RESEARCH ARTICLE

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Multi-time scale dynamics in power electronics-dominated power systems

Abstract Electric power infrastructure has recently undergone a comprehensive transformation from electro-magnetics to semiconductors. Such a development is attributed to the rapid growth of power electronic converter applications in the load side to realize energy conservation and on the supply side for renewable generations and power transmissions using high voltage direct current transmission. This transformation has altered the fundamental mechanism of power system dynamics, which demands the establishment of a new theory for power system control and protection. This paper presents thoughts on a theoretical framework for the coming semiconducting power systems.

Keywords power electronics, power systems, multi-time scale dynamics, mass-spring-damping model, self-stabilizing and en-stabilizing property, multi-time scale power system stabilizer

1 Introduction

Electrical power system today is experiencing historically a first revolution in primary energy sources moving from fossil fuel to fluctuating renewables, and a second revolution in major electrical equipments moving from iron-copper based machines to semiconductor based power converters in different sections of power generations, transmissions, and consumptions. Power converter-interfaced wind and photovoltaic generation are major work-forces for decarbonization of energy worldwide. The geographically uneven distribution of resources and loads in many regions of the world requires the deployment of high voltage direct current transmission (HVDC) for long-distance transmissions [1,2]. At the load side, large or small rotating motors, built decades ago, have been extensively driven from variable frequency converters to improve efficiency in power systems [3].

Electrical and mechanical states in a power system will undergo a dynamic process when subjected to disturbances. The characteristics of the process, which includes how the state locus moves and settles in time, are essential for protections and controls in power systems [4]. Those characteristics in a conventional power system are mostly determined from the integral behavior of the interconnected synchronous machines under the disturbances [5]. With the proliferation of power converters in various sections of power systems, the characteristics are increasingly being determined by the integral behavior of the interconnected power converters and other relevant devices in the system. Comprehensive studies have been conducted on the dynamics in conventional power systems, including stress analysis, line protection, stability analysis, and controls [6,7]; however, existing research on the dynamics of a semiconducting power system mostly focus on the individual power converter segment and have not yet considered the inevitable interactions among the diversified devices in the system. A theoretical framework for this emerging scenario is not in place yet to reflect practices and needs in the real world electric power industry.

The present paper offers insights regarding a theoretical framework for the dynamics in semiconducting power systems. It starts from discussing the multi-time scale feature of the dynamics in a semiconducting power system, as affected by the multi-time scale controls in typical power converter-interfaced devices. Then it proposes a universal mass-spring-damping model based on classic mechanics, with the aim of characterizing the inherent properties of diverse devices in a power system at each time scale of dynamics. To characterize the interactions among devices during dynamics at each time scale, the paper introduces a self-stabilizing and en-stabilizing

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concept to quantify how the dynamic behavior of an individual device in a system is affected by its own properties and those of other devices in the system, and how a device of one property differs from one with different property in the role it plays in system dynamics. Based on the self-stabilizing and en-stabilizing concept for the design of a multi-time scale stabilizer, a basic methodology is presented for optimizing the stress and stability of dynamics in a semiconducting power system.

2 Controllable multi-time scale dynamics in semiconducting power systems

2.1 Multi-time scale controls of converter-interfaced devices

As shown in Fig. 1, power converter interfaced devices displacing iron- and copper-based electric machines and lines, either at generation, transmission, and distribution, or load is a significant trend in today's power system development. Despite the differences in detailed control structures, which depend on applications, a typical power converter-interfaced device consists of a first time-scale controller for maintaining the flow of the alternating current (AC) through the converter output inductor (inductive energy storage component), a second time-scale controller for stabilizing the voltage across the converter direct current (DC) capacitor (capacitive energy storage component) or the AC grid terminal voltage, and a third time-scale controller for maintaining the speed of the mechanical drive train (kinetic energy storage component) or following the reactive power reference assigned from the wind or PV plant, as shown in Fig. 2.

