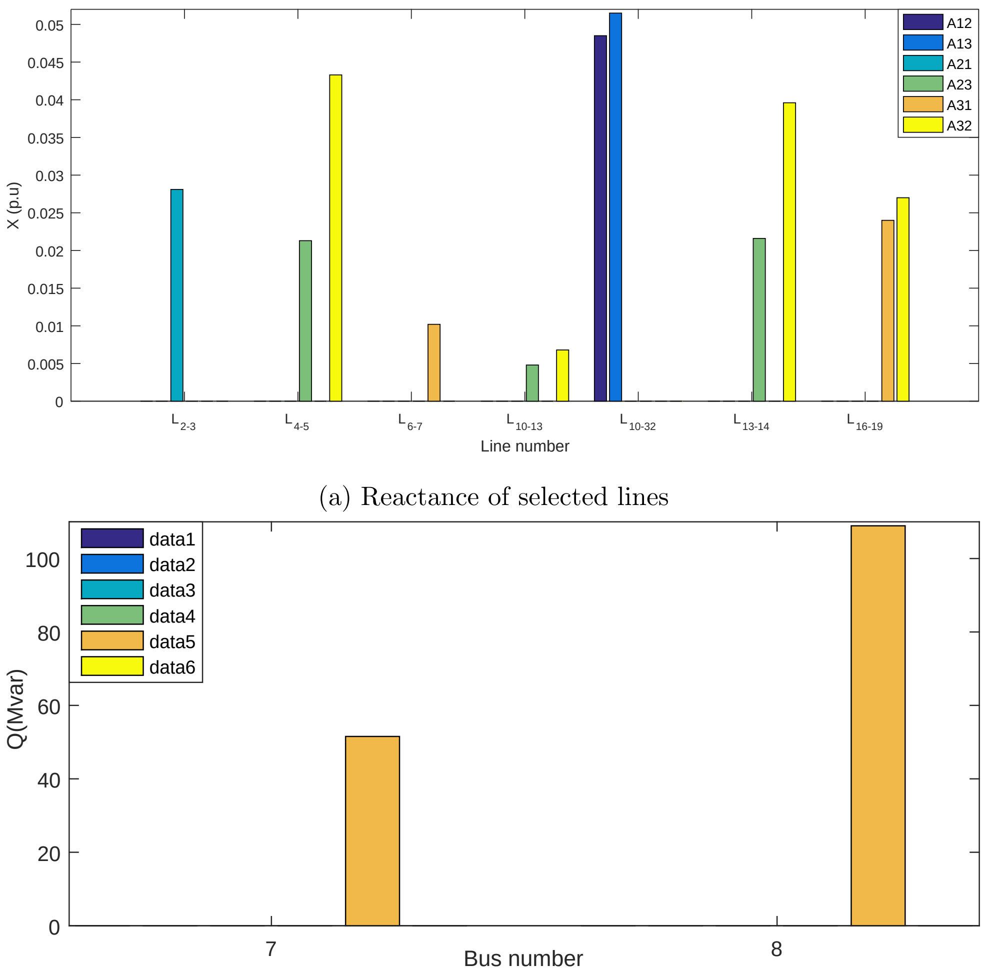
5.4.2 IEEE 39 Bus System

In this test network the distributed of buses in three areas are 14, 10 and 15 number of buses in $area_1$, $area_2$ and $area_3$ respectively. The $area_1$ consist of three generator buses and eleven load buses, in $area_2$ has two generator buses and eight load buses and other five generator buses and ten load buses in $area_3$. In the base case, the load value is 2384 MW and generated supply of 2327.9 MW in $area_1$, which is already deficient of 56.1 MW power. In $area_2$ the load value is 1221.6 MW and power supply of 790 MW is connected, which shows the deficient power of the area is 431.6 MW. And similarly 2648.6 MW of load and 3180 MW of power supply in $area_3$, thus there is an excess power of 531.4 MW in this area.

Table 5.20: Inter-area TTC values for IEEE 39 bus system.

Cases	A12	A13	A21	A23	A31	A32
W.o. FACTS	126.42	274.09	392.13	522.06	735.52	667
W. FACTS	130.66	283.30	579.46	565.45	824.56	748.88
% increase	3.39	3.36	47.77	8.32	12.11	12.28

The load and supply power value in the base case system according to the data given in Appendix .2 shows that the $area_3$ has more power supply than the load in the area, while the other two areas have deficiency in power supply compared to the load of the area. It means that $area_3$ is already supplying power to other two areas.



(a) Reactance of selected lines

(b) Reactive power injection of selected buses

Figure 5.27: Proposed FACTS location for inter-area TTC of IEEE 39 bus system

The network is analyzed for inter-area TTC computation by increasing the demand in the consumer area for the systems without FACTS and with FACTS devices on various locations based on the proposed criteria. The TTC value of the systems are given in Table 5.20. The inter-area TTC values of each area combination of the system have been enhanced by using the FACTS respective devices. The TTC of area combinations of $area_1$ and $area_2$ has increased by only 3.39% with only one series FACTS device at L_{10-32}. While the reverse combination when $area_2$ is supplying the power has enhanced by 47.77%. This combination has got the largest TTC value but using only one series FACTS device at L_{2-3}. In the combination of $area_1$ and $area_3$ as supplier and consumer respectively has the TTC enhanced to only 3.36% by only one series FACTS devices at L_{10-32}. In the reverse combination the TTC is enhanced by 12.11% using two series FACTS at L_{6-7} and L_{16-19} and two shunt FACTS devices at Bus_7 and Bus_8. The area combination of $area_2$ and $area_3$ has got three series locations for series FACTS devices and enhanced the TTC by 8.32%. While in the reverse combination 12.88% enhancement is achieved by four series FACTS devices at L_{4-5}, L_{10-13}, L_{13-14} and L_{16-19}. Thus a total of seven locations are selected for series for all the area combination and only two locations for shunt FACTS devices. The locations and sizes of the FACTS devices in each area combination for respective TTC enhancement are shown in Figure 5.27.

Table 5.21: Violation in Inter-area TTC for IEEE 39 bus system.

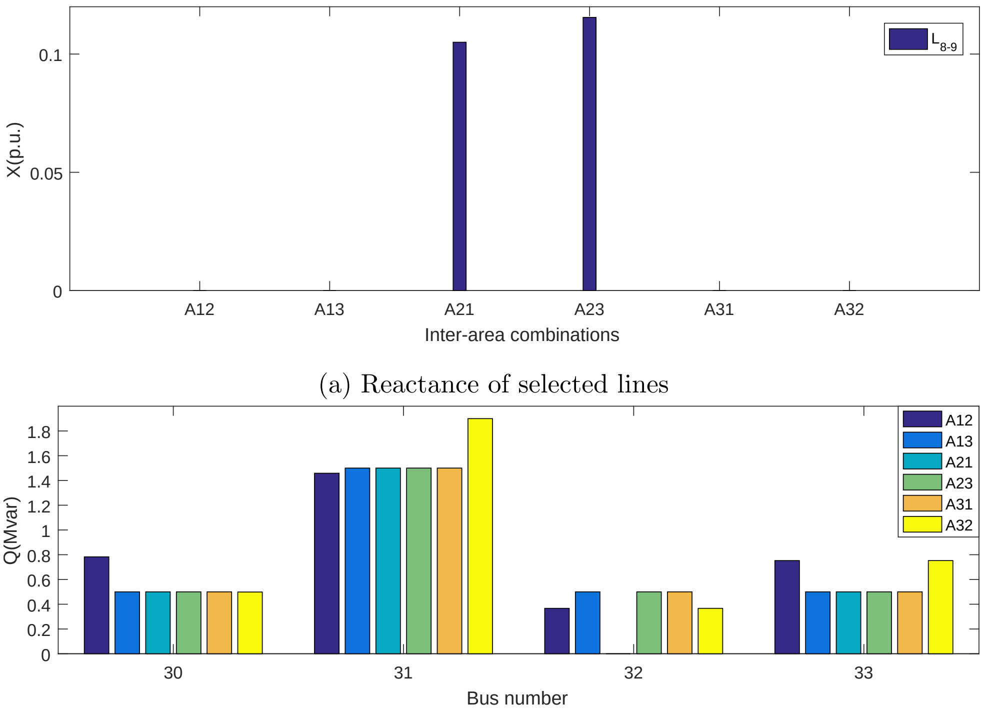
Cases	Outages	A12		A13		A21		A23		A31		A32	
		B	L	B	L	B	L	B	L	B	L	B	L
w.o FACTS	**Normal**	0	1	0	1	0	1	0	2	2	2	0	3
	L_{1-39}	0	1	0	1	0	1	0	3	2	3	0	3
	L_{3-4}	0	1	0	1	0	0	0	2	7	4	0	3
	L_{14-15}	0	1	0	1	0	1	0	0	4	2	0	3
	L_{16-17}	0	4	0	1	0	2	0	3	3	4	0	5
	L_{26-28}	0	1	0	1	0	1	0	1	2	2	0	4
	L_{26-29}	0	2	0	2	0	2	0	2	2	3	0	5
	G_{30}	0	1	0	3	0	0	0	3	6	6	0	8
	G_{31}	1	5	1	6	4	6	1	5	11	11	1	6
	G_{32}	1	0	1	1	11	2	10	3	12	9	11	6
	G_{33}	0	4	0	5	2	6	2	8	10	9	6	9
	G_{34}	1	4	2	5	2	5	2	8	10	9	4	8
	G_{35}	0	4	0	6	2	6	3	9	10	9	7	9
	G_{36}	0	4	0	5	0	6	0	7	9	10	3	10
	G_{37}	0	4	0	4	0	5	0	6	8	9	4	10
	G_{38}	0	9	0	10	6	8	9	10	11	14	13	13
	G_{39}	2	30	30	24	14	12	14	32	24	22	28	22
w. FACTS	**Normal**	0	0	0	0	0	0	0	0	0	0	0	0
	All cases	0	0	0	0	0	0	0	0	0	0	0	0

The system with and without FACTS for each area combination are evaluated in the contingency cases of inter-area line and generator outages. The violated number of buses and lines can be seen in Table 5.21. The system without FACTS has one violated line and no violated buses for each supplier consumer combination in normal case. While in contingency cases of line outage, there are different violated lines in each area combination and no violated bus. The only combination of $area_3$ and $area_1$ as supplier and consumer respectively has various violated buses in different contingency cases. For the respective TTC value in each area combinations the system without FACTS has various violated buses and lines in all the generator outage contingency cases. There are more violated lines in three generator G_{31}, G_{38} and G_{39} outage cases compared to other cases. The system with FACTS devices at the proposed locations has better performance in normal and contingency cases for the enhanced TTC values in terms of buses and lines violation and there is no violated buses or lines for any combinations in outage case.

5.4.3 IEEE 57 Bus System

The distribution of buses in three areas of this network are 17, 26 and 14 numbers in $area_1$, $area_2$ and $area_3$ respectively. In the base case data there are three generator buses with power of 40 MW and fourteen load buses with power demand of 214.4 MW in $area_1$. The $area_2$ has two generator buses of power supply 450 and twenty four load buses of 414.9 MW of power demand. And the last supposed $area_3$ consist of rest of the two generator buses with 788.66 MW of power supply and twelve load buses of 621.5 MW power demand. These three areas are interconnected by twenty two lines which are shown in the contingency cases. The computed inter area TTC values for both the system with and without FACTS in each area combination are given in Table 5.22.

There are only one series FACTS device selected and four locations are selected for shunt FACTS devices in each inter-area TTC enhancement of this test network as shown in the 5.28. Based on the used data of the network as given in Appendix .2, line capacity are quiet enough for the line flows and only one location for series FACTS device in only two inter-area combinations *i.e.*, $area_2$ to $area_1$ and $area_2$ to $area_3$. It can be seen that 76.6% in TTC is enhanced in the area combination of $area_1$ and $area_2$ as supplier consumer systems. While in the reverse combination of $area_1$ and $area_2$ due to the series FACTS device, TTC is enhanced more than 600%. Similarly the area combination of $area_2$ and $area_3$ as supplier and consumer more than 400% of the TTC is enhanced due to the series FACTS device but in the reverse combination only 88% TTC is enhanced. But in all the area combinations four locations Bus_{30}, Bus_{31}, Bus_{32} and Bus_{33} for shunt FACTS devices have provided the respective TTC enhancement as given in Table 5.8.



(a) Reactance of selected lines

(b) Reactive power injection of selected buses

Figure 5.28: Proposed FACTS location for inter-area TTC of IEEE 57 bus system

The analyzed network data of both the systems for each area combination in contingency cases are given in Table 5.23. It can be seen that in normal case there are five number of violated buses in area combinations of $area_{12}$ and $area_{32}$ and three violated buses in area combinations $area_{13}$ and $area_{31}$ for the system without FACTS. While in area combinations of $area_{21}$ and $area_{23}$ there is one violated line along with one violated bus for the respective TTC value. It can be seen that in six lines L_{1-2}, L_{6-7}, L_{6-8}, L_{9-12}, L_{9-13} and L_{11-13} outages cases the lines are violated along with the shown violated buses given in first two two rows. Similarly in other line outage cases, there are various violated number of buses in other line outage cases but more number of buses are violated in lines L_{1-15}, L_{27-28}, L_{36-37}, L_{37-38} and L_{22-38} outages cases. And similarly various violated buses and lines in generators G_1, G_3 but more in G_8 and G_12 outage cases. But all the buses are violated in three generator buses *i.e.*, G_2, G_6 and G_9.

Table 5.22: Inter-area TTC values for IEEE 57 bus system.

Cases	A12	A13	A21	A23	A31	A32
W.o. FACTS	31	63	7.91	15.71	61.90	30.72
W. FACTS	54	92	62	81	73	58
% increase	76.71	46.68	682.47	415.48	18.1	88.45

Table 5.23: Violation in Inter-area TTC for IEEE 57 bus system.

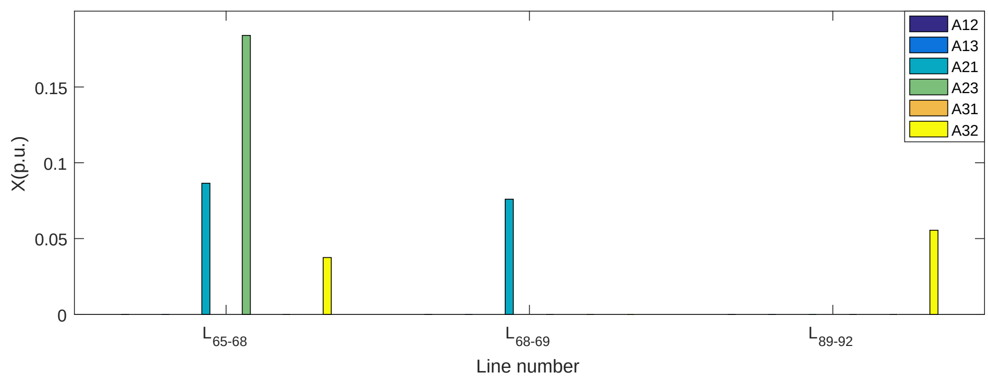
Cases	Outages	A12		A13		A21		A23		A31		A32	
		B	L	B	L	B	L	B	L	B	L	B	L
	Normal	5	0	3	0	1	1	1	1	3	0	5	0
	L_{1-2}, L_{6-7}, L_{6-8}	5	1	4	1	1	1	1	1	3	1	5	1
	L_{9-12}, L_{9-13}, L_{11-13}	5	1	4	1	1	1	1	1	3	1	5	1
	L_{6-7}	5	0	3	0	1	1	1	1	3	0	5	0
	,L_{13-15},L_{10-12}	5	0	5	0	1	1	1	1	4	0	5	0
	L_{1-15}	9	2	9	2	3	1	3	1	8	1	10	0
	L_{14-15}	6	0	5	0	2	1	3	1	5	0	7	0
	L_{23-24}	7	0	5	0	3	0	4	0	5	0	7	0
	L_{24-26}	7	0	9	0	4	1	4	1	8	0	8	0
	L_{27-28}	14	0	15	0	9	1	9	1	13	0	15	0
	L_{36-37}	13	0	13	0	12	1	13	1	13	0	13	0
w.o	L_{37-38}	16	0	16	0	15	1	16	1	16	0	16	0
FACTS	L_{37-39}	8	0	7	0	3	1	3	1	4	0	8	0
	L_{38-44}	6	0	6	0	1	1	3	1	5	0	7	0
	L_{22-38}	13	0	7	0	7	0	6	0	13	0	13	0
	L_{49-50}	4	0	3	0	1	1	1	1	1	0	4	0
	L_{40-56}	7	0	5	0	0	1	3	1	3	0	7	0
	L_{56-41}	5	0	6	0	1	1	2	1	4	0	5	0
	L_{56-42}	5	0	5	0	1	1	1	1	3	0	5	0
	G_1	7	1	8	1	3	2	3	2	5	1	7	1
	G_3	5	0	5	0	1	0	1	0	5	0	5	0
	G_8	15	4	14	5	6	4	7	4	11	4	15	4
	G_{12}	22	2	24	4	20	2	20	2	23	4	23	3
	G_2,G_6,G_9	57	0	57	0	57	0	57	0	57	0	57	0
	Normal	1	0	1	0	0	0	1	0	1	0	1	0
w.	**All lines**	1	0	1	0	0	0	1	0	1	0	1	0
FACTS	G_1,G_3,G_8,G_{12}	1	0	1	0	0	0	1	0	1	0	1	0
	G_2,G_6,G_9	57	0	57	0	57	0	57	0	57	0	57	0

The violated buses in the system with FACTS for all the area combination as shown in the Table 5.23. It can be seen there is only one violated bus and no violated line in all line outage cases.

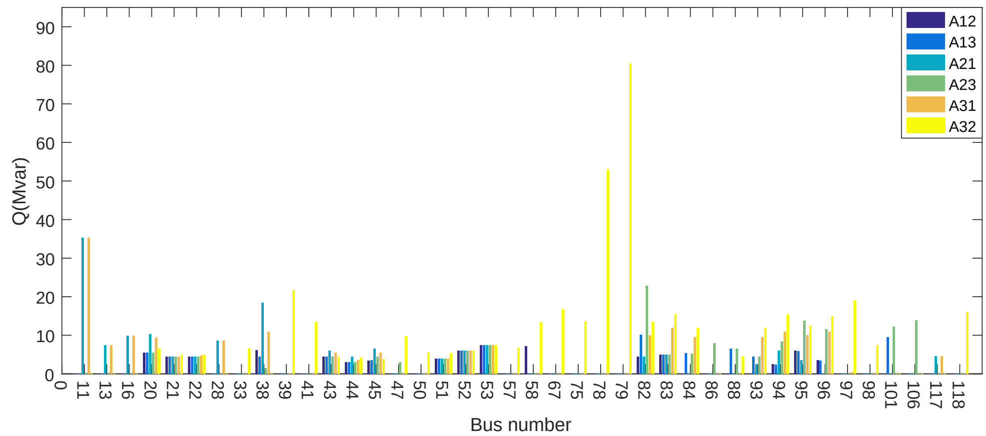
Except the three generators G_2, G_6 and G_9 outage cases, all the buses are violated same in system without FACTS.

5.4.4 IEEE 118 Bus System

This is a comparatively large test network and can be divided in more than three areas but divided only in three areas same as other test network. According to the division of buses in three defined areas of the network, 32 number of buses are collected in $area_1$, 30 number of buses in $area_2$ and 56 number of buses in $area_3$. In the base case data 1076 MW of power is supplied in $area_1$ by fourteen generators and 1175 MW of load demand is required to eighteen number of load buses. The $area_2$ has 2359.9 MW of power supplied by eleven number of generator buses and 2163 MW of demand from nineteen number of load buses. Similarly 939 MW of power is supplied by nineteen number of generator buses and 904 MW of power demand to twenty seven number of load buses is required. The three areas are interconnected by fifteen number of lines. The computed TTC of each area combination in both systems can be seen in Table 5.24, with corresponding percent enhancement.



