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A NOVEL CONTROL STRATEGY FOR VSC BASED HVDC IN MULTI-MACHINE POWER SYSTEMS

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ABSTRACT

The forced commutated voltage source converter (VSC) is becoming an interesting alternative for HVDC transmission, in this paper, the model of VSC based HVDC is established, and the model is applied to multi-machine power system including VSC based HVDC, a decoupled control strategy based on the established model is proposed, and the performance of HVDC in multi-machine power system is studied under three phase AC fault, validity of the proposed controller is verified by the simulation results.

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Keywords: *VSC HVDC, model, control, muti-machine*

1. INTRODUCTION

The conventional High Voltage Direct Current (HVDC) transmission systems are built up with line commutated Current Source Converters (CSC), in these converters, the turn-on of thyristors are controllable, however the turn-off occurs at the zero crossing of the AC current which is determined by the AC network voltage (i.e. line commutation), so it will bring commutation failure if AC voltage dip has occurred; on the other hand, a mass of reactive power are absorbed, so many schemes have been considered to reduce the disadvantageous large reactive volt-ampere(VAR) absorption of the conventional converter. Busemann [1] first suggested the use of series capacitors to force commutate the Thyristor bridge, and this concept has been considered in more detail [2][3]. A combination of several three-phase-controlled bridges with different firing angles has been proposed to reduce the VAR absorption [4][5].

The application of high power VSCs for HVDC is made possible by the development of high power turn-off devices and series connection of power electronics devices [6][7]. VSC-HVDC offers many merits compared with conventional line commutated HVDC, such as:

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(1). The converter will not fail to carry out commutation when waveform distortion or voltage dip has occurred in the AC system;
(2). Possibility to control the reactive power independently of the active power;
(3). Improved wave quality because of PWM control method;
(4). Connection of VSC based HVDC have no influence on short-circuit capacity ratio of power system.

In this paper, the VSC based HVDC in a multi-machine power system is regarded as active node, the state equation as well as the expressions of the injection current of the HVDC are deduced, then the equations are integrated into the AD (Algebraic- Differential) equation of power system, at the same time, a decoupled control strategy for the VSC based HVDC is proposed based on the established models, from the simulation results, it can be seen that the proposed control can enhance the stability of HVDC, at the same time, it have little influence on the system voltage and frequency stability.

2. MATHEMATICAL MODEL

A three-phase single line diagram of the VSC based HVDC is shown as Fig.1, the nodes of the HVDC are extracted like generator nodes in Fig.1.It is assumed that n machines exist in the power system.

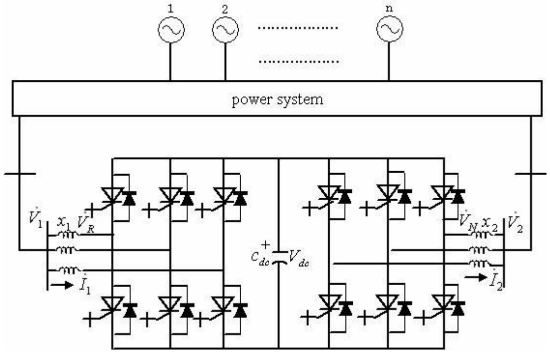

Figure 1. Model of VSC based HVDC in multi-machine power system

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:

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

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

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 VSC based HVDC can be written as

$$\dot{V}_1 = jx_1 \dot{I}_1 + \dot{V}_R \qquad (3)$$

$$\dot{V}_2 = -jx_2 \dot{I}_2 + \dot{V}_N \qquad (4)$$

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

Where x_1 and x_2 denote the equivalent commutation reactance of rectifier and inverter. Symbol R_e is real part.

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 (p.u.) in order to integrate them into the AD (Algebraic-Differential) 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:

$$V_{R\max} = \frac{1}{\sqrt{2}} V_{dc\max} \qquad (6)$$

$$V_{N\max} = \frac{1}{\sqrt{2}} V_{dc\max} \qquad (7)$$

If we let:

$$\frac{1}{\sqrt{2}} V_{dc\max} = k_1 V_{N1} = k_2 V_{N2} \qquad (8)$$

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

$$V_{N1} = \frac{1}{\sqrt{2}k_1} V_{dc\max} \qquad (9)$$

$$V_{N2} = \frac{1}{\sqrt{2}k_2} V_{dc\max} \qquad (10)$$

When $V_{dc\max}$ is chosen as base value of DC voltage and network's power rating S_r as the power base value [8], (1)(2) can be written in per unit form as (11)(12)

