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Optimal Placement of SVC in Power System for Voltage Stability Enhancement Using Genetic Algorithm

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Abstract

Voltage instability and voltage collapse are the foremost permanent concerns of electric utilities because of blackout event occurrences around the world. Flexible AC Transmission Systems (FACTS) has been proposed as the better alternative to overcome this, as in addition to improving voltage stability they improve system performance, reliability, quality of supply and also provide environmental benefit. The type of FACTS device and their location and setting in the system have different effect on power system. For determining that optimal location and rating which maximises voltage stability, this paper employs Genetic Algorithm (GA) based optimisation technique. Static Var Compensator (SVC) is the FACTS device used for improving voltage stability margin. To analyze the voltage stability of power system, Continuation Power Flow (CPF) analysis is used here. The study was conducted on IEEE 14 bus, modified IEEE 30 bus and 26 bus KSEB system and the optimal location and rating were identified.

Keywords: *Continuation power flow, FACTS, genetic algorithm, static var compensator.*

1. Introduction

The demand for electric power has been increasing from the time of its introduction. In the recent years, power demand has increased substantially and utilities have found it difficult to meet the ever increasing demand. The environmental, right of way and cost problems have delayed construction of both generation facilities and transmission lines which has led the above said crisis. Increasing electricity consumption also affects power system operation and it results in system working near stability limit. When a contingency condition, regardless its reason occurs in a power system, it leads the entire system to instability, and voltage drops in many buses intensively yielding to voltage collapse. The evidence for these are the widespread blackouts that occurred in the recent years. Insufficient reactive power support is the major factor that leads to voltage collapse. Providing necessary reactive power support is needed to maintain sufficient voltage stability margin. This ensures security of the power system against the short and long term instabilities and subsequent voltage degradation and voltage collapse [1].

In the early 1970's, it was recognized that a change is needed in the traditional practices used in system planning and operation because the existing mechanically operated switches were not fast enough from the stability point of view and need to be manually operated. The technological advancements in the semiconductor industry during those times led to the production of semiconductor switches which were very fast in their operation and could be automatically switched. This led to the era of Flexible Alternating Current Transmission System (FACTS) devices. Since the introduction of FACTS devices there has been a greater flexibility in power system operation. Also the stability of the power network was improved, the flows of heavily loaded lines were reduced and it helped to maintain the bus voltages at desired levels. Thereby, the FACTS utilization enhanced the performance of the power system [2].

The best performance is obtained from the FACTS devices only when they are optimally placed in the power system because one location will be best suited for a particular objective and not for other. Hence determination of optimal location is important. The investment cost of these devices is also huge. Hence determination of optimal rating is also necessary. For very small bus systems, simulation based work can be done to determine the optimal location and rating. But with increased number of buses simulation based technique is not favourable as they are time consuming and quite complex. Employing Artificial Intelligent (AI) techniques is proposed in this work as an alternative. Some common AI techniques are Genetic Algorithm (GA), Tabu Search (TS) algorithm, Simulated Annealing (SA) based approach, Particle Swarm Optimization (PSO) technique, artificial neural networks based algorithm, fuzzy logic based approach, adaptive neuro-fuzzy inference system. In this work GA based optimisation is used in determining optimal FACTS device location [1], [2].

2. FACTS Devices

The FACTS device concept was introduced by the Electric Power Research Institute (EPRI) in 1980. Since then facts devices have become more and more popular in power systems. The first device to be developed was the Static Var Compensator (SVC). They became popular in voltage stability enhancement and were employed in transmission and distribution systems. Later Gate Turn-Off (GTO) thyristor switches were developed. This led to the development of self commutated power electronic converter based FACTS devices. The introduction of the second generation FACTS devices became possible by the pioneering works by Indian Scientist Naraian G. Hingorani. These second generation FACTS device include Static Synchronous Compensator (Statcom), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) etc.

The primary application of FACTS is to enhance power transfer capabilities, allow more flexible control of power flows, as well as provide reactive power support. Besides they can also provide additional advantages like oscillation damping control, which improves power system small signal stability. Thus the objective of a FACTS installation in a power system is usually not to perform one single task, but for multiple tasks. Also the location of the FACTS device has a large impact on its performance with regard to the objective to be fulfilled. A location being the best for one objective may be less suitable for another objective. FACTS controllers can be divided into four categories based on their connection in the network. They include Shunt controllers, Series Controllers, Combined Series-Series Controllers, and Combined Series-Shunt Controllers. Shunt controllers are most suited for voltage support. Here the shunt controller SVC is employed for voltage stability enhancement [3].