(a) Reactance of selected lines



(b) Reactive power injection of selected buses

Figure 5.29: Proposed FACTS location for inter-area TTC of IEEE 118 bus system

There are a total of forty number of locations selected for shunt FACTS devices, while only three locations are selected for series FACTS devices as the line capacity of lines are quite enough. In the combination of $area_1$ and $area_2$, 6% TTC is increased by sixteen shunt FACTS devices but no series FACTS device is selected, while 50% of TTC is enhanced in the reverse combination. In the combination of $area_1$ and $area_3$, there is no TTC enhancement for $area_1$ as a supplier and $area_3$ as consumer but only the violated buses and lines are improved where as in the reverse combination in which $area_3$ is supplying, the TTC is enhanced by more than 100% with selection of twenty three shunt FACTS devices. Similarly in the combinations of $area_2$ and $area_3$ 65% TTC is enhanced by twenty three FACTS devices in which twenty two locations have shunt devices and only one location at L_{65-68} has series FACTS device when $area_2$ is supplying to $area_3$. And in the case of $area_3$ is supplying to $area_2$ thirty four locations are selected in which thirty two locations for shunt and two locations for series FACTS devices. Which have enhanced the TTC by more than 150% compared to the system with FACTS devices. The respective locations of FACTS devices along with corresponding sizes are shown in Figure 5.29 for all the six area combinations of the network.

Table 5.24: Inter-area TTC values for IEEE 118 bus system.

Cases	A12	A13	A21	A23	A31	A32
W.o.FACTS	504	288	465	288	339	532
W.FACTS	532	288	696	474	696	1538
% increase	6	0	50	65	105	216

Table 5.25: Violation in Inter-area TTC for IEEE 118 bus system.

Cases	Outages	A12		A13		A21		A23		A31		A32	
		B	L	B	L	B	L	B	L	B	L	B	L
w.o FACTS	**Normal**	3	0	1	0	3	0	0	1	2	0	2	0
	L_{15-33}, L_{30-38}, L_{75-77}	3	0	1	1	3	1	0	1	2	0	2	0
	L_{19-34}	3	0	1	1	4	1	0	1	2	0	2	0
	L_{69-70}, L_{69-75}, L_{75-118}	3	0	1	1	3	0	0	0	1	0	2	0
	L_{77-82}	3	0	3	1	3	0	2	1	6	0	6	0
	L_{80-96}, L_{96-97}	3	0	2	1	3	0	1	1	5	0	5	0
	L_{98-100}, L_{99-100}	3	0	1	1	3	0	0	1	5	0	6	0
	G_{10}, G_{12}	2	0	0	0	9	0	1	0	4	0	6	0
	G_{25}	2	0	0	1	4	0	0	0	3	0	3	0
	G_{26}, G_{31}	2	0	0	1	5	0	0	0	3	0	3	0
	G_{46}	4	0	1	1	3	0	0	0	2	0	4	0
	G_{49}	7	0	1	1	4	0	0	0	2	0	6	0
	G_{54}, G_{59}, G_{61}	3	0	1	1	3	0	0	0	2	0	2	0
	G_{65}, G_{G66}	3	0	1	1	4	0	0	0	2	0	2	0
	G_{69}	7	0	1	1	11	2	1	0	1	0	2	0
	G_{80}	3	0	1	1	3	1	0	1	4	0	4	0
	G_{87}, G_{103}, G_{111}	3	0	1	1	3	0	0	1	2	0	2	0
	G_{89}	4	0	5	1	3	1	4	1	2	0	3	0
	G_{100}	3	0	2	1	3	1	1	1	2	0	2	0
w. FACTS	**Normal**	0	0	1	0	0	0	2	0	0	0	1	0
	All cases	0	0	1	0	0	0	2	0	0	0	1	0

All the area combinations in both systems with and without FACTS devices for the corresponding increased demands are evaluated in contingency cases and the violated elements are given in Table 5.25. A normal and twelve number of inter-area connecting lines outage and nineteen number of generator outage cases are shown. There are few bus locations where the respective voltage limit is violated for the respective TTC value in all the inter-area cases. In three inter-area cases *i.e.*, between $area_1$ and $area_3$, $area_2$ and $area_1$ and $area_2$ and $area_1$, there are few lines violated along with the buses while in the rest of the area combination cases only buses are violated. Using FACTS devices at the proposed locations of the network, respective TTC of the area combinations could be increased along with the improvement of line flows and bus voltage magnitude. The only case of $area_2$ and $area_3$ has two violated buses for achieving 50% of improvement in TTC with no violated line in normal and contingency cases. Similarly in two other inter-area cases of $area_1$ and $area_3$ and $area_3$ and $area_2$ only one bus location is violated. But it can be seen that there is no violated line in any contingency cases for all the area combinations using FACTS devices. The analysis of this test network concluded that the TTC is more enhanced in those area combinations where series FACTS devices are being used as in transfer capability is more affected by the line capacity.

5.4.5 IEEE 300 Bus System

This is the largest network used for analysis which could be divided into many areas but for simplicity it is also divided into three areas and the analysis of this network for inter-area TTC is done and the results are shown. The number of buses in three areas are 107, 100 and 93. In the base case system twenty nine number of generator buses in $area_1$ supply 8721.9 MW and 6554.5 MW of power demanded by seventy eight number of load buses. In $area_2$ 8509 MW of power is supplied by nineteen number of generator buses with 9688.1 MW of demand by eighty one number of load buses. Similarly $area_3$ has 6704.4 MW of power supply provided by twenty one number of generator buses and area load of 7283.2 MW in seventy two number of buses.

In the analysis of inter-area TTC computation and enhancement of the test network for each area combination in the system with and without FACTS are quantitatively displayed in the Table 5.26. A total of thirty seven locations are selected for shunt FACTS devices based on the proposed criteria to increase the respective TTC of the network.

In the area combinations of $area_1$, $area_2$, 32% of TTC enhancement is achieved for $area_1$ as supplier and 43% of enhancement for the combination with $area_2$ as supplier. This is made possible by twenty one and eighteen number of bus locations with shunt FACTS devices respectively which have improved the voltage magnitudes at many bus locations. The combination of $area_1$ and $area_3$ has got 33% of enhancement in TTC for $area_1$ as supplier in the combination which is provided by fourteen number of bus locations with shunt FACTS devices. While in the combination with $area_3$ supplying to $area_1$, the TTC is enhanced by 26% by eighteen number of bus locations with shunt FACTS devices.

Table 5.26: Inter-area TTC values for IEEE 300 bus system.

Cases	A12	A13	A21	A23	A31	A32
W.o. FACTS	1,213	434	795	388	1,112	1,026
W. FACTS	1,770	651	1,394	484	1,498	1,531
% increase	32	33	43	20	26	33

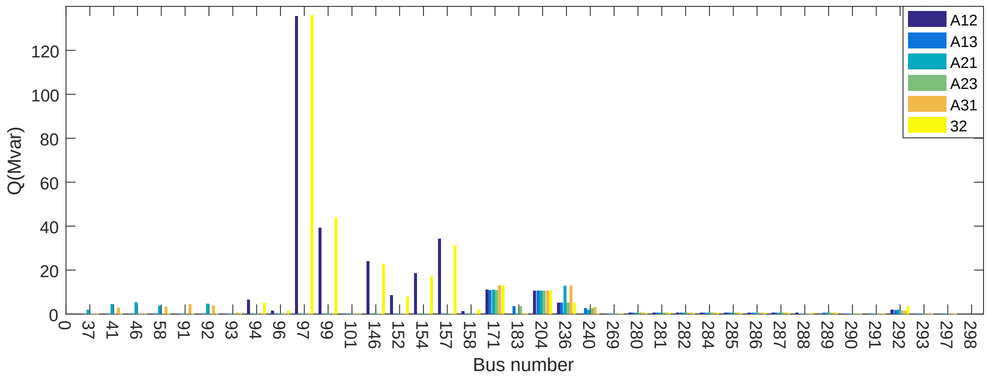


Figure 5.30: Reactive power injection of FACTS in IEEE 300 bus system

Table 5.27: Violation in Inter-area TTC for IEEE 300 bus system.

Cases	Outages	A12 Bus	A13 Bus	A21 Bus	A23 Bus	A31 Bus	A32 Bus
	Normal	14	14	15	15	15	30
	L_{31-266}	33	26	26	26	27	34
	L_{3-129},L_{7-110}	15	15	14	15	14	17
	L_{54-123}	15	15	17	15	14	16
	L_{57-190}	15	17	16	18	18	18
	L_{66-190},L_{67-190}, L_{89-93},	14	14	15	15	15	16
w.o FACTS	L_{68-173},L_{68-174}	14	14	16	16	16	18
	L_{91-93}	14	14	15	15	16	16
	L_{94-101}, $L_{169-210}$	15	15	16	16	16	17
	$L_{169-219}$	17	16	17	17	18	20
	$L_{208-169}$, L_{100-94}	14	14	15	15	14	16
	L_{180-57}	17	21	18	22	21	21
w. FACTS	**Normal**	3	4	5	4	5	3
	All cases	3	4	5	4	5	3

Similarly in the combinations of $area_2$, $area_3$, 20% of TTC is enhanced for $area_2$ as supplier with eighteen number of shunt FACTS devices. Where as twenty two number of shunt FACTS devices provide 33% of TTC enhancement for $area_3$ is supplying in the combination. The result of the network analysis for this network shows that the TTC is limited due to the bus voltage magnitudes in all area combinations and by improving the voltage magnitudes have further provided the respective enhancement in TTC.

The systems with and without FACTS devices are operated in contingency cases and the results of violated lines and buses in normal and line outage contingency cases are shown. In Table 5.27 the violated buses in both systems with and without FACTS devices for line outage cases are given. And it shows that various buses are violated in each areas combination. Looking to each line outage cases different number of buses are violated in each area combination *i.e.*, from fourteen to thirty four number of buses. It can be seen the line L_{31-266} outage case has more violated buses for all area combinations than other line outage cases and in the area combination of $area_3$ and $area_2$ more buses are violated in each line outage case than other area combinations.

Table 5.28: Violation in Inter-area TTC for IEEE 300 bus system.

Cases	**Outages**	**A12** Lines	**A13** Lines	**A21** Lines	**A23** Lines	**A31** Lines	**A32** Lines
	G_{69}	34	53	47	67	39	34
	G_{76}	18	16	18	24	20	22
	G_{77}	26	21	26	27	34	31
	G_{80}, G_{125}, G_{128}, G_{199}	15	15	16	23	18	18
	G_{88}	22	24	31	37	30	29
	G_{103}	33	19	21	28	26	36
	G_{120}	21	17	17	15	23	31
	G_{126}, G_{295}, G_{296}	18	15	17	15	19	28
	G_{131}	28	20	18	15	27	35
	G_{132}, G_{149}, G_{155}, G_{164}	20	15	16	15	20	29
	G_{156}	16	15	15	15	17	21
	G_{169}	44	66	40	58	28	115
	G_{177}	54	76	67	74	62	66
	G_{192}	21	30	26	29	24	30
w.o FACTS	G_{200}	32	55	38	55	34	43
	G_{201}, G_{206}, G_{212}	22	27	25	27	24	30
	G_{209}	26	36	29	38	27	33
	G_{217}	21	25	24	26	22	28
	G_{218}	41	70	57	69	44	31
	G_{220}	44	67	59	76	47	55
	G_{221}, G_{222}	18	24	20	23	18	23
	G_{247}	31	21	22	18	31	40
	G_{250}, G_{259}	19	15	18	15	20	28
	G_{251}	27	21	18	15	27	33
	G_{253}	17	15	16	15	20	24
	G_{254}, G_{261}	28	21	20	17	30	35
	G_{255}, G_{260}	37	30	33	30	40	43
	G_{256}, G_{258}	15	15	20	18	18	20
	G_{262}	22	27	28	27	27	27
	G_{265}	35	23	26	21	36	148

As the system is proposed to have shunt FACTS devices in order to resolve the inherent voltage problem in the network. So the FACTS devices have improve the voltages and thus give the opportunity for TTC enhancement. It can be seen that there are only three to five number of violated buses in each area combination. Therefore, further increase in loads have violated the given number of buses in the system with proposed FACTS devices for respective TTC enhancement in all area combinations.

The generator outage contingency cases which have only violated buses in each area combination for the respective TTC value are shown in Tables **??**. There are different number of violated buses in each area combination for each generator outage case. Each area combination perform differently for each generator outage case based on the location of the generator in the network and effect accordingly the other bus locations. The proposed FACTS devices have confined the violated buses to only three to five number of buses with enhanced TTC. The Table 5.29 shows the contingency cases of line and generator outage in which there are large number of violated buses and lines. In these cases it can be seen that there are violated buses and lines in more than one area combinations of the system without FACTS. The only line $L_{263-109}$ outage case has large number of violated buses as well as lines for the respective TTC values in each area combination. In six generators *i.e.*, G_{98}, G_{165}, G_{166}, G_{170}, G_{252} and G_{263} outage cases there are a large number of violated buses and lines in each area combinations. In other generators like *i.e.*, G_{122}, G_{215}, G_{248}, G_{248} and G_{264} outage cases there are few line violated in some area combinations but have large number of violated buses.

Table 5.29: Violation in Inter-area TTC for IEEE 300 bus system.

Cases	Outages	A12		A13		A21		A23		A31		A32	
		B	L	B	L	B	L	B	L	B	L	B	L
	$L_{263-109}$	196	114	75	24	158	198	155	184	184	162	211	267
	G_{98}	211	246	204	155	203	228	213	119	215	291	209	215
	G_{122}	61	2	28	0	43	1	27	0	164	101	53	29
	G_{165}	181	82	26	1	200	228	120	15	171	182	129	35
	G_{166}	200	124	47	1	139	84	196	161	192	175	176	227
w.o FACTS	G_{170}	209	230	192	277	187	182	215	276	165	191	113	219
	G_{215}	45	1	82	1	62	1	19	0	41	1	69	1
	G_{248}	40	1	24	0	28	0	21	0	43	1	47	1
	G_{249}	68	1	49	1	71	1	82	1	202	234	207	347
	G_{252}	175	143	86	6	84	8	144	55	175	164	70	0
	G_{263}	208	295	154	150	148	44	196	225	191	141	53	139
	G_{264}	68	1	28	0	43	1	27	0	133	80	101	0

The system with proposed FACTS devices have improved the system condition in such critical cases but only few buses are violated in these outage cases as given in Table 5.27. Although there is no series FACTS devices used in the system but still there is no violated lines in each area combination for these contingency cases.

5.5 Conclusion

In this chapter the analysis results of five IEEE test networks are discussed. The network analysis is based on two study cases in which the TTC is enhanced by increasing the static demand until the proposed criteria is violated. The characteristics of series and shunt FACTS devices used in order to improve the constraints of line loading and bus voltage magnitudes. The parameters of line impedance and shunt admittance are varied at the critical locations among the selected location based on sensitivity indices for both series and shunt FACTS devices. The improvement of the systems with proposed FACTS devices are compared with the system without FACTS in normal and contingency cases of line and generator outages. These results shows the importance of the method for identifying suitable locations in improving the system capability of transferring more power without installing new lines in the network upto certain time. Multiple FACTS devices are proposed to be placed at different locations that could enhanced the TCC for each network based on the network analysis in both defines study cases. The improvement achieved in total transmission capability (TTC) using FACTS devices for each network in comparison to the system without FACTS are summarized in Table 5.30.

Table 5.30: Overview of all systems

N/w	**FACTS**		**w.o.FACTS**		**Vio.**		**w. FACTS**		**Vio.**		**En.**
Bus	**Se**	**Sh**	**o.a.**	**i.a.**	**L**	**B**	**o.a.**	**i.a.**	**L**	**B**	**%**
30	9	8	251	19-43	1-2	0-3	255	35-94	0	0	7-178
39	7	2	296	126-736	1-2	0	333	121-835	0	0	3-48
57	1	4	1291	15-63	1-2	5-10	1342	54-62	0	0-1	18-682
118	5	40	5172	288-532	0-1	0-6	5401	288-1538	0	0-2	0-189
300	0	37	24706	388-1213	1-211	14-211	26436	484-1770	0	3-5	20-147

The IEEE 30 bus system is suffering from both line loading and voltage magnitude problem in enhancing the TTC. So it has got a total of nine series and eight shunt FACTS devices at different locations to have 7% increase in overall TTC and 18-178% of enhancement in various inter-area TTC with almost resolve the line corresponding problems. The IEEE 39 bus system is a bit line capacity dominant and TTC is limited by line capacity, therefore seven lines and only two shunt FACTS are selected. As a result it enhanced the overall TTC by 12% and 3-48% among the defined areas with no violated line in any case. IEEE 57 bus system is more voltage limit dominant in TTC calculation and has the capability to compensate more loads. It can be seen that the TTC is enhanced in overall system by 95% and 18-682% in different inter-area systems. Only one series and four shunt FACTS devices are required to provide the respective enhancement by resolving lines and buses violation. The IEEE 118 bus system is a large system which TTC is restricted more by bus voltage limits and somehow due to line loading in some cases. So five locations for series FACTS devices, while forty number of locations are selected for shunt FACTS devices which successfully provide the respective enhancement to TTC with improved line loading and bus voltage. 25% of TTC enhancement is achieved in overall system, where as 0-189% of enhancement among the various areas. The largest network analyzed in this work is IEEE 300 system which is observed to be voltage dominant. As the TTC is restrained by violating buses that's why thirty seven number of different locations for shunt FACTS devices that have provide 147% of TTC enhancement. Similarly 20-43% of TTC enhancement for different inter-area cases are achieved. These shunt devices not only improve the voltage magnitudes of the violating buses but also improve the line loading of violating line in different contingency cases.

6 RESULTS AND DISCUSSION OF DISTRIBUTED CONTROL SYSTEM

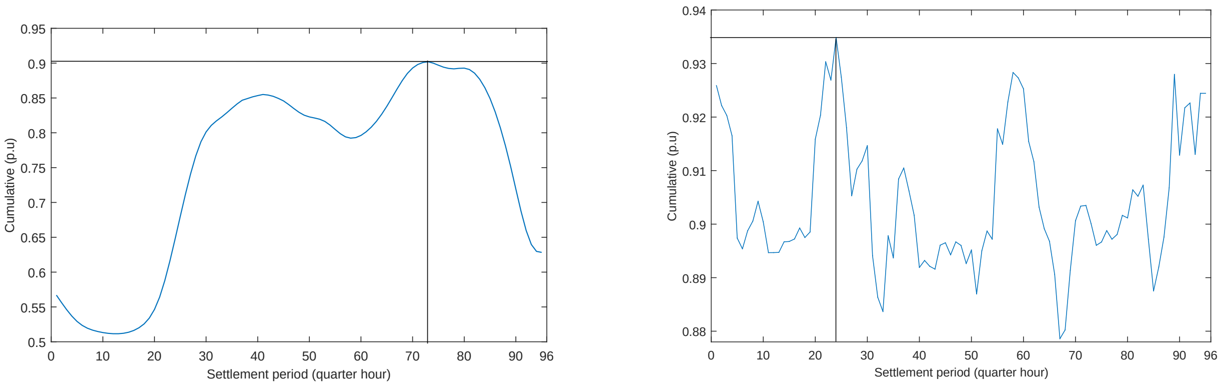
6.1 Introduction

The capacity of the transmission network is the common requirement in congestion management methods for secure power transaction commitments. The use of FACTS devices in resolving many power systems outstanding problems by providing the opportunities of influencing power flows and voltages and enhanced system security, voltage profile improvement and the transfer capacity enhancement without installment of high cost new transmission lines. Which could dynamically redirect the power flows from highly congested critical lines to other available transmission resources that might not be threatened by power flow overloading and lead the transaction commitments. In this chapter the results of the multi agent based control of FACTS devices which are dispersedly located in the network as proposed in chapter 5. The distributed coordination among the control agents to autonomously take control actions for each FACTS devices without the need of global information.

The same IEEE test networks are tested for dynamic simulation with all the locations for FACTS devices as proposed in previous chapter 5. Thy dynamic simulation is based on the dynamic load profile of 24 hours long where the load values at each load bus are changing at each instant. Thus creating an instantaneous congestion scenario which is subjected to congested management scheme of generator rescheduling and MAS based coordinated control of FACTS devices to reduce line overloading and bus voltage magnitude violation.

6.1.1 Dynamic Load Profiles

The load profile is basically the settlement period of daily, monthly or yearly consumption data of the connected loads. It represents the electric energy consumption of a segment of supply market customers. Two generalized synthetic load profiles are used with quarter hour settlement period for energy usage pattern across a day consumption and shown in Figure 6.1. In both profile the demand at each load are varying in a way to constitute the presented shape that providing the power flow of lines and voltage magnitudes at the buses and thus creating network congestion situation by lines overloading or voltage violation. The created situation would be different for different selected IEEE test networks.



