Determination of Firing Angle for Multiple SVCs to Improve Voltage Stability

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Abstract: **Transmission corridors between interconnected power systems or within countrywide transmission systems are limiting network performance or even market activities. Transfer limits due to voltage stability limits are most often based on off-line calculation, and must therefore be conservative enough to accommodate all credible operating conditions. At the same time phasor measurements units are becoming an increasingly accepted and available technology. Using these phasor measurements it is possible to monitor the power system using a time resolution down to milliseconds. This gives the possibility of a wide range of stability monitoring and control applications. This paper focuses on the steady state modeling and on the determination of firing angles of multiple Static Voltage Compensators connected in a large system for maintaining required voltages and hence monitoring and operation of transmission corridors with the help of synchronized phasor information. The method is used for an IEEE 9 bus system to explain in detail**

Keywords— ***FACTs Devices, SVC, Voltage Stability, Steady State Modelling, Matpower***

I. Introduction

THE ability of power systems to maintain constantly acceptable bus voltage at each node subject to various operating conditions such as normal operating conditions, load increase, changes in system configuration or the system being subjected to disturbance; is a very important characteristic of the system. The non-optimized control of VAR resources may lead to progressive and uncontrollable drop in voltage resulting in an eventual wide spread voltage collapse [1]. Flexible ac transmission system (FACTS) devices may provide significant benefits in terms of both, greater operating flexibility and extended voltage stability margins.

FACTS devices are being increasingly utilized in many electric power systems to enhance voltage control and system dynamic performance [2]-[4]. Among the existing devices, static VAR compensators (SVCs) have been found to improve voltage regulation as well as to increase voltage stability margins in several practical applications[5]-[7]. In most cases of SVC application, VAR control is used locally to maintain the required voltage at the connected bus. This method suffers from addressing the issue of maintaining the required voltage level at all buses with minimum reactive power injection/absorption to the system. Availability of phasor measurement units (PMUs) [8]-[9] with advanced features makes the system operator to receive the live bus conditions of a system at the control center which helps him to maintain a healthier system under contingency. In this paper multiple SVCs are used to maintain required voltages at the various buses. Generator model of SVCs is used to find the required susceptance of each SVC and a suitable firing angle of the TCR branch. The Model is used for a 9 bus test system.

II. Static Voltage Compensator (SVC)

Static VAR Compensators are shunt connected static generators and/or absorbers whose outputs are varied so as to control specific parameters of the electric power system. The term static is used to indicate that SVCs, unlike synchronous compensators, have no moving or rotating main components. Thus an SVC consists of static var generator or absorber devices and a suitable control device. A typical SVC consists of Thyristor-Switched Reactors (TSRs) and Thyristor-Switched Capacitors (TSCs) or a fixed Capacitor in parallel. The output of the compensator is controlled in steps by sequentially switching of TCRs and TSCs . The need for harmonic filtering as part of the compensator scheme could be eliminated by stepwise switching of reactors rather than continuous control.

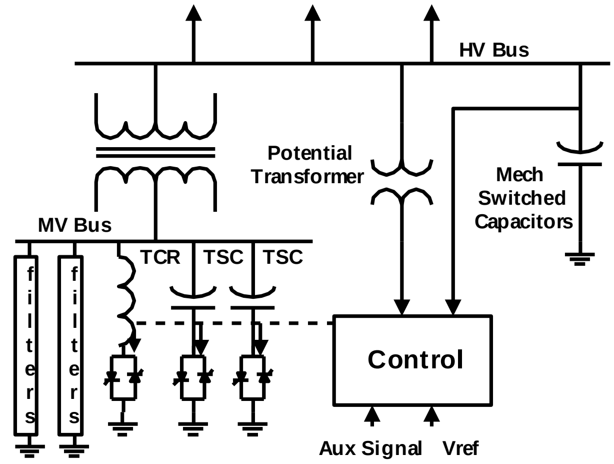

Fig.1: Typical static VAR system. The MSCs could be located at the *MV* bus, or remotely located.

II. MODELING OF SVC

The Static Var Compensator (SVC) equipment is composed by capacitors, thyristors and inductances [1].

There are two ways for modeling these devices. The first model considers SVC as variable impedance, which is adapted automatically to achieve the voltage control. This is called the passive model and its main disadvantage is the changing of nodal admittance matrix whenever there is a variation in the operation conditions of the power grid.

