IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 2, 2019, accepted January 7, 2019, date of publication January 21, 2019, date of current version February 8, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2893409

Decentralized Voltage and Power Control of Multi-Machine Power Systems With Global Asymptotic Stability

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This work was supported in part by the National Natural Science Foundation of China under Grant 51577085, and in part by the Scientific Research Foundation of Guangxi University under Grant XTZ160522.

ABSTRACT Maintaining power system stability is becoming urgent due to the large-scale interconnection of power grids and the high penetration of uncertain renewable energy sources. The excitation control and governor control of synchronous generators have been considered as two crucial measures for enhancing the power system stability. However, a major challenge is to simultaneously achieve global asymptotic stability (GAS), voltage regulation (VR), and power regulation (PR) in the excitation and governor control. In this paper, a Lyapunov-based decentralized control (LBC) is proposed to address this challenge. The time-derivative of the Lyapunov function is designed by the feedback control of synchronous generators in order to guarantee GAS. VR and PR are ensured by considering voltage and power deviations as the feedback variables. The simulation results on the New-England ten-machine power system validate the effectiveness of the proposed LBC in improving power system transient stability and simultaneously achieving VR and PR. Although the proportional–integral- and power system stabilizer-based control can also perform VR and PR, the proposed control has much better dynamic performance and can more significantly improve the system transient stability.

INDEX TERMS Excitation control, governor control, power regulation, power system stability, voltage regulation.

NOMENCLATURE

δ_i	Rotor angle.
ω_i	Rotor speed.
ω_0	Synchronous machine speed.
E'_{qi}	Transient EMF in the q-axis.
E_{qi}	EMF in the q-axis.
E_{fi}	Excitation voltage.
$P_{\mathrm{M}i}$	Mechanical power input.
P_{ei}	Active power of a generator unit.
P_{0i}	Expected value of the active power.
U_{ti}	Generator terminal voltage.
U_{0i}	Expected value of terminal voltage.
Q_{ei}	Reactive power of a generator unit.
D_i	Damping constant.
P_{Li}	Active power load.
Q_{Li}	Reactive power load.
T'_{d0i}	Time constant of excitation winding.
T_{Ji}	Inertia coefficient of a generator unit.
x_{di}	d-axis reactance.
x'_{di}	d-axis transient reactance.
x_{qi}	q-axis reactance.
$Y_{ij} = G_{ij} + jB_{ij}$	The *i*th row and *j*th column element of nodal admittance matrix.
I_{di}	d-axis current.
I_{qi}	q-axis current.
$C_{\mathrm{H}i}$	Power coefficient of high pressure cylinder.
$C_{\mathrm{I}i}$	Power coefficient of intermediate pressure cylinder.
$C_{\mathrm{L}i}$	Power coefficient of low pressure cylinder.

$P_{\mathrm{H}i}$	Power output of high pressure cylinder.
$P_{\mathrm{R}i}$	Power output of re-heater.
$P_{\mathrm{I}i}$	Power output of intermediate pressure cylinder.
$P_{\mathrm{L}i}$	Power output of low pressure cylinder.
$T_{\mathrm{W}i}$	Water starting time.
$T_{\mathrm{WS}i}$	Time constant of the servomotor of HTG system.
$T_{\mathrm{H}i}$	Time constant of high pressure cylinder.
$T_{\mathrm{HS}i}$	Time constant of the servomotor of high pressure cylinder.
$T_{\mathrm{R}i}$	Time constant of the re-heater.
$T_{\mathrm{I}i}$	Time constant of intermediate pressure cylinder.
$T_{\mathrm{IS}i}$	Time constant of the servomotor of intermediate pressure cylinder.
$T_{\mathrm{L}i}$	Time constant of low pressure cylinder.
$U_{\mathrm{W}i}$	Opening control signal of the guide vane.
$U_{\mathrm{H}i}$	Opening control signal of high pressure cylinder.
$U_{\mathrm{I}i}$	Opening control signal of intermediate pressure cylinder.
$\mu_{\mathrm{W}i}$	Water gate opening.
$\mu_{\mathrm{H}i}$	Steam valve opening of high pressure cylinder.
$\mu_{\mathrm{I}i}$	Steam valve opening of intermediate pressure cylinder.

I. INTRODUCTION

Modern electric power systems have complex dynamical properties, uncertain characteristics, lower system inertia, and smaller stability margins, mainly due to the expansion of the power grids and the high penetration of intermittent and uncertain renewable energy sources. The generator excitation control and governor control have been considered as two important measures to enhance the power system stability. Extensive research has been devoted to these two topics.

In particular, when considering the classical third-order model of the generator excitation systems, the power system stability can be greatly enhanced by advanced nonlinear methods such as Direct Feedback Linearization (DFL) [1] and Differential Geometrical Control (DGC) [2]. This is because the third-order excitation system model can be transformed into an equivalent linear system by these approaches. Due to the only equilibrium point of equivalent linear systems, Global Asymptotic Stability (GAS) can be ensured. However, this equivalent transformation will result in a deviation of the generator voltage from the expected value because of the feedback of power angle. In order to ensure generator Voltage Regulation (VR), developing nonlinear voltage controller becomes another important concern of the excitation controller design [3]–[5]. For instance, in [6] and [7], partial feedback linearization methods are proposed based on DGC to design excitation controllers to enhance power system stability. A detailed sub-transient model of machines is used to develop the nonlinear excitation control law based on DGC in [8]. Other approaches such as energy-based disturbance attenuation [9], *Hamiltonian* theory [10], and adaptive approach [11], [12], are also used to develop excitation controllers to improve the transient stability of power systems. There are also some attempts in generator excitation control system to simultaneously address GAS and VR based on *Lyapunov* function in multi-machine power system [13] and single-machine infinite-bus power system [14], respectively.

Besides generator excitation control, governor control is also viewed as one of the most effective measures to improve the power system stability, because the response of governor can be improved by the electro-hydraulic governor [15]. In [16], a DGC-based governor control is proposed for the steam-turbine governor system of the multi-machine power system to enhance system stability. In [17], an exact feedback linearization technique is applied to design the governor control for the hydraulic turbine governor system considering its inherent non-minimum phase property to ensure the stability of a single-machine infinite-bus system. However, the global stability cannot be guaranteed due to the local nature of the proposed control strategy. In [15], a nonlinear synergetic governor controller is proposed for turbine generators to enhance power system stability based on DGC. Although the steam turbine generator model can be exactly linearized, the rotor angle has to be introduced as the feedback, the reference value of which is hard to calculate due to dynamic power flow. Besides DGC, *Lyapunov*-based approaches have also been developed to design governor controllers and to improve the system stability with parametric uncertainties and exogenous disturbances [18], [19]. However, GAS is not addressed in theory.