3. Static Var Compensator (SVC)

The SVC is defined by IEEE as ``A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)". They are called static because they dont have any rotational components in them instead have power electronics based switches. The static switch employed is thyristor, without gate turn-off capability. SVC is basically a variable reactive admittance, which is controlled depending on the extent of voltage control needed. In other words when voltage varies, the firing angle of the static switch gets automatically varied thereby the reactive admittance gets varied which in turn controls the extent of reactive power getting injected or absorbed into the system as given in (1).

$$Q_{svc} = V^2 B_{svc} \qquad (1)$$

where Q_{svc} is the reactive power injected by SVC, V is the voltage of the line to which SVC is connected and B_{svc} is the susceptance of SVC [4].

3.1 Types of SVC

SVC is generally classified into two types –
1) Thyristor controlled and Thyristor-switched Reactor (TCR and TSR)
2) Thyristor-switched capacitor (TSC).

3.1.1 Thyristor Controlled and Thyristor Switched Reactor (TCR and TSR)

The TCR and TSR are shunt connected FACTS device. They consist of a fixed (usually air core) reactor and a bidirectional thyristor valve. Since both TCR and TSR consist of reactor banks, they absorb reactive power whenever connected to a power system. Hence it reduces voltage and is therefore used in over voltage situations. Due to the unavailability and high cost of large power rated thyristors usually a combination of thyristors are employed for constructing TCR and TSR. The Fig. 1 shows a single unit of TCR and TSR.

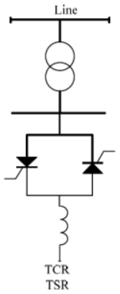

Figure 1: Line Diagram of TCR and TSR

The main difference between TCR and TSC is that in TCR the effective admittance of the device can be controlled in a smooth manner within its limit, while in TSR the effective admittance is not controllable rather it is fixed. So a group of such units are used and whenever desired, the required numbers are turned on. Hence the admittance variation in TSR is like a step like manner. The construction of TCR and TSC are similar but in TSR the firing angle is always kept at 0^o but for TCR it is kept variable [3], [4].

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

A TSC is a shunt connected FACTS device. It consists of a capacitor, a bidirectional thyristor valve and a relatively small surge current limiting reactor. This reactor is needed to primarily limit the surge current in the thyristor valve under abnormal operating condition. Since TSC consist of capacitor bank they always inject reactive power and thereby increase voltage. Hence TSC is used in low voltage situations. The Fig. 2 shows a single unit of TSC.

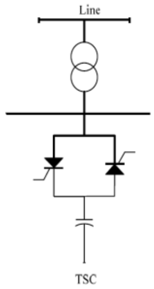

Figure 2: Line Diagram of TSC

A thyristor switched capacitor can be switched only at the instant the voltage on the capacitor equals the instantaneous value of supply voltage, otherwise there occurs switching transients. So for TSR there is a single switching instant. Hence firing angle control cannot be implemented in TSC and hence its admittance cannot be varied in a smooth manner. The admittance is varied in a step like manner switching various parallel connected TSC accordingly [3], [4].

4. Continuation Power Flow (CPF)

The objective of the work is voltage stability enhancement and hence a voltage stability assessment tool is needed. Many techniques are available for voltage stability assessment such as PV-QV curve analysis, QV sensitivity analysis, Continuation power flow analysis, QV modal analysis. This work employs CPF method. CPF is a static voltage stability assessment method. This method gives voltage stability in terms of a parameter called loading margin. Loading margin is the maximum allowable load increase from the base load condition before the system enters voltage collapse. Thereby it gives an idea about the allowable load increase for a system or voltage stability index. CPF also gives the complete PV curve of the system buses. Normal power flow fails to converge from the collapse point onwards since at the voltage collapse point the Jacobian matrix in the Newton Raphson method becomes singular. To continue power flow solving beyond collapse point, CPF is employed. Since it can continue power flow solution beyond collapse point it is called as 'Continuation' power flow [5].

