Optimal Power Flow Studies Using FACTS Devices

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Abstract: ***The subject of optimal power flow (OPF) has gained a lot of attention due to the high cost of electrical energy. The main objective function of OPF problem is optimizing specific objective functions such as power loss minimization and voltage profile improvement of power system by adjusting the power control variables and at the same time satisfying the equality and the inequality constraints. Flexible AC Transmission Systems (FACTS) has been proposed as the better alternative to overcome this, as in addition to improving system performance, reliability, quality of supply and also provide environmental benefit. Static Var compensator (SVC) has been employed to meet the objective of this project which is to evaluate optimal location of SVC for voltage improvement and loss minimization in power system. For determining that optimal location Power System Analysis Toolbox (PSAT) software Analysis is used here. The proposed algorithm has used to determine optimal placement of SVC controller and solving optimal power flow (OPF) to improve voltage profile and reduce the real power losses within real and reactive power generation limits, and SVC operation limit., and it can be obtained for IEEE standard bus systems. In order to determining the optimal location of SVC, the Continuation Power Flow (CPF) analysis is used here. The continuation power flow (CPF) is an accurate method for estimating the maximum loading margin and determined the "weakest bus" When the voltage collapse occurs. Continuation power flow (CPF) is done with PSAT Soft ware. The advantage of this simulated method is to develop a simple, fast and convenient procedure which can be applied effectively. Effectiveness of the proposed method is tested for IEEE 6 and IEEE 30 bus system using MATLAB/PSAT software.***

Keywords: Optimal power flow (OPF), FACTS Devices (SVC), Optimal location of SVC, PSAT Soft ware (CPF)

1. Introduction

In generally Power is generated in generating station, transmitted through transmission line and then distributed to consumers. Power flow analysis is the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities. Load flow studies are done using Newton-Raphson method. Transmission line is characterized by resistance, inductance, and capacitance. This will result in losses. These losses cannot be eliminated but it can be reduced. Voltage collapses typically occurs on power systems that are heavily loaded, faulted and/or have reactive power shortage. The only way to prevent the occurrence of voltage collapse is either to reduce the reactive power load or to provide the system with additional supply of reactive power before the system reaches the point of voltage collapse. [1-2]

The Optimal power flow (OPF) is the most important tool for power system planning, operation and control. The OPF problem is a nonlinear optimization problem. The OPF has been usually considered as the Minimization of an objective function representing the generation cost and/or the transmission loss minimization of the total voltage deviation at all load buses.[3-5]

The Optimal power flow (OPF) problem has been well known since 1960s. In 1962, Carpentier first introduced a generalized nonlinear programming formulation of the economic dispatch problem, including voltage, reactive power and operational constraints. Since then, the main focus of the research work has been on the technical aspects of network modeling, mathematical formulation, and solution of OPF. In this case, nonlinear techniques must be employed. Optimization is a mathematical tool to find the maximum or the minimum of a function subject to some constrains. Using lose function as objective function subjected to generator MW, transformer tapping, reactive power injection and controlled voltage as constrains. Using this we get optimal value for bus parameters such that transmission losses are minimum.[6-9]

Flexible AC Transmission Systems (FACTS) are the name given to the application of power electronics devices to control the power flows and other quantities in power systems. In addition to improving system performance, reliability, quality of supply and it is also providing environmental benefit. FACTS devices have become very popular in improving the overall performance of power system under both steady state and dynamic conditions. In the literature, many research works were carried out with FACTS devices being included in the power system analysis and optimization. They were introduced to discuss the control strategy of FACTS devices using multiobjective OPF. In addition to the steady state control of power flow and voltage, FACTS controllers can also contribute to both large and small signal dynamic performance of the power system.[10-13]

Optimal power flow (OPF) started, as one of the challenging needs for economic power system operations, in the early sixties.. The importance of incorporating FACTS devices in OPF cannot be over emphasized. This importance can be realized when looking to the benefits offered by FACTS devices, the good coordination needs between them, and the need for relaxing the operating limits that stop the OPF objective optimization. PSAT soft ware used solves the OPF problem. The proposed algorithm has used to determine optimal placement of SVC controller and solving optimal power flow (OPF) to improve voltage profile and reduce the real power losses within real and reactive power generation limits, and SVC operation limit, and it can be obtained for IEEE standard bus systems. .[14-17]