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

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

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 (5) becomes:

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

RHS of (5):

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

So (5) per unit form:

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

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

Above algebraic equations (3)(4) will be depicted in synchronous x - y coordinate format so as to integrate the Algebraic-Differential (AD) equations of power system as shown in (16)(17)

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

$$YV = I \qquad (17)$$

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

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

$$\begin{bmatrix} V_{1x} \\ V_{1y} \end{bmatrix} = \begin{bmatrix} 0 & -x_1 \\ x_1 & 0 \end{bmatrix}\begin{bmatrix} I_{1x} \\ I_{1y} \end{bmatrix} + \begin{bmatrix} k_1 m_1 \cos\theta_1 \\ k_1 m_1 \sin\theta_1 \end{bmatrix} V_{dc} \qquad (18)$$

$$\begin{bmatrix} V_{2x} \\ V_{2y} \end{bmatrix} = \begin{bmatrix} 0 & x_2 \\ -x_2 & 0 \end{bmatrix}\begin{bmatrix} I_{2x} \\ I_{2y} \end{bmatrix} + \begin{bmatrix} k_2 m_2 \cos\theta_2 \\ k_2 m_2 \sin\theta_2 \end{bmatrix} V_{dc} \qquad (19)$$

The equation (13) can be written similarly as

$$\frac{dV_{dc}}{dt} = \frac{k_1 m_1(\cos\theta_1 V_{1y} - \sin\theta_1 V_{1x})}{T_{dc}x_1} + \frac{k_2 m_2(\cos\theta_2 V_{2y} - \sin\theta_2 V_{2x})}{T_{dc}x_2} \qquad (20)$$

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

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

$$\begin{bmatrix} I_{1x} \\ I_{1y} \end{bmatrix} = \begin{bmatrix} 0 & 1/x_1 \\ -1/x_1 & 0 \end{bmatrix}\begin{bmatrix} V_{1x} \\ V_{1y} \end{bmatrix} + \begin{bmatrix} -k_1 m_1 \sin\theta_1 / x_1 \\ k_1 m_1 \cos\theta_1 / x_1 \end{bmatrix} V_{dc} \qquad (21)$$

$$\begin{bmatrix} I_{2x} \\ I_{2y} \end{bmatrix} = \begin{bmatrix} 0 & -1/x_2 \\ 1/x_2 & 0 \end{bmatrix}\begin{bmatrix} V_{2x} \\ V_{2y} \end{bmatrix} + \begin{bmatrix} k_2 m_2 \sin\theta_2 / x_2 \\ -k_2 m_2 \cos\theta_2 / x_2 \end{bmatrix} V_{dc} \qquad (22)$$

The equivalent system of Fig.1 is shown as Fig.2, in Fig.2, HVDC system is eliminated when two terminals are instead of two active nodes, where $-\dot{I}_1$ denotes the direction of the injection current. $\dot{I}_1$, $\dot{I}_2$ are represented by (21) (22)

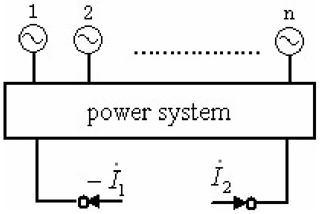

Figure 2. Equivalent system of Fig.1

On the other hand, the HVDC can be seen as a controllable voltage sources after (21)(22) are substituted into algebraic equation (17) and amending admittance matrix Y to Y'.

3. DESİGN OF THE PROPOSED CONTROL

The control design is based on the state equation of the converters, the equation is easy to write according to Kirchhoff's laws as shown (23)(24)

$$L_1 \frac{d[i_1]_{abc}}{dt} = [v_1]_{abc} - [v_R]_{abc} \tag{23}$$

$$L_2 \frac{d[i_2]_{abc}}{dt} = -[v_2]_{abc} + [v_N]_{abc} \tag{24}$$

Where L_1, L_2 are the commutation inductance of rectifier side and inverter side respectively, subscription abc represents three phase a, b and c, and i_1, i_2, v_1, v_2, v_R, v_N are instantaneous value corresponding the phasor $\dot{I}_1, \dot{I}_2, \dot{V}_1, \dot{V}_2, \dot{V}_R, \dot{V}_N$.

