OPTIMIZATION OF VAR RESOURCES FOR ENHANCEMENT OF GRID COMPATIBILITY OF DISTRIBUTION GENERATION

BY

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To my beloved parents and mentors

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In the name of Allah, the most Gracious and ever-Merciful. All praise is due to Allah; we praise Him, seek His help and ask for forgiveness. Peace be upon the Prophet Muhammad, his family, his companions and all those who follow him until the Day of Judgement.

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LIST OF ABBREVIATIONS

CHP	:	Combine Heat and Power
DFIG	:	Doubly Fed Induction Generator
DG	:	Distributed Generation
FACTS	:	Flexible AC Transmission System
GENCO	:	Generation Company
MILP	:	Mixed Integer Linear Programming
NDS	:	Non-Dominated Sorting
OLTC	:	Online Tap Changer
RPP	:	Reactive Power Planning
SVC	:	Static VAR Compensator
SVD	:	Singular Value Decomposition
TCPST	:	Thyristor Controlled Phase Shifting Transformer
TCSC	:	Thyristor Controlled Series Compensator
TCVR	:	Thyristor Controlled Voltage Regulator
TRANSCO	:	Transmission Company

ABSTRACT

Full Name	: Bilal Jehanzeb
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Power System has gone through much developmentboth in technology and infrastructure over the last 10 to 15 years. Today due to deregulation in the power system electricity is being treated as a commodity; as a result many investors are investing in the power system. This increased the penetration of distributed generation in the power system. For a DG to remain integrated with the grid it must meet some of the grid codes which are; frequency and bus voltage must remain within permissible limit and bus voltage must return within permissible range in 2sec or less. This means system stability is very important. One of the main reasons behind system instability is lack of proper reactive power support as it was in the case of 2003 blackout of NorthAmerica. So proper VAR planning needs to be done to improve voltage stability. There are many techniques and resources used to maintain the voltage of power system within limits e.g. Online Tap Changer (OLTC), shunt capacitors and FACTS devices. In this thesis reactive power planning (RPP) by optimal placement and sizing of reactive power resources that is FACTS in this case is to be done to improve system stability. Cost efficient reactive power planning using FACTS devices, to maximize loadability of the network and to improve voltage stability is done. Multi objective VAR planning will be done which will help system operator to select a proper reactive power plan for the system. In order to make sure DG fulfill the second grid code, RPP is done to improve voltage Recovery time at generator buses followed by a short duration fault. Differential Evolution algorithm is used for the optimal sizing and placement of FACTS devices. To illustrate this work IEEE standard systems are taken as test systems.

ملخص الرسالة

الاسم الكامل : بلال جهانزيب

عنوان الرسالة : التخطيط في كميه الطاقه الكهربائيه الغيرفعاله للحفاظ على مستوى معين للجهد الكهربائي لشبكه موصوله معمول داتا للطاقه الكهربائيه

التخصص : هندسةكهربائية

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في العقد الأخير كثير من التحسينات طرأت على نظام الطاقة الكهربائية في البنية التحتية او التكنولوجيا المستخدمة فيه. بناء على الانظمة المعمول بها هذة الايام بالامكان اعتبار الطاقة الكهربائية كسلعة; وبناء على ذلك قام العديد من المستثمرين بالاستثمار في مجال الطاقة الكهربائية. وهذا ادى الى عدم استقرار الجهد الكهربائي خلال عملية نقل الطاقة وتوزيعها. يجب الالتزام ببعض القوانين ليبقى مولد الطاقة متكاملا مع الشبكة الكهربائية, وهذة القوانين تتمثل في الآتي: التردد والجهد المنقول في الخط يجب ان لا يتعدى المدى المسموح به كذلك الجهد المنقول خلال الخط يجب ان يرجع خلال مدى لا تتعدى الثانيتين. وهذا يؤشر الى اهمية الحفاظ على ثبات الشبكة الكهربائية. احدى اهم العوامل المؤدية الى عدم ثبات الشبكة الكهربائية يتمثل في سوء التخطيط في مقدار القدرة الغير فعالة و التي تؤدي إلى انهيار نظام الطاقة كما حدث في امريكا في عام 2003 عندما تعطلت الشبكة بكاملها. لذلك يجب ان يكون هناك تخطيط جيد للتحسين من ثباتية الجهد الكهربائي خلال الشبكة الكهربائية. هناك العديد من التقنياتوالمصادر المستخدمة للحفاظ على الجهد من نظام الطاقة مثل التغيير المباشر ومكثف التوازي وأجهزة قياس التيار المتردد في خطوط النقل(FACTS devices).استخدام التخطيط الجيد في مقدار الطاقة الغير فعالة باستخدام أجهزة قياس التيار المتردد في خطوط النقل لزيادة الحمل الموجود على الشبكة او لتحسين استقرارية الجهد قد أنجز في هذه الأطروحة. وتم تحليل ايضا تأثير زيادة الحمل على استقرار النظام. تم عمل تخطيط للطاقة الغير فعالة لتطوير واستعادة وقت الجهد عند أماكن التوزيع متبوع مع فترة حدوث الخطأ.تم كذلك استخدام خوارزمية الفرق التفاضلية لتحديد الحجم المناسب لأجهزة قياس التيار المتردد في خطوط النقل الكهربائي وتحديد اين يتم وضع هذه الاأجهزة. ولتوضيح هذا العمل تم استخدام IEEEكنموذج لاختبار النظام.

CHAPTER 1

INTRODUCTION

Electric power system has gone through many evolutions over the last two decades. The integration of distributed generation and renewable sources into the network has changed the system dynamics and operational handling. Also due to the deregulation power system the concept of electricity market has been emerged, electricity is treated nowadays as a commodity; people buy and sell electricity in electricity market. Customers usually do not want any interruption in electricity supply. This can only be ensured if system is secure, reliable and stable. Therefore, several operational and technical issues and challenges arise regarding power system stability. Many researchers addressed system dynamics and stability through different approaches. Some issues regarding stability and security of the power system networks are discussed in this thesis and are stated below.

Power system stability is one of the major concerns in electric system. It can be classified as rotor angle stability, voltage stability and frequency stability. This thesis is concerned with VAR planning for improving voltage stability of the system. Different types of FACTS devices namely static VAR compensator (SVC), thyristor controlled series compensator(TCSC), thyristor controlled voltage regulator (TCVR) and Thyristor controlled phase shifting transformer (TCPST), will be optimally used to control voltage stability.

Another problem that power system is facing is transmission line overloading. Power consumption is increasing day-by-day, due to increase in population, advancement in technology and fast growing industrial development, this pushes the transmission network closer to its limit. TRANSCOs (transmission companies) operate the network at or near their maximum capabilities. This thesis will investigate the effect of VAR sources on the transmission line loadability and will optimally plan the placement and sizing of these VAR sources.

Due to deregulation in power sector, the penetration of distributed generation (DG) and renewable sources in the network is increasing steeply. But there are certain rules and codes that these DGs must follow which are; voltages and frequency must be within permissible limits and bus voltage must comeback within permissible limits in 2sec following a short duration fault. Failing to do so will cause disconnection of DG and ultimately causing problems for the network. This thesis will investigate the minimization of voltage recovery time at generator bus using VAR sources.

1.1 Motivation

In the last decade, various factors like deregulation, environmental and financial issues etc., forced electric power producers and system operators to fully utilize the transmission system capacities. But the problem of voltage instability and collapse is the constraint to achieve that goal. Voltage stability issue has become the primary concern surpassing rotor stability problem because of many factors: number of interconnections increased; new technology; long transmission lines; environmental concerns; increase in power consumption; and deregulation of electricity utilities. Today voltage instability issue has become one of the major research areas in power system field. Study has shown that many power collapse incidents occurred in the world were due to voltage instability [1], [2]. In metropolitan area of Tokyo (Japan) about 8-GW were lost due to voltage instability [3]. The reason for the 2003 blackout in North America was short-term voltage instability [4].

Many techniques are developed to deal with voltage instability problem and the attention has been given to this phenomenon by many industries and utilities. Many utilities included voltage stability analysis to be the part of their power system operation and planning. Most of the studies on stability analysis use power flow based simulations. Resources that are in common practice to mitigate this problem are Online Tap Changers (OLTC), shunt capacitors and FACTS devices.

Due to deregulation in electric power sector, many investors are spending in power generation. Small scaled local generation, using renewable energy or any other sources, near load centers (distributed generation) are encouraged over the recent years in many countries due to some economic and environmental reasons. The increase in penetration of distributed generation (DG) may cause reduction in transmission losses and better utilization of transmission lines but DGs are very responsive to network disturbance because of low inertia. This may cause operational and technical problems regarding stability of the system [5].

So the motivation of this work is to provide a better reactive power planning for system so that loss of millions of dollars, in case of blackouts, can be saved. Due to economic concerns system operators push system to maximum loading limits thus pushing system near to instability. So by doing efficient RPP loadability of the system can be increased. But system operators want to have a series of options (tradeoffs) between loadability and stability. Also due to competitive electricity market, the cost of VAR planning also matters. So multi objective VAR planning needs to be done. Also due to increasing penetrating of DG in the power system, the voltage recovery time which is one of the grid integration codes, needs to be investigated.

1.2 Objectives

This thesis attempts to address voltage stability in variety of ways to optimally size and locate VAR sources and application of operation indices to improve system response. The objectives of this work are as follows:

1. Optimal sizing and placement of VAR resources to maximize the transmission line loadability will be investigated.
2. L-index minimization to improve the voltage stability of the system using FACTS
3. Reactive power planning to minimize generator bus voltage recovery time after a short duration fault

1.3 Organization of Thesis

Chapter 2 is the detailed literature review, which covers basics of voltage stability and measurements done for the improvement of voltage stability and techniques and tools used for enhancement of voltage stability. Also, the issue of loadability and work done in this regard is discussed in detail. Reactive power planning (RPP) reported in literature for different sources and tools will be discussed in the chapter.

Chapter 3 is problem formulation and algorithms. Formulations for maximizing loadability, minimizing L-index and for improvement in voltage recovery time along with algorithms followed are presented.

Chapter 4 is the simulation results and discussion. In section 4.1, results of different scenarios to improve loadability are presented and discussed. Similarly, in section 4.2 results VAR planning to minimize L-index are discussed analytically. Section 4.3 presents the results for multiple objectives problem where loadability, cost of FACTS and L-index are taken simultaneously as an objective. Simulation results for improvement in voltage recovery are in the last section of the chapter.

Chapter 5 concludes the outcomes of this work and the contributions which can be added to this work in future.

Then there is a comprehensive list of reference and number of appendices at the end.

CHAPTER 2

LITERATURE REVIEW

Power system stability has been an issue of concern for the assurance of a reliable and secure power supply over the last few decades. Since then research has been undertaken about different types of instabilities and how they can lead a system to collapse [6]. IEEE and CIGRE joint task force has published definition and classification of power system stability [7]as shown in Figure2.1.

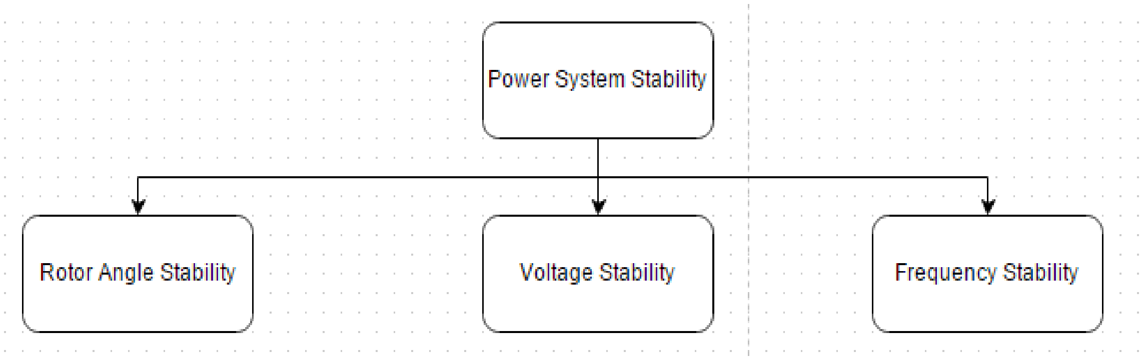

Figure 2.1 Power system stability classification

- Rotor angle stability is the ability of synchronous machine to stay synchronized in an interconnected power system when subjected to the disturbance.
- Voltage stability is the capability of power system to keep all the bus voltages within acceptable limits during both normal and post fault conditions.
- Frequency stability is the ability of the system to keep itself at a stable frequency following a sudden drop of load or generator outage.

This thesis is concerned with voltage stability. The literature review in the subsequent sections is devoted to voltage stability and means to mitigate this problem.

2.1 Voltage Stability

Voltage stability can be defined as the capability of power system to keep all the bus voltages within acceptable limits during both normal and post fault conditions[7]–[10]. In an electrical power system voltage instability is the result of continuous and uncontainable voltage decline due to a disturbance. These disturbances may be due to sudden change in load, line outages, generator outages or permutation of these events [10]. In last two decades, the major blackouts or the power interruptions all over the world were caused due to this voltage instability issue [8], [11], [12]. A serious economic loss was caused by this kind of incidents that is why voltage stability has been included in operation and planning of power systems.

Voltage stability can also be classified, on the bases of time frame of incident, as Static voltage stability and Dynamic voltage stability [13]–[16]. Unlike static voltage stability, exact mathematical modeling of motor, generator, load, transformer and reactive power sources are necessary for dynamic voltage stability analysis. Another classification can be done on the basis of large-disturbance voltage stability and small-signal voltage stability [7], [8]. In large disturbance, the differential equations of the system cannot be linearized and are solved by using numerical integration methods [15], [16]. While small-signal disturbance is handled by linearization of algebraic and differential equations around an operating point and modal analysis can be applied to analyze voltage stability as in [17].

Particularly single value decomposition (SVD) and modal techniques are of interest as illustrated by [8].

Some studies considered broad range of system conditions and contingencies in voltage stability analysis. In such cases, static analysis is much more effective and attractive because computationally it is much less intensive as compared to dynamic analysis. Also system dynamics are related to voltage stability are time-consuming [10]

2.2 Voltage Stability and Voltage Collapse Theory

Voltage collapse is defined as process which leads system voltage to a very low voltage point in a major part of power system[7]. There are many factors that cause voltage collapse [8]. Those are; sudden change in load, transmission line outage, generator outage, reactive power sources reaching their limits etc. These factors have a greater effect on production and transmission of reactive power. A concept of time scales is required. Time scales of variables vary from order of seconds like of SVCs to order of hours like of LTCs and load evolution.

Voltage drop is the major factor that causes voltage instability. Voltage drop occurs due to the flow of active and reactive power in the transmission lines, which restricts the power transfer and voltage support capabilities of transmission network [7]. Voltage stability also becomes endangered when reactive power sources reach their maximum capability limits due to the increase in reactive power demand. Usually major driving force behind voltage instability is loads. After the disturbance, restoration causes stress on already stressed network by increasing reactive power demand thus causing more voltage reduction.

Factors that affect voltage collapse are provided in the publication [18]. In Figure 2.2, load characteristics are shown which explain the phenomenon of voltage collapse. In normal conditions, system will be stable for both resistive as well as inductive loads. While in stressed condition, when reactance of the network is increased, system is stable for resistive loads only. For inductive loads, system is unstable.

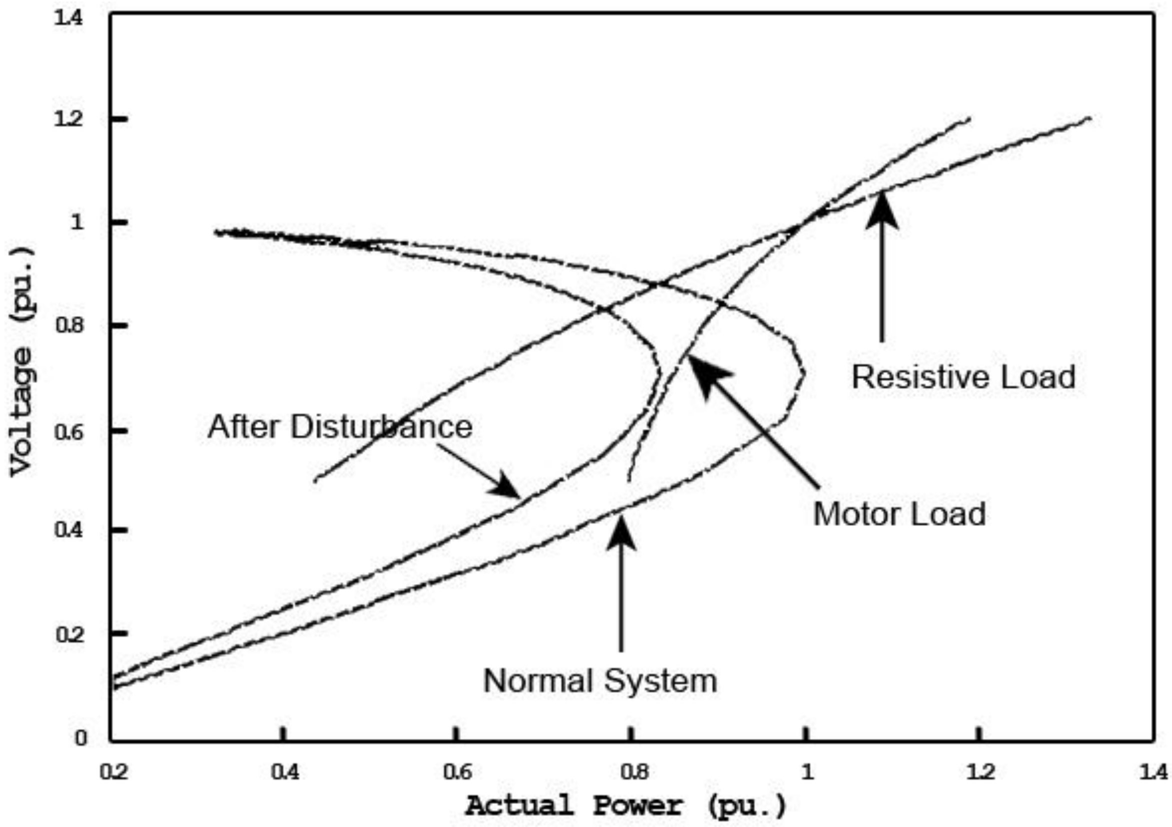

Figure 2.2 Stable and unstable system load characteristics

If voltage level drops to a level where motor stalls, reactive power demand suddenly increases, thus causing a further rapid drop in voltage level [19]–[21]. Under voltage relays installed in the network may operate in this condition and cut out heavy transmission lines causing interruption in supply for a large area. This massive load loss may cause large disturbance in the network and this may follow a voltage collapse if system is weak. Figure 2.3 shows a possible post disturbance voltage recovery behavior.