Traditionally, the excitation control and governor control are usually considered as two independent loops due to the difficulty in jointly designing controllers [16], [20], [21]. In order to design excitation control or governor control independently, assumptions that neglect the mutual influence of the excitation system and governor system must be introduced. In [16], a DGC-based method is proposed only for the steam turbine governor system to enhance transient stability, where the transient EMF in q-axis has to be assumed constant. In [20] and [21], a decentralized excitation control and steam valve control are discussed by DFL to improve system stability based on the assumption that the mechanical power and the transient EMF in q-axis are constant.

When the mutual interactions between excitation and governor control loops are considered, better transient stability can be achieved [22]. Taking into account this mutual interaction, DGC is applied to design the excitation control and governor control in [23]. The GAS can be achieved because the equivalent linear system only has one equilibrium point. However, since neither voltage deviation

nor power deviation is considered as feedback variables, VR and power regulation (PR) cannot be ensured. A nonlinear decentralized control of the excitation and steam-valve system is proposed to enhance power system stability based on DGC in [24], but PR cannot be achieved due to the lack of power deviation feedback. In [25], a high-order sliding mode technique is used to coordinate the excitation control and steam-valve control for multi-machine power systems without considering VR and PR. In [26], an adaptive backstepping approach is developed to coordinate the nonlinear excitation control and steam-valve control. However, without a voltage deviation feedback, VR cannot be achieved. Therefore, for the joint excitation control and governor control, achieving GAS, VR, and PR at the same time is still an open question.

In this paper, the work in [13] is extended to coordinate excitation control and governor control of multi-machine power systems to simultaneously fulfill GAS, VR, and PR by a *Lyapunov*-based control (LBC). The contributions can be summarized as follows.

- The GAS of a system is guaranteed by satisfying the condition of GAS in Lyapunov theorem based on the design of the eigenvalues of a symmetric real matrix;
- Voltage and power deviations are introduced as the feedback variables to determine the negative definiteness of the time-derivative of the *Lyapunov* function and to further ensure VR and PR;
- The proposed LBC method can simultaneously achieve VR, PR, and GAS based on local measurements.

The remainder of this paper is organized as follows. In Section II, the models of the generator excitation and governor control systems are introduced. In Section III, the control objectives on excitation and governor control systems are presented for different types of generators. In Section IV, *Lyapunov*-based decentralized excitation and governor control is proposed for multi-machine power systems. Simulations on the New-England ten-machine power system are provided to validate the effectiveness of the proposed control approach in Section V, which is followed by the conclusions in Section VI.

II. MODELS OF GENERATOR EXCITATION AND GOVERNOR CONTROL SYSTEMS

Generator control systems consist of the excitation control system and the governor control system.

A. EXCITATION CONTROL SYSTEM

Extensive research has been devoted to design decentralized excitation controllers to enhance power system stability [1]–[6]. The classical third-order model of the excitation control system is considered with fast excitation, i.e., the exciter time constant almost equals to zero, for which the mathematical models can be expressed as follows.

Mechanical equations:

$$\dot{\delta}_i = \omega_i - \omega_0 \tag{1}$$

$$T_{Ji}\dot{\omega}_i = (P_{mi}\omega_0 - P_{ei}\omega_0 - D_i(\omega_i - \omega_0)) \tag{2}$$

Generator electrical dynamic:

$$T'_{d0i}\dot{E}'_{qi} = (E_{fi} - E_{qi}) \tag{3}$$

Electrical equations:

$$E_{qi} = E'_{qi} + (x_{di} - x'_{di})I_{di} \tag{4}$$

$$I_{di} = \sum_{j=1}^{n} E'_{qj}(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \tag{5}$$

$$I_{qi} = \sum_{j=1}^{n} E'_{qj}(B_{ij}\sin\delta_{ij} + G_{ij}\cos\delta_{ij}) \tag{6}$$

Terminal voltage equations:

$$U_{tdi} = x'_{di}I_{qi} \tag{7}$$

$$U_{tqi} = E'_{qi} - x'_{di}I_{di} \tag{8}$$

$$U_{ti} = \sqrt{U_{tdi}^2 + U_{tqi}^2} \tag{9}$$

Power equations:

$$P_{ei} = E'_{qi}I_{qi} \tag{10}$$

$$Q_{ei} = E'_{q}I_{di} - x'_{d}I_{i}^2 \tag{11}$$

B. GOVERNOR CONTROL SYSTEM

The Hydraulic Turbine Governor (HTG) system and Steam Turbine Governor (STG) system are introduced here.

1) HTG CONTROL SYSTEM

The HTG control system is used to drive hydro-generator units, which exhibits high-order nonlinear behavior. If not considering the elasticity effect of the water column, the hydraulic turbine can be described as [23]:

$$\dot{P}_{\mathrm{M}i} = \frac{2}{T_{\mathrm{W}i}}(-P_{\mathrm{M}i} + \mu_{\mathrm{W}i} - T_{\mathrm{W}i}\dot{\mu}_{\mathrm{W}i}). \tag{12}$$

The water-gate servomotor regulating the water gate opening is represented by a first-order inertial system as:

$$\dot{\mu}_{\mathrm{W}i} = \frac{1}{T_{\mathrm{WS}i}}(-\mu_{\mathrm{W}i} + U_{\mathrm{W}i}). \tag{13}$$

2) STG CONTROL SYSTEM

The STG control system is used to drive the turbo-generator units. The Reheat-type Governor (RG) control system used for large steam-turbine generators can be described by (14)-(20) [27]:

High Pressure (HP) cylinder dynamic:

$$\dot{P}_{\mathrm{H}i} = \frac{1}{T_{\mathrm{H}i}}(C_{\mathrm{H}i}\mu_{\mathrm{H}i} - P_{\mathrm{H}i}). \tag{14}$$

The servomotor of the HP cylinder used to regulate the steam flow can be represented by

$$\dot{\mu}_{\mathrm{H}i} = \frac{1}{T_{\mathrm{HS}i}}(U_{\mathrm{H}i} - \mu_{\mathrm{H}i}). \tag{15}$$

Re-heater dynamic:

$$\dot{P}_{\mathrm{R}i} = \frac{1}{T_{\mathrm{R}i}}(\frac{P_{\mathrm{H}i}}{C_{\mathrm{H}i}} - P_{\mathrm{R}i}). \tag{16}$$

Intermediate Pressure (IP) cylinder dynamic:

$$\dot{P}_{\mathrm{I}i} = \frac{1}{T_{\mathrm{I}i}}(C_{\mathrm{I}i}P_{\mathrm{R}i}\mu_{\mathrm{I}i} - P_{\mathrm{I}i}). \tag{17}$$

The servomotor of the IP cylinder is used to regulate the steam valve opening and can be described by

$$\dot{\mu}_{\mathrm{I}i} = \frac{1}{T_{\mathrm{IS}i}}(U_{\mathrm{I}i} - \mu_{\mathrm{I}i}). \tag{18}$$

