# Partial Feedback Linearization Controller for Flexible Excitation System in Synchronous Generator*

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**Abstract.** The stability and control of power systems remain a challenge as the modern power system becomes more complex. A flexible excitation system (FES) based on fully controlled devices for the synchronous generator that can provide field voltage regulation and extra reactive power compensation, while the conventional half-controlled static excitation system (CSES) can only regulate field voltage for modern power systems stability enhancement. This paper applies the FES to the synchronous generator and proposes a nonlinear coordinated control strategy to enhance the voltage and rotor angle stability. To deal with the control of the nonlinear system which contains the synchronous generator and FES (SG-FES), the system is linearized to a two-input two-output system via partial feedback linearizing control (PFLC). With PFLC, the system is divided into a reduced-order linear part and a nonlinear dynamic autonomous part. The control method for SG-FES is tested with a single machine infinite bus (SMIB) system under a three-phase short circuit fault and small disturbance. The results show the effectiveness and better performance of the proposed control strategy compared with SG-CSES with conventional power system stabilizer, and avoid the need for rotor angle measurement compared with SG-FES with feedback linearization control.

**Keywords:** flexible excitation system · partial feedback linearizing control · nonlinear coordinated control strategy · power system stability.

## 1 Introduction

The modern power system becomes more complex due to the integration of converter-interfaced generation technologies, loads, and transmission devices. The fast dynamics of those new devices will significantly affect the power system stability [1, 2]. Under this circumstance, the stability of the power system is

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still heavily dependent on synchronous generators and it remains an indispensable component of power system [3]. Excitation systems are used for large synchronous generators to maintain the terminal voltage, rotor angle and frequency stability under a diversity of operating conditions in modern power systems. Conventional static excitation systems (CSESs) using half-controlled thyristor-based rectifiers can regulate the excitation voltage with the advantages of simple structure and high robustness [4], but some drawbacks of half-controlled thyristor still exist in CSESs, such as power quality problem [5], and especially the unsatisfactory performance due to the two control objectives, rotor angle and terminal voltage, being regulated via only one control variable, field voltage [6].

In recent years, a full-controlled devices-based flexible excitation system (FES) which aims at addressing the problems of the traditional half-controlled thyristor based excitation system is proposed [7, 8]. FES is a novel excitation system which offers benefits including minimal harmonic distortion, sinusoidal input current, the capability for bidirectional power transmission, and protection against de-excitation failure [9]. It consists of a chopper and a voltage source converter (VSC) to regulate the voltage and rotor angle respectively so that the two control objectives can be obtained independently, which is shown in Fig. 1.

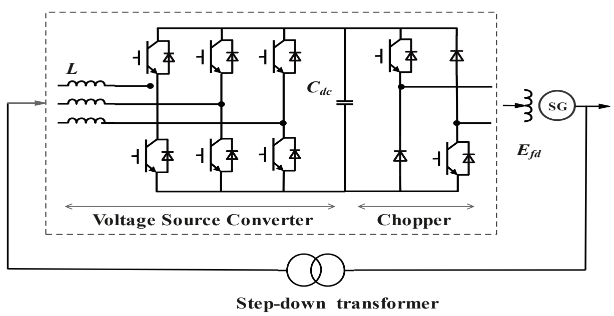



**Fig. 1.** Topology of a VSC and Chopper based FES

As a new excitation system with better comprehensive properties, several researchers studied the control strategies FES based synchronous generator. In [10], a coordinated optimization control strategy is proposed for the two damping channels of FES, the design of power system stabilizer (PSS) and reactive power damping controller can maintain the system stability simultaneously. Another coordinated control strategy to stabilise the voltage and power angle is proposed in [11]. This paper decouples the stator control loop and rotor control loop and then implements the linear optimal excitation control and adaptive amplitude limiter to obtain the control objectives. SG-FES is also used to achieve variable frequency starting in the pumped storage unit [12]. Focusing on damping the low-frequency oscillation in power systems, [13] proposes a novel structure for RPDC and implements the phase compensation method to design the parameters of RPDC. It is worth noting that all the aforementioned control strategies are based on the steady-state operating point and the controller parameters are tuned based on one operating point. However, the high nonlinearities of the power system equipped with FES make it difficult to timely and accurately tune the controller parameters to provide a fast and stable control performance over a wide range of operating conditions.

To deal with the control problem of a nonlinear system, an efficient and widely used method is feedback linearization control (FLC) [14]. Based on this method, a nonlinear system can be transformed into a linear system so that a series of linear methods can be adopted. In these years, some researchers have studied the implementation of FLC on the excitation system [15, 16]. In this research, the synchronous generator is fully linearized. The FLC has also been applied to the SG-FES for rotor angle and terminal voltage control in a single machine infinite bus (SMIB) system showing superior damping performance compared with linear control methods [17]. However, the difficulties of rotor angle measurement and weak robustness of using differentiators for the control of rotor angle pose barriers to implementing such controllers for real practice. Therefore, the partial feedback linearization control (FLC) which only linearize a part of the system is proposed for less state feedback and less differentiators[18]. PFLC is adopted to a traditional excitation system to enhance the rotor speed stability [19]. Despite this, PFLC is also applied to other parts of power system and has been proven as an efficient method to achieve the required control objectives such as mitigating subsynchronous resonance and regulating the VSC output [20–22].

