VOLTAGE STABILITY ANALYSIS AND IMPROVEMENT OF VOLTAGE PROFILE BY STATIC VAR COMPENSATOR

Dissertation submitted in fulfillment of the requirements for the award of the degree of

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in

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Submitted By

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DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, **"Voltage Stability Analysis and Improvement of Voltage Profile by Static Var Compensator"** in the partial fulfilment of the requirement for the award of the Degree of **Master of Engineering** in **Power Systems**, submitted to **Electrical & Instrumentation Engineering Department** of **Thapar University, Patiala**, is an authentic record of my own work carried under the supervision of **Dr. Sanjay K. Jain**. It refers others researcher's work which are duly listed in the reference section.The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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Abstract

The bus voltage in power system depends on reactive VAR support, the poor voltage regulation is indicative of deficient reactive VAR and system is regarded as weak system. Voltage stability analysis is essential for the well operation of power system. Through voltage stability analysis the maximum loading capacity of the system has been computed and the most sensitive bus has been found. If the load increases further, the voltage collapse can be resulted. The reactive power support by the SVC in the network can effectively increase the limits of bifurcation point and hence used for voltage profile improvement. For this purpose, optimal rating of SVC has been identified using Particle Swarm Optimization taking voltage deviation at the bus as the objective function. The methodology used for finding the saddle point of the system is continuation power flow and results obtained are tried to be implemented on IEEE 30-bus system.

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Nomenclature & Abbreviations

λ	Load factor
P_i	Injected Real Power
P_{gi}	Generated Real Power
P_{li}	Load Real Power
P_{ti}	Transmitted Power
Q_i	Injective Reactive Power
Q_{li}	Load Reactive Power
Q_{gi}	Generated Reactive Power
Q_{ti}	Transmitted Reactive Power
V_i	The voltage at the ith bus
V_j	Voltage at jth bus
δ_i	Bus angle at ith bus
δ_j	Bus angle at jth bus
θ_{ij}	Line admittance angle between bus i and j
y_{ij}	Admittance of line between bus i and j
Q_{lio}	Base reactive load at i^{th} load bus
P_{lio}	Base active load at i^{th} load bus
K_{li}	constant specifying rate of load change as λ varies
p	total particles in search space
P_{best}	Personal best Value of SVC
G_{best}	Global best value of SVC
v_p	Velocity of p^{th} particle
w_1	Inertia coefficient of PSO
c_1, c_2	Acceleration coefficients
CPF	Continuation Power Flow
ESC	Expected Security Cost
FACTS	Flexible AC Transmission System
GA	Genetic Algorithm

HVDC	High Voltage DC System
OLTC	On Load Tap Changing Transformers
PSO	Particle Swarm Optimisation
SVC	Static VAR Compensator
SLDC	State Load Dispatch Centres
TCR	Thyristor-Controlled Reactor
TSC	Thyristor-Switched Capacitor
RLDC	Regional Load Dispatch Centres

Introduction

1.1 OVERVIEW

With the growing urbanization and dependency on the electric power, generation capacity is being added to cater load demand. To meet the ever increasing demand of electricity various steps are being taken up like giving stress on non-conventional sources like wind and solar, besides this new power plants are being set up. But the main problem lies with the transmission system as a major portion of power being wasted in the process of transmission of electricity. One of the methods to increase the transmission capacity of the power system is by installing new infrastructure but this method is not economically viable as well as practically difficult due to various problems like a right of way, land cost, transmission lines from forest area or from the land which is highly cultivating. Due to all these problems, new methods are given the emphasis, in which compensation of the line plays a major role, because of the reactive power compensation transmission line can easily be loaded up to their thermal limit and the voltage profile of the system can also be maintained.

As we are living in an interconnected power system in the form of a grid, where the balance between reactive power supply and the load is the key requirement for the effective operation of the power system. If this balance is disturbed then there is a high probability of voltage instability occurrence, voltage collapse is an event of voltage instability in the system. It could be stated that the system is under the stage of voltage collapse or voltage instability when with increment of load or alteration of load demand, the system voltage will fall down continiously [1].

The basic condition for a voltage stable system is that as soon as the reactive power is injected into the system the bus voltage magnitude must also be incremented following the operating conditions of the system. Similarly, for a voltage unstable system, the injection of reactive power will cause the decrement of the voltage profile of the system. Therefore it can be concluded that V-Q sensitivity for a stable system is positive and that for an unstable system is negative.

If proper reactive power compensation is not provided, then it may cause the occurrence of blackouts like, 2012 Northern Grid Failure, India, this blackout has affected about 62 billion people or about 9 percent of the world population i.e. about half of India population [2]. The significant reasons that effects the voltage stability of the system can be defined as follows:

- Sudden increment of the load of system
- Reactive power compensation devices are operating on the marginal boundary of the system and can get distorted on a minor change.
- Sudden change on the OLTC due to load variation of the system
- Due to governor action of the generator which takes care of the dynamic load change
- Moment of any kind of fault or line tripping may eventually lead to the voltage instability.

These changes significantly effects the noraml operation of the system and hence cause the malfunctioning of three important pillars of the system generation, transmission and distribution. To avoid such phenomenon of voltage collapse there are many preventive measures adopted like:

- Turn off the shunt capacitor which may add on the fault level.
- OLTC must be immediately shut down.
- Generation shift is also a measure readily adopted.
- The load can be switched off.
- Reactive power booster for the generator which will be a backup plan and can compensate the voltage dip.

The foremost requirement for the proper planning and operation of the power system is to know about the voltage stability of the system, [3] gave a detailed description about voltage stability, covering both transient and longer-term phenomena. It provides us the tools for modeling the different equipments of the power system like a hydraulic turbine, governor system besides this, the detailed discussion of the transmission, distribution, and generation in a power system has been discussed.

The event of voltage collapse and voltage instability are quite closely related to each other, rather it could be said that that the voltage collapse is a final event which occures after voltage instability. It refers the sequence of events which generally occurs in the system when the instability of voltage occurs and may eventually lead to a blackout of the whole system.

The main cause of the voltage instability is the load and the miscellaneous characteristics of the load, due to this reason voltage stability problem is often referred as load stability problem. If the long transmission line system is considered, then it can be noted that system it is represented by series resistance and reactance and in shunt by admittance and capacitance. The shunt capacitance is one of the major sources of the reactive power of the system, but if the required demand of the system load for reactive power is quite high then it may cause the voltage to fall and as a result, the voltage stability problem may occur.

1.1.1 Classification of power system stability

Broadly the voltage instability event can be classified under four major heads which are classified according to the duration of fault level in the system, it can easily be inferred from the names as long term, short term and the severity of the fault level as large disturbance and small disturbance. A summary of these classifications is as shown in figure 1.1 [3].

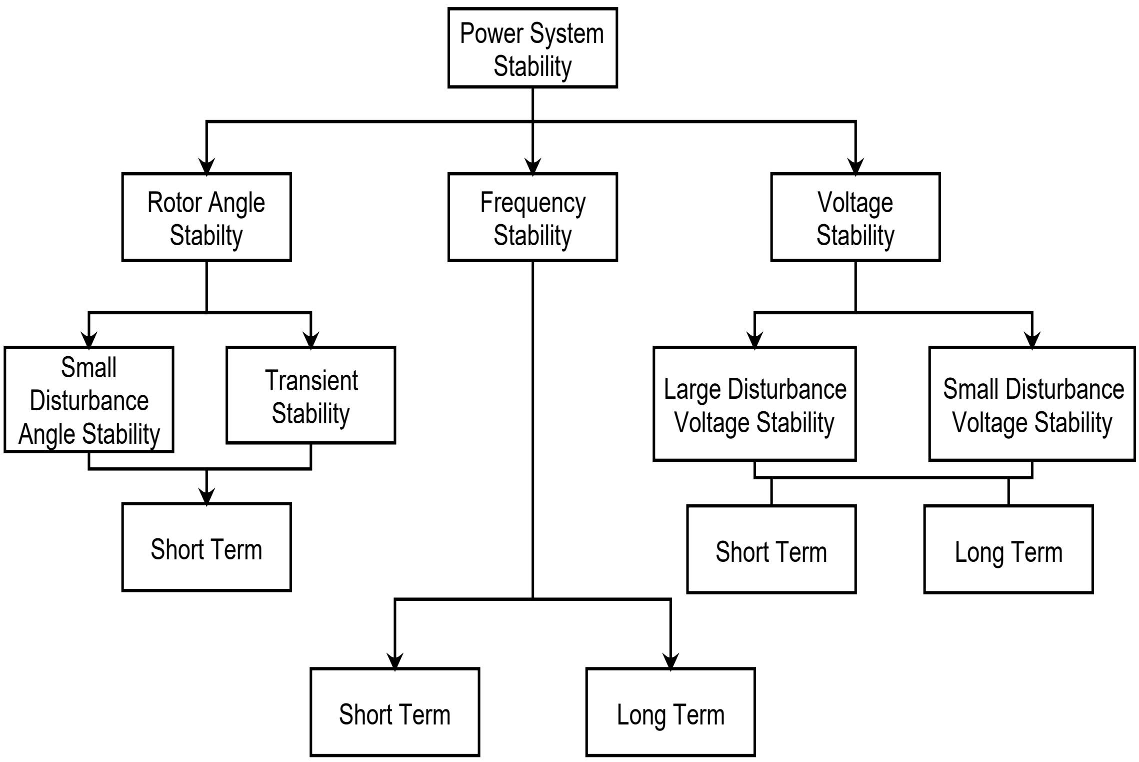

Fig. 1.1: Classification of voltage stability

- **Large disturbance voltage stability:**This condition is faced by the system when a major disturbance has occurred, like line tripping, generator unit failure or excess power flow through a single line.This capability is resolute by the system load features and interface of both continuous and discrete protections and control parameters. The duration for which this kind of instability can be observed is from few seconds to few minutes. The basic requirement for the observation and study purpose of these kinds of faults are simulation studies which can interact in a small time period. After this kind of fault if the system comes to study state and the voltage of each and every bus is under control then this kind of fault has been named as large disturbance voltage instability.

- **Small disturbance voltage stability:**The type of stability is mainly apprehensive when a small change in load occurs and the system recovers itself in a short duration of time to its original working style. The stability is mainly governed by load characteristics and the control system which is designed to function when such kind of disturbance occurs which may either be continuous or discrete. All the process which will eventually contribute to adding small disturbance voltage stability needed to be presented in steady state. Therefore, to estimate the stability margin it is needed to perform static analysis of the system.

- **Short-term voltage stability:**It is concerned with the loads which have a faster response like induction motor and power electronics based loads and HVDC loads. The period of interest ranges from few seconds to 1 minute and to analyses this kind of system first requirement is the formation of differential equations of the complete system components like the governor, exciter and so on.