The second model, called active model, represents SVC as a nodal power injection [10]. It uses active sources in the equivalent circuit, which can be easily incorporated in the all PF calculations including OPF. This is the approach we choose in this work. Generally, the active model uses the reactive power injected or consumed by the SVC as the state variable (Qs). The operational technical limits for this variable are:

$$Qmin \leq Qsvc \leq Qmax$$
$$Qmax = Bind \times Vref^2$$
$$Qmin = Bcap \times Vref^2$$

Where B_{ind} and B_{cap} are capacitive and inductive susceptances and V_{ref} is the reference for the bus voltage.

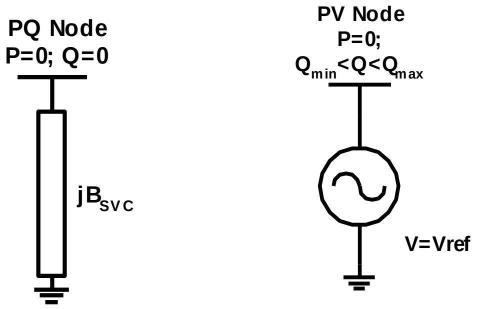

Figure.2: SVC Passive & active model

Static VAR Compensator's Equivalent Susceptance:

The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching. From the operational point of view, the SVC can be seen as a variable shunt reactance that adjusts automatically in response to changing 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. SVC's achieve their main operating Characteristic at the expense of generating harmonic currents and filters are employed with this kind of devices. 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 [11]. As far as steady-stale analysis is concerned, both configurations can be modeled along similar lines.

The variable TCR equivalent reactance, X_{ind},, at fundamental frequency, is given by [12],

$$\mathrm{X_{ind}} = \mathrm{X_L} \times \frac{\Pi}{2(\Pi - \alpha) + \sin(2\alpha)} \qquad (1)$$

X_L is the reactance of the TCR at fundamental frequency. 'α' is the firing angle of the thyristor measured from the instant of positive peak of the capacitor voltage. The SVC effective reactance X_{svc} is determined by the parallel combination of X_{cap} and X_{ind}.

$$X_{svc} = \frac{X_{cap} \times X_L}{\frac{X_c}{\pi}(2(\pi - \alpha) + \sin(2\alpha)) - X_L} \qquad (2)$$

Depending on the ratio X_c/X_L there is a value of firing angle that causes a steady-state resonance to occur. Fig. 2 depicts the SVC equivalent reactance at the fundamental frequency as function of firing angle, corresponding to a capacitive reactance of 1.4 p.u and a variable inductive reactance of 0.28 p.u.

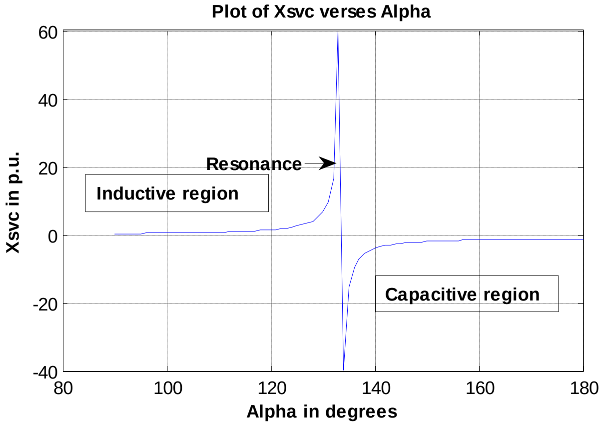

Fig.3: SVC equivalent reactance profile

The SVC equivalent susceptance is given by equation (3) whilst its profile, as function of firing angle, is given in Fig. 3.

$$B_{svc} = \frac{X_L - \frac{X_{cap}}{\pi}(2(\pi - \alpha) + \sin(2\alpha))}{X_{cap} X_L} \qquad (3)$$

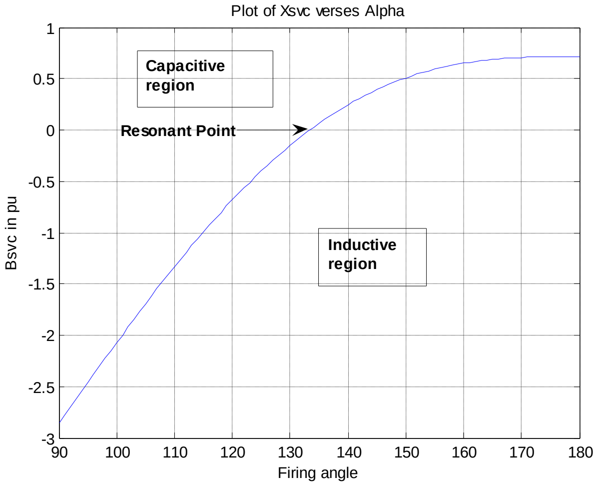

Fig.4: SVC equivalent susceptance profile

It is shown in Fig. 3 that the SVC equivalent susceptance profile depicts a continuous function of firing angle , i.e. B_{svc} varies in a continuous, smooth fashion in both operative regions. Hence, linearization **of** the SVC power flow equations, based on Q_{svc} with respect to firing angle, exhibits ***a*** better numerical behaviour than the linearised model based on X_{svc}.