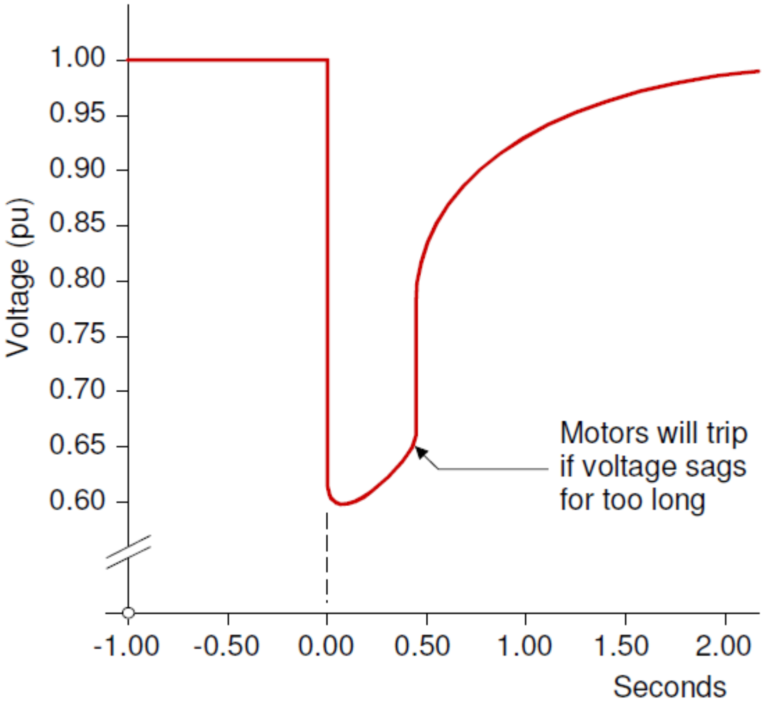

Figure 2.3 Typical voltage recovery curve after a disturbance

In [22] a number of cases of short-period voltage collapse incidents that occurred in the recent past are provided. And the reason in all the cases was unavailability of sufficient reactive power.

2.3 Voltage Control by VAR

Voltage, angle and impedance are the three variables that can be controlled directly and can make an impact on the performance of power system [23]. But the question arises that how to control these variables. There are a number of methods to maintain voltage stability. The use of under-voltage relays to shed load quickly (within one second) is an option but it may cause motor stalling[18], [22]. New transmission lines and transformer can be added to make system more secure and reliable but this approach is uneconomical. A lot of study has been done on minimizing the cost of reactive power planning for transmission network enhancement and reinforcement and to max benefits from them [24], [25].

Classification of VAR control devices is done into two:

a) Conventional devices
b) FACTS devices

I. Conventional devices
    - Series capacitors
    - Shunt capacitor
    - Online tap-changer transformers (OLTC)
    - Phase shifting transformer
    - Synchronous condenser

These equipments are also known as system protection scheme. In [26] Shunt capacitors are used for post-contingency voltage stability.

II. FACTS devices
    - Static Var Compensator (SVC)
    - Static Synchronous Compensator (STATCOMS)
    - Unified Power Flow Controller (UPFC)
    - Thyristor Controlled Series Compensator (TCSC)

- Thyristor Controlled Phase Shifter Transformer (TCPST)

Reactive power sources are of both types that is static and dynamic VAR sources. Depending on response time, SVC and TCSC fall in the category of dynamic reactive power sources while switched shunt capacitors fall in static VAR source. To improve voltage stability margin SVC and TCSC will be more effective and perform better than shunt capacitor but shunt capacitor are cheaper device for improving stability [27].

As already said SVC and TCSC are better in mitigating problem of voltage instability or voltage dip since they respond to the problem instantaneously and provide reactive power to the grid. Mechanical switching of conventional resources is slow. Despite of advancement in switching mechanism because of power electronics, still FACTS devices have advantage over them because of repeated and smooth control. Figure 2.4 shows the difference in switching speed of mechanical switches and power electronic switches.

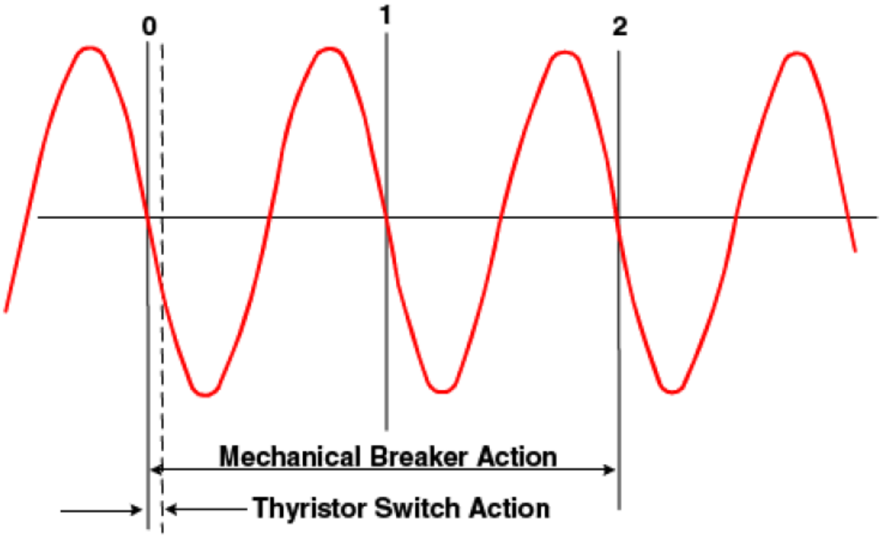

Figure 2.4 Switching speed of mechanical and power electronic switches

Cost of the reactive power source also plays an important role in the selection of reactive power compensation device. A detailed cost to benefit analysis is conducted in many literatures like in [25], [28] to select the reactive power source. Typical cost comparison of both types of VAR sources is given in the Table 2.1

Table 2.1 Cost comparison of reactive power sources

	Static Var		**Dynamic Var**	
	Mechanically switched shunt capacitor	Mechanically switched series capacitor	SVC	TCSC
Variable Cost ($millions/100MVar)	0.41	0.75	5	5
Fixed Cost ($million)	1.3	2.8	1.5	1.5

In order to justify the benefits of reactive power sources installed in the system some metrics must be quantified like transient stability, oscillation damping, voltage stability margins, voltage sag criteria etc. Each of these metrics can be measured as a physical quantity like power carried by the transmission line, generator output and load level of an area. Since these physical quantities can be monetized easily, it provide us basis to compare every possible combination of reactive power sources we choose for the enhancement of system. In this study, we will consider only reactive power planning for voltage stability.

2.4 Reactive Power Planning (RPP)

Reactive power planning has three main steps; selection of type of VAR source, optimal sizing and optimal placement of these devices in the system in such a way that they are able to support the system in normal conditions as well as in stressed conditions. Many studies and research have been done on this topic of optimal placement of FACTS. Those studies can be categorized on bases of two things those are; heuristic optimization and analytical technique. Many researchers used optimization algorithms like genetic algorithm (GA) [29]–[33], Tabu search (TA) [34], simulated annealing (SA) [35], particle swarm optimization (PSO) [36], [37], evolutionary algorithm (EA) [38], [39], bacterial swarming algorithm (BSA) [40], group search optimizer with multiple producer (GSOMP) [41], harmony search algorithm (HSA) [42], and bees algorithm (BA) [43]. Some of the researchers, instead of using optimization algorithms, used analytical methods to find optimal solution for this problem. Singularity analysis of the jacobian matrix [44]. FACTS were allocated in the system by sing line flow index in [45]. One author placed the devices using power angle characteristic [46]

There are two ways to use these FACTS devices, either use only one type of FACTS or use a combination of these devices. In first case, any number of devices of same type is chosen and then an optimal placement technique is applied to find the locations at which they have to be placed for best utilization. For example in [31], [44], [47] SVC are used, STATCOM in [37], TCSC in [32], and UPFC in [33]. In second case a mix of these devices are taken and then optimal placement is done. This approach contains the benefits of different types of FACTS. Many studies are done on multiple type FACT device placements for example in [38], [40], [41]SVC, TCSC, TCVR and TCPST are used. Planning is done while keeping economic concerns in mind. In a survey a comprehensive knowledge about the formulation of VAR planning and techniques for the planning is provided[48]. Previously, VAR sources were used in the system on the basis of some past experiences or estimations. But now many techniques have been developed to place them optimally according to the objective of placement, as in over case we will focus on placement of VAR sources to improve voltage stability.

VAR planning is a nonlinear optimization problem having many variables and parameters. These problems take a lot of time to be solved. However, mixed integer non-linear programming technique can be used to solve this problem in order to minimize cost of VAR sources and minimize power loss of system subject to power flow equality and inequality constraints. Before advancement in the study of stability and VAR resources modeling, capacitor was the only device used for reactive power re-enforcement. Capacitors were used to improve/maintain voltage levels during normal and stressed conditions [49]. But after realizing that voltage stability problem is far different from low voltage case many planners stated to concentrate on allocation of capacitors to mitigate stability problem by using stability indices. Methods to handle RPP problems are divided into two main categories; conventional techniques and heuristic techniques. Conventional techniques include reduced gradient method, Successive Quadratic Programming and Newton’s method the heuristics methods are Genetic Algorithm, Differential Algorithm, Tabu Search, Particle Swarm Optimization etc[50]. Due to advancement in power electronics and evolution of FACT devices both static and dynamic devices are used in the RPP.

In many literatures, voltage stability margin has been improved using static reactive power planning. One of the author has presented a technique to enhance voltage stability margin by identifying VAR control[51]. Two stage Reactive Power Planning was presented. In the first stage, minimization of VAR supply is done using an optimization algorithm. This means minimum VAR that would be enough to increase stability margin while satisfying all the system constraints. In second stage, locations for the placement of VAR sources are selected such that these devices are most effective. In this study, contingencies were also considered. Author in [52] used heuristic technique for the optimal placement of capacitors for voltage stability. This work shows the benefit of using genetic algorithm for the VAR planning problems. Publication [53] describes how static VAR compensation influences voltage stability. Voltage stabilities that correspond to static burification of power flow equations were considered in the study. Minimum singular value of Jacobian matrices and total reactive power generation were used as indicator of stability margin. Change in system parameters to influence reactive power was calculated in sensitivity analysis for the allocation of VAR source. Bus with highest sensitivity ratio was selected as the location of VAR source. Ajjarapu, et. al. in [54] presented a technique to minimize the shunt VAR support and maximize the real power transfer while avoiding voltage collapse. Continuation power flow (CPF) was used to identify the weak buses in the system for the placement of shunt devices. To find the peak loading point of system, Predictor-corrector optimization scheme is used. Sequential quadratic programming (SQP) algorithm is used for optimization and the objective function was the minimization of VAR injection. Y.L.Chen in [55] has proposed weak bus based RPP to resist voltage collapse. Jacobian matrix is decomposed using singular value decomposition. Then the algorithm uses right singular vector of decomposed jacobian matrix to identify the weak bus. That bus is chosen as the candidate for the shunt VAR device location. Simulated annealing (SA) was used for the optimal placement. Optimization was done to maximize the minimum singular value. Chang in [56] has proposed a hybrid optimization technique that uses langrange multiplier and parallel SA. The objectives of optimization are: minimization of I2R losses, maximization of voltage stability margin and voltage magnitudes at critical points. Fuzzy performance index is used for the assessment of each SVC based on three objectives. In [57] optimal placement of FACTS devices has been done using genetic algorithm (GA). GA can solve multi-objective optimization problems but the problem is that it takes time if system is large. In publication [58], a noval and fast method for the optimal placement of SVC on the basis of contingency analysis and system loadability is proposed. CPF and modal analysis are used as tools for selecting SVC location on the basis of loadability. Three performance indices are proposed on the basis of loadability margin, contingency and flattered voltage profile. System performance is checked for each of the case with and without SVC. In [59] a technique for the optimal placement of shunt VAR devices is presented. In this method, firstly critical modes within the zone of voltage collapse point are computed. Then the optimal locations for shunt devices are chosen by using system participation factor. Publication [60] shows the application of an OPF [61], to re-establish post contingency equilibrium. Restoration is done by doing generator terminal voltage adjustment, changing tap settings of LTC transformer, rescheduling of power and load shedding. Yorino in [62] suggested a new formulation for VAR planning including FACTS devices allocation using mixed integer linear programming (MILP). Formulation directly incorporates the cost of devices as well as cost of voltage collapse. Problem is decomposed into master problem and sub problems using Benders Decomposition. Because of the non-convexity of the problem due to system parameters, solution convergence is not guaranteed. Voltage stability margin is not considered in this formulation. In publication [63] a new method to enhance voltage stability margin by the optimal placement of series and shunt VAR compensation is proposed. This method allows reconfiguring the series and shunt capacitors under different prescribed contingencies. Forward/backward search is applied on different discrete configuration/combination of switches, represented on a graph. This problem is like a mixed integer linear programming problem. Actually, stability margin sensitivity with respect to reactance and susceptance of series and shunt capacitance respectively are used to select the location. This forward/backward algorithm is used to choose the candidate locations for the devices. A mixed integer linear programming is applied to compute proper amount of VAR devices to be installed at particular location for given set of contingencies.

The above mentioned literature is about the static reactive power planning for voltage stability. There are literatures, although few, which deal with the dynamic reactive power planning and the coordination of static and dynamic reactive power planning for voltage stability. Work on post fault voltage recovery time is done in [64]. In this work, a method to calculate minimum value of SVC which can satisfy the recovery time limits is presented. Boundary value problem is solved using numerical shooting problem to calculate Capacity of SVC. In publication[13]a procedure based on Q-V analysis is presented to determine suitable combination of dynamic and static reactive power sources at certain location. The point of intersection between post fault Q-V curve and minimum voltage determines dynamic reactive power requirement. Static VAR is determined by the intersection of post fault Q-V curve, with load modeled as constant power (less than dynamic reactive power determined in previous step), and minimum voltage required. In

[8], [65], [66] a method to recognize dynamic and static VAR compensation for electric system is given. Optimal locations for VAR compensation is selected by using optimal power flow techniques. Ratings of VAR devices are determined by Q-V analysis with constant power model. Time domain simulations were run to find optimal mix of dynamic and static VAR devices. Similar method is applied by Kolluri in [67] to get right combination of static and dynamic reactive power sources. In [68] multi-objective reactive power planning has been done against short-term voltage instability. The two objectives of this optimization are: minimizing total investment cost of VAR devices and minimizing unacceptable voltage drop/dip. STATCOM is used as dynamic VAR source. Optimal placement is done using decomposition based evolutionary algorithm. Trajectory sensitivity analysis used for the selection of candidate buses.

2.5 Distribution Networks with DGs

2.5.1 Impact of DGs

Electrical power system has been going through a lot of evolutions since last decade. One of these evolutions is the integration of distributed generation (DG) in the power systems. And electric power system planners and operators, energy policy makers and regulators as well as developers have shown great interest in DG [69]. The growth of DG is mainly and primarily driven by the environmental issues [70]. Economic, political and social concerns are also the cause of integration of DGs on such a large scale [71]. The need to avoid large investment on transmission and distribution networks and consideration of green house effect has encouraged this paradigm [72]. It is possible that DG will make quite a large percentage of electrical power supply in coming future, power sources will be sited near the loads in distribution network avoiding huge transmission lines cost[72]. Incorporating distributed generation in the conventional power system will provide environmental technical and economic benefits to the customers as well as generation companies (GENCOs)[72]. For example, because of less transmission network power losses will be reduced also investment on that network will be saved. Most of DGs needs power electronic converters to be integrated with the grid [72]. DGs have low inertia, these uniqueness and other characteristics of DGs may give rise to many operational and technical issues and challenges regarding power system stability [73]. If the number of DGs in the system and their sizes are small as compared to whole power system then their effect on the system can be neglected both operationally and technically. But if DGs are large in number and also of huge capacities then they change the dynamics of the system[72]. So the analysis of the power system including DGs has become an emerging problem and research area [73]. Combine Heat and Power (CHP) generation is one of the most favorable DG technologies today and will be used on large scale in near future [71]. Among many issues regarding power system having DGs, stability is one the most important issue [72], [73].

2.5.2 Reactive Power Planning Using FACTS

In [74] study has been done on the effect of SVC on the system performance and how system loadability and stability can be improved by the optimal use of FACT devices. Maximum power transferring capability criteria has been used for the optimal allocation of these devices. This study found that FACTS devices are the best replacement of slow mechanical devices and have good impact on loadability and stability improvement. High penetration of renewable sources like PV and wind has introduced operational difficulties in power system. In publication [75] effect of large wind farms connected to distribution systems on voltage stability is observed. Wind turbines have large induction generators which absorb large amount of reactive power from grid thus causing voltage instability. Effects of SVC and STATCOM were observed on system performance. Voltage stability margin is improved in case of transient as well as dynamic load variation using FACTS devices. In [76] VAR control and voltage control of distribution system having DGs is investigated. Also, the effect of synchronous machine-based DGs on that control is observed. In this literature, coordination of switched capacitors, feeder-switched capacitors and online tap changer (OLTC) have been done for voltage and VAR control. No communication between capacitors and OLTC is assumed. The main objective of proposed technique is to minimize the system losses. Results have shown that using proposed method, system losses, number of OLTC operation and voltage fluctuation has been reduced. OLTC operation is not affected by the reversely power flow due to DG. Observations and results show that if VAR demand is fulfilled by only capacitors that are available, then DG operation does not affect the system losses. In [77] genetic algorithm is used to improve the voltage stability of the system and to reduce system losses using FACTS devices. The effect of optimal placement of multiple types of devices was recorded in this study. In publication [78], a passive method to solve the problem of voltage rise limits and reactive power demand of DGs is presented. Using linear programming tap settings of transmission transformers and fixed power factors (PF) of generators are determined. This will enhance the utilization of existing voltage control resources without any expenditure. In [79] only TCSC are used to improve the loading capability of transmission line. PSO is used for optimization purpose. Similarly in [80] effect of SVC on system loadability and power losses is investigated. Genetic algorithm is used to find optimal location of SVC.