- **Long-term voltage stability:**All the slow acting devices are needed to be analyzed to study this kind of stability this load includes loads controlled thermostatically, on-load tap changing transformer and generator current limiter. As the process is slower in nature so thorough analysis of the system requires long-term simulation devices as the simulation time will be of several minutes extended.

1.1.2 Voltage collapse case studies in India

In the history of India, the most severe blackouts which have affected the Indian northern grid happened on 30^{th} and 31^{st} July 2012. The 30 July, 2012 blackout pretentious over 30 billion people and was momentarily the major power outage in history, including a number of people affected, much more severe than the happened on January 2001 blackout in Northern India (23 billion affected) [4]. Much more severe blackout actually happened on 31 July in India. The outage affected over 62 billion people, its severity can be assumed from the fact that it eventually affected 9$\%$ of the world population or in other words affected entirely all the northern states including northeast and half the Indias population.

At the time of this fault the acting chairmen of FICCI (Federation of Indian Chambers of Commerce and industry has given a statement that) Mr. Rajiv Kumar has given the statement that the foremost reason of the fault is the mismatch between demand and supply in India due to the large population of India. He also insisted on the involvement of new infrastructure in the modern economy like India so that these challenges can be easily met up. Hence to avoid these kinds of events in coming future FACTS can play an important role.

After the fault, the power ministry has demanded and complete report regarding the occurrence of the fault and the report was presented by a three-member team of Mr. S. C. Srivastava, Mr. A. Velayutham, and Mr. A. S. Bakshi who have presented their report on 16 August 2012.

In summary, the points presented by the report has majorly 4 reasons for the occurrence of the fault

- Inter-regional power transmission corridors were having a weak network and there was a lack of communication regarding the outage of line either it is scheduled for service purpose or forced due to fault;
- High voltage transmission line of Bina Gwalior of 400 KV was heavily loaded at that time;
- SLDC and RLDC are actually slow acting, as with the increment of the load at the center was not be able to meet up and state has actually demanded more supply power then actually allocated to them
- Protection System of Bina-Gwalior high voltage of 400 KV line had failed to respond.

1.1.3 FACTS devices and their control attribute

The FACTS technology can be effectively used to properly and judicially utalize the present infrastructure to its full extend so that human race can be benefitted the most. These devices are specifically meant to control the current and in turns control the power of the system and hence can be effectively implemented to increase both the active as well as reactive power flow. FACTS devices have many fold uses and significantly used for the variation of the power system parameters, these factors are basically used for increasing the transmission capacity of the line, along with this parameter which could be varied with these devices includes voltage, series impedance of the line and shunt admittance of line and ground, phase angle at each bus and power system damping oscillation.

Their are different kind of FACTS devices which can be effectively be implemented in the power system for its well operation. These devices readly reduces the operational cost of the power system by preventing different kinds of failure in the system as well as increasing the transmission limits of the transmission line, whichs adds to the major portion of the economics of system. Various types of FACTS controller and their control attributes have been presented in the following Table 1.1 [6].

Table 1.1: Summary of FACTS devices and their control attributes

FACTS CONTROLLERS	CONTROL ATTRIBUTES
Static VAR Compensator **SVC**	Voltage profile improvement , reactive power compensation, to damp out oscillation, increment of Transient and dynamic stability, voltage stability; reactive power compensation
Static synchronous compensator **STATCOM** without storage	Increment of voltage stability and damping out power system oscillations
Static synchronous compensator **STATCOM** with storage	Reactive power compensation and improvement of power system stability, automatic generation control
Static Synchronous Series Compensator **SSSC** without storage	Voltage stability, Current regulator, Restraining oscillation, transient and dynamic steadiness, , fault current restraining
Static Synchronous Series Compensator **SSSC** with storage	Current regulator, Restraining oscillation, transient and dynamic steadiness, voltage steadiness
Thyristor controlled series capacitor **TCSC**	Current regulator, Restraining oscillation, transient and dynamic steadiness, voltage firmness, fault current restraining, it is used to vary the reactance of the line
Thyristor controlled series reactor **TCSR**	Current regulator, Checking oscillation, transient and dynamic steadiness, voltage steadiness, fault current limiting
Thyristor controlled voltage regulator **TCVR**	Reactive power regulator, voltage control, damping oscillation, transient and dynamic steadiness, voltage stability
Thyristor controlled phase shifting transformer **TCPST** or **TCPR**	Active power regulator, restraining oscillation, transient and dynamic steadiness, voltage stability; varies the phase angle between two terminal voltage

Unified power flow controller **UPFC**	Active and reactive power control, voltage control, reactive power compensation, control dynamic oscillation, transient and dynamic steadiness, voltage stability, fault current limiting, line impedance, terminal voltage and the voltage angle can be controlled by one and the same device

1.2 LITERATURE REVIEW

The phenomenon of voltage collapse has taken a serious attention after the various blackouts throughout the world and it has become very important to understand the behavior of the power system during these kinds of events so that these events can be avoided and the power system can be made much more reliable.

To study the overloaded power system and its voltage profile continuation power flow is a strong tool as in normal power flow calculation methods the Jacobian matrix becomes singular as the system approaches the saddle point [5], this drawback has been successfully overcome in the case of this method. The paper has drawn some important intermediate results that can be used to find out the weakest bus of the system with the increment of the load.

To find the initial solution and to start the iterative process of the continuation power flow different methods can be used, of all these methods fast decoupled method will converge fast and will give correct results.

If it has been assumed that ownership is not an issue, then the main problem we face today is to utilize the available assets in best possible way out. To maximize the loading capacities of the system and enhance the voltage stability limit of the system FACTS plays a key role, [6] has given a detailed discussion on the implementation of these devices and their working attributes in various problems of the power system. The book has covered many stability issues of the power system like voltage collapse, transient stability, steady state stability, frequency collapse and widely explains the use of different FACTS devices to overcome such issues, and which device is suited best for which kinds of issue. In [7–10] authors have tried to find the optimal location of multiple FACTS devices for solving the multi-objective problems of power system like voltage profile of the system, transient stability, power system security and relieving congestion.

A multi-objective agenda is anticipated for congestion management where three opposing objective functions including total operating cost, voltage, and transient stability margins are all together optimized [11]. Along with the location, the size of the device also matters a lot in economic consideration. The purpose of the FACTS devices installation is to provide benefit for all entities accomplished by both minimizing annual device investment cost and maximizing annual benefit defined as the difference between expected security cost (ESC) with and without FACTS devices installation. In [12] the concern to improve the voltage profile of the system has been taken care of by using STATCOM, the rating of the device has been deducted using metaheuristic methods, the maximum operating point, the saddle or bifurcation point has been deducted with the continuation power flow method, but the original contribution of the work is to attain pre-specified voltage stability margin instead of increasing the load margin. The latest trend to study the voltage stability margin is by employing the phasor measurement unit also commonly termed as PMU, the function of these devices is to study the data variation in the system and continuously monitor the effect [13].

To find the weakest or the most sensitive bus in a system various approach has been presented by the authors in transmission as well as in distribution system, in earlier regards the approach followed was finding load sensitivity factor [5], [14, 15], the similar kind of approach has been utilized for distribution network on the terms of loss minimization in [16, 17].

The world is today looking toward the better options for sustainable natural resources to meet up its energy need in the future [18–20], by considering this fact in opinion, along with the tradition power system a model of wind power has also being combined in [21] and to study has being carried to allocate the FACTS devices and the objective under consideration is to minimize the device investment cost as well as system operating cost both under normal and contingencies states. The operating area can easily be extended by the employment of HVDC and FACTS and has been well presented [22], a 3D image has been used in the paper for the proper visualise of the area extension. Multiple FACTS devices placement is also a good option to improve the operating condition of the system along with the effect of HVDC system, to study the effect of the voltage stability PQ curves are also used and the effect of SVC, STATCOM, TCSC and HVDC have been studied. The transfer capacity of the power system is dependent on the line reactance with an inverse relation and to accommodate more power transfer with the same infrastructure TCSC installation is very promising option [22, 23], multi-objective study has been carried to find the adequate rating of the device and the line is also found out on which the device is needed to be placed Furthermore the minimum operating cost along with maximum loadability has been achieved. To find the maximum loadability of the system modal analysis is also a powerful tool, it has been used to determine the node for the SVC installation in the system, the cost of SVC installation [24, 25] is also being minimized.

Many researchers have done work on the voltage stability issue of the power system, in [26] the author has quoted a new generation of loads which will auto correct the profile of the system as these loads will serve as reactive power support to the system. To have this kind of facilities the first and foremost requirement is the smart home which has such kind of loads to provide end user compensation and reactive power support to the grid, another problem faced with this system was inaccurate load forecasting.

Instead of metaheuristic algorithms, deterministic algorithm like direct search algorithm can also be utilized to determine the proper location of the FACTS devices [27]. In this method, all the nodes will be checked one after the other which will be time-consuming process. To avoid such problems heuristic approach are much more deterministic and converge to a better result in short span of time, particle swarm optimization is used to a great extend for finding the correct location of the devices. But to select the different criteria for beginning the optimization [28], provides good outline like basic PSO, PSO parameter selection and its constraint handling, multi-objective handling, and discrete variable handling.

1.3 NEED OF VOLTAGE STABILITY ANALYSIS

Present-day power systems are highly complex and widespread and operating much closer to their breakdown limits due to economic, environmental, political, and technical factors. This scenario makes the power systems more vulnerable to stability and security problems. Voltage stability is referred to the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and/or after being subjected to a disturbance. The weak system will experience voltage variation during varying load. The voltage dip sometimes becomes serious and give rise to various quality problems, the voltage dip may lead to voltage collapse for critical stable system.

Several large-scale power system blackouts in the recent past all over the globe have been the consequences of instabilities characterized by voltage collapse phenomenon. Hence, a need to analysis of voltage stability is essential for sucessful operation of power system.

1.4 OBJECTIVE OF DISSERTATION

The main objective of work has been listed below:

- To find the maximum loading capacity at which the voltage profile of the system will get distorted with continuation power flow.
- To find the most sensitive bus in terms of voltage collapse with the increment of the load.
- To develop Particle Swarm Optimization based algorithm for SVC allocation.
- To find the optimal rating of Static VAR Compensator (SVC) for the enrichment of the voltage stability of the power system and analtyse its effect.

1.5 ORGANIZATION OF THE DISSERTATION

The complete dissertation work has been divided into five chapters:

- Chapter 1 presents overview of voltage stability, voltage stability analysis, objective and organization of the dissertation.
- Chapter 2 explains the continuation power flow to find the most sensitive bus of the system.
- Chapter 3 explains the modeling of SVC, the control attributes provided by it and optimal allocation of SVC using PSO.
- Chapter 4 summarises the results and disscussion with respect to analysis carried out on IEEE 30 bus system.
- Chapter 5 summarises the conclusion and scope of future work.