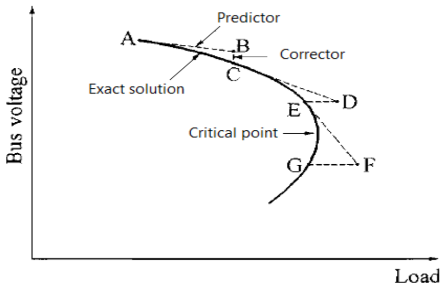

Figure 3: CPF predictor- corrector steps

The general principle of the CPF method is shown in Fig.3. The general principle behind CPF method is that it uses a predictor-corrector step to find a solution path of a set of power flow equations. The CPF technique starts from an initial solution usually the base load condition. It is shown as point (A) in the Fig. 3. From the point (A), a tangent predictor is used to estimate the solution (B) for a specified pattern of load increase. The corrector step then determines the exact solution (C) using a conventional power flow analysis with the system load assumed to be fixed. The voltages for a further increase in load are then predicted based on a new tangent predictor. The procedure goes on repeating to obtain the entire PV curve [4], [5].

5. Genetic Algorithm (GA)

Genetic algorithm is a popular optimisation algorithm, developed by John Holland and Goldberg. It is based on Darwin's theory of evolution which implies that the survival of an organism in nature is influenced by its fitness or strength. This Darwinian concept of evolution is employed in the algorithm to find a near optimal solution to different optimisation problems. A solution formed by genetic algorithm is usually represented as a fixed length string, called chromosome as shown in Fig. 4. A group of chromosomes is referred to as a population. A chromosome consists of genes and hence genes form the basic building block of a chromosome. The information related to a chromosome is contained in its genes. The information contained in them can be represented in many ways such as binary form, real number form, symbols or characters form etc. General representation in binary form of a chromosome is shown in Fig 4. The complete binary set or the chromosome represents a solution to the objective function [6].

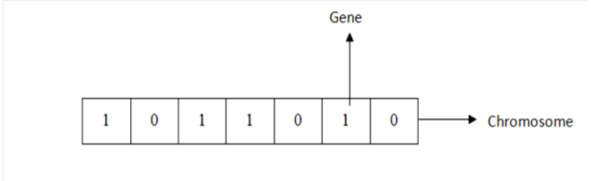

Figure 4: Chromosome structure

5.1 Basic Principle

GA begins by creating a random initial population. The algorithm after creating an initial population creates a sequence of new population. To create a new population, the algorithm scores each member of the current population by computing its fitness value. A fitness value is used to reflect the goodness of each member of the population. The individuals with the best fitness value in the current population are chosen as parents. Then some parents in the population will mate through a process called crossover thus producing new chromosomes named offspring. The offspring's gene composition is the combination of their parents. In a generation, a few chromosomes will also undergo mutation in their genes. The number of chromosomes which will undergo crossover and mutation is controlled by crossover rate and mutation rate. The fitness value of the chromosomes in this new population is again evaluated. The chromosome which has higher fitness value will have greater probability of being selected again in the next generation. The algorithm stops when one of the stopping criteria, such as the number of generations, time limit and fitness limit, is met. Towards the end, chromosome value will converge to a certain value which is the best solution for the problem [6], [7]. The general flowchart of GA algorithm is shown in Fig. 5.

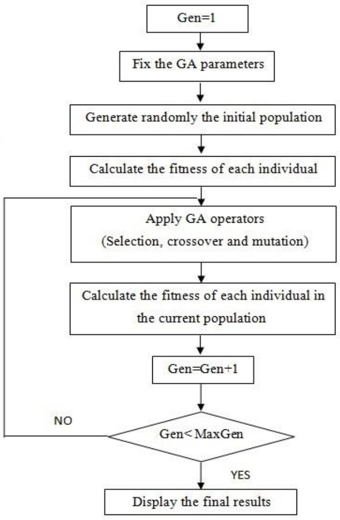

Figure 5: CPF predictor- corrector steps

6. GA Based Optimal SVC Placement

GA based optimal SVC placement is aimed at maximizing the objective function of voltage stability enhancement. This objective function can be formulated as in (3)

$$\text{Maximize} \quad \lambda \qquad (3)$$

Here λ is called the system loading margin which is a type of voltage stability index. The GA actually helps to find the optimal location and rating of SVC that would give maximum voltage stability enhancement. The chromosomes or solutions to the objective function in this problem should contain an optimal location and optimal rating which would provide maximum voltage stability enhancement. So there will be two fields for a single chromosome, one for the optimal location and another for the optimal rating. Such a chromosome would be a one as shown in Fig. 6.