In this paper, a nonlinear coordinated controller is designed for SG-FES, the contribution of this paper is as follow:

- With FES implemented to the synchronous generator, the field voltage and reactive power compensation can provide two damping channels through the full-controlled devices. Unlike the CSES, the control performance will not limited due to the single control input to regulate two control objectives.
- The nonlinear system is transformed into a partially linearized system via PFLC, therefore the linear control method can be implemented. Compared to linear control methods, the proposed PFLC for SG-FES can enhance the stability of power systems over a wide region of operating.
- The PFLC diminishes the need for rotor angle measurements and reduces the reliance on differentiators. These enhancements increase the robustness of the PFLC, making it more viable for practical applications.

The structure of this paper is as follow. In section II, the structure of FES is introduced, and the equivalent model of single machine infinite bus (SMIB) system is derived. In section III,

## 2 Structure of synchronous generator equipped with FES

### 2.1 Single machine infinite bus system with FES

Fig. 1 shows the FES topology, it composes of a voltage source converter (VSC), a back-end DC/DC chopper, and a step-down transformer. The primary role of

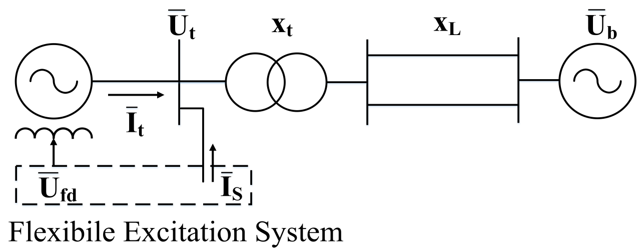



**Fig. 2.** SMIB including SG with a Flexible Excitation System

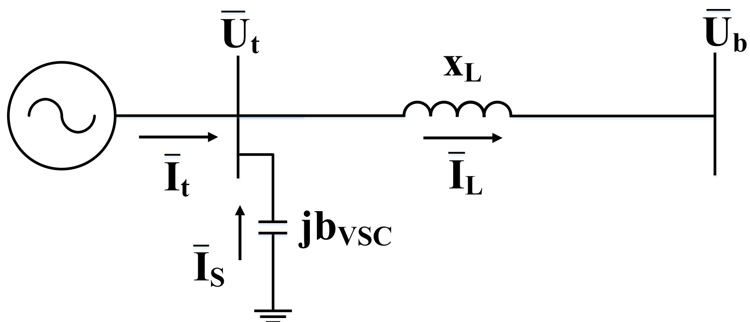



**Fig. 3.** Equivalent diagram of the SMIB with the SG-FES

the front-end VSC is to stabilize the DC capacitor voltage, allowing the chopper to solely manage the field voltage. Additionally, the front-end VSC facilitates the exchange of reactive power with the generator terminal. Consequently, the FES not only offers field voltage control similar to traditional static excitation systems but also introduces an additional control input through the adjustment of reactive power exchange and generator terminal voltage control. For simplicity in analysis, the VSC and chopper within the FES are presumed to efficiently regulate the reference field voltage and reactive power swiftly enough, making it unnecessary to consider their dynamics. Moreover, the dynamic model of the VSC is disregarded, and the reactive power interaction with the grid is treated as compensating the shunt admittance, $m_V SC$, and is simplified to a first-order system as 1:

$$\dot{m}_{\mathrm{VSC}} = \frac{1}{T_{\mathrm{FES}}} \left(-m_{\mathrm{VSC}} + m^*_{\mathrm{VSC}}\right) \tag{1}$$

where $m^*_{\mathrm{VSC}}$ represents the reference of $m_V SC$, $T_{\mathrm{FES}}$ is the time constant of FES. After implementing the FES, the structure of a synchronous generator is shown in Fig. 2, and it should be transformed to Fig. 3 which considers the effect of the equivalent shunt admittance so that the FES can be equivalent to an admitance:

$$\bar{I}_{\mathrm{L}} = \bar{I}_{\mathrm{t}} + \bar{I}_{\mathrm{s}} = \bar{I}_t + jb_{\mathrm{VSC}}\bar{U}_{\mathrm{t}} \tag{2}$$

$$\bar{U}_\mathrm{t} = jx_\mathrm{L}\bar{I}_\mathrm{L} + \bar{U}_\mathrm{b} = jx_\mathrm{L}\bar{I}_\mathrm{t} - x_\mathrm{L}m_\mathrm{VSC}\bar{U}_\mathrm{t} + \bar{U}_\mathrm{b} \tag{3}$$