Not much work has been done on VAR planning for the networks with renewable energy sources. In [81] VAR margin based reactive power planning for the improvement of dynamic voltage stability in distribution networks with wind generation has been proposed. Effect of composite loads, in distribution networks, on voltage dynamics is also observed through time domain analysis. Combination of distribution static synchronous compensator and shunt capacitors is used for voltage recovery after sudden fault or disturbance. Critical bus technique is used to select the optimal location of VAR devices. Percentage reactive power loadability of each bus is calculated and the bus with highest percentage is selected to be the optimal location of VAR device. In [82] a probabilistic method to solve the volt/VAR control problem in network with high wind power penetration is presented. Cost of energy generated and losses is selected to be the objective function. Frog leaping algorithm is used as an optimization technique to select the optimal values of reactive power to take from capacitors and tap changing transformers

2.6 Summary

Work for the improvement of voltage stability of the system and loadability, separately, is done in the literature using shunt capacitors, OLTC transformers and FACTS devices using non-linear programming techniques and heuristic techniques. But system operators want to have a series of options (tradeoffs) between loadability and stability. Also due to competitive electricity market, the cost of VAR planning also matters. So multi objective VAR planning needs to be done. The voltage recovery time improvement of system with renewable sources and DGs also needs to be investigated.

CHAPTER 3

PROBLEM FORMULATION AND ALGORITHMS

The formulation for increasing loadability, voltage stability and improving voltage recovery time are given in the following subsections.

3.1 Maximizing System Loadability

The objective is to maximize the Loadability of the system, i.e. real power transmission, while the constraints of system such as bus voltages limits and transmission line power carrying capability limits are met. The objective will be achieved by increasing the load factor (λ) in every iteration of optimization algorithm and power generation on generation buses will be scaled as below;

$$P_{Gi} = \lambda P_{G0i} \tag{3.1}$$

Where $P_{G0}$is the initial value of the generated power and P_G is the modified.

The initially value of load factor is taken λ=1. At load buses both real and reactive power are modified by the factor λ as shown in equation 3.2:

$$\begin{aligned} P_{Li} &= \lambda P_{L0i} \\ Q_{Li} &= \lambda Q_{L0i} \end{aligned} \tag{3.2}$$

Where $P_{L0}$and$Q_{L0}$is the initial value of real and reactive powers loads respectively and P_L and Q_L are the modified.

A greedy approach is applied to get maximum load factor by optimizing location and sizing of FACTS devices using heuristic algorithm. Differential evolution algorithm is used to optimize the size and location of FACTS devices. Optimization code is given in appendix A The objective function to maximize power system Loadability is formulized as

$$J = Max\left\{\lambda\right\} \tag{3.3}$$

And system constraints are:

$$S_l \leq S_{l\max} \tag{3.4}$$

$$\left|\Delta V_{bi}\right| \leq 0.05 \tag{3.5}$$

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} \tag{3.6}$$

Where S_{lmax} is the maximum power carrying capability of transmission line. And S_l is the actual apparent power in the line at any time. ΔV_{bi} is the difference in between the nominal voltage and run time voltage at that bus. P_g^{min} and P_g^{max} are the limits of bus power.

The algorithm for increasing loadability is shown in Figure 3.1

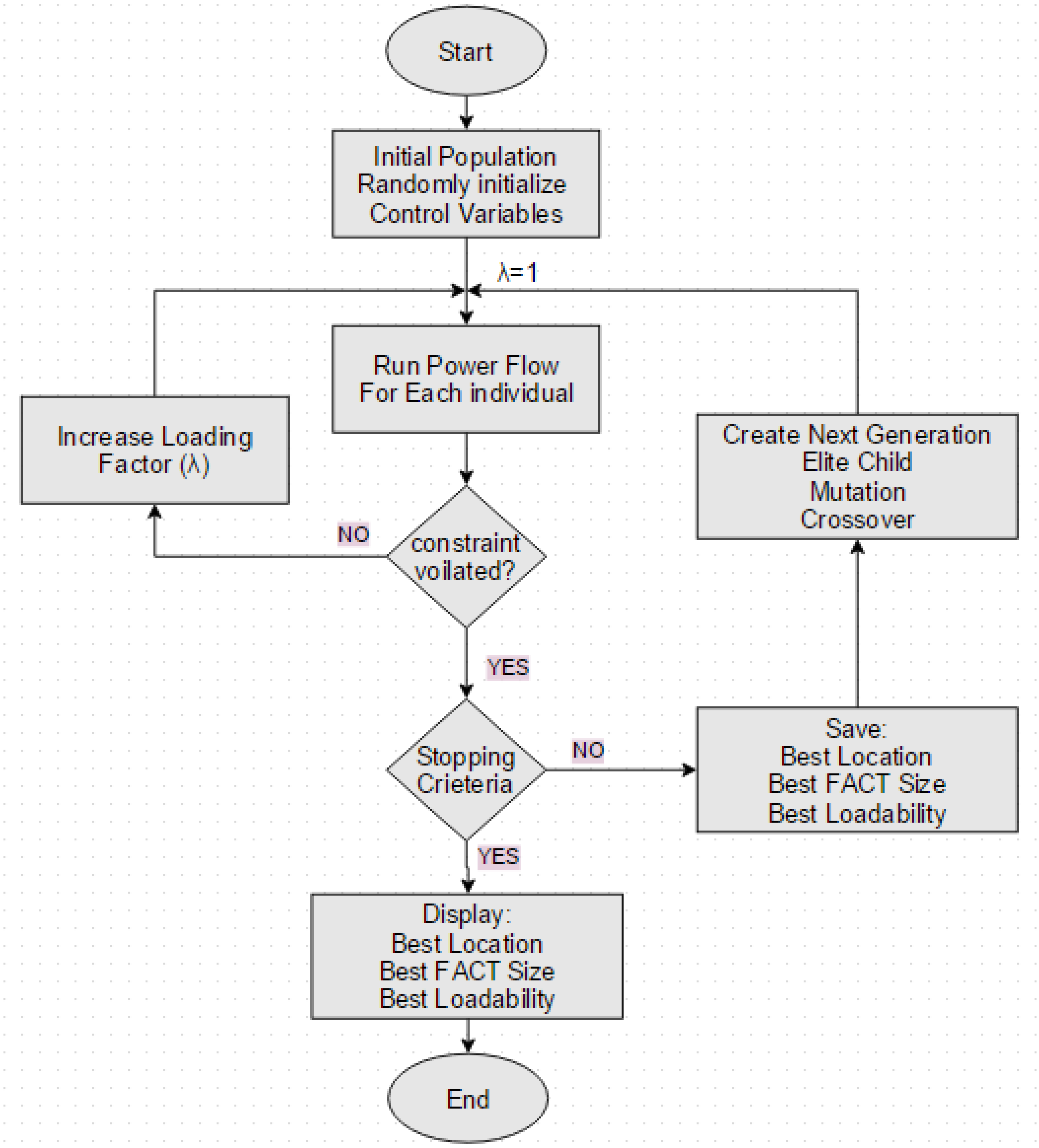

Figure 3.1 Algorithm for improving loadability

Initial population of control variables, which in this case are FACTS size and location, are generated randomly. Initial value of λ is set to be 1. Then for all those random combinations of control variables power flow is run and constraints are checked. If no constraint is violated loading factor λ is increased until anyone of the three constraintsgets violated. Stopping criteria in this algorithm is maximum number of generations. Stopping criteria is checked, if not met, best FACT location, size and best value of loadability is saved and next generation is created. Again the process is repeated for next generation. The process continues until stopping criteria is met. Best FACT location, size and maximum Loadability achieved is displayed.

3.2 Formulation for L-index

L index is an index defined to see how close a power system to instability is [17]. Voltage stability indicator L-index is used to evaluate the voltage stability of the bus [18]. The L-index value varies from 0 to 1 which reflects the magnitude and phase along with other load flow information. For multi-bus system;

$$I = Y * V \tag{3.7}$$

By separating the load buses from generator buses, equation (3.7) can write as

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{3.8}$$

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{3.9}$$

Where V_L and I_L are current and voltage for PQ buses, V_G and I_G are the currents and voltages of PV buses. Z_{LL}, F_{LG}, K_{LG} and Y_{GG} are the sub matrices of H while H is obtained by partial inversion of admittance matrix[83].

L-index of any bus can be expressed as

$$L_j = \left| \frac{S_{j+}^*}{Y_{jj} * V_j^2} \right| \tag{3.10}$$

The S^*_{j+} complex power in above formulation is the net effect of all the loads on that particular bus voltage status for which the L index is being calculated and Yjj are self-admittance of the bus for which L index is calculated obtained from above Y matrix.S^*_{j+}can be calculated using equation 3.11

$$S_{j+} = S_j + S_{jcorr} \tag{3.11}$$

Where $S_{jcorr}$is given by equation 3.12

$$S_{jcorr} = \left(\sum_{\substack{i \in LOADS \\ i \neq j}} \frac{Z^*_{ji}}{Z^*_{jj}} \frac{S_i}{V_i} \right) V_j \tag{3.12}$$

Where;

V_j=voltage of bus at which L-index is calculated

V_i=voltage of load bus i

S_i= complex power at load bus i

Z^*_{ji}=impedance between bus i and j

Z^*_{jj}=self impedance of bus j

The objective function will be

$$L = \min\{\text{Lindex}_{system}\} \tag{3.13}$$

Where

$$\text{Lindex}_{system} = \max\{\text{L}_1, \text{L}_2, \text{L}_3, \ldots\ldots.., \text{L}_n\} \tag{3.14}$$

And L_1,L_2,….,$L_n$are the L-indices of “n” load buses.

System constraints are;

$$S_l \le S_{l\max} \tag{3.15}$$

$$|\Delta V_{bi}| \le 0.05 \tag{3.16}$$

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \tag{3.17}$$

For maximizing Loadability or minimizing L-index the flow chart shown in Figure3.2 is followed.

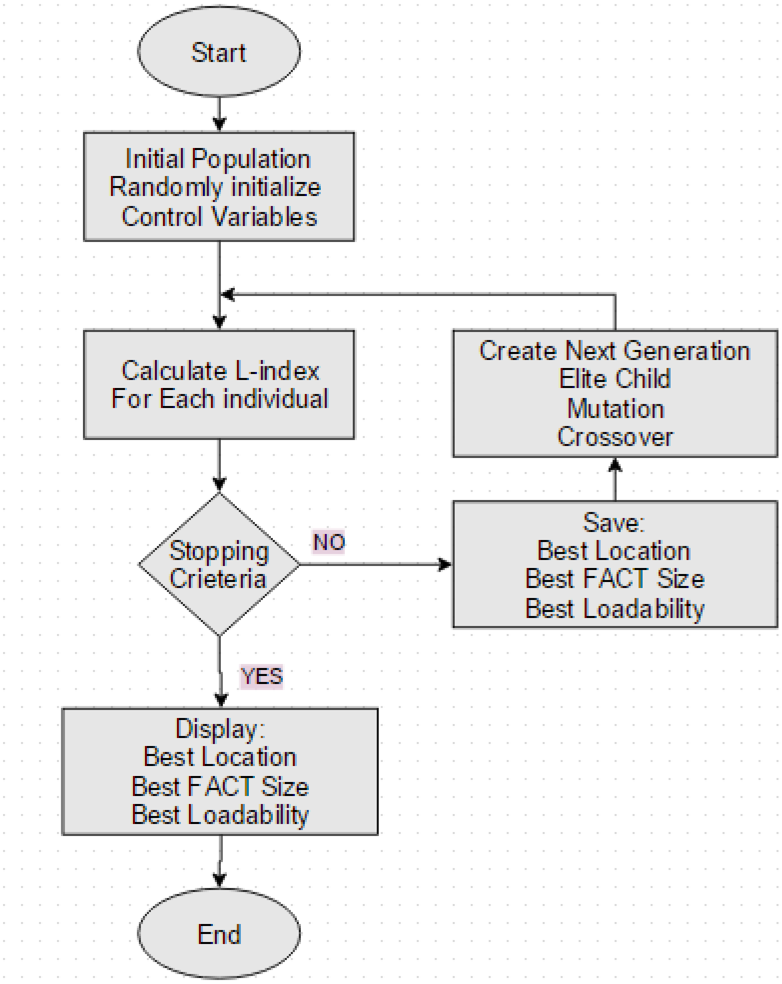

Figure 3.2 Algorithm for improving L-index

Initial population of control variables, which in this case are FACTS size and location, are generated randomly. For all those random combinations of control variables objective function that is L-index is evaluated. Stopping criteria in this algorithm is maximum generations. Stopping criteria is checked, if not met, best FACT location, size and best value of L-index is saved and next generation is created. Again objective function is evaluated for next generation. The process continues until stopping criteria is met. Best FACT location, size and best L-index is displayed.

3.3 Non Dominated Sorting Optimization Algorithm

To see the effect of loadability on system stability, loadability maximization and L-index minimization is done simultaneously, differential evolution algorithm is extended to solve multi-objective optimization problems using non-dominated sorting, same as used in NSGA-II [84]. The objective functions are maximizing loadability,L-index minimization (equation 3.3 &equation 3.13respectively) and minimization of cost of FACTS.

$$F_1 = max\left\{\lambda\right\}$$

$$F_2 = \min\{\text{Lindex}_{system}\}$$

$$F_3 = \min\{C_{FACTS}\}$$

Subject to following constraints

$$S_l \le S_{l\max}$$

$$\left|\Delta V_{bi}\right| \le 0.05$$

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}$$

Unlike single objective optimization, in this non-dominated sorting technique candidates for the next generation are not selected merely on the base of comparing objective function's value. All the 'N' candidates (where 'N' is number of population) from Parents generation and their 'N' offspring are combined together to form an intermediate population of '2N' candidates. Non-dominated sorting is applied to this intermediate population and all the members are divided in different groups called fronts. Candidate in the first front are completely non-dominant in the whole set of intermediate population.

Individuals in the second front are dominated by the ones in the first front. Individuals in each front are assigned a rank. Individuals in first rank are given rank 1and those in second front are assigned rank 2 and so on. Another parameter called crowding distance is calculated for each candidate to ensure best distribution of non-dominated solution. This crowding distance is basically measure of distance between two adjacent candidates. After sorting 'N' individuals are selected on the basis of rank and crowding distance. Individuals in the first rank are selected first then of second rank and so on. If number of individual in a front exceeds from 'N' then individual with highest distance are selected first. The principle of selection is shown in Figure 3.3

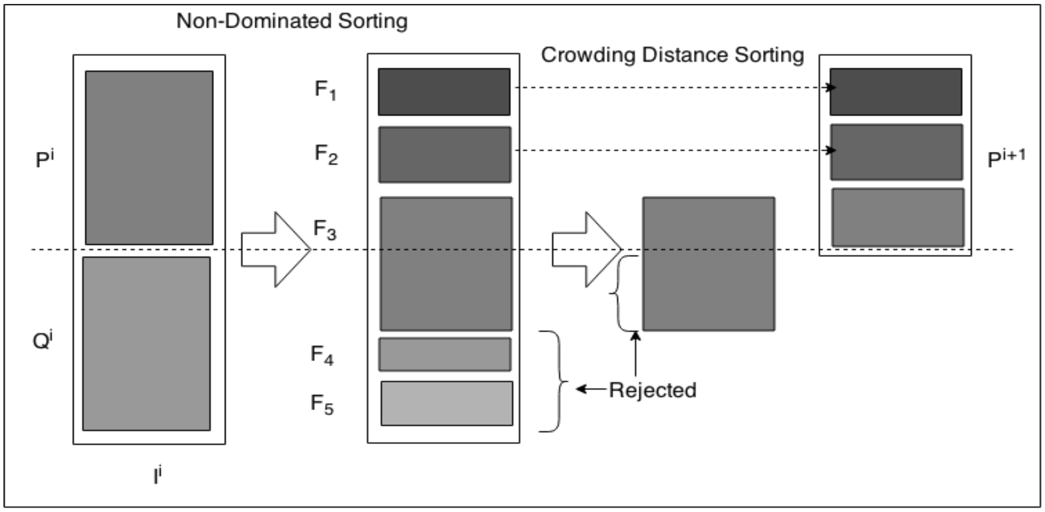

Figure 3.3 Selection of members for next generation

Where 'P^i' is set of parent population for i^{th} iteration, 'Q^i' is the set of offspring of i^{th} iteration, F_1 to F_5 represent the fronts and 'P^{i+1}' is the next generation.

Following are the basic steps of NSDE algorithm for any iteration;

1. $I^i = P^i \cup Q^i$ (where I is intermediate population)
2. $F = NDS(I)$ (where NDS is non-dominated sorting)

3. $P^{i+1} = \phi$ and $j = 1$
4. $while\left(lenght\left(P^{i+1}\right) \leq N\right)$
    a. Calculate crowding distance in front '*j*'
    b. $P^{i+1} = P^{i+1} \cup F_j$
    c. $i = i + 1$
5. Sort 'F' in descending order

Select mutants for next production of next generation based on rank and crowding distance. Figure 3.4 shows the flow chart for optimization of VAR sources to maximize loadability and minimize L-index simultaneously.

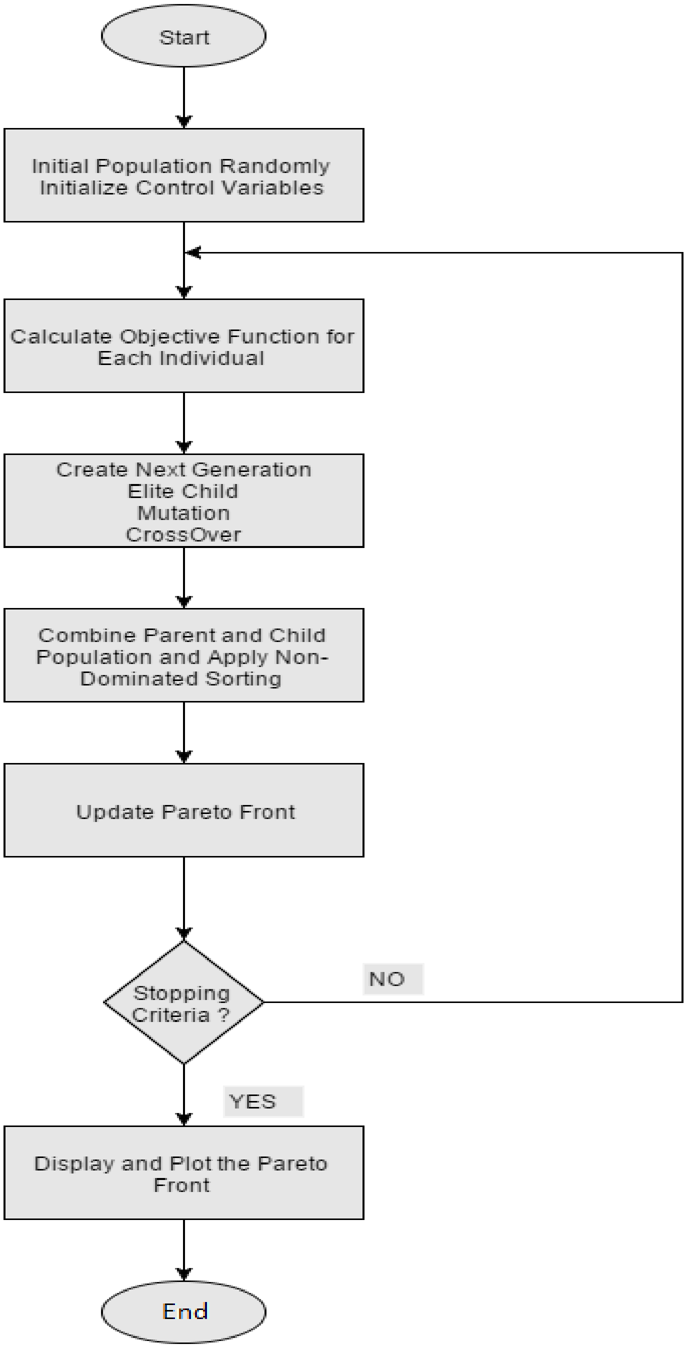

Figure 3.4 Algorithm for multi objective VAR planning

Initial population of control variables, which in this case are FACTS size and location, are generated. For all those random combinations of control variablesall objective functions are evaluated. Using mutation and cross over, next generation is created and objective functions are evaluated for them. Both, Parent and offspring are combined to make an intermediate generation. All the members of intermediate generation are sorted out in ranks using non-dominated sorting. Top 'N' candidates are selected to be the next generation. Stopping criteria is checked, if not met, again objective function is evaluated for this new generation. The process continues until stopping criteria is met. Pareto front is plotted when stopping criteria met.