For modeling and control design, three-phase variables in stationary frame can be transformed to d - q synchronous frame [9]. This yields

$$\begin{bmatrix} V_{1d} \\ V_{1q} \end{bmatrix} = C_{3s/2r} \begin{bmatrix} v_{1a} \\ v_{1b} \\ v_{1c} \end{bmatrix} \tag{25}$$

$$\begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} = C_{3s/2r} \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} \tag{26}$$

Where $C_{3s/2r}$ is transformation matrix from static abc coordinate to rotating d - q synchronous frame, it adopts orthogonal transformation matrix.

$$C_{3s/2r} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \end{bmatrix} \tag{27}$$

If we let the q axis in the synchronous frame coincide with y axis of synchronous x - y coordinate mentioned in section 2, component on q axis or d axis will equal to the one on the y axis or x axis for the same phasor. So on rectifier side, equation (23) will be transformed to:

$$\frac{dI_{1x}}{dt} = \omega I_{1y} + \frac{1}{L_1} V_{1x} - \frac{1}{L_1} V_{Rx} \tag{28}$$

$$\frac{dI_{1y}}{dt} = -\omega I_{1x} + \frac{1}{L_1} V_{1y} - \frac{1}{L_1} V_{Ry} \tag{29}$$

Similarly, for inverter side

$$\frac{dI_{2x}}{dt} = \omega I_{2y} + \frac{1}{L_2} V_{Nx} - \frac{1}{L_2} V_{2x} \tag{30}$$

$$\frac{dI_{2y}}{dt} = -\omega I_{2x} + \frac{1}{L_2} V_{Ny} - \frac{1}{L_2} V_{2y} \tag{31}$$

From equation (28)-(31), it can be seen that mutual interference exists in the x - y coordinate, so decouple control are therefore designed to decoupled the current control loops, at the same time, suitable outer control loop are also added to satisfied control requirement for VSC-HVDC. In a voltage source converter, DC voltage stability is related with the imbalance between the input power of one terminal and the output of the other [10][11], so control of DC voltage is chosen as one of outer control loop, the other control objective is the amplitude of the system voltage $\dot{V}_1$, as we known, in conventional HVDC, changes of system voltage is corrected by tap-change transformer. The control block diagram for rectifier in the proposed system is shown in Fig.3

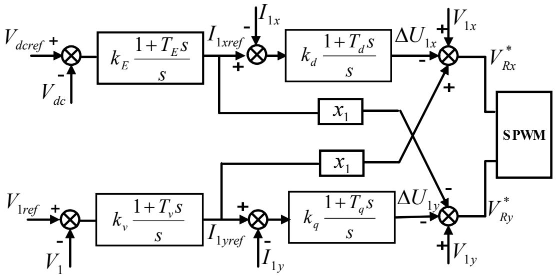

Figure 3. Control block diagram of controller of the rectifier

Where $x_1 = \omega L_1$, the voltage commands can be expressed as

$$V^*_{Rx} = V_{1x} - \Delta U_{1x} + x_1 I_{1yref} \tag{32}$$

$$V^*_{Ry} = V_{1y} - \Delta U_{1y} - x_1 I_{1xref} \tag{33}$$

I_{1xref}, I_{1yref} are the current reference, and the voltage commands for current regulation in (32)(33) are

$$\Delta U_{1x} = G_{1x}(s) \Delta I_{1x} \tag{34}$$

$$\Delta U_{1y} = G_{1y}(s) \Delta I_{1y} \tag{35}$$

where $\Delta I_{1x} = I_{1xref} - I_{1x}$, $\Delta I_{1y} = I_{1yref} - I_{1y}$ are the error currents in x -and y -axis, respectively.

The proportional-integral (PI) controllers given as following are adopted in (34) and (35)

$$G_{1x}(s)=k_d\frac{1+T_d s}{s} \tag{36}$$

$$G_{1y}(s)=k_q\frac{1+T_q s}{s} \tag{37}$$

In addition, current reference given as following are adopted in (32) and (33)

$$I_{1xref}=T_{1x}(s)(V_{dcref}-V_{dc}) \tag{38}$$

$$I_{1yref}=T_{1y}(s)(V_{1ref}-V_1) \tag{39}$$

where V_{dcref}, V_{1ref} are DC voltage reference and voltage amplitude reference on rectifier side, respectively, $T_{1x}(s)$, $T_{1y}(s)$ given as following are also PI regulator

$$T_{1x}(s)=k_E\frac{1+T_E s}{s} \tag{40}$$

$$T_{1y}(s)=k_v\frac{1+T_v s}{s} \tag{41}$$

Similarly, control on inverter side can be designed, however, control objective are active power P_2 and reactive power Q_2 instead of DC voltage V_{dc} and amplitude of $\dot{V}_1$. The control block diagram for inverter in the proposed system is shown in Fig.4

