Damping torque analysis of VSC-based system utilizing power synchronization control

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Abstract. Power synchronization control is a new control strategy of VSC-HVDC for connecting a weak power system. Different from the vector control method, this control method utilizes the internal synchronization mechanism in ac systems, in principle, similar to the operation of a synchronous machine. So that the parameters of controllers in power synchronization control will change the electromechanical oscillation modes and make an impact on the transient stability of power system. This paper present a mathematical model for small-signal stability analysis of VSC station used power synchronization control and analyse the impact of the dynamic interactions by calculating the contribution of the damping torque from the power synchronization control, besides, the parameters of controllers which correspond to damping torque and synchronous torque in the power synchronization control is defined respectively. At the end of the paper, an example power system is presented to demonstrate and validate the theoretical analysis and associated conclusions are made.

1. INTRODUCTION
Voltage Source Converter based high voltage direct current transmission(VSC-HVDC) has attracted the attention of many scholars and companies since this concept has been formally proposed [1], and has been used in new energy integration, distributed power access, isolated island transmission and other industry fields[2].

Even though the vector control is the popular control method, it also has some negative impacts of phase-locked loop (PLL) on the stability of VSC station. To eliminate the influence of PLL, power synchronization control [3], integrating amplitude phase control with vector control, with the main characteristic that there is no PLL in the controllers, is proposed.

The results in paper [4] showed that the stability of VSC utilizing power synchronization control will be improved more when the fixed voltage control is used in reactive loop rather than fixed reactive control. Paper [5] expended the power synchronization control to the VSC of DFIG and verifies this idea by the time domain simulation of a two terminal AC/DC network with DFIG. Paper [6] presents the advantages of power synchronization control are improving the damping of sub-synchronous oscillation and the stability of grid with weak connection compared to vector control.

Dynamic interactions between a VSC-based system and its connected power system have been an actively pursued issue in recent years[7]. The interactive performance in AC-DC of VSC utilizing
power synchronization control and the generator is similar, so that the damping torque analysis is used to determine the damping torque and synchronizing torque of VSC utilizing power synchronization control.

2. LINEARIZED MODEL

2.1 Linearized model of power synchronization control

![Figure 1. Power synchronization control system of the VSC](image)

Figure 1. Power synchronization control system of the VSC

Power synchronization control [3] is composed of both inner loop control and outer loop control. Different from the vector control, the power synchronization control utilizes the internal synchronization mechanism in ac systems, in principle, similar to the operation of a synchronous machine. By using this type of power-synchronization control, the VSC avoids the instability caused by a standard phase-locked loop in a weak ac-system connection. Moreover, a VSC terminal can give the weak ac system strong voltage support. From Fig. 1, it can have

$$
\Delta \delta = sK_p \Delta V_{sv} + K_p \Delta V_{sv} , \Delta V_{sv} = \Delta P_{g}/C V_{sv0} , \Delta V_{sv} = sK_p \Delta \psi_{g} + \Delta \psi_{g}
$$

(1)

2.2 Linearized model of Single-VSC infinite-bus power system

![Figure 2. Linearized model of Single-VSC infinite-bus power system](image)

Figure 2. Linearized model of Single-VSC infinite-bus power system

For the single-VSC connected to an infinite-bus power system shown by Fig. 3, it can have

$$
P_i = \frac{V_s \sin \delta}{X_i} , Q_i = \frac{V_s \cos \delta - V_i^2}{X_i}
$$

(2)

The $P_i$, $Q_i$ are active and reactive power supplied by the VSC station respectively. By linearizing Eq. (2) at an operating point of the power system, where $V_s = V_{s0}$, $\delta = \delta_0$, it can have

$$
\Delta P_i = -K_i \Delta \delta - K_i \Delta V_s \Delta Q_s = K_i \Delta \delta - K_i \Delta V_s
$$

(3)

Where, $K_i = \frac{V_s \cos \delta_0}{X_i} ; K_i = \frac{V_s \sin \delta_0}{X_i} ; K_i = \frac{V_s \cos \delta_0}{X_i} ; K_i = \frac{V_s \sin \delta_0}{X_i}

