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一种新的优化协调控制在轻型直流输电中的应用

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APPLICATION OF A NOVEL OPTIMAL COORDINATED CONTROL TO HVDC LIGHT

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ABSTRACT: HVDC Light is a new HVDC transmission system, based on Voltage Source Converters (VSC) and Pulse Width Modulation (PWM). The mathematical model of HVDC Light is established, an optimal coordinated control between the generator excitation and HVDC Light is proposed. The proposed controller is used to improve transient stability of the power system and to damp prolonged oscillation after a fault is cleared. Then the optimal coordinated control algorithm is applied to multi-machine power system with HVDC Light. The comparison is made between the proposed controller and independent controller for generator excitation and HVDC Light, the simulation results demonstrate that the proposed control strategy provides better damping characteristics.

KEY WORDS: Power system; HVDC Light; VSC; PWM; Coordinated control; Model

摘要：轻型直流输电是一种新型的直流传输技术，采用电压源型(VSC)换流站以及 PWM 控制技术。建立了轻型直流输电系统模型，提出一种在发电机励磁和轻型直流输电之间优化协调控制方法，用于改善系统暂态稳定和抑制系统故障后振荡。作为算例，该协调控制方法被用于含有轻型直流输电的多机系统，并将该优化协调控制与发电机励磁、轻型直流输电系统相互独立的控制做一比较，仿真结果表明，在系统大小扰动下，该控制能够给系统提供更好的阻尼特性。

关键词：电力系统；轻型直流输电；电压源型；脉宽调制；协调控制；模型

1　引言

Conventional HVDC transmission systems are built up with line commutated Current Source Converters (CSC)[1], with the appearance of high switching frequency and high power turn-off components, such as IGBT, IGCT[2-4], the application of VSC to the HVDC transmission is made possible. HVDC Light is a type of VSC based HVDC exactly, it is excellent for transmitting power to distant loads and feeding power from distant generation into network[5]. As in a VSC, the current can be switched off, there is no need for a network to commutate against, therefore, it has no risk of commutation failures when a voltage dip or waveform distortion has occurred in the AC system[6];On the other hand, HVDC Light needs no equipment for reactive power supply, such as static capacitors or synchronous rotating condensers, when used in a low short-circuit capacity power system, however, it is often needed for conventional HVDC.

Mathematical model of HVDC Light is established in this paper, mathematical equations in per unit form are derived in order to integrate them into differential algebraic equation of power system. The optimal coordinated control between generators and HVDC Light is designed based on the linearized equation of the whole system, and optimal control theory is applied. The proposed control scheme is used to damp the oscillation of power system during large disturbance. Multi-machine system is simulated to observe the damping characteristics of the proposed control strategy. The results with independent control [7-10] and proposed control are compared, and the simulation results demonstrate the proposed control strategy provides better damping features than independent control.

2 MATHEMATICAL MODEL

In n-machine power system, HVDC Light terminals can be extracted as active nodes from network, shown in Fig.1[1,11-12], where injecting current to the system is $-\dot{I}_1$ and $\dot{I}_2$, $\dot{V}_R$, $\dot{V}_N$ are bridge voltage of two converters, C_{dc}, V_{dc} denote capacitor value and DC link voltage, x_1, x_2 are equivalent commutation reactance of two sides. In the course of model establishment, simultaneous state of equivalent commutation reactance will be neglected, however, the dynamics of C_{dc} is described by differential equations. These simplifications are enough for the investigation of the influence between AC and DC system..

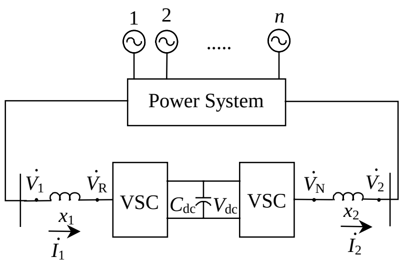

图 1 有 HVDC Light 的电力系统示意图

Fig.1 Diagram of power system with HVDC Light

If the sinusoidal pulse width modulation (SPWM) control scheme is adopted and only fundamental frequency components under balanced operation conditions are considered, the output voltage of the two converters can be represented by two phasors:

$$\dot{V}_R = \frac{1}{\sqrt{2}} m_1 V_{dc} \angle \theta_1 \tag{1}$$

$$\dot{V}_N = \frac{1}{\sqrt{2}} m_2 V_{dc} \angle \theta_2 \tag{2}$$

Where m_1 and m_2 denote the modulation index of the rectifier and inverter, θ_1 and θ_2 are the phase angles of the control wave.

When quasi-steady state is considered, the relationship between voltage and current on two sides of the valves can be represented by algebraic equation, moreover, the equation can be written in the form of single-phase equivalent since the quasi-static condition is assumed, however, the equation on the DC side of the converters is differential, so the equations about the HVDC Light can be written as

$$\dot{V}_1 = \mathrm{j}x_1\dot{I}_1 + \dot{V}_R \tag{3}$$

$$\dot{V}_2 = -\mathrm{j}x_2\dot{I}_2 + \dot{V}_N \tag{4}$$

$$C_{dc}V_{dc}\dot{V}_{dc} = R_e(\dot{V}_R\hat{\dot{I}}_1 - \dot{V}_N\hat{\dot{I}}_2) \tag{5}$$

Where x_1 and x_2 denote the equivalent commutation reactance of rectifier and inverter.

The variables in the above equation (1)~(5) are actual value referred to the DC capacitor side. It must be transferred to the form of per unit in order to integrate them into the DA (Differential-Algebraic) equations of power system. As we know, when the DC voltage reaches its maxim value $V_{dc\,max}$ and m_1, m_2 equal to one, the output voltage of converters also reaches its maxim value

$$V_{R\,max} = \frac{1}{\sqrt{2}} V_{dc\,max} \tag{6}$$

$$V_{N\,max} = \frac{1}{\sqrt{2}} V_{dc\,max} \tag{7}$$

If we let

$$\frac{1}{\sqrt{2}} V_{dc\,max} = k_1 V_{N1} = k_2 V_{N2} \tag{8}$$

Where V_{N1},V_{N2}represent the nominal voltage of two sides where HVDC Light system is connected, k_1, k_2 are coefficients. From (8), the following (9)、(10) can be get

$$V_{N1} = \frac{1}{\sqrt{2}k_1} V_{dc\,max} \tag{9}$$

$$V_{N2} = \frac{1}{\sqrt{2}k_2} V_{dc\,max} \tag{10}$$

When V_{dcmax} is chosen as base value of DC voltage and network's power rating S_r as the power base value [12], Equation(1)、(2) can be written in per unit form as Equation(11)、(12)

$$\dot{V}_{R*} = k_1 m_1 V_{dc*} \angle \theta_1 \tag{11}$$

$$\dot{V}_{N*} = k_2 m_2 V_{dc*} \angle \theta_2 \tag{12}$$

Where the subscript asterisk * denotes corresponding per unit values.