2.2 Controllable multi-time scale dynamics in semiconducting power systems

The AC current controller has the shortest time constant (10 ms), the DC voltage controller has a medium time constant (100 ms), and the mechanical speed controller has

the longest time constant (1000 ms). The time constant depends on the level of energy storage associated with the corresponding controller. When a disturbance lasts for shorter time period or has higher frequency happens, the behavior of a given device responding to the disturbance will be governed by the AC current controller. When the disturbance lasts for medium time period or has medium frequency, the behavior will be first governed by the AC current controller and then by the DC voltage controller. When the disturbance lasts for longer time period or has lower frequency, the behavior will be first governed by the AC current controller, then the DC voltage controller and finally the speed controller. In this way, the dynamics in a semiconducting power system subjected to a disturbance has a multi-time scale nature. This is due to the interactions among closely coupled devices in the system at each time scale, including, for example, interactions among rotors of wind turbines and drive trains of rotating machines at a rotor speed time scale.

2.3 Comparison with multi-time scale dynamics in conventional power systems

Problems of multi-time scale dynamics also exist in conventional power systems. Such problems are due to electromagnetic capacitive and inductive circuits along power lines at short time scales or mechanical drive train circuits in electric rotating machines at long time scales. However, except for the electromechanical time scale dynamics, which is affected by generator excitation controls, other electromagnetic time scale dynamics in a conventional power system are wholly circuit dependent, unlike in the case of a semiconducting power system, where the electromagnetic time scale dynamics are also influenced by controls, such as AC inductor current and DC capacitor voltage controllers.

2.4 The framework of dynamic problems in semiconducting power systems

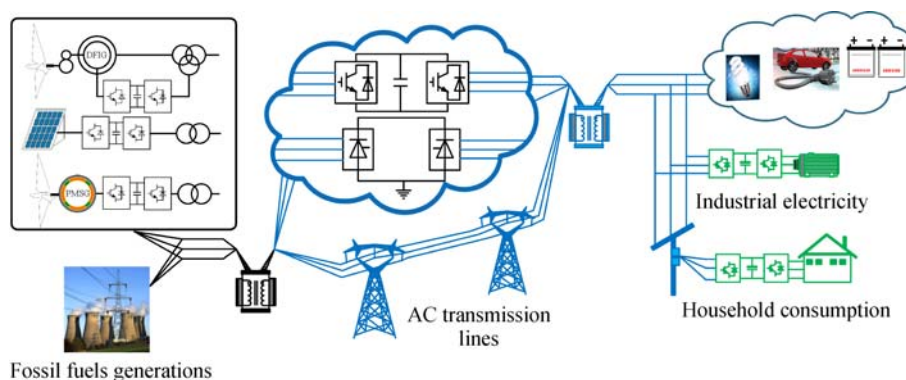A panoramic view of the framework of the dynamic

Fig. 1 Power converter-interfaced devices are increasingly being deployed in power system generation, transmission, and consumption

Fig. 2 Multi-time scale controls for rotor speed, DC voltage, AC active current, reactive power, AC voltage, and AC reactive current in a typical, direct-driven wind turbine

problems in a semiconducting power system is shown in Fig. 3. The characteristics of the dynamics in how the state locus moves and settles in time determine what stress profile a component in the system will be subject to and whether the system will be able to maintain stability following a disturbance. The characteristics are essential for the protection and control design of the system.

Fig. 3 Framework of dynamic problems encountered in semi-conducting power systems

3 Device-inherent properties: Mass-spring-damping model of back electromotive force

The generalized approach to the study system dynamics is to define devices and networks that couple the devices, describe the inherent property of the devices and networks, characterize the interactions among devices through the coupling networks, and design stabilizers to optimize the dynamics and stability of the system at each time scale.