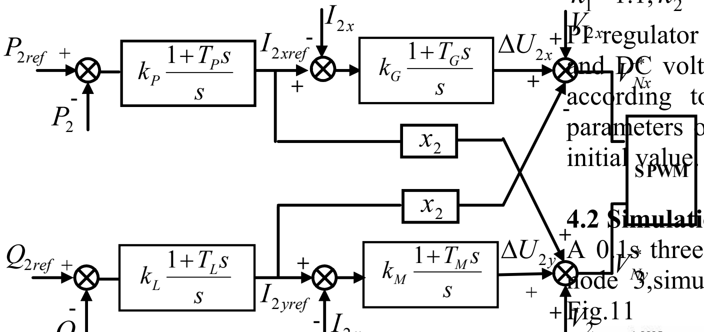

Figure 4. Control block diagram of controller of the inverter

where $x_2=\omega L_2$, P_{2ref} and Q_{2ref} are active power reference and reactive power reference, respectively.

The meaning of block in Fig.4 is similar with the ones in Fig.3, so it will not discussed again in this paper.

4. NONLİNEAR SİMULATİON RESULTS

4.1 System Conditions

The studied case is a three-machine power system including VSC based HVDC (Fig.5), where No.1 generator and No.2 generator are connected through parallel AC/DC system, L_1 and L_2 represent the load. The simulation program employs the HVDC model established in section 2,and the proposed control is applied.

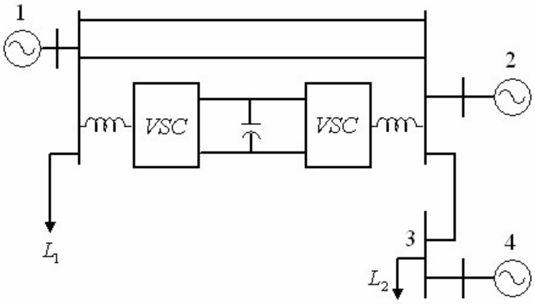

Figure 5. The diagram of three machines power system with HVDC

Basic parameters of the VSC based HVDC: x_1=0.2384, x_2=0.31, k_1=1.1, k_2=1.2, T_{dc}=0.5,the parameters of the PI regulator have influence on the AC voltage and DC voltage stability, so it can be regulated according to system situation, generally, the parameters of PI regulator can be given a small initial value. (See Appendix)

4.2 Simulation Results

A 0.1s three-phase to ground fault is applied at node 3,simulation results are shown in Fig.6-Fig.11