(a) Dynamic Load Profile 1

(b) Dynamic Load Profile 2

Figure 6.1: Dynamic Load Profiles

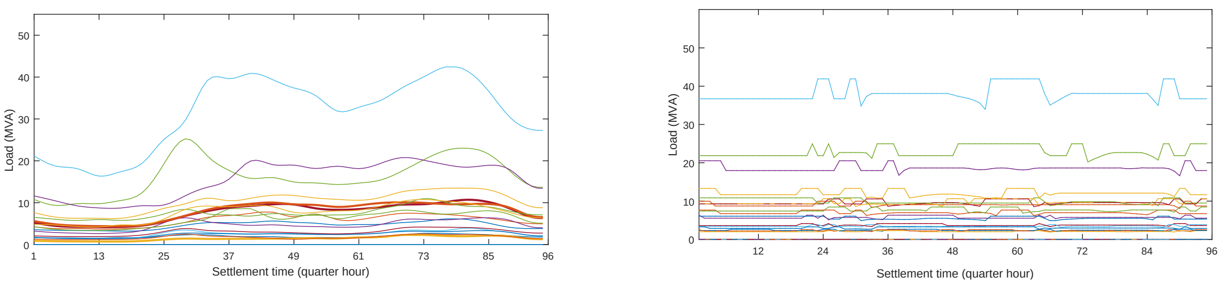
The load profile 1 gives a large variation in the cumulative load but varying slowly with the period of settlement time. In the first six hours the cumulative load is below 60% of the total installed load and remain above for the rest of the 18 hours. The load is varying smoothly and reached the maximum peak at 16th hour, and then dropped to 60% at the end. This load profile represent the smooth variation but large difference of demand in variation hours of the day for which the behavior of the power networks would be studied. Similarly the performance of the control strategy would be also studies in resolving the critical situation created due to the high power transfer between different parts of the networks. Similarly load profile 2 gives the demand variation a bit faster than the load profile 1 but the demand variation in the different interval of 24 hours time is comparatively small. Thus the same quarter hour of step size, the demand variation is more rapidly and varying within the 88-94% of the total installed load. This load profile is used to study the behavior of the power network in more dynamic load situation and similarly validating the proposed control strategy for FACTS devices control to handle the situation. The steady state system models are used for the power system operations study based on the load profiles. Five IEEE test networks *i.e.*, 30, 39, 57, 118 and 300 bus systems are subjected to conduct the study and the operation of power system with distributed coordinated control system (DCCS) of FACTS devices deployed at the proposed locations in chapter 3.

6.1.2 Congestion Management with and without FACTS Devices

The operational constraints of the transmission network become active during the load variation of the applied load profiles. The steady state operation of the power system based on the settlement period of load profiles is simulated with AC power flow equations. The lines flows and bus voltages are determined using Newton Raphson power flow method. The main focused constraints are line capacity limit and steady state voltage limits *etc*. The electric network is subjected to system without FACTS devices and the congestion is managed by generation rescheduling method. In this work the power injections and consumption are decided by the operator among the areas, to bring the violated constraints within the limits. The line loading is managed by increasing the power injection at the sending or source area, while the power demand of the receiving area is equivalently supplied locally with available generations. Similarly the bus voltage violation is handled by the supplying more power in the same area corresponding to minimum or maximum bus voltage limit. Thus in case of under voltage the power is supplied locally and conversely reduced the power supply for over voltage case. Generation rescheduling is based on the area so all the area generator would be participated in providing the required power.

6.2 IEEE 30 Bus System

The profile of all the loads in this network based on the load profile 1 and 2 are shown in Figure 6.2. The upper Figure shows the load profiles for the base case system data for load profile 1 and the lower Figure is based on the load profile 2. The proposed nine locations for series FACTS devices and nine locations for shunt FACTS devices are equipped with respective FACTS devices. The system is executed for the given time of 24 hours with dynamic load values at each settlement time interval of 15 minutes without FACTS devices, then congestion management is used in the system to avoid the congestion. Then the system with MAS based DCCS of FACTS devices is executed for the same load profile. The load profiles are based on the increased load for TTC enhancement as proposed in previous chapter as the load profile for base case data is not enough to create any congestion situation of line capacity or bus voltage magnitude limit violation.



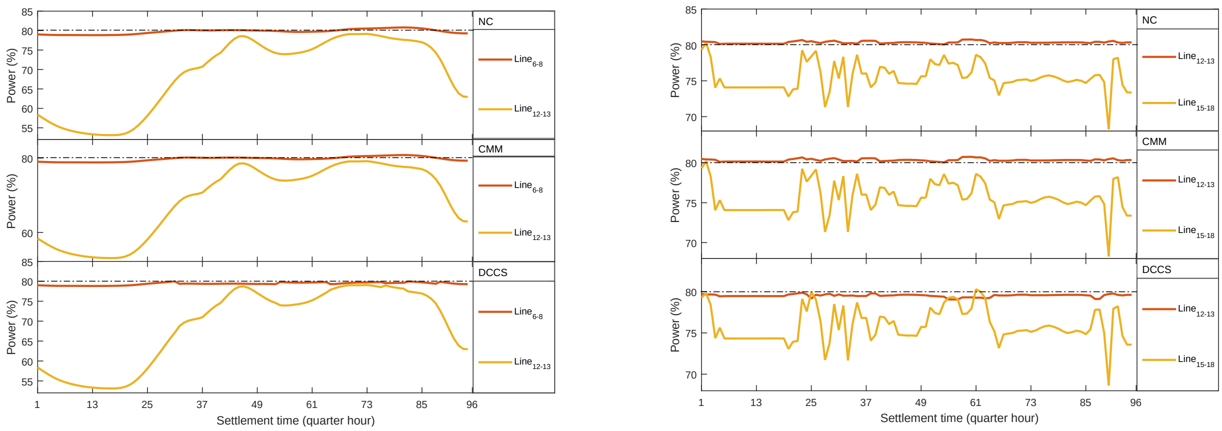
(a) Load profile 1

(b) Load profile 2

Figure 6.2: Load Profile of IEEE 30 bus system

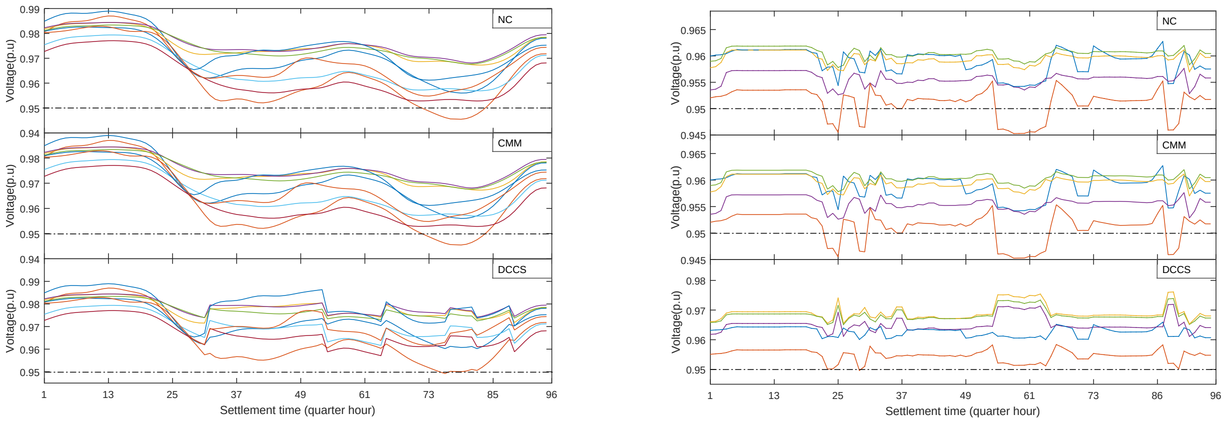
The steady state AC power flow simulation is run for the whole dynamic load duration and the line flows and bus voltages at each interval are determined. It is observed that all the line flows and bus voltages are within the limits and no violation occurred at any interval of time, but two lines loaded nearly 80% of the capacity in operating the load profiles for all three systems. In load profile 1 the two loaded lines $Line_{6-8}$ and $Line_{12-13}$ are shown in Figure 6.3(a) for three systems and the corresponding control of DCCS for FACTS can be seen to limit the line loading under the 80% of the capacity. In operating the load profile 2 also two lines $Line_{12-13}$ and $Line_{15-18}$ are loaded to 80% of the capacity and shown in Figure 6.3(b) where the corresponding reduction of loadings can be observed. These loaded lines are also carrying series FACTS devices and thus control the flows over these lines.

The voltage magnitudes in operating both load profiles are shown in Figure 6.4. Although there is no violation of the voltage magnitude in the system without FACTS but only one bus location Bus_8 has the magnitude below $0.95 p.u.$, at interval between $18th$ to $21th$ hour and therefore the same voltage profile is achieved using congestion management method. Whereas the DCCS based FACTS controlled has improved the voltage magnitudes above the lower voltage of $0.95 p.u.$, for the network in operating both the load profiles. And not only the magnitude of the bus locations with shunt FACTS devices are improved but also the neighbouring buses with these buses.



(a) High loaded lines flow for load profile 1 (b) High loaded lines flow for load profile 2

Figure 6.3: Power flow over high loaded lines of IEEE 30 bus system for both load profiles

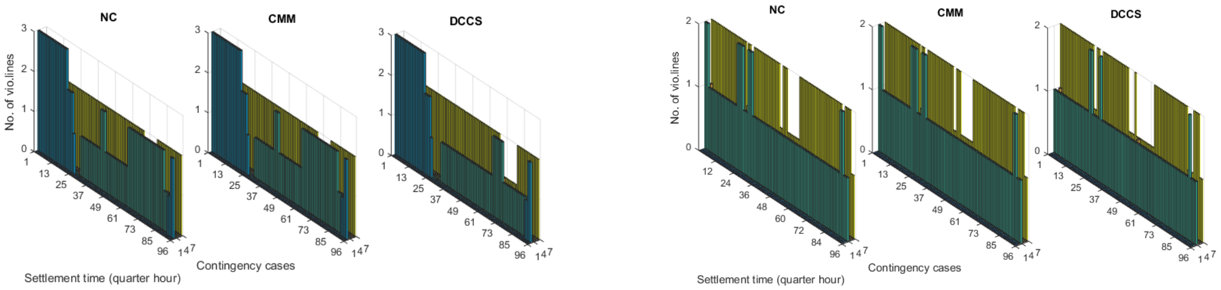


(a) Voltage profile 1 (b) Voltage profile 2

Figure 6.4: Voltage magnitude of IEEE 30 bus system for both load profiles

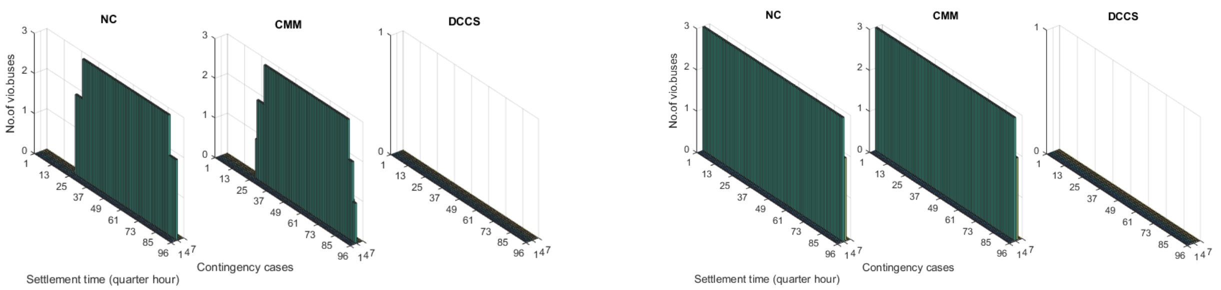
The systems are also subjected to contingency cases and the few lines and buses are violated in line outage cases and shown, while many buses and lines are violated in generator outages cases which couldn't be improved even by DCCS of FACTS devices. In load profile 1 three lines L_{4-12} and L_{10-20} and L_{28-27} outage cases, one to three number of lines are violated at different interval of settlement time in three systems and the respective improvement can be seen in Figure 6.5(a). While in load profile 2, one to two number of lines are violated in two lines L_{10-20} and L_{28-27} outage cases and shown in Figure 6.5(b). In L_{4-12} outage case which connect $area_1$ and $area_2$, the line loadings of only three lines L_{16-17}, L_{15-18} and L_{22-24} exceeded the defined capacity in the initial interval of settlement time but even couldn't be reduced due to the series FACTS devices at L_{15-18} and other surrounding series FACTS devices, because of the power dispatch from the generators to the respective demand of the loads. Ans similar situation happened for other two lines outage cases with slight possible improvement by congestion method and DCCS of FACTS at some interval of time. In processing load profile 2 one to two lines violated for whole settlement time in two lines L_{10-20} and L_{28-27} outage cases and DCCS can only provide the improvement as shown in the Figure 6.5(b).

The DCCS based controlled of FACTS devices has outperformed in improving the violated buses in both load profiles and shown in Figure 6.6. In L_{10-20} outage case during the processing of load profile 1 three bus locations Bus_{18}, Bus_{19} and Bus_{20} have voltage magnitude lower from the defined limit from the interval of $6th$ hour to the end of settlement time due to the dynamic load value and absence of the path to provide the power from G_{22} to the violated buses, at the same time it is also far from the G_{23}. The shunt FACTS at Bus_{18} and Bus_{19} has provided respective reactive power to improve the voltage magnitude as shown in Figure 6.6(a). In L_{10-17} outage case voltage violation occur at Bus_{16} and Bus_{17} which are improved by their own shunt FACTS devices. And in L_{28-27} outage case the magnitude of Bus_8 is improved by its own shunt FACTS. Similarly for load profile 2 in two line L_{10-20} and L_{10-17} outage cases the same buses have lower voltage magnitudes for the whole settlement time which are improved by the respective FACTS devices as shown in Figure 6.6(b).



(a) Violated lines for load profile 1 (b) Violated lines for load profile 2

Figure 6.5: Violated lines of IEEE 30 bus system in line outage contingency cases for both load profiles



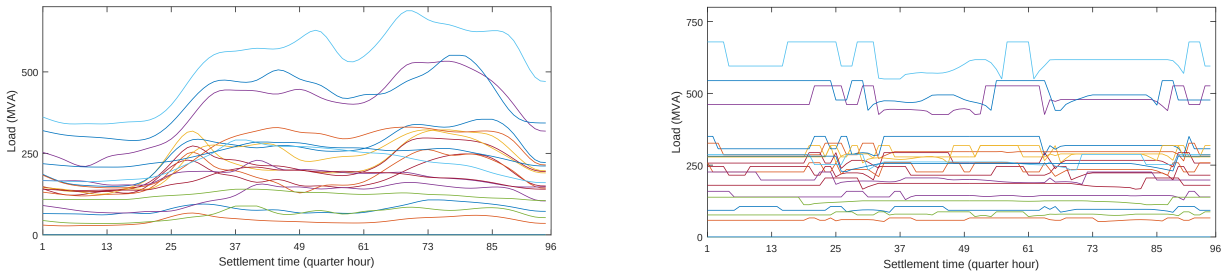
(a) Violated buses for load profile 1 (b) Violated buses for load profile 2

Figure 6.6: Violated buses of IEEE 30 bus system in line outage contingency cases for both load profiles

Applying the load profile 2, in normal case there is no violation in any of the bus or line, while the voltage magnitudes and line loadings are varied corresponding to the dynamic load profiles. In two lines L_{10-20} and L_{10-17} outage contingency cases have lines and buses violation at different interval of time. In L_{10-20} outage case the line loading of lines L_{15-18} has exceeded the capacity and two buses Bus_{19} and Bus_{20} have the voltage magnitude below the limit throughout the dynamic load settlement time while and the loading of L_{18-19} exceeded at for short time at different intervals. Similarly in line L_{28-27} outage case the loading of two lines L_{23-24} exceeded the capacity throughout the settlement time and the loading of L_{24-25} is within the capacity only for short time while exceeded for the whole time. Similarly one bus Bus_8 suffering the lower voltage from the define limits for the short interval of settlement time. Also two buses Bus_{16} and Bus_{17} are violated the voltage limit in L_{10-17} outage case for the whole settlement time. The DCCS of FACTS devices has improve the voltage magnitudes at all the buses in all line outage contingency cases as shown in Figure 6.6(b).

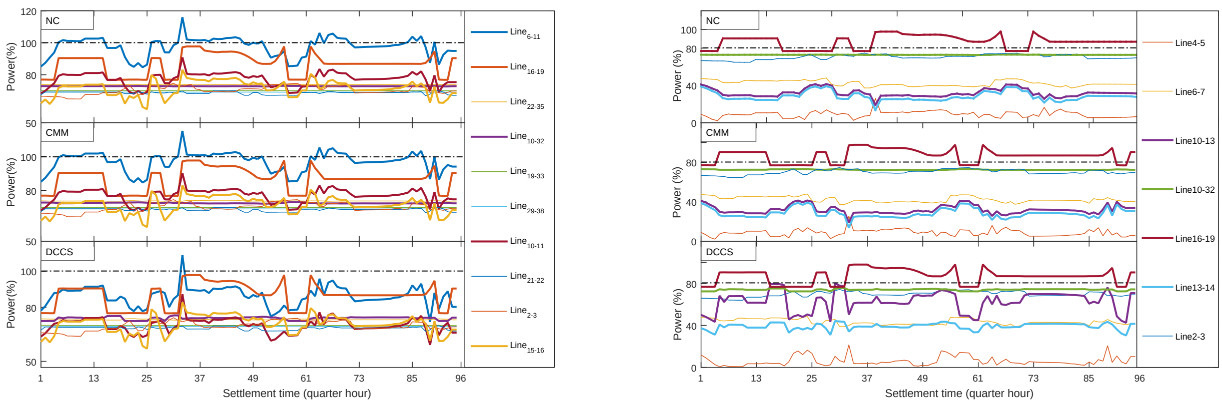
6.3 IEEE 39 Bus System

The load profiles for this network is given based on the proposed load profiles and given in Figure 6.7. The steady state power flow simulations for this network with proposed seven series FACTS and two shunt FACTS devices using load profile 2. The power flow and bus voltage magnitudes are examined for the systems without FACTS, using congestion management method and using MAS based DCCS of FACTS. Using load profile 1 for base case data, the power network couldn't have the feasible solutions and some line loading reached 200% of the line capacity. Therefore, the load profile 2 is used for base case load data.



(a) Load profile 1 (b) Load profile 2

Figure 6.7: Load Profiles of IEEE 39 bus system



(a) Loadings of ten highest loaded lines (b) Loadings of FACTS containing lines

Figure 6.8: Dynamic power flow of IEEE 39 bus system for load profile 2

In operating the power network for the load profile 2, it is observed that there is no violated bus for the whole 24 hours of settlement time. But the line loading at some lines are exceeded the capacity and such ten highly loaded lines are shown in the Figure 6.8(a) for the systems without

FACTS, with congestion management method and then with FACTS devices controlled by MAS based DCCS. It can be seen four lines L_{6-11}, L_{16-19}, L_{10-11} and L_{15-16} are highly loaded *i.e.*, more than 80% of the capacity in different interval of time in the system when no FACTS device is used. The highest loaded line is L_{6-11}, which loading even exceeded the specified line capacity. The second highest loaded line is L_{16-19} which loading is within the capacity but still exceeded the 90% of the capacity at different intervals. The two lines L_{10-11} and L_{15-16} achieved only the 80% line capacity and varying around it throughout the settlement time. The congestion management method of generator rescheduling has slightly reduced the line loading but couldn't bring the overloaded line L_{6-11} within the capacity limit at some interval of time.

The MAS based DCCS of FACTS devices has managed to reduced the loadings of these high loaded lines but only for a short interval at $8th$ hour as shown in the Figure 6.8(a). The Figure 6.8(b) shows the loading of eight lines with series FACTS devices in which only four lines L_{2-3}, L_{10-13}, L_{10-32} and L_{16-19} have participated in resolving the problem of line overloading. It can be seen that the lines L_{10-32} and L_{10-13} have led the access loading that reduced the loading of overloading lines under the capacity limit. The loading of L_{6-11} at $8th$ hour is still exceeded the capacity that is due to the loading of two controlling lines L_{10-32}, L_{10-13} reached 80% of the capacity defined as the maximum controlling limit and these are the only alternative path to the overloading lines. The loading of line L_{16-19} couldn't be much affected even by series FACTS device installed on this line due to the topological structure, as there is no other line available where the excess power could be diverted. And it is the only line that connect four buses Bus_{19}, Bus_{20}, Bus_{33} and Bus_{34} to rest of the network, through which the two generators at Bus_{33} and Bus_{34} are being dispatched. Similarly the loading of other high loaded line L_{10-11} is also brought within the 80% of the line capacity by the controlling lines L_{10-32}, L_{10-13}. These two lines take the excessive loading as an alternative path to reduce the loading of overloading line.