In recent years many types of controllers based FACTS devices such as: shunt Controllers (SVC, STATCOM), series Controllers (TCSC, SSSC) and hybrid Controllers (UPFC) integrated in the electricity market to improve the performances of the practical power system.The Minimization of real power losses, improving voltage profile of the buses and enhancing system stability by placing the Static Var compensator (SVC). Static VAR compensator is considered as simple injecting the reactive power into the transmission line. 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)". [18-21]

The type of FACTS device and their location and setting in the system have different effect on power system. For determining that optimal location Power System Analysis Toolbox (PSAT) software Analysis is used here. In order to determining the optimal location of SVC, the Continuation Power Flow (CPF) analysis is used here. The performance of shunt FACTS controller connected to the weakest bus is assessed by comparing voltage profile and steady state stability margin of the system. Voltage stability index can be used for determining the weakest line in a power system.The continuation power flow (CPF) is an accurate method for estimating the maximum loading margin and determined the "weakest bus" When the voltage collapse occurs. The "weakest bus" taken as optimal location of SVC. Continuation power flow (CPF) is done with PSAT Soft ware. The advantage of this simulated method is to develop a simple, fast and convenient procedure which can be applied effectively. Effectiveness of the proposed method is tested for IEEE 6 and IEEE 30 bus system using MATLAB/PSAT software. [22-25]

2. Problem formulation of OPF using SVC

2.1. Newton Raphson Power flow Method

The most widely used method for power flow solution is the Newton-Raphson (NR) method. NR method is found to be more efficient and practical. The number of iterations required to obtain a solution is independent of the system size and less. Since in the power flow problem real power and voltage magnitude are specified for the voltage-controlled buses, the power flow equation is formulated in polar form. This equation can be rewritten in admittance matrix as:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (1)$$

In the above equation, j includes bus i.

expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_{ij}| \angle \theta_{ij} + \delta_j \quad (2)$$

The complex power at bus i is

$$P_i - jQ_i = V_i^* I_i \quad (3)$$

Substituting form equation for in equation

$$P_i - jQ_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}||V_{ij}| \angle \theta_{ij} + \delta_j \quad (4)$$

Separating the real and imaginary parts,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (5)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (6)$$

The result is a linear system of equations that can be expressed as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (7)$$

Where ΔP and ΔQ are called the mismatch equations. The liberalized system of equations is solved to determine the next guess $(m + 1)$ of voltage magnitude and angles based on:

$$\delta_i^{(k+1)} = \Delta \delta_i^{(k)} + \delta_i^{(k)} \quad (8)$$

$$|V_i^{(k+1)}| = \Delta V_i^{(k)} + V_i^{(k)} \quad (9)$$

Where, i and j are ith and jth buses and k is no. of iterations.

2.2 Optimal Power flow (OPF) Problem Formulation

The Objective function of optimal power flow(OPF) can be formulated as a general constraints optimization problem as follows Minimization of power losses and also the improve the voltage profile.

2.2.1. Real Power losses minimization

This objective consists of minimizing real power losses in power system network, It can be expressed as

$$P_{losses} = \min\left(\sum_{k=1}^{NL} g_k \left[V_i^2 - V_j^2 - 2 V_i V_j \cos(\delta_i - \delta_j)\right]\right) \quad (10)$$

Where, g_k is the conductance,
V_i, V_j are voltages at bus i, j
δ_i, δ_j are voltage angle at bus i, j

2.2.2. Voltage profile improvement

Optimal location and size of SVC is determined such that voltage profile will improve. To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. Objective function for improve the of load bus voltage (VP) can be defined as:

$$VP = \sum_{k=1}^{Nbus} \left| V_k - V_k^{ref} \right| \quad (11)$$

Where ,V_k is the voltage magnitude at bus k.
Equality constraints: The equality constraints of the OPF reflect active and reactive power between productions

$$P_{Gi} = P_{Di} + P_L \quad (12)$$

$$Q_{Gi} = Q_{Di} + Q_L \quad (13)$$

Inequality constraints: These are the sets of all operational power system elements (generator, transformer, and compensators from production source to load bus).
Voltage limits:

$V_i^{min} \le V_i \le V_i^{max}$; i=1, 2….N no. of bus

Real power generation limits:

$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}$; i=1, 2 ..N no. of Generators

Reactive power generation limits:

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

SVC limits:

$$B_{svc}^{\min} \le B_{svc} \le B_{svc}^{\max}$$

$$Q_{svc}^{\min} \le Q_{svc} \le Q_{svc}^{\max}$$

2.3 Modeling of Static Var Compensator

Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. SVC is a shunt compensator that has both inductive and capacitive nature. It absorbs reactive power due to its inductive nature and injects reactive power due to its capacitive nature. It is connected in parallel with bus and if the bus voltage falls below lower limit then SVC acts as a capacitor and generates reactive power. If the bus voltage exceeds the upper limit then SVC acts as an inductor and absorbs reactive power. SVC total susceptance model: The SVC is taken to be a continuous, variable susceptance, which is adjusted in order to achieve a specified voltage magnitude. A changing susceptance Bsvc represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig. 2.1 SVC firing angle model: The equivalent reactance XSVC, which is function of a changing firing angle α, is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 2.2

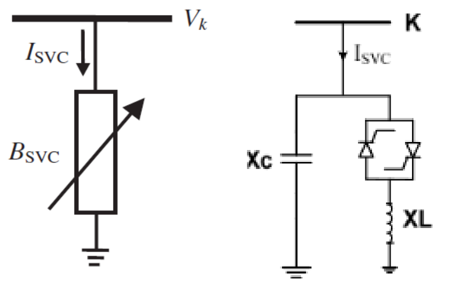

Figure 2.1: Total substance SVC model Fig.2.2: firing angle SVC model

The SVC is treated as a generator behind an inductive reactance when the SVC is operating within the limits. The SVC is represented by a shunt variable susceptance inserted at the bus. It may take values characterized by the reactive power injected or absorbed at the voltage of 1 p.u. The current drawn by the SVC is

$$I_{SVC} = j B_{SVC} V_k \qquad (14)$$

The reactive power drawn by the SVC, which is also the reactive power injected at bus k, is

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} \qquad (15)$$

The modified equation of the SVC is given by the Following equation where the total susceptance Bsvc is taken to be the state variable:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^i = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix}^i \begin{bmatrix} Q_k \\ \Delta B_{svc}/B_{svc} \end{bmatrix}^i \qquad (16)$$

at the end of iteration i, the variable shunt susceptance Bsvc updated according to the equation given below;

$$B_{SVC}^{(i+1)} = B_{svc}^{i} + \left(\frac{\Delta B_{svc}}{B_{svc}} \right)^i \qquad (17)$$

The changing susceptance represents the total SVC susceptance necessary to maintain the nodal voltage magnitude at the specified value.

2.4 Optimal location of SVC

To improve the voltage profile and minimize power losses of power system an alternative solution is to locate SVC. For determining that optimal location Power System Analysis Toolbox (PSAT) software Analysis is used here. The main functions of PSAT soft ware are: power flow analysis, continuation power flow analysis, N-1 contingency analysis. In order to determining the optimal location of SVC, the Continuation Power Flow (CPF) analysis is used here. The performance of shunt FACTS controller connected to the weakest bus is assessed by comparing voltage profile and steady state stability margin of the system. The optimal location of SVC has been selected on the basis of voltage stability index (VSI) .Voltage stability index can be used for determining the weakest bus in a power system. Continuation load flow analysis suitably modifies conventional load flow equations to become stable also in the singular point of the P-V curve and therefore to be capable to calculate both upper and lower part of the P-V curve. 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. 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. By continuation power flow (CPF) is an accurate method for estimating the maximum loading margin and determined the "weakest bus" When the voltage collapse occurs. Simulation and it is done by using Power System Analysis Toolbox (PSAT). Several steps have been achieved the objectives, the step used to simulate the bus system.

a) Modeling the bus system by using PSAT
b) Perform the power flow analysis (NR method).
c) Perform the CPF and draw PV curve to determine weak bus of the system
d) Identify the suitable location of SVC, So it gives optimal Performance.
e) Obtained the voltage magnitude and real power losses using with and without using SVC for optimal power flow studies.