Continuation Power Flow

2.1 INTRODUCTION

The method is mainly implemented for determining the smallest stability margin i.e. when load is incremented in a linear manner, the extent at which system stability is being compromised.

Initially, the starting point of the iteration has been found out corresponding to $\lambda = 0$ .Then the load of the system has been increased in a linear way and at a particular point of voltage instability and the Jacobian formed in the conventional power flow methods becomes singular, i.e. the determinant of the matrix becomes zero at this loading condition. To overcome

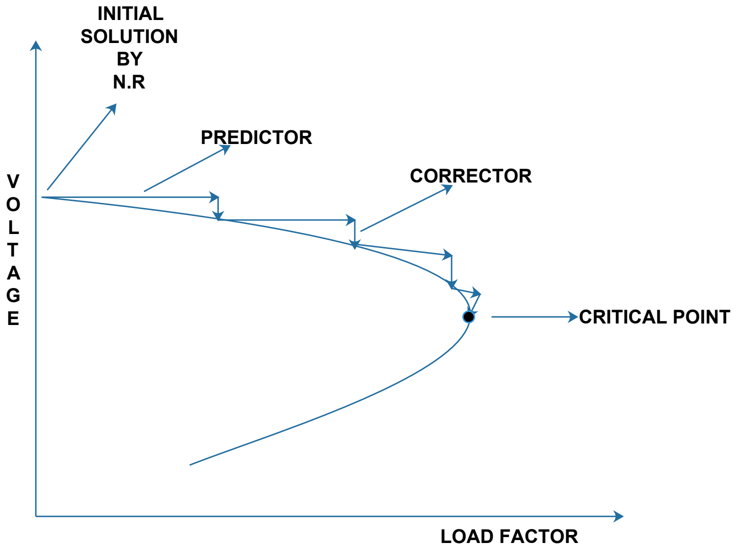

Fig. 2.1: Illustration of Predictor-Corrector Step

this difficulty continuation power flow has been used.The continuation power flow method is quite attractive in approxmation of the critical point in the power system. The continuation power flow captures this path-folowing feature by means of predictor-corrector scheme that adopts locally parameterized continuation techniques to trace the power flow solution paths.

The Fig. 2.1 shows a PV curve, the upper portion represents the stable operating region and the lower portion represents the unstable region. These points cannot be obtained by conventional power flow equations it needs a special approach and that method to trace the complete curve is provided using continuation power flow.

2.2 MATHEMATICAL REFORMULATION OF POWER FLOW EQUATIONS

In continuation power flow method, power flow equations are needed to be reformulated by expressing the load and the generation at a bus as a function of load parameter.To simulate the different load change scenarios, the P_{Li} and Q_{Li} can be modified as[5].
The new sets of equations can be considered as

$$\Delta P_i = P_{gi}(\lambda) - P_{li}(\lambda) - P_{ti} = 0 \tag{2.1}$$

Where

$$P_{ti} = \sum_{j=1}^{n} V_i V_j y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.2}$$

$$\Delta Q_i = Q_{gi}(\lambda) - Q_{li}(\lambda) - Q_{ti} = 0 \tag{2.3}$$

$$Q_{ti} = \sum_{j=1}^{n} V_i V_j y_{ij} sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.4}$$

Here there are few constraints in the load factor λ i.e. it will vary from zero to its critical value and that critical value is decided by the saddle point of the curve under consideration. In the consideration, zero specifies the base case or the starting case of the iteration and $\lambda_{critical}$ denotes the critical values. Here in the equations subscripts g, l, t is used to denote generated, load and transmitted power respectively.
To mimic the load change scenario, the real and reactive load equations can be reformulated as

$$P_{li}(\lambda) = P_{lio} + \lambda[K_{li} S_{\Delta base} cos(\phi_i)] \tag{2.5}$$

It can be stated that for the base case,

$$P_{lio} = K_{li} S_{\Delta base} cos(\phi_i) \tag{2.6}$$

so load equation can be reformulated as,

$$P_{li}(\lambda) = P_{lio} + \lambda[K_{li} P_{lio}] \tag{2.7}$$

And for the case of reactive power flow equation, there would be no change in the power flow equation as with the increment of the load, we would increase the reactive power of the system then it would not be possible to take into account the voltage droop in the system. Hence the reactive power equation can be shown as

$$Q_{li}(\lambda) = Q_{lio} \tag{2.8}$$

Now suppose the entire sets of equations be represented by F, then the problems can be articulated as a set of non-linear equations characterized by

$$F(x, \lambda) = 0 \tag{2.9}$$

Where,

$$x = \begin{pmatrix} \delta \\ V \end{pmatrix} \tag{2.10}$$

Now ones these equations are obtained then we can apply predictor step and then corrector to further increase the accuracy of the results.

2.3 PREDICTOR

The first task in the predictor process is to calculate the tangent vector[5].For this purpose power flow equations are represented as

$$F(\theta, V) = \lambda * K \tag{2.11}$$

Here,

θ= Bus voltage angle vector

V= Bus voltage magnitude vector

λ = Load Parameter

K= Represent load variation at each bus with change in load factor

The above equation is modified and rewritten as

$$F\left(\theta, V, \lambda\right) = 0 \tag{2.12}$$

Taking the partial derivative of the equation,

$$\left[F_\delta \;\; F_V \;\; F_\lambda\right] \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} = 0 \tag{2.13}$$

On the left side of equation is a matrix of partial derivative multiplied with the tangent vector. The former is the conventional power flow Jacobian augmented by one column F_λ.

$$\text{Tangent Vector} = \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} \tag{2.14}$$

There is, however, an essential hindrance to overcome before a novel arrangement can be found for the tangent vector. It can be easily observed that an extra variable has been inserted into the equation which is needed to be taken care of as the number of equations to solve the problem has not been altered. Thus there is a need of one more equation. This problem can be solved by pre-specifying one of the tangent vector component to ± 1. If the upper portion of the graph is to be traced, then +1 is used and if the lower portion of the graph is needed to be traced then -1 is used.

This results in

$$\begin{bmatrix} F_\delta \;\; F_V \;\; F_\lambda \\ e_j \end{bmatrix} [t] = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \tag{2.15}$$

Where e_j is representing a row vector in which every elements will be corresponding to zero except j^{th} element, which equals one. The basic objective is to choose a correct index for the j^{th} element and $t_j = 1$ will take care that the jacobian matrix will not be singular at the biffurcation point.After obtaining the tangent vector the next step in the process is of obtaining the predictor value[23]

$$Predicted\,value = \begin{bmatrix} \delta^o \\ V^o \\ \lambda^o \end{bmatrix} = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} \tag{2.16}$$

Where $'^{o}'$ denotes the predicted solution, and σ is a scalar value entitling step size.

2.4 STEP SIZE SELECTION

It is quite judicious decision to take the proper step length, if the dimension of the step length is large then it might be possible that critical point may pass away and the saddle point is missed and if the step length is small then number of iteration needed to reach the saddle point increases [5]. So the best method is to initial take the step length at a larger value and as the iteration increases then the step length is reduced.

$$(\sigma_j)_{new} = (\sigma_j)_{old} * \frac{N_{opt}}{N_j} \tag{2.17}$$

N_{opt}=optimal number of corrector iteration (5 for tolerance of 10^{-4}) and N_j=Number of iteration desirable to estimate the previous continuation step.

2.5 PARAMETERIZATION AND CORRECTOR:

The solution obtained in the predictor step is not the exact solution, it's just the predicted solution and to obtain the exact solution it is needed to be corrected so corrector step is to be applied. Really, an ideal approach to present this corrector is to develop parameterization, which is one of the essential procedure.There are many parameterization techniques which are commonly used such as

- Local parameterization
- Natural parameterization
- Arc-length parameterization
- Pseudo arc length parameterization

In my theses implementation of local parameterization is done, in this method, it is needed to specify one of the three state variable either bus angle or voltage or the load factor lambda hence in one way we need to augment the equation with a third variable [29]. State variables are specified in equation form as

$$x = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} \tag{2.18}$$

The dimension of the above equation is $2n_1$+n_2+1, where n_1 and n_2 are number of PQ and PV buses taken in the system of consideration.
And let

$$x_k = \eta \tag{2.19}$$

Where η is one of the predicted value of the system found in predictor process, as the number of variables is more and equation to be solved are one less.Thus the new set of equations are

$$\begin{bmatrix} F(x) \\ x_k - \eta \end{bmatrix} = 0 \tag{2.20}$$

Once the correct prediction of the index of 'k' is found out and the value to be specified as the prediction is found then the above set of the equation can be solved by using any of the load flow solution methodology, Newton-Raphson method has beeniplemented to solve above set of equations.

2.6 SELECTION OF CONTINUATION PARAMETER

There are several methods available in the literature for correctly finding the continuation parameter. The easiest way is to examine the tangent vector and notice the variable which has the highest rate of change in the tangent. The index of the highest change of the tangent vector will be the continuation parameter index specified as 'k' and corresponding to the continuation parameter index in the predictor will be the value of continuation parameter specified as "η" [29]

The initial guess for continuation parameter value and the index is kept as λ, whose initial position is $2n_1 + n_2 + 1$ of the tangent vector. But as the iteration continues λ will not be a good choice for continuation parameter and it is needed to be updated in each iteration.

Mathematically it can be sought out by applying the method of successive steps as

$$x_j : |t_j| = \max\{|t_1|, |t_2|, |t_3| .... |t_m|\} \tag{2.21}$$

where, $2n_1$+n_2+1 is the dimentional size of the tangent vector and index 'j' corresponds to the largest quantity of the tangent vector.

2.7 SENSING THE CRITICAL POINT

The basic aim of the corrector predictor method is to find out the saddle point or the critical point, in other words, the point to which power system can be maximum loaded. The main problem with the conventional load flow methods is that at critical or saddle point the Jacobian matrix becomes singular and the determinant of the matrix cannot be calculated.

In predictor-corrector scheme the saddle point can be determined by just observing the tangent vector. When the saddle point is reached then tangent vector component corresponding to lambda i.e. dλ becomes negative. It is the point we need to stop the further iterations as the critical point has been passed

2.8 A FLOW CHART DESCRIBING THE CONTINUATION POWER FLOW METHOD

The complete process of finding the bifurcation point and continuation power flow can be represented in the following figure 2.2. The process can be explained in stepwise approach as

- Start the process for the base case when lambda λ=0 i.e. these results can be easily obtained by Newton-Raphson methodology.
- Initially there is a requirement of the selection of the continuation parameter in the first iteration, generally, lambda is taken as the best choice for starting the process.
- After this calculation of tangent vector has to be done as explained earlier.
- The largest value of the tangent component will correspond to the continuation parameter for the next step.
- Check the convergence criteria if achieved then stop otherwise go to next step.
- Apply the corrector step to the predicted value.
- Note the value of the maximum λ for which bifurcation of the curve has been achieved that value corresponds to the critical λ of the system.