Low Pressure (LP) cylinder dynamic:

$$\dot{P}_{\mathrm{L}i} = \frac{1}{T_{\mathrm{L}i}}(\frac{C_{\mathrm{L}i}P_{\mathrm{I}i}}{C_{\mathrm{I}i}} - P_{\mathrm{L}i}). \tag{19}$$

For the reheat type of generation system, the mechanical power input can be calculated as:

$$P_{\mathrm{M}i} = P_{\mathrm{H}i} + P_{\mathrm{I}i} + P_{\mathrm{L}i} \tag{20}$$

where

$$P_{\mathrm{H}i} = C_{\mathrm{H}i}P_{\mathrm{M}i}, \quad P_{\mathrm{I}i} = C_{\mathrm{I}i}P_{\mathrm{M}i}, \; P_{\mathrm{L}i} = C_{\mathrm{L}i}P_{\mathrm{M}i},$$
$$C_{\mathrm{H}i} + C_{\mathrm{I}i} + C_{\mathrm{L}i} = 1.$$

III. CONTROL OBJECTIVES ON EXCITATION AND GOVERNOR CONTROL SYSTEMS

For the controller design of the excitation and governor systems, VR, PR, and GAS are here considered as control objectives, as mentioned in the introduction section. Therefore, the generator variables such as terminal voltage have to be introduced into the feedback to achieve such control objectives. For instance, the feedbacks of voltage and power can be used to perform VR and PR [4], whereas the rotor speed feedback can improve the transient stability of power systems [3]. For clarity, we respectively discuss these control objectives for the excitation control system and different types of governor control system, as follows.

A. CONTROL OBJECTIVE OF EXCITATION CONTROL SYSTEM

The excitation control system is the only way to ensure generator terminal voltage, and thus the terminal voltage should be used as the feedback of the excitation controller. Besides, in real power systems, the rotor speed is always used as the feedback input of power system stabilizer for excitation control to damp system oscillations [29]. Therefore, the control objectives of the excitation system should include

$$\begin{cases} \Delta U_{ti} = U_{ti} - U_{0i} \\ \Delta\omega_i = \omega_i - 1. \end{cases} \tag{21}$$

B. CONTROL OBJECTIVE OF GOVERNOR CONTROL SYSTEM

1) HTG CONTROL SYSTEM

The HTG control system is used to regulate the power output of hydro-generators by controlling the water flow. The key to controlling the water flow is to regulate the water-gate opening according to a regulation signal. Therefore, both the power output and the water gate opening are considered as the control objectives of the nonlinear control as:

$$\begin{cases} \Delta P_{ei} = P_{ei} - P_{0i} \\ \Delta\mu_{\mathrm{W}i} = \mu_{\mathrm{W}i} - P_{ei}. \end{cases} \tag{22}$$

2) STG CONTROL SYSTEM

For the reheat-type governor control system, PR is controlled by the steam-value opening of HP and IP cylinders. From (14), (15), and (20), the objective of the steam-valve opening of HP cylinder can be developed. Similarly, we can deduce the objective of the steam-valve opening of IP cylinder from (17) and (20). Accordingly, we consider the following objectives:

$$\begin{cases} \Delta P_{ei} = P_{ei} - P_{0i} \\ \Delta\mu_{\mathrm{H}i} = \mu_{\mathrm{H}i} - P_{ei} \\ \Delta\mu_{\mathrm{I}i} = \mu_{\mathrm{I}i} - P_{ei}/P_{\mathrm{R}i}. \end{cases} \tag{23}$$

IV. DECENTRALIZED VOLTAGE AND POWER CONTROL WITH GAS

We here design decentralized excitation and governor controllers to achieve GAS, VR, and PR based on the *Lyapunov* theorem.

A. LYAPUNOV FUNCTION

We consider a power system with n^1 hydro-generators denoted by a set G^1 and n^2 reheat-type turbo-generators denoted by a set G^2. The jth element in G^1 and G^2 are respectively denoted by g_j^1 and g_j^2. With the control objectives shown in (21)-(23), a *Lyapunov* function can be constructed as:

$$V = \frac{1}{2}\sum_{j\in G^1}\left(\Delta\omega^2_{g_j^1} + \Delta U^2_{t\,g_j^1} + \Delta P^2_{eg_j^1} + \Delta\mu^2_{\mathrm{W}g_j^1}\right) + \frac{1}{2}\sum_{j\in G^2}\left(\Delta\omega^2_{g_j^2} + \Delta U^2_{tg_j^2} + \Delta P^2_{eg_j^2} + \Delta\mu^2_{\mathrm{H}g_j^2} + \Delta\mu^2_{\mathrm{I}g_j^2}\right). \tag{24}$$

The time-derivative of V can be expressed as

$$\dot{V} = \Delta\boldsymbol{y}^T\Delta\dot{\boldsymbol{y}} \tag{25}$$

where

$$\Delta\boldsymbol{y} = [(\Delta\boldsymbol{y}_1^1)^T, \cdots, (\Delta\boldsymbol{y}_{n^1}^1)^T, (\Delta\boldsymbol{y}_1^2)^T, \cdots, (\Delta\boldsymbol{y}_{n^2}^2)^T]^T$$

and

$$\Delta\boldsymbol{y}_j^1 = \left[\Delta\omega_{g_j^1}, \Delta U_{tg_j^1}, \Delta P_{eg_j^1}, \Delta\mu_{\mathrm{W}g_j^1}\right]^T, \quad j = 1, \cdots, n^1$$

$$\Delta\boldsymbol{y}_j^2 = \left[\Delta\omega_{g_j^2}, \Delta U_{tg_j^2}, \Delta P_{eg_j^2}, \Delta\mu_{\mathrm{H}g_j^2}, \Delta\mu_{\mathrm{I}g_j^2}\right]^T, \quad j = 1, \cdots, n^2.$$

As in (25), the negative definiteness of $\dot{V}$ is determined by the differential trajectory $\Delta\dot{\boldsymbol{y}}$. Therefore, we need to design the differential trajectory $\Delta\dot{\boldsymbol{y}}$ through control inputs in order to ensure the negative definiteness of $\dot{V}$.

B. DESIGN OF DIFFERENTIAL TRAJECTORY $\Delta\dot{y}$

In order to design the differential trajectory $\Delta\dot{\boldsymbol{y}}$ through control inputs, we must build the relationship between $\Delta\dot{\boldsymbol{y}}$ and control inputs.

