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Optimal Placement and Sizing of SVC for Improving Voltage Profile of Power System

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Abstract - In emerging electric power systems, increased transactions often lead to the situations where the system no longer remains in secure operating region. The flexible AC transmission system (FACTS) controllers can play a vital role in the power system security enhancement. However, due to high capital investment, it is necessary to place these controllers optimally in a power system. FACTS devices can regulate the active and reactive power control as well as adaptive to voltage-magnitude control simultaneously because of their flexibility and fast control characteristics. Placement of these devices at optimal location can lead to control in line flow and maintain bus voltages in desired level and so improve voltage profile and stability margins.

This paper proposes a systematic method for finding optimal location of SVC to improve voltage profile of a power system. A contingency analysis to determine the critical outages with respect to voltage security is also examined in order to evaluate the effect of SVC on the location analysis. Effectiveness of the proposed method is demonstrated on IEEE 30-bus test system.

Keywords - *Contingency Analysis, FACTS devices, SVC, Voltage Performance Index, Voltage profile.*

I. INTRODUCTION

The electrical power system is continuously expanding in size and growing complexity all over the world. In recent years, the electricity industry has undergone several changes due to privatization all over the world which has affected power system management and energy markets [1]. The power system which are heavily loaded, faulted and/or having shortage of reactive power are the main reason for voltage collapse [2]. As the voltage collapse problem is closely related to reactive power planning including the contingency analysis, as these should be considered for the secure operation of the power system [3]. During the outage conditions of some critical lines, the generators are capable of supplying limited reactive power even sometimes the supplied reactive power cannot be used to fulfill the requirement of the network because the location is far from the generator point. Further, the real powers of the generators are reduced to supply the reactive power demand of the system. Hence, the reactive power compensators are used to maintain the voltage profile and there by improving the performances of the system [4].

Flexible Alternating Current Transmission Systems (FACTS) devices are being very popular for improving overall performance of the power system. FACTS devices are the solid state converters having capability of improving power transmission capacity, voltage profile, enhancing power system stability and security [5]. FACTS devices include static var compensator (SVC), thyristor controlled series compensator (TCSC), unified power flow controller (UPFC) etc. SVC and Statcom are connected in shunt with the system to improve voltage profile by injecting or absorbing the reactive power [6,7].

Like other FACTS devices, SVC is an expensive device; therefore it is important to find the optimal location and its size in a power system, so that voltage profile may be improved effectively. In [4], optimal placement of SVC based on reactive power spot price is discussed. In [8], a method optimal placement of SVC for static and dynamic voltage security enhancement has been developed. In [9,10], new SVC models and their implementation in Newton-Raphson load flow and optimal power flow algorithms has been is developed. Optimal location of SVC for voltage security enhancement using MOPSO is discussed in [11].

This paper focuses on the placement of SVC, for improving the voltage profile and reducing the real power losses. SVC is a shunt FACTS device which is designed to maintain the voltage profile in a power system under normal/contingency conditions. In practical power systems, all buses have different sensitivity to the power system security/stability, some buses are more and some are less. If SVC is allocated at more sensitive buses, it will effectively improve the voltage profile /stability [10].

Two models of SVC are usually implemented for load flow analysis of a power system [12]:

1) SVC Susceptance model:

A changing susceptance B_{SVC} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. This model is an improved version of SVC models.

2) SVC Firing angle model:

The equivalent susceptance, $\boldsymbol{B_{eq}}$ which is function of a changing firing angle,α is made up of the parallel combination of thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive susceptance. This is a new and more advanced SVC representation. This model provides information on the SVC firing angle required to achieve a given level of compensation.

II. SVC EQUIVALENT SUSCEPTANCE MODEL

Enhancement of power electronics technology including control methods have made possible the development of fast SVC's in the early 1970's. The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching circuits. From the operational point of view, the SVC can be considered as a variable shunt reactance that adjusts automatically according to the system operative conditions. Depending on the nature of the equivalent SVC's reactance, i.e., capacitive or inductive, the SVC draws either capacitive or inductive current from the network. Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC point of connection. The most popular configuration for continuously controlled SVC's is the combination of either fix capacitor and thyristor controlled reactor or thyristor switched capacitor and thyristor controlled reactor. For steady-stale analysis, both configurations can be modeled along similar lines [12,13].