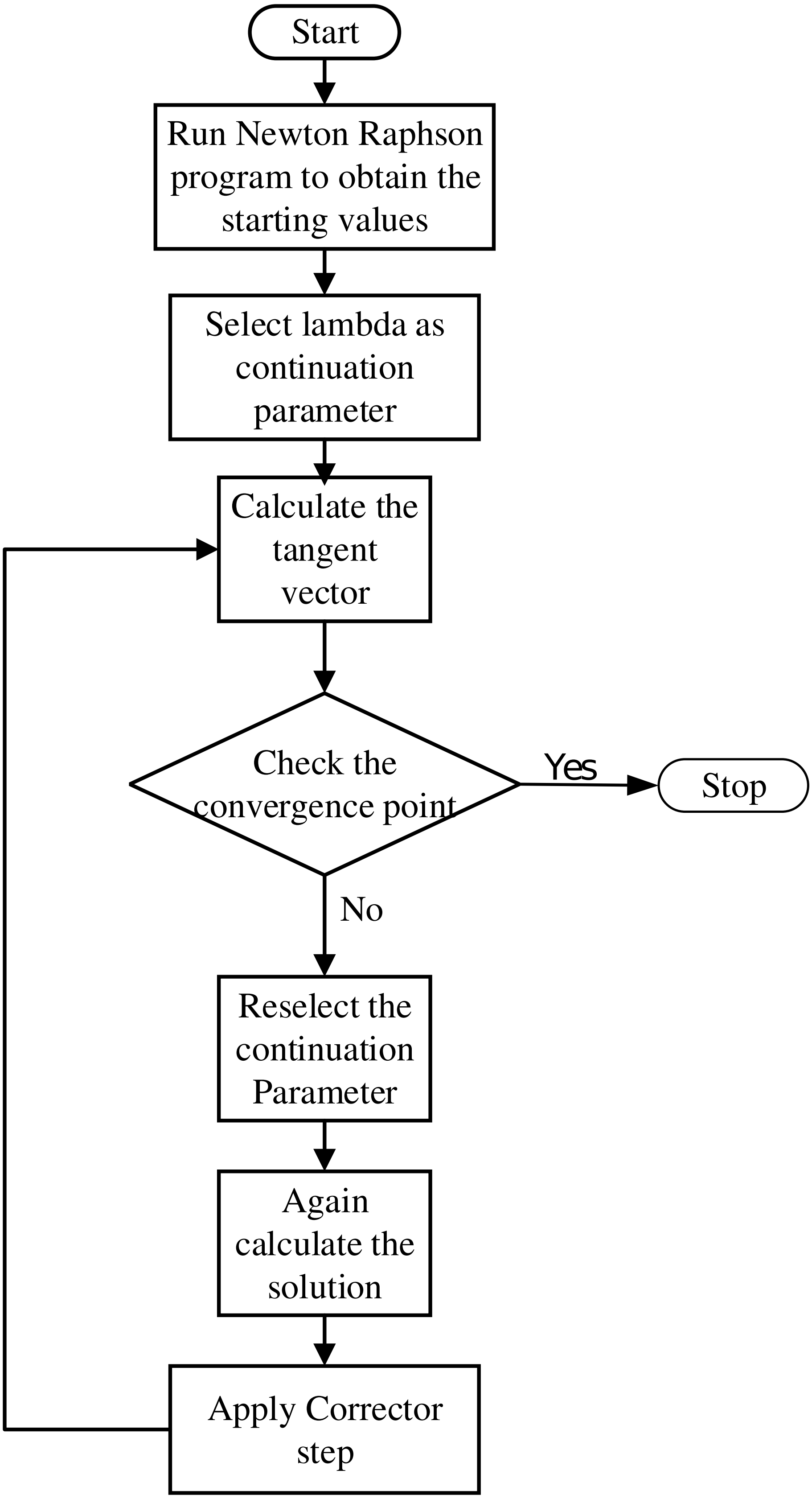

Fig. 2.2: Flow chart of continuation power flow

Optimum SVC realization using PSO

3.1 MODELLING OF SVC

Static Var compensators are mainly meant for the betterment of the profile of the system like power transfer capacity and voltage regulation. Two well-known shunt compensators generally implemented in the system are SVC and STATCOM. during the work, SVC has been tried to be implemented and as a result voltage breakover point of the system has been increased.

The optimum rating of SVC has been found out using heuristic methods. These methods are used as there is a guarantee of convergence which is not present in the gradient methods.The heuristic methods are mostly inspired by the nature's phenomenon, it is possible that these methods will converge but take time to converge so there is no dependence of starting the problem we may start the problem from any step and then may shift towards the gradient methods. Their are different approaches which can be sucessfully implemented for finding the optimum rating of FACTS devices like Particle Swarm Optimization, Gentic Algorithm, Ant Colony Optimization. During the course work PSO has been implemented and explained in breif.

3.1.1 Static Var Compensator (SVC)

According to IEEE SVC has been defined as follows [6] ”A shunt connected VAR source which is capable of either absorbing or supply reactive power so that the electrical system parameters can be taken care of especially voltage on the buses.”

Initially SVC has been considerd as a reactive generation source behind a reactance. SVC is not just a single device it basically consists of mainly three types of devices namely TCR, TSR, TSC.

Main characters of SVC are listed as follows

- Operation depends on the Capacitive and Inductive nature of the element.
- Independent of any kind of Rotating device so free from wear and tear and losses.

- Controlling of the device is done through power electronic based switches.

From a function point of view, it can be inferred that SVC is connected in shunt in the power network with SCRs acting as switches to control the active and reactive power flow in the network. The firing angle varies and the operating region varies as well from inductive to capacitive.

Hence it can be said that the main objective of the SVC is voltage regulation and reactive power compensation. As power electronic based switches are employed in the system so the speed of response is instant. Figure 3.1 shows the VI characteristics of SVC and it can be shown that SVC behaves well in inductive and capactive region.

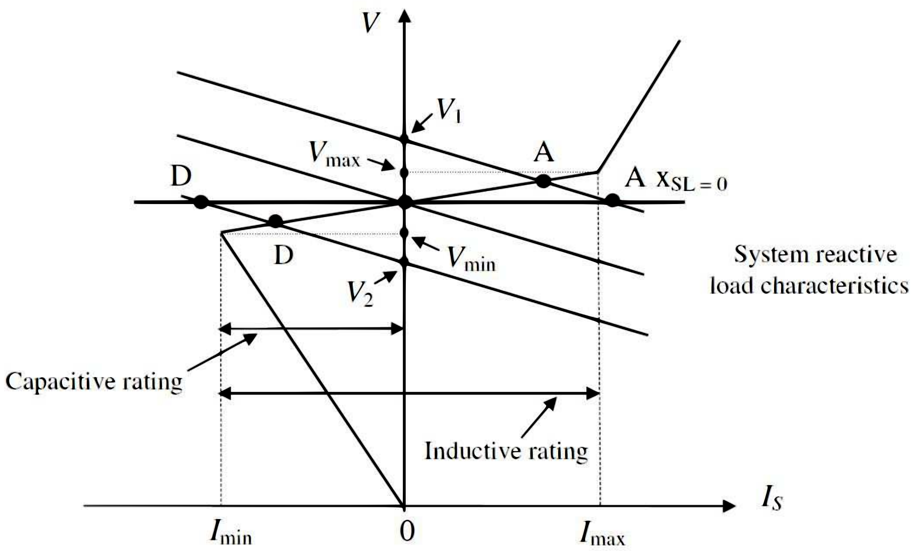

Fig. 3.1: VI characteristics of SVC

3.1.2 Thyristor-Controlled Reactor(TSR) and Thyristor-Switched Reactor (TCR)

TCR: TCR has been defined according to IEEE as [6] ”A shunt connected device which is having the objective to supply or absorb the reactive in the system by variation of the firing angle of the thyristor valves .”

Firing angle delay control method is used in TCR to control the current in the circuit from zero to rated value. By controlling the firing angle of the thyristor the current in the circuit can be varied and the switching of thyristor depends on the reference of the voltage waveforms. For $\alpha = 0$ the magnitude of the current is the maximum value and for $\alpha = 90$ the magnitude of the current becomes nil and the circuit behaves as an open circuit.

The amplitude of the current and be made to vary by changing the firing the angle of the circuit given by

$$I_L = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) \tag{3.1}$$

A basic diagram of single-phase thyristor controlled reactor (TCR) is shown in figure 3.2.

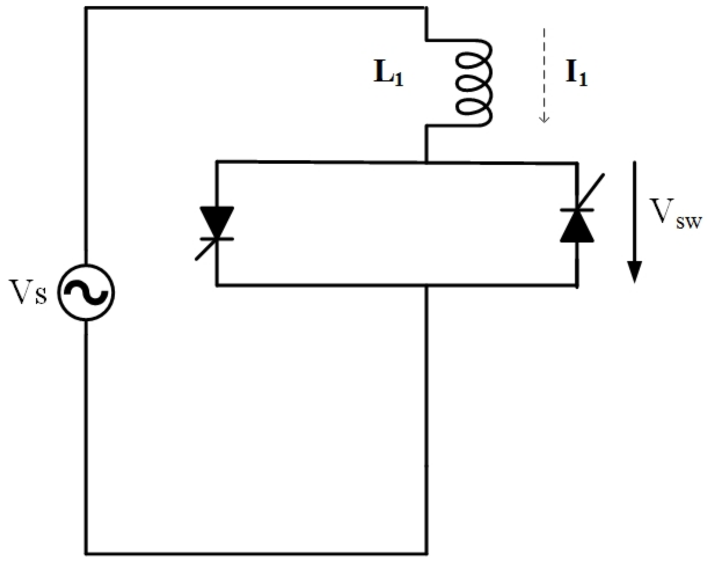

Fig. 3.2: Schematic of thyristor controlled reactor

The functioning of Thyristor Switched Reactor is similar(TSR) is similar to that of the Thyristor Controlled Reactor rather then it is fired at a fixed firing angle of 90 or 180, in simple terms either it will fully operate and act as a short circuit or it will behave as an open circuit. As a result of which the reactive current will be in proportion to applied voltage. The transmitted power vs firing angle characteristic of SVC can be shown in figure 3.3

3.1.3 Thyristor-Switched Capacitor (TSC)

According to IEEE TSC is defined as ”A shunt connected device which instead of varying in a continuous manner varies stepwise by controlling the thyristor to either conduct fully or remains off.”