For the Equation (5), after dividing both sides by the complex power base value S_r, LHS of Equation(5) becomes

$$C_{\mathrm{dc}}\frac{V_{\mathrm{dc\,max}}^{2}}{S_r}\frac{V_{\mathrm{dc}}}{V_{\mathrm{dc\,max}}}\frac{\mathrm{d}(V_{\mathrm{dc}}/V_{\mathrm{dc\,max}})}{\mathrm{d}t}= C_{\mathrm{dc}}\frac{V_{\mathrm{dc\,max}}^{2}}{S_r}V_{\mathrm{dc*}}\frac{\mathrm{d}V_{\mathrm{dc*}}}{\mathrm{d}t} \qquad (13)$$

RHS of Equation (5):

$$R_e(\dot{V}_{\mathrm{R}}\hat{\dot{I}}_1-\dot{V}_{\mathrm{N}}\hat{\dot{I}}_2)/S_r=R_e(\dot{V}_{\mathrm{R*}}\hat{\dot{I}}_{1*}-\dot{V}_{\mathrm{N*}}\hat{\dot{I}}_{2*}) \qquad (14)$$

So Equation (5) per unit form:

$$T_{\mathrm{dc}}V_{\mathrm{dc*}}\frac{\mathrm{d}V_{\mathrm{dc*}}}{\mathrm{d}t}=R_e(\dot{V}_{\mathrm{R*}}\hat{\dot{I}}_{1*}-\dot{V}_{\mathrm{N*}}\hat{\dot{I}}_{2*}) \qquad (15)$$

Where T_{dc} is introduced as a time constant of the HVDC, $T_{\mathrm{dc}}=C_{\mathrm{dc}}V_{\mathrm{dc\,max}}^{2}/S_r$, R_e is real part.

Above algebraic equations (3)、(4) should be written in x-y coordinate so as to integrate the Differential-Algebraic (DA) equations of power system as shown in Equation(16)、(17)

$$\dot{\boldsymbol{x}}=f(\boldsymbol{x},\boldsymbol{V}) \qquad (16)$$

$$\boldsymbol{YV}=\boldsymbol{I} \qquad (17)$$

Where $\boldsymbol{x}$ is state vectors of power system, $\boldsymbol{V}$ is system voltage, $\boldsymbol{Y}$ is admittance matrix, and $\boldsymbol{I}$ is node injecting current.

By substituting Equation(11)、(12) into Equation (3)、(4) and defaulting the per unit subscription asterisk, equation (3)、(4) can be written in per unit form as Equation (18)、(19) respectively.

$$\begin{bmatrix}V_{1x}\\V_{1y}\end{bmatrix}=\begin{bmatrix}0&-x_1\\x_1&0\end{bmatrix}\begin{bmatrix}I_{1x}\\I_{1y}\end{bmatrix}+\begin{bmatrix}k_1m_1\cos\theta_1\\k_1m_1\sin\theta_1\end{bmatrix}V_{\mathrm{dc}} \qquad (18)$$

$$\begin{bmatrix}V_{2x}\\V_{2y}\end{bmatrix}=\begin{bmatrix}0&x_2\\-x_2&0\end{bmatrix}\begin{bmatrix}I_{2x}\\I_{2y}\end{bmatrix}+\begin{bmatrix}k_2m_2\cos\theta_2\\k_2m_2\sin\theta_2\end{bmatrix}V_{\mathrm{dc}} \qquad (19)$$

The equation (13) can be written similarly as

$$\frac{\mathrm{d}V_{\mathrm{dc}}}{\mathrm{d}t}=\frac{k_1m_1(\cos\theta_1V_{1y}-\sin\theta_1V_{1x})}{T_{\mathrm{dc}}x_1}+\frac{k_2m_2(\cos\theta_2V_{2y}-\sin\theta_2V_{2x})}{T_{\mathrm{dc}}x_2} \qquad (20)$$

So the dynamics of HVDC Light in multi-machine power system can be descripted by Equation(18)、(19)、(20).

From Equation (18) and (19), equation of node injection current can be got

$$\begin{bmatrix}I_{1x}\\I_{1y}\end{bmatrix}=\begin{bmatrix}0&1/x_1\\-1/x_1&0\end{bmatrix}\begin{bmatrix}V_{1x}\\V_{1y}\end{bmatrix}+\begin{bmatrix}-k_1m_1\sin\theta_1/x_1\\k_1m_1\cos\theta_1/x_1\end{bmatrix}V_{\mathrm{dc}} \qquad (21)$$

$$\begin{bmatrix}I_{2x}\\I_{2y}\end{bmatrix}=\begin{bmatrix}0&-1/x_2\\1/x_2&0\end{bmatrix}\begin{bmatrix}V_{2x}\\V_{2y}\end{bmatrix}+\begin{bmatrix}k_2m_2\sin\theta_2/x_2\\-k_2m_2\cos\theta_2/x_2\end{bmatrix}V_{\mathrm{dc}} \qquad (22)$$

The HVDC Light can be seen as a controllable current sources after Equation(21)、(22) are substituted into algebraic equation (17), and amending corresponding elements in admittance matrix $\boldsymbol{Y}$.

After the injection current expressions are derived, the equivalent circuit of Fig.1 is shown as Fig.2.

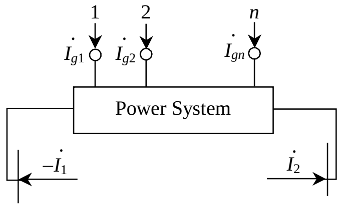

图 2　图 1 的等值电路

Fig.2　Equivalent circuit of Fig.1

In Fig.2, $-\dot{I}_1$ and $\dot{I}_2$ denote currents injected into system by HVDC Light, they are represented by Equation (21)、(22). $\dot{I}_{g1}$, $\dot{I}_{g2}$, …… , $\dot{I}_{gn}$ are current injected by generators.

