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A NOVEL METHOD OF ANALYSING THE DAMPING FUNCTION OF VSC BASED FACTS CONTROL – MULTI-MACHINE POWER SYSTEMS

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ABSTRACT
The Voltage Source Converter (VSC) based FACTS (Flexible AC Transmission Systems) devices are such as STATCOM (Static Synchronous Compensator), SSSC (Series Static Synchronous Compensator) and UPFC (Unified Power Flow Controller). In [1], a novel method of analysing the damping function of this type of VSC based FACTS control is proposed. The method is developed on the basis of the well-know equal-area criterion and small-signal analysis. In this paper, extension of the method to the application in multi-machine power systems is presented. It is concluded by theoretical analysis in the paper that there is little impact of STATCOM voltage control on the damping of power system oscillations. The conclusion is confirmed by simulation results.

KEY WORDS
Power system oscillations, FACTS, equal-area criterion

1. Introduction

The impact of FACTS control on damping power system oscillations has been a subject of research for many years. The reasons are in two folds. Firstly, for applications of FACTS to regulate voltage or/and power flow, we need to know whether it would bring about side effect to enhance or reduce the damping of power system oscillations. This will provide general guidance on the applications of FACTS. Secondly, we need to understand why and how FACTS control affects the damping of power system oscillations. This will help to gain better design of FACTS control or FACTS stabilizer to improve power system oscillation stability. In [2], damping torque analysis [3] is used to study SVC (Static Var Compensator) voltage control in the simple case of single-machine infinite-bus power systems. Analytical conclusions drawn in [2] have confirmed the results from previous simulations [4][5] that the SVC voltage control has little impact on the damping of power system oscillations. It is expected that the STATCOM (Static Synchronous Compensator) voltage control may behave just like that of SVC. However, it is only recently that authors have proved it through theoretical analysis based on a novel method proposed in [1].

STATCOM is one of new generation FACTS devices based on the Voltage Source Converter (VSC), like SSSC (Series Static Synchronous Compensator) and UPFC (Unified Power Flow Controller). Compared with conventional FACTS devices, such as SVC and TCSC (Thyristor-Controlled Series Compensator), those VSC based FACTS devices exhibit much better dynamic control performance and represent the future of FACTS applications in power systems. Hence focus of study in [1] is on the VSC FACTS devices. However, the novel method and study on the damping function of VSC FACTS control are presented in [1] for the simple case of single-machine infinite-bus power systems only.

In this paper, the novel approach proposed in [1] is extended to more general case of multi-machine power systems. The proposed method is based on the well-known equal-area criterion and small-signal stability analysis. By using the proposed method, the effectiveness of STATCOM voltage control on the damping of power system oscillations is explained clearly and simply. The analytical conclusion drawn is that the STATCOM voltage control imposes little effect on the damping of power system oscillations. In the paper, simulation results are presented that confirm the analytical conclusion.

2. The novel method for multi-machine power systems installed with VSC FACTS devices

2.1 Shunt or series-connected VSC FACTS device installed in a multi-machine power system

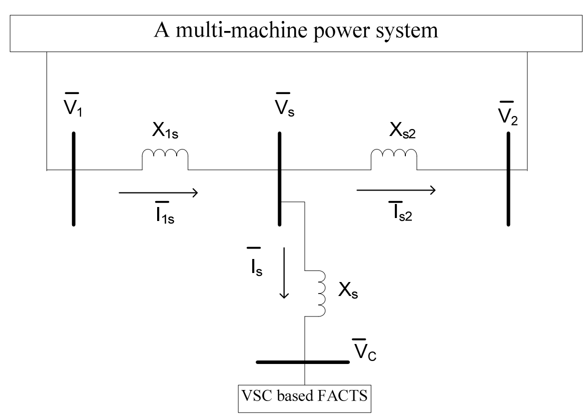


Figure 1. A multi-machine power system installed with a shunt-connected VSC based FACTS device