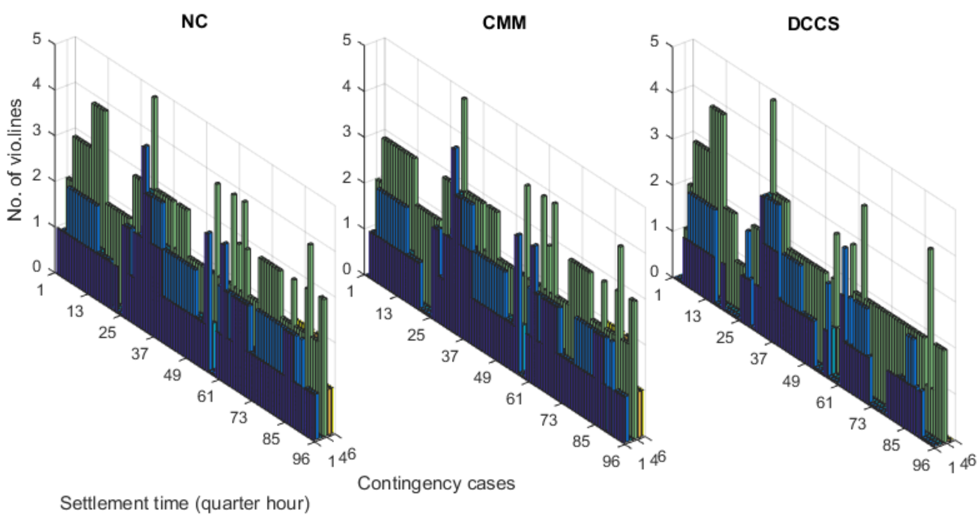
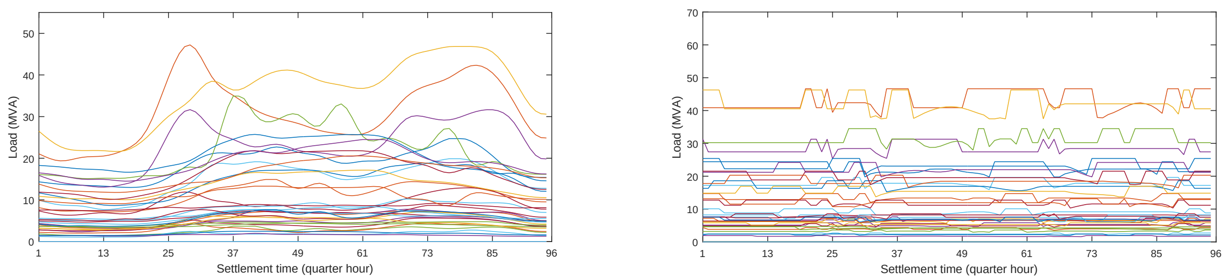


Figure 6.9: Lines violation of IEEE 39 bus system in line outages contingency cases for load profile 2

In the contingency of line outage cases, the voltage magnitude of all the bus locations are within their defined limits but only lines are violated in the system during the system operation of dynamic load throughout the settlement time. Number of lines violation in each of six lines outage contingency cases are shown in the Figure 6.9. In each case various lines are violated at different interval of time but more lines are violated in L_{16-17} outage case, because this is the only path to connect $area_1$ and $area_2$, and consequently the power flow burden is propagated to lines of $area_1$ and $area_3$ as now $area_2$ can be supplied via $area_2$ from $area_3$. Therefore, the maximum of five number of lines are overloaded for the respective load demand at various interval of time. As a result both congestion management method and DCCS could not reduced the corresponding line loading. Similarly the outage cases of inter-area lines L_{1-39} and L_{3-4} between $area_1$ and $area_2$ two to four number of lines are overloaded at some interval of settlement time. Which are somehow reduced by congestion management method and comparatively more improved even reduced to zero at some intervals of time by MAS based DCCS. In all other lines outage cases too the DCCS has comparatively reduced the number of violated lines than congestion management method as shown in Figure 6.9.

6.4 IEEE 57 Bus System

Based on the proposed algorithm for network analysis six locations are selected for shunt FACTS devices and one locations is selected for series FACTS device. The dynamic load profiles based on the proposed profiles for the increased loads with enhanced TTC as explained in previous chapter are used. The line loading and bus voltages of the network are quite within their operating limits for the base case system data and no line or buses are violated while using dynamic load profiles for base case load data. Therefore, the load profiles based on the increased demands are used to create the congestion situation by violating line or buses. The load profile of 24 hours settlement time are given in the Figure 6.10.

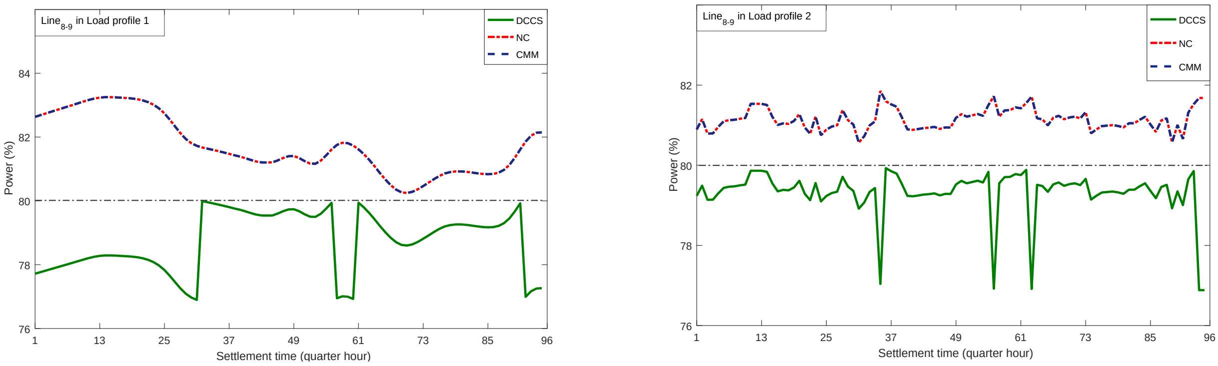


(a) Load profile 1 (b) Load profile 2

Figure 6.10: Load Profile of IEEE 57 bus system

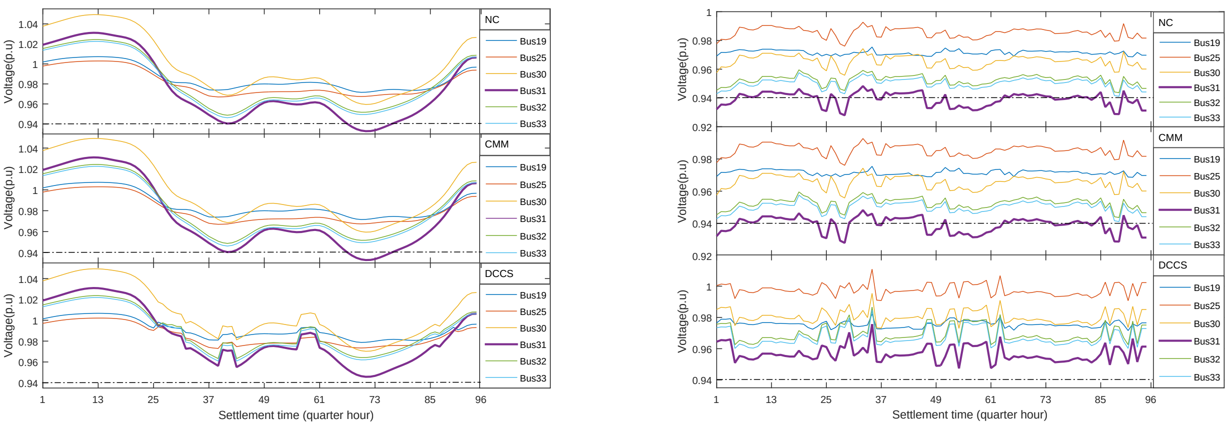
The only one line L_{8-9} in the network has loading which exceeded the 80% of line capacity for both load profiles throughout the 24 hours of settlement time. The loading of other lines are under the 40% of their capacities in the system without FACTS devices and using congestion management method. As the same line has the series FACTS device and therefore the power flow is controlled and being reduced under the 80% of the capacity for both load profiles as shown in Figure 6.11. The line basically connect two generation buses Bus_8 and Bus_9 in which the generator at Bus_9 connected most of the load buses which are far away from other generators. The demands of these connected load couldn't be supplied by generator at Bus_9 only and deficiency is obviously provided due to the contribution of generator at Bus_8. Resulted the high loading of L_{8-9} above 80% of the capacity due to the large power supplied from the generator at Bus_8. So the high power demand of the load buses in that area surely overload the line because the only path that connect these two buses which would provide the respective power for those buses. The series

FACTS device has to control the power of this critical line if congestion occurred due to violation. The loading of the line is not much affected by congestion management method as it is still within the capacity and there is no other generator available to supply the demand. But the only series FACTS devices at L_{8-9} has controlled the loading based on DCCS and can be seen to reduced the loading under the 80% of the line capacity in both load profiles. And the excess power is forcefully diverted to follow rather a long alternative path of $Bus_8 - Bus_7 - Bus_{29}$ to the demand of the load buses which are previously supplied through L_{9-55}.



(a) Power flow for load profile 1 (b) Power flow for load profile 2

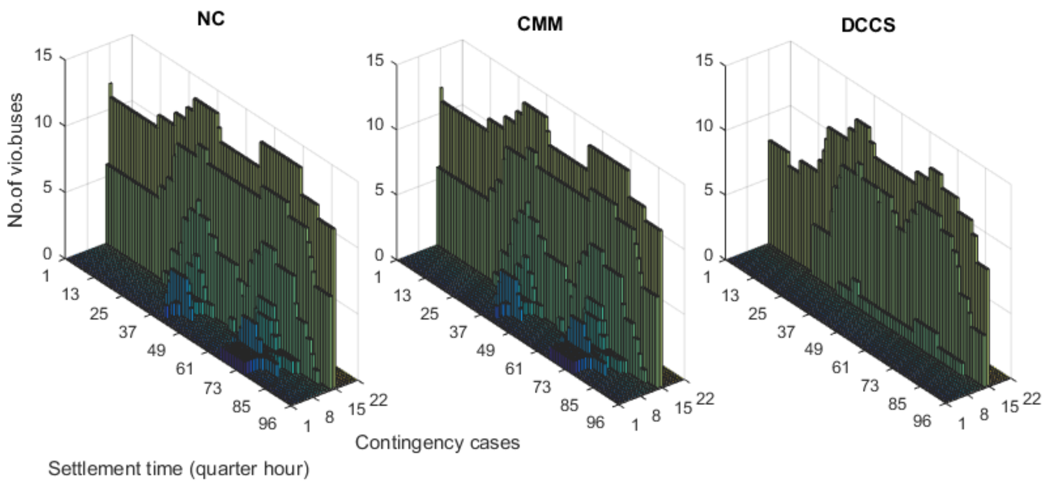
Figure 6.11: High loaded lines of IEEE 57 bus system in both load profiles



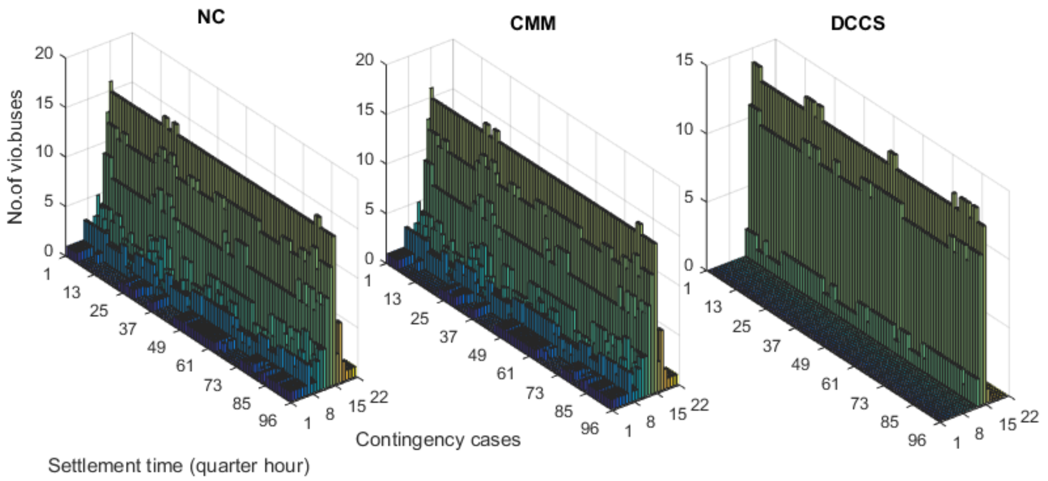
(a) Voltage Profile 1 (b) Voltage Profile 2

Figure 6.12: Dynamic Voltage profiles of IEEE 57 bus system for both load profiles

Similarly the bus voltage magnitude in operating both load profiles are observed to be within their supposed limits except Bus_{31} where the voltage magnitude dropped down the lower limit for short intervals of settlement time in load profile 1, while varying about the limit throughout the settlement time in load profile 2. The voltage profiles of six bus locations are shown in Figure 6.12 for the system without FACTS, using congestion management method and using FACTS devices controlled by autonomous agents in DCCS. And it can be seen that the bus voltage magnitudes are improved for all the bus locations using six FACTS devices. The voltage profile of Bus_{31} is still below the lower voltage limit using the congestion management method. The voltage profiles of all the buses are improved by the DCCS based FACTS controlled system throughout the settlement time of both load profiles. The FACTS devices coordinated though MAS system and carried out after 6th hour of settlement time in operating load profile 1, while in load profile 2 the control actions are taken from the second hour of the settlement time to the end.



(a) Violated buses for load profile 1



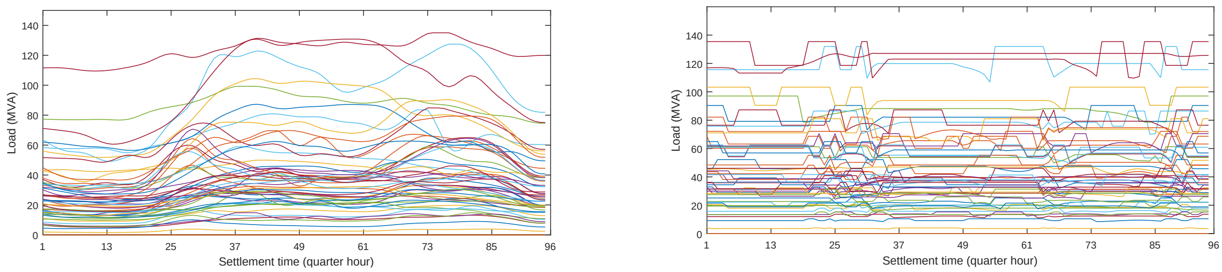
(b) Violated buses for load profile 2

Figure 6.13: Bus violation of IEEE 57 bus system in line outage contingency cases

In the contingency of line outage cases, no line is violated throughout the settlement time for both load profiles in all twenty two inter-area line outage cases. This shows that the line capacity of the lines in the system is high enough for the line loadings achieved in both load profiles and therefore could not be exceeded even in contingency cases. Only the voltage magnitude at some bus locations are dropped down in different line outage cases and the same happened in the system using congestion management method and the system with DCCS based control FACTS devices as displayed in Figures 6.13(a) and 6.13(b) for both load profiles. It can be seen that the violation of buses are resolved in most of the cases except in four lines L_{27-28}, L_{36-37}, L_{37-38} and L_{37-39} outage cases the violated buses are large enough. DCCS based FACTS devices have reduced the number of violated buses for these line outages cases but only left at few intervals which couldn't be reduced. This shows the critical position of the such lines in the secure transaction of power throughout the network, because such line connect load buses with generator buses and in case of such line outages the distance of loads become far away from generator buses. In generator outage cases it is observed that most of the buses are violated throughout the dynamic load settlement time and by using DCCS based FACTS devices could only reduced the number of violated buses.

6.5 IEEE 118 Bus System

The network is analyzed for TTC enhancement and four locations are proposed for series FACTS devices and thirty seven bus locations are selected for shunt FACTS devices. The dynamic load profiles of the network based on the selected profiles are given in the Figure 6.14. The load profiles are based on the increased loads as calculated for TTC based on the algorithm in previous chapter to achieve violation scenarios in line capacity or bus voltage limit that would create the congestion in the network.

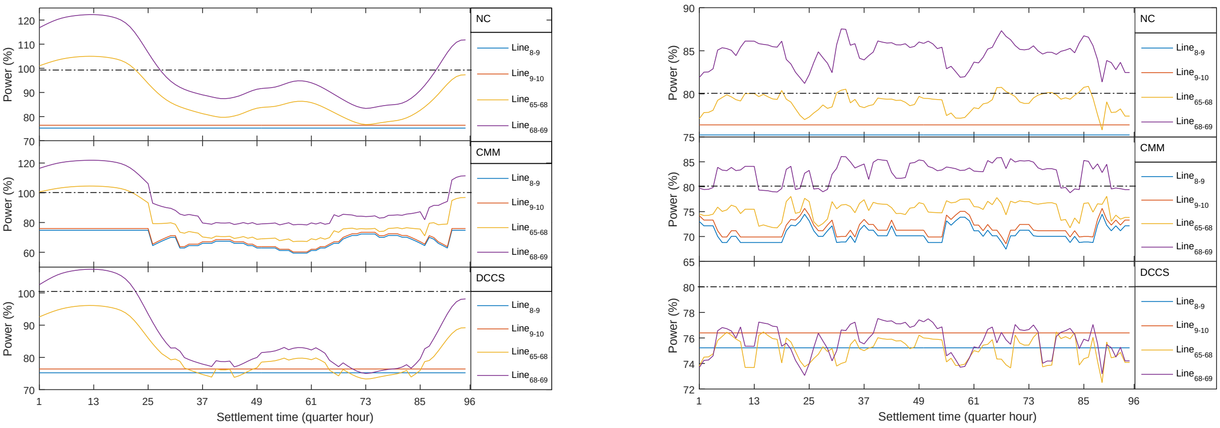


(a) Load profile 1 (b) Load profile 2

Figure 6.14: Load Profile of IEEE 118 bus system

In operating load profile 1 the loading of only two lines L_{65-68} and L_{68-69} are overloaded in the first six hours of settlement time and then remains high but within the capacity for rest of the time and later in the last hour the L_{65-68} got overloaded again as shown in Figure 6.14(a). Similarly two other lines L_{8-9} and L_{9-10} have also high loading nearly 80% of the capacity consistently throughout the settlement time. Using congestion management method in the system the loading of all the overloaded lines are reduced but still above the capacity limit in the respective overloading intervals. Thus the overloading of these two lines couldn't be resolved completely and could eventually activate the protection system.

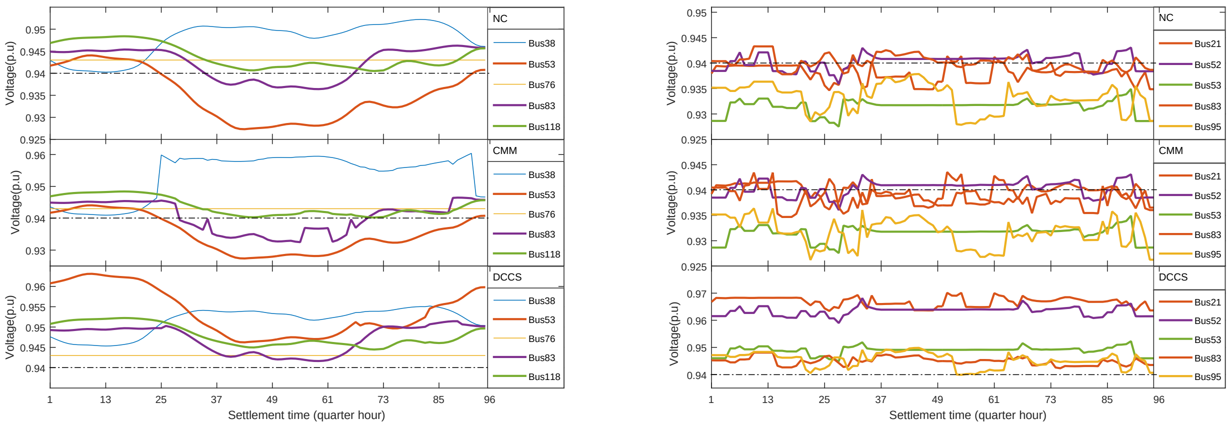
The DCCS of FACTS devices has successfully reduced the loading of all the overloaded lines quite enough under the capacity limit except only for the overloading hours where the loading of L_{68-69} is slight above the limit and of L_{65-68} is within the limit. In compared to the systems without FACTS and using congestion management method the loading of overloaded lines are well below the capacity limit. Four series FACTS devices in which L_{8-9} and L_{9-10} are coordinated together, while L_{65-68} and L_{68-69} are coordinated together in controlling the power flow of all the lines in their influential areas. The is because physically both groups are far away from each other and have less influences on each other. So as a result only devices on L_{65-68} and L_{68-69} participated that reduced the line loading to the shown level based on the maximum control capability. The excess power is diverted, which follow the path through line L_{69-77} and L_{77-80} and increased their flows by 10% and 8% respectively. But the projected load values of the utilized synthetic load in the first six hours of settlement time isn't feasible as the control action by DCCS for resolving congestion situation and couldn't reduced the loading of overloaded lines and eventually activate the protection system that halted the given power transaction.



