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The HVDC Supplementary Control for AC/DC Interconnected Power Grid Based on Hamilton Energy Function Theory

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***Abstract*—Low-frequency oscillation suppression of the interconnected power grid is an important factor for the stable operation of the power system. In this paper, the AC-DC interconnected power system is represented as the switched Hamilton system based on the centre of inertia (COI) equivalent method. The Hamilton energy function of the system is constructed from the viewpoint of the oscillation energy of the interconnected power system, which is then used as a uniform Lyapunov function to study the stabilization problem of the system. Then the high voltage direct current (HVDC) supplementary damping controller is designed aiming to reduce the oscillation energy thus the suppression of the oscillation is attained. The proposed control design procedure is fully based on nonlinear theory and can be widely used for practical power system with changing operation conditions. The feasibility of the proposed controller in the practical power system is discussed based on wide-area measurement system (WAMS). The simulation results of the EPRI 7 nodes system verify the correctness and effectiveness of the proposed method.**

***Index Terms*—Generalized dissipative Hamilton system, HVDC supplementary damping control, asymptotically stable, system equivalent, low-frequency oscillation.**

I. INTRODUCTION

Energy (or power) flow and balance are important factors for power system operation security and stability [1]. The imbalance between the power and the load in the sending-end grid and in the receiving-end grid both can lead to asynchronous movements of the two group generators, which may excite low-frequency oscillations and are of substantial danger that can lead to blackout. With the construction of the ultra-high voltage (UHV) power grid, AC/DC parallel power system will become more and more common. This hybrid structure has some obvious advantages. On one hand, thanks to the short-time overload capacity of high voltage direct current (HVDC), power modulation control can be used to compensate the energy imbalance while improving transient angle stability of the power system [2]. On the other hand, the voltage maintenance capability supplied by the AC line can help HVDC links recovering from short-term commutation failures or single/bipolar blocking faults. For example, China Southern Power Grid (CSPG) is a typical currently operating AC/DC parallel power grid which has accumulated a wealth of experience in operation and control [3].

With the constant expansion of the interconnected power system, low frequency oscillation problem, rather than transient angle stability problem, has become an urgent issue to be solved in power system utilization. For AC/DC parallel power system, the supplementary damping control effect of the DC links is particularly studied in the literature to suppress the oscillations [4]–[6]. Those formerly proposed methods are based on linearized theory and typically aiming for pole-zero reconfiguration, which may weaken or even deteriorate the practical damping effect when the actual operation condition deviates from the expected equilibrium point [7]. Therefore, some control design methods based on nonlinear theory are subsequently studied. In [8], a nonlinear state feedback linearization model of the AC/DC power system is proposed and the control strategy based on linear quadratic regulator is presented to enhance both the transient and the small-signal stability of the power system. However, the precision of the based mathematical model as well as the predicted operational parameters in control design process is of great concern to the desired control effect, which limits the application in practical power system that always with variously changing operation conditions. It is urgent and necessary to find a feasible controller design procedure of the HVDC supplementary control for practical applications in AC/DC parallel power systems.

Real-time operation status monitoring and simplification of the practical power system are the basis for control design. Thanks to the increasing utilization of the phasor measurement unit (PMU) and wide-area measurement system (WAMS) in power system, some online adaptive HVDC supplementary damping controllers are designed based on real-time measurement signals. In [9], the observed center of inertia (OCOI) of the power grid is described, and the

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measurement difference of the power angle between the two regional power grids are used as the input signals for HVDC modulation control while obtaining more useful information of the inter-area oscillation modes than the conventionally used signals. In [10], a coordinated robust design approach is planned for the wide-area HVDC and FACTS controllers aiming for stabilizing multiple inter-area oscillation modes in large-scale power systems. The coordination damping control of the multiple HVDC links is also draw considerable attentions in the literature since it is possible to obtain the remote control signals by a special optical fiber [11], [12].

Low-frequency oscillations between the two interconnected power grid areas can be seen as energy (or power) fluctuation from the energy point of view. The oscillation energy of the system, which can represent the severity of the oscillation, is proposed and used to design the damping control strategy based on Lyapunov stability theory [13]. Generalized Hamilton system has a more common structure and can represent some physical systems that have energy exchange with the environment, such as machinery system and power system. Specifically, a kind of port controlled generalized Hamiltonian system can be conveniently used for system stabilization control [14]–[16].