3.1 Back electromotive force (EMF) and mass-spring-damping model for converter-interfaced devices

Given the scale of power systems, the diversity of devices, and the complexity of converter interfaced devices, the development of a universal methodology for describing the inherent properties of devices is highly anticipated. Following the convention in synchronous machines, the voltage potential at the three phase-leg outputs can be defined as a back EMF for a converter-interfaced device. With disturbance set at a given time period or frequency, a corresponding controller will respond depending on the unbalance active power at the energy storage component and drive the motion of the back EMF's phase until the controller settles. Meanwhile, the controller of different time scales for reactive power balancing, as shown in Fig. 2, will also respond to drive the motion of the magnitude of the back EMF until the controller settles. The movement of the phase and the magnitude of the back EMF, which depends on the balance of active and reactive power, appropriately represent the inherent property of a con-verter-interfaced device at each time scale, without regard to the characteristics of the grid to which the device is attached. To easily study the dynamics of a large-scale system consisting of devices with diversified nature, the universal mass-spring-damping model based on classic mechanics, which is used to describe the motion of a mass under an unbalanced force, is deployed to describe the property the back EMF [8]. Therefore, the motion of a device's back EMF is the motion of a two-dimensional mass in a mechanics sense, in which the tangential mass for the motion follows a tangential direction (its state is described by the phase of the back EMF) and a radial mass for the motion follows a radial direction (its state is described by the magnitude of the back EMF). The simplified diagram is shown in Fig. 4.
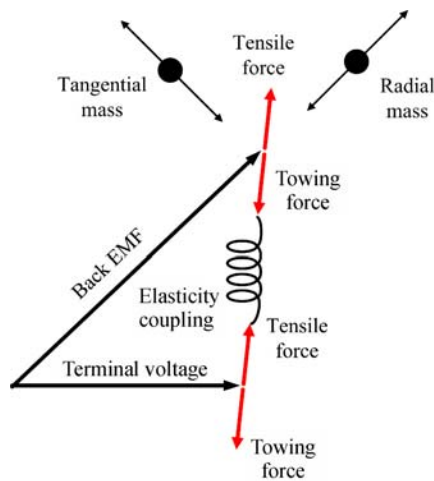
Fig. 4 Phase and magnitude motion of back EMF reflect the motions of the tangential mass and the radial mass in the tangential and the radial directions, respectively

3.2 Mass-spring-damping model for phase motion of back EMF

Taking the doubly fed induction generator (DFIG) wind turbine as an example, the mass-spring-damping model for the phase motion of its back EMF at the electromechanical timescale is resolved, as shown in Figs. 5(a) and 5(b). The model is built based on the linearization of the relationship between the active power output and the phase of the back EMF. The dynamics of the mechanical input power to the drive train of the wind turbine is ignored in the model. The model shows how the balance of power affects the phase acceleration of mass and how such a mass is determined from several parameters, including drive train, speed control, and phase-locked loop (PLL). The model also demonstrates how speed and displacement deviation generate damping and restoring power, and how damping coefficient within the machine itself is affected by speed control and PLL. A DFIG wind turbine can also perform with an inertia depending on the parameters of PLL, without necessarily resorting to the differentiation of grid frequency as the industry is mostly doing so for realizing virtual inertia. However, when the grid frequency differentiation approach is deployed, a mass-spring-damping model can be similarly derived in the form of the mass-damping-spring model. The same structure of the model is also applicable to other control variations, such as virtual synchronous control [9]. From this perspective, converter-interfaced generation under different controls will perform similarly to synchronous generators. The differences exist in the property of inertia and damping coefficient if these are control parameters and disturbance frequency dependent. Therefore, it can be claimed that converter-interfaced generations are variable inertia and damping synchronous machines in terms of the electrical property of the generation to the grid. Unlike the case of synchronous machines, where the mass is an algebraic constant, the mass in the DFIG model is not only adjustable through the speed control and PLL parameters, but also is dynamic, with the acceleration being dependent on the frequency content of the power unbalance.
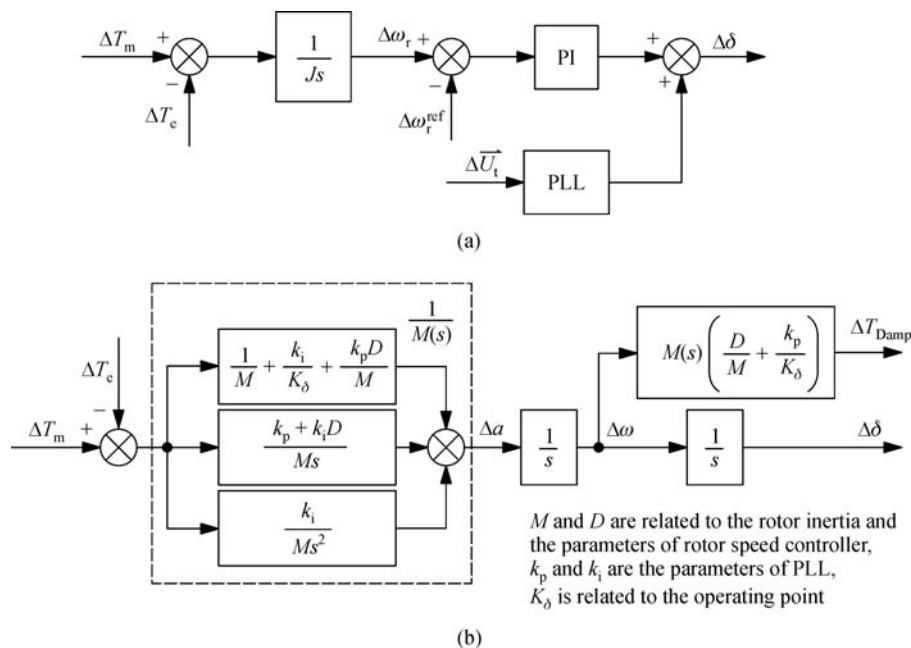