3.4 Formulation for Voltage Recovery Improvement

VAR source placement and sizing to minimize voltage recovery time is done using differential evolution algorithm. The objective function for this above mentioned problem is designed such that it minimizes system total energy loss and investment cost.

$$Min\sum_{i=1}^{n} C_i\left(q_i\right)+K*T*P_{loss} \tag{3.18}$$

And system constraints are:

$$S_l \le S_{l\max} \tag{3.19}$$

$$\left|\Delta V_{bi}\right| \le 0.05 \tag{3.20}$$

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \tag{3.21}$$

Where "$C_i(q_i)$" is the investment cost associated with the capacitor of "q" MVAr to be installed. P_{loss} is the system power losses, T is the time and K is the cost of energy loss. Figure 3.5 shows the flow chart to improve voltage recovery time

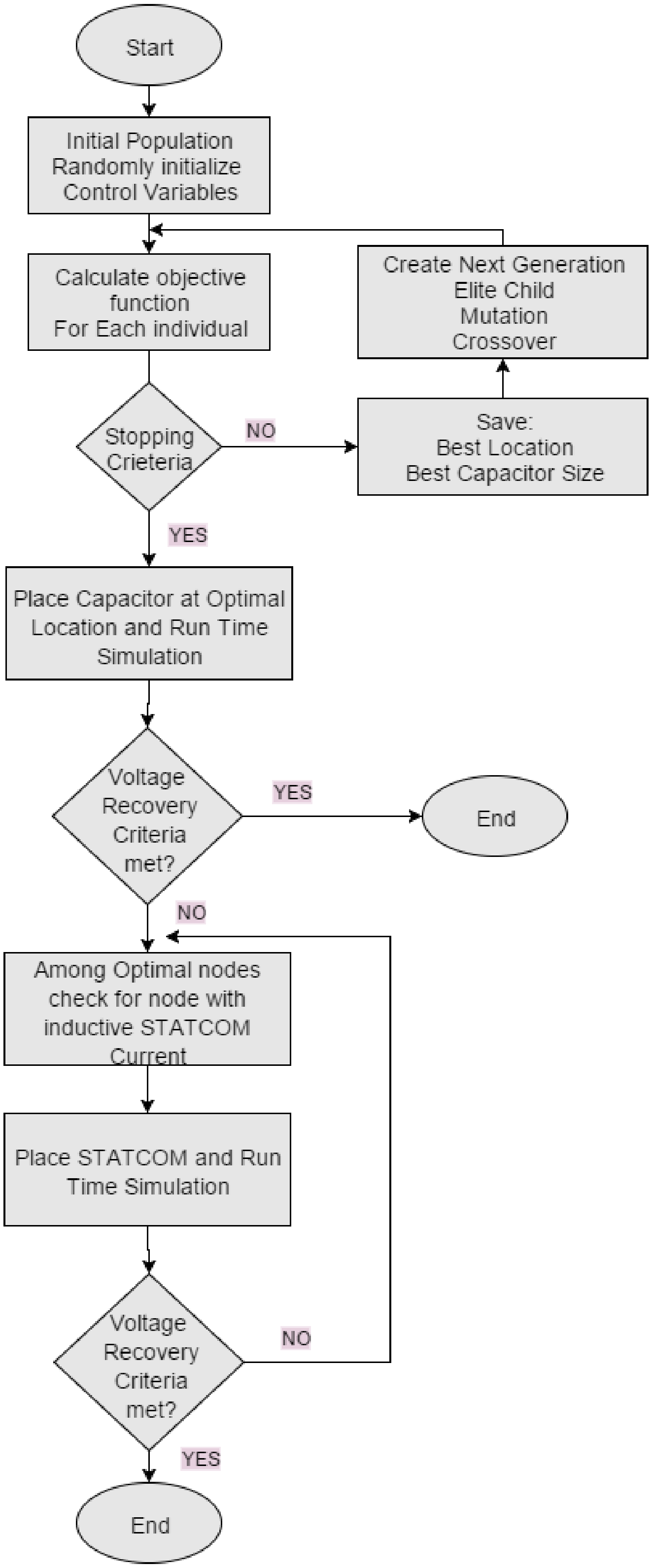

Figure 3.5 Flow chart for improving voltage recovery time

Using Differential evolution algorithm with objective function defined in equation 3.18 find the optimal location and size of capacitors and place them in the system. Run the time simulation with fault of certain duration and record voltage recovery time. If voltage recovery criteria meet, plot the results. If not, place a STATCOM on a node with inductive STATCOM current. Run the simulation again; keep on doing this until voltage recovery criteria meet.

CHAPTER 4

SIMULATION RESULTS

In order to verify the performance of the proposed algorithms, different test cases have been studied on the standard IEEE 30 bus system and IEEE 24 bus system. Data for both bus systems is given in the appendix B. Also modeling of FACTS devices used in the study is explained in the appendix C. IEEE30 bus system is shown in Figure 4.1.

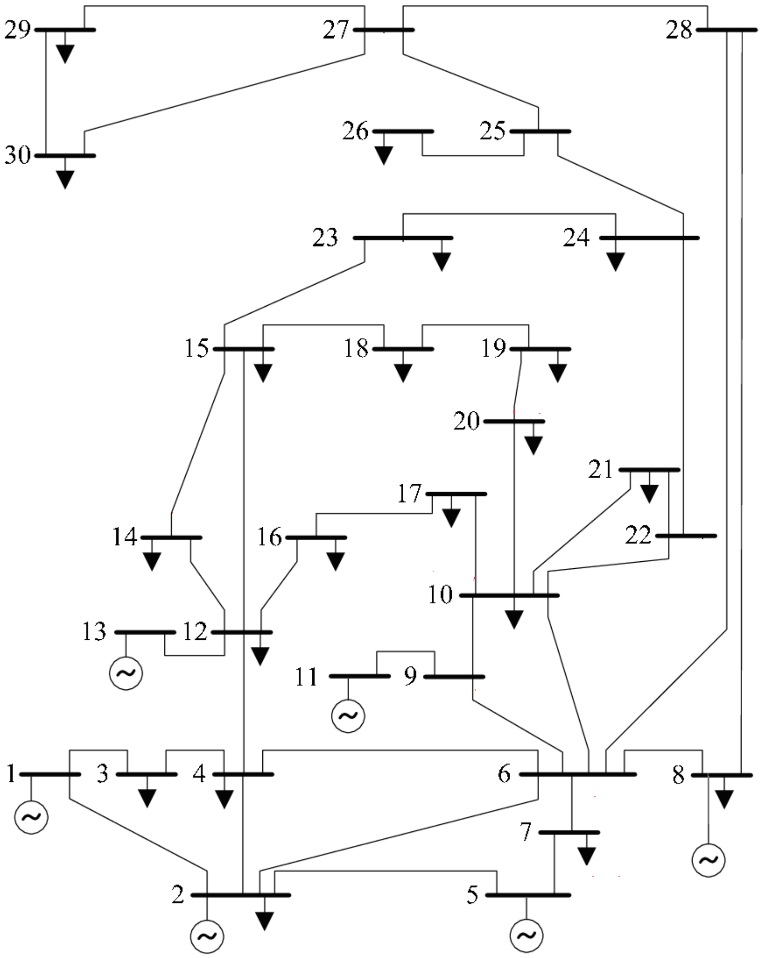

Figure 4.1 Single line diagram of IEEE 30 bus system

4.1 Increasing Loadability

The test systems taken for this study are IEEE 30 bus system and IEEE 24 bus system. Before increasing loadability to maximum, the initial loading conditions are at 100%. To increase loadability of the standard IEEE 30 bus system different scenarios have been studied as presented in Table 4.1 and Table 4.2.

4.1.1 IEEE 30bus System

4.1.1.1 Single FACTS Device

Table 4.1 summarizes the results for loadability using single FACTS device of each type in the system. The results show that by placing a single SVC at bus 24 with an optimal size of 34.82MVAR the loadability of the system can be increase upto 15% and a series compensation with X_{TCSC} value of -0.8 at branch 36 increase in loadability by 13.5 % can be achieved. A TCVR of 0.9588889 ratio at branch 41and TCPST of 8.66^o size give us increase in loadability by 12.1% and 7.8% respectively.

Table 4.1 Results for single FACTS device placement

Type	Location	Size	Loadability increased
SVC	Bus 24	32.47 MVar	1.15 (15%)
TCSC	Branch 36	-0.8 X_{TCSC}	1.135 (13.5%)
TCVR	Branch 41	0.958889 Ratio	1.121 (12.1%)
TCPST	Branch 33	8.66^o Degrees	1.078 (7.8%)

4.1.1.2 Multiple FACTS Devices

Results for multiple FACTS placement are summarized in Table 4.2, location along with the size of device and increase in loadability after placing the multiple types of FACTS devices are present in it. Case I describes the effect of the inclusion of 3 SVC's placement in the system. The result shows that loadability is increased up to 17%. In case II four TCSC's are placed to achieve the increase in loadability up to 20%. The third case shows the effect of the inclusion of multiple types of FACTS devices at optimum location in the system. The result shows that, the loadability is increased up to 21%, in this case 1SVC, 1TCSC, 1TCPST and 1TCVR has been placed in the system.

Table 4.2 Results for multiple device placements

No. of Devices	Type	Location	Size	Loadability Increased
3 (Single Type)	SVC	Bus 21	-26.6MVar	1.17 (17%)
	SVC	Bus 30	-10.2MVar	
	SVC	Bus 3	-40.9 MVar	
4 (Single Type)	TCSC	Branch 13	$-0.8X_{TCSC}$	1.20 (20%)
	TCSC	Branch 36	$-0.7205X_{TCSC}$	
	TCSC	Branch 41	$0.1387\ X_{TCSC}$	
	TCSC	Branch 5	$-0.7045X_{TCSC}$	
4 (Multiple Types)	SVC	Bus 29	-18.43MVar	1.21(21%)
	TCSC	Branch 2	$-0.6106\ X_{TCSC}$	
	TCVR	Branch 22	0.9208 Ratio	
	TCPST	Branch 15	-9.344^o Degrees	

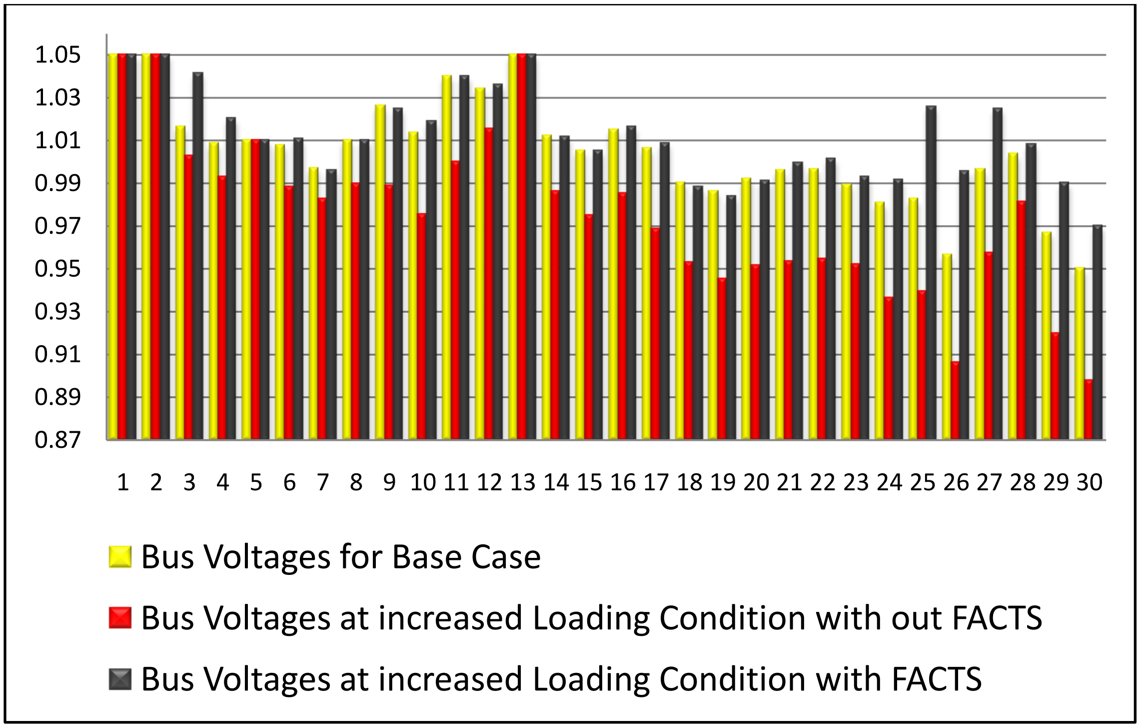

Figure 4.2 Effect of loading on bus voltage magnitude with and without FACTS

Figure 4.2 shows the voltage at each bus in three different cases. The yellow bars show the voltage level of the bus for the base case, the red bars show the voltage level of the bus when system loadability is increased by 21%and no FACTS device is included in the system and the gray bars show the voltage level of the bus when system loadability is increased by 21% and FACT devices are placed. It is observed that voltage at all the buses are within the permissible limits for the base case as shown by yellow bars but when loadability was increased by 21%, some of the bus voltages dropped below0.95pu which may leads the system to an unstable stage. But with the inclusion of FACTS devices, the voltages at each bus became within the specified permissible limit of 0.95 pu to 1.05pu voltage, which ensure the stability of the system.

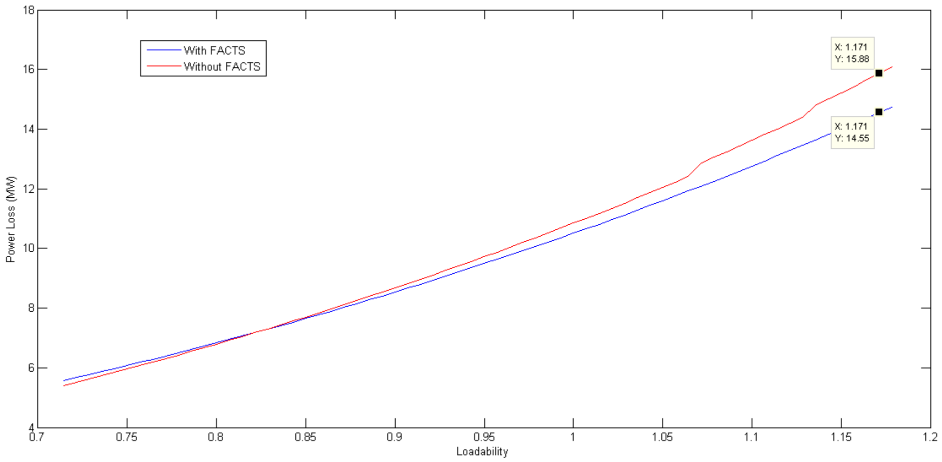

Figure 4.3 Effect of FACTS inclusion on system losses

Figure 4.3 shows the reduction in real losses with the inclusion of FACTS devices. It can be seen that for high loading conditions, by using FACTS devices the system losses at a particular loading condition are less as compare to system without FACT devices. When loading is increased to 1.17 (17% increased) losses in the system without FACTS are 15.88 MW and losses in system with FACTS are 14.55 MW. So there is a reduction in losses of 1.33 MW.

In [85], Four types of FACTS devices namely SVC, TCSC, TCVR, TCPST are used. Multiple FACTS (one device of each type) are used to enhance loadability of IEEE 30 bus system. Bacterial swarming algorithm is used for optimal placement and sizing of FACTS. Table 4.3 shows the comparison of results of this work with results reported in [85].

Table 4.3 Comparison of results with results reported in [85]

Number of Devices	Type	Max Loadability Obtained in This Work	Max Loadability Reported in [85]
4 Multiple Type	SVC	1.21 (21%)	1.158 (15.8%)
	TCSC		
	TCVR		
	TCPST		

From Table 4.3 we can see that maximum loadability achieved in [85] using 4 multiple type FACTS is 15.8% while in this work maximum loadability of 21% is achieved using same number and types of FACTS. So with proper placement and sizing 5.2% more increase in loadability is achieved.

4.1.2 IEEE 24bus System

Effect of FACT devices on loadability is also checked for IEEE 24 bus system. Table 4.3 shows the results for 24 bus system loadability maximization. According to Table4.4 maximum increase in loadability that can be achieved is 31%, by placing 2 SVCs and 2 TCSCs at optimal locations.

Table 4.4 Effect of FACTS on loadability of 24 bus system

No. of Devices	Type	Location	Size	Loadability Increased
3 (Single Type)	SVC	Bus 27	-97 MVar	1.19 (19%)
		Bus 7	-65.84 MVar	
		Bus 5	-100 MVar	

4 (Single Type)	TCSC	Branch 2	-0.7697 X_{TCSC}	1.11 (11%)
		Branch 31	-0.2382X_{TCSC}	
		Branch 13	-0.7956X_{TCSC}	
		Branch 13	-0.6996X_{TCSC}	
4 (Multiple Types)	SVC	Bus 3	-150 MVar	1.31(31%)
		Bus 8	-102.75 MVar	
	TCSC	Branch 1	0.1567 X_{TCSC}	
		Branch 10	-0.6030 X_{TCSC}	

4.2 PIV index based Loadability Maximization

PIV index is a reactive power performance index. It reflects the deviation of bus voltages from their nominal values, thus directly giving severity level of a bus to go out of limits in case of any contingency of increase in loadings. PIV index can be calculated using equation4.1.

$$PIV = K * \left[\frac{2(\mathrm{V}_i - \mathrm{V}_{in})}{V_{i\max} - V_{i\min}} \right]^2 \tag{4.1}$$

Where,

K = weighting factor,

V_i = voltage of bus i,

V_{in} = nominal voltage of bus i,

V_{imax} = maximum voltage limit,

V_{imin} = minimum voltage limit.

