Impact of Strong Dynamic Couplings between VSC-based Generation Units and Power Systems on Power System Electro-mechanical Oscillation Modes

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***Abstract*—The impact of a VSC-based generation unit on power system electro-mechanical oscillation modes (EOMs) is two-fold, changing power flow conditions and dynamically coupling with power systems. This paper focuses on the latter one. Usually the dynamic couplings between VSC-based generation units and power systems are thought to be weak due to the excellent performance of vector control. However, it is discovered in this paper that the dynamic couplings would be tremendous if the DC-link voltage control mode of the VSC coincided with any of the EOMs. Under the special condition of modal coincidence, damping of the affected EOM would be degraded substantially. Furthermore, it is found that the strength of dynamic couplings at the point of modal coincidence is positively correlated to the penetration level of the VSC-based generation unit. The effect of damping deterioration is worsened with the increasing of penetration level of the VSC-based generation unit when modal coincidence occurs. Both theoretical analysis and case study are presented in the paper to validate these findings.**

Keywords-voltage source converter; electro-mechanical oscillation mode (EOM); permenant-magnet synchronous generator; power system small signal stability; power system dynamics

I. INTRODUCTION

The large-scale exploitation of renewable energy is a promising solution for the sustainability of energy supply. Voltage source converter (VSC) has been accepted as the most attractive method for the grid integration of renewable energy sources. Therefore, it is of great significance to study the impact of VSC-based generation units on power system small-signal stability.

The research on VSC has become a hotly-pursued topic in recent years. It was reported in many published works that the grid-integration of VSC to a weak system might deteriorate power system small-signal stability [1]-[8]. A weak system is defined by the short-circuit ratio (SCR). Usually, the SCR of a strong system is larger than 3. The system is recognized as a weak system if the SCR is somewhere between 1 and 3 [1]-[2]. When VSC is connected to a weak system, the power handling capability may be limited, e.g. the transmission capability of a VSC-HVDC system is reduced to 40% when being connected to a system with a SCR of 1 [3]. In addition, the control mode associated with the phase-locked loop (PLL) of VSC, which is stable when VSC is connected to a strong system, may become unstable when VSC is connected to a weak system [4]. To deal with the stability deterioration brought about by weak system, some axillary control techniques were proposed. In [5], a power compensation control strategy combined with active damping control in inner loop was suggested. In [6], it was found that the negative damping provided by the AC-side voltage control of VSC would increase as system strength fell. Hence, it proposed to increase AC-bus control gain to restore stability when the system was weak.

The aforementioned research works were centered on the stability deterioration of VSC caused by connecting to a weak system. In the analysis, the power system was simply modeled as an infinite bus with fixed impedance, which represented system strength. Other dynamic characteristics of power systems were often neglected. As a result, the impact of VSC dynamics on power system electro-mechanical modes (EOMs) was rarely discussed.

To fill this gap, the impact of VSC dynamics on power system electro-mechanical modes (EOMs) is discussed in this paper. In [9], the impact of wind turbine generators (WTGs) on power system EOMs was classified into two aspects, changing power flow conditions and dynamically coupling with power systems. In this paper, the latter one is examined. In most cases, VSC-based power generation units using vector control are considered to be inertia-less. Nevertheless, in [10], evidence of strong dynamic couplings between converter control-based generators (CCBGs) and power systems was revealed. Participation factors suggested that CCBGs participated substantially in the EOMs of power systems. The phenomenon was reported, though, the explanation was absent. To fill in the theoretical gap, this paper is dedicated to identifying the inherent causes of strong dynamic couplings between VSC-based generation units and power systems.