Fig. 5 Mass-spring-damping model for the phase of the back EMF with DFIG at an electromechanical timescale. (a) Simplified diagram for the formation of the phase of the back EMF with DFIG; (b) the mass-spring-damping model for the phase of the back EMF with DFIG

3.3 Mass-spring-damping model for the magnitude motion of back EMF

The DFIG wind turbine machine is taken as an example. The mass-spring-damping model for the magnitude motion of its back EMF at the electromechanical time scale is also developed, as shown in Figs. 6(a) and 6(b). The model illustrates how the motion of the magnitude of the back EMF is influenced by the unbalance of reactive power. During normal operation, and when the magnitude is steady, the acceleration and the speed are both zero, unlike in the case of the phase, where the acceleration is zero but the speed is at 50 or 60 Hz. When the reactive power input and output become unbalanced, the net is stored in the "mass" behind the magnitude, which drives the mass to accelerate and the voltage magnitude to change accordingly depending on the speed. The net reactive power represents the difference between the reference peak instantaneous reactive power in an individual phase that is supplied to the converter and the actual peak instantaneous reactive power in the same phase that is supplied from the converter. The instantaneous reactive power in an individual phase that is supplied from the converter represents real power flow, which moves back and forth between supply and load along the line with three phases summing zero at any temporal and spatial point. The instantaneous reactive power in the same phase that is supplied to the converter comes from the sum of the supplied reactive power from the other two phases. In other words, the instantaneous reactive power supplied to the converter simply circulates among the three phases, which

are enabled by the three-phase interconnection of the converter. Therefore, the "mass," which stores the net reactive power, is physically enabled by the three-phase converter circuit, but its characteristics are determined by the control. The kinetic energy in the mass during the steady state is zero, because the speed is zero. However, it accumulates once an unbalance of reactive power and acceleration of the "mass" occurs. Moreover, the model also shows how speed deviation and magnitude deviation generate damping and restore reactive power to drive back the speed to zero and the magnitude to a steady state, respectively.

3.4 Mass-spring-damping model and dynamic voltage stability mechanism

The mass-spring-damping concept explains the dynamic motion of voltage magnitude based on classic mechanics; such a concept is expected to serve as a foundation for analyzing the mechanism of dynamic voltage stability in power systems, which remains a significant challenge for the power system dynamics community [10]. Similar to angle stability, which is a result of the dynamic interactions among tangential masses in the system, voltage stability is essentially a result of dynamic interactions among radial masses in the system. The motion of tangential mass affects the motion of the radial mass through the former's impact on reactive power, and the motion of the radial mass affects the motion of the tangential mass through the former's impact on active power. Therefore, the dynamics of the tangential masses and the radial masses in a power
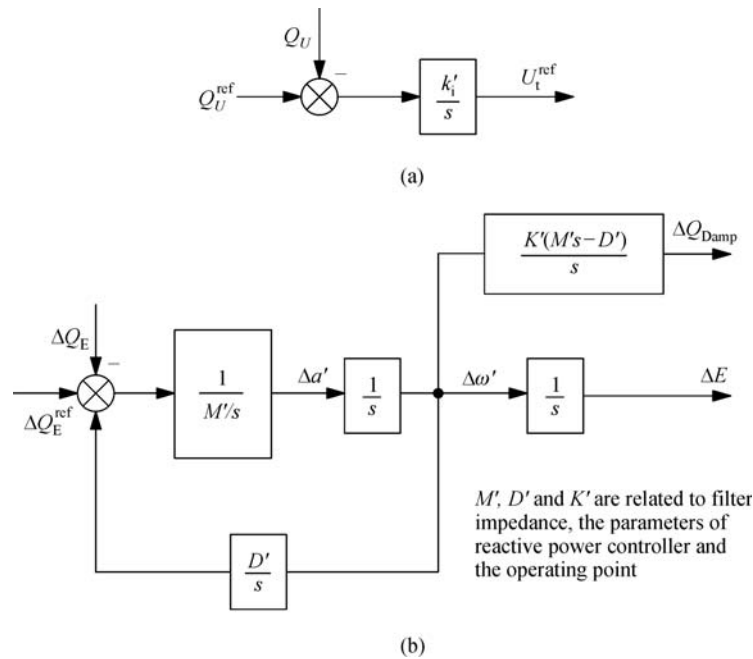