3. Results and Discussion

3.1 Results for IEEE 6 bus system

Firstly design the IEEE 6 bus by using PSAT software, is show in fig. 5.1.By using Continuation power flow (CPF) on PSAT software can get the PV curve of IEEE 6 bus system and also identify the weak bus during voltage collapse, and it is taken as the optimal bus for svc placement. The PV curve of IEEE 30 bus system is show in below figure 3.1.

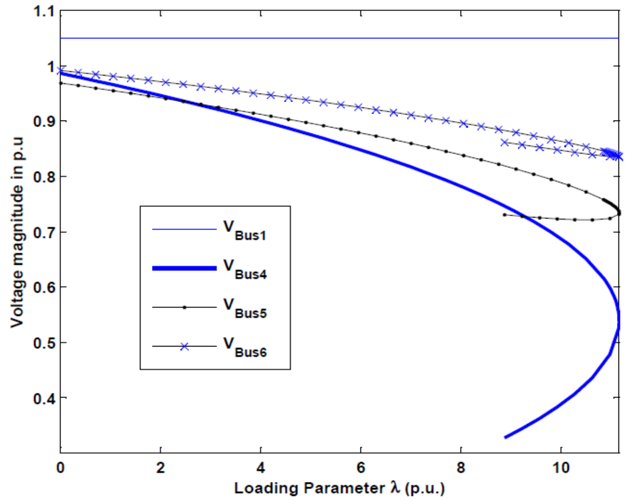

Figure 3.1: PV curve of IEEE 6 bus system Without SVC

From Fig. 3.1, It is clearly says that the voltage collapse occurs at the maximum loading parameter of 11.1607 and voltage magnitude of 0.57182 p.u. at bus no.4 (Dark line). So, weakest bus is taken as bus no.4. And it is taken as optimal bus for placement of SVC. And line 4-5 is gives better shunt compensation results.

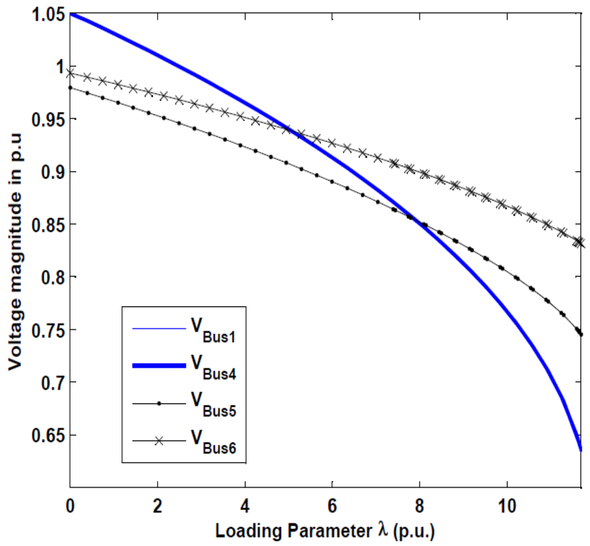

Figure 3.2: PV curve of IEEE 6 system with SVC at bus 4

The PV curve for IEEE 6 bus without SVC is seen As described in the earlier section, the SVC was placed in the weakest bus one at a time and it was found voltage profile and PV curve for IEEE 6 bus system with SVC at bus no. 4 is improved. From Fig.5 it is observe the maximum loading factor of 11.696 has increases when compared to the base case i.e. 11.1607 and also improve the voltage profile. So, bus 4 is the optimal location of SVC.