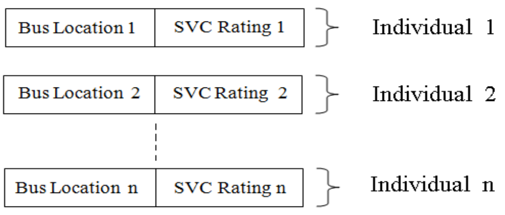

Figure 6: Structure of a random population

The population pool would consist of a set of chromosomes as shown in the Fig. 5. The GA evaluates each member of the population to find the one which provides largest voltage stability enhancement. The entries to each chromosome are found with a procedure as explained in the following section.

6.1 Determination of Optimal SVC Location

The location for SVC placement is chosen as the system buses. The feasible bus locations are chosen as those which do not contain generators, tap changing transformer and synchronous compensator, since these are already voltage controlled buses. The buses are chosen randomly from the feasible locations and evaluated.

6.2 Determination of Optimal SVC Rating

The rating or setting determination of SVC is also an important criterion for optimal SVC placement as the total investment cost depends on the rating of the equipment. The relation for choosing SVC rating is expressed as given in (4)

$$Q_L \leq Q \leq Q_U \qquad (4)$$

where Q is the SVC rating, Q_L and Q_U are the lower and upper limit of SVC rating. As seen from (4) the rating of the device is chosen between an upper limit and lower limit. The lower limit is chosen as a value usually lesser than the reactive power demand at any bus in the system at base load condition. The upper limit Q_U is chosen as in (5).

$$Q_U = Q_c - Q_b \qquad (5)$$

where Q_c is the reactive power demand at a bus at voltage collapse condition and Q_b is the reactive power demand at a bus at base load condition. The reactive power demand at base load condition is obtained by running power flow for the system at the base load condition. The reactive power demand at voltage collapse condition is obtained by running CPF. The entire process of determining optimal location and rating of SVC will be as shown in the flowchart in Fig. 7.

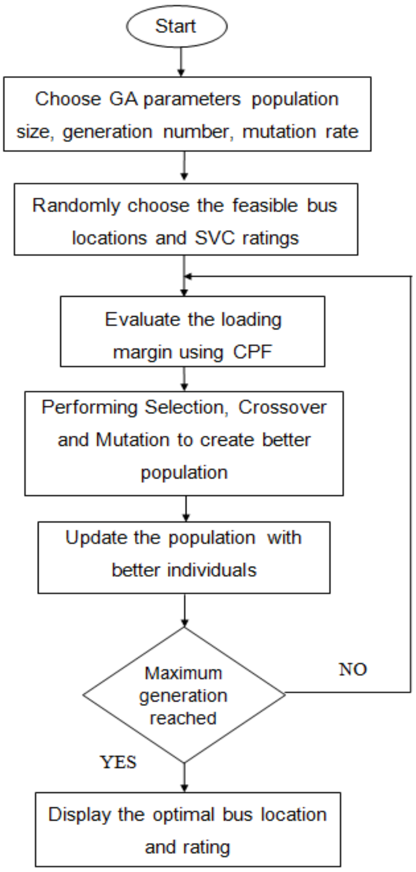

Figure 7: Flowchart for genetic algorithm based placement of SVC

7. Simulation and Coding Results

The simulation study mainly involves the modelling of the test systems and then analysing them using power flow and continuation power flow techniques. The modelling and analysis is done with the help Matlab-PSAT software. PSAT stands for Power System Analysis Toolbox. PSAT is a MATLAB toolbox for electric power system analysis and control. This software offers a user friendly interface and is easily understandable. PSAT can perform various operations like power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation. In this work CPF technique was used to determine the optimal location and rating of SVC for voltage stability improvement. The coding study uses genetic algorithm program developed in Matlab editor to determine the optimal bus location and rating for SVC. The program also makes use of PSAT modelled test systems and its function routines for SVC location and rating determination.

The test systems considered were the IEEE 14 bus system, modified IEEE 30 bus system and 26 bus Kerala State Electricity Board (KSEB) practical system. The systems were modelled in the PSAT software. The PSAT model single line diagram and the description of IEEE 14 bus, modified IEEE 30 bus and 26 bus KSEB system is given in the following sections.