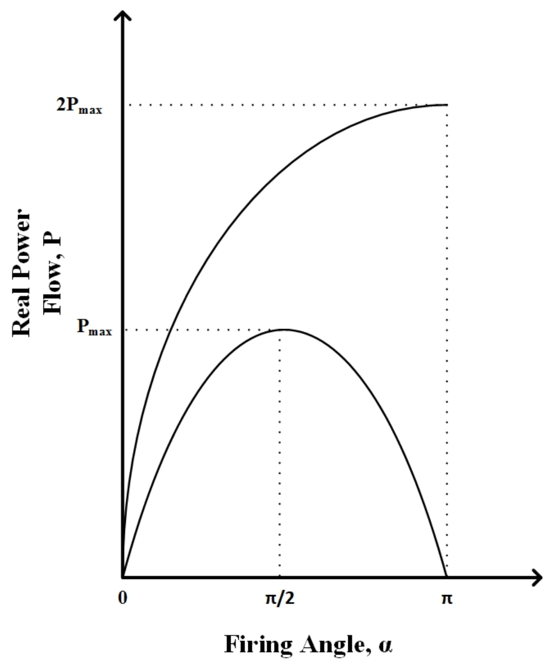

Fig. 3.3: Variation of power with and without SVC

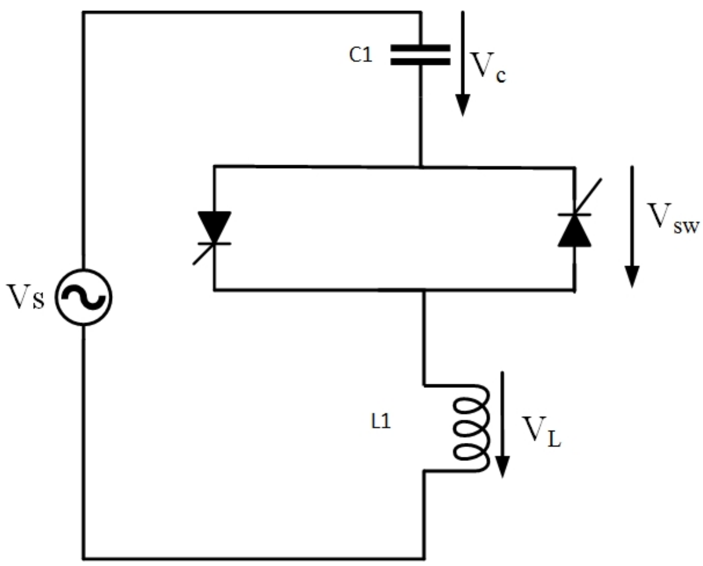

Fig. 3.4: Schematic of thyristor-switched capacitor

In the figure 3.4, a single-phase Thyristor-Switched Capacitor (TSC)has been represented. When the current passes its zero crossing the SCR must be switched. Its the moment when the capacitor voltage will reach its peak point. Ones the capacitor is charged to its peak value then it will remain isolated in the circuit and the voltage across the non-conducting thyristor varies in accordance with the applied voltage.

As soon as the thyristor switches are disconnected the voltage across the capacitor doesnt remain constant instead of its discharges immediately. There is an important condition which must be taken care of when we switch on the thyristor and it is that voltage across the switch must be equal to the applied voltage at the time of switching. However, it is likely possible to have the transient effect which switching the switches due to the effect of $\frac{dV_s}{dt}$, which can be minimized to a great extent by using an inductor and the charging of the capacitor can be brought down by using the relation of $I_c = C\frac{dV_c}{dt}$. But it could be easily noticed that it would be forming an L, C pair and hence can ultimately result in the formation of the oscillatory current.

The reactance offered by the TSC can be represented by the following equation stated as:

$$X_V = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \tag{3.2}$$

TSC can also be well operated in the capacitive mode also which is given as:

$$X_c = X_C \frac{\pi / r_s}{\sin 2\alpha - 2\alpha + \pi(2 - 1/r_s)} \tag{3.3}$$

The waveforms for the switching and the voltage which appears across the switch and the capacitor can be shown in the figure 3.5.

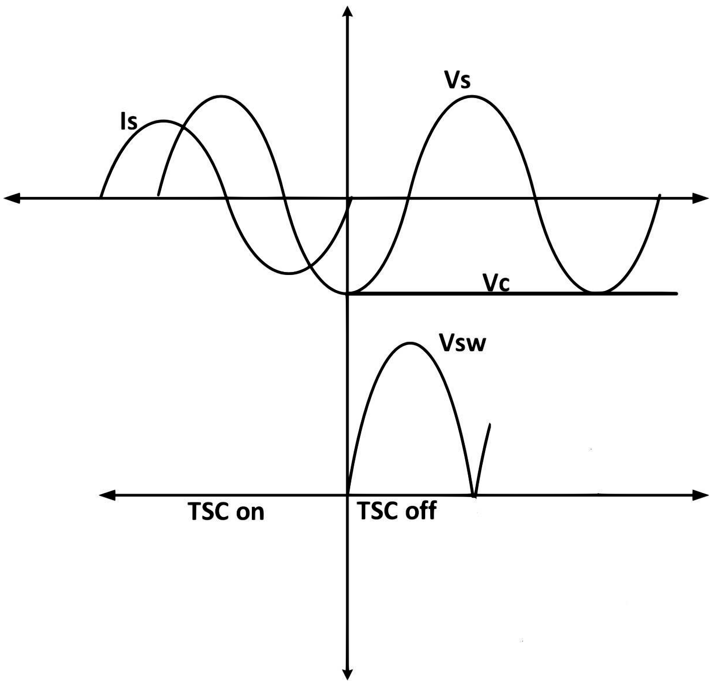

Fig. 3.5: Waveform explaining Thyristor-switched capacitor switching

From all these above explanation switchings of the capacitor is an independent phenomenon which is to be precisely turned on at the current zero level of the waveform so a zero voltage

detector is also needed.
Hence, SVC has been implemented to expand the voltage representation of the system and the relation between voltage and the firing angle of the device is given by:

$$V = V_{ref} + X_{SL}I \tag{3.4}$$

The above equation can easily be implemented to draw the voltage-current characteristic of the SVC which are already been shown in figure 3.1.

3.2 PARTICLE SWARM OPTIMIZATION

This algorithm is based on a class of algorithm called meta-heuristics. It is an intelligent algorithm. This algorithm is inspired by social behavior of animals like fish or birds. This algorithm is quite simple yet very powerful optimization, it has been successfully applied in machine learning, image processing, and operational research etc.
The algorithm works on the following principle

- Define a population of particle solution also called as swarm
- Each particle has a position in the optimization problem in the search space.
- A search space is the set of all possible solution to the optimization problem and our purpose is to find the best solution from the given set of solution.

Denote the position of particle ”p” in x-space as $x_p(t)$. In addition to the position, we have a velocity of each particle denoted as $v_p(t)$. The velocity defines the movement of particle ”p” in the sense of direction, distance and step size. In addition to the position and velocity every particle has a memory of its best result that is called personal best it is denoted by P_{best} and the whole system has a global best denoted by G_{best}. The complete process can be illustrated in figure 3.6, It can be noted that for global best subscript ”p” has not been used as it is the best result for the complete swarm.

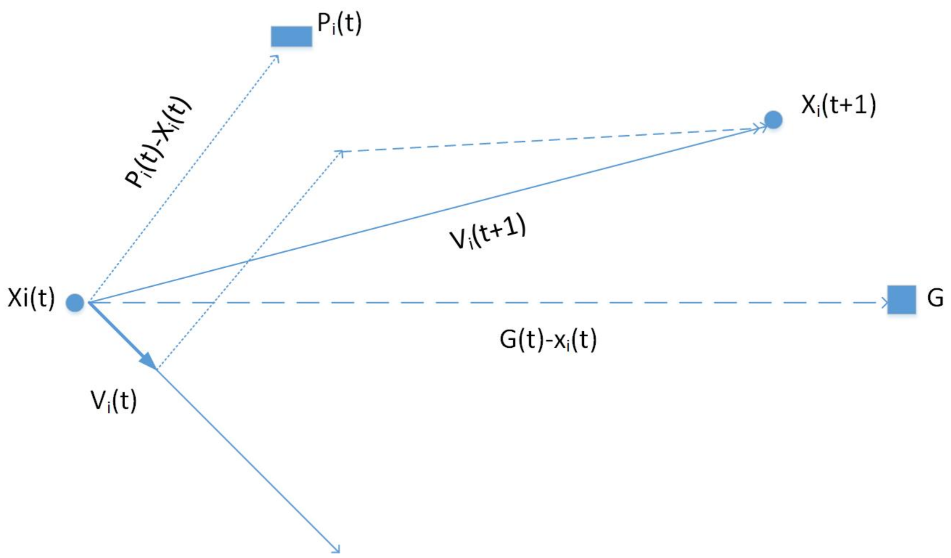

Fig. 3.6: Search mechanism for particle swarm optimization

In each generation, the particle will tend to move toward the global best keeping its personal best and velocity into consideration. The movement of particle towards its personal best is denoted as $P_{best}(t) - x_p(t)$ and for representation of movement towards global best is $G_{best} - x_p(t)$. The particle moves and keeps the track on all three vectors including velocity. So the newly updated position is given as and it will definitely the better result as it uses the previous best position velocity and the global best result [28].

$$x_p(t+1) = x_p(t) + v_p(t+1) \tag{3.5}$$

The velocity is also updated in every iteration as

$$v_p(t+1) = w_1 v_p(t) + c_1 \left\{P_{best}(t) - x_p(t)\right\} + c_2 \left\{G_{best} - x_p(t)\right\} \tag{3.6}$$

here w_1 is the inertia coefficient and c_1 and c_2 are the acceleration coefficient.

3.2.1 Inertia weight in PSO

In the most common variant of PSO, the velocity of the particle in the earlier iteration consistently gets multiplied with the constant commonly known as inertia constant.

Commonly inertia constant is linearly decremented during the course run of the program, by opting this methodology the convergence of the PSO will be faster.

3.3 APPLICATION OF PSO ON SVC REALIZATION

In this section, the PSO-based approach to find the optimal rating of the SVC has been analyzed. In finding the rating of SVC to increase the voltage stability limit of the power system PSO can be implemented as described in the following steps

1. Initialize a random population in the search space which is stored in the form of a matrix and of random nature, each particle is free to move in any direction in the search space.

$$P_i = (P_{i1}, P_{i2}, P_{i3}......P_{id}........P_{in}) \tag{3.7}$$

$$v_i = (v_{i1}, v_{i2}, v_{i3}......v_{id}........v_{in}) \tag{3.8}$$

   here P_i basically represent the different rating for the SVC for which best results are needed to be searched.

2. Each individual rating of SVC, the feasibility of the system is analyzed by considering the system constraints. Then all the feasible solutions of the population are selected.

3. Calculate the value of the objective function for each of the individual x_i, objective function for my project is defined as

$$F_{\min} = \min |V_{sensitive} - V_{referance}| \tag{3.9}$$

   Where V is the value of the voltage at the weakest bus needed to be improved and V_{ref} is the value of the voltage which is wished to be obtained.