In this paper, the AC/DC parallel power system is equivalently simplified based on the real-time measurement information. Using the centre of inertia (COI) simplification method, the motions of two equivalent machines are used to represent the dynamics between the two interconnected power grids. The oscillation energy properties of the system are fully preserved and the switched generalized Hamilton system is used to design a HVDC supplementary damping controller with the oscillation energy of the system as the Hamiltonian energy function. The exclusive aim of the control strategy lies in suppressing the oscillation energy and simultaneously damping the low-frequency oscillations. Specifically, no linearized approximation is needed during the control design process which makes the controller suitable for practical power systems that has a wide range of operating conditions. The simulation results of a test power system verify the feasibility and effectiveness of the proposed method.

The remainder of the paper is organized as follows: Section II briefly describes the equivalent system of AC/DC parallel power system. Section III illustrates the switched generalized Hamiltonian system realization based on the equivalent model considering the various operations, such as generator removal, load shedding, as well as setting changes of the HVDC. Then the control design process is detailed illustrated with some physical explanations. Section IV shows the simulation results with the proposed control strategies. Some conclusions are drawn in Section V.

II. WAMS BASED EQUIVALENCE OF AC/DC PARALLEL POWER SYSTEM

With the rapid development of power grid construction, the AC/DC parallel transmission line connecting two regional power grids are becoming more and more common, especially in the developing countries, such as India, Brazil and China. Generally speaking, this hybrid transmission structure originates from the expansion of the DC transmission line based on the existing AC transmission corridor with the growth of the load, such as the pacific intertie HVDC in America and the CSPG in China. The power modulation capability of HVDC can be used to enhance the dynamic stability of AC/DC power system while the appropriate simplification is an essential factor in the control design process. The commonly used equivalent structure of the AC/DC parallel power systems shown in Fig. 1 is suitable for interconnected power system oscillation analysis and control [17]. G_A and G_B are the equivalent generators of area A and B, respectively, which are modelled with the classical generator model. P_{LA} and P_{LB} are the loads with in the two areas, P_{dc} and P_{ac} are the power flow on the DC line and AC line, respectively, y_L is the equivalent susceptance of the AC line.

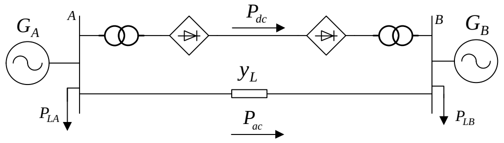


Fig. 1. The equivalent circuit of AC/DC interconnected system.

It needs to pay close attention to the energy or power fluctuation on the AC line when considering the low-frequency oscillation problems of the AC/DC parallel power system. For the complicated AC/DC hybrid power grid that has several AC lines, P_{ac} represents the sum of the power on all the related AC lines and y_L symbolizes the overall equivalent susceptance. Therefore, the simplified model shown in Fig. 1 can be used to solve the oscillation problems of practical AC/DC power system from the energy balance point of view. However, the traditionally used dynamical states of the equivalent model will inevitably lead to mismatch with the varying operating state and system parameters. The usage of WAMS and PMUs provides a possibility to real-timely update the parameters of the equivalent network. Suppose the desired information is all accessible with redundantly equipped PMUs, the equivalent parameters of Fig. 1 can be computed via the centre of inertia (COI) based equivalent methods as following:

$$\begin{cases} H_{A(B)} = \sum\limits_{i=1}^{n_{A(B)}} H_i, \\ \text{¢}_{A(B)} = \dfrac{\sum\limits_{i=1}^{n_{A(B)}} H_i \text{¢}_i}{\sum\limits_{i=1}^{n_{A(B)}} H_i}, \\ \mu_{A(B)} = \dfrac{\sum\limits_{i=1}^{n_{A(B)}} H_i \mu_i}{\sum\limits_{i=1}^{n_{A(B)}} H_i}, \end{cases} \tag{1}$$

where $i = 1, 2, ..., n_A(n_B)$ represent that the ith generator is within area A (or B), $H_{A(B)}$, $\text{¢}_{A(B)}$ and $\mu_{A(B)}$ are the inertia constants, the rotor angle and angular speed of the equivalent generators of area A (or B), respectively.

