

# Analysis of SVC's Impact on Out-of-step Oscillation Based on Direct Method Considering Admittance Effect

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**Abstract.** The widely employment of power electronic equipment in modern power system, may affect grid structure and system operation because of their diverse dynamic characteristics. In this paper, the impact of the static var compensators (SVC) on out-of-step oscillation is investigated based on the equal area criterion by considering SVC's admittance effect. Firstly, the variation pattern of bus voltage which is connected to SVC is concluded. Then the derivation of equation considering the admittance effect is given, which explains the ability of SVC to suppress out-of-step oscillation. SVC's impact on migration of out-of-step oscillation centre (OSOC) is discussed based on the expression of OSOC's electrical location. Moreover, the influence of SVC's response speed and capacity on its effect are presented by qualitative analysis. Finally, simulations on a two-end equivalent test system are carried out to verify the correctness of the theoretical analysis. It is found that the capacity and a response speed of SVC have significant effect on the out-of-step oscillation, while SVC have no distinct influence on location of OSOC.

## 1 Introduction

The technology of flexible AC transmission system (FACTS), which is based on the technology of power electronic and the technology of modern control, is widely applied in electric power system. Various FACTS controllers can increase the transmission capacity of the transmission system and enhance the stability by rapid regulation of system parameters, providing a powerful method for power system control.

As the power system becoming more and more complicated, out-of-step oscillations are easier aroused by disturbances on power system. On this occasion, System separation is a primary method to avoid fault spreading through the grid, which may cause a catastrophe in power system. The prerequisite for an effective separation scheme is to understand the dynamic behaviours of power system under an out-of-step oscillation. However, alteration in grid structure and system operating plan may change the characteristics of system out-of-step oscillation. For instance, unequal source



voltages in a two-machine system[1], uneven impedance of transmission line[2] and incoherent generating units[3] will result in migration of out-of-step oscillation centre (OSOC).

Static var compensators (SVC) is a kind of the most common FACTS controller, which has been employed in actual power system sophisticatedly. The studies about SVC concentrate on the following aspects: (1) Analysis of SVC's effect and corresponding mechanisms on improving voltage stability[4,5], and power transfer capacity[6], increasing system damping[7], as well as enhancing the static and dynamic stability of the power system[8-10]. (2) Determination of the best installation location for SVC to work[7, 8, 11]. (3) Design of effective control signals and strategies of SVC to achieve or boost their functions[9,10,12].

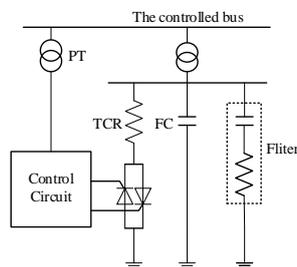
The existing researches mainly focus on how to improve power system stability, but there is rarely study about the influence of SVC's rapid dynamic response on system behaviour characteristics during out-of-step oscillation and corresponding system separation. With the popularization of SVC in power system, it is necessary to learn more about their impact on system out-of-step oscillation.

In this paper, the impacts of SVC on oscillation suppression and OSOC migration are analysed. Essentially, out-of-step oscillation belongs to the problem of system transient stability, so the analysis mainly focus on the impact on system transient stability.

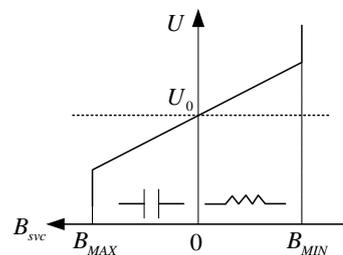
## 2 Analysis of SVC's impact on out-of-step oscillation

### 2.1 Fundamental of SVC and its transient model

Figure 1 illustrates the basic structure of a SVC made up of a thyristor-controlled reactor (TCR) and a fixed capacitor (FC). The equivalent reactance of TCR will alter as the thyristor being controlled by control circuit which derive its input signal from voltage deviation of the controlled bus, by which the reactive power provided by the SVC is regulated smoothly.



**Figure 1.** Structure of SVC composed of TCR and FC (Left)



**Figure 2.** The approximately relationship of SVC's equivalent

The voltage control mechanism of SVC during transient process is as follows: when the controlled bus voltage gets higher than the objective value, SVC absorbs reactive power, and it is equivalent to a reactance; on the contrary, when the voltage drops and gets lower than the objective value, SVC provides reactive power, and it is equivalent to a capacitor. The output equivalent susceptance of SVC versus the controlled voltage relationship can be approximately plotted in Fig. 2.

