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Enhanced Dynamic Stability of SMIB Power System Integrated with SMES using Fuzzy Logic-based Power System Stabilizer

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***Abstract*—This work presents a stabilization approach for the SMIB (Single Machine Infinite Bus) system by combining a fuzzy logic-based power system stabilizer (FPSS) and a Superconducting Magnetic Energy Storage (SMES) device. The goal is to enhance the dynamic stability of the electrical grid in the face of disturbances and load fluctuations. Three configurations were studied: SMIB with only SMES, SMIB with SMES and a conventional PSS, and finally SMIB with SMES controlled by FPSS. The simulation results show that the FPSS & SMES approach provides the best oscillation damping and faster stabilization of system variables, such as speed, power, tension and rotor angle, compared to the other configurations. This combination allows for more efficient disturbance management, thereby improving the robustness and reliability of the system. The results validate the effectiveness of FPSS in enhancing the dynamic stability of electrical systems integrating advanced technologies like SMES.**

***Keywords*— Fuzzy Logic, Stability, SMIB System, Power system Stabilizer, Robust control, SMES device, Oscillations.**

I. Introduction

The stability of electrical systems is a major challenge to ensure reliable grid operation and prevent disturbances that could affect power supply. Among the reference models for network stability analysis, the Single Machine Infinite Bus (SMIB) plays a crucial role in studying dynamic phenomena and developing advanced control strategies [1]. With the increasing demand for energy and the growing integration of renewable energy sources, it is essential to design more efficient stabilization techniques that can adapt to the network's varying operating conditions [2].

The Power System Stabilizer (PSS) is widely used to dampen electromechanical oscillations and improve grid stability. However, conventional PSSs lack flexibility in handling system parameter variations, limiting their effectiveness in dynamic conditions [3]. To address these limitations, integrating fuzzy logic into PSS design allows the stabilizer's response to dynamically adapt to network variations, providing better robustness and greater efficiency.

Moreover, energy storage systems, particularly Superconducting Magnetic Energy Storage (SMES), are recognized for their ability to enhance the transient response of electrical networks by regulating energy exchange and compensating for power fluctuations [4]. Combining a fuzzy logic-based PSS (FPSS) with SMES thus represents a promising approach to improving the stability and robustness of the SMIB system.

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In this work, we propose a stabilization strategy that combines FPSS and SMES, evaluating its effectiveness by comparing three system configurations. The first configuration consists of SMIB with SMES only, without a stabilizer. The second configuration integrates SMIB with SMES controlled by a conventional PSS. Finally, the third configuration combines SMIB with SMES controlled by FPSS.

The evaluation of these configurations is carried out through simulations that analyze system stability in terms of voltage, speed, power, and rotor angle.

The main contribution of this work lies in the combination of a fuzzy stabilizer with SMES device, highlighting its impact on improving system stability and damping oscillations. The results obtained demonstrate that this approach provides a better dynamic response than conventional techniques, thereby enhancing grid robustness.

The paper is structured as follows: the section 2 explains the mathematical model of the nonlinear electrical power system SMIB and modelling of SMES device. The design of the proposed approach control is presented in Section 3. The performances of the proposed approach (FPSS & SMES) are carried out by simulations for a power system SMIB with SMES unit that are depicted in Section 4.

II. MODELING OF THE POWER SYSTEM SMIB WITH SMES UNIT

A. SMIB Ssystem

Due to the complexity of power systems, it is common to adopt a modelling approach in the form of a machine connected to an infinite bus (SMIB). The model of the SMIB system used in this study consists of a turbine that transforms the energy from the source into rotational energy, on which a synchronous generator is placed to convert the mechanical power supplied by the turbine into electrical power [5]. This energy is then transferred to the power system through transmission lines, via a transformer that allows power to be transferred from one voltage level to another. In the context of this study, a Superconducting Magnetic Energy Storage (SMES) device is integrated into the SMIB system to improve stability of system by damping power oscillations. This model, schematically illustrated in Figure 1 includes:

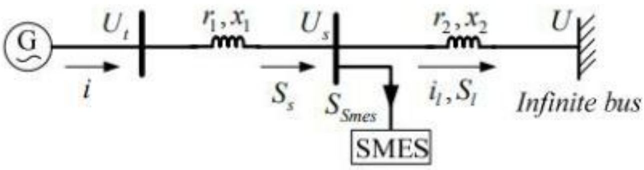

Fig.1 Single machine infinite bus SMIB model with SMES [6].