4. The position and the velocity after satisfying the required constraints are updated using the following equations

$$V_{ip}(t+1) = V_{ip}(t) + c_1 w_2 (P_{best} - X_{ip}) + c_2 w_2 (P_{best} - X_{ip}) \tag{3.10}$$

$$X_{ip}(t+1) = X_{ip}(t) + V_{ip}(t+1) \tag{3.11}$$

   Here c_1 and c_2 are two positive numbers and w_1 and w_2 are the random numbers varying randomly with in the interval of 0 to 1.

5. It can be observed that there are three terms in the velocity updating formulae

- The first term is the representation of the inertia term i.e. the propensity of the particle to remain in the similar direction as it was originally being.
- The second term is the representation of the self-knowledge of the particle, hence the particle would have a general tendency to move toward its own best experience scaled by the arbitrary weight of w_1.
- The third term is the representation of the global knowledge, as here the particles approaches toward the global best solution of all the particles of the swarm, scaled by the random weight of w_2.
- Step b to e are repeated until stopping criterion has been met.

The maximum and the minimum rating or the boundary of variation of SVC rating chosen vary from zero to 300 MVA.

Results and Discussion

4.1 ANALYSIS OF IEEE 30-BUS SYSTEM

The figure 4.1 represents an IEEE 30-bus system, there is 1 slack bus i.e. bus number 1, 5 PQ buses which can be labeled as bus number 2, 5, 8, 11, 13 and rest all are load buses. The system consists of 41 transmission line. The total load demand of the system is 283.4 MW.

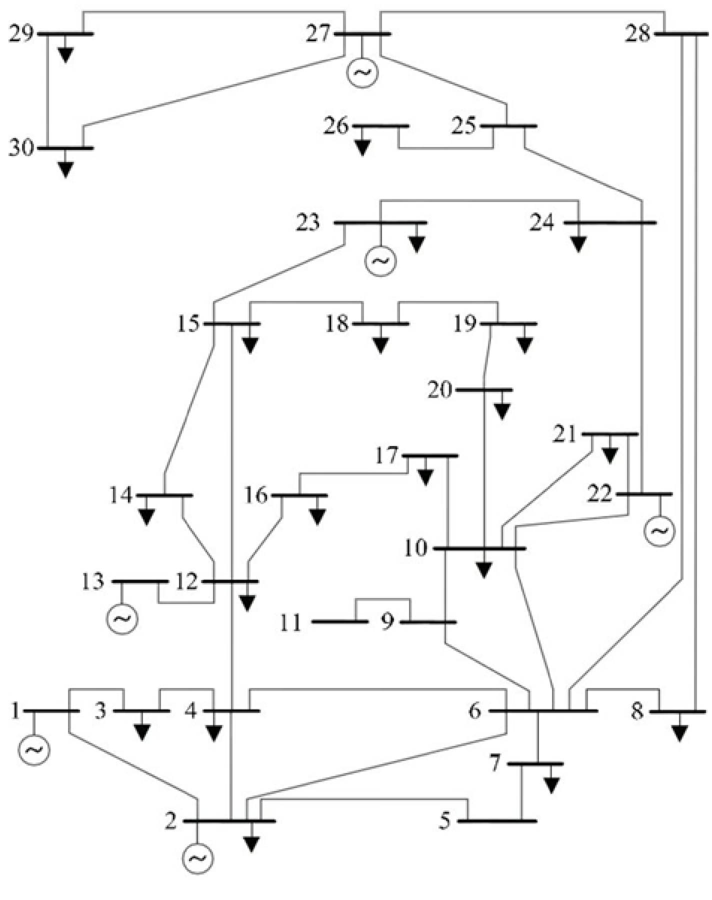

Fig. 4.1: Single line diagram of IEEE 30 bus system

To validate the results of the theses an IEEE 30-bus system has been considered. It has been assumed in the work that load doesn't vary with the voltage. Thus the load has been made to directly vary with the load factor. The work is validated for the case of linear load model instead of the non-linear system.

4.2 FLOWCHART TO IMPLEMENT SVC PLACEMENT

The complete process of SVC realization can be summarized in the following flow chart Fig. 4.2, it explains the achievement of voltage stability of the system along with the optimal selection of the SVC rating using particle swarm optimization algorithm.

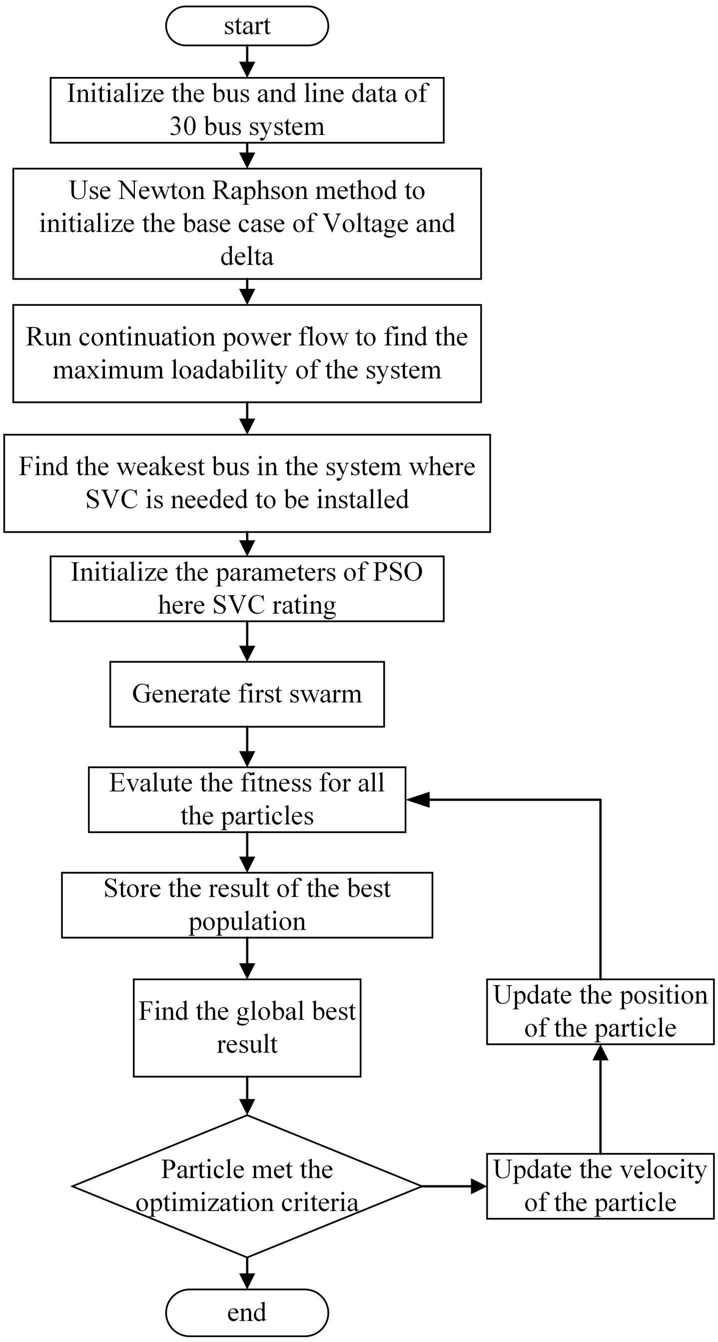

Fig. 4.2: Flow chart to implement SVC placement

4.3 BASE CASE OF CONTINUATION POWER FLOW ($\lambda = 0$)

To start the process of continuation power flow, first the base case or starting point of the process is needed to be find out, for finding the initial point Newton Raphson method has been opted. The initial data of line and bus are shown in the appendix table 5.1 and table 5.2 [4].
The converged results of the process can be shown below.

4.4 LOAD VARIATION AND VOLTAGE OF THE SYSTEM

Now the results shown in Table 4.1 are to be used for the process of starting the process of continuation power flow and will form the base case. It can be inferred from the results that these results hold for the case when the value of load factor λ is zero.
Now in continuation power flow, we know that we would increase the load on few selected nodes and the resulting results will be needed to note down. In my theses work the bus chosen for the increment of the load has been 21^{st}, it has been taken into account due to the initial heavy loading of the system. The results for the variation of voltage with the load variation can be shown in Table 4.2.

It can be observed from the above results that up to the load factor λ=0.14 the voltage variation is under the deviation of 5% i.e. from the base value of 0.90 to 1.05 but as the voltage is further incremented to λ=0.30 the voltage of some of the buses is out of the bond, the buses whose voltage is out of the limits are 14, 29, 30.
The graph for the buses whose voltage limits are not under bounded condition are shown in Fig. 4.3 and Fig. 4.4.

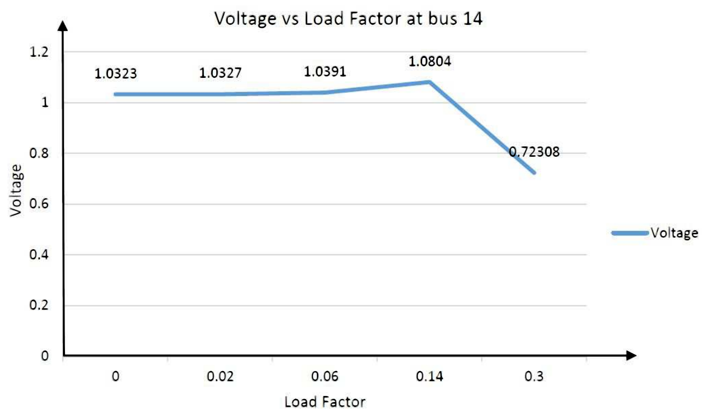

Fig. 4.3: Variation of voltage with load at 14^{th} ***bus***

Table 4.1: Base case load flow solution of IEEE 30-bus system

Bus number	Voltage(p.u.)	Delta(rad)
1	1.06	0
2	1.045	-0.093943313
3	1.020	-0.131373854
4	1.010	-0.161946711
5	1.01	-0.247058582
6	1.009	-0.192818689
7	1.002	-0.224292646
8	1.01	-0.205984971
9	1.039	-0.245263212
10	1.021	-0.273286539
11	1.082	-0.245263212
12	1.049	-0.263773967
13	1.071	-0.263773967
14	1.032	-0.279075267
15	1.025	-0.279189532
16	1.030	-0.272501412
17	1.019	-0.276745005
18	1.011	-0.289622401
19	1.006	-0.292396601
20	1.0097	-0.288634475
21	1.0084	-0.282832838
22	1.0122	-0.278701329
23	1.0088	-0.283036591
24	0.9993	-0.284274736
25	1.0034	-0.280276355
26	0.9855	-0.287808221
27	1.0147	-0.273012653
28	1.0080	-0.204278674
29	0.9947	-0.294847219
30	0.9831	-0.310528253