3　MODELING HVDC LIGHT INTO MULTI-MACHINE POWER SYSTEM

In this section, injection current equations of generators in power system with HVDC Light are derived,which will be used in later sections.

After two terminals of HVDC are regarded as two active nodes and equivalent injection current method are applied, at the same time, the passive nodes are eliminated, the circuit equation of network is

$$\begin{bmatrix}\boldsymbol{Y}_{11}&\boldsymbol{Y}_{12}&\boldsymbol{Y}_{13}\\\boldsymbol{Y}_{21}&Y_{22}&Y_{23}\\\boldsymbol{Y}_{31}&Y_{32}&Y_{33}\end{bmatrix}\begin{bmatrix}\dot{\boldsymbol{V}}_g\\\dot{V}_1\\\dot{V}_2\end{bmatrix}=\begin{bmatrix}\dot{\boldsymbol{I}}_g\\-\dot{I}_1\\\dot{I}_2\end{bmatrix} \qquad (23)$$

Where $\dot{\boldsymbol{I}}_g=[\dot{I}_{g1},\dot{I}_{g2},\ldots\dot{I}_{gn}]^{\mathrm{T}}$ is current vector of generator, $\dot{\boldsymbol{V}}_g=[\dot{V}_{g1},\dot{V}_{g2},\ldots\dot{V}_{gn}]^{\mathrm{T}}$ is terminal voltage vector of generator, n is number of machines in the network.

From Equation(3)、(4), following equations can be deduced

$$\dot{I}_1=\frac{\dot{V}_1-\dot{V}_{\mathrm{R}}}{\mathrm{j}x_1} \qquad (24)$$

$$\dot{I}_2=\frac{\dot{V}_{\mathrm{N}}-\dot{V}_2}{\mathrm{j}x_2} \qquad (25)$$

Equation (24)、(25) are substituted into Equation(23), then eliminating $\dot{V}_1$, $\dot{V}_2$, following expression can be got

$$\dot{\boldsymbol{K}}\dot{V}_g + \dot{\boldsymbol{A}}_{\mathrm{R}}\dot{V}_{\mathrm{R}} + \dot{\boldsymbol{A}}_{\mathrm{N}}\dot{V}_{\mathrm{N}} = \dot{\boldsymbol{I}}_g \tag{26}$$

where

$$\dot{\boldsymbol{K}} = \boldsymbol{Y}_{11} + \frac{\boldsymbol{Y}_{12}Y_{23}\boldsymbol{Y}_{31}}{\boldsymbol{Y}_P} - \frac{\boldsymbol{Y}_{12}}{\boldsymbol{Y}_P}(Y_{33} + \frac{1}{\mathrm{j}x_2})\boldsymbol{Y}_{21} + \frac{\boldsymbol{Y}_{13}Y_{32}\boldsymbol{Y}_{21}}{\boldsymbol{Y}_P} - \frac{\boldsymbol{Y}_{13}}{\boldsymbol{Y}_P}(Y_{22} - \frac{1}{\mathrm{j}x_1})\boldsymbol{Y}_{31}$$

$$\dot{\boldsymbol{A}}_{\mathrm{R}} = -\frac{\boldsymbol{Y}_{12}}{Y_P}(Y_{33} + \frac{1}{\mathrm{j}x_2})\frac{1}{\mathrm{j}x_1} + \frac{\boldsymbol{Y}_{13}Y_{32}}{Y_P\,\mathrm{j}x_1}$$

$$\dot{\boldsymbol{A}}_{\mathrm{N}} = -\frac{\boldsymbol{Y}_{12}Y_{23}}{Y_P\,\mathrm{j}x_2} + \frac{\boldsymbol{Y}_{13}(Y_{22} - \frac{1}{\mathrm{j}x_1})}{Y_P\,\mathrm{j}x_2}$$

$$Y_P = (Y_{22} - \frac{1}{\mathrm{j}x_1})(Y_{33} + \frac{1}{\mathrm{j}x_2}) - Y_{23}Y_{32}$$

$\dot{V}_{\mathrm{R}}, \dot{V}_{\mathrm{N}}$ are output AC voltage of converters(Fig.1).

If three-order reduced model[13-14] is used for generator, state equations of generators can be expressed as following:

$$\mathrm{d}\boldsymbol{\delta}/\mathrm{d}t = \omega_0(\boldsymbol{\omega} - \mathbf{1}) \tag{27}$$

$$\mathrm{d}\boldsymbol{\omega}/\mathrm{d}t = \boldsymbol{M}^{-1}(\boldsymbol{T}_m - \boldsymbol{T}_e - \boldsymbol{D}\Delta\boldsymbol{\omega}) \tag{28}$$

$$\mathrm{d}\boldsymbol{e}'_q/\mathrm{d}t = \boldsymbol{T}'^{-1}_{d0}[\boldsymbol{E}_{fd} - \boldsymbol{e}'_q - (\boldsymbol{x}_d - \boldsymbol{x}'_d)\boldsymbol{i}_d] \tag{29}$$

where

$\boldsymbol{\delta} = [\delta_1, \delta_2, ..., \delta_n]^{\mathrm{T}}$,

$\boldsymbol{\omega} = [\omega_1, \omega_2, ..., \omega_n]^{\mathrm{T}}$,

$\boldsymbol{T}_m = [T_{m1}, T_{m2}, ..., T_{mn}]^{\mathrm{T}}$,

$\boldsymbol{T}_{\mathrm{e}} = [T_{e1}, T_{e2}, ..., T_{en}]^{\mathrm{T}}$,

$\Delta\boldsymbol{\omega} = [\Delta\omega_1, \Delta\omega_2, ..., \Delta\omega_n]^{\mathrm{T}}$,