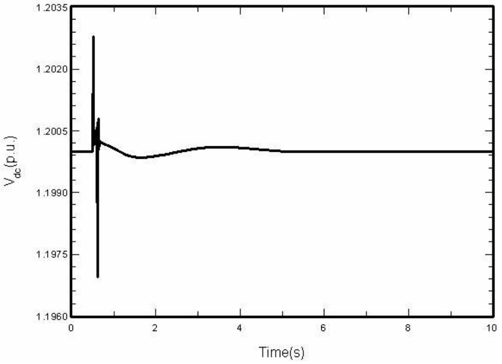

Figure 6. DC voltage response of HVDC system

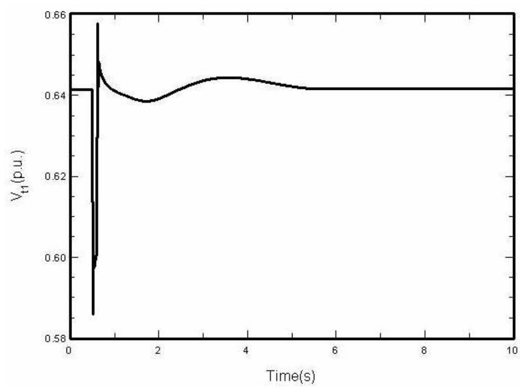

Figure 7. Terminal voltage response of No.1 machine

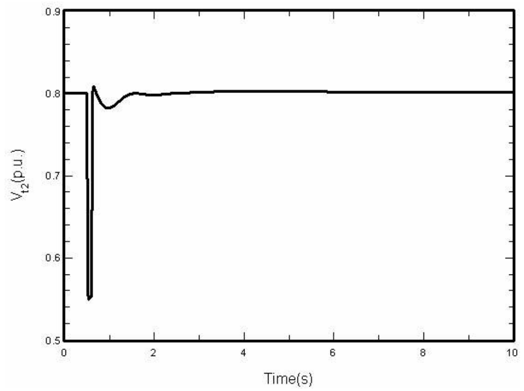

Figure 8. Terminal voltage response of No.2 machine

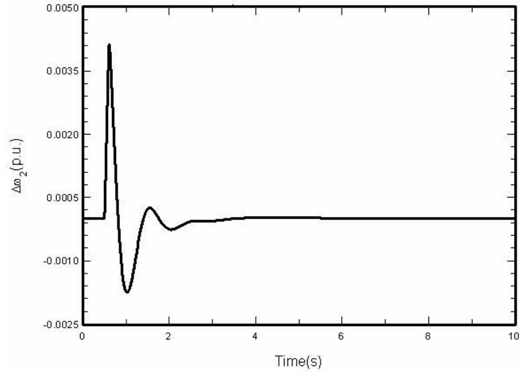

Figure 9. Speed response of No.2 machine

From the simulation results Fig.6-Fig.11, the following observations can be made: the VSC based HVDC plus the proposed control can recover rapidly from the system fault, and itself has better stability characteristic, on the other hand, for power system including VSC based HVDC, when the proposed control method is adopted, the HVDC system itself has no influence on the stability of system voltage and frequency.

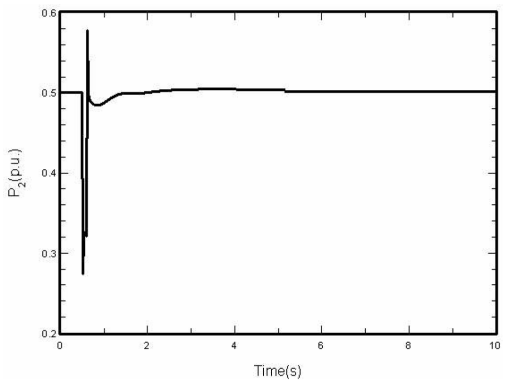

Figure 10. Active power output of inverter side

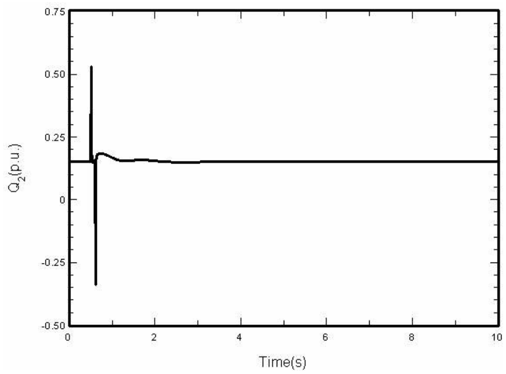

Figure 11. Reactive power output of inverter side

5. CONCLUSION

The mathematical model of VSC based HVDC is established in this paper, the model is applied to multi-machine power system simulation, and a novel control method based on the established model is proposed for HVDC system, with the proposed control, the reactive power and active power of HVDC system can be decoupling control. From the simulation results, it is shown that the VSC based HVDC with the proposed control design have better stability characteristic, either DC voltage or load flow, in addition, with the proposed control, VSC based HVDC system have little influence on the AC voltage and frequency stability of power systems.

6. APPENDIX

Main simulation parameters are listed as following

Generator parameters:

	x'_d	x_d	x_q	T'_{d0}	M
No.1	0.3186	0.9875	0.5502	6.7	38.36
No.2	0.2467	0.8667	0.5207	5.6	8.52
No.4	0.3789	0.8993	0.5819	6.3	10.6

PI regulator parameters:

$$k_E = 0.1, T_E = 0.02, k_d = 0.1, T_d = 0.02,$$
$$k_v = 0.1, T_v = 0.02, k_q = 0.1, T_q = 0.02,$$
$$k_P = 0.1, T_P = 0.02, k_G = 0.1, T_G = 0.02,$$
$$k_L = 0.1, T_L = 0.02, k_M = 0.1, T_M = 0.02$$

Transmission line parameters in p.u.:

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

*1 1 represents impedance and admittance of node 1, 1 2 represents impedance and admittance between node 1 and 2,same argument for others.

The loads parameters in p.u. (impedance):

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

VSC based HVDC parameters in p.u.:

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

7. ACKNOWLEDGEMENT

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