(a) Power flow for load profile 1 (b) Power flow for load profile 2

Figure 6.15: Dynamic power flow over high loaded lines of IEEE 118 bus system in load profiles

In load profile 2 the power system operation is satisfactory in resulting line loading within their capacity limits throughout the whole settlement time of the dynamic load. The only one line L_{68-69} has got the loading above the 80% of its capacity while the loading of L_{65-68} has very close to its 80% of capacity. The rest of lines are well below the 75% of the capacity in the system without any control or FACTS devices. The congestion management method has affectively reduced the line loading down to 80% of the capacity of the high loaded line L_{68-69} while rest of the lines have loading well reduced down the 75% of the line capacity as shown in Figure 6.15(b). The DCCS based FACTS devices can be seen in reducing the line loading of the respective high loaded lines L_{68-69} and L_{65-68} comparatively more under the 80% of the capacity. Here also the two series FACTS devices L_{68-69} and L_{65-68} have participated in controlling the power flow of these highly loaded lines and greatly reduced by diverting successfully to other low loaded lines. The other two lines with series FACTS devices have no overloaded lines in their effective influential area and therefore, no need of any control action to control the loading of lines.



(a) Voltage Profile 1 (b) Voltage Profile 2

Figure 6.16: Dynamic Voltage profiles at violating buses of IEEE 118 bus system

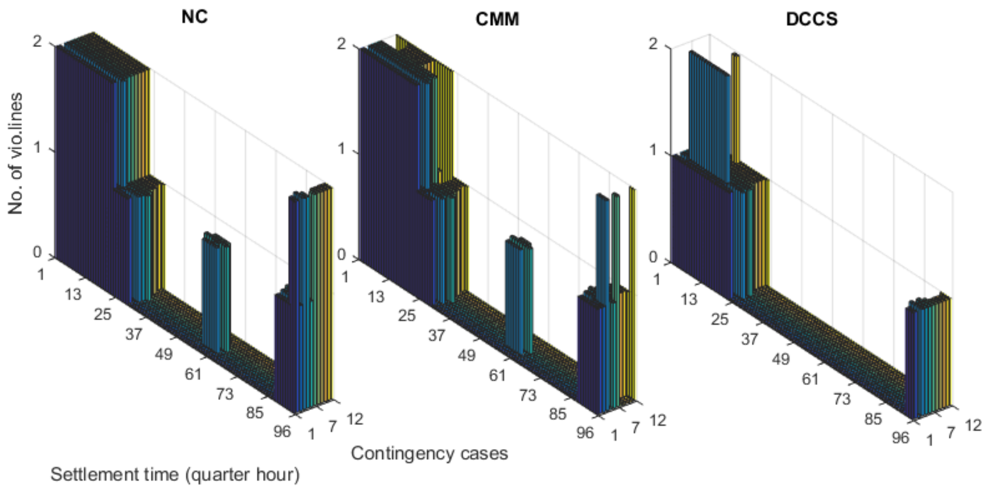
Similarly the dynamic voltage magnitude for both load profiles are shown in Figures 6.16. It can be seen that at five bus locations the voltage magnitudes are dropped down from $0.95p.u.$, value while operating load profile 1 in the system without any control. The voltage magnitudes of the bus locations Bus_{53} is more affected and dropped down the $0.93p.u.$, value while the Bus_{83} is second low voltage bus location which magnitude is below $0.94p.u.$, value after 7th hour of the settlement time. The congestion management method have improved the voltages magnitude of Bus_{38} only but not much affected other bus locations and even the low voltage buses Bus_{53} and Bus_{83} couldn't be improved. The DCCS controlled FACTS devices has effectively improved the voltage magnitudes of all the buses and no bus location has the magnitude below $0.94p.u.$, value as shown in Figure 6.16(a). Three shunt FACTS devices at Bus_{53}, Bus_{83} and Bus_{118} have participated in improving the voltage magnitudes of these violating buses.

In load profile 2 again the voltage magnitudes of five bus locations Bus_{21}, Bus_{52}, Bus_{53}, Bus_{83} and Bus_{95} are below $0.94p.u.$, throughout the whole settlement time in which the voltage magnitudes at Bus_{53} and Bus_{95} went below $0.93p.u.$, value at many intervals of time in the system without any control. The congestion management method has managed to improve the voltage magnitude of bus locations Bus_{21}, Bus_{52} and Bus_{83} which varied about $0.94p.u.$, value with load variation. The two bus locations Bus_{53} and Bus_{95} have magnitudes still below the defined limit of $0.94p.u.$,. The DCCS control of FACTS devices has successfully improved the voltage magnitudes of all these buses and non of the bus have magnitude below $0.94p.u.$, as shown in Figure 6.16(b). For this profile all five buses which are participated in DCCS for the voltage improvement.

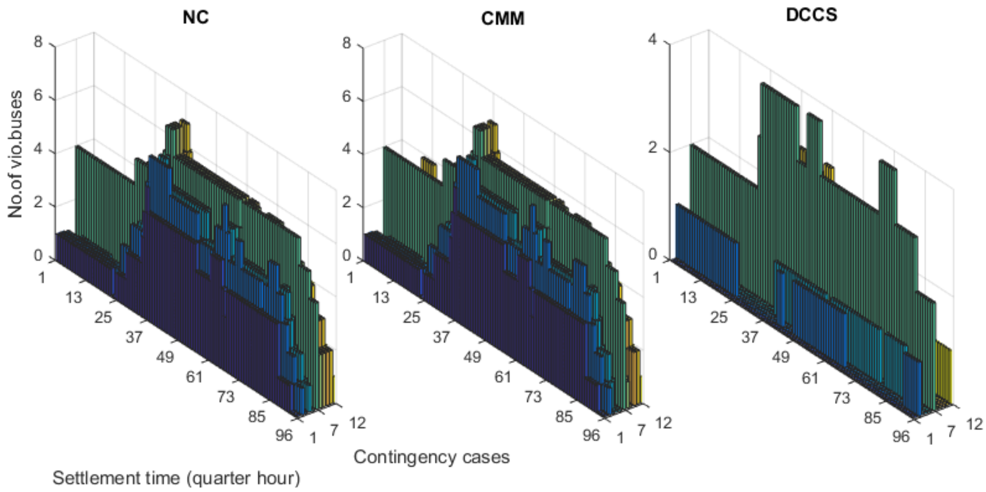
In contingency of twelve number of line outage cases the violation in line loading or bus voltage magnitudes of the three systems with no control, congestion management method and DCCS of FACTS devices in load profile 1 is shown in Figure 6.17. The violation of buses and lines at each interval of settlement time are determined. The Figure 6.17(a) shows that in the first 6 hours of settlement time the system with no control have two lines violated for all twelve contingency cases, while the system with congestion management method have reduced the violated lines for some line outage cases. The DCCS of FACTS devices have managed the line flows that has reduced the violated lines to only one line *i.e.,* L_{68-69} in most of the line outage cases. In the lines L_{69-70} outage case two lines L_{68-69} and L_{65-68} are overloaded for four hours and in L_{69-75} outage case the same lines are overloaded just for half an hour. After six hours of settlement time the system with no control and congestion management method have only one line L_{68-69} violated for from 13th to 15th hours in three line outage cases and then in last two hours two lines are violated again. In the DCCS of FACTS have reduced the lines loading and in the last hours one line L_{68-69} is violated in the system. So comparatively it can be seen that the DCCS of FACTS devices have reduced the violated lines compared to the system with no control and the system with congestion management for more time.

Similarly there are various number of violated buses from one to seven at different intervals of settlement time in the system with no control. The system with congestion management method has also the the similar number of violated buses throughout the settlement time as shown in Figure 6.17(b). The system with DCCS of FACTS devices has improved the voltage magnitudes at many buses and reduced the number of violated buses at different interval of time for all the contingency cases. But in three lines L_{30-38}, L_{96-97} and L_{99-100} outage cases the number of violated buses are reduced to only one bus and in L_{77-82} outage case two buses are violated in the first six hours of the settlement time. In the interval of 8 to $22th$ hour there are two to seven number of violated buses in the system with no control and some using congestion management method for different line outage cases. In the same interval of time in the system with DCCS of

FACTS have only one to four number of violated buses at different in six contingency cases while in other six contingency cases either there is one or no violated buses. Comparatively it can be seen that the system with DCCS of FACTS devices has got better results in improving lines and voltage magnitudes at buses in load profile 1.



(a) Violated lines



(b) Violated buses

Figure 6.17: Violated lines & buses of IEEE 118 bus system in contingency cases for Load profile 1

In the operation of load profile 2 with line outage contingency cases, there is no violated lines throughout the settlement time for all twelve contingency cases in the system with no control, with congestion management method and with DCCS of FACTS devices. But there are many buses where the voltage magnitudes are violated as shown in Figure 6.18 throughout the settlement time in all contingency cases for the system with no control. In the system with congestion management method also couldn't managed the voltage magnitudes improvement and thus the same number are violated buses are there in the system. The DCCS of FACTS devices has managed the improvement in six contingency cases no violated buses are left while in two contingency cases of lines L_{80-96} and L_{96-97} outage there are two to four number of violated buses at different interval of time. The only line L_{77-82} outage case there are four number of violated buses throughout the settlement time. The other three line outage cases have one violated bus left and that is only at different interval of time. In the generation outage cases all the buses are violated for the whole settlement time in both load profiles and even DCCS of FACTS couldn't managed the voltage violation.

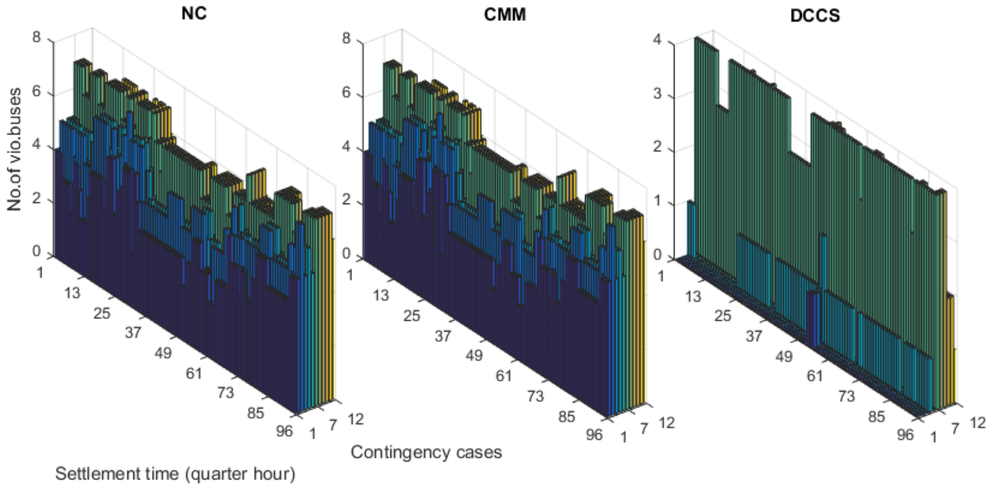
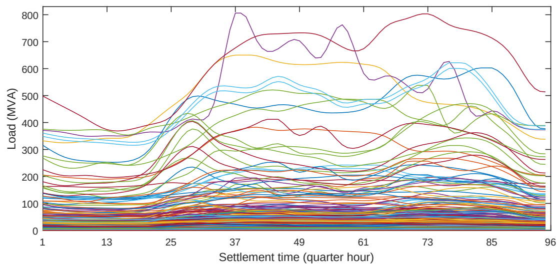


Figure 6.18: Violated buses of IEEE 118 bus system in contingency cases for Load profile 2

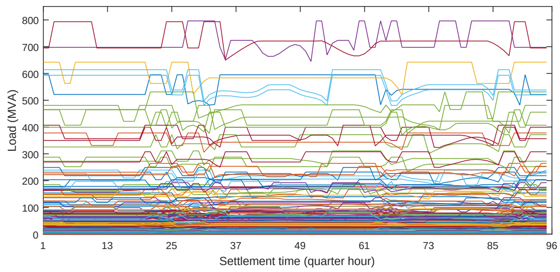
So it is observed that two out of four number of series FACTS devices and five out of thirty seven number of shunt FACTS devices are operated and have improved the line loadings and bus voltage magnitudes in dynamic load profiles. The locations of series and shunt FACTS devices are proposed based on the critical locations not only for overall network but also between inter-area TTC enhancement. But for the given generalized load profiles and congestion scenarios which are not practically related to specific network or system few number of FACTS devices have successfully provide the required improvement in the system.

6.6 IEEE 300 Bus System

The network analysed algorithm for TTC enhancement of overall as well as inter-areas between various area, suggested a total of thirty seven bus locations for shunt FACTS devices only with no series FACTS devices for this network. The load profiles for the network loads are based on the network base case data to evaluate the system operation as shown in Figure 6.19.

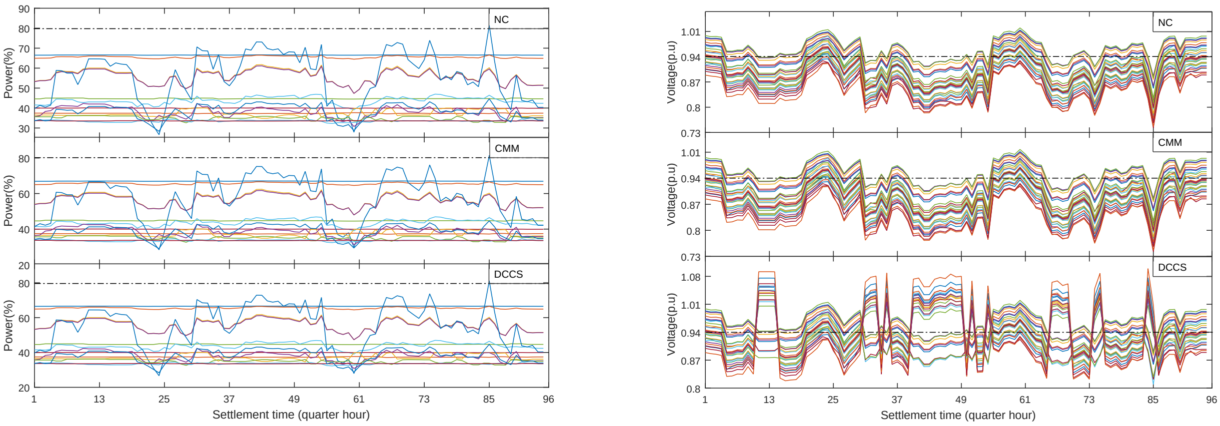


(a) Load profile 1



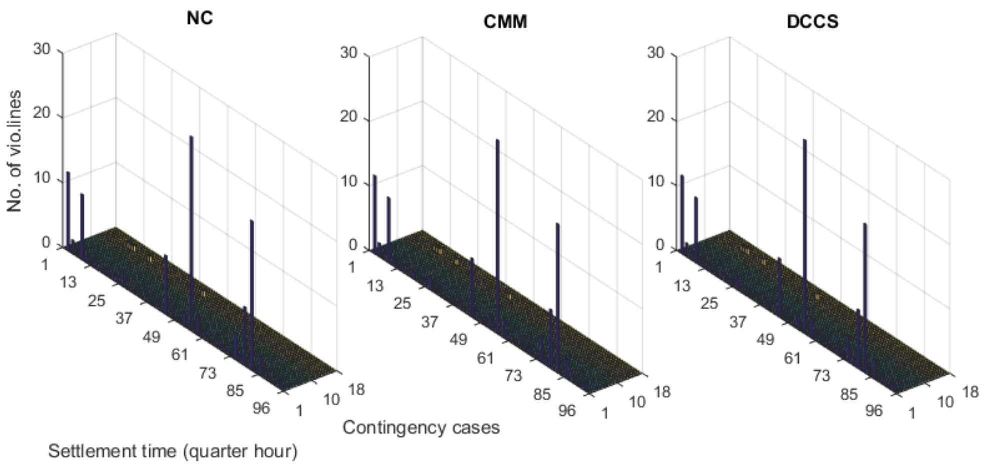
(b) Load profile 2

Figure 6.19: Load Profile of IEEE 300 bus system

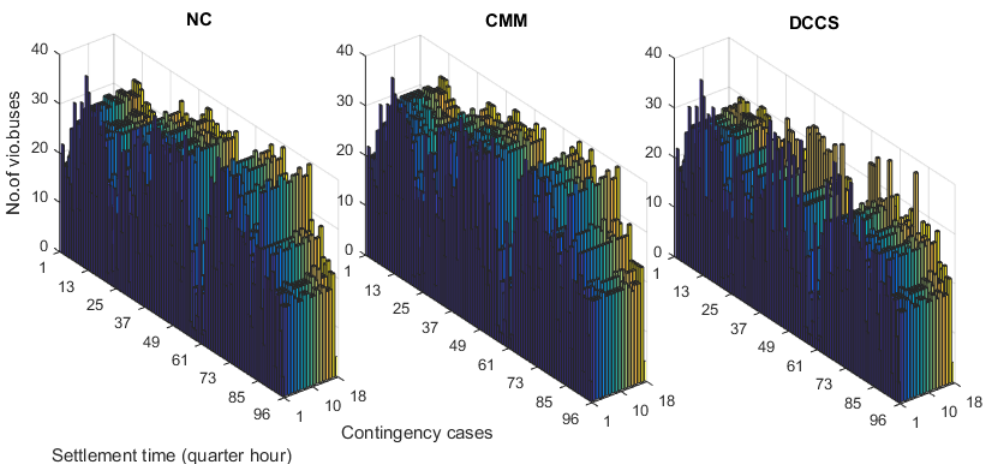


(a) Power flow of high loaded lines (b) Voltage magnitude of violated buses

Figure 6.20: Power flow & Voltage magnitude of IEEE 300 bus system for load profile 2



(a) Violated lines



(b) Violated buses

Figure 6.21: Violated lines & buses of IEEE 300 bus system in contingency cases for Load profile 2

The load profile 1 is not feasible for this network due to very large power flows and even at some intervals the solution of the power flow equations couldn't be converged. Therefore, only load profile 2 is used for system evaluation in dynamic load operation with no control, using congestion management method and using DCCS of FACTS devices.

In operating the load profile 2, most of the lines are loaded below the 50% of the line capacity and few line loading have reached the 60% of their line capacities. The loading of only one line has achieved the 80% of its line capacity at $21th$ hour of settlement time just for short time and as there is no series FACTS devices so the power flow is not controlled as shown in Figure 6.20(a). The Figure shows the fifteen highest loaded lines in the three systems with no control, using congestion management method and with DCCS of FACTS devices. And it is observed that all three systems have the same loading patterns within the capacity limit throughout the settlement time and no control is needed. In Figure 6.20(b), many buses can be seen those have voltages below the specified limits at most of the time of the dynamic load profile 2 in the system without control and in the system using congestion management method. But the system with DCCS of shunt FACTS devices can be seen with improvement in the voltage magnitudes for the same dynamic load profile 2. The plots in Figures 6.20 show that the network for the dynamic load 2 is not operated well and many buses in the system suffered from low voltage and the DCCS could improve the problem only at some bus locations but overall system performance couldn't be improved satisfactory.

The system operation of the network in contingency cases of line outages also have large number of violated lines and buses in no control using congestion management method and the DCCS of FACTS devices. All the three systems have similar number of violated lines in all contingency cases especially the line L_{31-266} outage case have more number of violated lines and buses than other cases which are shown in Figure 6.21. The DCCS of FACTS devices have comparatively slightly reduced the violated buses as shown in Figure 6.21(b). In this network there are some buses where over voltage happened in all three system in line L_{31-266} outage case and given in Figure 6.22.