$\boldsymbol{e}'_q = [e'_{q1}, e'_{q2}, ..., e'_{qn}]^{\mathrm{T}}$,

$\boldsymbol{E}_{fd} = [E_{fd1}, E_{fd2}, ..., E_{fdn}]^{\mathrm{T}}$,

$\boldsymbol{i}_d = [i_{d1}, i_{d2}, ..., i_{dn}]^{\mathrm{T}}$,

$T_{ei} = e'_{qi}i_{qi} + (x_{qi} - x'_{di})i_{di}i_{qi}$,

$\boldsymbol{M} = \mathrm{diag}(M_1, M_2, ..., M_n)$,

$\boldsymbol{D} = \mathrm{diag}(D_1, D_2, ..., D_n)$,

$\boldsymbol{T}'_{d0} = \mathrm{diag}(T'_{d01}, T'_{d02}, ..., T'_{d0n})$,

$\boldsymbol{x}_d = \mathrm{diag}(x_{d1}, x_{d2}, ..., x_{dn})$,

$\boldsymbol{x}'_d = \mathrm{diag}(x'_{d1}, x'_{d2}, ..., x'_{dn})$

The terminal voltage of the generator can be expressed in x-y coordinates as following[13].

$$\dot{\boldsymbol{V}}_g = \dot{\boldsymbol{e}}'_q - \mathrm{j}\boldsymbol{x}'_d\dot{\boldsymbol{I}}_g - \mathrm{j}(\boldsymbol{x}_q - \boldsymbol{x}'_d)\dot{\boldsymbol{I}}_q \tag{30}$$

where $\dot{\boldsymbol{I}}_g = [\dot{I}_{g1}, \dot{I}_{g2}, ..., \dot{I}_{gn}]^{\mathrm{T}}$, $\dot{\boldsymbol{I}}_q = [\dot{I}_{q1}, \dot{I}_{q2}, ..., \dot{I}_{qn}]^{\mathrm{T}}$.

Substituting (30) into (26), the expression of $\dot{\boldsymbol{I}}_g$ written in x-y coordinates:

$$\dot{\boldsymbol{I}}_g = \dot{\boldsymbol{K}}_d[\dot{\boldsymbol{e}}'_q - \mathrm{j}(\boldsymbol{x}_q - \boldsymbol{x}'_d)\dot{\boldsymbol{I}}_q + \dot{\boldsymbol{K}}_{\mathrm{R}}\dot{V}_{\mathrm{R}} + \dot{\boldsymbol{K}}_{\mathrm{N}}\dot{V}_{\mathrm{N}}] \tag{31}$$

where $\dot{\boldsymbol{K}}_d$, $\dot{\boldsymbol{K}}_R$, $\dot{\boldsymbol{K}}_N$ is constant complex matrix:

$$\dot{\boldsymbol{K}}_d = (\dot{\boldsymbol{K}}^{-1} + \mathrm{j}\boldsymbol{x}'_d)^{-1}$$

$$\dot{\boldsymbol{K}}_R = \dot{\boldsymbol{K}}^{-1}\dot{\boldsymbol{A}}_R$$

$$\dot{\boldsymbol{K}}_N = \dot{\boldsymbol{K}}^{-1}\dot{\boldsymbol{A}}_N$$

$$\dot{V}_R = V_R\mathrm{e}^{\mathrm{j}\theta_1}$$

$$\dot{V}_N = V_N\mathrm{e}^{\mathrm{j}\theta_2}$$

From equation (31), the following (32) can be got:

$$\dot{I}_{gi} = \sum_{k=1}^{n} K_{dik}[e'_{qk}\mathrm{e}^{\mathrm{j}(\delta_k + \beta_{dik})} + (x_{qk} - x'_{dk})i_{qk}\mathrm{e}^{\mathrm{j}(\delta_k - 90^\circ + \beta_{dik})} + K_{Rk}V_R\mathrm{e}^{\mathrm{j}(\theta_1 + \beta_{Rk} + \beta_{dik})} + K_{Nk}V_N\mathrm{e}^{\mathrm{j}(\theta_2 + \beta_{Nk} + \beta_{dik})}] \tag{32}$$

Where

$\dot{K}_{dik} = K_{dik}\mathrm{e}^{\mathrm{j}\beta_{dik}}$, $\dot{K}_{Rk} = K_{Rk}\mathrm{e}^{\mathrm{j}\beta_{Rk}}$, $\dot{K}_{Nk} = K_{Nk}\mathrm{e}^{\mathrm{j}\beta_{Nk}}$, $i = 1, 2, ..., n$

Equation(32) is expressed on x-y coordinates, applying the conversion(33)、(34) to equation(32) in d_i-q_i coordinates, we get Equation (35)、(36)

$$\boldsymbol{i}_{dq} = \boldsymbol{T}\boldsymbol{I}_g \tag{33}$$

$$\boldsymbol{V}_{dq} = \boldsymbol{T}\boldsymbol{V}_g \tag{34}$$

where

$\boldsymbol{i}_{dq} = [i_{d1}, i_{q1}, i_{d2}, i_{q2}, ..., i_{dn}, i_{qn}]^{\mathrm{T}}$,

$\boldsymbol{I}_g = [I_{gx1}, I_{gy1}, I_{gx2}, I_{gy2}, ...I_{gn1}, I_{gn2}]^{\mathrm{T}}$,

$\boldsymbol{V}_{dq} = [V_{d1}, V_{q1}, V_{d2}, V_{q2}, ..., V_{dn}, V_{qn}]^{\mathrm{T}}$,

$\boldsymbol{V}_g = [V_{gx1}, V_{gy1}, V_{gx2}, V_{gy2}, ..., V_{gxn}, V_{gyn}]^{\mathrm{T}}$,

$\boldsymbol{T} = \mathrm{diag}(T_1, T_2, ...T_n)$, $\boldsymbol{T}_i = \begin{bmatrix} \sin\delta_i & -\cos\delta_i \\ \cos\delta_i & \sin\delta_i \end{bmatrix}$,

$i = 1, 2, ...n$

$\boldsymbol{T}$ is the transformation matrix, δ_i is the power angle of No. i machine.

$$i_{di} = \sum_{k=1}^{n} K_{dik}[-e'_{qk}\sin\delta_{ikd} + (x_{qk} - x'_{dk})i_{qk}\cos\delta_{ikd} + K_{Rk}V_R\sin\theta_{Rk} + K_{Nk}V_N\sin\theta_{Nk}] \tag{35}$$

$$i_{qi} = \sum_{k=1}^{n} K_{dik}[e'_{qk}\cos\delta_{ikd} + (x_{qk} - x'_{dk})i_{qk}\sin\delta_{ikd} + K_{Rk}V_R\cos\theta_{Rk} + K_{Nk}V_N\cos\theta_{Nk}] \tag{36}$$

where

$\delta_{ikd}=\delta_k+\beta_{dik}-\delta_i$, $\theta_{Rk}=\delta_i-(\theta_1+\beta_{Rk}+\beta_{dik})$, $\theta_{Nk}=\delta_i-(\theta_2+\beta_{Nk}+\beta_{dik})$, $i=1,2,...n$

Equation (35)、(36) are generator current represented in d_i-q_i coordinates.