For IEEE 30 bus system PIV is calculated for each bus and are ranked from best to worst. Bus numbers along with their rankings are given in Table 4.5;

Table 4.5 PIV index based bus ranking of 30 bus system

Bus#	Rank	Bus#	Rank	Bus#	Rank
1	1	15	11	10	21
2	2	17	12	16	22
5	3	6	13	3	23
8	4	20	14	25	24
13	5	4	15	24	25
7	6	18	16	9	26
22	7	11	17	29	27
27	8	23	18	12	28
28	9	14	19	26	29
21	10	19	20	30	30

Based on PIV ranking buses are divided into 2 zones i.e.. green and red. Buses in the Green zone are the most stable one as their voltage level is near nominal, in this case top 50% of the buses are in green zone and in red region the bus voltages are very close to maximum or minimum voltage limits. In previous section, loadability was increased overall at all the buses by same ratio (λ). But as some of the bus voltages in the system were close to their limits, they prevented the possible loadability increase on other buses. In this case loadability is increased on the buses in green only and

RPP is done for the system. Results for this case are compared with the results obtained in section 4.1.1.1 and 4.1.1.2 and are presented in the Table 4.6

Table 4.6 Comparison of loadability with and without PIV consideration

FACTS	**Increase in Loading (MW)**		**Difference (MW)**
	W/O PIV Consideration	With PIV Consideration	
1 SVC	42.37	72.12	29.75
1 TCSC	38.18	55.20	17.02
1 TCVR	34.18	55.20	21.02
1TCPST	22.03	63.69	41.66
3 SVC	48.02	76.42	28.40
4 TCSC	56.5	99.78	43.28
MULTI	58.47	63.69	5.22

From the results in the Table4.5 we can see that there is a considerable difference in maximum loadability which we achieved for the buses in the green zone.

4.3 L-index Improvement

L-index is optimized using differential evolution algorithm to place the FACTS devices in order to achieve the maximum voltage stability. The system L-index is considered to be the largest value of L-index at a particular bus.

4.3.1 IEEE 30bus System

For IEEE 30bus test system the following Table4.7 summarize that system's L-index at 100% loading, without using any FACT device, is 0.1444 and is improved using FACT devices up to 0.0982.

Table 4.7 L-index improvement of 30 bus system using FACTS devices

No. of FACTS	**Type**	**Location**	**Rating**	**System L-index**	
				Without FACTS	Using FACTS
1	SVC	Bus 24	36.60 MVAR	0.1444	0.1276
1	TCSC	Branch 12	$-0.6340X_{TCSC}$	0.1444	0.1270
1	TCVR	Branch 12	0.8945 ratio	0.1444	0.1352
1	TCPST	Branch 33	0.95^o Degrees	0.1444	0.1370
3	SVC	Bus 21	32 MVAR	0.1444	0.1250
		Bus 28	26.2 MVAR		
		Bus 3	15.32 MVAR		
4	TCSC	Branch 15	$-0.6055X_{TCSC}$	0.1444	0.0982
		Branch 36	$-0.6851X_{TCSC}$		
		Branch 41	$-0.8X_{TCSC}$		
		Branch 14	$-0.8X_{TCSC}$		

4	SVC	Bus 21	30.31 MVAR	0.1444	0.107
	TCSC	Branch 16	$-0.8X_{TCSC}$		
	TCVR	Branch 33	1.044 ratio		
	TCPST	Branch 8	-20^{o} Degrees		

The L-index is evaluated at every bus with and without the placement of FACTS devices. For 3 SVC case comparison is shown in Figure 4.4.

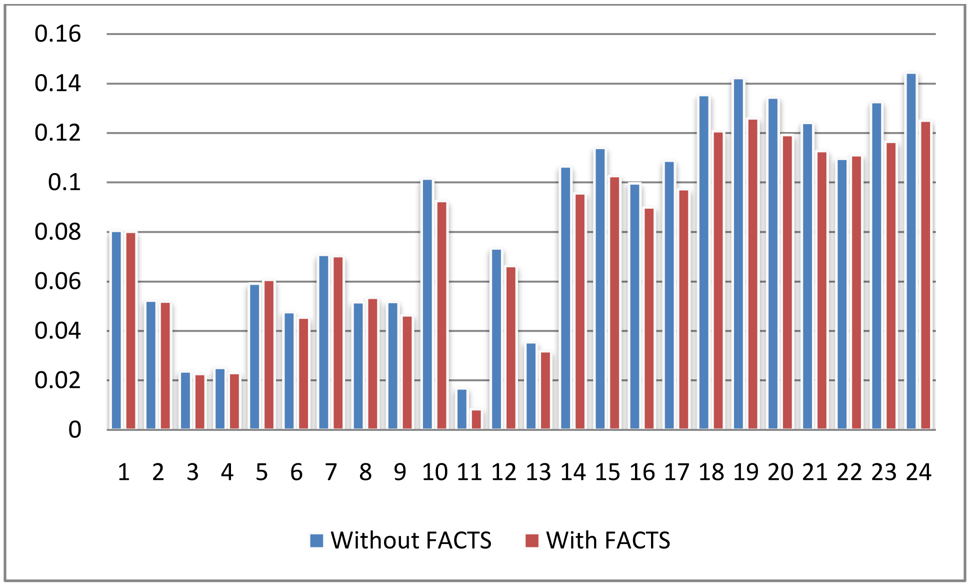

Figure 4.4 Comparison of L-index of buses without and with 3 SVC

In [86] genetic algorithm is used for the optimal placement and sizing of TCSC to improve system stability. Table 4.3 shows the comparison of results of this work with results reported in [86]

Table 4.8 Comparison of results with results reported in [86]

Variables	Results of this work	Results reported in [86]
TCSC location	Branch 15 Branch 36 Branch 41 Branch 14	Branch 13 Branch 14 Branch 12 Branch 16
X_{TCSC}	-0.6055 -0.6851 -0.8 -0.8	-0.4723 -0.4192 -0.4038 -0.4913
L-index	0.0982	0.1008

It can be seen that minimum L-index of 1.008 was achieved by placing the TCSC with optimal size and location reported in [86]. But with the optimal size and location obtained in this work value of system L-index is 0.0982, less then that obtained in [86].

4.3.2 IEEE 24bus System

The effect of FACT devices on voltage stability for IEEE 24 bus system is also checked. Table 4.9 shows the results for 24 bus system L-index minimization. The following Table 4.9 summarize that system's L-index without using any FACT device is 0.314 and is improved using FACT devices up to 0.2309.

Table 4.9 Lindex improvement of 24 bus system using FACTS devices

No. of FACTS	**Type**	**FACTS Location**	**Rating**	**System L-index**	
				Without FACTS	Using FACTS
3	SVC	Bus 9	121.7 MVAR	0.314	0.304
		Bus 17	150 MVAR		
		Bus 3	150 MVAR		
4	TCSC	Branch7	$-0.6510X_{TCSC}$	0.314	0.2685
		Branch 1	$-0.2888X_{TCSC}$		
		Branch 13	$-0.7773X_{TCSC}$		
		Branch 25	$-0.7103X_{TCSC}$		
4	SVC	Bus 28	150 MVAR	0.314	0.2309
		Bus 8	61.15 MVAR		
	TCSC	Branch 27	$-0.5746X_{TCSC}$		
		Branch 23	$-0.7996X_{TCSC}$		

4.4 Multiple Objective VAR Planning

For multiple objectives VAR planning non-dominated sorting differential evolution algorithm (NSDE) is used. Two cases are simulated for multiple objectives problem, case1 has two objectives i-e loadability and L-index while case 2 consist of 3objectives i-e. Loadability, L-index and cost of FACTS

4.4.1 Loadability vs L-index

Using NSDE optimal placement and sizing of FACTS devices is done to find optimal tradeoffs between loadability and L-index. Both single type FACTS and multiple type FACTS cases are investigated.Figure4.5-4.10 shows Pareto fronts for all cases i-e 1SVC, 1TCSC, 1TCVR, 1TCPST, 3SVC and multiple type FACTS. These pareto fronts give a clear picture to the system operator about the stability level of the system at higher loading conditions, so that he can manage the his operations more efficiently and effectively.

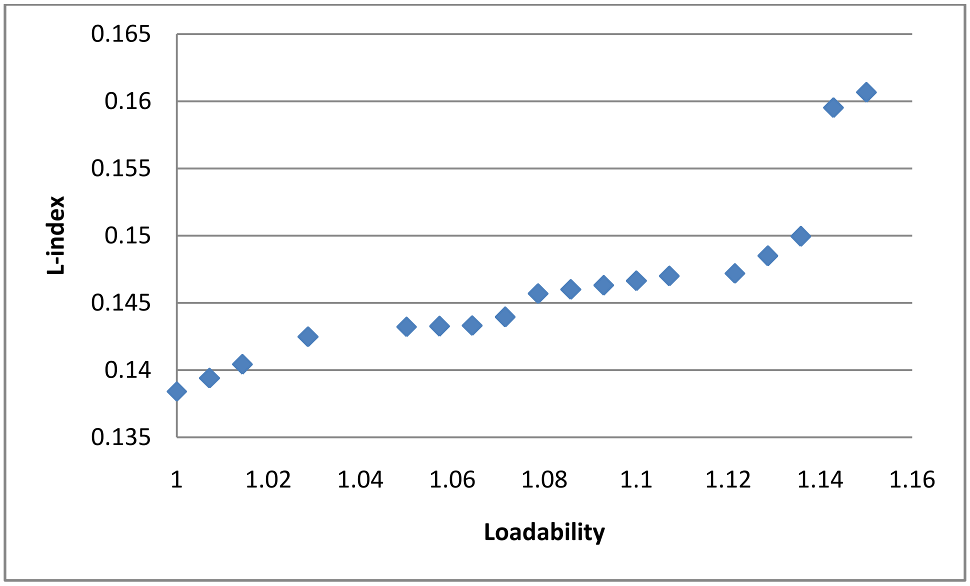

Figure 4.5 Pareto front for loadability vs L-index using single SVC

Figure 4.5 shows the Pareto optimal front for single SVC case. At maximum loadability of 115% the value of L-index is 0.1606 while at 100% loadability value of L-index is reduced to 0.138. A number of tradeoffs in between the two extremes are available from the Pareto front for the system operator.

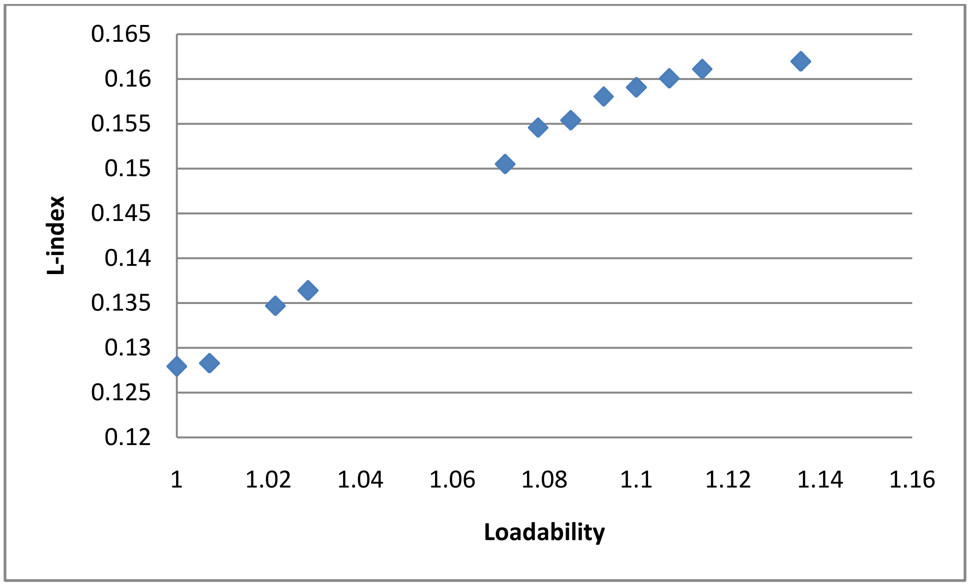

Figure 4.6 Pareto front for loadability vs L-index using single TCSC

Figure 4.6 shows the results for single TCSC, minimum value of L-index is 0.1278 for the base (100% loading) case and its value increases to 0.1618 for maximum loadability of 113.5% that can be achieved using single TCSC. Numbers of options in term of loading levels and corresponding L-index are available for the operator to choose.

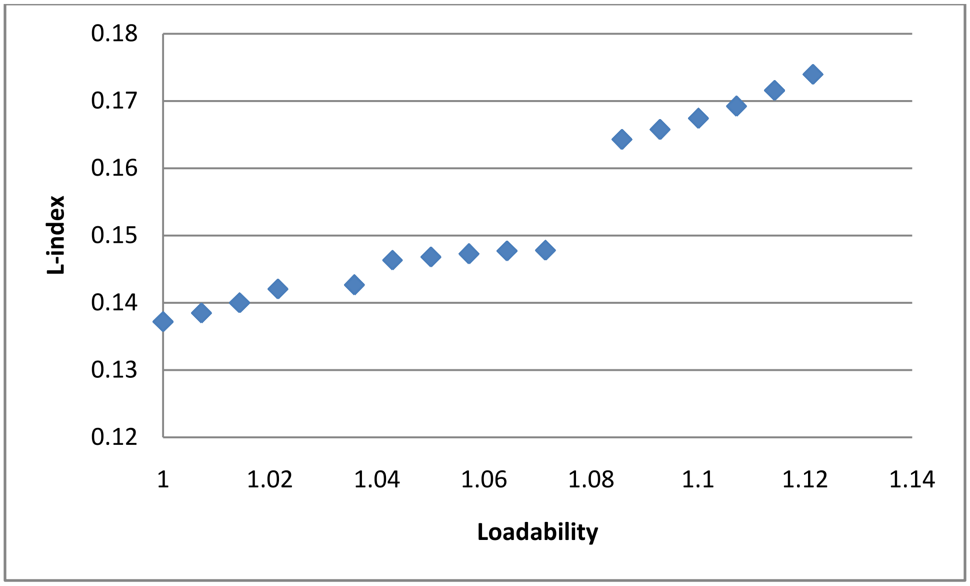

Figure 4.7 Pareto front for loadability vs L-index using single TCVR

In Figure4.7 optimal Pareto front for single TCVR shows the number of tradeoff between loadability and L-index, as loadability increases 1 to 1.12. At maximum loadability of112%the value of L-index value is 0.1738. Minimum value of L-index is 0.137.

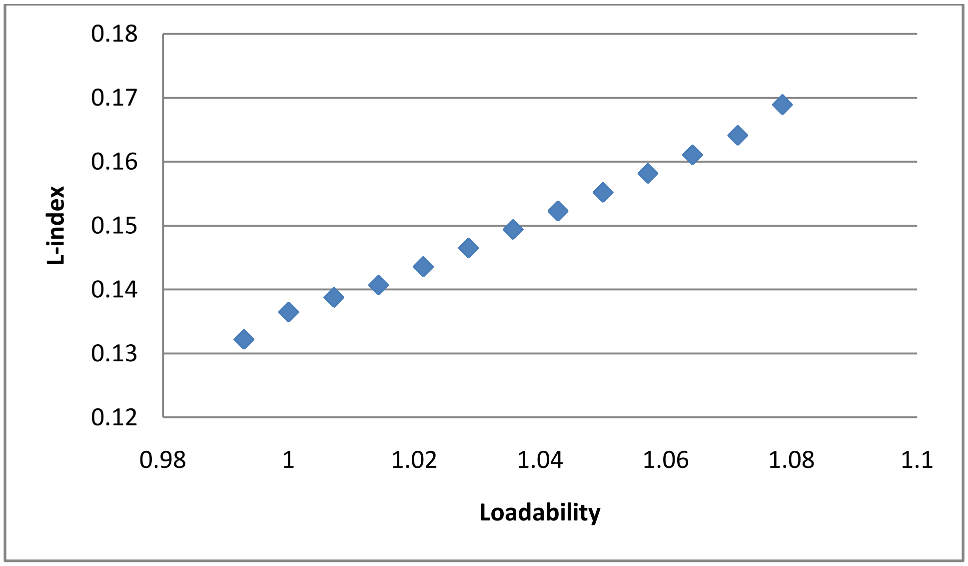

Figure 4.8 Pareto front for loadability vs L-index using single TCPST

From the Pareto front in Figure4.8 it can be seen that by using single TCPST maximum increase in loadability that can be achieved is 7.86% and L-index at that point is at a high value of 0.1688. For loading conditions from 1 to 1.078 (maximum) corresponding L-index values are given by Figure 4.8.

So we can see that out of all singe FACTS devices case 1SVC is the best option for the system operator as it provides maximum loadability of all at the cost of lowest L-index value. Now for the multi-FACTS case results for two scenarios are shown below.

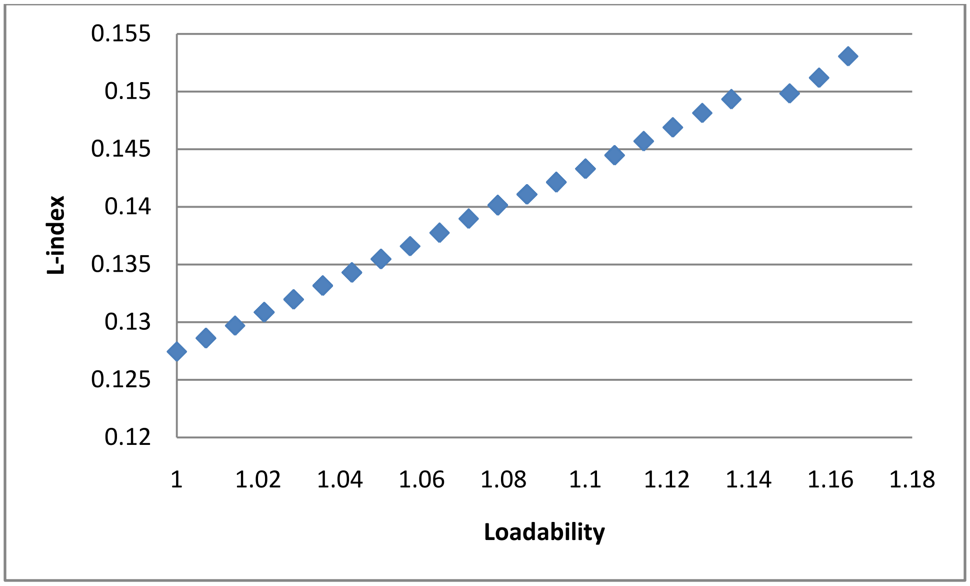

Figure 4.9 Pareto front for loadability vs L-index using 3 SVC

In Figure 4.9 Pareto front for 3SVC case is shown. Maximum increase in loadability and the corresponding L-index value are 16.4 % and 0.153 respectively. Minimum value of L-index is 0.127 for base case.