Without loss of generality, we assume a VSC based FACTS device is installed on the transmission line between node 1 and 2 in a multi-machine power system as shown by Figure 1. From Figure 1 we have

$$\overline{V}_S = jX_{s2}\bar{I}_{s2} + \overline{V}_2 = jX_{s2}[\bar{I}_{1s} - (\frac{\overline{V}_S - \overline{V}_C}{jX_S})] + \overline{V}_2$$
$$= jX_{s2}\bar{I}_{1s} - \frac{X_{s2}}{X_S}\overline{V}_S + \frac{X_{s2}}{X_S}\overline{V}_C + \overline{V}_2$$

Hence

$$\overline{V}_S = \frac{jX_{s2}}{1+\frac{X_{s2}}{X_S}}\bar{I}_{1s} + \frac{X_{s2}}{X_S(1+\frac{X_{s2}}{X_S})}\overline{V}_C + \frac{\overline{V}_2}{1+\frac{X_{s2}}{X_S}} \quad (1)$$

From Figure 1 and by using Eq.(1) we can obtain

$$\overline{V}_1 = jX_{1s}\bar{I}_{1s} + \overline{V}_S = j(X_{1s} + \frac{X_S X_{s2}}{X_S + X_{s2}})\bar{I}_{1s}$$
$$+ \frac{X_{s2}}{X_S + X_{s2}}\overline{V}_C + \frac{X_S}{X_S + X_{s2}}\overline{V}_2 = jX\bar{I}_{1s} + \overline{V} \quad (2)$$

where

$$X = (X_{1s} + \frac{X_S X_{s2}}{X_S + X_{s2}}),$$
$$\overline{V} = \frac{X_{s2}}{X_S + X_{s2}}\overline{V}_C + \frac{X_S}{X_S + X_{s2}}\overline{V}_2 = a\overline{V}_C + b\overline{V}_2$$

Hence the active power delivered along the transmission line is

$$P = \frac{V_1 V}{X}\sin\delta' \quad (3)$$

where $\overline{V}$ is an imaginary voltage that represents the control effect of shunt-connected VSC FACTS control and δ' is the angle between $\overline{V}_1$ and the imaginary voltage $\overline{V}$, that we name it to be imaginary angle.

If the VSC FACTS device is installed in series along the transmission line as shown by Figure 2, that is SSSC. From Figure 2 we have

$$\overline{V}_1 = jX_{1s}\bar{I}_{1s} + \overline{V}_C + \overline{V}_2 = jX_{1s}\bar{I}_{1s} + \overline{V}' \quad (4)$$

where $\overline{V}' = \overline{V}_C + \overline{V}_2$ is the imaginary voltage representing the effect of VSC FACTS control. Comparing Eq.(2) and (4) we can see that the systems of Figure 1 and 2 are electrically equivalent as far as the discussion based on the imaginary voltage is concerned. While a UPFC electrically is just the combination of a STATCOM and a SSSC. Hence in the following, we will only discuss the case of the shunt-connected VSC FACTS device, since exactly same conclusions can be drawn for the power system installed with the SSSC or UPFC.

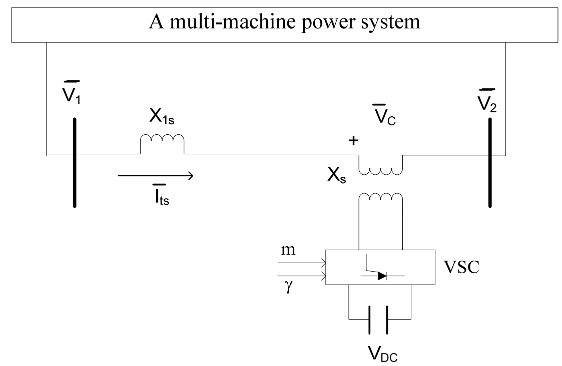


Figure 2. A multi-machine power system installed with a series-connected VSC based FACTS device