7.1 IEEE 14 bus system without SVC

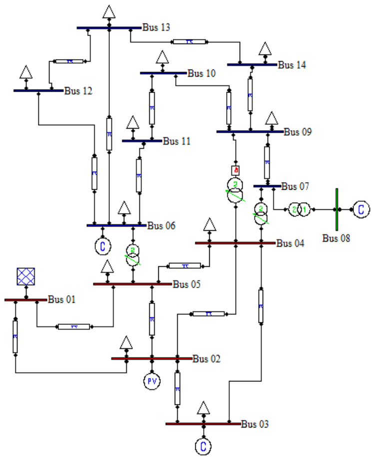

Figure 8: PSAT model of IEEE 14 bus system

IEEE 14 bus system shown in Fig. 8 consists of five synchronous machines with IEEE type-1 exciters, three of which are synchronous compensator used only for reactive power support. The system also has 16 transmission lines, 4 tap changing transformer and 11 loads. The total real and reactive power generation in the system is 272.6 MW and 101.99 Mvar. The 11 loads in the system totals to 259 MW and 73.5 Mvar. The losses in the system are 13.6 MW and 28.49 Mvar.

The power flow analysis of the system gives the base load voltage profile as shown in Fig. 9. The system voltage profile at loadability limit of 1.47 is also shown in Fig. 9.

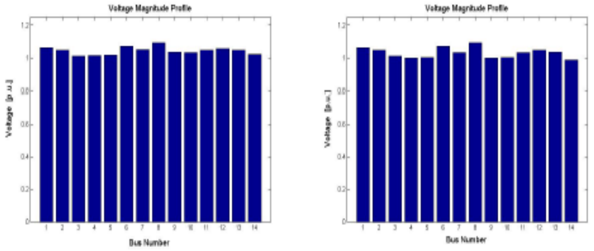

Figure 9: System voltage profile at base load and at loadability limit of IEEE 14 bus system without SVC

The system load ability limit is the extent to which the system can be loaded without violating transmission line flow limit, generator reactive power limit and bus voltage limit. The CPF analysis gives the system loading margin as 4.033, which means that the system enters voltage collapse after the system load exceeds 4.003 times the base load. The CPF analysis can also provide the PV curve of lowest three voltage stable buses in the system. It is illustrated in Fig. 10

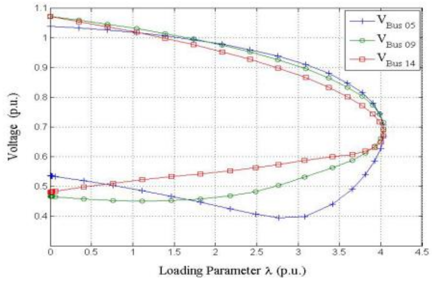

Figure 10: PV curve of lowest three voltage stable buses of IEEE 14 bus system without SVC

7.2 Modified IEEE 30 bus system without SVC

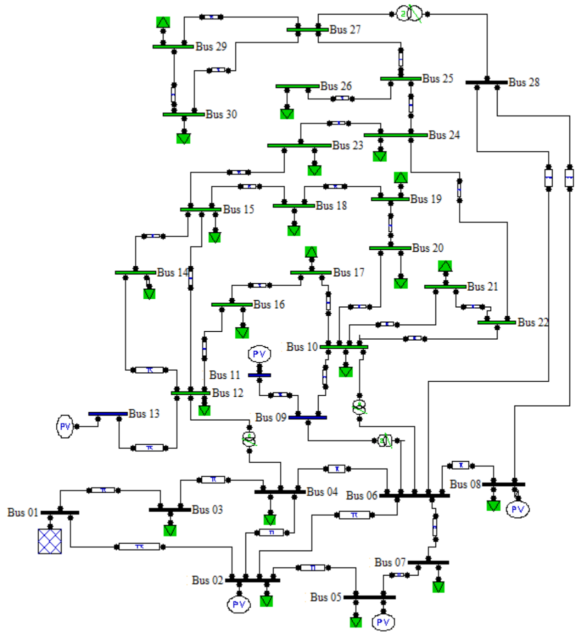

Figure 11: PSAT model of modified IEEE 30 bus system

The modified IEEE 30 bus system as shown in Fig. 11 consists of six synchronous machines. All of these are synchronous generators. The system also has 37 transmission lines, 4 tap changing transformers and 21 loads. The total real and reactive power generation in the system is 290.77 MW and 122.988 Mvar. There are 21 loads in the system totalling to 283.4 MW and 126.2 Mvar. The losses in the system are 7.368 MW and -3.2118 Mvar.

The power flow analysis of IEEE 30 bus system gives the base load voltage profile as shown in Fig. 12. The system voltage profile at loadability limit of 1.702 is also shown in Fig. 12. The CPF analysis of the system gives the system loading margin as 3.0661 and the PV curves of least voltage stable buses is shown in Fig. 13.

