Small-Signal Dynamic Analysis of LCC-HVDC with STATCOM at the Inverter Busbar

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Abstract. This paper develops a linearized small-signal dynamic model of a Line-Commutated-Converter based HVDC (LCC-HVDC) system with STATCOM at the inverter busbar, and validates its accuracy by comparing time-domain responses from small-signal model and PSCAD-based simulation results. Considering the potential impact of Phase-Locked-Loop (PLL) parameters on the study system and the close connection of STATCOM and LCC inverter station at AC busbar, this paper investigates the impact of PLL gains and AC voltage control parameters of STATCOM on the system small-signal stability. The studies show that (i) the PLL gain has highly impact on the study system and smaller PLL gains are preferable; (ii) larger values of both the proportional gain and the integral gain of AC voltage controller of STATCOM could result in oscillation/instability of the system.

1. Introduction
Line-Commutated-Converter based HVDC (LCC-HVDC) system has been widely used in long-distance and large-capacity power transmission [1]. However, it is prone to suffer from commutation failure (CF) and cascaded CFs in multi-in feed scenarios [2]-[4]. Many reactive power compensators are considered to be utilized to regulate the AC busbar voltage at the inverter side to mitigate the CFs of LCC-HVDC link [5]-[7], and one potential option is the utilization of Voltage-Source-Converter (VSC) type STATCOM device [6].

The existing literatures have fully investigated the steady-state and transient-state performances of LCC-HVDC with STATCOM [7]-[8]. However, it is also necessary to investigate the impact of the control parameters on the system dynamic behaviors by Eigen-analysis approach [9]-[12].

In this paper, a small-signal dynamic model of a LCC-HVDC link with STATCOM at the inverter bulbar is developed and validated by the Eigen-analysis from Mat lab and the electromagnetic transient (EMT) simulation from PSCAD/EMTDC. Considering i) the potential adverse impact of Phase-Locked Loop (PLL) parameters on the small-signal stability of LCC and VSC stations [9],[13] and ii) close connection of STATCOM and LCC inverter station at AC bulbar, this paper mainly investigates the impact of PLL gains and AC voltage control parameters of STATCOM on the system small-signal stability. The results show that smaller PLL gains are preferable and larger values of both
the proportional gain and the integral gain of AC voltage controller of STATCOM may cause system instability.

2. Study System

2.1. Description of the study system

The configuration of a LCC-HVDC system with STATCOM (HVDC-STATCOM system) at the inverter bus is shown in Figure 1(a). The LCC-HVDC system is composed of a twelve-pulse LCC inverter station, connected to the AC system by converter transformer A. The VSC-type STATCOM is connected to the AC bulbar at the inverter side of the HVDC system by converter transformer B. Figure 1(b) shows a one line diagram of the study system used for developing the small-signal model. The AC system is modeled as an impedance consisting of $R_s$ and $L_s$; the LCC station is modeled by a phase reactor $L_T$, a loss resistance $R_T$ and a current-source $i_c$ representing the AC-side current output of the LCC station; and the STATCOM is modeled by $L_2$, $R_2$ and a voltage-source $v_{2c}$ representing the AC-side voltage output of the STATCOM. Both the LCC and the STATCOM are synchronized by the PLL to the PCC (Point of Common Coupling, PCC) positive sequence voltage $v_{pcc}$.

![Figure 1. (a) System configuration of the study system, (b) One line diagram of the study system.](image-url)
2.2. Control modes of the study system

1) Control mode of the LCC station

The LCC station of Figure 1(a) adopts a constant extinction angle control. The control block diagram of the LCC is shown in Figure 2(a).

2) Control mode for the STATCOM

The STATCOM adopts the classical vector current control (VCC) which is shown in Figure 2(b).

The outer controllers, including the DC voltage controller and the AC voltage controller, provide the current references $i_{2d_{ref}}$ and $i_{2q_{ref}}$ to the inner control loop. The inner control loop generates the converter AC-side voltage $v_{2cd}$ and $v_{2cq}$.

3. System dynamic model

3.1. Small-signal dynamic model

To investigate the stability and dynamic performance of the HVDC-STATCOM system, a small-signal dynamic model is derived in this paper, including the model of the AC system and PLL function, the LCC station, the STATCOM and the control system in the previous section.

The nonlinear dynamic model of the HVDC-STATCOM system can be described in the form of...
\[ x = f(x,u) \]  
\[ \Delta x = A\Delta x + B\Delta u \]  

By the linearization of (1) at the operating point, the small-signal dynamic model of the system is derived as

The state vector \( x \) has 29 state variables, and the input variable can be described as \( \Delta u = [\Delta \gamma_{\text{ref}}, \Delta U_{\text{dc}2\text{ref}}, \Delta v_{\text{ref}}] \).