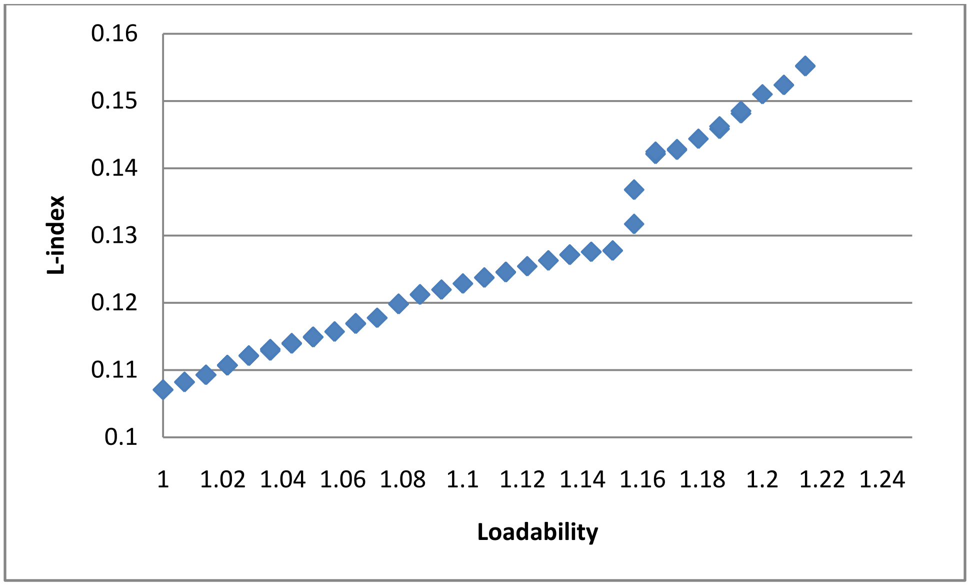

Figure 4.10 Pareto front for loadability vs L-index using multiple type FACTS

In case of multiple type FACTS devices 1 SVC, 1TCSC, 1TCVR and 1 TCPST is used. Pareto front in Figure 4.10 shows all optimal trade-offs between loadability and L-index. Maximum increase in loadability is 21% and the corresponding value of L-index for that is 0.156. Minimum value of L-index is 0.107.

So for the operator best option here is the multi-FACTS devices case. But some time economical constraint can be the important factor in reactive power planning so in next section cost of the FACTS devices is also included as a third objective function.

4.4.2 Loadability vs L-index vs Cost

Simulation results for this case i.e. loadability vs L-index vs cost, are shown in Figure 4.11-4.14. Simulations were run for 1SVC, 1TCSC, 3SVC and multiple FACTS cases. For each case the Figure gives a number of tradeoffs between loadability and L-index and the cost in $/MVAR for FACTS devices placed. In this case the combination of FACTS devices for each point on Pareto front is cost efficient. Power system planner can choose any of the combination according to his system requirement and budget. The maximum and minimum limits of loadability and L-index are same (as expected) as in case 1. Due to 3 objective functions, the Pareto front graphs are in 3-D. Since the explanation for all the points in the Pareto front is not possible, the maximum and minimum cost of FACTS and corresponding loadability and L-index values achieved for each case are explained below each Figure.

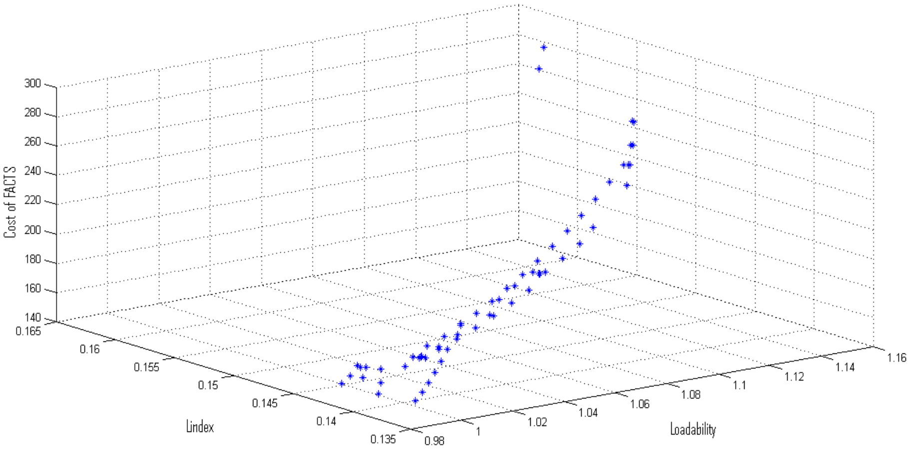

Figure 4.11 Pareto front for case 2 using single SVC

For single SVC case maximum loadability if 1.15 and corresponding minimum L-index value of 0.16 can be achieved at the cost of 284.6 $/MVAR. While minimizing L-index value, at 100% loadability condition (i-e λ=1), up to 0.138 will cost 150.9 $/MVAR. System operator can choose any combination within these extremes.

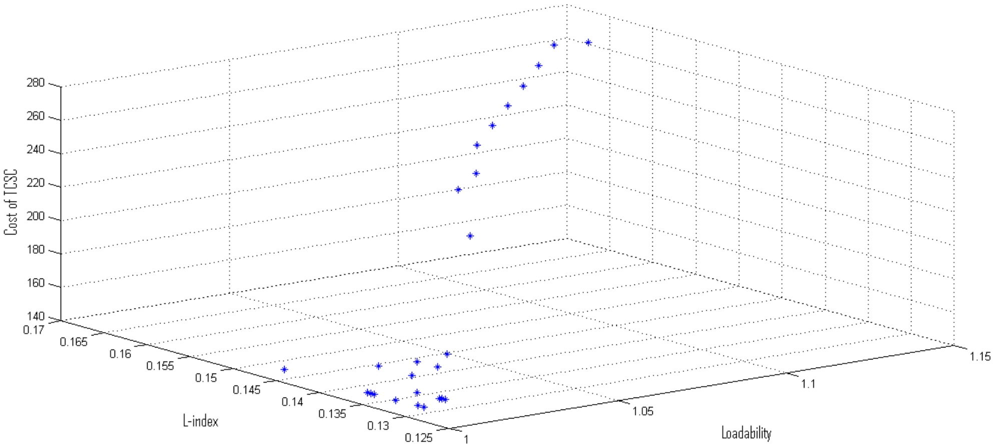

Figure 4.12 Pareto front for case 2 using single TCSC

In case of single TCSC at the cost of 273.4 \$/MVAR maximum loadability of 1.135 and the corresponding minimum L-index value of 0.161 can be achieved. While at λ=1 minimum L-index of 0.14 can be achieved at the cost of 147.5 \$/MVAR.

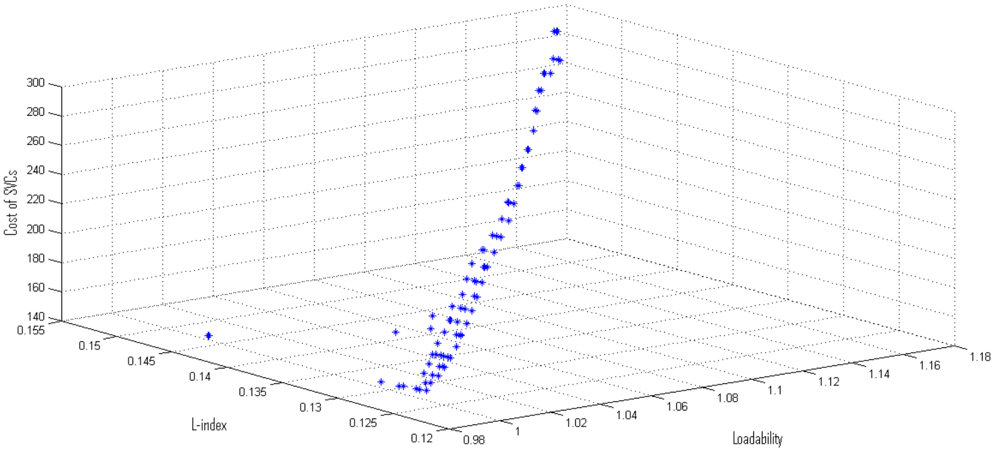

Figure 4.13 Pareto front for case 2 using 3 SVC

For 3 SVC case maximum loadability if 1.164 and corresponding minimum L-index value of 0.152 can be achieved at the cost of 292.1 \$/MVAR. While minimizing L-index value, at 100% loadability condition (i-e λ=1), up to 0.126 will cost 152 \$/MVAR. System operator can choose any combination within these extremes.

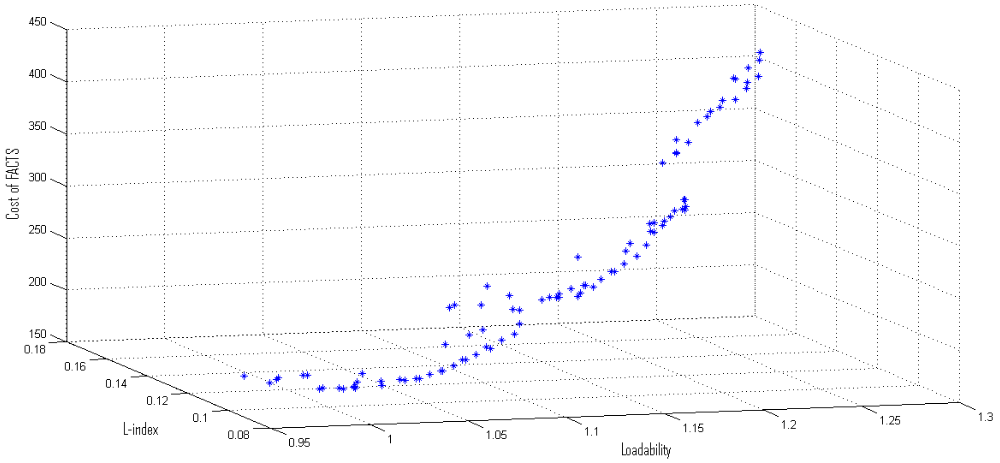

Figure 4.14 Pareto front for case 2 using multiple type FACTS

In case of multiple FACTS, at the cost of 405.3 \$/MVAR maximum loadability of 1.3 and the corresponding minimum L-index value of 0.1776 can be achieved. While at λ=1 minimum L-index of 0.124 can be achieved at the cost of 157.6 \$/MVAR.

4.5 Voltage Recovery Time of Network Following a Fault

IEEE 30 bus system is used for this case. Before doing analysis and reactive power planning, the voltage response against the fault at different buses is shown in the Figure.4.15.

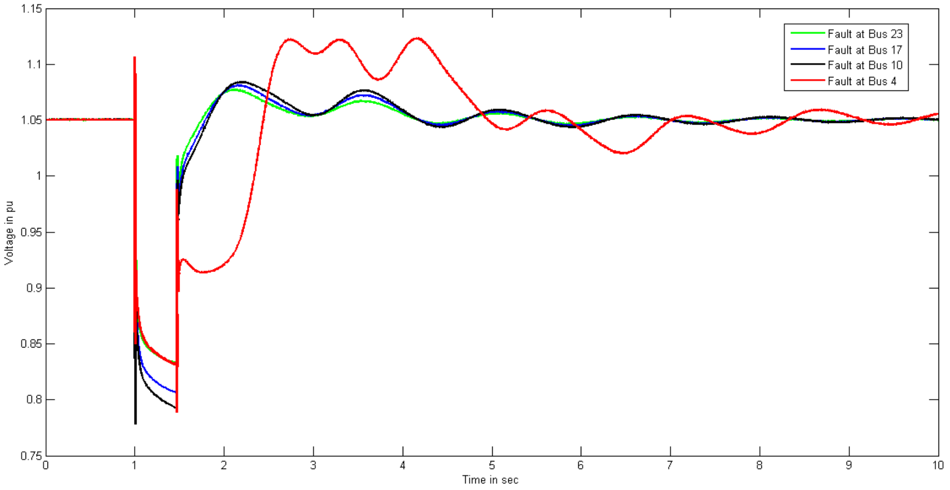

Figure 4.15 Voltage profile of bus 13 against the fault at different buses

Figure shows the voltage profile of bus 13 against fault at bus 23, 17, 10 and 4. As expected voltage response for the fault at bus which is nearest to generator buses is severe, and as we move away the response become less and less severe. So analysis in the next two sections is done for the fault at bus number 4.

4.5.1 With Synchronous Generators

DG units in this case are simple synchronous generators. There are six generators in this IEEE 30 bus system to supply total load. According to IEEE 1547 standard for interconnecting distributed resources with electrical power systems, voltage recovery time for DG bus after a short duration fault must be less than 2 second. This requires dynamic compensation using reactive power sources to bring back bus voltage to pre-fault condition.

Capacitors and STATCOM are used as VAR source in this work. For optimal capacitor placement, Differential Evolution algorithm with objective function of minimizing system loses and total investment cost on capacitors as illustrated in section 3.4 is used. About 40% of the buses are chosen to be the candidate for capacitor placement. After capacitor placement if voltage still does not come back within the permissible limits then out of these nodes (on which capacitors are placed) one with highest inductive reactive current I_R is chosen to be the candidate for the STATCOM placement. Table 4.10 shows the results of optimization algorithm for capacitor placement and decision for STATCOM placement.

Table 4.10 Optimal size and location of capcitors

Optimal Bus	Capacitor size (MVAr)	Statcom current Iq	Decision to Place Statcom
20	0.1008	capacitive	No
30	3.0041	capacitive	No
14	0.148	capacitive	No
16	0.3988	capacitive	No
2	**1.2022**	**inductive**	**Yes**
19	2.3316	capacitive	No
22	3.0514	capacitive	No
12	0.1013	capacitive	No
23	0.623	capacitive	No

As mentioned before and in [87], post fault voltage recovery requirement is that the DG bus voltage must be brought back to 90% to 110%of its normal operating voltage within 2 sec after a fault has taken place at a location near to generator bus. In this work, IEEE 30 bus test system is subjected to a three phase fault at bus 4 and the fault is cleared after 0.45 sec. Time simulation is run for three cases i-e without VAR sources, with capacitors, with STATCOM (if needed), under same operating conditions. In first case no FACTS device and capacitor is placed in the network. Fault is placed for the above mentioned time and voltage recovery at generator nodes is analyzed and recovery time is noted. Voltage recovery time is not less than 2sec for all the generator buses as shown in Table

4.9 so there is a need of reactive power compensation. Optimal sizes and locations of capacitors obtained using DE are listed in Table4.8. These capacitors are then placed at optimal locations for reactive power compensation. Simulation is run again for this case and recovery time is recorded. Still voltage recovery time is not less than 2sec for bus 11 and bus 13. Now in order place STATCOM reactive current I_R at each of the optimal location is checked. Currents at all nodes but 2 were capacitive, so according to defined criteria node 2 is selected to place STATCOM. In third case STATCOM is placed at node 2 and again voltage recovery time is recorded after running simulation. Now voltage recovery time at all the generator nodes are within 2 sec as per IEEE 1547 standard. Figure 4.16 shows the comparison of post fault voltage recovery at bus 2 for all three cases, namely without capacitors, with capacitors and with STATCOM at bus 2. Figure4.17-4.20 shows the comparison of post fault voltage recovery at bus 5, bus 8, bus 11, bus 13 respectively where other generator units are connected for the same cases. Table4.9 shows all the results in tabulated form. At nodes 11 and 13 no arrangement other than case three works i-e they need both static and dynamic reactive power compensation to bring back voltage within permissible limits in 2sec. For nodes 2, 5 and 8 all arrangements work fine.