The nonlinear dynamic of the power system SMIB is described by two-axis model in time domain as follows [7]:

- Electrical part:

$$\frac{dE_d^{'}}{dt} = \frac{1}{T_{q_0}^{'}}\left(\left(x_d^{'} - x_q\right).I_q - E_d^{'}\right) \quad (1)$$

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{d_0}^{'}}\left(\left(x_d^{'} - x_d\right).I_d + E_{fd} - E_q^{'}\right) \quad (2)$$

The terminal voltage equations of the synchronous generator can be written as:

$$V_{td} = -V \sin\delta + R_e I_d + x_e I_q \quad (3)$$

$$V_{tq} = V \cos\delta + R_e I_q - x_e I_d \quad (4)$$

$$V_t = \sqrt{V_{td}^{\ 2} + V_{tq}^{\ 2}} \quad (5)$$

$$P_e = E_d^{'} I_d + E_q^{'} I_q \quad (6)$$

- Mechanical part:

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The equations that describe the dynamic mechanical of the generator:

$$\frac{d\delta}{dt} = \omega_0.(\omega - \omega_r) \tag{7}$$

$$\frac{d\omega}{dt} = \frac{1}{M}\left((P_m - P_e) - D.(\omega - \omega_r)\right) \tag{8}$$

The differential equations describing the steam–turbine–governor system is given by:

$$\frac{d\Delta P_m}{dt} = \frac{1}{T_{RH}}.\left(K_{RH}T_{RH}.\frac{d\Delta P_c}{dt} - \Delta P_m\right) \tag{9}$$

$$\frac{d\Delta P_c}{dt} = \frac{1}{T_{CH}}.(\Delta P_h - \Delta P_m) \tag{10}$$

$$\frac{d\Delta P_h}{dt} = \frac{1}{T_{SM}}.(\Delta P_r - \Delta P_h) \tag{11}$$

$$\frac{d\Delta P_r}{dt} = \frac{1}{T_{SR}}.(K_G.\Delta\omega - \Delta P_r) \tag{12}$$

The configuration of exciter and AVR is represented as following

$$\frac{dE_{fd}}{dt} = \frac{1}{T_E}\left(K_E.(V_{tr} - V_t - V_s) - E_{fd}\right) \tag{13}$$

$$\frac{dV_s}{dt} = \frac{1}{T_{FE}}\left(K_F.\frac{dE_{fd}}{dt} - V_s\right) \tag{14}$$

The complete model of the nonlinear SMIB system used in this work is shown in Figure 2. It consists of several components: the electrical part with a synchronous generator connected to the infinite bus through transmission lines, the mechanical part with the turbine providing rotational energy to the generator, and the excitation system that regulates the generator's voltage for stable operation [8]. Additionally, the SMES device is integrated to enhance network stability by damping power oscillations caused by disturbances or load fluctuations. These combined elements allow for the simulation and analysis of the dynamic behaviour of the SMIB system.