Substituting Eq. (3) into Eq. (1), and $K_p = 0$, it can be obtained that

$$
\Delta \delta = -K_{g1} \Delta \delta + K_{p1} \Delta V_{sv} + K_{p2} \Delta V_{sv} ; \Delta V_{sv} = -K_{g2} \Delta \delta - K_{g3} \Delta V_{sv} \Delta V_{sv} = -K_{g4} \Delta \delta - K_{g5} \Delta V_{sv}
$$

(4)

Where, $K_{g1} = \frac{K_{g1}}{CV_{sv0}} ; K_{p1} = \frac{K_{p1}}{CV_{sv0}} ; K_{g2} = \frac{K_{g2}}{CV_{sv0}} ; K_{g2} = \frac{K_{g2}}{CV_{sv0}} ; K_{g3} = -K_1 K_4$
Eq.(4) is the linearized model of Single-VSC infinite-bus power system, which can be shown by Fig.2. The linearized model can be written in the form of state-space representation of Eq. (4), where

\[
\dot{X} = AX, \quad X = \begin{bmatrix} \Delta \delta \\ \Delta V_{\text{vsc}} \\ \Delta V_{g} \end{bmatrix}, \quad A = \begin{bmatrix} -K_{d1} & K_{p1} & K_{v1} \\ -K_{d2} & 0 & -K_{v2} \\ -K_{d3} & 0 & -K_{v3} \end{bmatrix}
\]

(5)

3. CONFERENCE PAPER PREPARATION

3.1 Damping torque and synchronizing torque

The damping torque analysis (DTA)[8] was developed to decide the damping of power oscillations in the single-VSC infinite-bus power system, considering that the character of VSC utilizing power synchronization control is similar to generator.

From the upper part (active power loop) of Fig.2 it can have

\[
\Delta \delta = -K_{d1} \Delta \delta - (K_{v1}K_{d2} + K_{v1}K_{d3}) \Delta \delta + \left( \frac{K_{v1}K_{v2} + K_{v1}K_{v3}}{K_2} \right) \Delta T, \quad K_{v1} = K_{p1}
\]

(6)

If the contribution from the lower part (reactive power loop) of the linearized model, \(\Delta T\), is not considered, the active power loop of the VSC of Fig.2 is described by the following second-order differential equation

\[
\Delta \ddot{\delta} + K_{d1} \Delta \dot{\delta} + \left( K_{v1}K_{d2} + K_{v1}K_{d3} \right) \Delta \delta = 0
\]

(7)

Solution of Eq. (7) is

\[
\Delta \delta(t) = a e^{-\frac{K_{d1}}{2}} \cos \omega_{\text{NOF}} t + b
\]

(8)

Where \(a\) and \(b\) are two constants and \(\omega_{\text{NOF}} = \frac{1}{2} \sqrt{K_{v1}^2 - 4(K_{v1}K_{d2} + K_{v1}K_{d3})}\) which is called the angular frequency of natural oscillation.

Eq. (8) determines the variations of active power supplied by the VSC during dynamic transient, when the power system is subject to small disturbances. Eq. (8) indicates that the damping of the oscillation of the single-VSC infinite-bus power system is determined by the coefficient of the first-order derivative in the second-order differential equation of Eq. (8) \(K_{d1}\).

The electric torque contributed from the reactive loop of the linearized model can be decomposed into two components, which can be put into Eq. (6).

\[
\Delta T = T_{\text{d}} \Delta V_{\text{vsc}} + T_{\text{i}} \Delta \delta
\]

(9)

Obviously from the discussion on Eq. (7) above, it is easy to understand that the \(T_{\text{d}} \Delta V_{\text{vsc}}\), contributes to the damping of the power oscillation. This component is called the damping torque.