After substituting 2 into 3, $\bar{U}_\mathrm{t}$ can be rewritten as:

$$\bar{U}_\mathrm{t} = \frac{jx_\mathrm{L}\bar{I}_\mathrm{t} + \bar{U}_\mathrm{b}}{1 + x_\mathrm{L}b_\mathrm{VSC}} = jx_{lz}\bar{I}_\mathrm{t} + \frac{\bar{U}_\mathrm{b}}{c_\mathrm{VSC}} \tag{4}$$

where $c_\mathrm{VSC} = 1 + x_\mathrm{L}b_\mathrm{VSC}$, $x_{lz} = x_\mathrm{L}/c_\mathrm{VSC}$. It can be demonstrated in Fig. that the FES is equal to a impedance $x_lz$ with a voltage $\bar{U}_\mathrm{b}c_\mathrm{VSC}$ connecting to an infinite bus. In general, the single machine infinite bus (SMIB) system can be represented as:

$$\begin{cases} \dot{\delta} = \omega_0(\omega - 1) \\ \dot{\omega} = \frac{1}{T_j}\left(P_\mathrm{m} - P_\mathrm{t} - D(\omega - 1)\right) \\ \dot{E}'_q = \frac{1}{T'_{d0}}\left(E_{fd} - E_q\right) \\ \dot{m}_\mathrm{VSC} = \frac{1}{T_\mathrm{FES}}\left(-m_\mathrm{VSC} + m^*_\mathrm{VSC}\right) \end{cases} \tag{5}$$

$$\begin{cases} P_\mathrm{t} = \frac{E'_q U_\mathrm{b}}{c_\mathrm{VSC}x'_{dz}}\sin\delta - \frac{U_\mathrm{b}^2}{2c_\mathrm{VSC}^2}\frac{\left(x_q - x'_d\right)}{x'_{dz}x_{qz}}\sin 2\delta \\ E_q = \frac{E'_q x_{dz}}{x'_{dz}} - \frac{\left(x_d - x'_d\right)U_b\cos\delta}{c_\mathrm{VSC}x'_{dz}} \\ v_{td} = \frac{x_q U_\mathrm{b}\sin\delta}{c_\mathrm{VSC}x_{qz}}, \quad v_{tq} = \frac{x_{lz}E'_q}{x'_{dz}} + \frac{U_\mathrm{b}x'_d\cos\delta}{c_\mathrm{VSC}x'_{dz}} \\ U_t = \sqrt{v_{td}^2 + v_{tq}^2} \\ x'_{dz} = x'_d + x_{lz}, x_{dz} = x_d + x_{lz}, x_{qz} = x_q + x_{lz} \end{cases} \tag{6}$$

### 2.2 multi machines system with FES

## 3 Design of PFLC for FES

### 3.1 PFLC

As discussed in the past section, the synchronous generator is a nonlinear system after implementing the FES. In general, a nonlinear system can be expressed as:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \tag{7}$$

where $x$ is the state variables of the system, $u$ is the control variables, $y$ is the output vector. $f(x)$, $g(x)$ and $h(x)$ are the incidence matrices. By applying the Lie Derivative to $h(x)$ along $f(x)$, the new scalar function denoted as is $L_f h(x)$:

$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) = \sum_{i=1}^{n} \frac{\partial h(x)}{\partial x_i} f_i(x) \tag{8}$$

If the $i{-}th$ order Lie derivative of $h(x)$ with $g(x)$ is not equal to zero ($L_g L_f^i h(x) \neq 0$) in a neighborhood $\gamma$, so the system have relative degree $i + 1$ in $\gamma$.

The relative degree of a system is influenced by the choice of its output. In nonlinear control theory, the concept of relative degree is crucial, as it significantly affects the design of nonlinear controllers. When the relative degree of a system matches its order (n), the system can be considered fully linearizable or exactly linearizable. However, if the relative degree is less than n, the system is only partially linearized. In such cases, the zero dynamic design approach is applicable. So for the nonlinear system, Assume that $i \leq n$, it has the following equation:

$$L_g L_f^{1-1} h(x) = L_g L_f^{2-1} h(x) = \cdots = L_g L_f^{n-2} h(x) = 0 \tag{9}$$

$$L_g L_f^{i-1} h(x) \neq 0 \tag{10}$$

Then map the equations from $x$ space to $z$ sqace:

$$z_1 = y = h(x) = L_f^{1-1} h(x) \tag{11}$$

So that the derivative of $z_1$ can be expressed as:

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} \dot{x} \tag{12}$$

Then use (7) to represent $\dot{x}$:

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} f(x) + \frac{\partial h(x)}{\partial x} g(x) u = L_f^{2-1} h(x) + L_g L_f^{1-1} h(x) u \tag{13}$$

If $L_g L_f^{1-1} h(x) = 0$, (13) is rewritten as:

$$\dot{z}_1 = L_f h(x) = z_2 \tag{14}$$

and the same to $\dot{z}_{i-1}$. But $L_g L_f^{i-1} h(x) \neq 0$, so that $\dot{z}_r$ is equal to:

$$\dot{z}_r = L_f^i h(x) + L_g L_f^{i-1} h(x) u \tag{15}$$

The power system model described by equations (5) to (6) can be expressed using the form of equation (7) where

$$X = \begin{bmatrix} \delta \; \omega \; E_q' \; b_{VSC} \end{bmatrix}^T \tag{16}$$

$$u_1 = E_{fd} \tag{17}$$

$$u_2 = b_{VSC}^* \tag{18}$$

$$g_1 = \begin{bmatrix} 0 \; 0 \; \frac{1}{T_{d0}'} \; 0 \end{bmatrix}^T \tag{19}$$

$$g_2 = \begin{bmatrix} 0 \; 0 \; 0 \; \frac{1}{T_Q} \end{bmatrix}^T \tag{20}$$

and

$$y_1 = U_t - U_{t0} \tag{21}$$

$$y_2 = \omega - \omega_0 \tag{22}$$

By means of calculating the Lie derivative for each output, the relationship between inputs and outputs can be represented as