4　COORDINATED CONTROL DESIGN

4.1　Linearization of system

The state equation of multi-machine including HVDC system is rewritten as following:

$$\mathrm{d}\boldsymbol{\delta}/\mathrm{d}t=\omega_0(\boldsymbol{\omega}-\mathbf{1}) \tag{37}$$

$$\mathrm{d}\boldsymbol{\omega}/\mathrm{d}t=\boldsymbol{M}^{-1}(\boldsymbol{T}_m-\boldsymbol{T}_e-\boldsymbol{D}\Delta\boldsymbol{\omega}) \tag{38}$$

$$\mathrm{d}\boldsymbol{e}'_q/\mathrm{d}t=\boldsymbol{T}'^{-1}_{d0}[\boldsymbol{E}_{fd}-\boldsymbol{e}'_q-(\boldsymbol{x}_d-\boldsymbol{x}'_d)\boldsymbol{i}_d] \tag{39}$$

$$\frac{\mathrm{d}V_{\mathrm{dc}}}{\mathrm{d}t}=\frac{k_1m_1(\cos\theta_1V_{1y}-\sin\theta_1V_{1x})}{T_{\mathrm{dc}}x_1}+\frac{k_2m_2(\cos\theta_2V_{2y}-\sin\theta_2V_{2x})}{T_{\mathrm{dc}}x_2} \tag{40}$$

where $$T_{ei}=e'_{qi}i_{qi}+(x_{qi}-x'_{di})i_{di}i_{qi} \tag{41}$$

Equation(37)~(39) and (41) will be linearized as following

$$\Delta\dot{\boldsymbol{\delta}}=\omega_0\Delta\boldsymbol{\omega} \tag{42}$$

$$\Delta\dot{\boldsymbol{\omega}}=\boldsymbol{M}^{-1}(\Delta\boldsymbol{T}_m-\Delta\boldsymbol{T}_e-\boldsymbol{D}\Delta\boldsymbol{\omega}) \tag{43}$$

$$\Delta\dot{\boldsymbol{e}}'_q=\boldsymbol{T}'^{-1}_{d0}(\Delta\boldsymbol{E}_{fd}-\Delta e'_q-(\boldsymbol{x}_d-\boldsymbol{x}'_d)\Delta\boldsymbol{i}_d) \tag{44}$$

$$\Delta T_{ei}=i_{qi0}\Delta e'_{qi}+e'_{qi0}\Delta i_{qi}+(x_{qi}-x'_{di})i_{di0}\Delta i_{qi}+(x_{qi}-x'_{di})i_{qi0}\Delta i_{di} \tag{45}$$

Linearization of Equation(40) needs some manipulation, briefly, linearization expression of Equation(40) can be got as following Equation(46) if considering Equation(26) and Equation(30)、(35)、(36) simultaneously

$$\Delta\dot{V}_{\mathrm{dc}}=\boldsymbol{K}_\delta\Delta\boldsymbol{\delta}+\boldsymbol{K}_{e'_q}\Delta\boldsymbol{e}'_q+K_{\mathrm{dc}}\Delta V_{\mathrm{dc}}+K_{m_1}\Delta m_1+K_{\theta_1}\Delta\theta_1+K_{m_2}\Delta m_2+K_{\theta_2}\Delta\theta_2 \tag{46}$$

where

$\Delta\boldsymbol{\delta}=[\Delta\delta_1,\Delta\delta_2,...,\Delta\delta_n]^{\mathrm{T}}$, $\Delta\boldsymbol{e}'_q=[\Delta e'_{q1},\Delta e'_{q2},...,\Delta e'_{qn}]^{\mathrm{T}}$

Substituting Equation (1)、(2) into Equation(35)、(36) and linearizing Equation(35)、(36)

$$\Delta\boldsymbol{i}_d=\boldsymbol{a}_\delta\Delta\boldsymbol{\delta}+\boldsymbol{a}_{e'_q}\Delta\boldsymbol{e}'_q+\boldsymbol{a}_{\mathrm{dc}}\Delta V_{\mathrm{dc}}+\boldsymbol{a}_{m_1}\Delta m_1+\boldsymbol{a}_{\theta_1}\Delta\theta_1+\boldsymbol{a}_{m_2}\Delta m_2+\boldsymbol{a}_{\theta_2}\Delta\theta_2 \tag{47}$$

$$\Delta\boldsymbol{i}_q=\boldsymbol{b}_\delta\Delta\boldsymbol{\delta}+\boldsymbol{b}_{e'_q}\Delta\boldsymbol{e}'_q+\boldsymbol{b}_{\mathrm{dc}}\Delta V_{\mathrm{dc}}+\boldsymbol{b}_{m_1}\Delta m_1+\boldsymbol{b}_{\theta_1}\Delta\theta_1+\boldsymbol{b}_{m_2}\Delta m_2+\boldsymbol{b}_{\theta_2}\Delta\theta_2 \tag{48}$$

Then Equation (47)、(48) are substituted into Equation (43)、(44) and (45)

$$\Delta\dot{\boldsymbol{\omega}}=\boldsymbol{M}^{-1}\Delta\boldsymbol{T}_m+\boldsymbol{A}_\delta\Delta\boldsymbol{\delta}+\boldsymbol{A}_{e'_q}\Delta\boldsymbol{e}'_q+\boldsymbol{A}_{\mathrm{dc}}\Delta V_{\mathrm{dc}}+\boldsymbol{A}_{m_1}\Delta m_1+\boldsymbol{A}_{\theta_1}\Delta\theta_1+\boldsymbol{A}_{m_2}\Delta m_2+\boldsymbol{A}_{\theta_2}\Delta\theta_2-\boldsymbol{M}^{-1}\boldsymbol{D}\Delta\boldsymbol{\omega} \tag{49}$$

$$\Delta\dot{\boldsymbol{e}}'_q=\boldsymbol{T}'^{-1}_{d0}\Delta\boldsymbol{E}_{fd}+\boldsymbol{B}_\delta\Delta\boldsymbol{\delta}+\boldsymbol{B}_{e'_q}\Delta\boldsymbol{e}'_q+\boldsymbol{B}_{\mathrm{dc}}\Delta V_{\mathrm{dc}}+\boldsymbol{B}_{m_1}\Delta m_1+\boldsymbol{B}_{\theta_1}\Delta\theta_1+\boldsymbol{B}_{m_2}\Delta m_2+\boldsymbol{B}_{\theta_2}\Delta\theta_2 \tag{50}$$