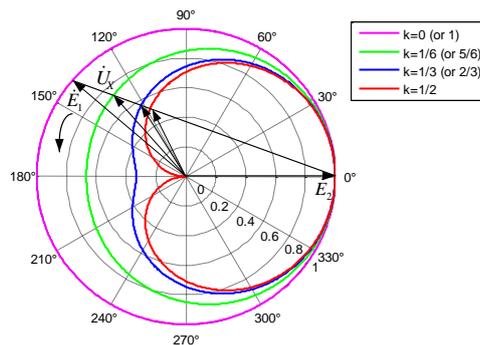
Therefore, a SVC can be considered in the analysis of power system's transient behaviours, as a various shunt susceptance determined by voltage deviation.

### 2.2 Variation pattern of bus voltage during out-of-step oscillation

As SVC is a kind of FACTS controller that controls bus voltage directly, it is necessary to get a clear idea of the variation pattern of voltage at the controlled bus during out-of-step oscillation. When out-of-step oscillation occurs in a two-machine equivalent system, relative angular difference between two machines will get greater and it varies periodically in a cycle of  $0^\circ \sim 360^\circ$ . With  $\dot{E}_1$ ,  $\dot{E}_2$  representing the e.m.f. of the two generators respectively,  $\delta$  is the angular difference by which  $\dot{E}_1$  leads  $\dot{E}_2$ , and  $\dot{E}_2$  as a reference vector, the variation of  $\dot{E}_1$  and  $\delta$  is shown in Fig. 3. Moreover,  $Z_\Sigma$  represents the total

equivalent impedance between the two generators, and  $\dot{U}_X$  represents the bus voltage at a random point X, which is  $Z_X$  far in electric distance away from the end where the voltage is  $\dot{E}_1$ . Assume that  $|\dot{E}_1| = |\dot{E}_2|$ , then  $|\dot{U}_X|$  versus  $\delta$  relationship can be described as (1), where  $k = Z_X / Z_\Sigma$ . Figure 4 also shows the plots of  $|\dot{U}_X|$  as a function of  $\delta$  under polar coordinates, in which curves in various colors representing  $|\dot{U}_X|$  at different points.

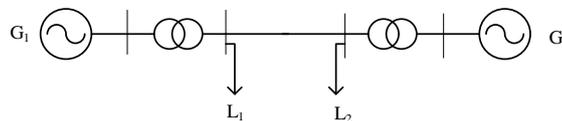
$$|\dot{U}_X| = |\dot{E}_N| \sqrt{2(k^2 - k)(1 - \cos \delta) + 1} \quad (1)$$



**Figure 3.** Curve of  $|\dot{U}_X|$  at different points as  $\delta$  varies from  $0^\circ$ - $360^\circ$

### 2.3 Impact of SVC's admittance effect on power system transient stability

Figure 4 illustrates a two-machine equivalent system with two generators and a suitable amount of load.

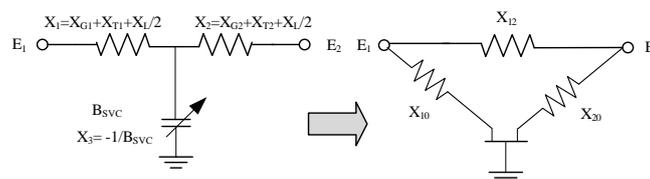


**Figure 4.** A two-machine equivalent system

The relative acceleration equation describing the effect of unbalanced torque on relative motion of the two generators' rotors, is established as (2), in which  $P'_E$ ,  $P_{em}$  and  $\gamma$  can be referred in [13]:

$$M_{eq} \frac{d^2 \delta}{dt^2} = P_M - [P'_E + P_{em} \sin(\delta - \gamma)] \quad (2)$$

As a kind of passive var compensator, SVC can be considered as a variable shunt susceptance  $B_{SVC}$  from the point of component characteristic. Figure 5 demonstrates the equivalent circuit of the two-machine system with a SVC installed at a random bus on the tie line, and its transformation by Y- $\Delta$  rule.  $X_{T1}$ ,  $X_{T2}$  represent the reactance of transformers, and  $X_{L1}$ ,  $X_{L2}$  represent the reactance of transmission line.