Table 4.2: Variation of voltage with load factor

Bus No. \ Lambda	0	0.02	0.04	0.14	0.30
1	1.06	1.06	1.06	1.06	1.06
2	1.045	1.045	1.045	1.045	1.045
3	1.0201	1.0206	1.0228	1.0696	0.99447
4	1.011	1.0114	1.0135	1.0556	0.9432
5	1.01	1.01	1.01	1.01	1.01
6	1.01	1.0102	1.0111	1.0343	0.96456
7	1.0022	1.0024	1.003	1.0209	0.96866
8	1.01	1.01	1.01	1.01	1.01
9	1.0395	1.0396	1.0395	1.0502	1.0285
10	1.0217	1.0218	1.0211	1.0297	1.0333
11	1.082	1.082	1.082	1.082	1.082
12	1.0498	1.05	1.052	1.0725	0.99577
13	1.071	1.071	1.071	1.071	1.071
14	1.0323	1.0327	1.0391	1.0804	0.72308
15	1.0253	1.0254	1.0278	1.0371	0.90461
16	1.0307	1.0309	1.0317	1.0623	0.98129
17	1.019	1.0192	1.0187	1.0393	1.0137
18	1.0117	1.0117	1.0125	1.0084	0.96712
19	1.0068	1.0068	1.0061	0.99745	1.0213
20	1.0098	1.0097	1.0086	1.0025	1.0379
21	1.0085	1.0082	1.007	0.99025	0.96836
22	1.0122	1.0126	1.0129	1.0452	1.086
23	1.0088	1.0086	1.0077	0.9906	0.96554
24	0.99936	0.99974	1.0017	1.0337	1.1257
25	1.0035	1.0039	1.0093	1.0506	1.2472
26	0.98555	0.98644	0.99971	1.0867	1.0530
27	1.0148	1.0147	1.0137	1.0071	0.98249
28	1.0081	1.0082	1.0087	1.0258	0.97509
29	0.99474	0.99385	0.98539	0.91588	0.75705
30	0.98316	0.98218	0.97285	0.89602	0.72155

The graph shown in Fig. 4.5 represents the decrement of the bus voltage with the load of the system, it can be easily inferred that when the load of the system during the initial conditions was 283.4 MW and with the value of becoming equal to 0.3 it means that the system load is increased by 85.02 MW. When the load factor is 0.3 the voltage of the bus has fallen up to 0.72 pu.

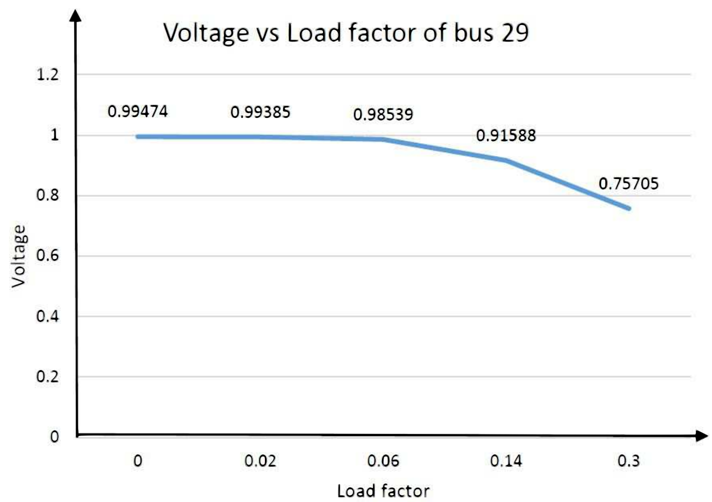

Fig. 4.4: Variation of voltage with load at 29^{th} ***bus***

In the case of bus number 29 and 30, the initial voltage has fallen to a large extent which can be made to improved bus providing the proper level of compensation.

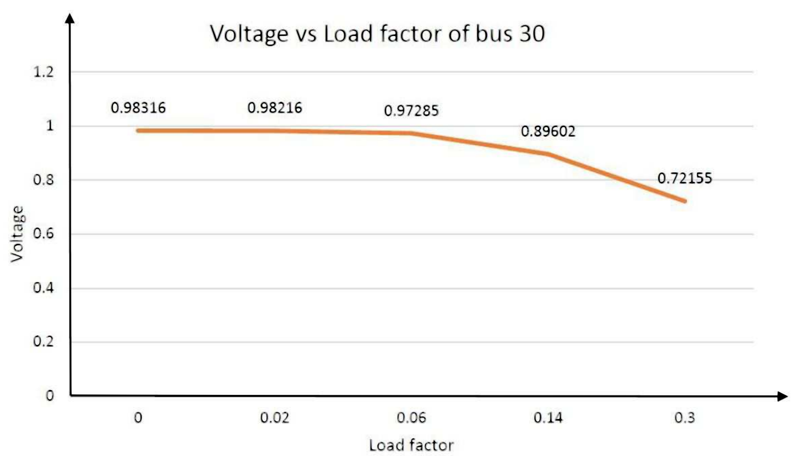

Fig. 4.5: Variation of voltage with load at 30^{th} ***bus***

In the case of bus 30, the voltage has taken a sharp dip of 0.72 pu with the increment of the load to 0.3 times.
Hence with the proper examination of the system behavior, the voltage stability of the system can be deducted and the safe operating point of the system can be found out easily. The bifurcation point or the saddle point of the system can also be found out with the graph.

4.5 SEARCHING THE MOST SENSITIVE BUS OF THE SYSTEM

The weakest bus or most sensitive bus of the system can be found out on the system by simply calculating the Voltage sensitivity factor (VSF). It can be inferred that the maximum change of the bus voltage with the change in load.

To find the weakest bus of the system the VSF at each bus node is needed to be calculated. The formulae to be used for the calculation can be stated as

$$VSF = \frac{Change\,in\,Voltage\,of\,the\,bus}{Change\,in\,load} \tag{4.1}$$

The bus with the largest VSF is the weakest bus in the system and hence the need of SVC placement is to be done on that bus only. In the test system under consideration bus number **29** is the weakest bus of the system, hence the SVC is placed on that bus. Now, the general point of discussion is the optimal rating of the SVC for the placement such that the objective of the theses validated.

4.6 APPLICATION OF PSO FOR SVC RATING

The most sensitive bus of the system can be found by calculating the VSF of all the buses in the system. As soon as the most sensitive bus was found out the main objective of the work is to advance the voltage profile at that node.

Objective function under consideration can be stated as follows

$$Objective\,function = \min |V_{Weakest\,bus} - V_{ref}| \tag{4.2}$$

In the course work, the reference voltage has been taken as 1 pu, which is the ideal bus voltage of the system. With the increment of the load at bus number 21, the voltage profile of the bus **29** is the most sensitive bus.
The rating of SVC for which the error can be minimized to a value up to $1.8 * 10^{-6}$ is 61.05

MVA. The graphical representation of bus with and without the SVC installation can be found out as shown in the Fig. 4.6.

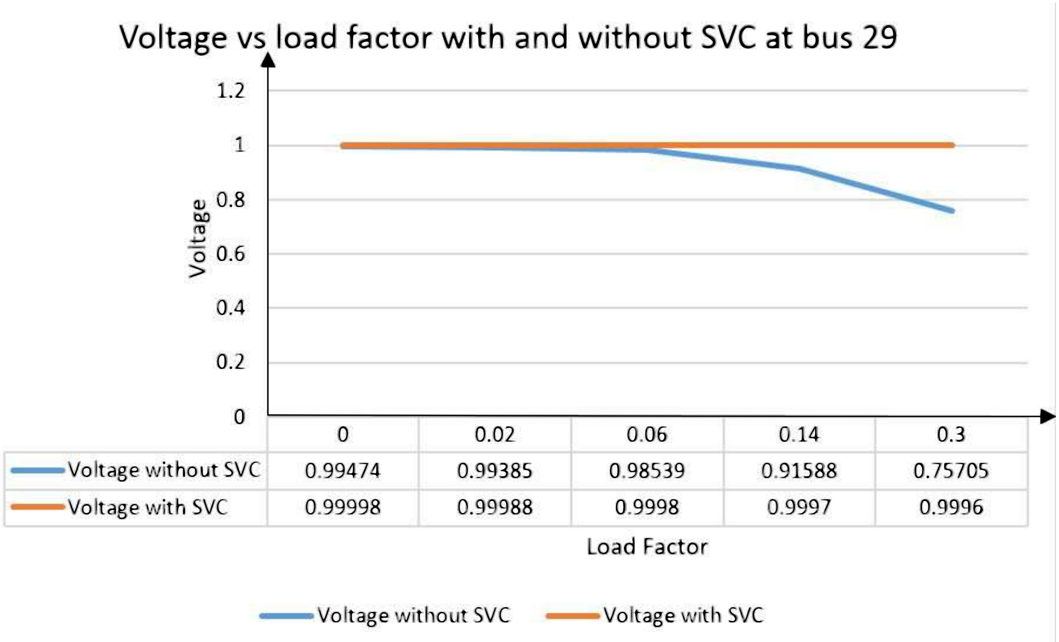

Fig. 4.6: Comparison of bus voltage of weakest bus with and without SVC

4.7 PARAMETERS OF PSO TO BE SELECTED

To start the iterative process, the parameters of the PSO are needed to be specifically specified. These parameters will decide the convergence rate of the program. The parameters selected in the work are listed in Table 4.3.

The size of the population will determine the solution evaluated for each particle and the results of each size will be stored and the result with the best solution will be stored out separately and named as a local best solution. The solution so obtained is for the single process has to be evaluated for a number of iteration and the best result so obtained is then named as a global best solution. The number of iterations is directly proportional to the accuracy of the system.

Personal and global acceleration coefficient will determine the rate of convergence towards the personal and global best values.

Table 4.3: Selected parameters of PSO

Parameters	Values
Maximum Number of iterations	50
Size of population	100
Inertia Coefficient	1
Damping Parameter	0.99
Personal Acceleration Coefficient	2
Global Acceleration Coefficient	2

4.8 MINIMIZATION OF ERROR WITH ITERATIVE PROCESS

The error is the objective function that is needed to be minimized. As the iterative process starts the objective to achieve the minimum error or the difference between the most sensitive bus and the reference nodal voltage is to be under the limit. It can be inferred from the figure that the local best or local minimum value has been achieved in many instances but the least value is achieved at the 32^{nd} iteration. Hence the conclusion can be drawn that PSO doesnt get stuck at the local minima rather it tries to become minimum at the global best solution of the process. The minimum error of $1.8 * 10^{-6}$ has been achieved in the 32^{nd} iteration with the rating of SVC at that moment to be 61.05 MVA.

Conclusions and Scope of Future Work

5.1 CONCLUSIONS

The presented optimization problem for minimizing the objective of voltage deviation has been achieved and the complete work of the thesis has been carried out in the following manner:

- In the initial stages of the work the voltage stability analysis of the system has been conducted and saddle point has been achieved.
- The most sensitive bus in the system is found out using continuation power flow method.
- The voltage profile of that weakest bus is improved.
- The optimal rating of the SVC has been achieved for the system using particle swarm optimization method.