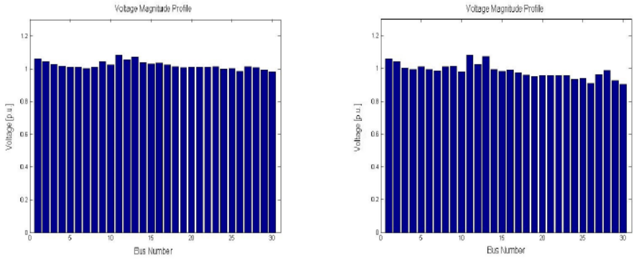

Figure 12: System voltage profile at base load and at loadability limit of modified IEEE 30 bus system without SVC

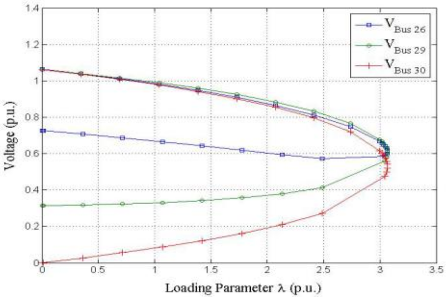

Figure 13: PV curve of lowest three voltage stable buses of modified IEEE 30 bus system without SVC

7.3 26 Bus KSEB System without SVC

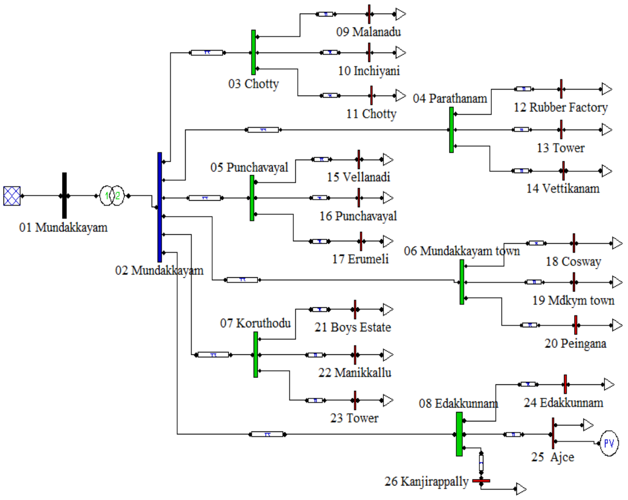

Figure 14: PSAT model of 26 bus KSEB system

The considered 26 bus KSEB system is basically a distribution system coming under Mundakkayam substation. The system has 24 transmission lines, one step down transformer and 18 loads. The Fig. 14 shows the PSAT model of the 26 bus KSEB system. The total real and reactive power generation in the system is 2.6775 MW and 1.0116 Mvar. There are 18 loads in the system which totals to 2.5764 MW and 0.877 Mvar. The losses in the system are 0.101 MW and 0.1351 Mvar.

The power flow analysis of 26 bus KSEB system gives the base load voltage profile as shown in Fig. 15. The system voltage profile at loadability limit of 1.8874 is also shown in Fig. 15. The CPF analysis gives the system loading margin as 4.7324 and the PV curves of least voltage stable buses is shown in Fig. 16.

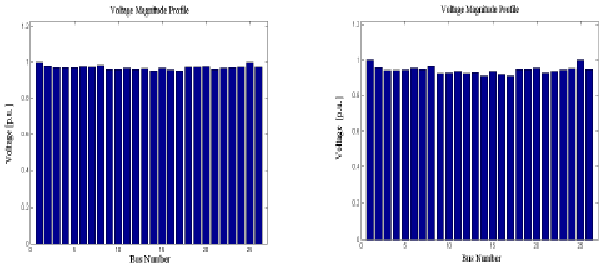

Figure 15: System voltage profile at base load and at loadability limit of 26 bus KSEB system without SVC

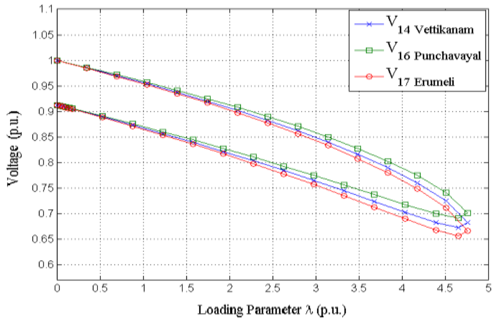

Figure 16: PV curve of lowest three voltage stable buses of 26 bus KSEB system without SVC

7.4 Coding Results

The genetic algorithm based program for determining optimal location of SVC was done using MATLAB editor. The GA parameter such as the crossover rate is chosen as 0.8 and mutation rate as 0.2. The particle size and generation number chosen for 14 bus is 32 and 50, of modified 30 bus is 64 and 100 and of 26 bus KSEB system is 64 and 100. The results obtained after running the program is obtained as follows. For IEEE 14 bus an SVC of 49 MVAr rating placed at bus 9 would provide the largest voltage stability. For IEEE 30 bus .