III. MODELING OF SVC

Early SVC model used for power flow analysis treats the SVC as a generator behind an inductive reactance when operating within limits. This reactance represents the SVC voltage regulation characteristic, i.e., SVC's slope X_{st} [2]. A simpler representation assumes that the SVC slope is zero for voltage regulation. This assumption may be acceptable as long as the SVC is operating within limits, but may lead to gross errors if the SVC is operating close to its reactive limits [5]. This is shown in Fig. 1. For low loading conditions consider the upper characteristic of the system. If the slope is taken to be zero, then the generator will violate within its minimum reactive limit, point $B_{X_{SL=0}}$. However, the generator will operate well within limits if the SVC slope is taken into account, point B [9,12]. The SVC characteristic is represented by connecting the generator to an auxiliary bus coupled to the high-voltage bus by an inductive reactance which is equal to the per unit slope on the SVC slope. The auxiliary bus is represented as a PV-type bus whereas the high-voltage bus is taken as a PQ-type. When it is operated outside the limits, then the generator representation becomes invalid. In such cases, it is necessary to change the SVC representation to a fixed reactive susceptance. This combined generator-susceptance model gives accurate results. However, both representations require a different number of buses. The generator uses two or three buses whereas the fixed susceptance uses only one bus**.**

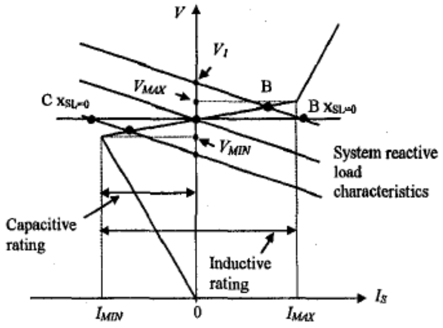

Fig. 1 : Voltage- Current Characteristics of SVC

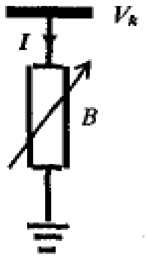

Fig. 2 : Variable Shunt Susceptance Model

While implementing this model for load flow analysis, it may require the Jacobian reordering and redimensioning during the iterative solution. And also it becomes necessary to verify whether or not the SVC can return to operation inside the limits. It interesting to note that for operation outside limits, it is important to model the SVC as a susceptance and not as a generator set at its violated limit $Q_{voilated}$, ignoring this point will lead to inaccurate results. The reason is that the amount of reactive power drawn by the SVC is given by the product of the fixed susceptance, B_{fixed} and the nodal voltage magnitude V_k. As V_k is a function of network operating conditions, the amount of reactive power drawn by the fixed susceptance model may differ from the reactive power drawn by the generator model, i.e.

$$Q_{voilated} \neq -B_{fixed} V_k^2 \qquad (1)$$

SVC LOAD FLOW MODELS

The circuit shown in Fig. 2 is used to derive the SVC's nonlinear power equations and the linearised equations required by Newton's load flow method. In general, the transfer admittance equation for the variable shunt compensator is,

$$I_{svc} = j\, B_{SVC}\, V_K \qquad (2)$$

And the reactive power equation is,

$$Q_k = -\, V_k^2 B_{SVC} \qquad (3)$$

In SVC susceptance model the total susceptance B_{SVC} is taken to be the state variable, therefore the linearized equation of the SVC is given by

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta B_{SVC/}\ B_{SVC} \end{bmatrix} \qquad (4)$$

At the end of iteration *i* the variable shunt susceptance B_{SVC} is updated according to (5).

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + (\Delta B_{SVC}\ /B_{SVC})^{(i)}\ B_{SVC}^{(i-1)} \qquad (5)$$

This changing susceptance value represents the total SVC susceptance which is necessary to maintain the nodal voltage magnitude at the specified value (1.0 p.u. in this paper).

IV. PROBLEM FORMULATION

A. Nodal Voltage Magnitude Controlled by SVC

The implementation of the variable shunt susceptance models in a Newton-Raphson load flow algorithm requires the incorporation of a nonstandard type of bus, namely *PVB*. This is a controlled bus where the nodal voltage magnitude and active and reactive powers are specified while the SVC's total susceptance B_{SVC} is handled as state variable. If B_{SVC} is within limits the specified voltage magnitude is attained and the controlled bus remains PVB-type. However, if B_{SVC} goes out of limits, so the bus becomes PQ-type. In this situation, the SVC will act as an unregulated voltage compensator whose production or absorption reactive power capabilities will be a function of the nodal voltage at the SVC point of connection to get the voltage 1.0 p.u.