In this paper the buses connected with SVCs are considered as PV bus with zero active power generation and with SVC reactive power limits. The generator voltages are fixed at V_{ref}. The load flow study is performed in static environment, which gives the amount of reactive power required at the bus to maintain V_{ref} at the SVC connected buses. From the required reactive power, susceptance (Bsvc) of SVCs and hence their corresponding firing angles are calculated. This paper also incorporates the techniques of finding the limiting firing angles of multiple SVCs subject to limiting values of voltages at generator buses and L-index at load buses. L-index [13]-[14] is a suitable indicator of the degree of criticality at load buses to sustain voltage instability. In this paper, the L-index is calculated for all the load buses and the buses having higher value of L-index are identified as the most critical buses, for placement of SVCs.
The flow chart for evaluating the firing angles in N-R Method is given in figure: 5.

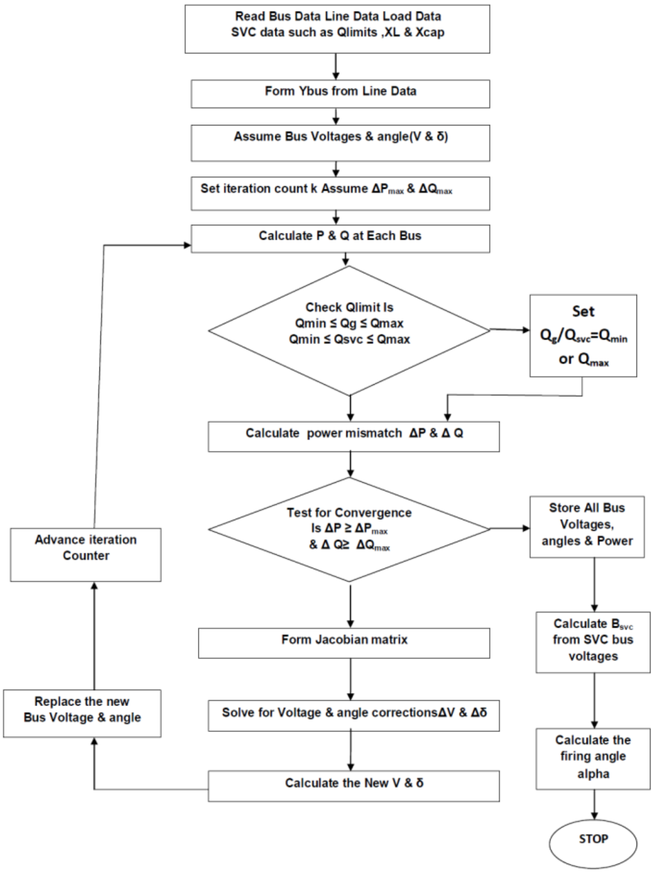

Fig.5: Flow chart for determining the firing angle of SVC s

III. LOAD FLOW TEST CASE

9-bus test system is used to assess the effectiveness of SVC models developed in this paper. Fig.7 below show the single line diagram of system, with 230 kv and 100MVA base has been considered. The data of system can be found in [15]. Three cases are considered and for each case the results are obtained in a MATPOWER [16] platform. For Case-1, the SVC is connected at bus 8; For Case-2, the SVC is connected at bus-6 and For Case-3, the SVC is connected simultaneously at bus 5,6 and 8.

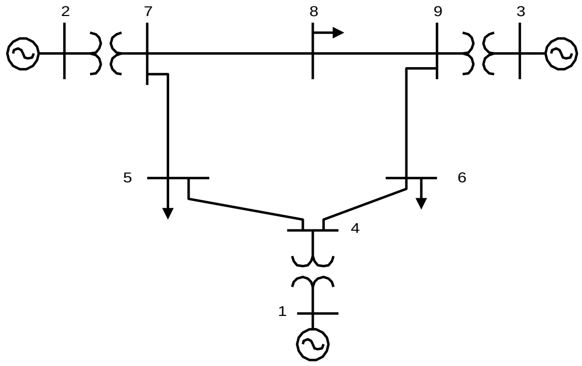

Fig.6: 9-Bus Test system

CASE-1:

SVC is connected to bus 8, the control aim to keep the voltage at that bus at 1.0 pu. The values XCap and XL are chosen as 1.4 pu and 0.28 pu,. The convergent is obtained after 4 iterations. SVC absorbs 21.86 MAVR from bus 8 in order to keep the voltage magnitude at 1 pu, with firing angle of 128.56^0 and Bsvc equal to -0.2186 pu. Table (1) gives the voltage magnitude and phase angle for all buses of the system with and without SVC.