For the excitation control system, the time-derivative of the terminal voltage in $\Delta \boldsymbol{y}$ of (25) can be deduced from (3)-(4), (7)-(9), and (21) for each generating unit as [13]:

$$\Delta \dot{U}_{ti} = c_i^{\mathrm{E}} + d_i^{\mathrm{E}} E_{fi} \tag{26}$$

where c_i^{E} and d_i^{E} describe the relationship between $\Delta \dot{U}_{ti}$ and the excitation voltage E_{fi} as

$$c_i^{\mathrm{E}} = \frac{1}{U_{ti}}[x_{qi}^2 I_{qi}\dot{I}_{qi} - \frac{1}{T'_{d0i}}\sqrt{U_{ti}^2-(x_{qi}I_{qi})^2} \cdot (\sqrt{U_{ti}^2-(x_{qi}I_{qi})^2} + x_{di}I_{di} + T'_{d0i}x'_{di}\dot{I}_{di})]$$

$$d_i^{\mathrm{E}} = \frac{\sqrt{U_{ti}^2-(x_{qi}I_{qi})^2}}{U_{ti}T'_{d0i}} = \frac{U_{tqi}}{U_{ti}T'_{d0i}}.$$

For the HTG control system, the time-derivative of $\Delta\mu_{\mathrm{W}i}$ in $\Delta \boldsymbol{y}$ can be obtained from (13) and (22) as

$$\Delta\dot{\mu}_{\mathrm{W}i} = c_i^{\mathrm{W}} + d_i^{\mathrm{W}} U_{\mathrm{W}i}, \tag{27}$$

where

$$c_i^{\mathrm{W}} = -\frac{\mu_{\mathrm{W}i}}{T_{\mathrm{WS}i}} - \dot{P}_{ei}, \quad d_i^{\mathrm{W}} = \frac{1}{T_{\mathrm{WS}i}}.$$

Likewise, $\Delta\dot{\mu}_{\mathrm{H}i}$ and $\Delta\dot{\mu}_{\mathrm{I}i}$ can be derived from (15), (18), and (23) for a reheat-type governor system as:

$$\begin{cases} \Delta\dot{\mu}_{\mathrm{H}i} = c_i^{\mathrm{H}} + d_i^{\mathrm{H}} U_{\mathrm{H}i} \\ \Delta\dot{\mu}_{\mathrm{I}i} = c_i^{\mathrm{I}} + d_i^{\mathrm{I}} U_{\mathrm{I}i}, \end{cases} \tag{28}$$

where

$$c_i^{\mathrm{H}} = -\frac{\mu_{\mathrm{H}i}}{T_{\mathrm{HS}i}} - \dot{P}_{ei}, \quad d_i^{\mathrm{H}} = \frac{1}{T_{\mathrm{HS}i}}, \quad c_i^{\mathrm{I}} = -\frac{\mu_{\mathrm{I}i}}{T_{\mathrm{IS}i}} - \dot{P}_i, \quad d_i^{\mathrm{I}} = \frac{1}{T_{\mathrm{IS}i}}$$

and

$$P_i = \frac{P_{ei}}{P_{\mathrm{R}i}}.$$

While applying the approach in [13], (21)-(23) can be used to actively construct a completely controllable linear system with (26)-(28), as follows:

$$\Delta\dot{\boldsymbol{y}} = \boldsymbol{A}\Delta\boldsymbol{y} + \boldsymbol{B}(\boldsymbol{c} + \boldsymbol{d}\boldsymbol{u}), \tag{29}$$

where

$$\boldsymbol{A} = diag\left(\boldsymbol{A}_1^1, \cdots, \boldsymbol{A}_{n^1}^1, \boldsymbol{A}_1^2, \cdots, \boldsymbol{A}_{n^2}^2\right)$$

$$\boldsymbol{B} = diag\left(\boldsymbol{B}_1^1, \cdots, \boldsymbol{B}_{n^1}^1, \boldsymbol{B}_1^2, \cdots, \boldsymbol{B}_{n^2}^2\right)$$

$$\boldsymbol{c} = \left[(\boldsymbol{c}_1^1)^T, \cdots, (\boldsymbol{c}_{n^1}^1)^T, (\boldsymbol{c}_1^2)^T, \cdots, (\boldsymbol{c}_{n^2}^2)^T\right]^T$$

$$\boldsymbol{u} = \left[(\boldsymbol{u}_1^1)^T, \cdots, (\boldsymbol{u}_{n^1}^1)^T, (\boldsymbol{u}_1^2)^T, \cdots, (\boldsymbol{u}_{n^2}^2)^T\right]^T$$

$$\boldsymbol{d} = diag\left(\boldsymbol{d}_1^1, \cdots, \boldsymbol{d}_{n^1}^1, \boldsymbol{d}_1^2, \cdots, \boldsymbol{d}_{n^2}^2\right).$$

Here we have

$$\boldsymbol{A}_j^1 = \begin{bmatrix} a^1_{g_j^1} & a^2_{g_j^1} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & a^3_{g_j^1} & a^4_{g_j^1} \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \boldsymbol{B}_j^1 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\boldsymbol{c}_j^1 = [c^{\mathrm{E}}_{g_j^1}, c^{\mathrm{W}}_{g_j^1}]^T, \quad \boldsymbol{u}_j^1 = [E_{fg_j^1}, U_{\mathrm{W}g_j^1}]^T, \quad \boldsymbol{d}_j^1 = \begin{bmatrix} d^{\mathrm{E}}_{g_j^1} & 0 \\ 0 & d^{\mathrm{W}}_{g_j^1} \end{bmatrix},$$

and

$$\boldsymbol{A}_j^2 = \begin{bmatrix} a^1_{g_j^2} & a^2_{g_j^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a^3_{g_j^2} & a^4_{g_j^2} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \boldsymbol{B}_j^2 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\boldsymbol{c}_j^2 = [c^{\mathrm{E}}_{g_j^2}, c^{\mathrm{H}}_{g_j^2}, c^{\mathrm{I}}_{g_j^2}]^T, \quad \boldsymbol{u}_j^2 = [E_{fg_j^2}, U_{\mathrm{H}g_j^2}, U_{\mathrm{I}g_j^2}]^T,$$

$$\boldsymbol{d}_j^2 = \begin{bmatrix} d^{\mathrm{E}}_{g_j^2} & 0 & 0 \\ 0 & d^{\mathrm{H}}_{g_j^2} & 0 \\ 0 & 0 & d^{\mathrm{I}}_{g_j^2} \end{bmatrix}.$$

Let $\boldsymbol{v} = \boldsymbol{c} + \boldsymbol{d}\boldsymbol{u}$, (29) can be rewritten as

$$\Delta\dot{\boldsymbol{y}} = \boldsymbol{A}\Delta\boldsymbol{y} + \boldsymbol{B}\boldsymbol{v} \tag{30}$$

Remark 1: Equation (30) is designed to regulate the differential trajectory $\Delta\dot{\boldsymbol{y}}$ through control inputs. According to linear control theory, by properly selecting the constants $a^i_{g_j^1}$ and $a^i_{g_j^2}$ $(i = 1, 2, 3, 4)$ we can make sure that the system in (30) is a completely controllable linear system.