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} = \begin{bmatrix} L_f y_1(X) \\ L_f^2 y_2(X) \end{bmatrix} + \begin{bmatrix} L_{g_1} y_1(X) & L_{g_2} y_1(X) \\ L_{g_1} L_f^1 y_2(X) & L_{g_2} L_f^1 y_2(X) \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{23}$$

The relative degree of outputs $y_1$ and $y_2$ are $r_1 = 1$ and $r_2 = 2$, respectively. Therefore, the overall relative $r = r_1 + r_2 = 1 + 2 = 3$ is less than the order of the system.

In previous steps, the first $r$ order equations are transformed into a linear system.

which represents the internal dynamics of the th subsystem. Since the internal dynamic of the system is zero, it has no effect on the overall stability of power systems.

Since the internal dynamics of the transformed system have no effect on the overall stability of multimachine power systems, the partial feedback linearizing excitation control law can be implemented.

The PFLC law can be designed to achieve as

$$\begin{bmatrix} u_{i1} \\ u_{i2} \end{bmatrix} = \begin{bmatrix} L_{g_1} y_1(X) & L_{g_2} y_1(X) \\ L_{g_1} L_f^1 y_2(X) & L_{g_2} L_f^1 y_2(X) \end{bmatrix}^{-1} \left( - \begin{bmatrix} L_f y_1(X) \\ L_f^2 y_2(X) \end{bmatrix} + \begin{bmatrix} v_{i1} \\ v_{i2} \end{bmatrix} \right) \tag{24}$$

Linear control variables are defined to achieve the tracking control of $U_t$, $\delta$ with references $U_t^*$, $\delta^*$ as

$$\begin{aligned} \begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} &= \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \\ v_1 &= k_{11} e_1 \\ v_2 &= k_{21} \dot{e}_2 + k_{22} e_2 \end{aligned} \tag{25}$$

where $k_{11}, k_{21}$, and $k_{22}$ are gains of linear controller, and $e_1 = \Delta U$ and $e_{i2} = \Delta\omega$ are tracking errors.

## 4 Results

In this section, the control performance of the proposed PFLC controller for SG-FES is compared with the performance of the FLC for SG-FES and the AVR/PSS for SG-FES. The inputs of the AVR/PSS are the deviation of rotor speed and the terminal voltage, and the FLC requires full-state feedback. The proposed PFLC can ease the requirement of rotor angle measurement. The test system SG-FES connected to the infinite bus is shown in Fig. 3. The SMIB parameters are given in Table 1. The control inputs are bounded as $|u_1| \leq 5$ p.u. and $|u_2| \leq 0.1$ p.u.

**Table 1.** Parameters of SMIB with the FES

| | | |
|---|---|---|
| d-axis synchronous reactance | $x_d$ | 1.2 |
| q-axis synchronous reactance | $x_q$ | 0.3 |
| d-axis transient reactance | $x'_d$ | 0.3 |
| Line reactance | $x_L$ | 0.2 |
| Nominal synchronous speed | $w_0$ | $2\pi f$ |
| Rotor inertia constant | $T_j$ | 9.48 |
| d-axis OC transient time constant | $T'_{do}$ | 5.9 |
| Mechanical input power | $P_m$ | 1 |
| Damping | $D$ | 0.1 |
| Bus voltage | $U_b$ | 1 |
| Reactive power regulator time constant | $T_Q$ | 0.1 |

All in per unit except that $T_j$, $T'_{d0}$ and $T_Q$ are in second.

### 4.1 Case 1: Three-phase short circuit fault

A three-phase short circuit, occurring at the end of the transmission line near the infinite bus, is introduced into the system for 0.1 seconds. To evaluate the effectiveness of the PFLC, comparative results with FLC and traditional linear control are presented. System responses are shown in Fig. 4. The control inputs response is illustrated in Fig. 5.

The voltage and rotor speed oscillation can be better damped by the proposed controller for SG-FES (green solid line) compared to the SG-CSES with AVR/PSS (black dotted line) Although the SG-FES system equipped with FLC (red dashed line) can deliver comparable oscillation damping performance, the proposed controller eases the need for rotor angle measurement. This enhancement significantly facilitates the implementation of the proposed controller in practical settings.

### 4.2 Case 2: Changes in voltage reference

3% step change of the reference terminal voltage is applied at 2 s to validate the proposed controller performance under small disturbance. Fig.6 compares the control performance of SG-FES under FLC and PFLC and the results of an SG-CSES controlled by conventional controller AVR/PSS. It is clear from the figure that the SG-FES with the proposed scheme (green solid line) is superior to that of CSES-AVR/PSS (black dotted line) and performs better than the FLC (red dashed line), in terms of settling time.