CASE-2:

SVC is connected to bus 6, to keep the voltage at bus 6 at 1.0 pu. The of values XC and XL are chosen as 0.293 pu and 0.059 pu, The convergent is obtained after 4 iterations. SVC absorbs 13.72 MAVR from bus 6 in order to keep the voltage magnitude at 1 pu, with final firing angle of $132.601\ ^0$ and BSVC equal to -0.1372 pu. The voltage magnitude and phase angle for all buses of the system with SVC are given in table: 1

TABLE 1: VOLTAGES AT BUSES WITH & WITHOUT SVCS

	Without SVC		**With SVC at Bus 8**		**With SVC at Bus 6**	
Bus no	**Voltage**	**Ang(deg)**	**Voltage**	**Ang(deg)**	**Voltage**	**Ang(deg)**
1	1.04	0	1.04	0	1.04	0
2	1.025	9.28	1.025	9.425	1.025	9.276
3	1.025	4.665	1.025	4.739	1.025	4.671
4	1.026	-2.217	1.024	-2.226	1.021	-2.229
5	0.996	-3.989	0.992	-3.998	0.992	-4.02
6	1.013	-3.687	1.009	-3.696	1	-3.646
7	1.026	3.72	1.019	3.827	1.024	3.708
8	1.016	0.728	1	0.827	1.014	0.711
9	1.032	1.967	1.027	2.027	1.029	1.965

CASE-3:

To see the effect of multiple SVCs the generator voltages are set at 1 p.u and L-index is calculated at each bus. It was found that bus 5,6 & 8 are having higher index and hence three svc are used at these buses with following specifications.

TABLE 2: SVC SPECIFICATIONS

Bus no	**Qmax**	**Qmin**	**Xcap in pu**	**XL in pu**

5	50	-50	0.293	0.059
6	50	-50	0.293	0.059
8	50	-50	1.4	0.28

In this case also the solution converges after 4 iterations and the results are shown in table 3 & 4.

TABLE 3: VOLTAGES AND L-INDEXES AT BUSES WITHOUT SVC

	Without SVC		
Bus	**Voltage**	**Ang(deg)**	**L-index**
1	1	0	NA
2	1	9.669	NA
3	1	4.771	NA
4	0.987	-2.407	0.0853
5	0.958	-4.35	0.1673
6	0.975	-4.017	0.1394
7	0.996	3.799	0.0711
8	0.986	0.622	0.1135
9	1.003	1.926	0.0581

TABLE 4: BUS VOLTAGE, BSVC & ALPHA WITH SVCS

	With SVCs at 5,6,&8					
Bus	**Voltage**	**Ang(deg)**	**L-index**	**Qsvc in MVAR**	**Bsvc in pu**	**Alpha in degrees**
1	1	0	NA	NA	NA	NA
2	1	9.539	NA	NA	NA	NA
3	1	4.796	NA	NA	NA	NA
4	1.006	-2.352	0	NA	NA	NA
5	1	-4.309	NA	41.45	0.4145	135.4334
6	1	-3.955	NA	13.26	0.1326	133.9526
7	1.009	3.745	0	NA	NA	NA
8	1	0.653	NA	6.64	0.0664	135.0255
9	1.012	1.975	0	NA	NA	NA

IV. CONCLUSION

In this paper steady-state generator models of SVC and from the required SVC reactive power the firing angles of each SVCs is calculated simultaneously for multiple SVCs connected to system. To demonstrate the effectiveness and robustness of the proposed models, a Newton-Raphson method incorporating a programme to determine the firing angle of each SVC was developed for desired bus voltage profile improvement. Then the proposed models and algorithm were implemented on 9-bus test system for different case studies. The results obtained show the effectiveness and robustness of the proposed method; moreover the power solution using the Newton-Raphson algorithm developed incorporating firing angle model possesses excellent convergence characteristics. MATPOWER-4.05b [12] with some modifications for finding L-index & firing angle alpha is used to execute all programs.

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