Remark 2: With complete controllability, the poles of (30) can be arbitrarily arranged through virtual inputs $\boldsymbol{v}$, which means that the trajectory of time-derivative $\Delta\dot{\boldsymbol{y}}$ can be controlled by virtual inputs based on pole arrangements. Therefore, we can use (30) to regulate the negative definiteness of (25).

Remark 3: Noted that (30) is constructed with the variables such as voltage and power deviations to determine the negative definiteness of the time-derivative of the Lyapunov function. Therefore, GAS is closely related to VR and PR, and thus GAS, PR, and VR are considered simultaneously.

For (30), the virtual control can be designed as

$$\boldsymbol{v} = -\boldsymbol{K}\Delta\boldsymbol{y}, \tag{31}$$

where

$$\boldsymbol{K} = diag(\boldsymbol{k}_1^1, \cdots, \boldsymbol{k}_{n^1}^1, \boldsymbol{k}_1^2, \cdots, \boldsymbol{k}_{n^2}^2)$$

and

$$\boldsymbol{k}_j^1 = \begin{bmatrix} k^1_{g_j^1} & k^2_{g_j^1} & 0 & 0 \\ 0 & 0 & k^3_{g_j^1} & k^4_{g_j^1} \end{bmatrix}$$

$$\boldsymbol{k}_j^2 = \begin{bmatrix} k^1_{g_j^2} & k^2_{g_j^2} & 0 & 0 & 0 \\ 0 & 0 & k^3_{g_j^2} & k^4_{g_j^2} & 0 \\ 0 & 0 & 0 & 0 & k^5_{g_j^2} \end{bmatrix}.$$

The decentralized excitation and governor control can be obtained from $\boldsymbol{v} = \boldsymbol{c} + \boldsymbol{d}\boldsymbol{u}$ and (31) as

$$\boldsymbol{u} = \boldsymbol{d}^{-1}(-\boldsymbol{K}\Delta\boldsymbol{y} - \boldsymbol{c}), \tag{32}$$

which is actually

$$\boldsymbol{u}_j^1 = \begin{bmatrix} E_{fg_j^1} \\ U_{\mathrm{W}g_j^1} \end{bmatrix} = \begin{bmatrix} (-k^1_{g_j^1}\Delta\omega_{g_j^1} - k^2_{g_j^1}\Delta U_{tg_j^1} - c^{\mathrm{E}}_{g_j^1})/d^{\mathrm{E}}_{g_j^1} \\ (-k^3_{g_j^1}\Delta P_{eg_j^1} - k^4_{g_j^1}\Delta\mu_{\mathrm{W}g_j^1} - c^{\mathrm{W}}_{g_j^1})/d^{\mathrm{W}}_{g_j^1} \end{bmatrix},$$

$$\boldsymbol{u}_j^2 = \begin{bmatrix} E_{fg_j^2} \\ U_{\mathrm{H}g_j^2} \\ U_{\mathrm{I}g_j^2} \end{bmatrix} = \begin{bmatrix} (-k^1_{g_j^2}\Delta\omega_{g_j^2} - k^2_{g_j^2}\Delta U_{tg_j^2} - c^{\mathrm{E}}_{g_j^2})/d^{\mathrm{E}}_{g_j^2} \\ (-k^3_{g_j^2}\Delta P_{eg_j^2} - k^4_{g_j^2}\Delta\mu_{\mathrm{H}g_j^2} - c^{\mathrm{H}}_{g_j^2})/d^{\mathrm{H}}_{g_j^2} \\ (-k^5_{g_j^2}\Delta\mu_{\mathrm{I}g_j^2} - c^{\mathrm{I}}_{g_j^2})/d^{\mathrm{I}}_{g_j^2} \end{bmatrix}.$$

C. JUSTIFICATION ON GAS

Substituting (29) and (32) into (25), the time-derivative of the *Lyapunov* function can be rewritten as:

$$\dot{V} = \Delta\boldsymbol{y}^T \boldsymbol{\Phi} \Delta\boldsymbol{y}, \tag{33}$$

where

$$\boldsymbol{\Phi} = \boldsymbol{A} - \boldsymbol{BK}. \tag{34}$$

In (34), it is difficult to decide the negative definiteness of $\boldsymbol{\Phi}$. We define a symmetric real matrix $\boldsymbol{\Psi} = \boldsymbol{\Phi} + \boldsymbol{\Phi}^T$. According to matrix theory, the negative definiteness of $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$ is equivalent. For the generator excitation and governor models, we can ensure that all of the eigenvalues of $\boldsymbol{\Psi}$ are negative real numbers by properly choosing the coefficient $\boldsymbol{K}$. Therefore, $\boldsymbol{\Phi}$ can be negative definite, i.e., we have:

$$\dot{V} = \Delta\boldsymbol{y}^T \boldsymbol{\Phi} \Delta\boldsymbol{y} < 0 \text{ for any } \Delta\boldsymbol{y} \neq \boldsymbol{0}. \tag{35}$$

Let $\Delta\boldsymbol{x}$ be the state deviation vector of dynamic equations of a power system. If we have

$$\dot{V} = \Delta\boldsymbol{y}^T \boldsymbol{\Phi} \Delta\boldsymbol{y} < 0 \text{ for any } \Delta\boldsymbol{x} \neq \boldsymbol{0}. \tag{36}$$

then GAS can be accomplished according to the *Lyapunov* theorem. Therefore, we need to prove that for any $\Delta\boldsymbol{x} \neq \boldsymbol{0}$, there is $\Delta\boldsymbol{y} \neq \boldsymbol{0}$.

For convenience, we arrange $\Delta\boldsymbol{x}$ and $\Delta\boldsymbol{y}$ as:

$$\begin{cases} \Delta\boldsymbol{x} = [\Delta\delta_1, \Delta E'_{q1}, \Delta\omega_1, \cdots, \Delta\delta_n, \Delta E'_{qn}, \Delta\omega_n, \Delta\boldsymbol{x}_g]^T \\ \Delta\boldsymbol{y} = [\Delta U_{t1}, \Delta P_{e1}, \Delta\omega_1, \cdots, \Delta U_{tn}, \Delta P_{en}, \Delta\omega_n, \Delta\boldsymbol{y}_g]^T \end{cases} \tag{37}$$

where $n = n^1 + n^2$; $\Delta\boldsymbol{x}_g$ and $\Delta\boldsymbol{y}_g$ are the state vector and feedback vector of the governor systems.