The paper is organized as follows. Firstly, the linearized model of a VSC-based generation unit is established. The transfer function between the variation of active power output of the VSC-based generation unit and the variation of the voltage of PCC is found. According to the transfer function, it is figured out that the transfer function is small when the control system of the VSC is of good performance. In this case, the dynamic couplings between the VSC-based generation unit and the power system are ignorable. Thus, the impact on the EOMs is trivial. However, the dynamic couplings would be tremendous if the DC-link voltage control mode of the VSC coincided with one of the EOMs of the power system, since the transfer function is large. The special condition of strong couplings is named modal coincidence in this paper. When the condition of modal coincidence is met, the damping of the affected EOM is reduced substantially. This case has to be given due attention since the system risks losing stability. Finally, simulation is carried out to validate these findings.

II. Theoretical Analysis

Usually a VSC-based generation unit is thought to exhibit weak dynamics in power system disturbances due to the application of fast vector control. In this section, however, the possibility of strong dynamic couplings between a VSC-based-generation unit and power systems and its subsequent impact on power system EOMs are considered. Firstly, the linearized model of a VSC-based generation unit is established. Based on the linearized model, theoretical analysis is carried out to demonstrate the impact of strong dynamic couplings on power system EOMs.

A. Linearized Modal of a VSC-based Generation Unit

Figure 1 shows the typical configuration of a VSC-based generation unit. The power source can be a PMSG or a photovoltaic panel or anything connected to the power system via a VSC. Since all the electrical power generated by the power source is fed into the grid through the VSC, the impact of dynamic interactions between the VSC-based generation unit and the power system on power system EOMs is mainly determined by the dynamic responses of the interfacing VSC.

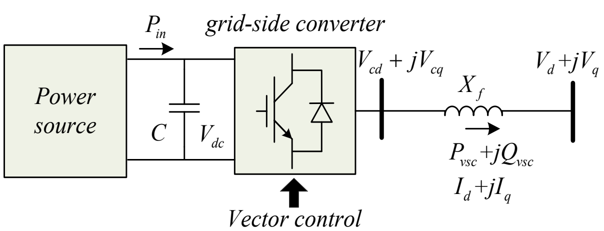

Figure 1. Configuration of a VSC-based generation unit.

Take *d*-axis as the direction of the voltage of PCC, the mathematical representation of the VSC can be described as

$$\begin{cases} \dfrac{d}{dt} I_d = \dfrac{\omega_B}{X_f}(V_{cd} - V_d) + \omega_B I_q \\ \dfrac{d}{dt} I_q = \dfrac{\omega_B}{X_f}(V_{cq} - V_q) - \omega_B I_d \end{cases} \tag{1}$$

where I_d and I_q denote the *d*-axis and *q*-axis currents of the VSC, V_{cd} and V_{cq} represent the *dq* components of the AC-side output voltage. V_d and V_q are the *dq* components of the voltage of PCC. ω_B is the nominal angular speed of the power system.

Figure 2 shows the control strategy for VSC. Based on Figure 2, the following relationship can be obtained.

$$\begin{cases} \dfrac{d}{dt} x_{id} = K_{i\_id}(I_d^{ref} - I_d) \\ V_{cd} = K_{p\_id}(I_d^{ref} - I_d) + x_{id} + V_d - X_f I_q \end{cases} \tag{2}$$

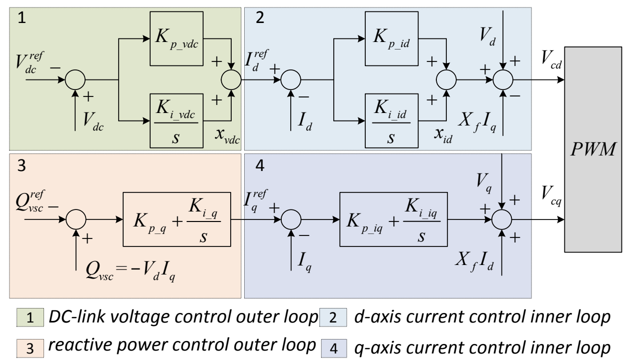

Figure 2. Control strategy of interfacing VSC.