2.2 Small-signal stability analysis

Effect of shunt-connected VSC FACTS control on power system dynamics is directly through the exchange of reactive power between the STATCOM and power system via the regulation of magnitude of $\overline{V}_C$ by STATCOM control. Power oscillation along the transmission line is mainly affected by the variation of difference of phase angle of voltage, δ', at node 1 and 2. Influence of changes of magnitude of voltage at node 1 and 2, V_1 and V_2, is indirect and small that can be ignored. Hence from Eq.(3) and considering the effect of VSC FACTS control, we can obtain the small-signal variation of active power delivered along the transmission line 1-2 in the power system of Figure 1 to be

$$\Delta P = \Delta P_{tsdelta}(\Delta\delta') + \Delta P_{control}(\Delta V_C) = \left.\frac{\partial P}{\partial \delta'}\right|_0 \Delta\delta' + \left.\frac{\partial P}{\partial V_C}\right|_0 \Delta V_C$$
$$= \frac{V_{10}V_0}{X}\cos\delta'_0\,\Delta\delta' + \frac{V_{10}}{X}\sin\delta'_0 \left.\frac{\partial V}{\partial V_C}\right|_0 \Delta V_C \quad (5)$$

From Eq.(2) we can draw the phasor diagram of the power system of Figure 1 as shown by Figure 3. From Figure 3 we have

$$V^2 = (bV_2 + aV_c\cos\gamma)^2 + (aV_c\sin\gamma)^2$$
$$= b^2V_2^{\,2} + 2abV_2V_c\cos\gamma + a^2V_c^{\,2}$$

Hence

$$\frac{\partial V}{\partial V_C} = \frac{1}{V_0}(abV_{20}\cos\gamma_0 + a^2V_{c0})$$

$$\Delta P_{control} = \frac{V_{10}}{V_0 X} \sin\delta'_0 \,(abV_{20}\cos\gamma_0 + a^2 V_{c0})\Delta V_c \qquad (6)$$

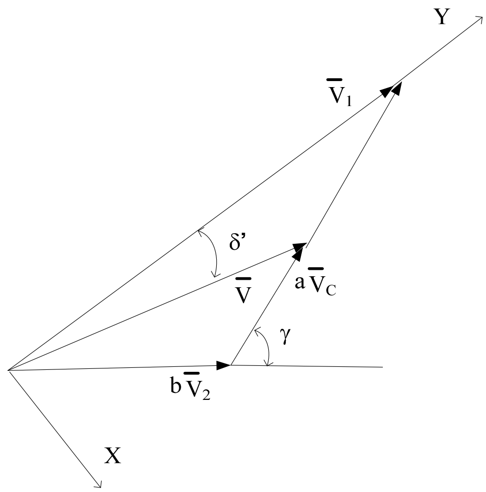


Figure 3. Phasor diagram

Main function of STATCOM is voltage regulation. For simplicity, we assume that STATCOM voltage regulator adopts a proportional control law with the gain to be K_{vol}, that is

$$V_c = V_{c0} + K_{vol}(V_{sref} - V_s)$$

Linearization of the above equation gives

$$\Delta V_c = -K_{vol}\Delta V_s$$

From Appendix we have

$$\Delta V_c = \frac{-K_{vol}C_2}{1 + K_{vol}C_1}\Delta\delta' \qquad (7)$$

Substituting Eq.(7) into (6) we have

$$\Delta P_{control} = \frac{V_{10}}{V_0 X}\sin\delta'_0\,(abV_{20}\cos\gamma_0 + a^2 V_{c0}) \frac{-K_{vol}C_1}{1 + K_{vol}C_2}\Delta\delta' \qquad (8)$$

Hence from Eq.(5) and (8) we have

$$\Delta P = \Delta P_{tsdelta}(\Delta\delta') + \Delta P_{control}(\Delta V_C) = C_{delta}\Delta\delta' \qquad (9)$$

Eq.(9) indicates that with the STATOM voltage control, the resulted variation of active power delivered along the transmission line, with the forced variation from STATCOM control added, is proportional to the deviation of the imaginary angle δ'. Small-signal power oscillation of the power system can be analyzed based on the equal-area criterion as illustrated in Figure 4 and 5 as follows.