B. Transmission Losses Minimization

The proposed algorithm also considers the transmission loss minimization for selecting optimal location of SVC. Transmission loss minimization is responsible for the redistribution of the reactive power throughout the network, which in turn induces changes in the active power generated by the slack bus. It has been observed that if the network losses were reduced in only 0.15%, a more uniform voltage profile was observed at all the buses of a power system. The real power losses can be calculated using (6).

$$P_L = \sum_{k=1}^{nl} g_k \left[V_i^2 + V_j^2 - 2 V_i V_j \cos(\delta_i - \delta_j) \right] \qquad (6)$$

Where *nl* is the number of transmission lines; g_k is the conductance of the *kth* line; $V_i \angle \delta_i$ and $V_j \angle \delta_j$ are the voltages at the end buses *i* and *j* of the *kth* line.

C. Voltage Deviations

In a power system, it is desirable to maintain the voltage deviations within ±5%. In this paper, the optimal location and size of SVC is determined by observing minimum value of VD. Voltage deviation is calculated as follows:

$$VD = \sum_{i=1}^{NB} (1 - V_i) \text{ if } V_i < 1 \qquad (7)$$

V. CASE STUDIES

The proposed algorithm for optimal placement and sizing of SVC has been implemented on IEEE 30 bus system [14]. This system comprises of one slack bus, 5 *PV* buses, 24 *PQ* buses and 41lines. For optimal placement of SVC, single line outage contingencies are simulated in the sample power system and to evaluate the severity of a contingency, Voltage Power Index (VPI) using (8) has been used.

$$VPI = \sum_{i=1}^{NB} (\Delta |V_i| / \Delta\, |V_i^{max}|)^{2m} \qquad (8)$$

Where $\Delta|V_i|$ is the difference between the voltage magnitude for line outage condition and base case voltage magnitude; $\Delta|V_i^{max}|$ is the value set by the utility engineers indicating how much they wish to limit a bus voltage from changing on outage case. This has been observed that NR load flow converges for 37 line outages out of 41 line outages. Line outage 36 provides highest value of VPI and hence this line outage is the most severe contingency. To place an SVC optimally, this line outage condition has been analyzed. The voltage profile for line outage 36 of IEEE 30-bus system is shown in table 1. It is clear from table 1 the voltages at bus 30, 29, 27 and 26 are very low. These 4 buses are used for optimal location of SVC. The developed load flow program also calculates the rating of SVC to maintain the voltage magnitude 1.0 p.u. at the connected bus. The voltage profiles for line outage 36 with SVC placed at bus nos. 30 29, 27 and 26 are shown in table 1.

Table 2 depicts the performance of the sample power system with and without SVC when outage of line no. 36 occurs. It includes required SVC rating to maintain voltage magnitude 1.0 p.u. at the connected bus, voltage deviations and real and reactive power losses. As observed from the table, the size of SVC is found minimum when SVC is located at bus 26 but it does not maintain voltage 0.95 p.u. at bus 29 and 30. The bus location 27 is discarded due to the large size of SVC. The optimal location for SVC is found at bus 30 because the voltage deviation is 0.0653p.u. which is minimum of all the four cases. The size of SVC at bus 29 is slightly smaller than obtained at bus 30, but voltage deviations and real and reactive power losses are slightly greater than that obtained for bus 30.

Fig. 3 illustrates the voltage profile of the sample power system without SVC and with SVC placed at bus 29 and at bus 30 under outage condition of line no. 36. This can be observed from Fig. 3, that minimum deviation are obtained when SVC was placed at bus 30. Thus, optimal location for SVC placement is bus 30.

VI. CONCLUSION

In this paper, a method for optimal placement and sizing of SVC has been proposed for improving voltage profile in a power system considering the most severe single line outage contingency. The proposed approach has been implemented on IEEE 30-bus system. The criteria for selection of optimal placement of SVC were to maintain the voltage profile, minimize the voltage deviations and to reduce the power losses under single line outage contingencies. Simulations performed on the test system shows that the optimally placed SVC maintains the voltage profile, minimizes the deviations and also reduces the real and reactive power losses.