Substituting the second equation of (2) into the first equation of (1), we get

$$\frac{d}{dt} I_d = \frac{\omega_B K_{p\_id}}{X_f}(I_d^{ref} - I_d) + \frac{\omega_B x_{id}}{X_f} \tag{3}$$

Linearizing (2) and (3), and taking Laplace Transform, we can have

$$\Delta I_d = \frac{\omega_B K_{p\_id} s + \omega_B K_{i\_id}}{X_f s^2 + \omega_B K_{p\_id} s + \omega_B K_{i\_id}} \Delta I_d^{ref} \tag{4}$$

According to Figure 2, the DC-link voltage control satisfies

$$\Delta I_d^{ref} = \frac{K_{p\_vdc} s + K_{i\_vdc}}{s} \Delta V_{dc} \tag{5}$$

The dynamics of the DC-link capacitor can be described as

$$C V_{dc} \frac{dV_{dc}}{dt} = P_{in} - P_{vsc} \tag{6}$$

where P_{in} and P_{vsc} represent the active power injected into the capacitor and the active power injected into the power system respectively. Linearizing (6), we get

$$\Delta V_{dc} = \frac{\Delta P_{in} - \Delta P_{vsc}}{C V_{dc0} s} \tag{7}$$

The active power injected into the power system P_{vsc} can be described as

$$P_{vsc} = V_d I_d + V_q I_q = V_{pcc} I_d \tag{8}$$

Linearizing (8), we can have

$$\Delta P_{vsc} \approx I_{d0}\Delta V_{pcc} + V_{pcc0}\Delta I_d \tag{9}$$

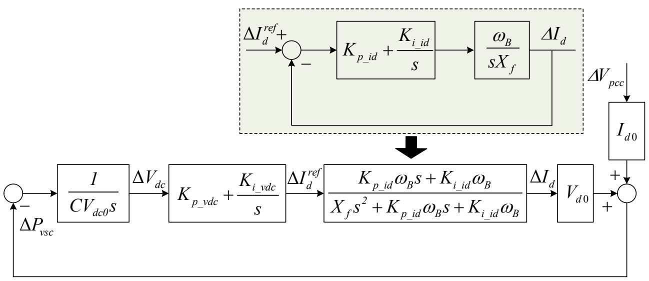

Figure 3. Control diagram of DC-link voltage control.

Based on the mathematical derivation from (1) to (9), we can get the control diagram as presented in Figure 3. From Figure 3, it can be seen that there is a connection between the variation of the voltage of PCC ΔV_{pcc} and the active power variation of the VSC ΔP_{vsc} . When the voltage of PCC V_{pcc} changes due to power system disturbances, the active power injection of the VSC P_{vsc} varies accordingly.

Based on Figure 3, we can obtain the following transfer function.

$$G_p(s) = \frac{\Delta P_{vsc}}{\Delta V_{pcc}} = \frac{CV_{dc0}s^2 I_{d0}}{CV_{dc0}s^2 + V_{pcc0}K_{p\_vdc}K_{id}(s)s + V_{pcc0}K_{i\_vdc}K_{id}(s)} \tag{10}$$

where $K_{id}(s) = \frac{\omega_B K_{p\_id}s + \omega_B K_{i\_id}}{X_f s^2 + \omega_B K_{p\_id}s + \omega_B K_{i\_id}}$

In (10), the inner-loop transfer function $K_{id}(s)$ can be approximated to be $K_{id}(s) \approx 1$, thus it can have

$$G_p(s) = \frac{CV_{dc0}s^2 I_{d0}}{CV_{dc0}s^2 + V_{pcc0}K_{p\_vdc}s + V_{pcc0}K_{i\_vdc}} \tag{11}$$

In the same way, based on Figure 2, the reactive power transfer function can be obtained to be

$$G_q(s) = \frac{\Delta Q_{vsc}}{\Delta V_{pcc}} = \frac{-I_{q0}s}{(1 + V_{pcc0}K_{p\_q})s + V_{pcc0}K_{i\_q}} \tag{12}$$

Denote λ_i as the EOM of concern when $\Delta P_{vsc} + j\Delta Q_{vsc} = 0$. This is the case when the dynamics of the VSC are not taken into account. When the dynamics of the VSC are considered, $\Delta P_{vsc} + j\Delta Q_{vsc} \neq 0$, denote the EOM of concern as λ_e . Thus the impact brought about by the dynamic couplings between the VSC and the power system on the EOM of concern can be measured by $\lambda_e - \lambda_i$. The bigger $|\lambda_e - \lambda_i|$ is, the larger the impact is.