The HVDC controller can be modelled with a first-order inertia element since only the energy imbalance and oscillations problem of the power system are considered. Under even damping distribution assumption, denote $D_i / H_i \equiv K_{DH}$ is the same for the two equivalent generators, with D_i is the damping coefficient of the generator. Then the dynamic of the equivalent system can be written as:

$$\begin{cases} \dot{\text{¢}}_{AB} = \mu_{AB}, \\ \dot{\mu}_{AB} = -\ K_{DH}\mu_{AB} - K_{\Sigma}(\mathrm{P}_{dc} + \mathrm{P}_{ac}) + P_{\Sigma}, \\ \dot{P}_{dc} = \dfrac{1}{T_d}(-P_{dc} + P_{dc0} + u_{dc}), \end{cases} \tag{2}$$

$$\mathrm{P}_{\Sigma} = \left(\frac{\mu_0}{H_A}\mathrm{P}_{mA} - \frac{\mu_0}{H_B}\mathrm{P}_{mB} \right) - \left(\frac{\mu_0}{H_A}\mathrm{P}_{LA} - \frac{\mu_0}{H_B}\mathrm{P}_{LB} \right), \tag{3}$$

$$K_{\Sigma} = \frac{\mu_0}{H_A} + \frac{\mu_0}{H_B}, \tag{4}$$

where $\text{¢}_{AB} = \text{¢}_A - \text{¢}_B$, $\mu_{AB} = \mu_A - \mu_B$, P_A, P_B represent the sum of the active power output of the generators within area A and B; P_{mA}, P_{mB} are the sum of the prime mover input power of the generators within area A and B; P_{dc} and P_{ac} are the power flow on the DC and AC line, respectively; $P_{ac} = U_A U_B y_L \sin \text{¢}_{AB}$, U_A and U_B are the voltage magnitude at the equivalent buses that are measurable; $\mu_0 = 314.1593$ rad/s is the synchronous angular speed, the other parameters are all in per-unit unless stated otherwise.

Remark1: The whole power through the transmission corridor is related to the dynamics of the equivalent generators. So the sum of the power on both the HVDC line and AC line is included in (2). The transient process of HVDC is assumed to have little effect on the overall stability of the system since the action time of inverter is quite short and the set power can be reached instantaneously.

III. THE DAMPING CONTROLLER DESIGN BASED ON OSCILLATION HAMILTONIAN ENERGY FUNCTION

A. *Basic Theory and Preliminary*

Consider a nonlinear system

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})\mathbf{u}, \tag{5}$$

where $\mathbf{x} = [x_1, x_2, \ldots x_n]^T \in \mathbb{R}^n$ is the state vector, $f(x)$ and $g(x)$ are continuous vector functions with proper dimensions; $\mathbf{u}$ is the input control vector. If there exists a positive definite function $H(\mathbf{x})$ such that the system (5) can be represented as

$$\dot{\mathbf{x}} = [\mathbf{J} - \mathbf{R}]\frac{\partial H}{\partial \mathbf{x}} + \mathbf{P}(\mathbf{x}) + g(\mathbf{x})\mathbf{u}, \tag{6}$$

where $\mathbf{J}$ is anti-symmetric matrix, $\mathbf{R}$ is symmetric positive definite matrix, $\mathbf{P}$ is a mapping of the state $\mathbf{x}$ with corresponding dimensions, then system (6) is called a pseudo-generalized Hamiltonian system [18], hence we have the following theorem.

Theorem 1: If $\mathbf{u} = \mathbf{u}^*$ makes the following equation holds

$$\mathbf{P}(\mathbf{x}) + g(\mathbf{x})\mathbf{u} = 0, \tag{7}$$

then the following controller

$$\mathbf{u} = \mathbf{u}^* - \mathbf{K}\frac{\partial H}{\partial \mathbf{x}} \tag{8}$$

makes the system asymptotically stable in the vicinity of the equilibrium point $\mathbf{x}_0$, $\mathbf{K}$ is a positive diagonal matrix to be determined.