Table 1: Voltage magnitude of IEEE 6 bus system before and after placement of SVC:

Bus no.	Voltage magnitude in p.u	
	Without SVC	With SVC
1	1.050	1.050
2	1.050	1.050
3	1.050	1.050
4	0.985	1.050
5	0.968	0.979
6	0.991	0.994

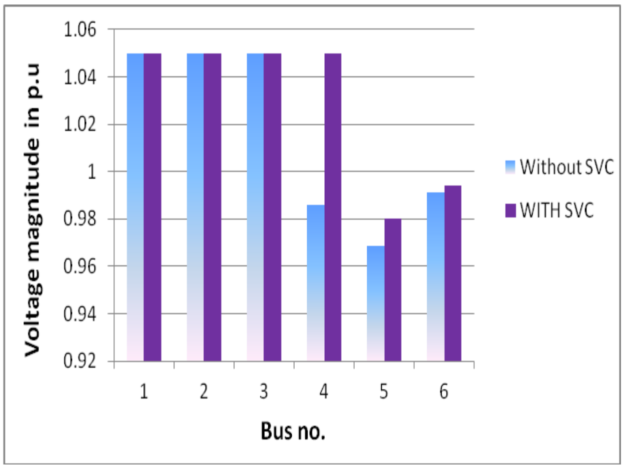

Figure 3.3: voltage magnitude in case of with and without SVC

From table no.1 and fig no. 3.3 it is observe that the voltage profile of load buses will be improved. The optimal reactive power injected by SVC bus no.4 is 10.926 Mvar. The corresponding total active power loss is 9.0451 MW reduced from base case i.e. 9.8754 MW. So, the OPF down by using optimal location of SVC.

3.2 Results for IEEE 30 BUS system:

Firstly design the IEEE 30 bus by using PSAT software, is show in fig.5.2. IEEE 30 bus systems of 6 generators buses and 24 load bus and also 41 transmission lines. Bus no. 1 is taken as the slack bus. By using PSAT soft ware By run the NR load flow method and also get the power flow data i.e. voltage magnitude and angle, real and reactive power generation and load. By using Continuation power flow (CPF) on PSAT software can get the PV curve of IEEE 30 bus system and also identify the weak bus during voltage collapse, and it is taken as the optimal bus for svc placement. The PV curve of IEEE 30 bus system is show in below figure 8. In the PV curve can take least three bus voltage magnitude i.e V_{bus} 26, V_{bus} 29, V_{bus} 30. Is show in below figure .3.4

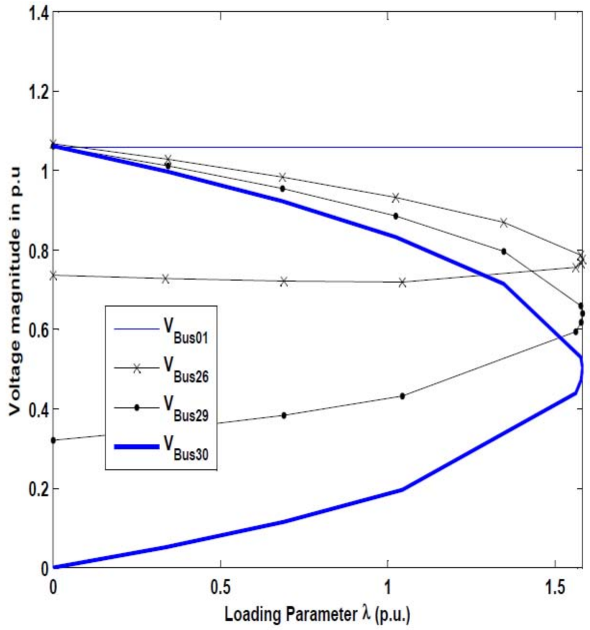

Figure 3.4: PV curve of IEEE 30 bus system Without SVC

Fig. 3.4. It is clearly observe that the voltage collapse occurs at the maximum loading parameter of 1.5819 and voltage magnitude of 0.473 p.u at bus no.30, So, the optimal location of SVC is bus no.30 and line 30-29 is gives best Line for shunt compensation.