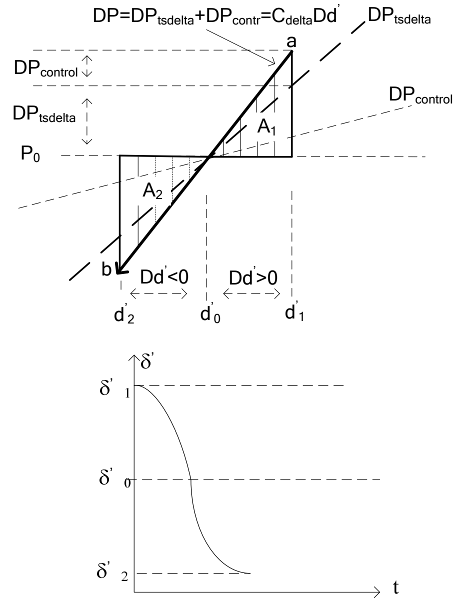


Figure 4. Effect of STATCOM voltage control on power system oscillation damping (1)

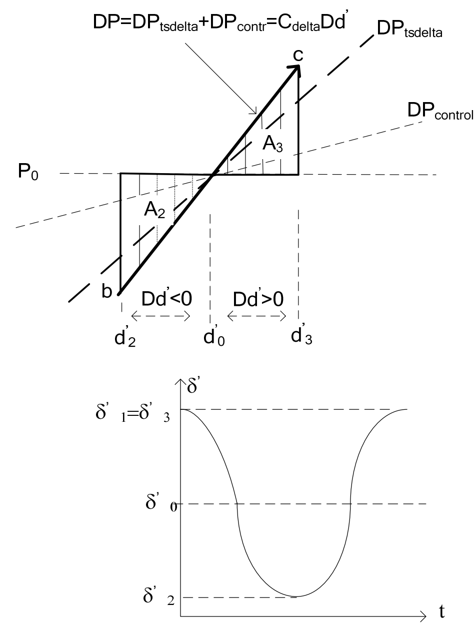


Figure 5. Effect of STATCOM voltage control on power system oscillation damping (2)

In Figure 4, the group of lines is the linearization of P -δ' curves for small-signal analysis. At the steady-state, the system operates at point (δ'_0, P_0) on the linearized P - δ' curve. We assume that the small-disturbance oscillation starts from point 'a' in Figure 4. At point 'a', Δδ'>0 and the resulted increase of P has two parts as shown in Figure 4 and Eq.(9). The first part is $\Delta P_{tsdelta}$ caused directly by Δδ' and the second is $\Delta P_{control}$ due to STATCOM voltage control. When point 'a' moves down with decreasing P from δ'_1 to δ'_0, the movement is along the line $\Delta P = C_{delta}\Delta\delta'$ above the line $\Delta P_{tsdelta}$ because $\Delta\delta' > 0$. This forms area A_1 . From δ'_0 to δ'_2 , the movement is still along the line $\Delta P = C_{delta}\Delta\delta'$ but below the line $\Delta P_{tsdelta}$ because $\Delta\delta' < 0$. The movement stops only when the operating point arrives at point 'b' where $A_2 = A_1$. Obviously, we should have $\delta'_2 = \delta'_1$ as the result of $A_2 = A_1$. Similarly, when point 'b' moves up, operating point will not stop until it arrives at point 'c' where $A_3 = A_2$, resulting in $\delta'_3 = \delta'_2$ as shown by Figure 5.

From the analysis above we can conclude that the voltage control implemented by the VSC FACTS (STATCOM) device imposes little influence on the damping of power system oscillations. This is the conclusion obtained in [1] for a single-machine infinite-bus power system installed with VSC FACTS devices. It can be seen from the analysis above that the conclusion is correct for the general case of the multi-machine power system installed with STATCOM.