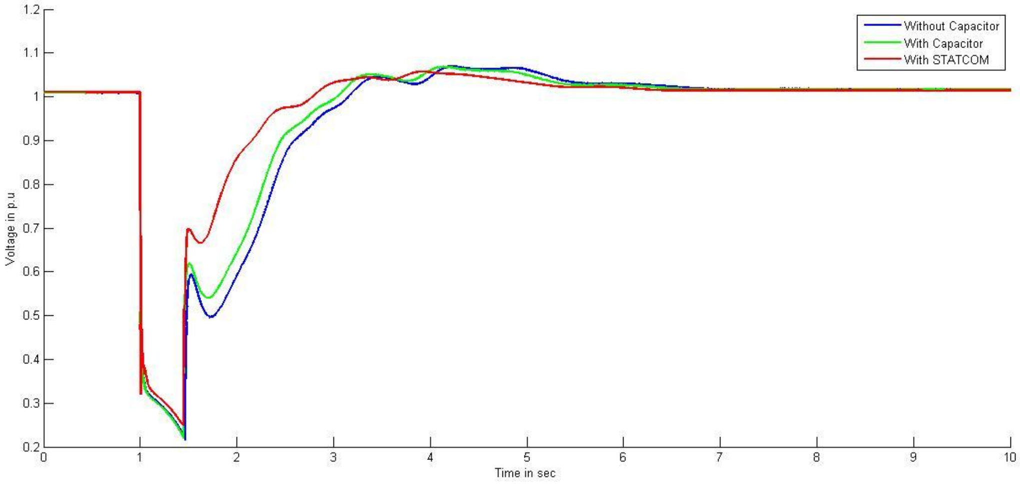

Figure 4.16 Voltage recovery at bus 2

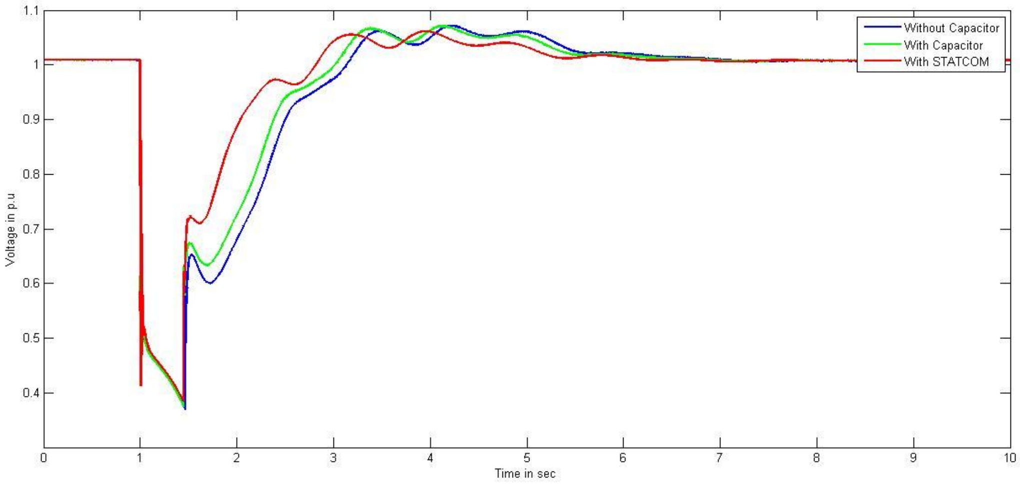

Figure 4.17 Voltage recovery at bus 5

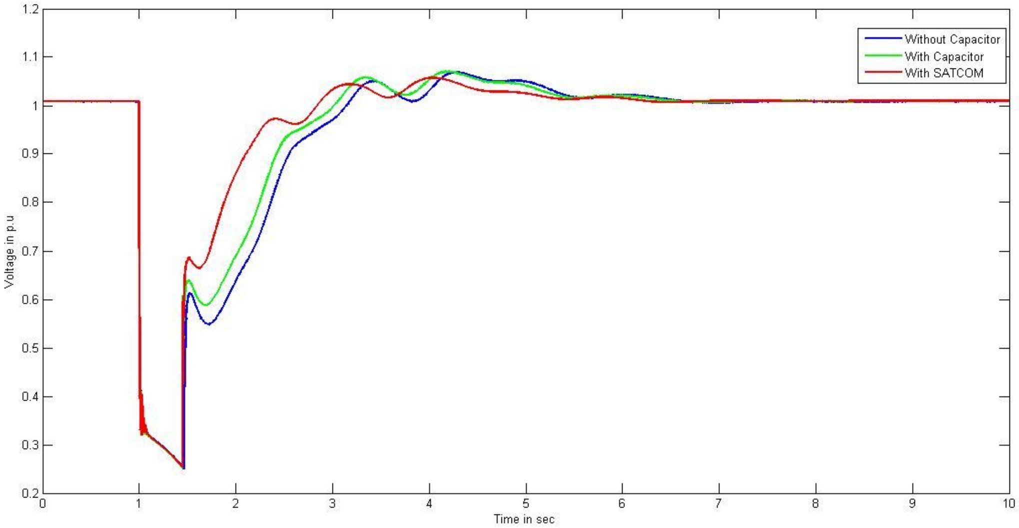

Figure 4.18 Voltage recovery at bus 8

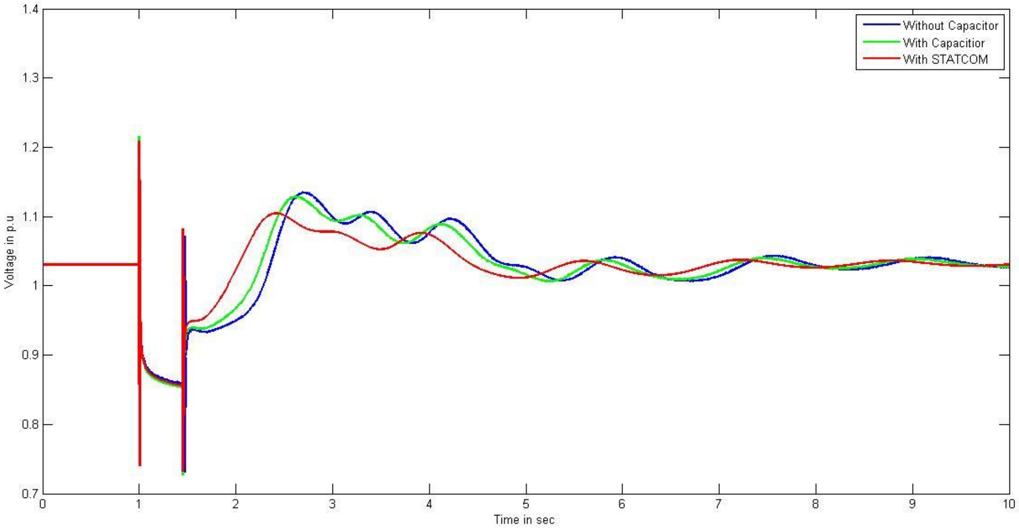

Figure 4.19 Voltage recovery at bus 11

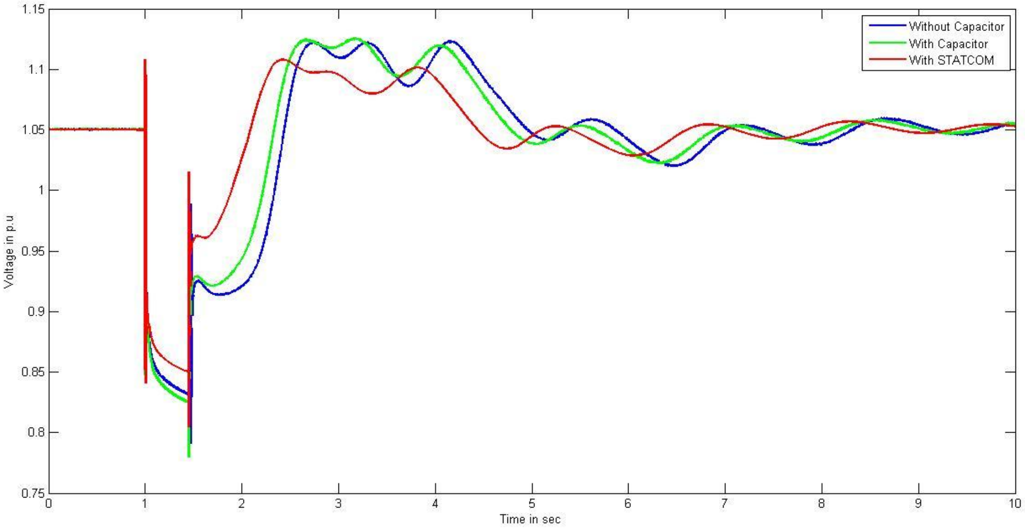

Figure 4.20 Voltage recovery at bus 13

Table 4.11 shows the voltage recovery time at buses in all three cases.

Table 4.11 Voltage recovery time

Generator Bus	Without Capacitor	With Capacitor	With STATCOM at Optimal Location
2	1.596 sec	1.452 sec	1.158 sec
5	1.500 sec	1.381 sec	1.035 sec
8	1.548 sec	1.418 sec	1.105 sec
11	2.531 sec	2.310 sec	1.514 sec
13	3.440 sec	3.318 sec	1.614 sec

4.5.2 With Added Wind DG

In this study, we investigate the power system performance after installing a wind power plant, instead of the conventional generator at Bus 8 and 13. Wind turbine with doubly fed induction generator (DFIG) model available in Simulink is used in this study. The generator is accompanied by AC-DC-AC convertor which has two sides' i-e rotor side and grid side. Rotor side convertor is connected rotor winding and converts AC input to DC output. Grid side converter is attached to grid through stator terminals and converts DC to AC. The stator winding transfers bulk of the power produced by wind generator; the slip power is transferred via the utility-side power converter. In this case, it was assumed that the wind turbines have a power factor range from 0.9 lagging to 0.9 leading. The operation mode of WTDFIG is set to voltage control mode. Because the wind generators use a power converter to control reactive power output, the response time is short compared to the response time of a conventional synchronous generator.

Two synchronous generators, one at bus 8 and other at bus13 are replaced by two wind farms of 21 MW consisting of fourteen 1.5 MW wind turbines with terminal voltage of 0.575kv connected to a 132 kV bus through 0.575kv/132kv transformer. The dynamic simulation was carried out the same way as in the previous section. Normal operation started from $t = 0$ s to $t = 1$ s, then a 0.4s fault was applied. Wind speed is assumed to be constant during the simulation. Time simulations are run to observe voltage recovery time at generator buses. A same criterion for capacitor placement is followed in this as in previous section. Table4.12 shows the size and location of capacitors to be placed in the system. After placing the capacitors voltage recovery time of each DG bus comes within

2sec of time, which is the grid requirement for DG integration as shown in Figure 4.21-4.25. Voltage recovery time before and after capacitor placement is shown in Table 4.13.

Table 4.12 Optimal size and location of capcitors

Optimal Bus	Capacitor size (MVAr)
18	0.540
30	1.740
23	4.290
21	0.626
1	0.52
15	0.700
17	0.580.
19	4.27.
29	0.500
26	2.376

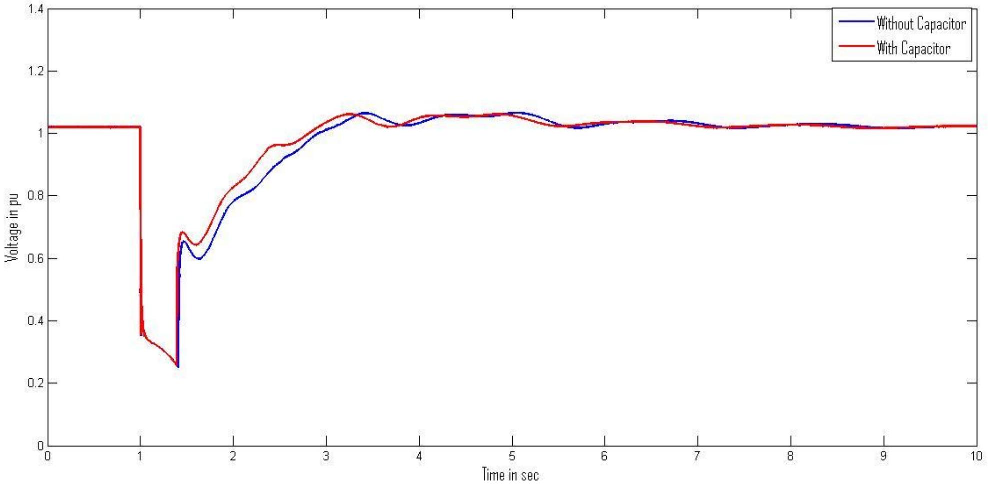

Figure 4.21 Voltage recovery at bus 2

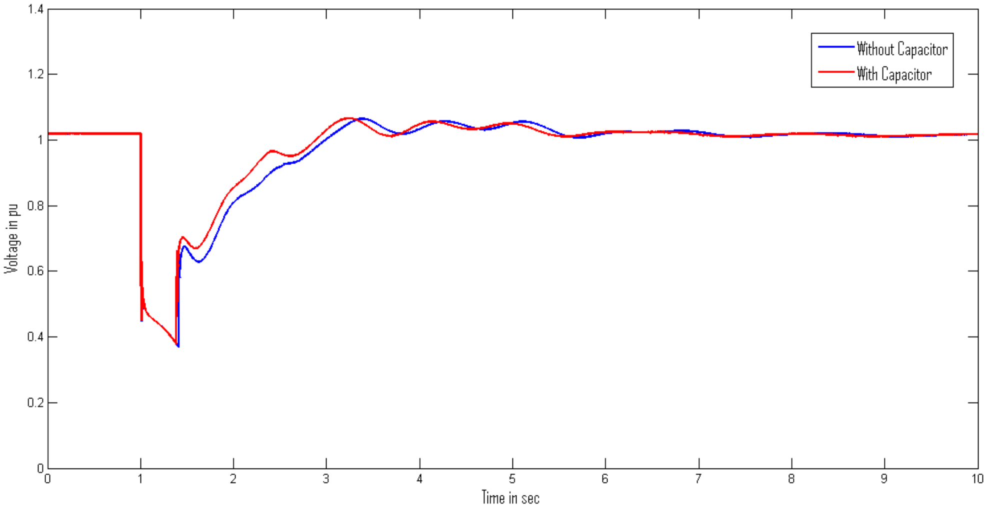

Figure 4.22 Voltage recovery at bus 5

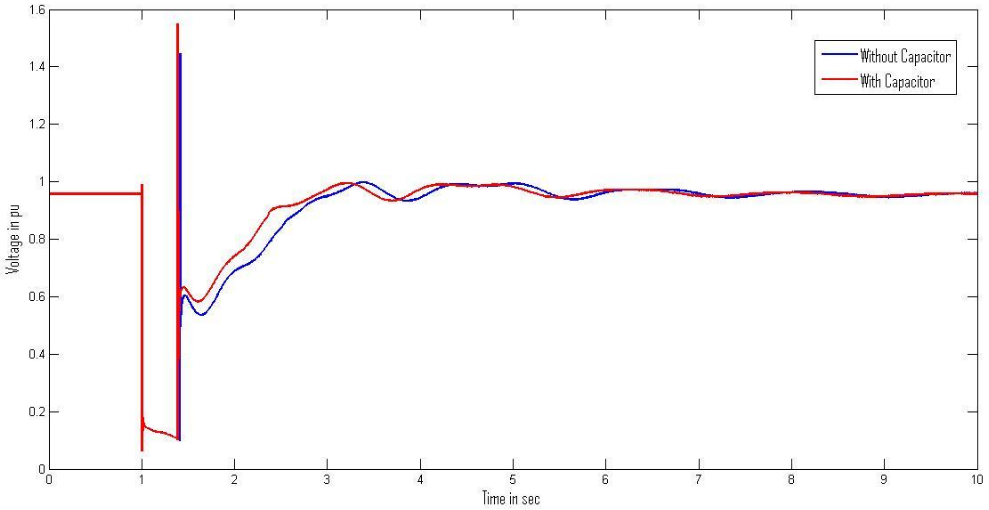

Figure 4.23 Voltage recovery at bus 8

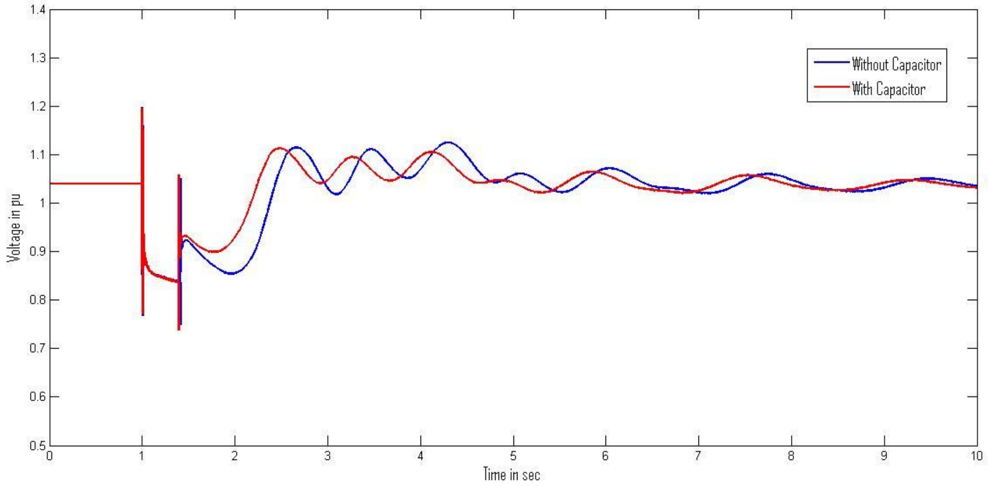

Figure 4.24 Voltage recovery at bus 11

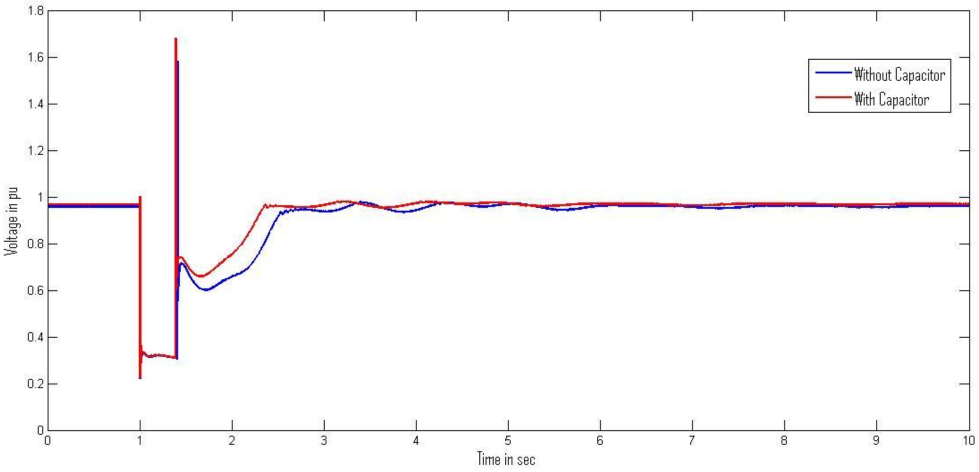

Figure 4.25 Voltage recovery at bus 13

Table 4.13 shows voltage recovery time at buses for both cases.

Table 4.13 Voltage recovery time

Generator Bus	Without Capacitor	With Capacitor
2	1.48 sec	1.25 sec
5	1.40 sec	1.18 sec
8	1.71 sec	1.39 sec
11	3.50 sec	1.6 sec
13	1.49 sec	1.26 sec

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

Voltage stability is of very high importance in power system operations. An optimal VAR planning is done, using differential evolution algorithm, to improve voltage stability of the system. FACTS devices (SVC, TCSC, TCVR, TCPST and STATCOM) are used as VAR source and IEEE 30 bus system is used as a test system for simulations.

In this work voltage stability is investigated in three different ways. First to check the system stability in case of high loadings, loadability is maximized and its effect on system bus voltages is checked. VAR planning is done to keep system within stability region in case of high loading conditions. Then voltage stability indices are used to investigate and improve the stability of system in normal conditions, L-index is used in this work. Voltage recovery time of generator bus voltage, followed by a short duration fault, is also improved by an optimal VAR planning.

Unlike [88] this work does not simply provide the system's maximum loadability but provides clear picture to the system operator that how much system becomes close to instability at a certain loading condition as we go on increasing loadability, thus providing number of options (tradeoffs) to the operator. Also the cost of FACTS devices is taken into consideration while doing VAR planning in this work. The idea of PIV index base loadability maximization has shown that if certain buses are considered for loadability maximization, more number of MW (load) can be served as compared to previous consideration of overall system's loadability. Voltage recovery time at generator bus is not only investigated for the system with synchronous generators but also for systems with wind farms.

5.2 Future Work

For future work, system can be considered as a deregulated system. Operator of a deregulated system needs to run contingency analysis continuously in order to avoid instability, so VAR planning will have to be done taking effect of contingencies into account. VAR planning for this case will be considered as an ancillary service. Planning should be cost effective in order to maximize the social welfare.