Neglecting the change of power of priming mover $\Delta\boldsymbol{T}_m$, Synthesizing Equation(42)、(46)、(49)、(50)we have

$$\begin{bmatrix}\Delta\dot{\boldsymbol{x}}\\ \Delta\dot{V}_{\mathrm{dc}}\end{bmatrix}=\begin{bmatrix}\boldsymbol{A}_1 & \boldsymbol{A}_2\\ \boldsymbol{A}_3 & K_{\mathrm{dc}}\end{bmatrix}\begin{bmatrix}\Delta\boldsymbol{x}\\ \Delta V_{\mathrm{dc}}\end{bmatrix}+\begin{bmatrix}\boldsymbol{B}_1 & \boldsymbol{B}_2\\ \mathbf{0} & \boldsymbol{B}_3\end{bmatrix}\begin{bmatrix}\Delta\boldsymbol{u}_1\\ \Delta\boldsymbol{u}_2\end{bmatrix} \tag{51}$$

where

$\Delta\boldsymbol{x}=[\Delta\boldsymbol{\delta},\Delta\boldsymbol{\omega},\Delta\boldsymbol{e}'_q]^{\mathrm{T}}$, $\Delta\boldsymbol{u}_1=\Delta\boldsymbol{E}_{fd}$,

$\Delta\boldsymbol{u}_2=[\Delta m_1,\Delta\theta_1,\Delta m_2,\Delta\theta_2]^{\mathrm{T}}$, $\boldsymbol{A}_1=\begin{bmatrix}\mathbf{0} & \omega_0\boldsymbol{I} & \mathbf{0}\\ \boldsymbol{A}_\delta & -\boldsymbol{M}^{-1}\boldsymbol{D} & \boldsymbol{A}_{e'_q}\\ \boldsymbol{B}_\delta & \mathbf{0} & \boldsymbol{B}_{e'_q}\end{bmatrix}$,

$\boldsymbol{A}_2=\begin{bmatrix}\mathbf{0}\\ \boldsymbol{A}_{\mathrm{dc}}\\ \boldsymbol{B}_{\mathrm{dc}}\end{bmatrix}$, $\boldsymbol{A}_3=[\boldsymbol{K}_\delta\quad 0\quad \boldsymbol{K}_{e'_q}]$, $\boldsymbol{B}_1=\begin{bmatrix}\mathbf{0}\\ \mathbf{0}\\ \boldsymbol{T}'^{-1}_{d0}\end{bmatrix}$,

$\boldsymbol{B}_2=\begin{bmatrix}\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \boldsymbol{A}_{m_1} & \boldsymbol{A}_{\theta_1} & \boldsymbol{A}_{m_2} & \boldsymbol{A}_{\theta_2}\\ \boldsymbol{B}_{m_1} & \boldsymbol{B}_{\theta_1} & \boldsymbol{B}_{m_2} & \boldsymbol{B}_{\theta_2}\end{bmatrix}$, $\boldsymbol{B}_3=[K_{m_1}\quad K_{\theta_1}\quad K_{m_2}\quad K_{\theta_2}]$

Equation (51) is the linearized expression of the whole system.

4.2　Optimal coordinated control design

The proposed control scheme is based on linearized expression (51), let

$\Delta\boldsymbol{X}=\begin{bmatrix}\Delta\boldsymbol{x}\\ \Delta V_{\mathrm{dc}}\end{bmatrix}$, $\boldsymbol{A}=\begin{bmatrix}\boldsymbol{A}_1 & \boldsymbol{A}_2\\ \boldsymbol{A}_3 & K_{\mathrm{dc}}\end{bmatrix}$, $\boldsymbol{B}=\begin{bmatrix}\boldsymbol{B}_1 & \boldsymbol{B}_2\\ \mathbf{0} & \boldsymbol{B}_3\end{bmatrix}$,

$\Delta\boldsymbol{u}=\begin{bmatrix}\Delta\boldsymbol{u}_1\\ \Delta\boldsymbol{u}_2\end{bmatrix}$, Equation (51) becomes

$$\Delta\dot{\boldsymbol{X}}=\boldsymbol{A}\Delta\boldsymbol{X}+\boldsymbol{B}\Delta\boldsymbol{u} \tag{52}$$

Based on linear optimal control theory, for the performance index

$$J=\frac{1}{2}\int_0^\infty(\Delta\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Q}\Delta\boldsymbol{X}+\Delta\boldsymbol{u}^{\mathrm{T}}\boldsymbol{R}\Delta\boldsymbol{u})\mathrm{d}t \tag{53}$$

where $\boldsymbol{Q}$, $\boldsymbol{R}$ are weight matrix.

The optimal control law is

$$\Delta \boldsymbol{u} = -\boldsymbol{K}\Delta \boldsymbol{X} \tag{54}$$

and

$$\boldsymbol{K} = \boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} \tag{55}$$

where $\boldsymbol{P}$ is the solution of the Riccati equation

$$\boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} - \boldsymbol{P}\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{Q} = \boldsymbol{0} \tag{56}$$

5　SIMULATION

5.1　Simulation Conditions

A case of three-machine power system with HVDC Light connected is studied (Fig.3), where L_1, L_2 represent load, and load is simulated with impedance.

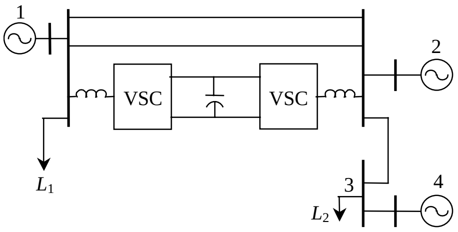

图 3　有 HVDC Light 的 3 机系统

Fig.3　Three-machine system with HVDC Light

In the simulation, two disturbance scenarios are tested:

Case 1:A three-phase fault of 0.1s duration is assumed to occur at 0.5s at node 3.Simulation results with the proposed controller are shown in Fig.4~Fig.7.