**Figure 5.** The equivalent circuit of a two-machine system with SVC and its transformation by Y- $\Delta$  rule

Ignore the resistance of transmission lines and transformers as well as the capacitance of lines to ground, thus the element  $Y_{12}$  in node admittance matrix  $Y$  can be obtained as:

$$Y_{12} = -j \frac{X_3}{X_\Sigma} = \frac{1}{X_1 X_2 / X_3 + X_1 + X_2} \angle \pm 90^\circ \quad (3)$$

where

$$X_\Sigma = jX_1 jX_2 + jX_1 jX_3 + jX_2 jX_3 \\ = -(X_1 X_2 + X_1 X_3 + X_2 X_3)$$

Substituting the above expression for  $Y_{12}$  in  $P'_E$ ,  $P_{em}$  and  $\gamma$  gives:  $P_{em} = \frac{E_1 E_2}{X_1 + X_2 + X_1 X_2 / X_3}$ ,

$\gamma = 0^\circ$  and  $P'_E = 0$ .

Then (3) can be simplified as:

$$M_{eq} \frac{d^2 \delta}{dt^2} = P_M - P_e \quad (4)$$

where  $P_e = P_{em} \sin \delta$  is the  $P-\delta$  relationship in the power system.

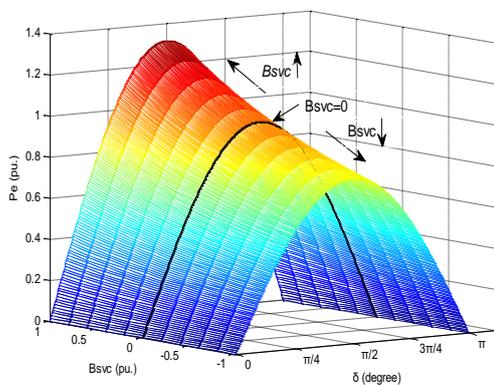
Equation (5) is in a form of single machine infinite bus system, in which the unbalance between  $P_M$  and  $P_{em}$  will cause the relative motion between two machines instead of that between single machine and infinite bus. It is reasonable to consider mechanical power of generators  $P_M$  as constants, therefore the only factor influencing the relative rotational motion of the two generator is the electromagnetic power  $P_{em}$ .

Now, we can probe the influence of SVC's admittance effect on transient stability of two-machine system by the expression of  $P_{em}$ . Here we rewrite it as follows:

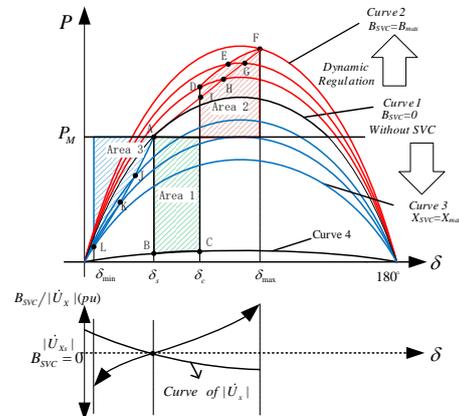
$$P_{em} = \frac{E_1 E_2}{X_1 + X_2 - B_{SVC} X_1 X_2} \quad (5)$$

Equation (5) can be described as Fig. 6, from which we can see that when SVC's apparent susceptance is capacitive, i.e.  $B_{SVC} > 0$ , it releases reactive power and the  $P-\delta$  curve is uplifted gradually as  $B_{SVC}$  getting greater. On the contrary, when SVC's apparent susceptance is inductive, i.e.  $B_{SVC} < 0$ , it absorbs reactive power and the  $P-\delta$  curve is lowered as  $B_{SVC}$  getting smaller.

Based on the rule of SVC to regulate bus voltage stated in Sect. 2.1, the impact of SVC on the stability of equivalent two-machine system during the transient process can be demonstrated by Fig. 7.