According to (11) and (12), the dynamic couplings between the VSC and the power system are ignorable as long as transfer function $|G_p(\lambda_i)|$ and $|G_q(\lambda_i)|$ are sufficiently small. This condition is met in most cases since the control parameters of the VSC are usually well tuned, e.g. if K_{p_vdc} , K_{i_vdc} , K_{p_q} and K_{i_q} in (11) and (12) are very large, $|G_p(\lambda_i)| \approx 0$, $|G_q(\lambda_i)| \approx 0$. When $|G_p(\lambda_i)|$ and $|G_q(\lambda_i)|$ are sufficiently small, the dynamic couplings of the VSC with the power system are too weak to impose any observable impact on power system EOMs, hence, $|\lambda_e - \lambda_i|$ is ignorable.

Nevertheless, there is a special condition where the dynamic couplings are outstanding. From (11), it is easy to notice that there is an oscillation mode related to the DC-link voltage control of VSC. This mode can be calculated by

$$\lambda_{vsc} = -\frac{V_{pcc0}K_{p\_vdc}}{2} + \frac{\sqrt{V_{pcc0}^2 K_{p\_vdc}^2 - 4CV_{dc0}V_{pcc0}K_{i\_vdc}}}{2} \tag{13}$$

Based on (13), (11) can be rewritten as

$$G_p(s) = \frac{\Delta P_{vsc}}{\Delta V_{pcc}} = \frac{CV_{dc0}s^2 I_{d0}}{CV_{dc0}(s - \lambda_{vsc})(s + \lambda_{vsc})} \tag{14}$$

If the EOM of concern λ_i is located near to the control mode of the VSC λ_{vsc} , the transfer function $|G_p(\lambda_i)|$ in (14) can be exceptionally large. In this case, the dynamic couplings are tremendous. Hence, the impact induced by the dynamic couplings $|\lambda_e - \lambda_i|$ can be substantial. The special condition when $\lambda_{vsc} \approx \lambda_i$ is named modal coincidence in this paper. Although whether the impact on the damping of the EOM of concern $real(\lambda_e - \lambda_i)$ is negative or not cannot be ascertained, the case of modal coincidence has to be given due attention since there is potential risk of damping degradation if the impact is negative.

In addition, from (14), it can be noted that in the case of modal coincidence, transfer function $|G_p(\lambda_i)|$ is positively correlated to I_{d0} , which rises as the steady-state active power output of VSC P_{vsc0} increases. This is to say, the larger the penetration of the VSC P_{vsc0} is, the stronger the dynamic couplings are, the larger $|\lambda_e - \lambda_i|$ is.

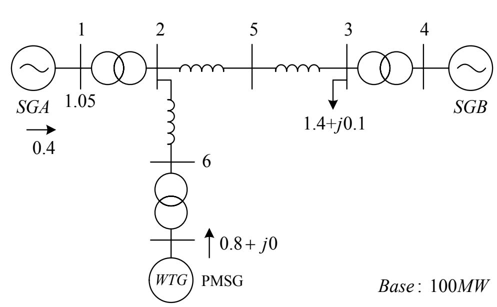

Figure 4. An example power system with a PMSG.