### 4.3 Case 3: The three-machine power system

The 3-machine 9-bus system shown in Fig. 7 is considered as the test system to evaluate the performance of the proposed PFLC. The parameters of the multi-machine power system can be seen in Table 2. All SGs are equipped with FESs and each generator is simulated using a third-order model.

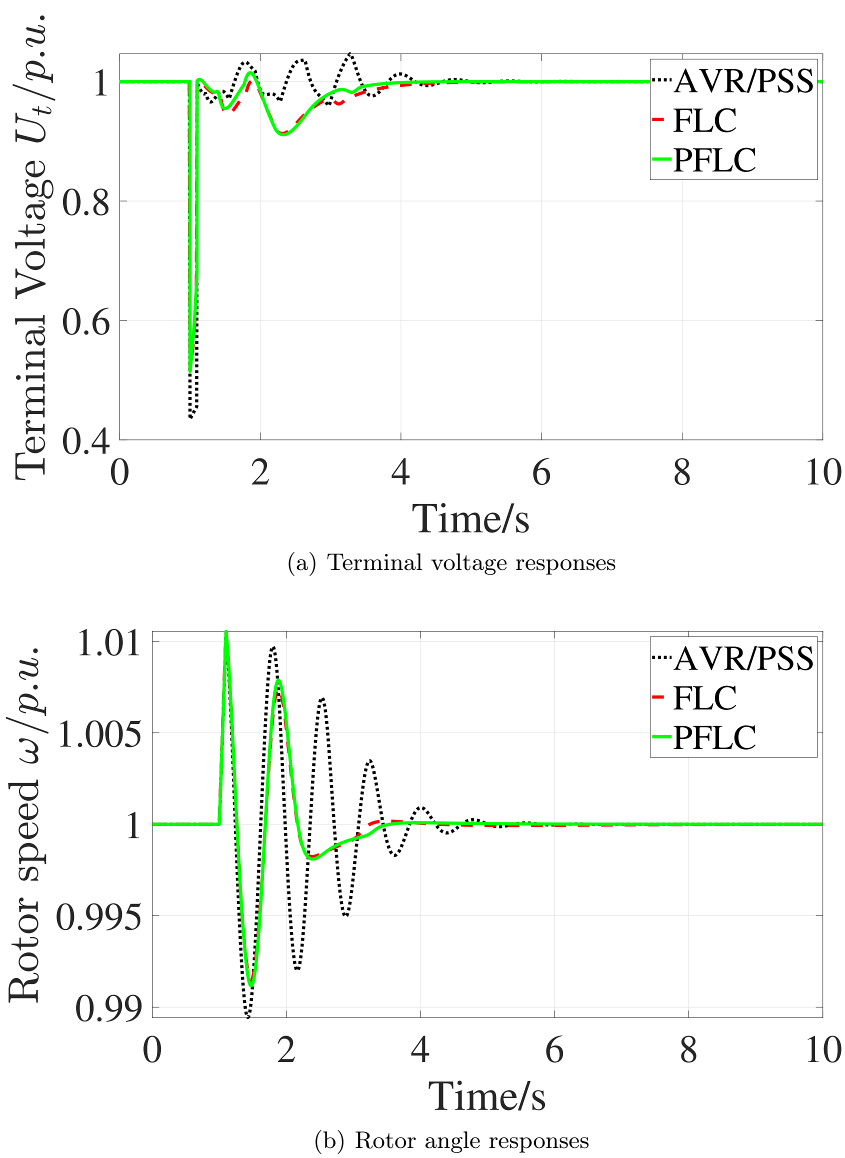
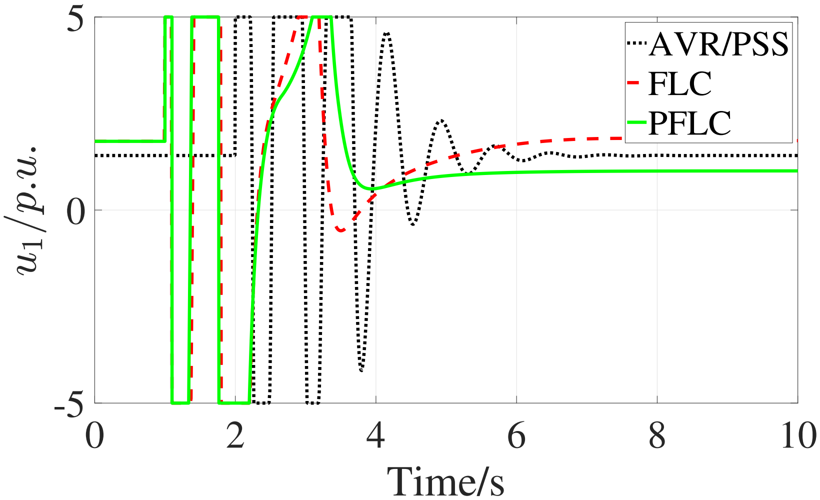
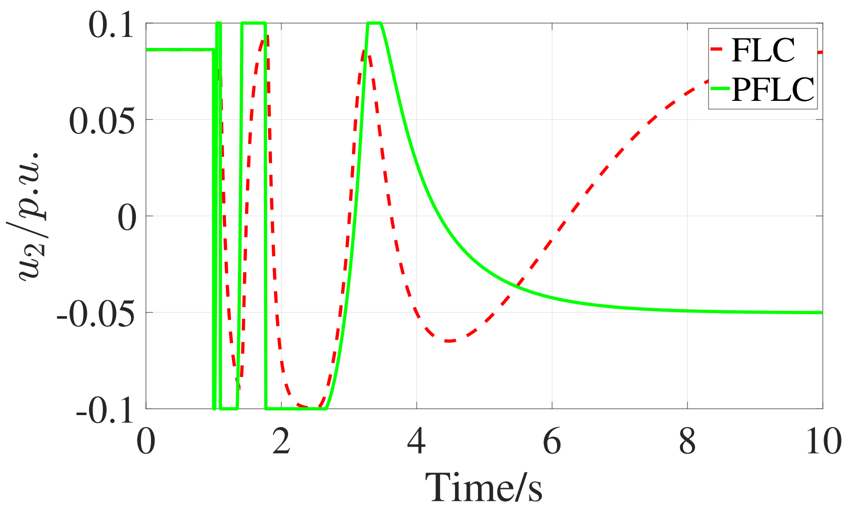