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Appendix A

Main Function:

```
%% Evolutionary Algorithm : Differential Evolution %%
% For minimization problem

clearall
clc
closeall

Nvar = 2; %variables to be optimised
Npop = 100; %population size
maxgen = 100; %max no of generations
F = 0.9; %mutation factor
CR = 0.4; %Crossover factor
ter_cr = 0;

%Minimum & Maximum constratint over variables

vmin = [1,10];    % minimum value of each variable
vmax = [30,100];  % maximum value of each variable

% niter=1; %iteration counter
Oldx = zeros(Npop,Nvar);
Oldfit = zeros(Npop,1);
forIpop = 1:Npop
% Call to initial population generation
Cursol = initial_pop(Npop,Nvar,vmin,vmax);
Oldx(Ipop,:) = Cursol(1,:);
% Call to objective calculation function
    [Oldfit(Ipop,:)] = Objective(Npop, Nvar, Cursol);
Ipop
%     end
end
Optimal_sol = [];
% Fitness evaluation for initial generation

[bestval_opt,index_opt] = min(Oldfit)
best_sol_opt = Oldx(index_opt,:)

forigen = 1:maxgen

forIpop = 1:Npop
Cursol = Oldx(Ipop,:);
% Call to mutation process
        Mutant(Ipop,:) =
Mutation(Npop,Nvar,vmin,vmax,Oldfit,Cursol,F,best_sol_opt,Oldx);
end
% Call to crossover process
    Trial = Crossover(Npop,Nvar,Oldx,Mutant,CR);
```

```
forIpop = 1:Npop
Cursol = Trial(Ipop,:);
Trialfit(Ipop,1) = Objective(Npop, Nvar, Cursol);
end
% New generation production
fori = 1:Npop
if (Trialfit(i,1) <Oldfit(i,1))
Newx(i,1:Nvar) = Trial(i,1:Nvar);
else
Newx(i,1:Nvar) = Oldx(i,1:Nvar);
end
end
% New generation evaluation
forIpop = 1:Npop
Cursol = Newx(Ipop,:);
Newfit(Ipop,1) = Objective(Npop, Nvar, Cursol);
end
    [best,index] = min(Newfit);
% Optimal Sol Update
if (best <bestval_opt)
bestval_opt = best
best_sol_opt = Newx(index,:);
end
Oldx = Newx;
Optimal_sol(igen,1) = bestval_opt;
ifigen> 1
ifOptimal_sol(igen-1) == Optimal_sol(igen)
ter_cr = ter_cr + 1;
ifter_cr> 70
break;
end
else
ter_cr = 0;
end
end
igen
end
plot(Optimal_sol)
%*********************************************************************%
```

Mutation:

```
function [Mutant] =
Mutation(Npop,Nvar,vmin,vmax,Oldfit,Cursol,F,best_sol,Oldx)
for j=1:2
    m1=floor(1+rand()*(Npop-1));
    m2=floor(1+rand()*(Npop-1));
while (m2==m1)
        m2=floor(1+rand()*(Npop-1));
end
ifOldfit(m1)<=Oldfit(m2)
mate(j)=m1;
else
mate(j)=m2;
end
```

```
end
mate1=mate(1);
mate2=mate(2);

for j = 1:Nvar
        Mutant(1,j) = Cursol(1,j) + F*(best_sol(1,j)- Cursol(1,j)) +
F*(Oldx(mate1,j) - Oldx(mate2,j));
if (j==1)
Mutant(1,j) = round(Mutant(1,j));
end
if (Mutant(1,j) <vmin(j))
Mutant(1,j) = vmin(j);
elseif (Mutant(1,j) >vmax(j))
Mutant(1,j) = vmax(j);
end
end

return
%*****************************************************************%
```

Crossover:

```
%% Crossover function for DE
function [Trial] = Crossover(Npop,Nvar,Oldx,Mutant,CR)
fori = 1:Npop
for j = 1:Nvar
        Probability=CR;
flip=flip1(Probability);
if flip==1
Trial(i,j) = Oldx(i,j);
else
Trial(i,j) = Mutant(i,j);
end
end
end
%*****************************************************************%
```

Appendix B

Data for IEEE 30 bus system

Generator Data:

Gen No	Pimin (MW)	Pimax (MW)	Qimin (MVAr)	Qimax (MVAr)	ai	bi	ci	αi	βi	γi
1	50	200	-	-	0.0038	2.0	0.0	0.013	-1.100	22.98
2	20	80	20	100	0.0175	1.8	0.0	0.020	-0.100	25.31
3	15	50	15	80	0.0625	1.0	0.0	0.027	-0.010	25.51
4	10	35	15	60	0.0083	3.3	0.0	0.029	-0.005	24.90
5	10	30	10	50	0.025	3.0	0.0	0.029	-0.004	24.70
6	12	40	15	60	0.025	3.0	0.0	0.027	-0.006	25.30

Bus Data:

Bus No.	Load		Bus No.	Load	
	P (MW)	Q (MVAr)		P (MW)	Q (MVAr)
1	0	0	16	3.5	1.8
2	21.7	12.7	17	9	5.8
3	2.4	1.2	18	3.2	0.9
4	7.6	1.6	13	9.5	3.4
5	94.2	19	20	2.2	0.7
6	0	0	21	17.5	11.2
7	22.8	10.9	22	0	0
8	30	30	23	3.2	1.6
9	0	0	24	8.7	6.7
10	5.8	2	25	0	0
11	0	0	26	3.5	2.3
12	11.2	7.5	27	0	0

13	0	0	28	0	0
14	6.2	1.6	29	2.4	0.9
15	8.2	2.5	30	10.6	1.9

Bus No.	Susceptance
10	19
24	4

Line Data:

Line No.	From Bus	To Bus	Series Impedance (p.u)		Half Line Charging Susceptance (p.u)	Tap Setting	MVA Rating
			R	X			
1	1	2	0.01920	0.05750	0.02640	-	130
2	1	3	0.04520	0.18520	0.02040	-	130
3	2	4	0.05700	0.17370	0.01840	-	65
4	3	4	0.01320	0.03790	0.00420	-	130
5	2	5	0.04720	0.19830	0.02090	-	130
6	2	6	0.05810	0.17630	0.01870	-	65
7	4	6	0.01190	0.04140	0.00450	-	90
8	5	7	0.04600	0.11600	0.01020	-	70
9	6	7	0.02670	0.08200	0.00850	-	130
10	6	8	0.01200	0.04200	0.00450	-	32
11	6	9	0.00000	0.20800	0.00000	1.0155	65
12	6	10	0.00000	0.55600	0.00000	0.9629	32
13	9	11	0.00000	0.20800	0.00000	-	65
14	9	10	0.00000	0.11000	0.00000	-	65
15	4	12	0.00000	0.25600	0.00000	1.0129	65
16	12	13	0.00000	0.1400	0.00000	-	65
17	12	14	0.12310	0.25590	0.00000	-	32
18	12	15	0.06620	0.13040	0.00000	-	32
19	12	16	0.09450	0.19870	0.00000	-	32
20	14	15	0.22100	0.19970	0.00000	-	16

21	16	17	0.08240	0.19320	0.00000	-	16
22	15	18	0.10700	0.21850	0.00000	-	16
23	18	19	0.06390	0.12920	0.00000	-	16
24	19	20	0.03400	0.06800	0.00000	-	32
25	10	20	0.09360	0.20900	0.00000	-	32
26	10	17	0.03240	0.08450	0.00000	-	32
27	10	21	0.03480	0.07490	0.00000	-	32
28	10	22	0.07270	0.14990	0.00000	-	32
29	21	22	0.01160	0.02360	0.00000	-	32
30	15	23	0.10000	0.20200	0.00000	-	16
31	22	24	0.11500	0.17900	0.00000	-	16
32	23	24	0.13200	0.27000	0.00000	-	16
33	24	25	0.18850	0.32920	0.00000	-	16
34	25	26	0.25440	0.38000	0.00000	-	16
35	25	27	0.10930	0.20870	0.00000	-	16
36	28	27	0.00000	0.36900	0.00000	0.9581	65
37	27	29	0.21980	0.41530	0.00000	-	16
38	27	30	0.32020	0.60270	0.00000	-	16
39	29	30	0.23990	0.45330	0.00000	-	16
40	8	28	0.06360	0.20000	0.02140	-	32
41	6	28	0.01690	0.05990	0.00650	-	32

Data for IEEE 24 bus system:

Bus Data:

Bus no	Load		Generation			
	MW	MVAR	MW	MVAR	Qmin	Qmax
1	108	22	172	0	-50	80
2	97	20.7	172	0	-50	80
3	180	37	0	0	0	0
4	74	15	0	0	0	0
5	71	14	0	0	0	0

6	136	28	0	0	0	0
7	125	25	240	0	0	180
8	171	35	0	0	0	0
9	175	36	0	0	0	0
10	195	40	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	265	54	285.3	0	0	240
14	194	39	0	35	-50	200
15	317	64	215	0	-50	110
16	100	20	155	0	-50	80
17	0	0	0	0	0	0
18	333	68	400	0	-50	200
19	181	37	0	0	0	0
20	128	26	0	0	0	0
21	0	0	400	0	-50	200
22	0	0	300	0	-50	80
23	0	0	660	0	-125	310
24	0	0	0	0	0	0

Line Data:

Line no	From Bus	To Bus	Series Impedance pu		Half Line Charging Susceptance (p.u)	Tap Setting	Line Limits
			R	X			
1	1	2	0.0026	0.0139	0.23055	1	175
2	1	3	0.0546	0.2112	0.0285	1	175
3	1	5	0.0218	0.0845	0.01145	1	350
4	2	4	0.0328	0.1267	0.01715	1	175
5	2	6	0.0497	0.192	0.026	1	175
6	3	9	0.0308	0.119	0.0161	1	175
7	3	24	0.0023	0.0839	0	1	400
8	4	9	0.0268	0.1037	0.01405	1	175

9	5	10	0.0228	0.0883	0.01195	1	350
10	6	10	0.0139	0.0605	1.2295	1	175
11	7	8	0.0159	0.0614	0.0083	1	350
12	8	9	0.0427	0.1651	0.02385	1	175
13	8	10	0.0427	0.1651	0.02385	1	175
14	9	11	0.0023	0.0839	0	1	400
15	9	12	0.0023	0.0839	0	1	400
16	10	11	0.0023	0.0839	0	1	400
17	10	12	0.0023	0.0839	0	1	400
18	11	13	0.0061	0.0476	0.04995	1	500
19	11	14	0.0054	0.0418	0.04395	1	500
20	12	13	0.0061	0.0476	0.04995	1	500
21	12	23	0.0124	0.0966	0.1015	1	500
22	13	23	0.0111	0.0865	0.0909	1	500
23	14	16	0.005	0.0389	0.0409	1	500
24	15	16	0.0022	0.0173	0.0182	1	500
25	15	21	0.0063	0.049	0.0515	1	1000
26	15	21	0.0063	0.049	0.0515	1	500
27	15	24	0.0067	0.0519	0.0545	1	500
28	16	17	0.0033	0.0259	0.02725	1	500
29	16	19	0.003	0.0231	0.02425	1	500
30	17	18	0.0018	0.0144	0.01515	1	500
31	17	22	0.0135	0.1053	0.1106	1	1000
32	18	21	0.0033	0.0259	0.02725	1	1000
33	18	21	0.0033	0.0259	0.02725	1	1000
34	19	20	0.0051	0.0396	0.04165	1	500
35	19	20	0.0051	0.0396	0.04165	1	500
36	20	23	0.0028	0.0216	0.02275	1	500
37	20	23	0.0028	0.0216	0.02275	1	500
38	21	22	0.0087	0.0678	0.0712	1	500

Appendix C

Modeling of all the FACTS devices used in this work are given below;

SVC:

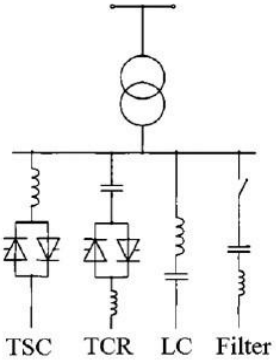

Figure C.1 SVC model

Static Var compensator (SVC) is an electrical device that provides fast-acting reactive power on high voltage transmission network. SVC's are capable to regulate voltage and enhance the stability of the system. SVC is modeled as injected reactive power at the bus. The typical values of SVC are presented in eq. 1.1 where Qmax=150.

$$-Q_{SVC\max} \le Q_{SVC} \le Q_{SVC\max} \tag{C.1}$$

TCSC

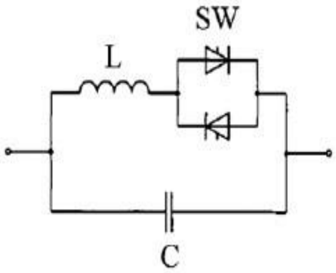

Figure C.2 TCSC model

The inclusion of TCSC (thyristor controlled series capacitor) in power flow works as a capacitive or inductive compensation. The modeling of TCSC is presented in eq.1.2 to modify series reactance. The typical value of k_{TCSC} ranges from -0.8 to 0.2.

$$\begin{aligned} & x_{TCSC} = k_{TCSC} x_{ik} \\ & k_{TCSC\min} \le k_{TCSC} \le k_{TCSC\max} \\ & -0.8x_{ik} \le x_{TCSC} \le 0.2x_{ik} \\ & x_{ik}^{'} = x_{TCSC} + x_{ik} \\ & x_{ik}^{'} = \left(1 + k_{TCSC}\right) x_{ik} \end{aligned} \tag{C.2}$$

x_{TCSC} is TCSC reactance while x_{ik} is reactance of the line between bus i and k

TCVR

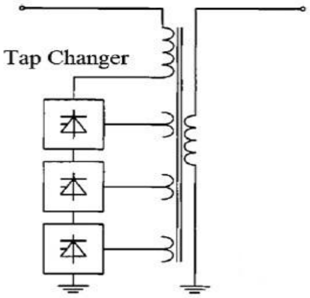

Figure C.3 TCVR model

The TCVR (thyristor controlled voltage regulator) is used to modify the bus voltage magnitude. It can be modeled as a tap changer transformer. Modeling of TCVR is presented in eq.1.3

$$\begin{aligned} & V_{TCR} = k_{TCVR} V_i \\ & -k_{TCVR\max} \le k_{TCVR} \le k_{TCVR\max} \\ & V_i^{'} = \left(1 + k_{TCVR}\right) V_i \\ & 0.85V_i \le V_i^{'} \le 1.15V_i \end{aligned} \tag{C.3}$$

Where the typical value of k_{TCVR} ranges from 0.15 to -0.15, V_i is the nominal bus voltage and $V_i^{'}$ is the updated bus voltage.

TCPST

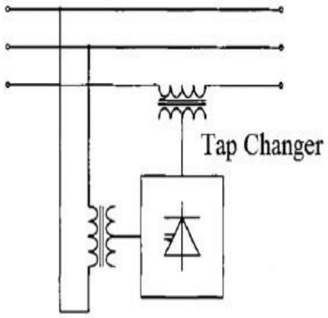

Figure C.4 TCPST model

Thyristor controlled phase shifting transformer (TCSPT) is modeled as a phase shifting transformer. The voltage angle between sending and receiving end is regulated using TCSPT [32]. The typical value of $\delta_{TCPST\max}$ =20^{o}.

$$-\delta_{TCPST\max} \le \delta_{TCPST} \le \delta_{TCPST\max} \tag{C.4}$$

VITAE

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Name	:	**Bilal Jehanzeb**
Nationality	:	**Pakistani**
Age	:	**24**
Languages	:	**English, Urdu**

Professional Qualification:

- **M.E** in Electrical Engineering from **King Fahd University of Petroleum &Minerals**, Saudi Arabia.
- **B.E**. in Electrical (Power) Engineering from **COMSATS University,** Pakistan.

Professional Profile:

I am an Electrical Power Engineer. During my 6 year professional education I have done some good engineering projects ranging from design and planning to protection of power system. I have worked on 220kv GIS grid protection and relay coordination using ETAP, application of FACTS devices to improve network loadability and stability, design and development of future plans for power systems with increased future loads and electricity bidding strategy for day-a-head electricity markets for GENCOs.

I am an enthusiastic team player. My goal is to Work for an Organization where I can further develop myself as a true professional & contribute in the growth of the Organization

Key Skills & Attributes:

- Power system protection Schemes
- Relay coordination and Load Flow analysis of 220kv grid using ETAP
- Fault analysis and short circuit calculations for equipment selection of 220kv grid
- CT/VT sizing and Relay Setting calculations
- Heuristic optimization techniques
- Confident Communicator: Possess good, clear, and concise presentation skills
- Effective contributor: Capable of voicing opinions and giving valuable inputs whenever needed
- Quick and enthusiastic in study: Enjoy learning new skills, technologies and cultures

Electrical Software Skills:

AutoCAD, ETAP 7, MATLAB, FORTRAN, C++, Simulink, Visio, Power world simulator

Employment History:

a) **Company:** **King Fahd University of Petroleum and Minerals**
Duration: **August 2013- Till Date**

Designation: **Research Assistant**

Projects:

- Electricity bidding strategy in day-a-head electricity market using Model Predictive Controller
- Design and development of future plans for power systems with increased future loads.
- Optimal placement and sizing of multiple type FACTS to increase loadability and stability of system
- Optimal placement and sizing of FACTS to improve post fault voltage recovery at Distributed Generation (DG) bus

b) **Company:** **Terbela Hydro Power Plant.**
Duration: **June 2011- August 2011**

Designation: **Internee**

Power Plant

- Total installed capacity of power plant is 3478MW
- Switchyard has voltage levels of 220kv and 500kv

Internship Departments & fields

- Protection & Instrumentation
- Study of generator & transformer protection and relays
- Study of Switchyard equipments
- Gained practical knowledge of power plant generator operations
- Studied Protection Schemes
- Electrical Drawing Reading

Academic Projects (COMSATS Institute of Information Technology, Pakistan):

- Study and analysis of 220kv Grid chashma, Pakistan
    - Detailed fault analysis, load flow analysis, short circuit calculation, CT/PT sizing and relay coordination was done.

Major Courses:

- Renewable Energy
- Power System Planning
- Power System Analysis
- Power System Operation and Control
- Power Generation
- Power Transmission
- Power Distribution and Utilization
- Power System Protection
- Power Electronics
- High Voltage Engineering

Achievements:

- Full Funded Scholarship at King Fahd University of Petroleum and Minerals for Ms in Electrical Engineering
- **Chancellor's Gold Medal** of COMSATS Institute of Information Technology (CIIT) Pakistan for securing top position in BS. Electrical Engineering, at institute level (in all 7 Campuses of CIIT)
- **Campus Gold Meda**l of COMSATS Institute of Information Technology (CIIT) Abbottabad Campus Pakistan for securing top position in BS. Electrical Engineering, at campus level
- Scholarship Holder on Academic basis throughout MS and BS studies