Fig. 6 DFIG reactive power control diagram and the mass-spring-damping representation of the motion of the magnitude of the back EMF. (a) Typical reactive power control diagram for wind turbines; (b) mass-spring-damping model for magnitude motion of the back EMF

system are coupled, that is, angle stability and voltage stability are mutually coupled.

As discussed above, angle stability is a synchronization problem, voltage stability can also be viewed as a synchronization problem, and they both are an integral part of the back EMF's rotating vector synchronization problem.

3.5   Grid network modeling based on classic mechanics

The mass-spring-damping model can be universally deployed to describe the inherent properties of the varying load and generation devices in the system. A review of how grid network, which couples those devices, is still necessary and should be characterized from the mechanics perspective, especially HVDC technology is increasingly displacing conventional AC technology in power transmission. For the problem of a given time scale, wherein the time constant of the grid network is sufficiently short, the network is modeled as a spring in algebraic equations. If the time constant is comparable to the time scale of the problem, modeling the network algebraically becomes inappropriate, and the network must be modeled as a mass to represent the dynamics. For the problem at the AC current time scale, the HVDC light converter station must be modeled as a device taking into account its current controls and the coupling network in the mass-spring-damping model. For the DC voltage time scale problem, the HVDC light station shall be modeled as a device in the mass-spring-damping form, with the coupling grid network among the devices modeled in algebraic equations. For the rotor speed time scale problem, the HVDC light line can be modeled as spring in algebraic equations, but with a spring constant that is controllable by the high-level control of the HVDC station.

Figure 7 shows how the devices of generations and loads work with the coupling grid network when the network is viewed as a spring. Each back EMF of a device interacts with others via the spring network; in this context, the output power of the device governing the motion of the back EMF of the device is determined.

The mass-spring-damping models shown in Figs. 5 and 6 are small signal results and are applicable to the linear systems. Other factors will have to be considered, if the models are deployed for large signal dynamics analysis of non-linear systems.

4   Interaction between back EMFs: Self-stabilizing and en-stabilizing properties of back EMFs

4.1   Priority research on dynamic interaction mechanisms

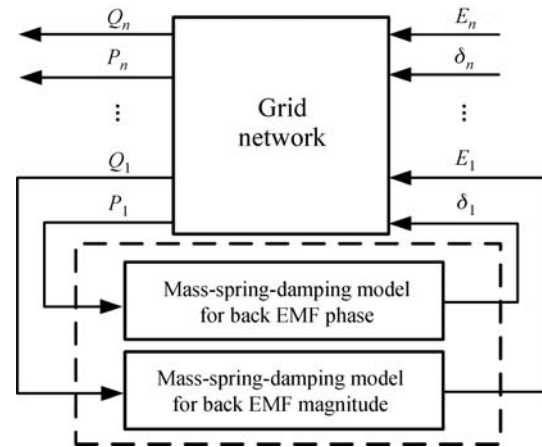Diverse devices in a system can be seen as a mass. System dynamics is then determined from the interactions among

Fig. 7   Interaction mechanism among the back EMF of devices through the grid network

the masses, based on the inherent properties of such masses and the grid coupling network. Disciplined exploration focusing on these interactions should be highly prioritized. Conventional approaches for the dynamic study of power systems, such as model-based analysis for small signal dynamics and energy function-based analysis for large signal dynamics, are mostly based on an integral methodology. While they provide a panoramic view of the dynamics of the system as a whole, they normally do not offer engineers sufficient insights as to how the dynamics of an individual device is affected by other devices and how the roles of a device's properties differ from others in system dynamics. For example, in today's power system, how the dynamics of different generations affect each other and how new generation systems, such as wind and PV, can be optimized to improve their role in system dynamics.