III. Case Study

To verify the analysis carried out in the preceding section, simulation is performed on the example power system shown in Figure 4. The steady-state active power output of the PMSG P_{vsc0} is set to be 0.8 p.u.. When the PMSG is modeled as a constant power source, $\Delta P_{vsc} + j\Delta Q_{vsc} = 0$, the EOM of concern is denoted as λ_i. When the dynamic model of the PMSG is used, $\Delta P_{vsc} + j\Delta Q_{vsc} \neq 0$, the EOM of concern is denoted as λ_e. Thus, the impact of dynamic couplings on the EOM of concern can be indicated by $\lambda_e - \lambda_i$. The VSC mode associated with the DC-link voltage control of the grid-side converter of the PMSG is represented by λ_{vsc}, which can be calculated by (13).

A. Impact of Dynamic Couplings as Caused by Paramerter Tuning

TABLE I. Modal Computation Results

	K_{p_vdc} / K_{i_vdc}	λ_{vsc}	λ_e	$\lvert\lambda_e - \lambda_i\rvert$
Case A	0.2/20	-0.93401 + j14.426	-0.29324 + j7.9587	0.010614
Case B	0.03/6.2	-0.37699 + j8.8187	-0.1386 + j8.3362	0.39765

When the PMSG is modeled as a constant power source, $\lambda_i = -0.29169 + j7.9692$, there are no dynamic couplings between the PMSG and the power system. The modal computation results when PMSG dynamics are taken into account are presented in Table I, where two cases are considered. In Case A, the control parameters of the DC-link voltage control of the grid-side converter of the PMSG are tuned to be $K_{p\_vdc} = 0.2$, $K_{i\_vdc} = 20$. In Case B, the parameters are changed to be $K_{p\_vdc} = 0.03$, $K_{i\_vdc} = 6.2$. From Table I, it can be seen that

1) In case A, the impact of dynamic couplings $\lvert\lambda_e - \lambda_i\rvert$ is small, since the VSC mode λ_{vsc} is far from the EOM of concern λ_i.
2) $\lvert\lambda_e - \lambda_i\rvert$ in Case B is much larger than case A, indicating the presence of strong dynamic couplings. This is due to the modal coincidence of λ_{vsc} and λ_i, which leads to substantial damping degradation of the EOM of concern, as can be seen from λ_e in Case B.

Participation factors are a direct indicator of modal couplings. Figure 5 and Figure 6 show the participation factors of all the state variables in λ_e in Case A and Case B respectively. From Figure 5 and Figure 6, it can be seen that the PMSG hardly participates in λ_e in Case A. However, strong participation of the PMSG in λ_e is observed in Case B, indicating the presence of strong dynamic couplings. Moreover, the computational results of Figure 6 suggest that the state variables related to the DC-link voltage control are responsible for the modal couplings.

Finally time-domain simulation is carried out to validate the analytical results, as shown in Figure 7 and Figure 8. From 1 second to 1.1 second, the mechanical torque of SGA increases by 10%. From Figure 7 and Figure 8, it can be seen that

1) The dynamic active power exchange between the PMSG and the power system increases tremendously in Case B as compared with Case A, indicating the presence of strong dynamic couplings in Case B.
2) The damping of the EOM is degraded substantially in Case B, which means that modal coincidence has a negative impact on the affected EOM.

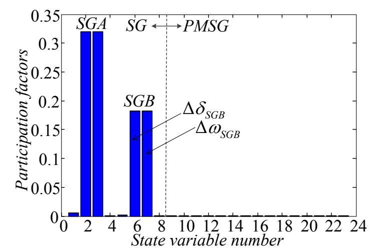

Figure 5. Participation factors in λ_e in Case A.

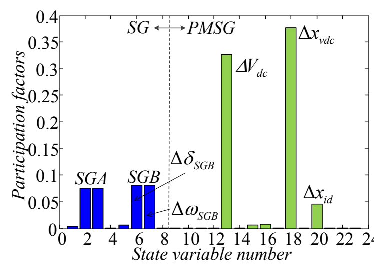

Figure 6. Participation factors in λ_e in Case B.