**Fig. 4.** Response of SG-CSES with AVR/PSS and SG-FES with FLC and PFLC during a three-phase short circuit fault in the SMIB system

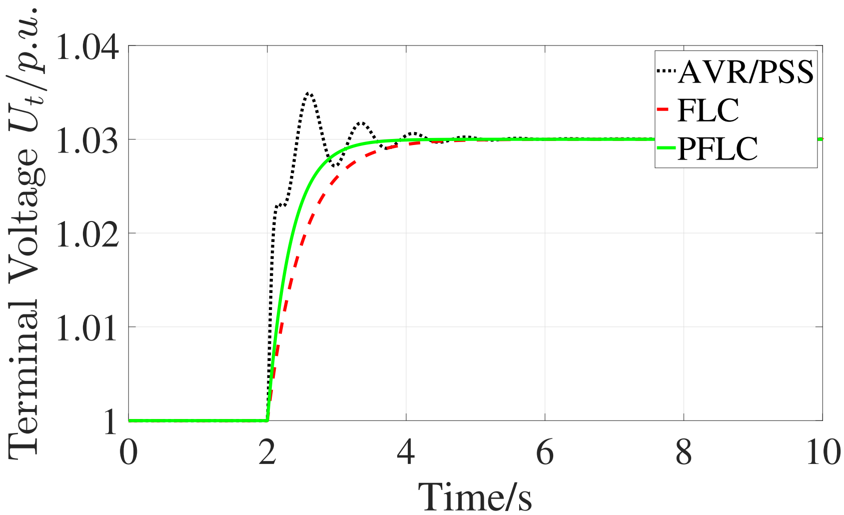



(a) Control input $u_1$

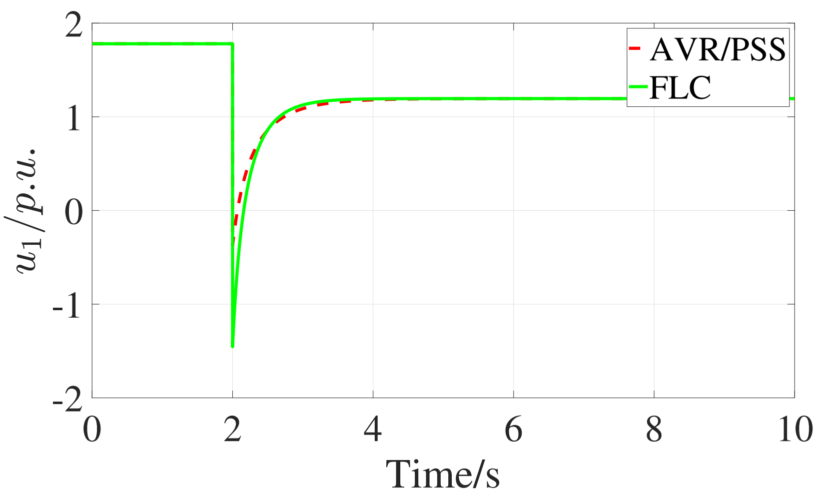



(b) Control input $u_2$

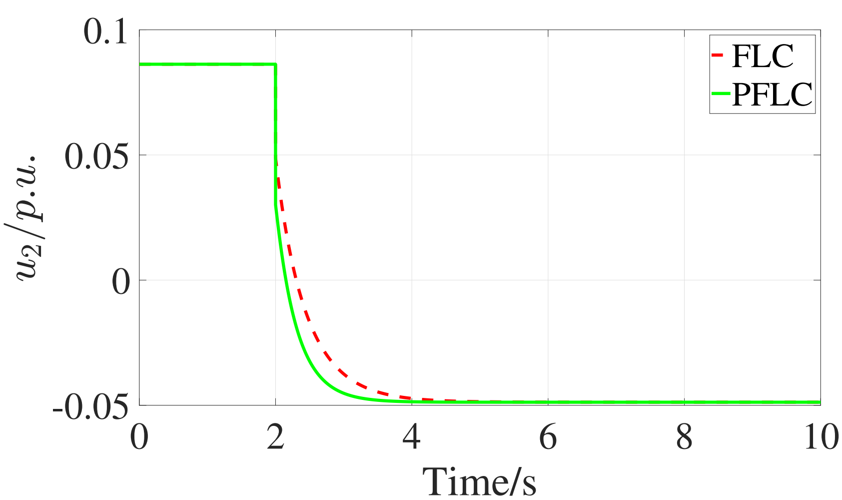
**Fig. 5.** Controllers response of SG-CSES and SG-FES during a three-phase short circuit fault in the SMIB system