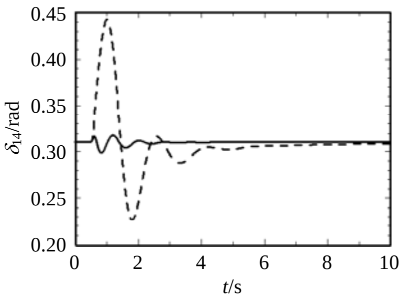

图 4　第一种情况下 1 号机对 4 号机相对功角

Fig.4　Response of No.1 machine rotor angle respect to No.4 machine for case 1 disturbance

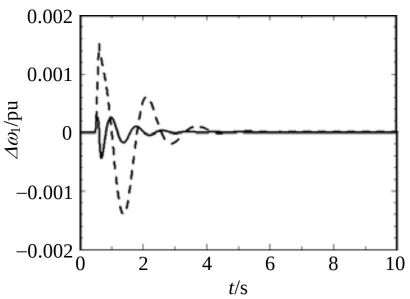

图 5　第一种情况下 1 号机角频率变化

Fig.5　Response of No.1 machine speed for case 1 disturbance

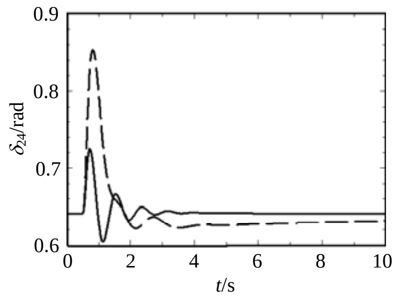

图 6　第一种情况下 2 号机对 4 号机相对功角

Fig.6　Response of No.2 machine rotor angle respect to No.4 machine for case 1 disturbance

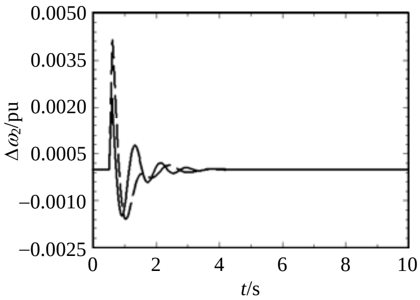

图 7　第一种情况下 2 号机角频率变化

Fig.7　Response of No.2 machine speed for case 1 disturbance

Case 2: 5% step in the power of No.1 machine, Simulation results with the proposed controller are shown in Fig.8~Fig.10.

The comparison is made between the proposed coordinated control and independent control for generators and HVDC Light respectively.

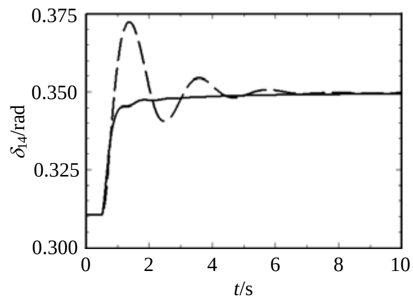

图 8　第二种情况下 1 号机对 4 号机相对功角

Fig.8　Response of No.1 machine Rotor angle respect to No.4 machine for case 2 disturbance

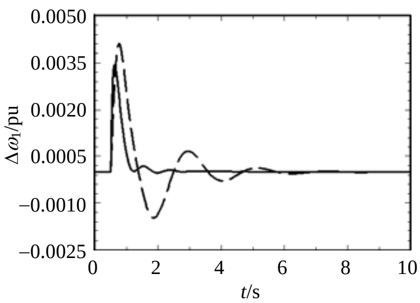

图 9　第二种情况下 1 号机角频率变化

Fig.9　Response of No.1 machine speed for case 2 disturbance

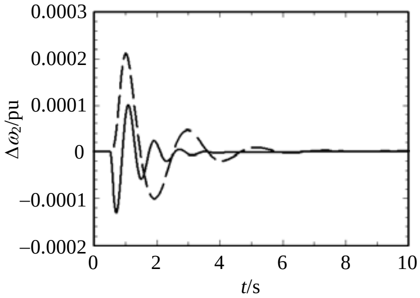

图 10　第二种情况下 2 号机角频率变化

Fig.10　Response of No.2 machine speed for case 2 disturbance

5.2　Simulation Results

Response with the proposed controller is shown in Fig.4~Fig.10 (real line). Dash line is the result of independent control, where LOEC is used for generators, and HVDC Light adopts PI regulation[6-9,15]. From simulation results, it can be observed that proposed control scheme provide better damping characteristics during large disturbance of power system.

The proposed coordinated control scheme is investigated in a more complicated four-machine power system shown in following Fig.11.In Fig11, HVDC light is connected between node 4 and node 5,where HVDC Light is replaced by corresponding injection current $-\dot{I}_1$ and $\dot{I}_2$, and No 8 machine represents infinite bus system.

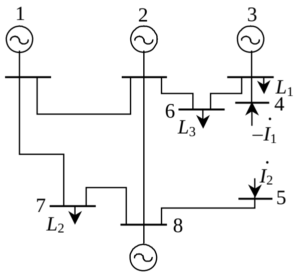

图 11　有 HVDC Light 的 4 机系统

Fig.11　Four-machine system with HVDC Light

Different from the former, AVR+PSS will be adopted by generator excitation control. It is assumed that a three-phase short circuit fault occurs at node 1.Simulation results are shown in Fig.12~Fig16.

In Fig.12~16, real line is the response waves with proposed coordinated control, dashed lines represent the independent control for generators and HVDC Light, where AVR+PSS is used in generator and general PI controller is adopted in HVDC Light.