Proof: Directly calculate the derivative of the Hamilton function H with respect to $\mathbf{x}$ along the trajectory of (5), we have

$$\dot{H} = \frac{\partial^{\mathrm{T}} H}{\partial \mathbf{x}}\dot{\mathbf{x}} = \frac{\partial^{\mathrm{T}} H}{\partial \mathbf{x}}[\mathbf{J} - \mathbf{R}]\frac{\partial H}{\partial \mathbf{x}} + \frac{\partial^{\mathrm{T}} H}{\partial \mathbf{x}}[\mathbf{P}(\mathbf{x}) + g(\mathbf{x})\mathbf{u}]. \tag{9}$$

As $\mathbf{J}$ is anti-symmetric and $\mathbf{R}$ is symmetric positive definite, substitute the controller of (8) into (9) yields

$$\dot{H} = -\frac{\partial^{\mathrm{T}} H}{\partial \mathbf{x}}[\mathbf{K} + \mathbf{R}]\frac{\partial H}{\partial \mathbf{x}} \le 0. \tag{10}$$

It means that the control strategy of (8) will always aims to decrease the function value of H, which ultimately stabilizes the system to the desired equilibrium point.

B. *AC/DC Power System Switched Hamilton Realization*

The above theorem is under a continuity assumption and can't be directly used to some physical systems. There exist various switching operations in power system. Therefore, the parameters in (2) are concerned with the current operational state of the power system. For example, the equivalent inertia of each regional power grid is the sum of the inertia of the currently running generators, the equivalent susceptance y_L is related to the transmission line switching mode. The switching operations need to be considered in order to design a practically used controller. Suppose $\pm_i \in \mathrm{M}\ \ (i = 1, 2, \ldots, N)$ represent all the possible switching operations in power system, which consists of generator tripping, load shedding, transmission line opening and the desired equilibrium changing, and so on. The state variables are defined as $\mathbf{x} = [\text{¢}_{AB}\ \mu_{AB}\ P_{dc}]^T$, which are continuous. The other parameters in (2) can be seen as functions related to $\pm_i$. Then the dynamics of the equivalent AC/DC power system shown in Fig. 1 can be written as:

$$\begin{cases} \dot{\text{¢}}_{AB} = \mu_{AB}, \\ \dot{\mu}_{AB} = P_{\Sigma}(\pm_i) - K_{DH}\mu_{AB} - K_{\Sigma}(\pm_i)[\mathrm{P}_{dc} + U_A U_B y_L(\pm_i)\sin \text{¢}_{AB}], \\ \dot{P}_{dc} = \dfrac{1}{T_d}[-P_{dc} + P_{dc0}(\pm_i) + u_{dc}], \end{cases} \tag{11}$$

where $K_{\Sigma}(\pm_i)$ represents the influence of the generator switching operations to the equivalent inertia constant, $y_L(\pm_i)$ symbols the transmission line operation to the equivalent susceptance, $P_{\Sigma}(\pm_i)$ is the original power imbalance related to both generator switching and load shedding, $P_{dc0}(\pm_i)$ is the specified value of the power on DC line that given by operating personnel. Thanks to the supervisory control and data acquisition (SCADA) system in power grid, all the switching operations can be supposed to be measurable. Then (11) fully represents the real-time dynamics of the equivalent AC/DC parallel power system.

Generalized Hamiltonian system is an important structure in stabilizing control of some physical systems, such as machinery system and power system. For the equivalent power system with switching operations as (11), it is more suitable to represent it with the switching generalized Hamiltonian systems. Define $H_{eq} = H_A H_B / (H_A + H_B)$ is the equivalent inertia of the whole system, then the oscillation energy function of the system can be represented as

$$H(\pm_i, \mathbf{x}) = \frac{1}{2} H_{eq}(\pm_i)\mu_{12}^2 + \text{ª} K_d [P_{dc} - P_{dc0}(\pm_i)]^2 + \\ + H_{eq}(\pm_i)\int_{\text{¢}_{AB0}(\pm_i)}^{\text{¢}_{AB}} \left[K_{\Sigma}(\pm_i)(P_{dc} + P_{ac}(\pm_i)) - P_{\Sigma}(\pm_i)\right] d\text{¢}_{AB}, \quad (12)$$

where the first item represents the oscillation kinetic energy of the two equivalent generators because the synchronous rotation of the two generators have no contribution to the oscillation energy, the second item represents the differential storage energy in HVDC system which also influence the oscillation energy with respect to the predefined settings, the last part is the potential energy that related to the relative positions of the equivalent generator rotators. K_d is a constant coefficient related to the rated transmission power of the DC line, ª is an undetermined weight coefficient of the deviation of energy in HVDC to the Hamiltonian energy function.