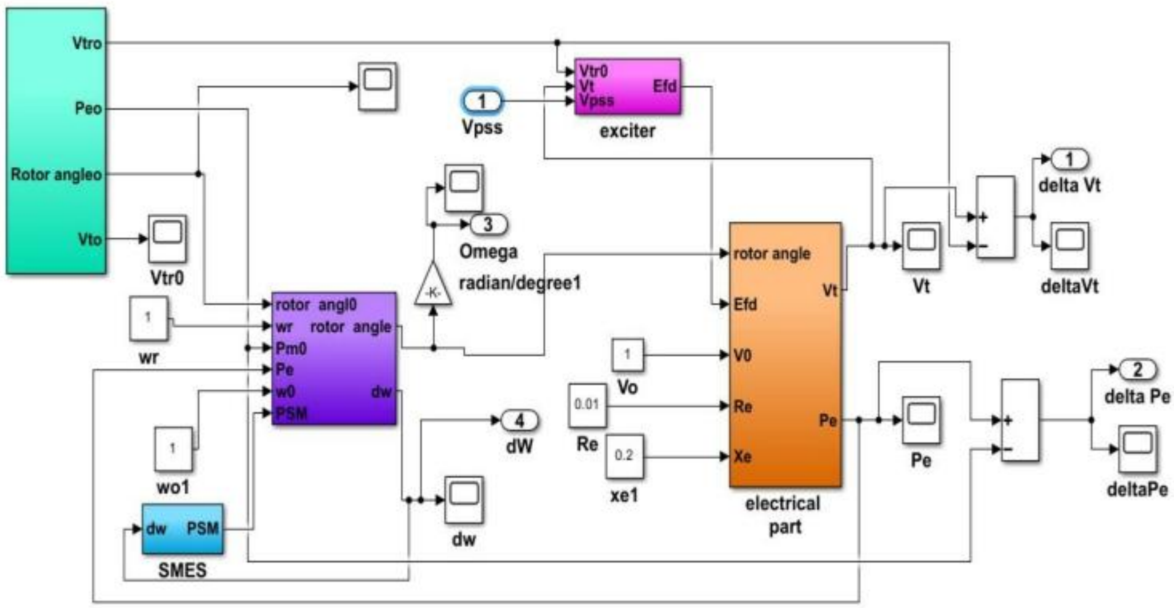

Fig.2 The Complete Model of the Nonlinear Power System SMIB included SMES.

B. Superconducting Magnetic Energy Storage Modelling (SMES)

The Superconducting Magnetic Energy Storage (SMES) system is an energy storage technology based on superconducting coils kept at extremely low temperatures, allowing energy to be stored in the form of a magnetic field. The SMES system includes a cryogenic system to maintain the coils at their optimal temperature, as well as a power conditioning system (PCS) to manage energy exchanges between the SMES and the electrical grid [9]. This system is particularly used to stabilize power grids by quickly releasing large amounts of energy when needed, making it an effective tool for compensating demand fluctuations or providing backup power. The SMES schematic diagram is displayed in Figure 3:

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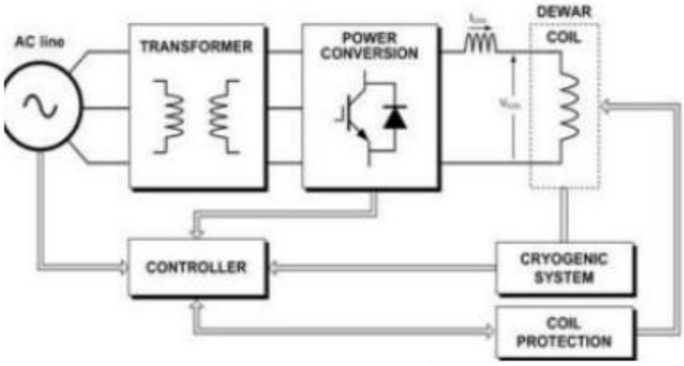

Fig.3 Typical schematic diagram of SMES unit [10].

As a result, power can be absorbed from or released to the power system as needed. At steady state, the SMES should not consume any real or reactive power. The voltage $V_{SM}$of the DC side of the converter is expressed by [11]:

$$V_{SM} = D * V_{DC} \tag{15}$$

$$I_{SM} = \frac{1}{L_{SM}} \int_{t_0}^{t} V_{DC} d\tau + I_{SM0} \tag{16}$$

$$P_{SM} = V_{SM} * I_{SM} \tag{17}$$

$$V_{SM} = \frac{1}{2} L_{SM} * I_{SM}^2 \tag{18}$$

Equation (15), where V_{DC} represents the voltage in the DC link capacitor, D is the duty cycle and VSM is the voltage across the SMES coil, describes the charging mode of the SMES [11]. The current in the SMES is given by equation (16). The energy both delivered and stored by the SMES is shown in equation (17), and the energy stored specifically in the SMES coil is described by equation (18). The SMES Block diagram is given in Figure 4:

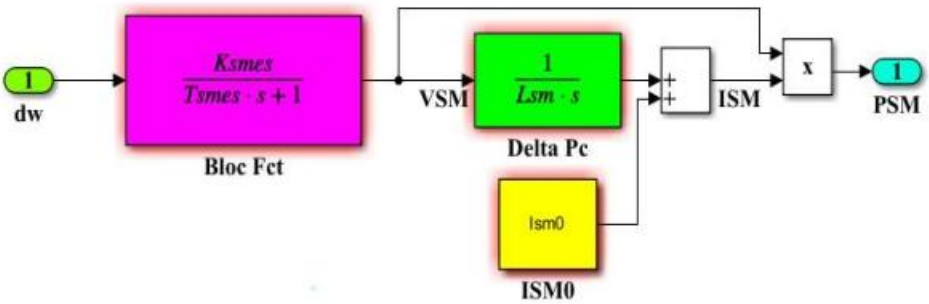

Fig.4. Block diagram of SMES unit control system.