Table 1: Coding Results

Bus System	Bus Location	SVC Rating	Loading Margin
IEEE 14 bus system	9	49	4.1053
Modified IEEE 30 bus system	30	5	3.9106
26 bus KSEB system	24	302	4.823

7.5 IEEE 14 bus system with SVC at Bus 9

By placing SVC of 49 MVAr rating at bus 9, the voltage profile at base load and at previous loadability limit is improved as shown in Fig. 17 and 18.

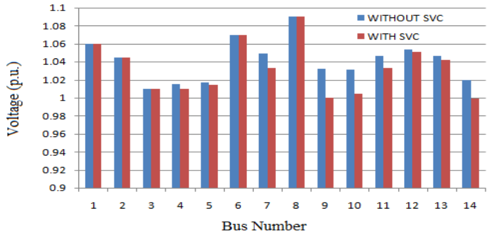

Figure 17: Comparison of voltage profile at base load of IEEE 14 bus system

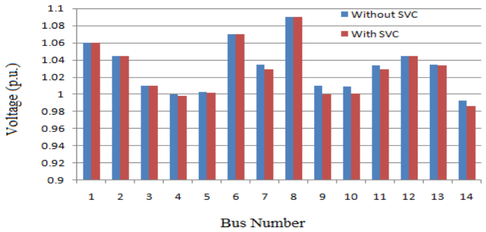

Figure 18: Comparison of voltage profile at initial loadability limit (1.47) of IEEE 14 bus system

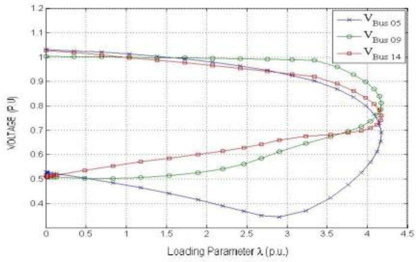

Figure 19: PV curve of IEEE 14 bus system after SVC placement

From Fig. 17 and 18 it is clear that the system voltage profile is improved to 1 p.u after SVC placement. Also the system loading margin is improved from 4.003 to 4.1053 and loadability limit from 1.47 to 1.76. Both these indicate an improvement in system voltage stability. Again it is also evident from the PV curve in Fig. 19 that the system is now having flatter voltage profile compared to the case without SVC which also proves the same.

7.6 Modified IEEE 30 bus system with SVC at Bus 30

After placing SVC of 5 MVAr rating at bus 30, the voltage profile at base load and at previous loadability limit is improved as shown in Fig. 20 and 21. From Fig. 20 and 21 it is clear that the system voltage profile is improved to 1 p.u after SVC placement. Also the system loading margin is improved from 3.0661 to 3.9106 and loadability limit from 1.702 to 2.417 after SVC placement. Both these indicate an improvement in system voltage stability. Again it is also evident from the PV curve in Fig. 22 that the system is now having flatter voltage profile compared to the case without SVC which also proves the same.

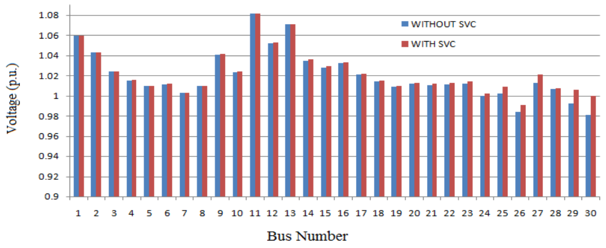

Figure 20: Comparison of voltage profile at base load of modified IEEE 30 bus system

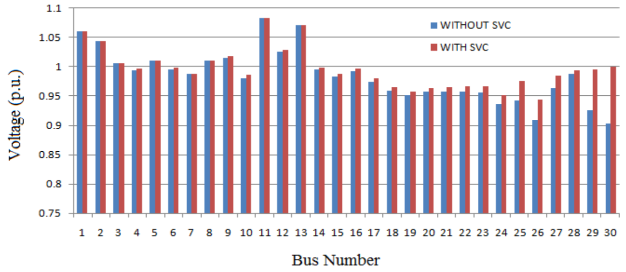

Figure 21: Comparison of voltage profile at initial loadability limit (1.702) of modified IEEE 30 bus system