Directly calculate the partial derivation of (12) with respect to the state variables, we can obtain

$$\dot{\mathbf{x}} = \left[\mathbf{J}(\pm_i) - \mathbf{R}(\pm_i)\right]\frac{\partial H}{\partial \mathbf{x}} + \mathbf{P}(\mathbf{x}) + \mathbf{G}u_{dc}, \quad (13)$$

where

$$\mathbf{J}(\pm_i) = \begin{bmatrix} 0 & \frac{1}{H_{eq}} & 0 \\ -\frac{1}{H_{eq}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{R}(\pm_i) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{K_{DH}}{H_{eq}} & 0 \\ 0 & 0 & \frac{1}{2\text{ª} K_d T_d K_{\Sigma}} \end{bmatrix},$$

$$\mathbf{P}(\mathbf{x}) = \begin{bmatrix} 0 \\ 0 \\ H_{eq}(\pm_i)K_{\Sigma}(\pm_i)(\text{¢}_{12} - \text{¢}_{120}) \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

According to the physical meanings of the parameters in (13), $\mathbf{J}(\pm_i)$ and $\mathbf{R}(\pm_i)$ are anti-symmetric matrix and symmetric matrix, respectively. The structure parameters of the system in (13) are updated according to the switching operations of the system. Thus the switching Hamiltonian realization of the AC/DC parallel power system is successfully accomplished. The structure of the system satisfies the condition of (7), thus the control design method shown in *Theorem 1* can be extended to the HVDC supplementary damping control design which will be discussed in the sequel.

C. HVDC Supplementary Damping Control Design

Let $\mathbf{x}_{i0} = [\text{¢}_{AB0}(\pm_i)\ \mu_{AB0}\ \ P_{dc0}(\pm_i)]^T$ are the equilibrium points that related to the *i*th switching operation state, and suppose each equilibrium point is uniquely determined by the corresponding operation strategy. Define $u = u_{dc} + u_p$ and let $u_p = \mathbf{G}^T P(\mathbf{x})$, then the system shown in (13) can be rewritten as

$$\dot{\mathbf{x}} = \left[\mathbf{J}(\pm_i) - \mathbf{R}(\pm_i)\right]\frac{\partial H}{\partial \mathbf{x}} + \mathbf{G}u. \quad (14)$$

For each switching operation state, we have

$$\left.\frac{\partial H(\pm_i, \mathbf{x})}{\partial \mathbf{x}}\right|_{\mathbf{x}_{i0}} = 0. \quad (15)$$

Therefore, H can be used to discuss the uniformly Lyapunov stable problems of the system provided that H is a regional minimum point for each $\mathbf{x}_{i0}$. The positive definiteness properties of the Hessian matrix of H at each equilibrium point $\mathbf{x}_{i0}$ can be chosen as a sufficient and conservative condition. And under the unidirectional power transmission assumption, it holds that $\text{¢}_{AB} \in (0^{\circ}, 90^{\circ})$ since the transient stability of the power system needs to be satisfied in the first place. Therefore, the Hamiltonian energy function shown in (12) can be chosen as the uniform Lyapunov function to stabilize the system as soon as the following conditions satisfied

$$\cos\text{¢}_{AB} > \frac{K_{\Sigma}}{2K_d y_L(\pm_i)}. \quad (16)$$

Then the following control strategy

$$u = -kG^T \frac{\partial H(\pm_i, \mathbf{x})}{\partial \mathbf{x}} \quad (17)$$

makes the system stable since by derivation calculus to the Lyapunov function of (12) along the trajectory of (14) yields

$$\dot{H} = \frac{\partial^T H}{\partial \mathbf{x}}\left\{\left[\mathbf{J}(\pm_i) - \mathbf{R}(\pm_i)\right] - k\mathbf{G}\mathbf{G}^T\right\}\frac{\partial H}{\partial \mathbf{x}} = \\ = -\frac{\partial^T H}{\partial \mathbf{x}}\left[\mathbf{R}(\pm_i) + k\mathbf{G}\mathbf{G}^T\right]\frac{\partial H}{\partial \mathbf{x}} \le 0, \quad (18)$$

where $\mathbf{R}(\pm_i)$ represents the internal damping of the system and k is the undetermined coefficient of the control signal. And the equal sign holds only when $\mathbf{x} = \mathbf{x}_{i0}$ in the *i*th switching operation period. Hence the system is asymptotically stable to the equilibrium point with respect to the last operation. Consequently, the control strategy in (17) can be rewritten as