4.2   Self-stabilizing and en-stabilizing concepts

As shown in Fig. 7, the speed or displacement of the phase or magnitude that deviates from a steady state in one device leads to the deviations of power and back EMF in all other devices in the system via the coupling network of the grid. The corresponding power deviation in a studied device is the sum of the power components from the device itself, which results from the deviation of its speed and displacement assuming that no deviations in other devices, and the power components from other devices. The dynamics of a device in the system is affected not only by the property of the device itself, but also by the properties of other devices. The charter in a device to stabilize itself when disturbed is the device's self-stabilizing property, while the charter in other devices to stabilize the disturbed device is other devices' en-stabilizing property. A coupled typical two-mass system is described below

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}$$

$$+ \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$= F. \tag{1}$$

The self-stabilizing property represents the relation between the deviation of the disturbed device's own state and the deviation of the power produced by the disturbed device itself. The en-stabilizing property thus represents the relation between the deviation of another device's state and the deviation of the power produced by the disturbed device, as shown in Eq. (1). The en-stabilizing property can be expressed from the deviation of the state of the disturbed device as

$$\begin{cases} m_1 \ddot{x}_1(s) + [c_{11} - c_{12} g_{21}(s)] \dot{x}_1(s) \\ \quad + [k_{11} - k_{12} g_{21}(s)] x_1(s) = F_1(s) \\ m_2 \ddot{x}_2(s) + [c_{22} - c_{21} g_{12}(s)] \dot{x}_2(s) \\ \quad + [k_{22} - k_{21} g_{12}(s)] x_2(s) = F_2(s) \end{cases} \tag{2}$$

In Eq. (2), c_{11} or c_{22} refers to the self-stabilizing damping coefficient, which represents the corresponding power deviation of the device from the speed deviation of the device itself; c_{12} or c_{21} refers to the en-stabilizing damping coefficient representing the corresponding power deviation of Device 1 or 2 from the speed deviation of Device 2 or 1, while $g_{21}(s)$ or $g_{12}(s)$ refers to en-stabilizing to a self-stabilizing transfer function between the response of the state of Device 1 or 2 when the corresponding state of Device 2 or 1 is excited. Thus, how the dynamics and the stability of a studied device are affected by other devices can be expressed by the effects of other devices on the mass, damping, and restoring forces of the studied device.

4.3 Conceptual look on the en-stabilizing property of wind turbines

Figure 5 shows that, for a wind turbine that uses PLL for grid synchronization, when PLL is designed fast, the phase of the turbine back EMF follows the phase change of the grid terminal voltage instantly at the electrometrical time scale. Therefore, the output power of the turbine will not respond to the phase deviation of the grid terminal voltage and equivalently will not respond to phase deviations of the back EMF of other devices in the system. Unlike synchronous generators, a wind turbine with fast PLL shows no en-stabilizing property in terms of phase dynamics to other devices in the system. However, wind turbines can show an en-stabilizing property in a system with a parameter change. Figure 8 shows how the PLL
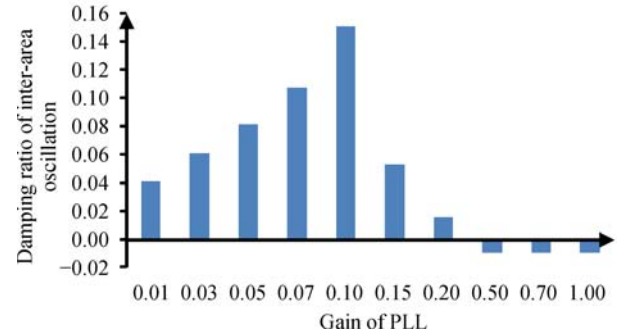