We need to show that for any nonzero element of $\Delta\boldsymbol{x}(\Delta\delta_i$, $\Delta E'_{qi}$, $\Delta\omega_i$, or $\Delta\boldsymbol{x}_g)$, there is $\Delta\boldsymbol{y} \neq \boldsymbol{0}$. Specifically, 1) When $\Delta\delta_i$ or $\Delta E'_{qi}$ is not equal to zero, ΔU_{ti} and ΔP_{ei} cannot be equal to zero at the same time because in that case the generators will not be controllable; 2) When $\Delta\omega_i \neq 0$, there is $\Delta\boldsymbol{y} \neq \boldsymbol{0}$, because $\Delta\omega_i$ is an element of $\Delta\boldsymbol{y}$; 3) Considering the models and the physical characteristics of the governor systems, we can deduce $\Delta\boldsymbol{x}_g \neq \boldsymbol{0} \Rightarrow \Delta\boldsymbol{y}_g \neq \boldsymbol{0}$. For example, when $\Delta\mu_{Ci}$ in $\Delta\boldsymbol{x}_g$ is not equal to zero, ΔP_{ei} in $\Delta\boldsymbol{y}_g$ will not be equal to zero, that is because the change of the steam valve opening will surely result in the change of power output.

Therefore, for any $\Delta\boldsymbol{x} \neq \boldsymbol{0}$, there is indeed $\Delta\boldsymbol{y} \neq \boldsymbol{0}$. This means that (36) holds, and thus GAS is guaranteed.

D. DISCUSSION ON PERFORMING GAS, VR, AND PR

The *Lyapunov* function in (24) is constructed by a quadratic form of the feedback in (21)-(23). The time-derivative of the *Lyapunov* function is also designed as a quadratic form of the feedback through control inputs based on the design of a differential trajectory. Therefore, GAS is closely related to the tracking errors of the system variables such as the terminal voltage and the active power. While achieving the stability of a system, the voltage and power deviations are also decreasing. When the system finally stabilizes in a steady state due to the feedback control, the tracking errors of the voltage and power will also be eliminated. Therefore, GAS, VR, and PR are achieved simultaneously.

V. SIMULATION AND DISCUSSIONS

A. POWER SYSTEM MODEL

In order to validate the effectiveness of the proposed nonlinear controller, we consider the New England ten-machine power system as illustrated in Fig. 1. Generators 1-5, 8, and 9 are large reheat-type generators, generators 6 and 7 are hydro- generators, and generator 10 represents the infinite bus. More details about the parameters of this system can be found in [31].

The physical limits of the excitation voltages for the excitation control systems are set as

$$-5 \leq E_{fg_j^1} \leq 5, \quad -5 \leq E_{fg_j^2} \leq 5$$

The physical limits of the governor control systems are:

$$0 \leq \mu_{\mathrm{W}g_j^1} \leq 7, \quad 0 \leq \mu_{\mathrm{H}g_j^2} \leq 10, \; 0 \leq \mu_{\mathrm{I}g_j^2} \leq 1.1.$$

B. PARAMETER CALCULATION

For generators 1-9, the models in (30) have a total of 43 orders. By using the parameters in Table I, we have

$$\mathrm{rank}([\,\boldsymbol{B}\ \boldsymbol{AB}\ \boldsymbol{A}^2\boldsymbol{B}\ \cdots\ \boldsymbol{A}^{42}\boldsymbol{B}\,]) = 43,$$

and thus the linear system in (30) is completely controllable.

TABLE 1. Parameters of matrix A in (29).

$a^1_{g_j^1}, a^1_{g_j^2}$	$a^2_{g_j^1}, a^2_{g_j^2}$	$a^3_{g_j^1}, a^3_{g_j^2}$	$a^4_{g_j^1}, a^4_{g_j^2}$
-300	-300	-10	10

When one considers the feedback gains in Table II, all of the eigenvalues of the matrix $\boldsymbol{\Psi}$ in Section IV.C are negative real number and thus $\boldsymbol{\Psi}$ is negative definite. Consequently, the matrix $\boldsymbol{\Phi}$ is also negative definite. In this context, GAS can be guaranteed because the condition in (35) and (36) is satisfied.

As in Table II, we use the same gains for each generator. The system performance may be improved by choosing different feedback gains for different generators, which, however, is out of the scope of this paper.

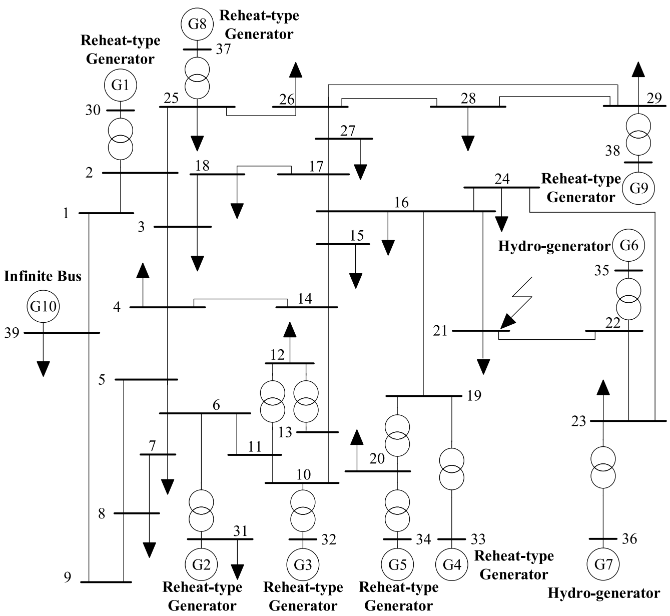

FIGURE 1. The ten-machine New-England power system.

TABLE 2. Gains of nonlinear feedbacks in (31).

$k^1_{g^1_j}, k^1_{g^2_j}$	$k^2_{g^1_j}, k^2_{g^2_j}$	$k^3_{g^1_j}, k^3_{g^2_j}$	$k^4_{g^1_j}, k^4_{g^2_j}$	$k^5_{g^2_j}$
-500	40	15	15	15

TABLE 3. Simulation scenarios for performing VR.

	Terminal Voltage (p.u.)				
	G 1	G 2	G 3	G 4	G 5
Initialization	1.0475	0.9820	0.9831	0.9972	1.0123
Regulation	1.0225	1.0070	1.0081	1.0222	1.0373
	G 6	G 7	G 8	G 9	
Initialization	1.0493	1.0635	1.0278	1.0265	
Regulation	1.0743	1.0385	1.0028	1.0015	

C. SIMULATION ANALYSIS

In order to demonstrate the effectiveness of the proposed LBC, we compare it with the case that the Proportional Integral (PI) controllers and Power System Stabilizers (PSSs) are considered, which is called PI/PSS for simplicity. PI and PSS1A [28] are used for the generator excitation systems with the feedback of generator terminal voltages and rotor speeds, while the governor systems are equipped with PI controllers [15], [30], where active powers and rotor speeds are considered as the feedback variables.