In the context of this study, the SMES is integrated into the SMIB system to enhance the dynamic stability of the grid. The integration of SMES allows for rapid modulation of the energy injected into the grid to dampen power oscillations generated by disturbances, such as load variations or faults. With its ability to quickly provide or absorb energy, the SMES plays an important role in improving system stability, reducing the risk of destabilization, and optimizing the management of power fluctuations.

III. THE FUZZY LOGIC BASED ON POWER SYSTEM STABILIZER FPSS

A. Power System Stabilizer (PSS)

The stability of an electrical system mainly depends on power system stabilizers (PSS), which limit generator oscillations by adjusting its excitation system. The conventional PSS operates by taking the variation in the

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generator's speed (Δω) as input and generating an output signal, Vpss, which regulates the generator's excitation [12].

The transfer functions of the conventional Power System Stabilizer (CPSS) are as follows:

$$U_{PSS} = K_{PSS}\frac{sT_W}{1+sT_W}\left(\frac{(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)}\right)\Delta\omega(s) \quad (19)$$

Where K_{PSS} is a PSS gain, T_W Washout Time constant, T_1, T_2, T_3, T_4, is a Time constants.

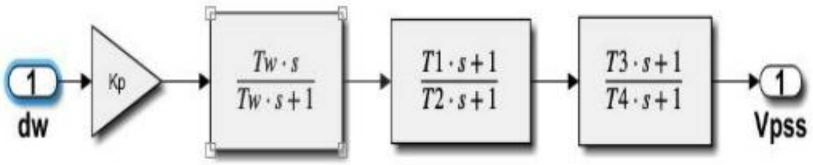

Fig.5 Block diagram of power system stabilizer (PSS) [13].

In the SMIB system, the PSS is crucial for maintaining network stability by reducing power oscillations caused by disturbances or load variations. By quickly adjusting the excitation, the PSS helps stabilize the system, ensuring better energy management under dynamic conditions. However, the performance of the stabilizer can be limited by significant variations in system parameters, affecting its effectiveness.

B. Fuzzy power system stabilizer (FPSS)

In this work, we developed a Fuzzy Power System Stabilizer (FPSS) controller using fuzzy logic to replace the conventional Power System Stabilizer (CPSS) in order to evaluate and compare the performance of both devices. The system used in this study is the SMIB system integrated with the SMES device. The goal is to enhance the dynamic stability of this combined system by leveraging fuzzy logic's ability to manage uncertainty and non-linearity. The FPSS controller is based on a flexible rule base and a decision-making approach inspired by human logic, allowing it to better adapt to network disturbances and adjust the generator's excitation more effectively than the conventional CPSS.
To design this controller, we used the fuzzy logic toolbox in MATLAB, selecting Gaussian membership functions for the inputs $(\Delta\omega, \Delta\omega^{'})$ and output U_{FPSS}, and defining 25 rules to optimize its performance shown in the table 1 [8]. The membership functions of the inputs and the output are described by (NB, NS, ZE, PS, PB) having different ranges in the universe of discourse. A figure (6, 7) illustrates the membership function for the inputs and the output the fuzzy logic controller.

- Inputs :

- Δω : Signal of the speed error.
-Δω': signal the acceleration of the machine.

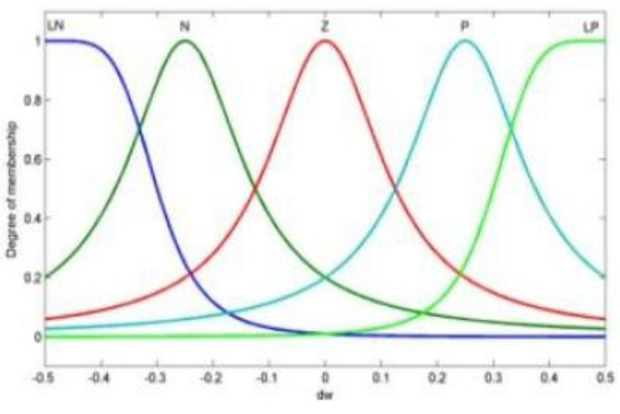

Fig.6. Membership Function Of Input 1 (Δω) and (Δω)'.