3. Demonstration of example power systems

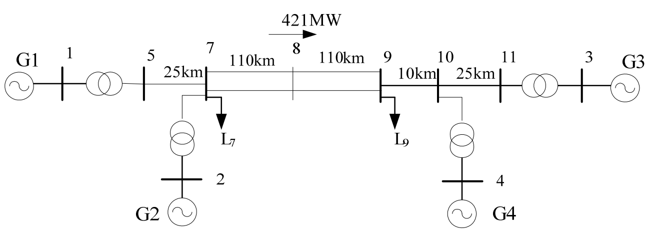
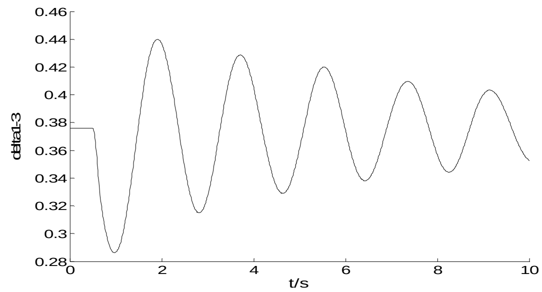


Figure 6. A 4-machine power system installed with a STATCOM

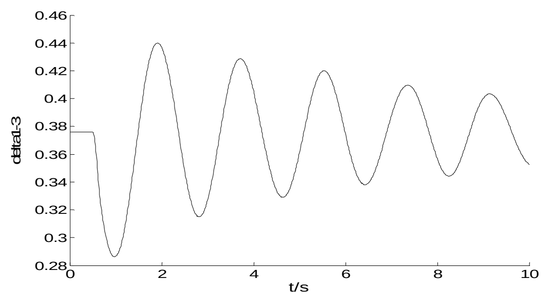
Figure 6 shows a 4-machine power system with a STATCOM installed at node 7. Figure 7 gives the simulation results of the power system without and with STATCOM voltage control. From Figure 7 we can obviously see that STATCOM voltage control provides no damping to power system oscillation.

4. Conclusion

A general analytical method to study the damping effect of VSC based FACTS control is proposed in [1]. That is based on the equal-area criterion and small-signal stability analysis and presented in [1] for single-machine infinite-bus power systems in [1]. The method can be used to explain clearly and simply why and how a VSC based FACST control can affect the damping of power system oscillation. Major contribution of this paper is the extension of the proposed method in [1] to the more general case of a multi-machine power system installed with VSC based FACTS devices. For the presentation of the extension, the paper uses the STATCOM voltage control as an example. By using the proposed method, the paper demonstrates analytically why the STATCOM voltage control has no impact on the damping of power system oscillations. In the paper, simulation results are presented.



(a) without STATCOM voltage control



(b) with STATCOM voltage control

Figure 7. Simulation results

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Appendix 1

From the phasor diagram of Figure 3 and Eq.(2) we have

$$jV_1 = jX(I_{1sX} + jI_{1sY}) + \overline{V}$$

Hence

$$I_{tsY} = \frac{V\sin\delta'}{X}, \quad I_{tsX} = \frac{V_1 - V\cos\delta'}{X}$$

While

$$jV_1 = jX_{1s}\bar{I}_{1s} + \overline{V}_s = jX_{1s}\bar{I}_{1s} + V_{sX} + jV_{sY}$$

that gives

$$V_{sX} = X_{1s}I_{tsY} = \frac{X_{1s}}{X}V\sin\delta'$$

$$\begin{aligned} V_{sY} &= V_1 - X_{1s}I_{tsX} = V_1 - \frac{X_{1s}}{X}(V_1 - V\cos\delta') \\ &= \frac{X - X_{1s}}{X}V_1 + \frac{X_{1s}}{X}V\cos\delta' \end{aligned} \qquad \text{(I1)}$$

We also have

$$V_s^2 = V_{sX}^2 + V_{sY}^2 \qquad \text{(I2)}$$

By using Eq.(I1) and (I2) we can obtain

$$\Delta V_s = \frac{\partial V_s}{\partial \delta'}\Delta\delta' + \frac{\partial V_s}{\partial V_C}\Delta V_C = C_1\Delta\delta' + C_2\Delta V_C$$

where

$$C_1 = \frac{V_0}{V_{s0}}\frac{X_{1s}}{X}(V_{sX0}\cos\delta'_0 - V_{sY0}\sin\delta'_0)$$

$$C_2 = \frac{(abV_{20}\cos\gamma_0 + a^2V_{c0})}{V_0V_{s0}}\frac{X_{1s}}{X}(V_{sX0}\sin\delta'_0 + V_{sY0}\cos\delta'_0)$$