3.2 Theoretical basis of the damping torque analysis

With the general linearized model of the single-VSC finite-bus power system being used, the explanation can be easily provided. From Figure 2 it can have

\[
s^2 \Delta \ddot{\delta} + s \Delta \dot{\delta} + \left( K_{v1}K_{d2} + K_{v1}K_{d3} \right) \Delta \delta = \left( \frac{K_{v1}K_{v2} + K_{v1}K_{v3}}{K_2} \right) \Delta T, \quad \Delta T(s) = F_{\text{dss}}(s) \Delta \delta(s)
\]

(10)

Where \(F_{\text{dss}}(s)\) is the transfer function from \(\Delta \delta(s)\) to \(\Delta T(s)\). Combining two equations and the characteristic equation of the system, and the solution of the characteristic equation is the eigenvalue of the state matrix of the system model given by Eq. (4). One of the pair of complex solution is called the oscillation mode. Its real part defines the damping of power oscillation. Denote the mode as \(\lambda_\omega = \xi_\omega + j\omega_\omega\). The second equation of Eq. (10) in the complex frequency domain is

\[
\Delta T(\lambda_\omega) = F_{\text{dss}}(\lambda_\omega) \Delta \delta(\lambda_\omega)
\]

(11)
Also in the complex frequency domain, the first equation of Eq. (4) becomes:
\[
\Delta V_{\text{sc}}(\omega) = \frac{\delta + j\omega}{sK_{pp} + K_{p}} \Delta \delta(\omega) + \frac{\delta}{sK_{pp} + K_{p}} \Delta \omega(\omega) + \frac{\delta}{sK_{pp} + K_{p}} \Delta \omega(\omega)
\]  
(12)

Let the electric torque defined by Eq. (9) be decomposed as follows
\[
\Delta T(\omega) = T_d + \omega T_w = T_d + \omega T_{\omega}(\omega)
\]  
(13)

From Eq. (11), (12) and (13) it can be obtained that
\[
T_d = \frac{sK_{pp} + K_{p}}{\omega} \text{Im}\{\tilde{F}_{\text{acta}}(\omega)\}, T_w = \text{Re}\{\tilde{F}_{\text{acta}}(\omega)\} - \frac{T_d \omega}{sK_{pp} + K_{p}}
\]  
(14)

The above derivation indicates that in the complex frequency domain, the electric torque can be decomposed into damping and synchronizing torque according to Eq.(13). Substituting Eq.(13) into (10) it can have
\[
(\omega^2 + K_{pp} K_{pp} + (K_{pp} K_{pp} + K_{pp} K_{pp})) \Delta \delta(\omega) + \frac{K_{pp} K_{pp} + K_{pp} K_{pp}}{K_2} T_d \Delta \omega(\omega) + \frac{K_{pp} K_{pp} + K_{pp} K_{pp}}{K_2} T_d \Delta \omega(\omega)
\]  
(15)

4. EXAMPLE

4.1. Calculation of linearized model

The structure of single-VSC infinite-bus power system is shown in Fig.3. Parameters are
\[K_{pp} = 0.942, K_{ps} = 60.288, K_{pq} = 10, K_{pq} = 0.0, C = 3 pu, X = 0.05, P = 0.8, V_{pp} = 1.01, V_{pp} = 1.0.\]

At the steady-state operating point, it can be obtained that \(Q = 0.184\). The line current is \(I_{pp} = 0.821 \angle -12.953^\circ\). The terminal voltage of the generator is \(V = jX_I, T = 1.0092 + j0.04\). From (3), it can be calculated that \(K_1 = 20.184, K_2 = 0.792, K_3 = 0.8, K_4 = 19.984\) and \(A\) in (5) is

\[
\begin{bmatrix}
\Delta \delta \\
\Delta \phi \\
\Delta V_g
\end{bmatrix} =
\begin{bmatrix}
-0.6341 & 60.3 & -0.0248 \\
-0.6732 & 0 & -0.0264 \\
8 & 0 & -199.84
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \phi \\
\Delta V_g
\end{bmatrix}
\]

Eigenvalues of the above state matrix are computed to be \(\lambda = -199.84, \lambda = -0.3174 \pm j 6.3677\)

4.2. Damping torque analysis and nonlinear simulation

From (11) and Fig.(2), it can be calculated that
\[
\tilde{F}_{\text{acta}}(s) = -\frac{K_1 S^2 + K_1 s^2}{1 + K_1 s} - \frac{K_1 (s K_{pp} + K_{pq}) K_{pp}}{s + K_1 (s K_{pp} + K_{pq})} = \frac{s K_1 K_{pp} K_{pp} + K_1 K_{pp} K_{pq}}{(K_1 K_{pp} + 1) s + K_1 K_{pp}}
\]  
(16)