$$u_{dc} = -k^{ª} K_d \left[P_{dc} - P_{dc0}(\pm_i)\right] - \\ -(k+1)H_{eq}(\pm_i)K_{\sum}(\pm_i)\left[¢_{AB} - ¢_{AB0}(\pm_i)\right], \qquad (19)$$

where P_{dc0} and $¢_{AB0}$ are the desired operational state of the HVDC rated power and the rotor angle difference between the equivalent generators of the two regional power grid, respectively, which can be calculated based on the corresponding switching operation. The other variables in the above controller can be acquired via the equivalent method based on WAMS shown in (2). Therefore, the controller is directly applicable with appropriate parameters k and $ª$ to be determined, which can be chosen according to the desired convergence behaviour by trial and error.

The proposed controller is actually an adaptive controller. The initial states and the operating points are assumed to be measurable or accessible, which is reasonable and prospective for the power system as more and more PUMs and WAMS are used. Compared with the traditional decentralized controllers, the distant signals can be accessed to stabilize the system in the newly proposed method hence it can obtain a better effect since the power system stability problem is an overall stability problem. The main aim of the controller of (19) lies in the decrease of the oscillation energy thus damping out the inter-area low-frequency oscillations. The application of the controller needs the synchronous measurement of the generator operating state and the switching operations such as generator trip, load shedding, transmission line cut off, and so on. The increasing usage of PMU and WAMS in power system makes that implementation possible and consequently realizes the online stability analysis and control.

IV. THE PRACTICAL APPLICATION AND SIMULATION RESULTS

The EPRI 7 nodes power system is chosen as an example to illustrate the practical implementation of the proposed controller. Suppose sufficient PMUs are installed and the desired information is all measurable and the communication delay can be neglected. The online equivalent simplification is indispensable for nonlinear control design for the complex systems, such as large power system since it has the curse of dimensionality problem. The retainment of the critical characteristics of the whole system in equivalent process is of great importance to the effectiveness of the subsequently designed controller. In the proposed control design procedure, the essential properties of the oscillation energy in simplification process are fully reserved. The overall energy of the system can be seen as the sum of the energy distributed in each separate element, such as generators, transmission lines and loads. Therefore, the equivalent system has the same value in the oscillation energy with respect to the original power system as soon as the online real-time measuring data are used in the simplification procedure as shown in (1). The switching operations can also be known as soon as possible with help of the remote sensing equipment while the desired operational points of the newly reconstructed power system can be immediately accessed from the energy management system (EMS). Consequently, the information needed to form the controller shown in (19) are all directly or indirectly available which demonstrates the practical feasibility of the proposed control design method. The limit element is needed to be taken into consideration when the controller is used in real power system.

Practical usage of the controller would be the best way to verify its effectiveness and correctness. However, the request of continuous electricity supply makes it impossible to test the control strategy on operational power system. Fortunately, some accurate simulators are available in power system study. In this paper, the EPRI 7 nodes power system (shown in Fig. 2) is modelled with PSCAD software which provides state variable measuring modules that can simulate the functions of the PMUs. The parameters and power flow of the generators can be seen in [19]. The parameters of the transformers, transmission lines and loads are given in Fig. 2 in per unit with the based power of 100MVA. Therefore, the operational states can be accessed just as the practical power system and the controller shown in (19) is implemented to the HVDC link which is the same with the First Benchmark HVDC model provided by CIGRE [20]–[22].