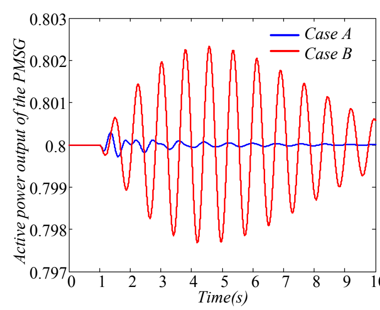

Figure 7. Time-domain simulations.

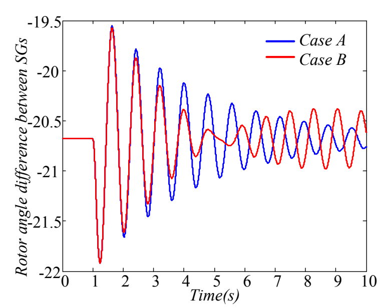

Figure 8. Time-domain simulations.

The computational results displayed above are completely consistent with the theoretical analysis made in the previous section.

B. Impact of Dynamic Couplings as Affected by the Penetration of the PMSG

It has been theoretically validated that the impact of dynamic couplings between VSC-based generation units and power systems is positively corelated to the penetration of VSC-based generation unit P_{vsc0} at the point of modal coincidence. In this section, simulation is carried out to verify this statement.

TABLE II. MODAL COMPUTATION RESULTS

P_{vsc0}	λ_e	$\lvert\lambda_e - \lambda_i\rvert$
0.1	-0.29925 + j8.1497	0.18066
0.4	-0.24522 + j8.2534	0.28797
0.8	-0.1386 + j8.3362	0.39765

The active power output of the PMSG at steady-state is varied from P_{vsc0}=0.1 to P_{vsc0}=0.8. The modal computation results are presented in Table II. From Table II, it can be seen that the impact of dynamic couplings, which is measured by $\lvert\lambda_e - \lambda_i\rvert$, rises as the penetration of the PMSG P_{vsc0} increases. As can be seen from the second column of the table, the damping degradation of the EOM is the worst when P_{vsc0}=0.8.

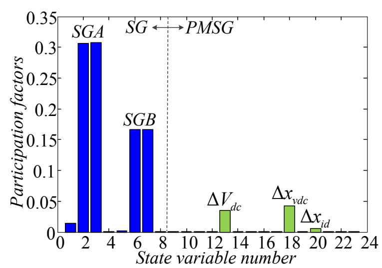

Figure 9. Participation factors in λ_e when P_{vsc0}=0.1.

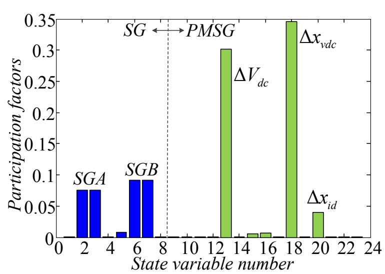

Figure 10. Participation factors in λ_e when P_{vsc0}=0.8.

The enhancement of dynamic couplings between the PMSG and the power system can also be confirmed in the participation factors. The participation facotors for P_{vsc0}=0.1 and P_{vsc0}=0.8 are presented in Figure 9 and Figure 10 respectively. From the figures, it can be known that the participation of the PMSG in λ_e rises as P_{vsc0} increases. The phenomenon suggests that the dynamic couplings between the PMSG and the power system are enhanced as P_{w0} rises, indicating the correctness of the previous analysis.

IV. CONCLUSIONS

The paper investigates the impact of dynamic couplings between VSC-based generation units and power systems on power system electro-mechanical oscillation modes (EOMs). It is found that strong dynamic couplings between interfacing VSC and power systems are present when the control mode of VSC associated with the DC-link voltage control coincides with any of the EOMs of power systems. This phenomenon is called modal coincidence in this paper. It is demonstrated in the paper that the effect of strong dynamic couplings is detrimental to the damping of the affected EOM when modal coincidence happens. Furthermore, the strength of modal coincidence is positively correlated to the penetration level of VSC-based generation unit. In another word, the effect of modal coincidence is enhanced with the increasing of penetration level of VSC-based generation unit.

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