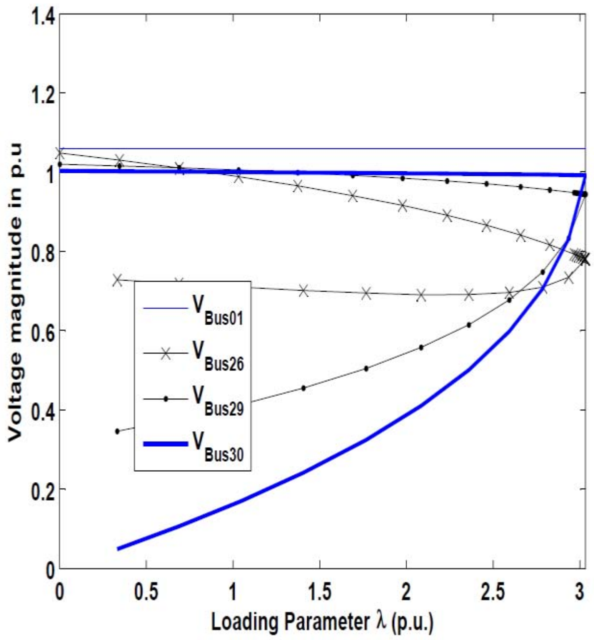

Figure 3.4: PV curve of IEEE 30 system with SVC at bus30

As described in the earlier, the SVC was placed in the weakest bus one at a time and it was found that The voltage profile and PV curve will improve with SVC placed at bus no. 30. From Fig. 3.4. It is observe the maximum loading factor of 3.0338 has increases when compared to the base case and also improve the voltage profile. So, bus 30 is the optimal location of SVC.

Table 3: Voltage magnitude of IEEE 30 bus system before and after placement of SVC:

Bus no.	Voltage magnitude in p.u	
	Without SVC	With SVC
1	1.060	1.060
2	1.045	1.045
3	1.023	1.025
4	1.015	1.017
5	1.010	1.010
6	1.010	1.012
7	1.007	1.008
8	1.010	1.010
9	1.025	1.029
10	1.015	1.023
11	1.038	1.038
12	1.039	1.043
13	1.040	1.040
14	1.022	1.027
15	1.011	1.018
16	1.018	1.023
17	1.012	1.019
18	1.010	1.017
19	1.003	1.011
20	1.005	1.013
21	1.001	1.011
22	1.001	1.012
23	0.995	1.008
24	0.984	1.004
25	0.961	1.008
26	0.942	0.990
27	0.956	1.019
28	1.002	1.007
29	0.905	1.005
30	0.859	1.000

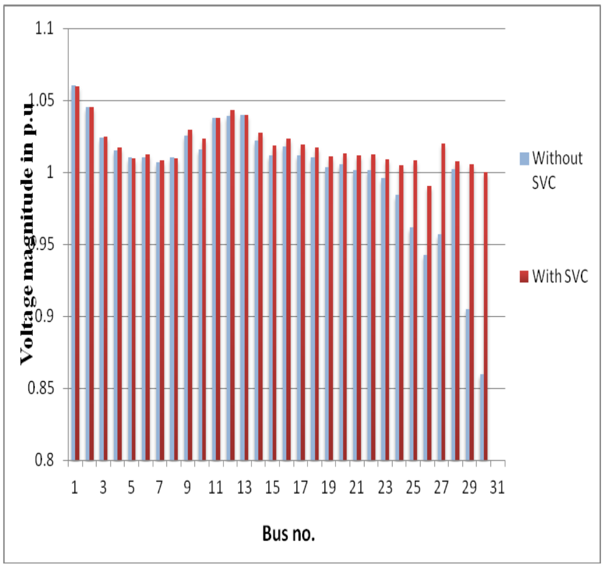

Figure 3.5: voltage magnitude in case of with and without SVC of IEEE 30 bus system

From table no.3 and fig no. 10 it is observe that the voltage profile of load buses will be improved. From table no.4, it is also observe that active power losses will be minimized. The optimal reactive power injected by SVC at bus no.4 is 20.311 Mvar, the corresponding total active power loss is 9.548 MW reduced from base case i.e. 10.786 MW. So, the OPF down by using optimal location of SVC.