### 3.2. Small-signal model validation

The HVDC-STATCOM system of Figure 1(a) is also developed in PSCAD/EMTDC platform to validate the derived small-signal model. The LCC system is developed based on the CIGRE benchmark model [14], and the system parameters are given in Table 1. The parameters of the STATCOM are shown in Table 2.

#### Table 1. Parameters of LCC system

| Parameter                              | Value                          |
|----------------------------------------|--------------------------------|
| AC system SCR                          | 2.0, 84°                       |
| RMS value of PCC                       | 1.0p.u. (230kV, 50Hz)          |
| Rated active power                     | 1.0p.u. (1000MW)               |
| Converter reactance \( X_T \)          | 0.18 p.u.                      |
| Converter transformer ratio            | 230/209.2288 kV                |
| Single transformer capacity            | 591.79 MVA                     |
| PLL gain (\( K_{pPLL} = 5 \times K_{iPLL} \)) | 10                              |
| Extinction angle controller            | \( K_p = 20, K_i = 500 \)      |
| Measure time constant \( T_m \)        | 0.001                           |

#### Table 2. Parameters of STATCOM system

| Parameter                              | Value                          |
|----------------------------------------|--------------------------------|
| Rated DC voltage (\( U_{\text{dc}2} \)) | 1.0p.u. (+250kV)               |
| DC capacitor \( C_{dc} \)              | 200 \( \mu \)F                 |
| Converter reactance \( X_2 \)          | 0.15 p.u.                      |
| The transformer ratio                  | 230/230 kV                     |
| DC voltage controller                  | \( K_{pu}=0.5, K_{iu}=50 \)    |
| AC voltage controller                  | \( K_{pv}=0.5, K_{iv}=50 \)    |
| Inner \( i_d \) controller             | \( K_{p1}=2, K_{i1}=50 \)      |
| Inner \( i_q \) controller             | \( K_{p2}=2, K_{i2}=50 \)      |
| Measure time constants \( T_{mvd} \)   | 0.01                           |
| Measure time constants \( T_{mvq} \)   | 0.01                           |

To validate the accuracy of the small-signal model, this section compares time-domain responses obtained from the small-signal model in Mat lab and the detailed time-domain simulation in PSCAD/EMTDC. The system operates at nominal operation state (\( \gamma_{\text{ref}} = 15^\circ \), \( v_{\text{pccref}} = 1.0 \text{p.u.} \), \( U_{\text{dc}2\text{ref}} = 1.0 \text{p.u.} \)), and the STATCOM absorbs 0.009p.u. Reactive power. The imposed disturbances are step-changes in extinction angle of LCC (Case 1), and AC-side voltage of STATCOM (Case 2).
Case 1: A $\gamma$ step changes from 1.0 p.u. (15°) to 0.95 p.u. (14.25°) at time $t=3s$ and from 0.95 p.u. to 1.0 p.u. at time $t=4.5s$. The comparison results are shown in Figure 3. Figure (a), (b), (c), (d) compare the dynamic characteristics of extinction angle, active power $P_s$, PCC voltage $v_{pcc}$ and DC voltage $U_{dc2}$ of STATCOM when the extinction angle is step-changed.

![Figure 3](image1.png)  
*Figure 3. Time-domain response under step change*

![Figure 4](image2.png)  
*Figure 4. Time-domain response under $v_{pcc}$ step change*
Case 2: A $v_{pccref}$ step changes from 1.0p.u. to 0.95p.u. at time $t=3s$ and from 0.95 p.u. to 1.0p.u. at time $t=4.5s$. The comparison results are shown in Figure 4.

Close agreement of the dynamic responses from the small-signal model and time-domain simulation in Figure 3-4 validates the accuracy of the small-signal dynamic model.

4. Small-signal dynamic analysis

4.1. Impact of PLL gain $K_{pPLL}$

Initially, the HVDC-STATCOM system operates at nominal operation point ($SCR=2.0 \angle 84^\circ$, $\theta_{ref}=15^\circ$, $P_{dc}=1.0p.u.$, $v_{pccref}=1.0p.u.$, $U_{dc2ref}=1.0p.u.$). The PLL gain $K_{pPLL}$ increases from 5 to 100 ($K_{iPLL}=K_{pPLL}$), and the root loci of the eigenvalues are shown in Figure 5(a).