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- Output:

- VFPSS: voltage stabilization.

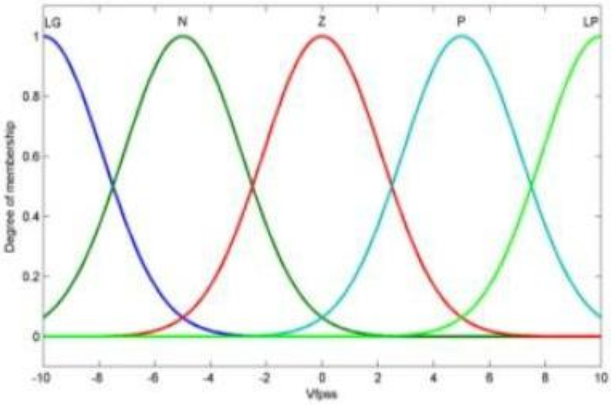

Fig.7 Membership Functions of Output (VFPSS).

- Rules base :

The fuzzy logic rules of the Fuzzy power system stabilizer are given in table I.

TABLE I. THE FUZZY RULE BASE

$\Delta\omega$ / $\Delta\omega'$	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

$\theta 1,..,\theta n$ represent the centroids of M membership functions which are allocated to the controller output U_{FPSS}. Thus, for M rules, the output of the controller is [14]:

$$U_{FPSS} = \frac{\sum_{i=1}^{M} \beta_i \theta_i}{\sum_{i=1}^{M} \beta_i} = \theta^T \xi \qquad (20)$$

Where : $\xi = [\xi_1, \xi_2, \dots, \xi_M]$, $\xi_i = \frac{\beta_i}{\sum_{i=1}^{M} \beta_i}$ and $\theta^T = [\theta_1 \dots\dots \theta_M]$.

β_i is the degree of activation of each ith rule.

By comparing the results obtained with both the CPSS and the FPSS, we analysed the fuzzy controller's ability to reduce power oscillations and improve system stability under different dynamic conditions, highlighting the potential advantages of this approach over the traditional method.

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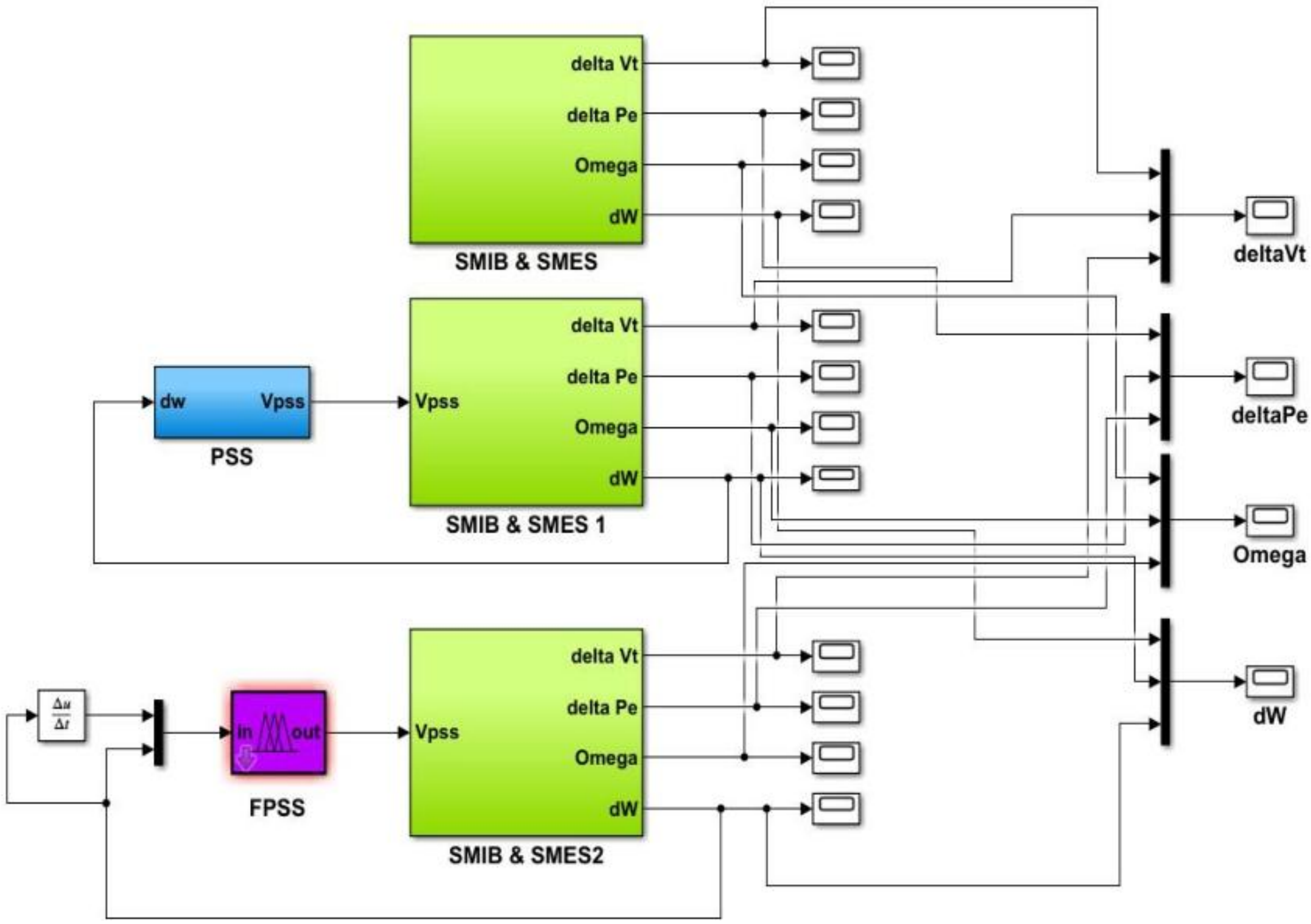