4. Conclusion

The subject of optimal power flow (OPF) has gained a lot of attention due to the high cost of electrical energy. The main objective function of OPF problem is power loss minimization and voltage profile improvement of power system by adjusting the power control variables and at the same time satisfying the equality and the inequality constraints. FACTS devices have gained importance in power system because they offer increased power transfer capability, better controllability of power flow, increased stability of power system. In this project, SVC has been employed to meet the voltage improvement and loss minimization. The simulations are done by using PSAT and continuation power flow technique. By using PSAT soft ware can find the optimal location of SVC and also improve the voltage magnitude and real power losses. Continuation power flow (CPF) is find weak bus when voltage collapse is occurs. The proposed algorithm has used to determine optimal placement of SVC controller and solving optimal power flow (OPF) to improve voltage profile and reduce the real power losses within real and reactive power generation limits, and SVC operation limit. The algorithm was tested on the IEEE 6 bus, IEEE 30 bus system. Hence the optimal power flow (OPF) is obtained by using the optimal location of SVC for IEEE 6 and 30 bus system.

5. Annexure

5.1. Annexure-1: PSAT Model of IEEE 6 Bus System

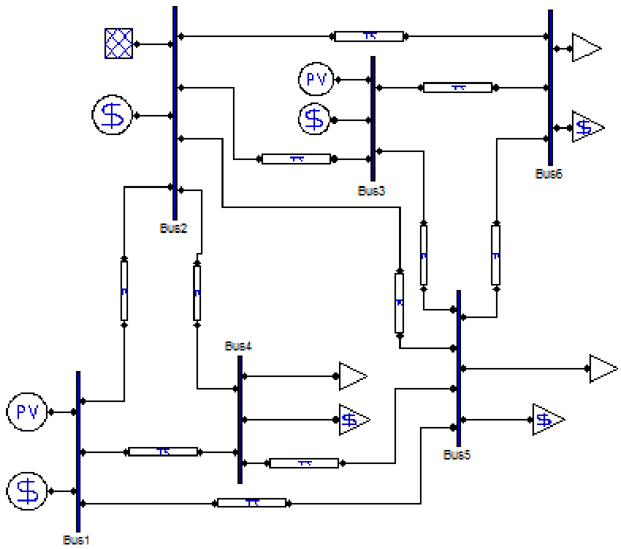

Figure 5.1: PSAT Model of IEEE 6 Bus System

IEEE 6 bus system is totally consists of 3 generator buses ,3 load buses and 11 transmission lines.

5.2. Annexure-2: PSAT Model of IEEE 30 Bus Systems:

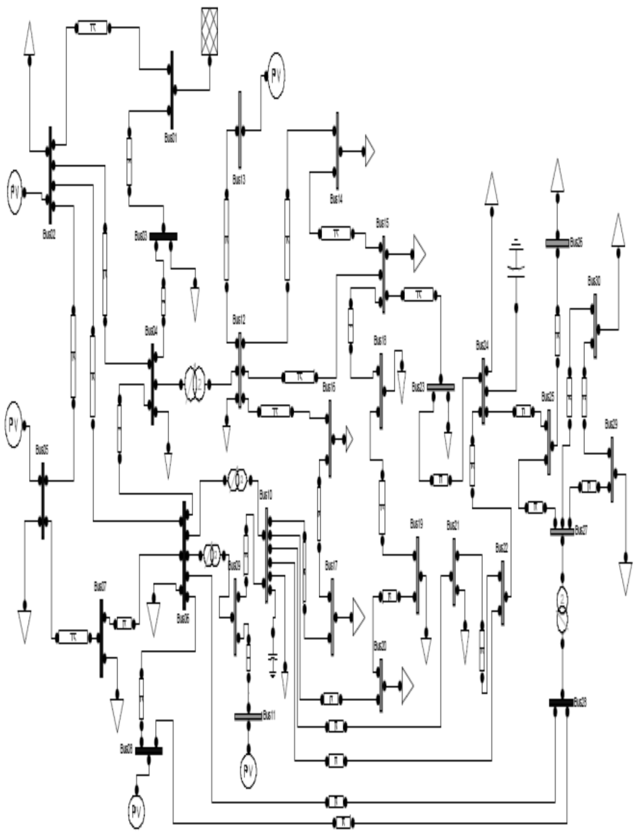

Figure 5.2: PSAT model of IEEE 6 bus system

IEEE 6 bus system is totally consists of 6 generator buses , 24 load buses and 41transmission lines.

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