**Figure 6.** The variation of  $P-\delta$  relationship with  $B_{SVC}$  in equivalent two-machine test system (left)



**Figure 7.** The mechanism of the impact of SVC's dynamic characteristics on system transient stability (right)

As shown in Fig. 7, the two-machine system operates normally without any fault and its operating condition is represented by point A on Curve 1, with the angular difference  $\delta_s$ , bus voltage amplitude  $|\dot{U}_{xs}|$ , and SVC output susceptance  $B_{SVC} = 0$ . When the system suffers a severe disturbance, generator electrical power  $P_e$  drop dramatically and the  $P-\delta$  curve lowers from Curve 1 to Curve 4. With a constant mechanical power of  $P_M$ , the rotors of the two generators tend to accelerate relatively, which leads  $\delta$  to get greater. When  $\delta$  increases to  $\delta_c$ , the disturbance is cleared. Suppose that system structure is fully restored to its predisturbance condition and  $\dot{E}_1$  and  $\dot{E}_2$  are constant. Based on the equal area criterion, the acceleration area of  $\delta$  is showed as Area 1. According to Sect. 2.2, when  $\delta$  varies within the range of  $0^\circ-180^\circ$ , voltage magnitude  $|\dot{U}_x|$  at point X will decline as  $\delta$  increases, which leads increase of  $B_{SVC}$ . As  $B_{SVC}$  increases, system  $P-\delta$  curve is uplifted from Curve 1 to Curve 2 gradually and the operating point traces the path D-E-F (suppose that voltage magnitude decrease enough so that  $B_{SVC}$  reaches to  $B_{max}$ ) instead of Curve 1, which increases the deceleration area (illustrated as Area 2) remarkably. When point F is reached,  $\delta$  begins to decrease because of the unbalanced torque; the operating point retraces the path F-E-D and then to A with  $|\dot{U}_x|$  declining to the initial value  $|\dot{U}_{xs}|$ . After the operating point passes A,  $\delta$  is smaller than  $\delta_c$  and  $|\dot{U}_x|$  is smaller than  $|\dot{U}_{xs}|$ , which results in that  $B_{SVC}$  becomes inductive, and its value turns to negative and gets more and more smaller as  $\delta$  getting smaller. The variation of  $B_{SVC}$  leads the  $P-\delta$  curve descent to Curve 3. At the same time, the operating point traces the path A-J-K-L, with the deceleration area (Area 3), which is also augmented compared with the case without SVC.

#### 2.4 Impact of SVC's admittance effect on location of OSOC

According to the expression of  $f(\delta)$  in an equivalent two-machine system, which is given in [1], when  $k_e$  is constant, the electrical location of out-of-step oscillation center is fixed. As  $f(\delta) = Z_{osc} / Z_{eq}$ , the physical location of OSOC on the transmission lines is determined by the distribution of impedance over lines. Unlike thyristor controlled series capacitors (TCSC), SVC, as a shunt susceptance, will not change the impedance distribution along transmission lines. So SVC have no influence on location of OSOC.

#### 2.5 Sensitivity analysis of SVC's relevant factors

- Response speed

The analysis above that SVC is beneficial to improve the system transient stability is based on the precondition that the regulation of SVC has enough response speed which can catch up with the variation of the controlled bus voltage. If SVC response speed cannot meet this demand, its dynamic change of output equivalent susceptance  $B_{SVC}$  may lags behind the change of controlled voltage or angular difference  $\delta$ , resulting in that this two changes are not consistent or even opposite, which may limit SVC's ability to suppress out-of-step oscillation or even worsen system stability, including to induce the occurrence of out-of-step oscillation and action of separation devices.

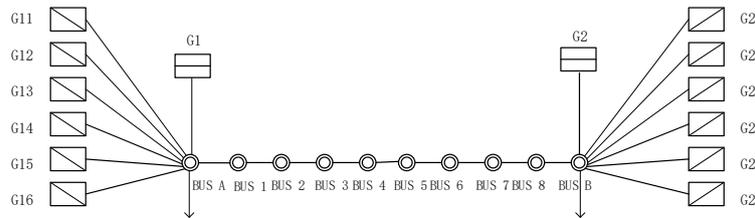
- Capacity

It has been stated in Sect. 2.2 that the bus voltages near OSOC have greater oscillation amplitude than others during the out-of-step oscillation. Due to the angular difference  $\delta_s$  before the disturbance, the initial voltage magnitude at any point on the transmission line is between their maximum and minimum value, which will appear during out-of-step oscillation. So, in order to maintain the initial voltage magnitude, it is required for SVC not only to have enough capacitive capacity, but also to provide moderate inductive capacity when the controlled voltage is higher than its initial value, which is beneficial to alleviate high-magnitude voltage oscillations and improve voltage stability.

### 3 Case Study

In this part, the impacts of SVC on an equivalent two-end system and Northwest China power grid are investigated through time-domain simulation by PSD-BPA program.

A two-end equivalent system is shown in Fig. 8. Transmission lines of 220kV connect the generators on two sides and a suitable amount of load is distributed on Bus 1~Bus 8. A disturbance is exerted to this system and then the performance of the system as well as the impact of SVC are investigated.