(a) Terminal voltage responses




(b) Control input $u_1$




(c) Control input $u_2$

**Fig. 6.** Response of SG-CSES with AVR/PSS and SG-FES with FLC and PFLC during a a +3% step change of the voltage reference

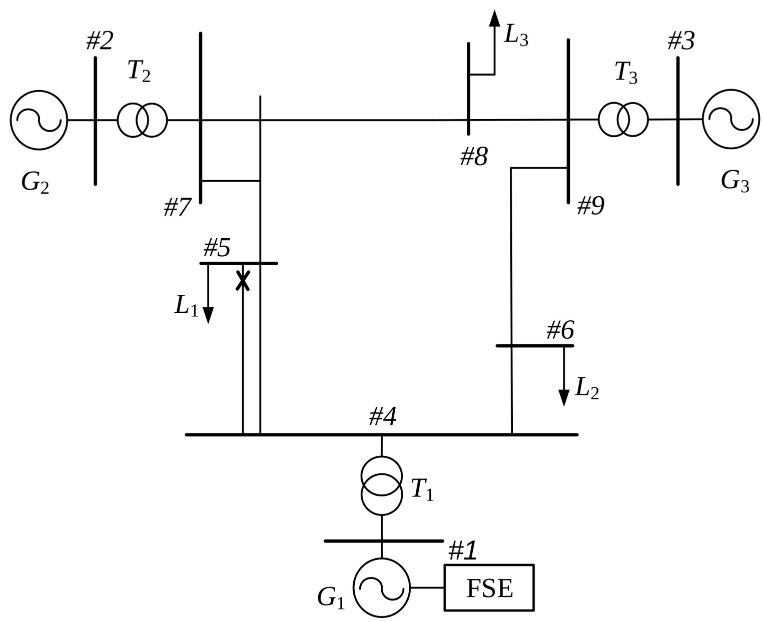



**Fig. 7.** Three-machine power system

**Table 2.** Three-machine power system parameters

| Parameters | $G_1$ | $G_2$ | $G_3$ | Line no. | Impedence |
|---|---|---|---|---|---|
| $x_d$ | 1.86 | 1.67 | 1.75 | 5-7 | 0.405 |
| $x_{d1}$ | 0.335 | 0.306 | 0.342 | 4-5(1);(2) | 0.23;0.23 |
| $T_{do}$ | 6.9 | 6.9 | 6.9 | 4-6 | 0.205 |
| $H$ | 5.25 | 4.5 | 4 | 6-9 | 0.185 |
| $D$ | 2.5 | 2.5 | 2.5 | 7-8 | 0.325 |
| | | | | 8-9 | 0.255 |

The performance of PFLC for SG-FES is compared with the performance of a conventional AVR/PSS for SG-CSES and FLC for SG-FES. The limiter magnitude of the excitation voltage and equivalent compensated admittance are $\pm 9pu$ and $\pm 0.1pu$, respectively. Note that the control gains of FLC are designed based on the pole placement method and listed as follows $k_{i11} = 6$, $k_{i21} = 27$, $k_{i22} = 27$, $k_{i21} = 9$. The PFLC uses the same control gains as the FLC.

At $t = 4s$, a three-phase short circuit occurs on the transmission line between bus 4.5 and bus 5, indicated as point 'x'. The short circuit lasts for a duration of $0.1s$ in the three-machine system. Due to the page limits, only the system response of SG(1)-CSES with AVR+PSS, SG(1)-FES with FLC and SG(1)-FES with PFLC are illustrated in Fig. 8-Fig. 9.

Fig. 8(a)-8(b) show the voltage and rotor speed response of SG(1) with CSES-AVR/PSS, FES-FLC and FES-PFLC. Note that PFLC can damp both rotor angle and voltage oscillations within 1 $s$ faster than FLC and AVR/PSS.

## 5 Conclusion

A nonlinear coordinated controller for a synchronous generator with FES is proposed in this paper. The detailed FES is first analyzed, and then a PFLC is designed and implemented to partially linearize the FES part as a two-input two-output linear sub-system. Based on this, a coordinated controller is designed to separately control the terminal voltage and rotor angle of synchronous generator. The effectiveness of the proposed controller is verified through the test on SMIB system and three-machines system. The control performance of PFLC is significantly better than FLC and the conventional controller.