The complete study has been conducted on IEEE 30 bus system and the results so obtained have been presented in the work.

5.2 SCOPE OF FUTURE WORK

The work has been successfully implemented there is still a lot of future scopes left in the work which can be listed as following:

- Although the work has been successfully implemented on a IEEE 30-bus system it can further be applied to a very large system consisting of large bus network
- Voltage improvement has been achieved neglecting the other aspects of the power system like the cost of the system, frequency stability and another transient factor, that can also be implemented in the future.
- The algorithm applied is for solving a single objective function in the project work, it can be further extended to multi-objective work.

- Multi-type FACTS device can be placed in the system for solving other problem of the system like power flow control, impedance control, power angle control.

List of Publications

- V. Saini and S.K. Jain,"Voltage Stability Enhancement through the Optimum SVC realization by Particle Swarm Optimization," communicated to *Journal of Electrical Engineering & Technology*

References

[1] A. G. Expósito, A. Gomez-Exposito, A. J. Conejo, and C. Canizares, *Electric energy systems: analysis and operation*. CRC Press, 2016.

[2] India blackouts leave 700 million without power — world news — the guardian. Accessed 06 June 2017. [Online]. Available: https://www.theguardian.com/world/2012/india-blackoutelectricitypowercuts

[3] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control*. McGraw-hill New York, 1994, vol. 7.

[4] C. Wang and M. H. Nehrir, "Analytical approaches for optimal placement of distributed generation sources in power systems," *IEEE Transactions on Power Systems*, vol. 19, no. 4, pp. 2068–2076, Nov 2004.

[5] V. Ajjarapu, *Computational techniques for voltage stability assessment and control*. Springer Science & Business Media, 2007.

[6] N. G. Hingorani and L. Gyugyi, *Understanding facts*. IEEE press, 2000.

[7] E. Ghahremani and I. Kamwa, "Optimal placement of multiple-type facts devices to maximize power system loadability using a generic graphical user interface," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 764–778, 2013.

[8] M. Esmaili, H. A. Shayanfar, and R. Moslemi, "Locating series facts devices for multi-objective congestion management improving voltage and transient stability," *European journal of operational research*, vol. 236, no. 2, pp. 763–773, 2014.

[9] R. S. Wibowo, N. Yorino, M. Eghbal, Y. Zoka, and Y. Sasaki, "Facts devices allocation with control coordination considering congestion relief and voltage stability," *IEEE Transactions on power systems*, vol. 26, no. 4, pp. 2302–2310, 2011.

[10] D. Radu and Y. Besanger, “A multi-objective genetic algorithm approach to optimal allocation of multi-type facts devices for power systems security,” in *Power Engineering Society General Meeting, 2006. IEEE.* IEEE, 2006, pp. 8–pp.

[11] R. S. Wibowo, N. Yorino, M. Eghbal, Y. Zoka, and Y. Sasaki, “Facts devices allocation with control coordination considering congestion relief and voltage stability,” *IEEE Transactions on power systems*, vol. 26, no. 4, pp. 2302–2310, 2011.

[12] L. Rocha, R. Castro, and J. Jesus, “An improved particle swarm optimization algorithm for optimal placement and sizing of statcom,” *International Transactions on Electrical Energy Systems*, 2015.

[13] H.-Y. Su and C.-W. Liu, “Estimating the voltage stability margin using pmu measurements,” *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 3221–3229, 2016.

[14] R. Al Abri, E. F. El-Saadany, and Y. M. Atwa, “Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation,” *IEEE transactions on power systems*, vol. 28, no. 1, pp. 326–334, 2013.

[15] R. Kalaivani and S. Dheebika, “Enhancement of voltage stability and reduction of power loss using genetic algorithm through optimal location of svc, tcsc and upfc,” *Journal of Engineering Science and Technology*, vol. 11, no. 10, pp. 1470–1485, 2016.

[16] A. Singh and S. Parida, “Novel sensitivity factors for dg placement based on loss reduction and voltage improvement,” *International Journal of Electrical Power & Energy Systems*, vol. 74, pp. 453–456, 2016.

[17] P.-C. Chen, V. Malbasa, Y. Dong, and M. Kezunovic, “Sensitivity analysis of voltage sag based fault location with distributed generation,” *IEEE Transactions on Smart Grid*, vol. 6, no. 4, pp. 2098–2106, 2015.

[18] P. Sharma and A. Kumar, “Thevenins equivalent based p–q–v voltage stability region visualization and enhancement with facts and hvdc,” *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 119–127, 2016.

[19] Y. Tang, H. He, J. Wen, and J. Liu, “Power system stability control for a wind farm based on adaptive dynamic programming,” *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 166–177, 2015.

[20] A. Elmitwally, A. Eladl, and J. Morrow, "Long-term economic model for allocation of facts devices in restructured power systems integrating wind generation," *IET Generation, Transmission & Distribution*, vol. 10, no. 1, pp. 19–30, 2016.

[21] P. Prabhakar and A. Kumar, "Voltage stability boundary and margin enhancement with facts and hvdc," *International Journal of Electrical Power & Energy Systems*, vol. 82, pp. 429–438, 2016.

[22] C. A. Canizares and Z. T. Faur, "Analysis of svc and tcsc controllers in voltage collapse," *IEEE Transactions on power systems*, vol. 14, no. 1, pp. 158–165, 1999.

[23] Y.-C. Chang, "Multi-objective optimal thyristor controlled series compensator installation strategy for transmission system loadability enhancement," *IET Generation, Transmission & Distribution*, vol. 8, no. 3, pp. 552–562, 2013.

[24] M. Khaleghi, M. M. Farsangi, H. Nezamabadi-pour, and K. Y. Lee, "Voltage stability improvement by multi-objective placement of svc using modified artificial immune network algorithm," in *Power & Energy Society General Meeting, 2009. PES'09. IEEE.* IEEE, 2009, pp. 1–7.

[25] Y.-C. Chang, "Multi-objective optimal svc installation for power system loading margin improvement," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 984–992, 2012.

[26] A. Abessi, V. Vahidinasab, and M. S. Ghazizadeh, "Centralized support distributed voltage control by using end-users as reactive power support," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 178–188, 2016.

[27] A. Karimi and R. Raisinejad, "Optimal placement facts device to increase voltage stability margin using direct search algorithm," *Journal of Fundamental and Applied Sciences*, vol. 8, no. 3S, pp. 2984–2995, 2016.

[28] A. R. Jordehi, J. Jasni, N. I. A. Wahab, and M. Z. A. A. Kadir, "Particle swarm optimisation applications in facts optimisation problem," in *Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International.* IEEE, 2013, pp. 193–198.

[29] V. Ajjarapu and C. Christy, "The continuation power flow: a tool for steady state voltage stability analysis," *IEEE transactions on Power Systems*, vol. 7, no. 1, pp. 416–423, 1992.

Appendix

Table A.1: Bus data of IEEE 30-bus system

Bus No.	**Type**	**Voltage(V)**	**Delta(rad)**	P_G**(kW)**	Q_G**(kVAR)**	P_L	Q_L	Q_{max}	Q_{min}
1	1	1.06	0	-	-	0	0	0	0
2	2	1.045	0	40	50	21.7	12.7	-20	60
3	3	1	0	0	0	2.4	1.2	0	0
4	3	1.06	0	0	0	7.6	1.6	0	0
5	2	1.01	0	0	37	94.2	19	-40	40
6	3	1	0	0	0	0	0	0	0
7	3	1	0	0	0	22.8	10.9	0	0
8	2	1.01	0	0	37.3	30	30	-15	50
9	3	1	0	0	0	0	0	0	0
10	3	1	0	0	0	5.8	2	0	0
11	2	1.082	0	0	16.2	0	0	-6	24
12	3	1	0	0	0	11.2	7.5	0	0
13	2	1.071	0	0	10.6	0	0	-6	24
14	3	1	0	0	0	6.2	1.6	0	0
15	3	1	0	0	0	8.2	2.5	0	0
16	3	1	0	0	0	3.5	1.8	0	0
17	3	1	0	0	0	9	5.8	0	0
18	3	1	0	0	0	3.2	0.9	0	0
19	3	1	0	0	0	9.5	3.4	0	0
20	3	1	0	0	0	2.2	0.7	0	0
21	3	1	0	0	0	17.5	11.2	0	0
22	3	1	0	0	0	0	0	0	0
23	3	1	0	0	0	3.2	1.6	0	0
24	3	1	0	0	0	8.7	6.7	0	0

25	3	1	0	0	0	0	0	0	0
26	3	1	0	0	0	3.5	2.3	0	0
27	3	1	0	0	0	0	0	0	0
28	3	1	0	0	0	0	0	0	0
29	3	1	0	0	0	2.4	0.9	0	0
30	3	1	0	0	0	10.6	1.9	0	0

Table A.2: Line data of IEEE 30-bus system

From bus	To Bus	R	X	T/F ratio	b/2
1	2	0.0192	0.0575	1	0.0264
1	3	0.0452	0.1652	1	0.0204
2	4	0.057	0.1737	1	0.0184
2	6	0.0581	0.1763	1	0.0187
6	7	0.0267	0.082	1	0.0085
6	28	0.0169	0.0599	1	0.065
6	8	0.012	0.042	1	0.0045
6	9	0	0.208	0.978	0
5	7	0.046	0.116	1	0.0102
6	10	0	0.556	0.969	0
9	11	0	0.208	1	0
4	6	0.0119	0.0414	1	0.0045
3	4	0.0132	0.0379	1	0.0042
9	10	0	0.11	1	0
4	12	0	0.256	0.932	0
12	13	0	0.14	1	0
12	14	0.1231	0.2559	1	0
12	15	0.0662	0.1304	1	0
12	16	0.0945	0.1987	1	0
27	29	0.2198	0.4153	1	0

14	15	0.221	0.1997	1	0
16	17	0.0824	0.1923	1	0
15	18	0.1073	0.2185	1	0
18	19	0.0639	0.1292	1	0
19	20	0.034	0.068	1	0
10	20	0.0936	0.209	1	0
10	17	0.0324	0.0845	1	0
10	21	0.0348	0.0749	1	0
10	22	0.0727	0.1499	1	0
21	23	0.0116	0.0236	1	0
15	23	0.1	0.202	1	0
22	24	0.115	0.179	1	0
2	5	0.0472	0.1983	1	0.0209
23	24	0.132	0.27	1	0
24	25	0.1885	0.3292	1	0
25	26	0.2544	0.38	1	0
25	27	0.1093	0.2087	1	0
28	27	0	0.396	0.968	0
27	30	0.3202	0.6027	1	0
29	30	0.2399	0.4533	1	0
8	28	0.0636	0.2	1	0.0214

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