Fig.8 The complete model of power system (SMIB & SMES) with controllers.

The developed controllers are integrated into a Single Machine Infinite Bus (SMIB) system equipped with a Superconducting Magnetic Energy Storage (SMES) unit, as shown in Figure 8. This integration aims to enhance the system's stability and optimize its performance under various operating conditions.

IV. SIMULATION RESULTS

The parameter values of the SMIB system are presented in Table 2 [8]. For the transient stability analysis of the system and to demonstrate the performance and efficiency of the (SMIB & SMES) system with the proposed FPSS control, the deviations of the rotor angle, angular speed, electrical power, and terminal voltage of the generator are shown in Figures 9 to 12.

The operating point used in the simulation [7, 8]:

$$P = 0.8\,(pu) \quad ; \quad Q = 0.496\,(pu) \quad ; \quad \delta = 37.26^{\circ}$$
$$V_t = 1.11\,(pu) \quad ; \quad \omega = 1\,(pu)$$

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TABLE II. THE PARAMETERS VALUES OF THE SMIB SYSTEM

Parameter	**Value**	*Parameter*	**Value**
P_0	0.8	K_E	400
Q_0	0.496	T_E	0.05 s
V	1	K_F	0.025
R_e	0.01	T_{FE}	1 s
x_d	1.7	K_{RH}	0.3
ω_0	1	T'_{d_0}	5.9
T_{RH}	8 s	T'_{q_0}	0.075
T_{CH}	0.05 s	D	0
T_{SR}	0.1 s	M	4.74
K_G	3.5	x_q	1.64
T_{SM}	0.2 s	x'_d	0.245
ω_r	1	x_e	0.2

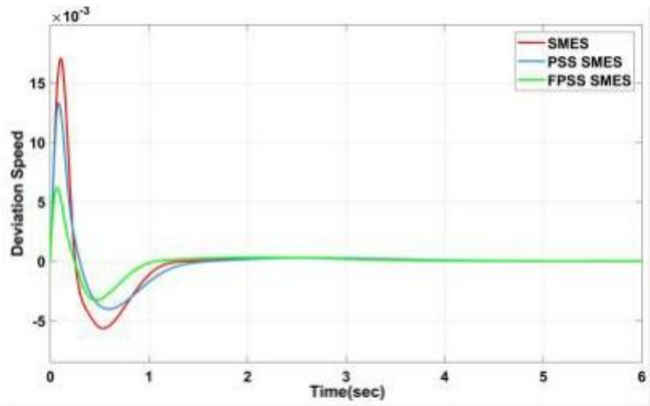

Fig. 9 Deviation speed.