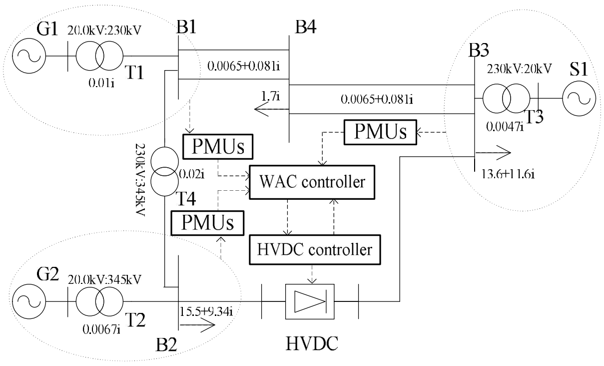
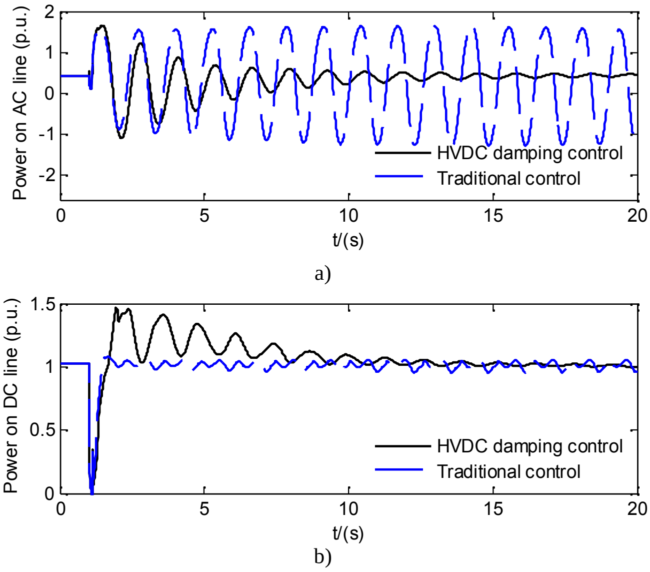


Fig. 2. WEPRI7 AC/DC interconnected system.

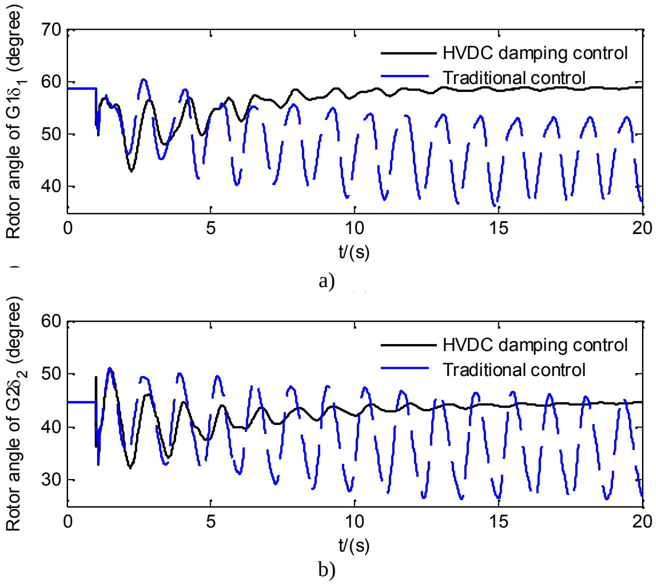


a)

b)

Fig. 3. The active power of AC and DC line.

The proposed supplementary damping controller with the parameters of $K_d = 1.0$, $k = 2.0$, $ª = 0.5$ by trial and error is implemented and applied to the power order at the rectifier, so the power flow of the DC line fluctuates according to the controller thus provides a damping effect. The traditional fixed turn-off angle controller at the inverter is chosen as a contrast. The dynamic of the system after an instantaneous short circuit disturbance at Bus B3 is analysed under the two controllers. The dynamics of the power fluctuations on the AC line and DC line are shown in Fig. 3. Chose the generator G3 as the reference, the rotor angle of G1 and G2 with respect to G3 are shown in Fig. 4. The rotor rotating speed, active power output of G1 and G2 are displayed in Fig. 5 and Fig. 6, respectively.



a)

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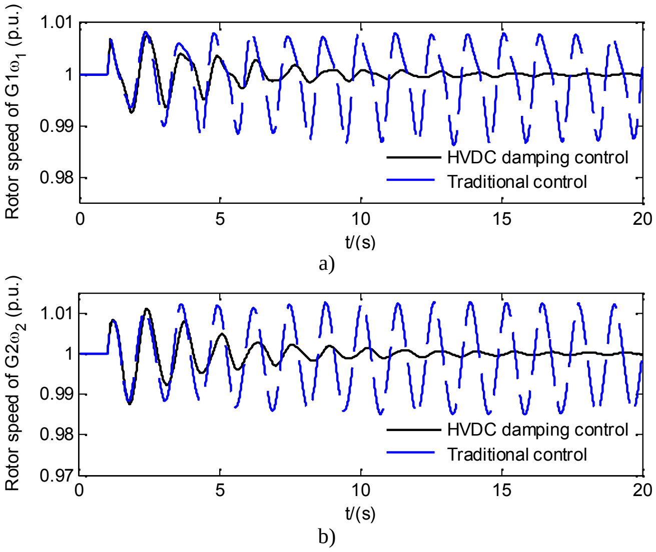
Fig. 4. The power angle of G1 and G2.