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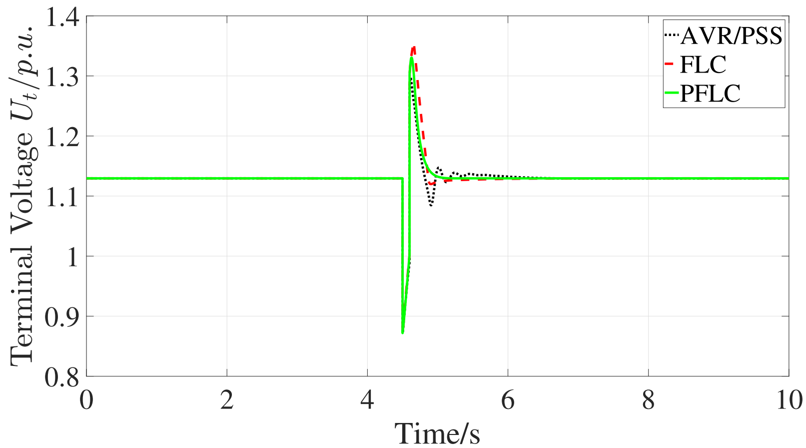
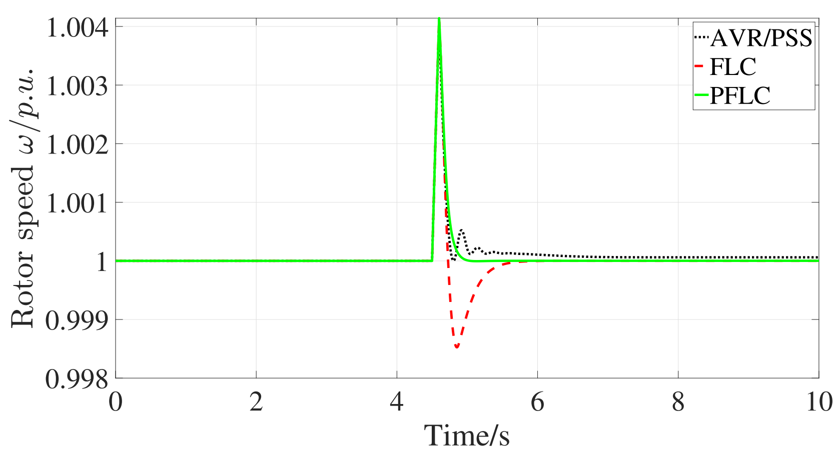
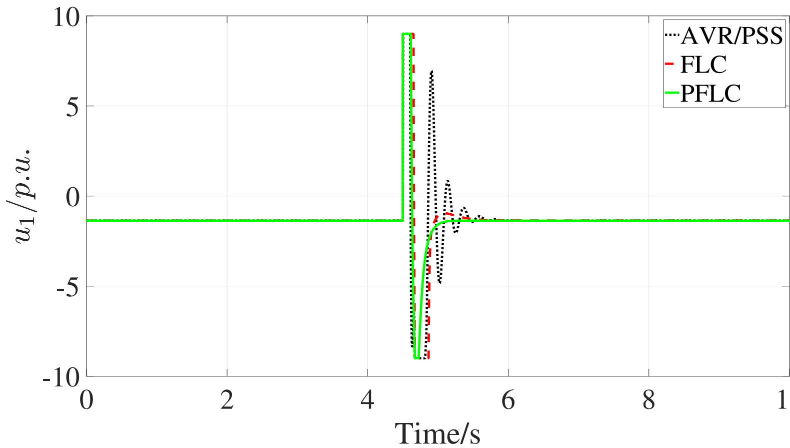



(a) Terminal voltage responses

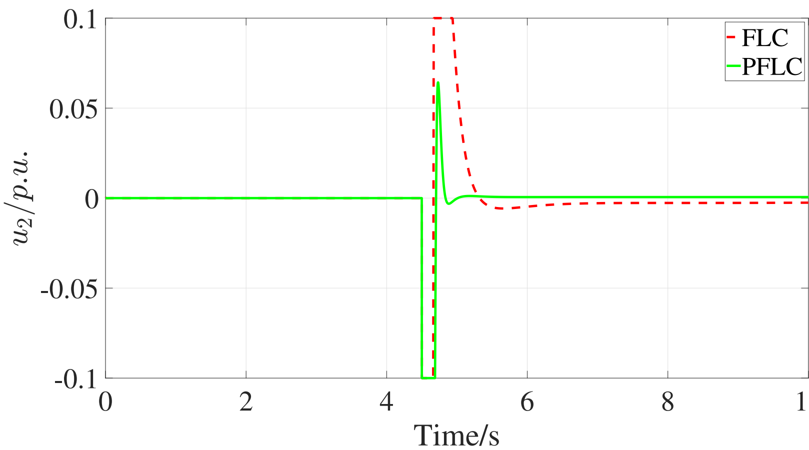



(b) Rotor angle responses

**Fig. 8.** Response of SG(1)-CSESs with AVR/PSS and SG(1)-FES with FLC and PFLC during a three-phase-to-ground fault in the three-machine system




(a) Control input $u_1$




(b) Control input $u_2$

**Fig. 9.** Controllers response of SG(1)-CSESs and SG(1)-FES during a three-phase-to-ground fault in the three-machine system

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