Fig. 8 Corresponding damping ratios of inter-area modes with the variations of PLL gain in wind turbines

parameter change impacts the damping of oscillations among conventional generations. For reactive power controlled wind turbine, as shown in Fig. 6, it can show an en-stabilizing property, with specifics not further discussed, to the deviations of the magnitude of other devices, as the dynamics of the magnitude of the turbine's back EMF, can show inertia, damping and restoring forces to the magnitude deviations of other devices in the system. Figure 9 shows how the voltage control parameter change of wind generation impacts the damping of oscillations among conventional generations.
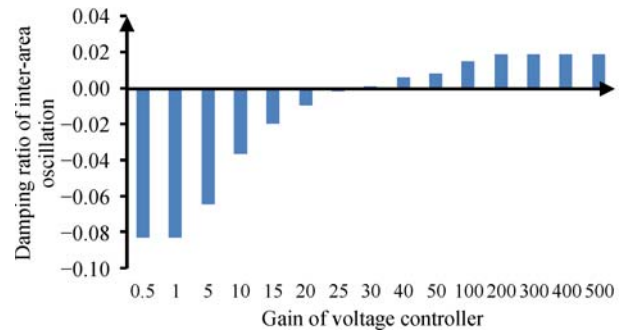

Fig. 9 Corresponding damping ratios of inter-area modes with the variations of voltage controller gain in wind turbines

Equations (1) and (2) are obtained based on linear system background and are applicable for linear system analysis. For a large signal analysis of a non-linear system, while the basic concept holds the insightful, power deviation of a studied device is non-linearly dependent on state deviations of all devices in the system, which includes the studied device itself and other devices in the system. In this case, the self-stabilizing and en-stabilizing characteristics become mutually dependent. It remains a significant challenge to quantitatively analyze the contribution of the self-stabilizing property of the studied device and contributions of the en-stabilizing property of

the other devices in the system to the dynamics and stability of the studied device.

5   Multi-time scale power system stabilizer

The dynamics of a system is at the end the dynamics of an individual device in the system. Equation (1) shows that, for any individual device, the corresponding force generated from state deviation to restore the state is a linear sum of the force that generated from the state deviation of the device itself when assuming that no deviations with other devices and the forces that generated from the state deviations of other devices. The equation can be decoupled to Eq. (2), which shows the net force generated from the state deviation of the studied device itself. This equation physically explains that the stability and dynamics of an individual device are affected by the parameters of all devices and the coupling network. Further studies are needed, such as the sensitivity of the dynamics of an individual device to system parameters, the stability margin related to the given system parameter space, and system designing to ensure stability within the constraints of the device and network parameters.

Without considering further the complexity, the conceptual approach for stability designing the system is to derive the dynamic relationship between net damping and restoring forces versus speed and displacement for each device shown in Fig. 10, and to design the system parameters to ensure sufficient damping and restoring across all frequency spaces.
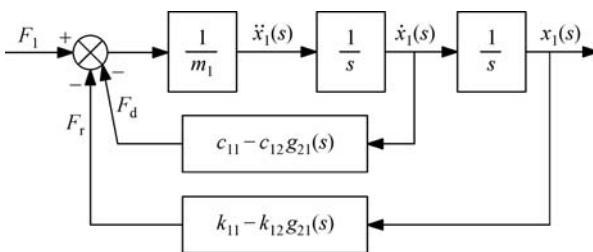

Fig. 10   Block diagram that represents Eq. (2) how net damping and restoring forces are generated from speed or displacement deviation

6   Conclusions

Power system dynamics is being increasingly challenged by power converters that have come to dominate all sections of the system. This development has led to the fundamental changes in the physical mechanisms of dynamics, and thus creates urgent need for new theoretical efforts to fill the space. The challenge relates to how states move and settle in terms of dynamic quality in the first place and dynamic stability in the second place, which is as the case in traditional power system the foundation for power system protection and controls. The major problem in the semiconducting power system is the study of multi-time scale dynamics when responding to system disturbances, as determined by multi-time scale controllers in power converter-based devices. An approach to analyze the problem at each time scale is to model the inherent properties of devices based on the mass-spring-damping model, which is universally deployed in classic mechanics to provide a common language base for the study of a large-scale system consisting of diverse devices. The analytical framework for the multi-time scale problem includes the concepts of self-stabilizing and en-stabilizing, which can offer physical insights that can help engineers understand how the dynamics of individual devices will be affected by other devices and how devices of different properties play distinct roles in system dynamics. This helps especially in clarifying the role of renewable generations in the system dynamics, and how they should perform in the future as the penetration levels increase. Finally, a multi-time scale stabilizer concept, together with a design approach for the stabilizer, is discussed on the surface but emphasizing the need for optimal inherent property regulations especially for renewable generations and HVDC stations since their growing applications in power systems.

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