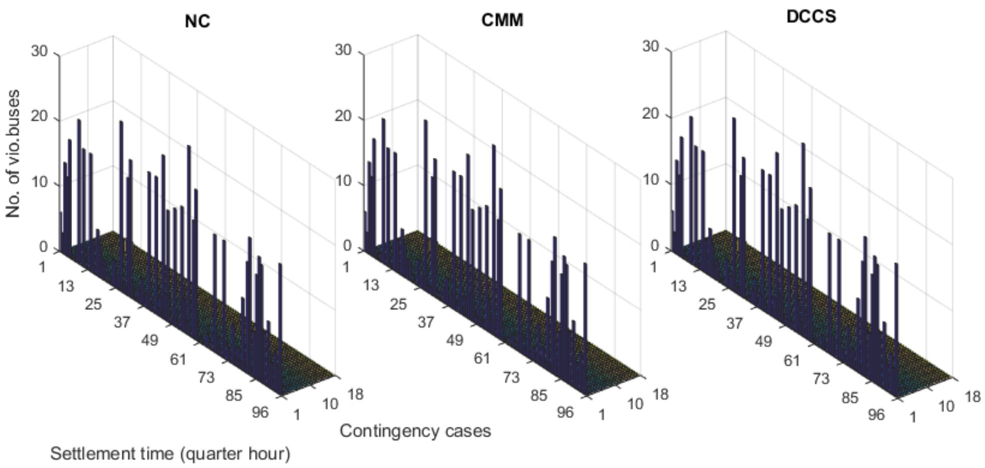


Figure 6.22: Over voltage buses of IEEE 300 bus system in contingency cases for Load profile 2

6.7 Concluding Remarks

The chapter described the results of validation of Distributed Coordinated Control System of multiple FACTS devices using different size of standard IEEE 30, 39, 57, 118 and 300 bus systems with dynamic load profiles which provide the congestion situation in power system operation by violating the line capacity and bus voltage magnitudes limits. Two load profiles provide different situations, as operating load profile 1 there are large power flow over the lines, while operating load profile 2 voltage magnitudes are violated at many bus locations. Both series and shunt FACTS devices are placed based on the locations proposed by the network analysis algorithm for TTC enhancement. Each network is subjected to operate in congested situation which are supposed to be improved by congestion management method of generation rescheduling and by DCCS of FACTS devices. Each network respond differently and DCCS has out performed for all the systems in reducing line loading and bus voltage improvement. Few FACTS devices participated out of total number of FACTS devices based on the requirement.

7 CONCLUSION AND FUTURE RECOMMENDATIONS

7.1 Conclusion

The modern power systems are undergoing changes in supplying power to various load centers with high degree of reliability. The conventional power stations due to economical, environmental and safety reasons are usually located remote from load centers. The generations from renewable resources are being focused in last recent decades as a cheap and environmental friendly sources of power supply and ancillary services in different power networks. In European electricity system power flows are increasing along the lines connecting different zones of North with high wind offshore potentials and South zone with solar potentials, while a large loads are located in Central Europe with lower potentials of renewable energy sources(RES). Consequently there could be a generation gap due to variable productions like a surplus production at one zone and the shortage at the other. So the storage facility would be always released for compensation of energy gaps and also energy reserves in case of less storage availability. The development of cross border trades which are initially planned for providing mutual support are nowadays used for commercial purposes between different energy markets for arbitraging the opportunities and ultimately stressing the cross-border backbones. This motivate the up gradation of aged transmission infrastructure along with other critical changes, utilization of advanced technology in transmission network. Thus the innovation in transmission system would required to increase the transmission capacity and make it more flexible and responsive in handling such sudden changes due to the variable generations.

In the basic transmission planning process of TSOs first of all scenarios of the framework and boundary conditions for specific area are developed and reliability of the network without any expansion is analyzed in normal as well as in contingency conditions. Static and dynamic security criteria including $(n-1)$ criterion are applied in the scenarios. The possible transmission reinforcements/strategies are devised in the presence of critical situation that could overcome the constraints. Then the cost and benefits of the candidate solutions are analyzed and ranked with priority order. These solutions ranging from upgrading/updating of the existing assets to build new lines and the use of innovative transmission technologies. The increasing development of power electronics in power system, the liberalized electricity market and the contribution of other operational factors, the FACTS devices utilization become necessary in power systems. The electricity is seem to be a commodity rather than a service in liberalized market, as the energy transactions are initiated based on the mutual contracts among the market participants. The injections and withdrawals of energy quantities are scheduled corresponding to the mutual contracts by sellers and buyers. The physical structure of the network lead the corresponding power flows, monitored and controlled to avoid system congestion or occurrence of instability in transaction commitments of the traded energy quantities. And the open access to the transmission grid in higher utilization of transmission assets, resulting a frequent network congestion. The grid operators have still the central role in controlling and coordinating the energy production according to the consumer demands for the overall system reliability. The FACTS devices with a variety of types and capabilities could enhance the transmission capacity and provide the control ability to network operator which make it more flexible and reliable with a comparative limited environmental impacts. Moreover, this could offer the opportunity of integrating more variable RES power plants in the power system as targeted by European power networks.

FACTS devices have the ability to provide useful features for transmission network planning and operation *i.e.*, power flow and voltage control, fast response to dynamic issues and relieving congestion. These devices could provide the control of variable energy sources and facilitate their integration. The feature of reactive power flow control could increase the transmission capacity of the network, freeing active power capacity of high loaded lines, increase the stability limit to the thermal limit. The series FACTS like TCSC, SSSC and IPFC could provide power flow control and transient stability improvement. The shunt FACTS like SVC, STATCOM provide the voltage control and stability issues. Similarly the combined shunt/series like TCPST, DFC and UPFC devices have provided several features of both types of devices, providing a balance between the different properties. These devices could be of thyristor controlled or more advanced voltage source controlled, quickly control one of the parameters that directly impacting the power flow *i.e.*, series impedance, nodal voltage amplitude, nodal voltage angular difference, line current, and shunt impedance *etc.*, are discussed in literature. The most versatile and expansive device is the UPFC, which independently and simultaneously control all the three parameters, installed worldwide only two in the United States and one in South Korea and recently in Brazil, China and India. The most widespread utilized thyristor controlled FACTS device is SVC for voltage control and oscillation damping. In Europe there are few installation of SVC some of which have the additional feature of relocatability as in England. TCSC can provide the dynamic stability and power flow control by regulating the series impedance which are also frequently used worldwide, whereas only one is installed in Europe at Sweden. STATCOM is voltage sourced controlled also already deployed to provide a fast control of voltage and reactive power and is very useful for wind power plants integration.

In planning the transmission system with FACTS devices, mostly optimally placement is preferred for transfer capability enhancement, minimizing the line losses, and reduce transmission congestion *etc.* The optimal placement are always considered to be theoretical due to the optimization algorithm limitations. The problem is formulated with respect to the specific problem in the area and the over all network is seldom explored. Subsequently, these studies are more specific and could not be utilized for the FACTS placement in whole network and therefore, limited to certain area or region. Although many references in literature, proposed the optimal parameters at either already specified locations (problem specific locations) or the locations based on the sensitivity factors (in network utilization). TSOs are required to explore the whole network based on the physical or electric aspects and identify suitable locations where FACTS devices could provide more benefits not only for the particular area and specific region but could contribute in the overall controllability of the network. Unfortunately, it is difficult to find any reference which focused on this aspects so far. The reason may be the cost and complexity of FACTS devices, which could not get the significant attention in large scale installation. But it is now become necessary to integrate FACTS devices for its interesting characteristics which could make the network more flexible and reliable in liberalized market.

The presented work is more emphasizing on the requirement of network planning by proposing a method that analyses the power network for identifying critical locations in terms of constraints violation, which are the main concern in enhancing the transfer capability of the network. Such critical locations are more suitable for FACTS placement because that would be always needed in resolving transmission congestion, which is more often expected to be happened nowadays. Besides the variety of FACTS devices like series, shunt and combination of both could provide the power flow and bus voltage control and stability improvement. The electric characteristic of lines in the network constitute the power distribution among the lines based on their impedance and the paths having less impedance are more likely to be overloaded and become critical, but could not be visible in current situation. Therefore, an algorithm is developed which identify the critical locations in terms of lines which would overloads and/or buses that suffered low voltages in increasing the power transfer between sources and sinks. Sensitivity indices are initially used for selecting the locations like PI for lines and $L-Index$ for buses. But the critical locations are further explored from these selected locations which violate 80% of the line capacity and those bus locations where the bus voltage limits are being violated due to increased load demands or less availability of reactive power, thus limiting the transfer capability. The electrical parameters of line impedance and shunt admittance are varied that mimic the FACTS devices features, are utilized for TTC enhancement. The set of locations are finalized both for series and shunt FACTS devices that have strong influence in TTC enhancement. Both overall system TTC as well as inter-area TTC are used to identify all possible critical locations expected for the respective topology of the network. IEEE test networks have been used for validation of significant TTC enhancement with corresponding locations for series and shunt FACTS devices.

The previous algorithm addressed the planning of FACTS devices in meshed transmission networks for increasing transfer capability. Each device has a significant influence area to its surrounding neighbourhood in the transmission network. The elements in the influential area of each FACTS device vary based on the type of device and its surrounding network topology. Such elements are found based on sensitivity analysis of the interconnections and electrical distances from the FACTS devices. Consequently there are some elements of the network which are influenced by multiple FACTS devices. Series FACTS devices have mostly influenced the flows of the lines connected in series or parallel, while shunt FACTS devices influenced mostly voltages of neighbouring buses in the area. Distributed coordinated control system DCCS is implemented which make use of agents in deciding the control actions for FACTS devices to control the power flow and voltage magnitudes of violating elements in the influential areas. The current state information are exchanged among the agents, which are carrying the measured values of respective data of bus voltages or line loadings *etc.*, based on which the control action are decided for each FACTS device. The control actions related to influential area of certain FACTS devices are decided based on the local information of the elements but in case of common influenced elements coordination is performed among several FACTS devices that influenced the elements. And the state information are exchanged through common elements. The summary of the control strategy adopted for network congestion due to high loaded lines or violating bus voltages are given as follows:

- The state information of the elements are updated in a regular interval, and exchanged among the agents of neighbouring elements.

- The control actions are decided according to the status and requirement of the elements in influential area of each FACTS devices.
- The mutual influences of FACTS devices on each other as well as on common elements according to the defined control actions are exchanged among the control agents.
- The control actions are modified with corresponding addition of mutual influences on the elements.
- The control actions are finalized due to the local elements requirement, mutual effects of influential FACTS devices along with the central control which may be required for across the border trade, to be adjusted by the TSO.
- The control priority for each FACTS device is based on the direct connected elements, the elements neighbours to direct connected elements and the last is the control objectives adjusted by the central control.

The series FACTS devices is a bit complex compared to shunt FACTS devices because shunt FACTS devices provide only improvement to the bus voltages in the area. And there will be no counter effect except some buses could get over voltage due to multiple FACTS devices compensation, but that is not the case because the controlling agents are regularly updated about the states and could stop if the respective voltages are improved to the required value. The series FACTS devices are updated with IncGroup and DecGroup groups of elements based on the connection and power flow over the lines, the control actions would be adjusted according to the power flow of respective element. If the controlling line belongs to the IncGroup of more than one series FACTS devices then the control will be straight forward as influencing FACTS devices could collaborate in controlling the power flow of the line. But if it belongs to different groups of the FACTS devices (IncGroup of one and DecGroup of other) then counter effect the control actions could be prohibit the reduction. The coordinated control will work in such situation and the control actions will be optimized for FACTS device based on the sensitivity factors. Thus the controlling right will be win by the FACTS device which is more sensitive and less contradicting. The coordinated control system, therefore is more complex and need extra data exchange. The situation would be more difficult if the coordinating devices are located in different control areas because it bring more complexity. Anyhow, there are several benefits that coordinated control system can provide.

- Coordinated control could protect the FACTS devices from overcompensation due to the mutual influences of neighbourhood.
- The counter productive control actions could be resolved by coordination among the FACTS devices in different control areas.
- The topology change caused due to major system disturbance, could be sensed by regular updating the elements states and adapted according to the coordinated control actions.

The multiple FACTS devices are going to be necessary in modern power grid, and the coordination control could reduce the mutual influential conflicts and increase the overall transmission capacity to avoid transmission congestion.

In current study the locations for FACTS devices are specified based on the critical situation of operating constraints while analysing the power networks in order to determine the power transfer capability of a network in iterative increase of power transfer between sources and sinks. The thermal line capacity and bus voltage stability are the two main concerned constraints in the algorithm development. The intrinsic power transfer capability of a network is determined that should securely facilitate the power exchange in different defined cases of supplier and consumer in the network. The identified critical locations are subjected to the variation of the candidate FACTS parameters which would help in determining the possible enhancement in the network capability by improving the respective constraint. Further the possible enhancement is foresighted with subjected size and type of FACTS device suited to provide the required improvement in the violating constraints. Consequently the network is furnished with multiple FACTS devices at specified different locations which could possibly interact with each other while controlling certain network parameter and may effect the control objective. Thus distributed coordinated control strategy is implemented for FACTS devices control. That have efficiently reduce the mutual contradicting effects in the influential area of each FACTS device while coordinating with neighbouring devices in multi agent system (MAS). All the concerned element are equipped with agents that exchanged the state information, based on which control agents have decided the control actions for FACTS devices. The coordinated actions of the FACTS devices enable the efficient network utilization, reacting to the current situation, thus relieving congestion with enhanced transmission capacity and improve system performance.

7.2 Directions for Future Extension

The transmission planning for expansion is a very complex and long term process which encircle the handling of several uncertainties and considering different risks, recent challenges and trends *etc.*, and it become more complex in liberalized market. Transmission system operators (TSOs) have to minimize the investment and operational costs in planning power network expansion for overcoming bottlenecks and achieving social welfare according to the regulation. Which would ensure the efficient and economical operation of the network, while considering the static and dynamic constraints. Generally, the transmission grid expansion is lagging behind the generation development due to the comparatively longer time taking of erecting new lines for transfer capability. The TSOs and other stakeholders handled the time gaps by devising different scenarios on market trends, system boundary conditions and make use of the experiences of grid planners and operators. The first stage of the transmission planning process is the analysis of the system reliability and security of the area under study. Then the cost and benefits of the candidate solutions of the transmission reinforcements/strategies are analyzed. In this study a generalized analysis method is proposed that could identify the critical locations in any power network, where FACTS devices could significantly enhance the transfer capability of the network and which will provide potential controlling features to network operators. So the method could not provide only the identification of the critical location in specific problem but also suggest some other locations in the network which should be equipped with respective FACTS devices to plan the network for future load growth.

The presented work shows in the planning of FACTS placement based on the analysis of the network with projected load growth which relieved the resulted stress by the increased demands and provide enhancement in transfer capability. The analysis is based only on the electric characteristics of the physical lines and the static constraints in normal and contingency cases are compared with the system without FACTS devices. But for practical installation further analysis of cost and benefits in the defined transmission planning process should also be done. In this study the analysis is limited to only three area division of each network, which seems to be not enough for large network like IEEE 300 bus system. For instance there should be some criteria (*e.g.*, number of buses *etc.*) based on which the area or zone could be defined that would help in analyzing the whole network for critical locations identification. In the results smaller networks are shown with quite significant improvements while for the large networks like IEEE 300 bus system the complete improvement is not achieved, one reason is the incompatibility of the load profiles for the network, as the profiles are not specifically related to it. Similarly the dynamic stability of the system with FACTS devices on proposed locations needs to be assessed, because in the presented study the main focus is on the static stability of the network either in the planning phase or in the operational phase.

In the operational phase of the presented work, network congestion scenarios based on the synthetic load profiles, are being resolved providing the respective improvement in the violating constraints along with coordination among the FACTS devices. So it need further study of including the communication delays and related issues, while resolving the congestion problem. And in the development of DCCS for FACTS devices coordination should be further extended to other controllers in order to explore their effects and collaborative control improvements in operation.

The planning phase analyzed the locations with sizes for FACTS devices in order to enhance transfer capability to the maximum possible value, it is important to note that the sizes would be over estimated so that further critical locations could be determined. The analytical method is suggested for TTC calculation in order to get more accurate results if the computation time is large along with computation burden. As the planning phase does not need faster computation which is requirement of operational phase but accuracy and multiple real time aspects are needed to identify the locations before practical implementation. Therefore, it may be suggested for the future studies that other respective features of practical network should be added which could give better picture in practical implementation. Similarly the actual implementable size calculation would be not only on the TTC enhancement but rather stability and security improvement should be added. And thus for better exploration the TTC should be calculated from from inter-area down to inter-node, which would support the liberalized energy market for multi-lateral transactions. The last requirement of today energy market is the integration of variable supply of RES, so in the operational phase variable generation scenarios are to be studied for the DCCS of FACTS devices to validate the flexibility and control ability of the network.

Appendix

.1 The relation of line power flow and bus power injection

The Power Transfer Distribution Factor PTDF [73] is defined as the ratio of the fraction of power flow on line l for a unit MW of power transaction between sending bus s and receiving bus r. Mathematically it can be describes as follows:

$$PTDF_{s,r,l} = \frac{\Delta f_l}{\Delta P_{s\ to\ r}}$$

The DC power flow is one of the simple and fast method to calculate the PTDF. To model the effect on bus phase angles for a transfer of P MW power from bus s to bus r can be done using the linear power flow equation as:

$$\Delta\theta = [X]\,\Delta P$$

where

$$\Delta P = \begin{bmatrix} 0 \\ \vdots \\ +P_s \\ -P_r \\ \vdots \\ 0 \end{bmatrix}$$

The phase angle changes are

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \\ \vdots \\ \\ \Delta\theta_n \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & & \\ & & & \\ \vdots & & \ddots & \\ & & & \\ X_{n1} & & & X_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ +P_s \\ -P_r \\ \vdots \\ 0 \end{bmatrix}$$

The phase angles change on bus i and j are given as

$$\Delta\theta_i = X_{is}P_s - X_{ir}P_r$$

$$\Delta\theta_j = X_{js}P_s - X_{jr}P_r$$

The change in flow on line l between bus i and bus j, is given as

$$\Delta f_l = \tfrac{1}{x_l}\left(\Delta\theta_i - \Delta\theta_j\right)$$

then

$$\Delta f_l = \tfrac{1}{x_l}\left(\left(X_{is}P_s - X_{ir}P_r\right) - \left(X_{js}P_s - X_{jr}P_r\right)\right)$$

$$\Delta f_l = \tfrac{1}{x_l}\left(X_{is}P_s - X_{ir}P_r - X_{js}P_s + X_{jr}P_r\right)$$

$$\Delta f_l = \tfrac{1}{x_l}\left(\left(X_{is} - X_{js}\right)P_s - \left(X_{ir} - X_{jr}\right)P_r\right)$$

$$\Delta f_l = S_{l,s}P_s - S_{l,r}P_r$$

Where

$$S_{m,n} = \tfrac{1}{x_l}\left(X_{m_s n} - X_{m_r n}\right)$$

The matrix which shows the relation of the power flow over the line m with the power injection on the bus n.