TABLE 1. VOLTAGE PROFILE OF IEEE 30-BUS SYSTEM WTHOUT AND WITH SVC

Voltage Profile with Outage of Line No. 36					
Bus Number	***Without SVC***	***With SVC***			
		at bus 30	***at bus 29***	***at bus 27***	***at bus 26***
1	1.06	1.06	1.06	1.06	1.06
2	1.043	1.043	1.043	1.043	1.043
3	1.0186	1.0198	1.0197	1.0199	1.0196
4	1.0093	1.0108	1.0107	1.0109	1.0106
5	1.01	1.01	1.01	1.01	1.01
6	1.0095	1.0108	1.0107	1.0109	1.0106
7	1.0019	1.0027	1.0027	1.0028	1.0026
8	1.01	1.01	1.01	1.01	1.01
9	1.0374	1.0433	1.0431	1.0439	1.0426
10	1.0184	1.0299	1.0295	1.0311	1.0285
11	1.082	1.082	1.082	1.082	1.082
12	1.0481	1.0537	1.0536	1.0543	1.0531
13	1.071	1.071	1.071	1.071	1.071
14	1.0292	1.0374	1.0371	1.0383	1.0364
15	1.0196	1.03	1.0297	1.0311	1.0288
16	1.0282	1.0363	1.0361	1.0372	1.0354
17	1.0159	1.0264	1.0261	1.0275	1.0252
18	1.0068	1.0177	1.0174	1.0188	1.0164
19	1.0024	1.0136	1.0132	1.0147	1.0123
20	1.0056	1.0169	1.0165	1.018	1.0156
21	1.0022	1.0175	1.017	1.0191	1.0157
22	1.0017	1.0181	1.0175	1.0198	1.0161
23	0.9957	1.015	1.0144	1.017	1.0128
24	0.9729	1.0041	1.0031	1.0074	1.0005
25	0.9135	0.9872	0.9848	0.995	0.9785
26	0.8938	0.9689	0.9665	0.9769	1
27	0.8884	0.9893	0.9861	1	0.9555
28	1.0137	1.0147	1.0147	1.0148	1.0146
29	0.8651	0.9892	1	0.9796	0.9341
30	0.8517	1	0.9735	0.9679	0.9217

TABLE 2. PERFORMSNCE OF IEEE 30-BUS SYSTEM WTHOUT AND WITH SVC

Power System Performance with Outage of Line No. 36					
Bus Number	***Without SVC***	***With SVC***			
		at bus 30	***at bus 29***	***at bus 27***	***at bus 26***
SVC Rating (p.u.)		-0.1206	-0.1158	-0.1308	-0.1044
Real Power Losses(p.u)	0.179	0.1381	0.1383	0.1355	0.1400
Reactive Power Losses(p.u)	0.4877	0.2789	0.2795	0.2737	0.2828

VII. ACKNOWLEDGMENT

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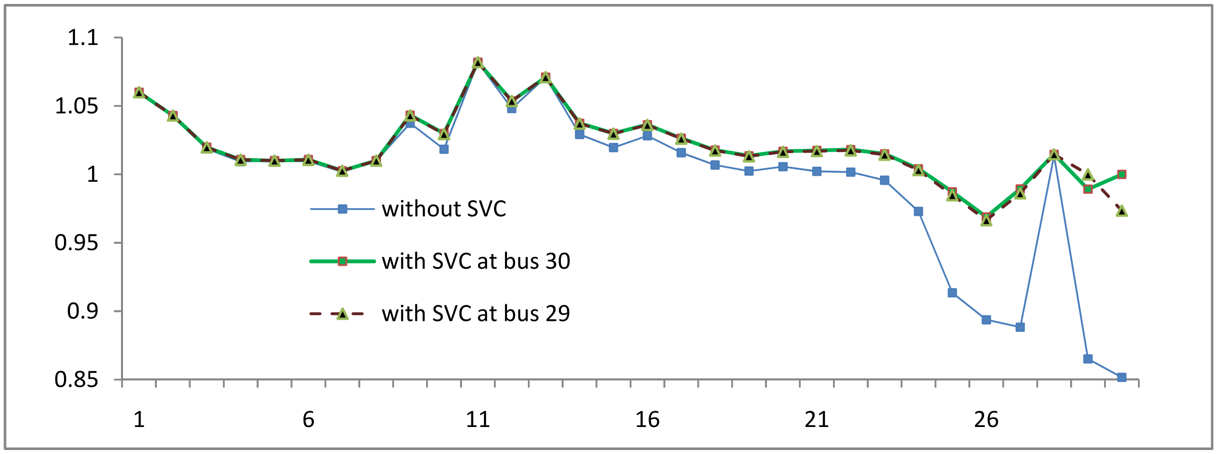

Fig. 3 : Voltage Deviations with and without SVC

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