Here, we only choose Generator 1 (reheat-type generator) and Generator 6 (hydro-generator) for demonstration. The results for the other generators are similar and thus are not given.

1) PERFORMING VR

We add step changes for the references of the generator terminal voltages, as shown in Table III. As illustrated in Fig. 2, both LBC and PI/PSS control can achieve voltage regulation for Generators 1 and 6 due to the voltage feedback and maintain the power outputs of the generators at initial values because of the power feedback. However, comparing with PI/PSS control, the LBC has much better performance in tracking the regulation target and suppressing system oscillations.

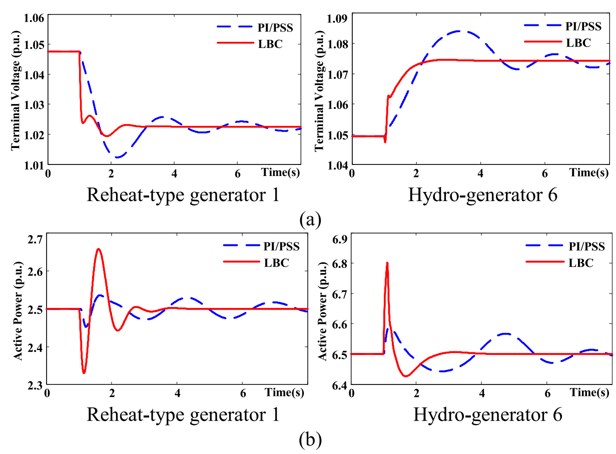

FIGURE 2. Dynamic responses for performing VR.

2) PERFORMING PR

In order to test the controller performance in PR, we add step changes for the references of the generator active power, as shown in Table IV. The dynamic responses are shown in Fig. 3.

TABLE 4. Simulation scenarios for performing PR.

	Active Power (p.u.)				
	G 1	G 2	G 3	G 4	G 5
Initialization	2.500	5.160	6.500	6.320	5.080
Regulation	2.745	4.644	5.850	6.952	5.588
	G 6	G 7	G 8	G 9	
Initialization	6.500	5.600	5.450	8.300	
Regulation	5.850	6.160	5.995	7.470	

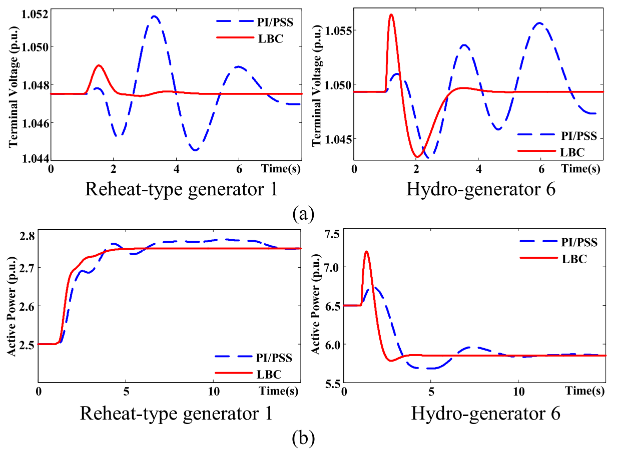

FIGURE 3. Dynamic responses for performing PR.

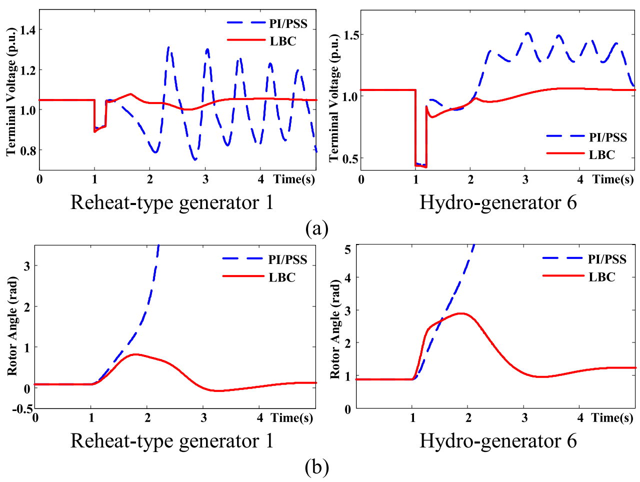

FIGURE 4. Dynamic responses for a three phase fault.

It is seen that PR can be achieved by both LBC and PI/PSS control, while maintaining the initial voltages. This is because voltage and power deviations are considered as the feedback for LBC and PI/PSS control. However, similar to VR, LBC shows better dynamic performance than the PI/PSS does.

3) THREE-PHASE SHORT CIRCUIT FAULT

The power system is subjected to a three-phase short circuit fault at the beginning of line 21-22 at 1 second, as shown in Fig. 1, and the fault line is removed after 0.2 second. As shown in Fig. 4, with LBC, the stability of power systems can be maintained. However, for this case that PI/PSS control is considered, the power system loses the stability. Therefore, compared with the case by PI/PSS control, the power system stability can be improved by LBC.

In order to further show the advantages of the proposed LBC over PI/PSS in enhancing system stability, Critical Clearing Time (CCT) is calculated by trial and error for different line faults, as shown in Table V. Comparing with the PI/PSS control, the CCTs of LBC are significantly increased under all test cases. This is because the LBC can ensure the GAS of a system in theory.

TABLE 5. CCT comparisons for excitation control and governor control methods.

Fault Location	Line Removed	Critical Clearing Time (CCT)	
		LBC (s)	PI/PSS (s)
Bus 3	Line 3-4	0.347	0.173
Bus 6	Line 6-7	0.400	0.203
Bus 8	Line 8-9	0.614	0.283
Bus 13	Line 13-14	0.404	0.204
Bus 16	Line 16-17	0.138	0.103
Bus 17	Line 17-27	0.272	0.148
Bus 21	Line 21-22	0.202	0.148
Bus 28	Line 28-29	0.219	0.089

VI. CONCLUSION

VR, PR, and GAS are of great importance for power system security and thus need to be considered in the excitation and governor control design. However, simultaneously fulfilling GAS, VR, and PR in the excitation and governor control design is very challenging.

In this paper, we propose a decentralized excitation and governor controller to address this challenge. The GAS of the power system can be guaranteed in theory by the proposed *Lyapunov*-based controller. VR and PR are achieved by introducing both voltage and power deviations into the feedback control. With the feedback of voltage and power deviations, the proposed controllers are used to determine the negative definiteness of the time-derivative of the *Lyapunov* function to guarantee GAS. Simulation results on the New-England ten-machine power system demonstrate the effectiveness of the proposed control method. Compared with the PI/PSS-based control, the proposed control has much better dynamic performance and significantly increased CCT.