.2 Utilized IEEE Test System Data

IEEE 30 Bus Branch Data

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
1	1	2	0.02	0.06	0.03	130
2	1	3	0.05	0.19	0.02	130
3	2	4	0.06	0.17	0.02	65
4	3	4	0.01	0.04	0	130
5	2	5	0.05	0.2	0.02	130
6	2	6	0.06	0.18	0.02	65
7	4	6	0.01	0.04	0	90
8	5	7	0.05	0.12	0.01	70
9	6	7	0.03	0.08	0.01	130
10	6	8	0.01	0.04	0	65
11	6	9	0	0.21	0	65
12	6	10	0	0.56	0	32
13	9	11	0	0.21	0	65
14	9	10	0	0.11	0	65
15	4	12	0	0.26	0	65
16	12	13	0	0.14	0	65
17	12	14	0.12	0.26	0	32
18	12	15	0.07	0.13	0	32
19	12	16	0.09	0.2	0	32
20	14	15	0.22	0.2	0	16
21	16	17	0.08	0.19	0	16
22	15	18	0.11	0.22	0	16
23	18	19	0.06	0.13	0	16
24	19	20	0.03	0.07	0	32
25	10	20	0.09	0.21	0	32
26	10	17	0.03	0.08	0	32
27	10	21	0.03	0.07	0	32
28	10	22	0.07	0.15	0	32
29	21	22	0.01	0.02	0	65
30	15	23	0.1	0.2	0	32
31	22	24	0.12	0.18	0	16
32	23	24	0.13	0.27	0	16
33	24	25	0.19	0.33	0	16
34	25	26	0.25	0.38	0	16
35	25	27	0.11	0.21	0	32
36	28	27	0	0.4	0	65
37	27	29	0.22	0.42	0	16
38	27	30	0.32	0.6	0	16
39	29	30	0.24	0.45	0	16
40	8	28	0.06	0.2	0.02	32
41	6	28	0.02	0.06	0.01	32

IEEE 39 Bus Branch Data

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
1	1	2	0.0035	0.0411	0.6987	600
2	1	39	0.001	0.025	0.75	1000
3	2	3	0.0013	0.0151	0.2572	500
4	2	25	0.007	0.0086	0.146	500
5	2	30	0	0.0181	0	900
6	3	4	0.0013	0.0213	0.2214	500
7	3	18	0.0011	0.0133	0.2138	500
8	4	5	0.0008	0.0128	0.1342	600
9	4	14	0.0008	0.0129	0.1382	500
10	5	6	0.0002	0.0026	0.0434	1200
11	5	8	0.0008	0.0112	0.1476	900
12	6	7	0.0006	0.0092	0.113	900
13	6	11	0.0007	0.0082	0.1389	480
14	6	31	0	0.025	0	1800
15	7	8	0.0004	0.0046	0.078	900
16	8	9	0.0023	0.0363	0.3804	900
17	9	39	0.001	0.025	1.2	900
18	10	11	0.0004	0.0043	0.0729	600
19	10	13	0.0004	0.0043	0.0729	600
20	10	32	0	0.02	0	900
21	12	11	0.0016	0.0435	0	500
22	12	13	0.0016	0.0435	0	500
23	13	14	0.0009	0.0101	0.1723	600
24	14	15	0.0018	0.0217	0.366	600
25	15	16	0.0009	0.0094	0.171	600
26	16	17	0.0007	0.0089	0.1342	600
27	16	19	0.0016	0.0195	0.304	600
28	16	21	0.0008	0.0135	0.2548	600
29	16	24	0.0003	0.0059	0.068	600
30	17	18	0.0007	0.0082	0.1319	600
31	17	27	0.0013	0.0173	0.3216	600
32	19	20	0.0007	0.0138	0	900
33	19	33	0.0007	0.0142	0	900
34	20	34	0.0009	0.018	0	900
35	21	22	0.0008	0.014	0.2565	900
36	22	23	0.0006	0.0096	0.1846	600
37	22	35	0	0.0143	0	900
38	23	24	0.0022	0.035	0.361	600
39	23	36	0.0005	0.0272	0	900
40	25	26	0.0032	0.0323	0.531	600
41	25	37	0.0006	0.0232	0	900
42	26	27	0.0014	0.0147	0.2396	600
43	26	28	0.0043	0.0474	0.7802	600
44	26	29	0.0057	0.0625	1.029	600
45	28	29	0.0014	0.0151	0.249	600
46	29	38	0.0008	0.0156	0	1200

IEEE 57 Bus Branch Data

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
1	1	2	0.0083	0.028	0.129	250
2	2	3	0.0298	0.085	0.0818	250
3	3	4	0.0112	0.0366	0.038	250
4	4	5	0.0625	0.132	0.0258	250
5	4	6	0.043	0.148	0.0348	250
6	6	7	0.02	0.102	0.0276	250
7	6	8	0.0339	0.173	0.047	250
8	8	9	0.0099	0.0505	0.0548	250
9	9	10	0.0369	0.1679	0.044	250
10	9	11	0.0258	0.0848	0.0218	250
11	9	12	0.0648	0.295	0.0772	250
12	9	13	0.0481	0.158	0.0406	250
13	13	14	0.0132	0.0434	0.011	250
14	13	15	0.0269	0.0869	0.023	250
15	1	15	0.0178	0.091	0.0988	250
16	1	16	0.0454	0.206	0.0546	250
17	1	17	0.0238	0.108	0.0286	250
18	3	15	0.0162	0.053	0.0544	250
19	4	18	0	0.555	0	250
20	4	18	0	0.43	0	250
21	5	6	0.0302	0.0641	0.0124	250
22	7	8	0.0139	0.0712	0.0194	250
23	10	12	0.0277	0.1262	0.0328	250
24	11	13	0.0223	0.0732	0.0188	250
25	12	13	0.0178	0.058	0.0604	250
26	12	16	0.018	0.0813	0.0216	250
27	12	17	0.0397	0.179	0.0476	250
28	14	15	0.0171	0.0547	0.0148	250
29	18	19	0.461	0.685	0	250
30	19	20	0.283	0.434	0	250
31	21	20	0	0.7767	0	250
32	21	22	0.0736	0.117	0	250
33	22	23	0.0099	0.0152	0	250
34	23	24	0.166	0.256	0.0084	250
35	24	25	0	1.182	0	250
36	24	25	0	1.23	0	250
37	24	26	0	0.0473	0	250
38	26	27	0.165	0.254	0	250
39	27	28	0.0618	0.0954	0	250
40	28	29	0.0418	0.0587	0	250
41	7	29	0	0.0648	0	250
42	25	30	0.135	0.202	0	250
43	30	31	0.326	0.497	0	250
44	31	32	0.507	0.755	0	250
45	32	33	0.0392	0.036	0	250

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
46	34	32	0	0.953	0	250
47	34	35	0.052	0.078	0.0032	250
48	35	36	0.043	0.0537	0.0016	250
49	36	37	0.029	0.0366	0	250
50	37	38	0.0651	0.1009	0.002	250
51	37	39	0.0239	0.0379	0	250
52	36	40	0.03	0.0466	0	250
53	22	38	0.0192	0.0295	0	250
54	11	41	0	0.749	0	250
55	41	42	0.207	0.352	0	250
56	41	43	0	0.412	0	250
57	38	44	0.0289	0.0585	0.002	250
58	15	45	0	0.1042	0	250
59	14	46	0	0.0735	0	250
60	46	47	0.023	0.068	0.0032	250
61	47	48	0.0182	0.0233	0	250
62	48	49	0.0834	0.129	0.0048	250
63	49	50	0.0801	0.128	0	250
64	50	51	0.1386	0.22	0	250
65	10	51	0	0.0712	0	250
66	13	49	0	0.191	0	250
67	29	52	0.1442	0.187	0	250
68	52	53	0.0762	0.0984	0	250
69	53	54	0.1878	0.232	0	250
70	54	55	0.1732	0.2265	0	250
71	11	43	0	0.153	0	250
72	44	45	0.0624	0.1242	0.004	250
73	40	56	0	1.195	0	250
74	56	41	0.553	0.549	0	250
75	56	42	0.2125	0.354	0	250
76	39	57	0	1.355	0	250
77	57	56	0.174	0.26	0	250
78	38	49	0.115	0.177	0.003	250
79	38	48	0.0312	0.0482	0	250
80	9	55	0	0.1205	0	250

IEEE 118 Bus Branch Data

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
1	1	2	0.0303	0.0999	0.0254	1000
2	1	3	0.0129	0.0424	0.01082	1000
3	4	5	0.00176	0.00798	0.0021	1000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
4	3	5	0.0241	0.108	0.0284	1000
5	5	6	0.0119	0.054	0.01426	1000
6	6	7	0.00459	0.0208	0.0055	1000
7	8	9	0.00244	0.0305	1.162	1000
8	8	5	0	0.0267	0	1000
9	9	10	0.00258	0.0322	1.23	1000
10	4	11	0.0209	0.0688	0.01748	1000
11	5	11	0.0203	0.0682	0.01738	1000
12	11	12	0.00595	0.0196	0.00502	1000
13	2	12	0.0187	0.0616	0.01572	1000
14	3	12	0.0484	0.16	0.0406	1000
15	7	12	0.00862	0.034	0.00874	1000
16	11	13	0.02225	0.0731	0.01876	1000
17	12	14	0.0215	0.0707	0.01816	1000
18	13	15	0.0744	0.2444	0.06268	1000
19	14	15	0.0595	0.195	0.0502	1000
20	12	16	0.0212	0.0834	0.0214	1000
21	15	17	0.0132	0.0437	0.0444	1000
22	16	17	0.0454	0.1801	0.0466	1000
23	17	18	0.0123	0.0505	0.01298	1000
24	18	19	0.01119	0.0493	0.01142	1000
25	19	20	0.0252	0.117	0.0298	1000
26	15	19	0.012	0.0394	0.0101	1000
27	20	21	0.0183	0.0849	0.0216	1000
28	21	22	0.0209	0.097	0.0246	1000
29	22	23	0.0342	0.159	0.0404	1000
30	23	24	0.0135	0.0492	0.0498	1000
31	23	25	0.0156	0.08	0.0864	1000
32	26	25	0	0.0382	0	1000
33	25	27	0.0318	0.163	0.1764	1000
34	27	28	0.01913	0.0855	0.0216	1000
35	28	29	0.0237	0.0943	0.0238	1000
36	30	17	0	0.0388	0	1000
37	8	30	0.00431	0.0504	0.514	1000
38	26	30	0.00799	0.086	0.908	1000
39	17	31	0.0474	0.1563	0.0399	1000
40	29	31	0.0108	0.0331	0.0083	1000
41	23	32	0.0317	0.1153	0.1173	1000
42	31	32	0.0298	0.0985	0.0251	1000
43	27	32	0.0229	0.0755	0.01926	1000
44	15	33	0.038	0.1244	0.03194	1000
45	19	34	0.0752	0.247	0.0632	1000
46	35	36	0.00224	0.0102	0.00268	1000
47	35	37	0.011	0.0497	0.01318	1000
48	33	37	0.0415	0.142	0.0366	1000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
49	34	36	0.00871	0.0268	0.00568	1000
50	34	37	0.00256	0.0094	0.00984	1000
51	38	37	0	0.0375	0	1000
52	37	39	0.0321	0.106	0.027	1000
53	37	40	0.0593	0.168	0.042	1000
54	30	38	0.00464	0.054	0.422	1000
55	39	40	0.0184	0.0605	0.01552	1000
56	40	41	0.0145	0.0487	0.01222	1000
57	40	42	0.0555	0.183	0.0466	1000
58	41	42	0.041	0.135	0.0344	1000
59	43	44	0.0608	0.2454	0.06068	1000
60	34	43	0.0413	0.1681	0.04226	1000
61	44	45	0.0224	0.0901	0.0224	1000
62	45	46	0.04	0.1356	0.0332	1000
63	46	47	0.038	0.127	0.0316	1000
64	46	48	0.0601	0.189	0.0472	1000
65	47	49	0.0191	0.0625	0.01604	1000
66	42	49	0.0715	0.323	0.086	1000
67	42	49	0.0715	0.323	0.086	1000
68	45	49	0.0684	0.186	0.0444	1000
69	48	49	0.0179	0.0505	0.01258	1000
70	49	50	0.0267	0.0752	0.01874	1000
71	49	51	0.0486	0.137	0.0342	1000
72	51	52	0.0203	0.0588	0.01396	1000
73	52	53	0.0405	0.1635	0.04058	1000
74	53	54	0.0263	0.122	0.031	1000
75	49	54	0.073	0.289	0.0738	1000
76	49	54	0.0869	0.291	0.073	1000
77	54	55	0.0169	0.0707	0.0202	1000
78	54	56	0.00275	0.00955	0.00732	1000
79	55	56	0.00488	0.0151	0.00374	1000
80	56	57	0.0343	0.0966	0.0242	1000
81	50	57	0.0474	0.134	0.0332	1000
82	56	58	0.0343	0.0966	0.0242	1000
83	51	58	0.0255	0.0719	0.01788	1000
84	54	59	0.0503	0.2293	0.0598	1000
85	56	59	0.0825	0.251	0.0569	1000
86	56	59	0.0803	0.239	0.0536	1000
87	55	59	0.04739	0.2158	0.05646	1000
88	59	60	0.0317	0.145	0.0376	1000
89	59	61	0.0328	0.15	0.0388	1000
90	60	61	0.00264	0.0135	0.01456	1000
91	60	62	0.0123	0.0561	0.01468	1000
92	61	62	0.00824	0.0376	0.0098	1000
93	63	59	0	0.0386	0	1000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
94	63	64	0.00172	0.02	0.216	1000
95	64	61	0	0.0268	0	1000
96	38	65	0.00901	0.0986	1,046	1000
97	64	65	0.00269	0.0302	0.38	1000
98	49	66	0.018	0.0919	0.0248	1000
99	49	66	0.018	0.0919	0.0248	1000
100	62	66	0.0482	0.218	0.0578	1000
101	62	67	0.0258	0.117	0.031	1000
102	65	66	0	0.037	0	1000
103	66	67	0.0224	0.1015	0.02682	1000
104	65	68	0.00138	0.016	0.638	1000
105	47	69	0.0844	0.2778	0.07092	1000
106	49	69	0.0985	0.324	0.0828	1000
107	68	69	0	0.037	0	1000
108	69	70	0.03	0.127	0.122	1000
109	24	70	0.00221	0.4115	0.10198	1000
110	70	71	0.00882	0.0355	0.00878	1000
111	24	72	0.0488	0.196	0.0488	1000
112	71	72	0.0446	0.18	0.04444	1000
113	71	73	0.00866	0.0454	0.01178	1000
114	70	74	0.0401	0.1323	0.03368	1000
115	70	75	0.0428	0.141	0.036	1000
116	69	75	0.0405	0.122	0.124	1000
117	74	75	0.0123	0.0406	0.01034	1000
118	76	77	0.0444	0.148	0.0368	1000
119	69	77	0.0309	0.101	0.1038	1000
120	75	77	0.0601	0.1999	0.04978	1000
121	77	78	0.00376	0.0124	0.01264	1000
122	78	79	0.00546	0.0244	0.00648	1000
123	77	80	0.017	0.0485	0.0472	1000
124	77	80	0.0294	0.105	0.0228	1000
125	79	80	0.0156	0.0704	0.0187	1000
126	68	81	0.00175	0.0202	0.808	1000
127	81	80	0	0.037	0	1000
128	77	82	0.0298	0.0853	0.08174	1000
129	82	83	0.0112	0.03665	0.03796	1000
130	83	84	0.0625	0.132	0.0258	1000
131	83	85	0.043	0.148	0.0348	1000
132	84	85	0.0302	0.0641	0.01234	1000
133	85	86	0.035	0.123	0.0276	1000
134	86	87	0.02828	0.2074	0.0445	1000
135	85	88	0.02	0.102	0.0276	1000
136	85	89	0.0239	0.173	0.047	1000
137	88	89	0.0139	0.0712	0.01934	1000
138	89	90	0.0518	0.188	0.0528	1000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
139	89	90	0.0238	0.0997	0.106	1000
140	90	91	0.0254	0.0836	0.0214	1000
141	89	92	0.0099	0.0505	0.0548	1000
142	89	92	0.0393	0.1581	0.0414	1000
143	91	92	0.0387	0.1272	0.03268	1000
144	92	93	0.0258	0.0848	0.0218	1000
145	92	94	0.0481	0.158	0.0406	1000
146	93	94	0.0223	0.0732	0.01876	1000
147	94	95	0.0132	0.0434	0.0111	1000
148	80	96	0.0356	0.182	0.0494	1000
149	82	96	0.0162	0.053	0.0544	1000
150	94	96	0.0269	0.0869	0.023	1000
151	80	97	0.0183	0.0934	0.0254	1000
152	80	98	0.0238	0.108	0.0286	1000
153	80	99	0.0454	0.206	0.0546	1000
154	92	100	0.0648	0.295	0.0472	1000
155	94	100	0.0178	0.058	0.0604	1000
156	95	96	0.0171	0.0547	0.01474	1000
157	96	97	0.0173	0.0885	0.024	1000
158	98	100	0.0397	0.179	0.0476	1000
159	99	100	0.018	0.0813	0.0216	1000
160	100	101	0.0277	0.1262	0.0328	1000
161	92	102	0.0123	0.0559	0.01464	1000
162	101	102	0.0246	0.112	0.0294	1000
163	100	103	0.016	0.0525	0.0536	1000
164	100	104	0.0451	0.204	0.0541	1000
165	103	104	0.0466	0.1584	0.0407	1000
166	103	105	0.0535	0.1625	0.0408	1000
167	100	106	0.0605	0.229	0.062	1000
168	104	105	0.00994	0.0378	0.00986	1000
169	105	106	0.014	0.0547	0.01434	1000
170	105	107	0.053	0.183	0.0472	1000
171	105	108	0.0261	0.0703	0.01844	1000
172	106	107	0.053	0.183	0.0472	1000
173	108	109	0.0105	0.0288	0.0076	1000
174	103	110	0.03906	0.1813	0.0461	1000
175	109	110	0.0278	0.0762	0.0202	1000
176	110	111	0.022	0.0755	0.02	1000
177	110	112	0.0247	0.064	0.062	1000
178	17	113	0.00913	0.0301	0.00768	1000
179	32	113	0.0615	0.203	0.0518	1000
180	32	114	0.0135	0.0612	0.01628	1000
181	27	115	0.0164	0.0741	0.01972	1000
182	114	115	0.0023	0.0104	0.00276	1000
183	68	116	0.00034	0.00405	0.164	1000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
184	12	117	0.0329	0.14	0.0358	1000
185	75	118	0.0145	0.0481	0.01198	1000
186	76	118	0.0164	0.0544	0.01356	1000