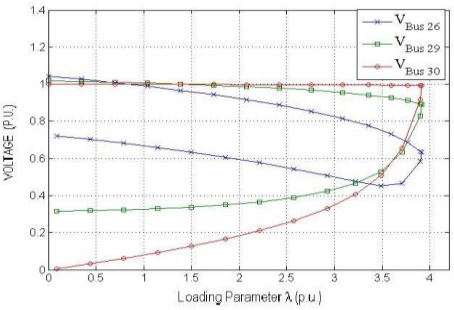

Figure 22: PV Curve of Modified IEEE 30 Bus System after SVC Placement

7.7 26 Bus KSEB System with SVC at Bus 24

After placing SVC of 302 kVAr rating at bus 24, the voltage profile at base load and at previous loadability limit is improved as shown in Fig. 23 and 24. From Fig. 23 and 24 it is clear that the system voltage profile is improved to 1 p.u after SVC placement. Also the system loading margin is improved from 4.7324 to 4.823 and loadability limit from 1.8874 to 2.2712 after SVC placement. Both these indicate an improvement in system voltage stability.

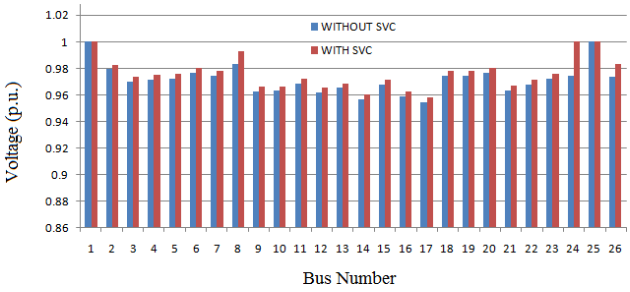

Figure 23: Comparison of Voltage Profile at Base Load of 26 Bus KSEB System

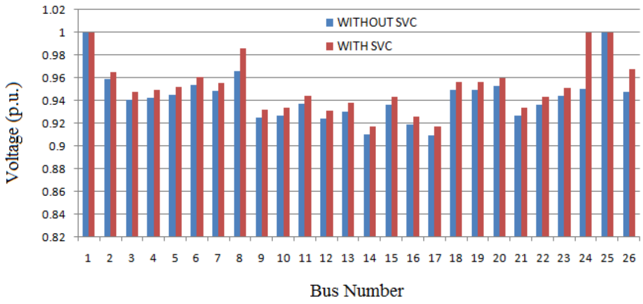

Figure 24: Comparison of Voltage Profile at Initial Loadability Limit (1.8874) of 26 Bus KSEB System

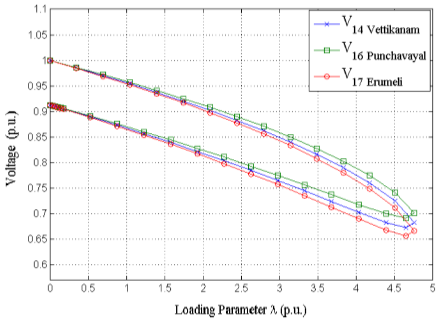

Figure 25: PV Curve of 26 Bus KSEB System After SVC Placement

8. Conclusion

FACTS devices have gained importance in power system sector in the last 20 years because they offer increased power transfer capability, better controllability of power flow, increased stability of power system. The placement of these devices is however needed to be properly planned or the desired performance may not be obtained and the huge investment would go in vain. This work proposes a genetic algorithm based placement strategy that would determine the most favourable SVC location and its rating which maximizes voltage stability. The algorithm was tested on the IEEE 14 bus, modified IEEE 30 bus system and practical KSEB system. By programming based analysis it was found that the maximum voltage stability will be obtained by placing 49 MVAr rated SVC at 9th bus for IEEE 14 bus system, 5 MVAr rated SVC at 30th bus for IEEE 30 bus system and 302 kVAr rated SVC at 24th bus for KSEB practical system respectively. This algorithm is helpful especially for large bus systems as simulation based analysis would be highly time consuming and cumbersome. Hence this technique can be used for various FACTS placement strategies in large bus systems .

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