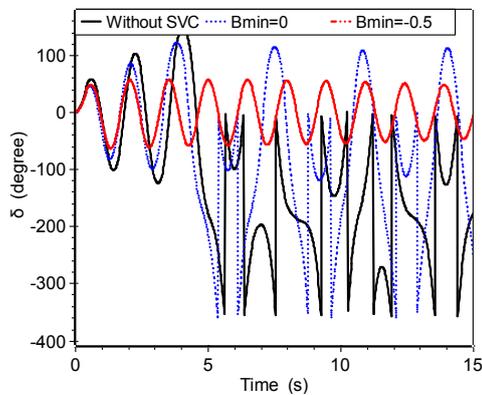
**Figure 8.** A two-end –equivalent test system

● SVC’s ability to suppress the out-of-step oscillation

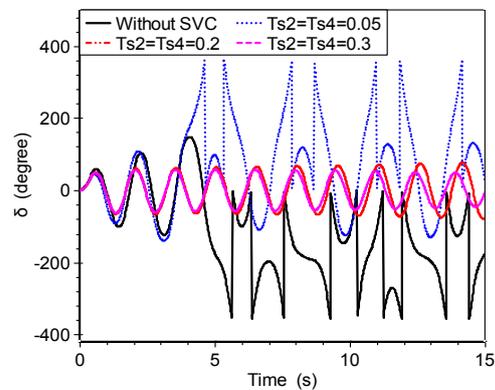
After suffering from a severe disturbance, the curve of angular difference  $\delta$  of the mentioned system with/without SVC are illustrated in Fig. 9. It can be seen that the black curve (without SVC) goes out of step at 5s; the red curve (with a SVC at Bus 4 and another at Bus 5) tend to be stable. So, it can be concluded that SVC is beneficial to avoid the out-of-step oscillation.

● SVC’s impact on the location of oscillation center

Tab. 1 lists the locations of out-of-step oscillation center in the system with a SVC installed at different places. A more severe disturbance is adopted to induce out-of-step oscillation. It can be found that it has no distinct impact on the oscillation center locations whether there is a SVC in the system or where the SVC to be installed.



**Figure 9.** The curve of  $\delta$  in the system containing SVC with different capacities (Left)



**Figure 10.** The curve of  $\delta$  in the system containing SVC with different response speed (Right)

**Table 1.** Locations of OSOC with SVC at different positions in a two-end equivalent system

Positions of SVC	Without SVC	Bus 1	Bus 4
Location of OSOC	Line 4-5	Line 4-5	Line 4-5

● Impact of SVC’s response speed

SVC’s response can be expedited by increasing the parameter of  $T_{s2}$  and  $T_{s4}$ .

As can be seen from Fig. 10 that: 1) Compared with the result without SVC, the system with SVCs which have deficient response speed ( $T_{s2} = T_{s4} = 0.05$ ) is easier to lose synchronism; 2) When the response speed of SVC reaches a certain value that is just enough to improve system stability, the faster SVCs respond, the better they are for suppression of out-of-step oscillation.

- Impact of SVC's capacity

Figure 9 shows the curve of  $\delta$  in the system under the conditions of two different settings of  $B_{MIN}$  (a.  $B_{MIN} = 0$  ; b.  $B_{MIN} = -0.5$  ), which means SVC have inductive capacity of (a) 0 pu or (b) 0.5 pu. It can be seen that SVC with certain amount of inductive capacity prevent the system from oscillating.

#### 4 Conclusion

The impact of SVC on out-of-step oscillation is investigated from two main perspectives. One is SVC's effect on suppressing the out-of-step oscillation (or improving system transient stability, in the other words) and location of oscillation center. And the other is how SVC's response speed and capacity influence its effect. By theoretical analysis and simulations, it can be concluded that:

(1) The dynamic variation of SVC's output equivalent susceptance can increase the deceleration area effectively in system transient process, which is beneficial to improve system transient stability and avoid out-of-step oscillation.

(2) SVC have no influence on the location of OSOC, or SVC will not cause OSOC migration in the other words, as the location of OSOC is related to the impedance distribution of transmission lines and SVC change the equivalent impedance between generators not its distribution on transmission lines.

(3) Response speed is a vital factor influencing SVC's performance. High response speed improves SVC's ability to prevent out-of-step oscillation, whereas response speed deficiency may deteriorate system transient stability by speeding up the occurrence of system out-of-step oscillation.

(4) Capacity of a SVC needs to be customized according to voltage characteristic of the controlled bus. Although SVC is a kind of var compensators, inductive capacity is still necessary for them to suppress out-of-step oscillation, especially when they are installed near OSOC, where the bus voltage oscillation amplitude is much greater than others during out-of-step oscillation.

#### 5 Acknowledgement

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