IEEE 300 Bus Branch Data

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
1	37	9001	6.00E-05	0.00046	0	2000
2	9001	9005	0.0008	0.00348	0	2000
3	9001	9006	0.02439	0.43682	0	2000
4	9001	9012	0.03624	0.64898	0	2000
5	9005	9051	0.01578	0.37486	0	2000
6	9005	9052	0.01578	0.37486	0	2000
7	9005	9053	0.01602	0.38046	0	2000
8	9005	9054	0	0.152	0	2000
9	9005	9055	0	0.8	0	2000
10	9006	9007	0.05558	0.24666	0	2000
11	9006	9003	0.11118	0.49332	0	2000
12	9006	9003	0.11118	0.49332	0	2000
13	9012	9002	0.07622	0.43286	0	2000
14	9012	9002	0.07622	0.43286	0	2000
15	9002	9021	0.0537	0.07026	0	2000
16	9021	9023	11,068	0.95278	0	2000
17	9021	9022	0.44364	28,152	0	2000
18	9002	9024	0.50748	32,202	0	2000
19	9023	9025	0.66688	3,944	0	2000
20	9023	9026	0.6113	36,152	0	2000
21	9007	9071	0.4412	29,668	0	2000
22	9007	9072	0.30792	2,057	0	2000
23	9007	9003	0.0558	0.24666	0	2000
24	9003	9031	0.73633	46,724	0	2000
25	9003	9032	0.76978	48,846	0	2000
26	9003	9033	0.75732	48,056	0	2000
27	9003	9044	0.07378	0.06352	0	2000
28	9044	9004	0.03832	0.02894	0	2000
29	9004	9041	0.36614	2,456	0	2000
30	9004	9042	10,593	54,536	0	2000
31	9004	9043	0.1567	16,994	0	2000
32	9003	9034	0.13006	13,912	0	2000
33	9003	9035	0.54484	34,572	0	2000
34	9003	9036	0.15426	16,729	0	2000
35	9003	9037	0.3849	25,712	0	2000
36	9003	9038	0.4412	29,668	0	2000
37	9012	9121	0.23552	0.99036	0	2000
38	9053	9533	0	0.75	0	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
39	1	5	0.001	0.006	0	2000
40	2	6	0.001	0.009	0	2000
41	2	8	0.006	0.027	0.054	2000
42	3	7	0	0.003	0	2000
43	3	19	0.008	0.069	0.139	2000
44	3	150	0.001	0.007	0	2000
45	4	16	0.002	0.019	1,127	2000
46	5	9	0.006	0.029	0.018	2000
47	7	12	0.001	0.009	0.07	2000
48	7	131	0.001	0.007	0.014	2000
49	8	11	0.013	0.0595	0.033	2000
50	8	14	0.013	0.042	0.081	2000
51	9	11	0.006	0.027	0.013	2000
52	11	13	0.008	0.034	0.018	2000
53	12	21	0.002	0.015	0.118	2000
54	13	20	0.006	0.034	0.016	2000
55	14	15	0.014	0.042	0.097	2000
56	15	37	0.065	0.248	0.121	2000
57	15	89	0.099	0.248	0.035	2000
58	15	90	0.096	0.363	0.048	2000
59	16	42	0.002	0.022	1.28	2000
60	19	21	0.002	0.018	0.036	2000
61	19	87	0.013	0.08	0.151	2000
62	20	22	0.016	0.033	0.015	2000
63	20	27	0.069	0.186	0.098	2000
64	21	24	0.004	0.034	0.28	2000
65	22	23	0.052	0.111	0.05	2000
66	23	25	0.019	0.039	0.018	2000
67	24	319	0.007	0.068	0.134	2000
68	25	26	0.036	0.071	0.034	2000
69	26	27	0.045	0.12	0.065	2000
70	26	320	0.043	0.13	0.014	2000
71	33	34	0	0.063	0	2000
72	33	38	0.0025	0.012	0.013	2000
73	33	40	0.006	0.029	0.02	2000
74	33	41	0.007	0.043	0.026	2000
75	34	42	0.001	0.008	0.042	2000
76	35	72	0.012	0.06	0.008	2000
77	35	76	0.006	0.014	0.002	2000
78	35	77	0.01	0.029	0.003	2000
79	36	88	0.004	0.027	0.043	2000
80	37	38	0.008	0.047	0.008	2000
81	37	40	0.022	0.064	0.007	2000
82	37	41	0.01	0.036	0.02	2000
83	37	49	0.017	0.081	0.048	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
84	37	89	0.102	0.254	0.033	2000
85	37	90	0.047	0.127	0.016	2000
86	38	41	0.008	0.037	0.02	2000
87	38	43	0.032	0.087	0.04	2000
88	39	42	0.0006	0.0064	0.404	2000
89	40	48	0.026	0.154	0.022	2000
90	41	42	0	0.029	0	2000
91	41	49	0.065	0.191	0.02	2000
92	41	51	0.031	0.089	0.036	2000
93	42	46	0.002	0.014	0.806	2000
94	43	44	0.026	0.072	0.035	2000
95	43	48	0.095	0.262	0.032	2000
96	43	53	0.013	0.039	0.016	2000
97	44	47	0.027	0.084	0.039	2000
98	44	54	0.028	0.084	0.037	2000
99	45	60	0.007	0.041	0.312	2000
100	45	74	0.009	0.054	0.411	2000
101	46	81	0.005	0.042	0.69	2000
102	47	73	0.052	0.145	0.073	2000
103	47	113	0.043	0.118	0.013	2000
104	48	107	0.025	0.062	0.007	2000
105	49	51	0.031	0.094	0.043	2000
106	51	52	0.037	0.109	0.049	2000
107	52	55	0.027	0.08	0.036	2000
108	53	54	0.025	0.073	0.035	2000
109	54	55	0.035	0.103	0.047	2000
110	55	57	0.065	0.169	0.082	2000
111	57	58	0.046	0.08	0.036	2000
112	57	63	0.159	0.537	0.071	2000
113	58	59	0.009	0.026	0.005	2000
114	59	61	0.002	0.013	0.015	2000
115	60	62	0.009	0.065	0.485	2000
116	62	64	0.016	0.105	0.203	2000
117	62	144	0.001	0.007	0.013	2000
118	63	526	0.0265	0.172	0.026	2000
119	69	211	0.051	0.232	0.028	2000
120	69	79	0.051	0.157	0.023	2000
121	70	71	0.032	0.1	0.062	2000
122	70	528	0.02	0.1234	0.028	2000
123	71	72	0.036	0.131	0.068	2000
124	71	73	0.034	0.099	0.047	2000
125	72	77	0.018	0.087	0.011	2000
126	72	531	0.0256	0.193	0	2000
127	73	76	0.021	0.057	0.03	2000
128	73	79	0.018	0.052	0.018	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
129	74	88	0.004	0.027	0.05	2000
130	74	562	0.0286	0.2013	0.379	2000
131	76	77	0.016	0.043	0.004	2000
132	77	78	0.001	0.006	0.007	2000
133	77	80	0.014	0.07	0.038	2000
134	77	552	0.0891	0.2676	0.029	2000
135	77	609	0.0782	0.2127	0.022	2000
136	78	79	0.006	0.022	0.011	2000
137	78	84	0	0.036	0	2000
138	79	211	0.099	0.375	0.051	2000
139	80	211	0.022	0.107	0.058	2000
140	81	194	0.0035	0.033	0.53	2000
141	81	195	0.0035	0.033	0.53	2000
142	85	86	0.008	0.064	0.128	2000
143	86	87	0.012	0.093	0.183	2000
144	86	323	0.006	0.048	0.092	2000
145	89	91	0.047	0.119	0.014	2000
146	90	92	0.032	0.174	0.024	2000
147	91	94	0.1	0.253	0.031	2000
148	91	97	0.022	0.077	0.039	2000
149	92	103	0.019	0.144	0.017	2000
150	92	105	0.017	0.092	0.012	2000
151	94	97	0.278	0.427	0.043	2000
152	97	100	0.022	0.053	0.007	2000
153	97	102	0.038	0.092	0.012	2000
154	97	103	0.048	0.122	0.015	2000
155	98	100	0.024	0.064	0.007	2000
156	98	102	0.034	0.121	0.015	2000
157	99	107	0.053	0.135	0.017	2000
158	99	108	0.002	0.004	0.002	2000
159	99	109	0.045	0.354	0.044	2000
160	99	110	0.05	0.174	0.022	2000
161	100	102	0.016	0.038	0.004	2000
162	102	104	0.043	0.064	0.027	2000
163	103	105	0.019	0.062	0.008	2000
164	104	108	0.076	0.13	0.044	2000
165	104	322	0.044	0.124	0.015	2000
166	105	107	0.012	0.088	0.011	2000
167	105	110	0.157	0.4	0.047	2000
168	108	324	0.074	0.208	0.026	2000
169	109	110	0.07	0.184	0.021	2000
170	109	113	0.1	0.274	0.031	2000
171	109	114	0.109	0.393	0.036	2000
172	110	112	0.142	0.404	0.05	2000
173	112	114	0.017	0.042	0.006	2000
174	115	122	0.0036	0.0199	0.004	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
175	116	120	0.002	0.1049	0.001	2000
176	117	118	0.0001	0.0018	0.017	2000
177	118	119	0	0.0271	0	2000
178	118	1201	0	0.6163	0	2000
179	1201	120	0	-0.3697	0	2000
180	118	121	0.0022	0.2915	0	2000
181	119	120	0	0.0339	0	2000
182	119	121	0	0.0582	0	2000
183	122	123	0.0808	0.2344	0.029	2000
184	122	125	0.0965	0.3669	0.054	2000
185	123	124	0.036	0.1076	0.117	2000
186	123	125	0.0476	0.1414	0.149	2000
187	125	126	0.0006	0.0197	0	2000
188	126	127	0.0059	0.0405	0.25	2000
189	126	129	0.0115	0.1106	0.185	2000
190	126	132	0.0198	0.1688	0.321	2000
191	126	157	0.005	0.05	0.33	2000
192	126	158	0.0077	0.0538	0.335	2000
193	126	169	0.0165	0.1157	0.171	2000
194	127	128	0.0059	0.0577	0.095	2000
195	127	134	0.0049	0.0336	0.208	2000
196	127	168	0.0059	0.0577	0.095	2000
197	128	130	0.0078	0.0773	0.126	2000
198	128	133	0.0026	0.0193	0.03	2000
199	129	130	0.0076	0.0752	0.122	2000
200	129	133	0.0021	0.0186	0.03	2000
201	130	132	0.0016	0.0164	0.026	2000
202	130	151	0.0017	0.0165	0.026	2000
203	130	167	0.0079	0.0793	0.127	2000
204	130	168	0.0078	0.0784	0.125	2000
205	133	137	0.0017	0.0117	0.289	2000
206	133	168	0.0026	0.0193	0.03	2000
207	133	169	0.0021	0.0186	0.03	2000
208	133	171	0.0002	0.0101	0	2000
209	134	135	0.0043	0.0293	0.18	2000
210	134	184	0.0039	0.0381	0.258	2000
211	135	136	0.0091	0.0623	0.385	2000
212	136	137	0.0125	0.089	0.54	2000
213	136	152	0.0056	0.039	0.953	2000
214	137	140	0.0015	0.0114	0.284	2000
215	137	181	0.0005	0.0034	0.021	2000
216	137	186	0.0007	0.0151	0.126	2000
217	137	188	0.0005	0.0034	0.021	2000
218	139	172	0.0562	0.2248	0.081	2000
219	140	141	0.012	0.0836	0.123	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
220	140	142	0.0152	0.1132	0.684	2000
221	140	145	0.0468	0.3369	0.519	2000
222	140	146	0.043	0.3031	0.463	2000
223	140	147	0.0489	0.3492	0.538	2000
224	140	182	0.0013	0.0089	0.119	2000
225	141	146	0.0291	0.2267	0.342	2000
226	142	143	0.006	0.057	0.767	2000
227	143	145	0.0075	0.0773	0.119	2000
228	143	149	0.0127	0.0909	0.135	2000
229	145	146	0.0085	0.0588	0.087	2000
230	145	149	0.0218	0.1511	0.223	2000
231	146	147	0.0073	0.0504	0.074	2000
232	148	178	0.0523	0.1526	0.074	2000
233	148	179	0.1371	0.3919	0.076	2000
234	152	153	0.0137	0.0957	0.141	2000
235	153	161	0.0055	0.0288	0.19	2000
236	154	156	0.1746	0.3161	0.04	2000
237	154	183	0.0804	0.3054	0.045	2000
238	155	161	0.011	0.0568	0.388	2000
239	157	159	0.0008	0.0098	0.069	2000
240	158	159	0.0029	0.0285	0.19	2000
241	158	160	0.0066	0.0448	0.277	2000
242	162	164	0.0024	0.0326	0.236	2000
243	162	165	0.0018	0.0245	1,662	2000
244	163	164	0.0044	0.0514	3,597	2000
245	165	166	0.0002	0.0123	0	2000
246	167	169	0.0018	0.0178	0.029	2000
247	172	173	0.0669	0.4843	0.063	2000
248	172	174	0.0558	0.221	0.031	2000
249	173	174	0.0807	0.3331	0.049	2000
250	173	175	0.0739	0.3071	0.043	2000
251	173	176	0.1799	0.5017	0.069	2000
252	175	176	0.0904	0.3626	0.048	2000
253	175	179	0.077	0.3092	0.054	2000
254	176	177	0.0251	0.0829	0.047	2000
255	177	178	0.0222	0.0847	0.05	2000
256	178	179	0.0498	0.1855	0.029	2000
257	178	180	0.0061	0.029	0.084	2000
258	181	138	0.0004	0.0202	0	2000
259	181	187	0.0004	0.0083	0.115	2000
260	184	185	0.0025	0.0245	0.164	2000
261	186	188	0.0007	0.0086	0.115	2000
262	187	188	0.0007	0.0086	0.115	2000
263	188	138	0.0004	0.0202	0	2000
264	189	208	0.033	0.095	0	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
265	189	209	0.046	0.069	0	2000
266	190	231	0.0004	0.0022	6.2	2000
267	190	240	0	0.0275	0	2000
268	191	192	0.003	0.048	0	2000
269	192	225	0.002	0.009	0	2000
270	193	205	0.045	0.063	0	2000
271	193	208	0.048	0.127	0	2000
272	194	219	0.0031	0.0286	0.5	2000
273	194	664	0.0024	0.0355	0.36	2000
274	195	219	0.0031	0.0286	0.5	2000
275	196	197	0.014	0.04	0.004	2000
276	196	210	0.03	0.081	0.01	2000
277	197	198	0.01	0.06	0.009	2000
278	197	211	0.015	0.04	0.006	2000
279	198	202	0.332	0.688	0	2000
280	198	203	0.009	0.046	0.025	2000
281	198	210	0.02	0.073	0.008	2000
282	198	211	0.034	0.109	0.032	2000
283	199	200	0.076	0.135	0.009	2000
284	199	210	0.04	0.102	0.005	2000
285	200	210	0.081	0.128	0.014	2000
286	201	204	0.124	0.183	0	2000
287	203	211	0.01	0.059	0.008	2000
288	204	205	0.046	0.068	0	2000
289	205	206	0.302	0.446	0	2000
290	206	207	0.073	0.093	0	2000
291	206	208	0.24	0.421	0	2000
292	212	215	0.0139	0.0778	0.086	2000
293	213	214	0.0025	0.038	0	2000
294	214	215	0.0017	0.0185	0.02	2000
295	214	242	0.0015	0.0108	0.002	2000
296	215	216	0.0045	0.0249	0.026	2000
297	216	217	0.004	0.0497	0.018	2000
298	217	218	0	0.0456	0	2000
299	217	219	0.0005	0.0177	0.02	2000
300	217	220	0.0027	0.0395	0.832	2000
301	219	237	0.0003	0.0018	5.2	2000
302	220	218	0.0037	0.0484	0.43	2000
303	220	221	0.001	0.0295	0.503	2000
304	220	238	0.0016	0.0046	0.402	2000
305	221	223	0.0003	0.0013	1	2000
306	222	237	0.0014	0.0514	0.33	2000
307	224	225	0.01	0.064	0.48	2000
308	224	226	0.0019	0.0081	0.86	2000
309	225	191	0.001	0.061	0	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
310	226	231	0.0005	0.0212	0	2000
311	227	231	0.0009	0.0472	0.186	2000
312	228	229	0.0019	0.0087	1.28	2000
313	228	231	0.0026	0.0917	0	2000
314	228	234	0.0013	0.0288	0.81	2000
315	229	190	0	0.0626	0	2000
316	231	232	0.0002	0.0069	1,364	2000
317	231	237	0.0001	0.0006	3.57	2000
318	232	233	0.0017	0.0485	0	2000
319	234	235	0.0002	0.0259	0.144	2000
320	234	237	0.0006	0.0272	0	2000
321	235	238	0.0002	0.0006	0.8	2000
322	241	237	0.0005	0.0154	0	2000
323	240	281	0.0003	0.0043	0.009	2000
324	242	245	0.0082	0.0851	0	2000
325	242	247	0.0112	0.0723	0	2000
326	243	244	0.0127	0.0355	0	2000
327	243	245	0.0326	0.1804	0	2000
328	244	246	0.0195	0.0551	0	2000
329	245	246	0.0157	0.0732	0	2000
330	245	247	0.036	0.2119	0	2000
331	246	247	0.0268	0.1285	0	2000
332	247	248	0.0428	0.1215	0	2000
333	248	249	0.0351	0.1004	0	2000
334	249	250	0.0616	0.1857	0	2000
335	3	1	0	0.052	0	2000
336	3	2	0	0.052	0	2000
337	3	4	0	0.005	0	2000
338	7	5	0	0.039	0	2000
339	7	6	0	0.039	0	2000
340	10	11	0	0.089	0	2000
341	12	10	0	0.053	0	2000
342	15	17	0.0194	0.0311	0	2000
343	16	15	0.001	0.038	0	2000
344	21	20	0	0.014	0	2000
345	24	23	0	0.064	0	2000
346	36	35	0	0.047	0	2000
347	45	44	0	0.02	0	2000
348	45	46	0	0.021	0	2000
349	62	61	0	0.059	0	2000
350	63	64	0	0.038	0	2000
351	73	74	0	0.0244	0	2000
352	81	88	0	0.02	0	2000
353	85	99	0	0.048	0	2000
354	86	102	0	0.048	0	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
355	87	94	0	0.046	0	2000
356	114	207	0	0.149	0	2000
357	116	124	0.0052	0.0174	0	2000
358	121	115	0	0.028	0	2000
359	122	157	0.0005	0.0195	0	2000
360	130	131	0	0.018	0	2000
361	130	150	0	0.014	0	2000
362	132	170	0.001	0.0402	0	2000
363	141	174	0.0024	0.0603	0	2000
364	142	175	0.0024	0.0498	-0.087	2000
365	143	144	0	0.0833	0	2000
366	143	148	0.0013	0.0371	0	2000
367	145	180	0.0005	0.0182	0	2000
368	151	170	0.001	0.0392	0	2000
369	153	183	0.0027	0.0639	0	2000
370	155	156	0.0008	0.0256	0	2000
371	159	117	0	0.016	0	2000
372	160	124	0.0012	0.0396	0	2000
373	163	137	0.0013	0.0384	-0.057	2000
374	164	155	0.0009	0.0231	-0.033	2000
375	182	139	0.0003	0.0131	0	2000
376	189	210	0	0.252	0	2000
377	193	196	0	0.237	0	2000
378	195	212	0.0008	0.0366	0	2000
379	200	248	0	0.22	0	2000
380	201	69	0	0.098	0	2000
381	202	211	0	0.128	0	2000
382	204	2040	0.02	0.204	-0.012	2000
383	209	198	0.026	0.211	0	2000
384	211	212	0.003	0.0122	0	2000
385	218	219	0.001	0.0354	-0.01	2000
386	223	224	0.0012	0.0195	-0.364	2000
387	229	230	0.001	0.0332	0	2000
388	234	236	0.0005	0.016	0	2000
389	238	239	0.0005	0.016	0	2000
390	196	2040	0.0001	0.02	0	2000
391	119	1190	0.001	0.023	0	2000
392	120	1200	0	0.023	0	2000
393	7002	2	0.001	0.0146	0	2000
394	7003	3	0	0.01054	0	2000
395	7061	61	0	0.0238	0	2000
396	7062	62	0	0.03214	0	2000
397	7166	166	0	0.0154	0	2000
398	7024	24	0	0.0289	0	2000
399	7001	1	0	0.01953	0	2000
400	7130	130	0	0.0193	0	2000

continue...

Line No.	Sn. Bus	Rc. Bus	r (p.u.)	x (p.u.)	b (p.u.)	P (MVA)
401	7011	11	0	0.01923	0	2000
402	7023	23	0	0.023	0	2000
403	7049	49	0	0.0124	0	2000
404	7139	139	0	0.0167	0	2000
405	7012	12	0	0.0312	0	2000
406	7017	17	0	0.01654	0	2000
407	7039	39	0	0.03159	0	2000
408	7057	57	0	0.05347	0	2000
409	7044	44	0	0.18181	0	2000
410	7055	55	0	0.19607	0	2000
411	7071	71	0	0.06896	0	2000

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Curriculum Vitae

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Education

Since 2014	Doctoral student at Faculty of Electrical Engineering and Information Technology, Technische Universität Wien, Vienna, Austria, supervised by Prof. Wolfgang Gawlik.
2006 – 2009	M.Sc. (Eng.) Electrical Engineering COMSATS Institute of Information Technology Abbottabad.
2000 – 2004	B.E. Electrical Engineering at University of Engineering and Technology, Peshawar, Pakistan.

Professional History

Since 2013	PhD Student at Complex Energy Systems, Energy Department, Austrian Institute of Technology GmbH, Vienna, Austria.
2009 – 2013	Lecturer at Department of Electrical Engineering, COMSATS Institute of Information Technology (CIIT) , Abbottabad, Pakistan.
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2005	Electrical Engineer in CRWON Engineering Works Lahore, Pakistan.
2004	Internee Telephone Industries of Pakistan, Haripur, Pakistan.

Journal Articles

- U.Ikram, W. Gawlik, and P. Palensky,"Analysis of Power Network for Line Reactance Variation to Improve Total Transmission Capacity" Special Issue Electric Power Systems Research 2017. *Energies*, Energies 2016, 9(11), 936; doi: 10.3390/ en9110936, 10 November 2016.
- H. Ali, U. Ikram, M. Irfan, M. Shahzad, M. Aftab, "Genetic Algorithm Based PID tuning for Controlling Paraplegic Humanoid Walking Movement," in *International Journal of Computer Science Issues*, vol. 9, no. , pp. 275–285, 2012.
- L. Khan, U.Ikram, T. Saeed, K.L. Lo, 1,"Virtual Bees Algorithm Based Design of Damping Control System for TCSC" *Australian Journal of Basic and Applied Sciences*, Issues,: 1-18 pp, 2010, ISSN 1991-8178.
- L. Khan, U.Ikram, T. Saeed, K.L. Lo,"Hierarchical VBA based TCSC Robust damping control system design" *Australian Journal of Basic and Applied Sciences*, Issues,: 4132-4148 pp, 2009, ISSN 1991-8178.

Engineering Tools and Programming Skills

- MATLAB (Command line, Simulink)
- DIgSILENT PowerFactory (Comprehensive Power Systems Simulation package)
- Power System Analysis Tool (PSAT)
- Programming Languages (Python, Assembly, Visual BASIC)
- Programmable Logic Controllers (PLC) programming (Siemens and LG PLCs)
- National Instruments Multisim (Electronic Circuit simulation package)

Achievements

- Secured scholarship to pursue PhD studies from Vienna University of Technology, Austria.
- Conducted 3 days Professional Development Workshop on "PLC and SCADA Development", organized by EE deptt: COMSATS Abbottabad under Pakistan Engineering Council.
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- Student Member Institute of Electrical and Electronics Engineers (IEEE), USA
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