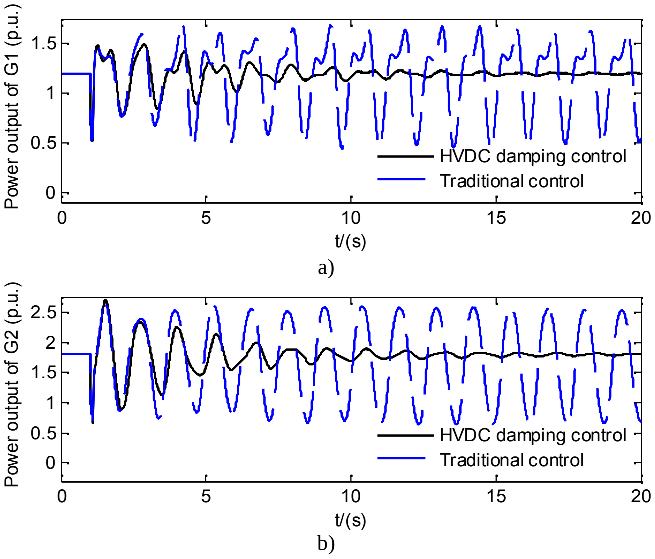


a)

b)

Fig. 5. Generator angular velocity response of G1 and G2.

From these figures we can see that the system will experience a big power/energy oscillation at a frequency of about 0.8 Hz after the disturbance. The traditional control strategy, i.e., the lead-lag control using the frequency difference between the sending and the receiving power grids, aims for maintaining a smooth power transmission in the DC line while with little damping effect, under which the system will go through a severe power/energy fluctuations. The rotor angle and the active power output of the generators will oscillate for a long time. When the newly proposed supplementary HVDC control scheme is applied to the test power system, the short time over load capability of the DC link is taken advantage of to counteract the power/energy imbalance between the two regional power grids. And it is obvious in the figure that the generator power, angle, and interconnect line power flow will have better damping and the oscillation will rapidly disappear. Therefore, the effectiveness and feasibility of the presented HVDC supplementary damping controller are verified.



a)

b)

Fig. 6. The active power of G1 and G2.

Remark 2: The traditional controller is designed based on linearized model and the gain value is chosen with respect to the predefined equilibrium point. Therefore the control effect is closely related to the operation state of the system. A bigger proportionality coefficient can speed up the modulation but increase the overshoot at the same time. The newly proposed controller has more clear physical meaning and a wide range of application for different operating states.The proposed control scheme can enhance dynamic stability of AC/DC parallel power system by improving oscillation damping for all operating conditions. When switching operations occurs that the structure of the system are reconstructed, this scheme does not require the adjustment of the formulation of the controller, only the equivalent parameters of the simplified system need to be real-timely updated which is convenient with the help of WAMS.

V. CONCLUSIONS

In this paper, a supplementary HVDC damping control strategy based on Hamiltonian energy theory and online measurement simplification is presented. The equivalent model of the AC/DC parallel power system is obtained using the COI equivalent method, in which the equivalent parameters are updated based on the real time measurement data from WAMS. Then theoretically, a special generalized Hamilton structure is studied, the stabilization control design method is proposed for the system with a specified structure. The oscillation energy between the inter-connected regional power grid is chosen as the Hamiltonian energy function and proven to be a uniformly Lyapunov function under some reasonable assumption for the AC/DC interconnected power system, hence the switching generalized Hamiltonian system realization of the equivalent system is achieved.

Then the stabilizing controller is designed aiming to decrease the oscillation energy thus can damp out the oscillations ultimately. The sufficient conditions of the power system parameters are detailed studied for practical usage. The mechanism of the dynamic process for the proposed controller is explained. The power modulation capacity of HVDC is taken advantage of to suppress the low-frequency oscillations of the AC/DC parallel power system. The feasibility of the controller in practical power system is discussed under the assumptions that the variables or parameters in the control strategy are directly measureable or indirectly available. The EPRI 7 node system is modelled via the PSCAD software, the dynamics of the system and the measurements are precisely simulated. The simulation results verify the effectiveness and correctness of the proposed control algorithm.

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