The electromechanical oscillation modes of the power system are \(\lambda = -0.3174 \pm j 6.3677\). From (16), it can be \(\tilde{F}_{\text{acta}}(\lambda) = -0.031726 + 0.0010125 i\). The electromechanical oscillation modes of the power system are \(\lambda = -0.3174 \pm j 6.367\). The electric torque and damping synchronizing torque can be decomposed as \(T_{d1} = 0.05, T_{d2} = -0.03\). Substituting above answers into (15) it can have solutions to be \(\lambda = -0.3188 + j6.368\). It is proved that the (14) is correct to analyze the damping torque. Consider that \(\lambda \approx jw, \tilde{F}_{\text{acta}}(\lambda) \approx \tilde{F}_{\text{acta}}(jw)\), it can be
\[
T_{d1} = \frac{w}{w} \text{Im}\{\tilde{F}_{\text{acta}}(jw)\} \approx \frac{w}{w} \text{Im}\{\tilde{F}_{\text{acta}}(jw)\} = \frac{w_1 K_1 K_{pp} K_{pq}}{(K_1 K_{pp} + 1) w + w_1 (K_1 K_{pp} + 1)}
\]  
(17)
Damping torque of VSC is obviously impacted by parameters of reactive power loop. The influence of $K_{q_i}$ on the system damping torque is calculated under different values of $K_{q_i}$, which is showed in Fig. 4(a). The other parameters are the same as 4.1.

**Figure 4(a).** The damping torque with different $K_{q_i}$.

**Figure 4(b).** Nonlinear simulation with different $K_{q_i}$.

From Fig. 4(a), it can be concluded that: The impact of $K_{q_i}$ on damping torque is positive, and the damping torque will increase firstly and then decrease with the increase of $K_{q_i}$. This phenomenon indicate that the impact of $K_{q_i}$ on damping torque will not be unidirectional, the optimal value is existence with about 1.

Table I shows the change of the oscillation mode with the $K_{q_i}$ value is changed. It can be found that the damping of the system oscillation mode increases firstly and then decreases with the increase of $K_{q_i}$.

| $K_{q_i}$ | mode            |
|----------|-----------------|
| 0.1      | $-0.43468+j6.521$ |
| 0.5      | $-0.46217+j6.475$ |
| 1        | $-0.46061+j6.418$ |
| 5        | $-0.34574+j6.352$ |
| 10       | $-0.31987+j6.361$ |
| 20       | $-0.30776+j6.368$ |

The system in Fig. 3 is simulated to verify the correctness of the above analysis. Three phase short circuit fault occurs in the line at 1s for 0.1s, the fluctuation curve of the output active power of VSC is shown in Fig. 4(b). The simulation parameters are as follows, others are the same as 4.1. Case A: $K_{q_i} = 1$, $P_g = 0.8pu$; Case B: $K_{q_i} = 20$, $P_g = 0.8pu$.

Damping torque of VSC is also impacted by K2, K3 and K4, which are defined by the output power of VSC, from (3). The influence of output active power, $P_g$, on the system damping torque is calculated under different values of $P_g$, which is showed in Fig. 5(a). The other parameters are the same as 4.1.
Figure 5(a). The damping torque with different $P_g$. Figure 5(b). Nonlinear simulation with different $P_g$.

From Fig.5(a), it can be concluded that: The impact of $P_g$ on damping torque is positive, and the damping torque will increase with the increase of $P_g$. This phenomenon indicates that the impact of $P_g$ on damping torque will be more positive with the increase of $P_g$.

Table II shows the change of the oscillation mode with the $P_g$ is changed. It can be found that the damping of the system oscillation mode becomes better with the increase of $P_g$.

The system in Fig.3 is simulated to verify the correctness of the above analysis. Three phase short circuit fault occurs in the line at 1s for 0.1s, the fluctuation curve of the output active power of VSC is shown in Fig.5(b). The simulation parameters are as follows, others are the same as 4.1. Case: C: $K_{qi} = 1$, $P_g = 0.4$pu; Case: D: $K_{qi} = 1$, $P_g = 2.0$pu.

5. CONCLUSION

a) The reactive loop of the VSC can make an influence on the damping torque, so that the suitable parameters of the reactive loop will make modes better.

b) The damping torque will increase with the increase of the output active power, so that the active power of VSC should be increased possibly within the limitation.

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