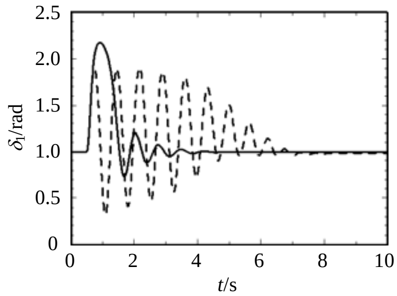

图 12　1 号机功角响应

Fig.12　Response of No.1 machine Rotor angle

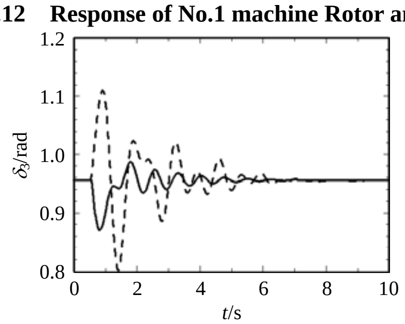

图 13　3 号机功角响应

Fig.13　Response of No.3 machine Rotor angle

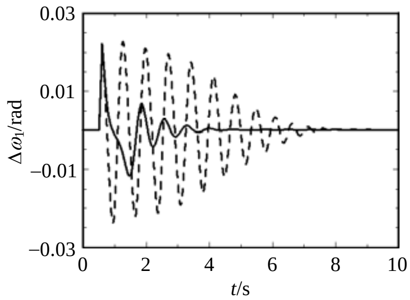

图 14　1 号机角频率变化

Fig.14　Response of No.1 machine speed

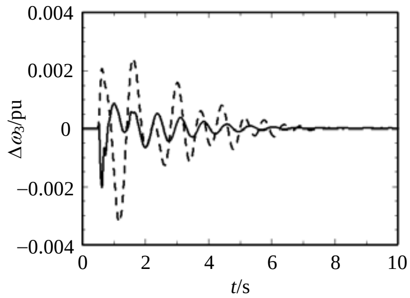

图 15　3 号机角频率变化

Fig.15　Response of No.3 machine speed

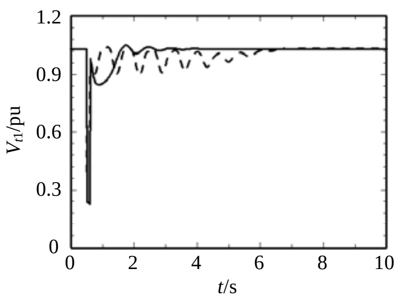

图 16　1 号机端电压

Fig.16　Response of No.1 machine terminal voltage

Simulation results demonstrate the effectiveness of the proposed coordinated control strategy,and significant improvement in system dynamic responses is obtained.

6 CONCLUSIONS

Mathematical model of HVDC Light in multi-machine power system is derived, a coordinated optimal control scheme between generator excitation and HVDC Light is designed based on the linearized equations of whole system, from simulation results, it can be observed that the proposed control scheme can better damp oscillation during large disturbance of power system than independent control for generator and HVDC Light respectively.

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APPENDIX: SIMULATION DATA

附表 1 发电机参数
Tab.A1 Generator parameters Unit:pu

	x_d'	x_d	x_q	T_{d0}'	M
No.1	0.3186	0.9875	0.5502	6.7	9.0
No.2	0.2467	0.8667	0.5207	5.6	8.52
No.3	0.3789	0.8993	0.5819	6.3	10.6

附表 2 图 3 中的输电线参数
Tab.A2 Transmission line parameters of Fig.3 Unit:pu

Bus code	Impedance		Admittance
	R	X	$B/2$
1 1*	0.2305	0.115	0
1 2	0.06	0.3	0.27
2 2	0.42	0.15	0.08
2 3	0.02	0.2	0.18
3 3	0.65	0.27	0.00
3 4	0.05	0.03	0.01
4 4	1.0	0.5	0.00

Note: 1 1* represents impedance, admittance of node 1 to the ground, 1 2 represents impedance, admittance between node 1 and 2, same argument for others.

The loads (impedance) parameters in p.u. of Fig.3 L_1=1.0+j0.6, L_2 =0.6+j0.4

附表 3 图 3 中发电机运行点参数
Tab.A3 Generators operating points of Fig.3 Unit:pu

No. of generator	Type*	P/pu	Q/pu	V/pu
1	−1	2.8	0.0	1.03
2	−1	2.1	0.0	1.02

Note:*Type: 1—PQ Bus; −1—PV Bus; 0—Slack bus.

附表 4　图 11 中发电机运行点参数

Tab.A4　Generators operating points of Fig.11　　Unit:pu

No. of generator	Type	P	Q	V
1	–1	2.8	0.0	1.03
2	–1	2.1	0.0	1.02
3	–1	2.3	0.0	1.03
8	0	0.0	0.0	1.0

HVDC Light operating points:

P_1+jQ_1=0.5+j0.1

P_1+jQ_1=0.5+j0.15

Where: P_1, Q_1—active and reactive power fed by system on rectifier side；P_2, Q_2—the active and reactive power feeding into the system by HVDC Light.

附表 5　图 11 中的输电线参数

Tab.A5　Transmission line parameters of Fig.11　　Unit:pu

Bus code		Impedance		Admittance
		R	X	B/2
1	2	0.060	0.30	0.27
1	7	0.005	0.03	0.00
2	6	0.010	0.05	0.00
2	8	0.020	0.20	0.18
3	4	0.010	0.06	0.00
3	6	0.013	0.4	0.12
4	4	0.8	0.6	0.0
5	5	0.6	0.4	0.00
5	8	0.0132	0.1	0.00
7	8	0.005	0.03	0.00
8	8	1.0	0.5	0.00

The loads (impedance) parameters in p.u. of Fig.11

L_1=1.0+j0.6, L_2 =0.6+j0.4, L_3 =0.8+j0.6

LOEC and parameters:

$$\Delta E_{fd} = K_p\Delta P + K_\omega\Delta\omega + K_V\Delta V_t$$

$$K_p = 12;\ K_\omega = -20;\ K_V = 20$$

AVR+PSS:

$$E_{fd} = K_a\Delta V_t + K_i\int\Delta V_t\mathrm{d}t$$

$$V(s) = -\frac{K_d}{K_a}\frac{sT_q}{1+sT_q}\frac{1+sT_1}{1+sT_2}\omega(s)$$

K_a=200, K_d=250, K_i=1.0, T_q=1.5, T_1=2.0, T_2=0.2

HVDC Light parameters in p.u.

x_1=0.2384, x_2=0.31, k_1=1.1, k_2=1.2, T_{dc}=0.5

PI controller parameters for HVDC Light:

k_E=0.1, T_E=100.0, k_d=0.1, T_d=0.02, k_V=0.1, T_V=1.0, k_q=0.1, T_q=0.02, k_P=0.1, T_P=0.02, k_G=0.1, T_G=0.02, k_L=0.1, T_L=0.02, k_M=0.1, T_M=0.02

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