REFERENCES

[1] J. W. Chapman, M. D. Ilic, C. A. King, L. Eng, and H. Kaufman, "Stabilizing a multimachine power system via decentralized feedback linearizing excitation control," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 830–839, Aug. 1993.

[2] Q. Lu, Y. Sun, Z. Xu, and T. Mochizuki, "Decentralized nonlinear optimal excitation control," *IEEE Trans. Power Syst.*, vol. 11, no. 4, pp. 1957–1962, Nov. 1996.

[3] C. Zhu, R. Zhou, and Y. Wang, "A new decentralized nonlinear voltage controller for multimachine power systems," *IEEE Trans. Power Syst.*, vol. 13, no. 1, pp. 211–216, Feb. 1998.

[4] Y. Guo, D. J. Hill, and Y. Wang, "Global transient stability and voltage regulation for power systems," *IEEE Trans. Power Syst.*, vol. 16, no. 4, pp. 678–688, Nov. 2001.

[5] G. Gurrala and I. Sen, "A nonlinear voltage regulator with one tunable parameter for multimachine power systems," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1186–1195, Aug. 2011.

[6] M. A. Mahmud, H. R. Pota, M. Aldeen, and M. J. Hossain, "Partial feedback linearizing excitation controller for multimachine power systems to improve transient stability," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 561–571, Mar. 2014.

[7] M. A. Mahmud, M. J. Hossain, H. R. Pota, and A. M. T. Oo, "Robust partial feedback linearizing excitation controller design for multimachine power systems," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 3–16, Jan. 2017.

[8] A. K. Singh and B. C. Pal, "Decentralized nonlinear control for power systems using normal forms and detailed models," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1160–1172, Mar. 2018.

[9] Y. Liu, T. Chen, C. Li, Y. Wang, and B. Chu, "Energy-based L_2 disturbance attenuation excitation control of differential algebraic power systems," *IEEE Trans. Circuits Syst., II, Exp. Briefs*, vol. 55, no. 10, pp. 1081–1085, Oct. 2008.

[10] F. Shi and J. Wang, "Stabilising control of multi-machine power systems with transmission losses based on pseudo-generalised Hamiltonian theory," *IET Control Theory Appl.*, vol. 6, no. 2, pp. 173–181, Jan. 2012.

[11] T. K. Roy, M. A. Mahmud, W. Shen, A. M. T. Oo, and M. E. Haque, "Robust nonlinear adaptive backstepping excitation controller design for rejecting external disturbances in multimachine power systems," *Int. J. Elect. Power Energy Syst.*, vol. 84, pp. 76–86, Jan. 2017.

[12] Y. Wan and F. Milano, "Nonlinear adaptive excitation control for structure preserving power systems," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3107–3117, May 2018.

[13] H. Liu, Z. Hu, and Y. Song, "Lyapunov-based decentralized excitation control for global asymptotic stability and voltage regulation of multi-machine power systems," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 2262–2270, Nov. 2012.

[14] N. Wang, H. Liu, W. Cheng, X. Sun, and L. Tan, "Energy stability excitation control for the synchronous generator unit," in *Proc. CSEE*, vol. 33, no. 28, Oct. 2013, pp. 81–87.

[15] X. Ju, P. Zhao, H. Sun, W. Yao, and J. Wen, "Nonlinear synergetic governor controllers for steam turbine generators to enhance power system stability," *Energies*, vol. 10, no. 8, pp. 1–16, 2017.

[16] Q. Lu and Y. Z. Sun, "Nonlinear stabilizing control of multimachine systems," *IEEE Trans. Power Syst.*, vol. 4, no. 1, pp. 236–241, Feb. 1989.

[17] F. Yang, H. Lei, Y. Sun, W. Lin, and T. Shen, "Control of hydraulic turbine generators using exact feedback linearization," presented at the IEEE Int. Conf. Control Automat., Xiamen, China, Jun. 2010.

[18] W. Li, T. Lan, and W. Lin, "Nonlinear adaptive robust governor control for turbine generator," presented at the IEEE Int. Conf. Control and Automation, Xiamen, China, Jun. 2010.

[19] S. Liu, D. Li, and C.-E. Huang, "Nonlinear robust control with high gain observer for governor of hydro-turbine generator sets," presented at the Intell. Control Automat., Beijing, China, Jul. 2012.

[20] Y. Guo, D. J. Hill, and Y. Wang, "Nonlinear decentralized control of large-scale power systems," *Automatica*, vol. 36, no. 9, pp. 1275–1289, 2000.

[21] Y. Wang, G. Guo, and D. J. Hill, "Nonlinear decentralized coordinated control for multimachine power systems," in *Proc. Int. Conf. Energy Manage. Power Del.*, Nov. 1995, pp. 102–107.

[22] M. Djukanovic, M. Novicevic, D. Dobrijevic, B. Babic, D. J. Sobajic, and Y.-H. Pao, "Neural-net based coordinated stabilizing control for the exciter and governor loops of low head hydropower plants," *IEEE Trans. Energy Convers.*, vol. 10, no. 4, pp. 760–767, Dec. 1995.

[23] M. J. Jin, W. Hu, F. Liu, S. W. Mei, and Q. Lu, "Nonlinear co-ordinated control of excitation and governor for hydraulic power plants," *IEE Proc.-Gener. Transmiss. Distrib.*, vol. 152, no. 4, pp. 544–548, Jul. 2005.

[24] J. Wu, A. Yokoyama, Q. Lu, M. Goto, and H. Konishi, "MIMO decentralized nonlinear control of generator and turbine to enhance transient stability of power system," *IEEJ Trans. Power Energy*, vol. 121, no. 2, pp. 224–233, 2008.

[25] G. Kenné, A. M. Fombu, and J. de Dieu Nguimfack-Ndongmo, "Coordinated excitation and steam valve control for multimachine power system using high order sliding mode technique," *Electr. Power Syst. Res.*, vol. 131, pp. 87–95, Feb. 2016.

[26] T. K. Roy, M. A. Mahmud, W. Shen, and A. M. T. Oo, "Non-linear adaptive coordinated controller design for multimachine power systems to improve transient stability," *IET Gener. Transmiss. Distrib.*, vol. 10, no. 13, pp. 3353–3363, Jun. 2016.

[27] Q. Lu, S. Mei, and Y. Sun, *Nonlinear Control Systems and Power System Dynamics*. Beijing, China: Publishing House of Science, 2008.

[28] *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Standard 421.5-2005, Apr. 2006.

[29] *IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems*, IEEE Standard 421.2-1990, May 1990.

[30] IEEE Working Group Report, "Hydraulic turbine and turbine control models for system dynamic studies," *IEEE Trans. Power Syst.*, vol. 7, no. 1, pp. 167–179, Feb. 1992.

[31] M. Pai, *Energy Function Analysis for Power System Stability*. Norwell, MA, USA: Kluwer, 1989.

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