![Figure 5](image)

**Figure 5.** (a) Loci of the eigenvalues when $K_{pPLL}$ changes, (b) Damping of dominant mode when $K_{pPLL}$ changes

Figure 5(a) shows that the system can keep stable when $K_{pPLL} < 49$, and the results also show that the stability margin decreases gradually as $K_{pPLL}$ increases. The damping ratio of the dominate mode marked in green oval of Figure 7(a) is also shown in Figure 5(b). It can be seen that with the increase of $K_{pPLL}$, the damping of the dominant mode decreases, which may induce system oscillation/instability.

Figure 6 shows the dynamic response of the study system in PSCAD/EMTDC when the PLL gain $K_{pPLL}$ is step-changed from 5 to 100 at time $t=3s$. It can be observed that the system becomes unstable after the step-change of $K_{pPLL}$. This result consits with the result of Figure 5.

![Figure 6](image)

**Figure 6.** Dynamic response from PSCAD when $K_{pPLL}$ changes
In this section, the normalized participating factor [15] is used as a measure of the relative participation of each state variable with respect to different modes. With respect to the largest state-variable in the dominant mode of Figure 5(a), the normalized magnitudes of the participation factors are scaled. Figure 7 shows the comparison results of the participating factor when $K_{pPLL} = 10$ and $K_{pPLL} = 100$.

From the results, it can be seen that the participation factors of the PLL-related state variables ($v_{peccq}$, $\theta$ and $\omega$) are significantly increased when $K_{pPLL} = 100$ compared with those of $K_{pPLL} = 10$. Therefore, the PLL function would have higher impact on the small-signal stability of the system with larger PLL gains.

![Figure 7. Participation factor of the state variables of dominant mode when KpPLL changes](image)

**Figure 7.** Participation factor of the state variables of dominant mode when KpPLL changes

### 4.2. Impact of Proportional gain ($K_{pv}$) of AC voltage control

Initially, the study system operates at nominal operation point. Figure 8 evaluates the effects of the proportional gain $K_{pv}$ on the system eigenvalues when $K_{pv}$ varies from 0.1 to 5.

![Figure 8. (a) Loci of the eigenvalues when Kpv changes, (b) Damping of dominant mode when Kpv changes](image)

**Figure 8.** (a) Loci of the eigenvalues when Kpv changes, (b) Damping of dominant mode when Kpv changes
Figure 8(a) shows the loci of the eigenvalues when $K_{pv}$ changes. It can be seen that the acceptable maximum value of $K_{pv}$ is 2.834, which means the system will be unstable if $K_{pv}$ is bigger than 2.834. The damping of the dominant mode is shown in Figure 8(b). With the increase of $K_{pv}$, the damping of the dominant mode is decreasing to negative, and the instability of the system is reached when $K_{pv} > 2.834$.

To validate the influence of $K_{pv}$, the dynamic response of the study system from the PSCAD/EMTDC is presented in Figure 9 when $K_{pv}$ is step-changed from 0.5 to 5 at time $t=3s$. It can be observed that the system becomes unstable because of the step-change. This result agrees with the result of Figure 8.

![Figure 9. Dynamic response from PSCAD when Kpv changes](image)

4.3. Impact of Integral gain ($K_{iv}$) of AC voltage control

Initially, the study system operates at nominal operation point. Figure 10 evaluates the impact of the integral gain $K_{iv}$ on the system eigenvalues when $K_{iv}$ is increased from 1 to 250.

![Figure 10. (a) Loci of the eigenvalues when Kiv changes, (b) Damping of dominant mode when Kiv changes](image)

Figure 10(a) presents the loci of the eigenvalues when $K_{iv}$ changes, showing that the system can keep stable when $K_{iv} < 139$. The damping ratio of the dominant mode is also shown in Figure 10(b). It can be seen that with the increase of $K_{iv}$, the damping of the dominant mode decreases, which may induce system oscillation/instability.
To validate the impact of $K_{iv}$, the time-domain response of the study system from the PSCAD/EMTDC is presented in Figure 11. Initially the system operates under stable state until $K_{iv}$ is step-changed from 5 to 250 at time $t=3s$, illustrating that the system becomes unstable due to the step-change. This observation agrees with the result in Figure 10.

5. Conclusion

This paper develops a linearized small-signal dynamic model of a LCC-HVDC system with STATCOM at the inverter busbar, and validates its accuracy by comparing time-domain responses from small-signal model and PSCAD-based simulation results. Based on eigen-analysis, the system dynamic behaviors are investigated and the following conclusions are obtained:

The PLL gain can highly impact on stability of the study system, and a larger PLL gain is not preferred.

Larger values of the proportional gain of AC voltage controller of STATCOM may lead to lower damping of the dominant modes for the HVDC-STATCOM system.

Larger values of the integral gain of AC voltage controller of STATCOM is not preferable, which could induce the instability of the system.

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