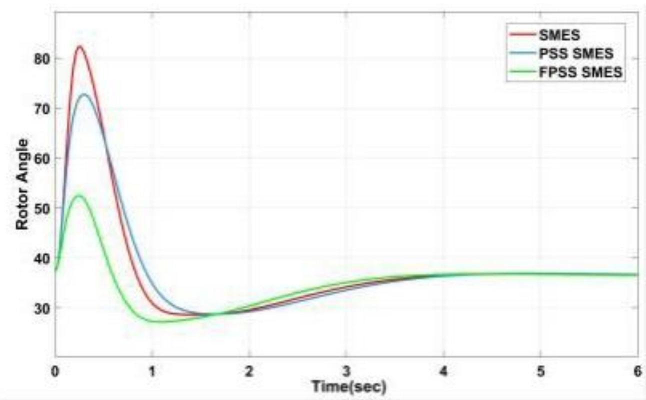

Fig.10 Rotor angle.

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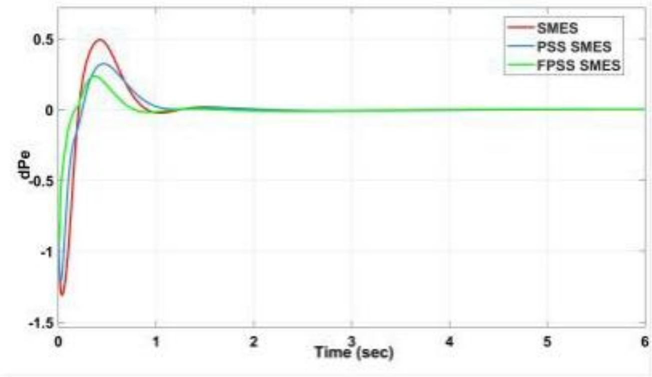

Fig.11 Electric power deviation.

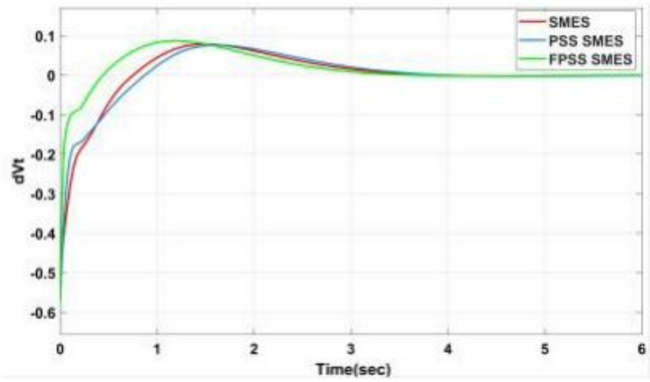

Fig.12 Terminal voltage deviation.

SMIB system integrated with SMES device. The approach using only the SMES demonstrates some ability to mitigate oscillations, but it remains insufficient to ensure rapid and effective stabilization. The integration of a CPSS improves the system's response by reducing oscillations and accelerating convergence to a stable state, although its rigidity limits its effectiveness under variable dynamic conditions. In contrast, the combination of FPSS with SMES proves to be the most effective, offering optimal oscillation damping and faster stabilization of various system variables, including speed, rotor angle, electrical power, and terminal voltage.

Thus, using FPSS in addition to SMES enables more efficient disturbance management, enhancing the robustness and reliability of the power system. This flexible and adaptive approach ensures better transient stability, making it a particularly promising solution for improving power grid performance in the face of fluctuations and unforeseen disturbances.

V. CONCLUSION

In this work, we started with the modeling of the nonlinear SMIB system, describing its dynamics and the challenges related to its stability. Then, we detailed the SMES device, explaining its operation and integration into the SMIB system to enhance energy storage and management performance. Finally, we implemented a robust control FPSS based on Fuzzy logic system, designed to optimize oscillation damping and strengthen system stability. The simulation results showed that the proposed approach (FPSS & SMES) is the most effective among the studied strategies. It ensures efficient oscillation attenuation and faster stabilization of system variables, providing a better transient response and increased robustness against disturbances. These findings confirm the relevance of FPSS as an effective solution for improving the dynamic stability of power systems integrating superconducting energy storage.

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