Coordinated fuzzy logic-based virtual inertia controller and frequency relay scheme for reliable operation of low-inertia power system

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Abstract
Coordination between protection and control devices is crucial for maintaining continuous operation of power systems. Existing strategies suffer from improper coordination of control and protection devices. Moreover, high penetration levels of renewable energy sources result in lowering the overall power system inertia. Therefore, this paper presents a robust fuzzy-logic control (FLC) method for superconducting magnetic energy storage (SMES) in low inertia power systems. The new proposed FLC enables robust and wide operating range for SMES compared to the widely employed controllers. The proposed FLC method and load frequency control are coordinated to emulate virtual inertia. In addition, a cooperate coordination between frequency relay and proposed controller is preserved to maintain reliable operation of low inertia power systems. To prove the effectiveness of proposed coordination strategy, it has been tested considering different load and renewable energy sources (RESs) disturbances with varying inertia level of the selected case study. The results demonstrate that the proposed FLC method can achieve robust SMES operation as virtual inertia controller (VIC) at wide operating range. Moreover, cooperative operation of VIC and frequency protection is preserved using the proposed coordination strategy. The power system availability, frequency regulation, and dynamic stability are improved using the proposed method.

1 INTRODUCTION

Recently, the increase of renewable energy sources (RESs) utilisation in power systems has turned out to be inevitable. However, the intermittent energy generations from the RESs cause fluctuation problems of power system frequency and voltage due to their dependency on weather conditions. These problems may lead to limiting the high penetration levels of RESs in power systems [1, 2]. Moreover, RESs employ the power electronic converters for the integration and power exchange with the grid. These converters lead to lowering the overall system inertia. Consequently, there will be a lack of frequency/voltage stabilisation of the RESs-based power systems compared to conventional synchronous generators-based power systems [3]. Hence, the electrical power system could become unsafe with more extensions of RESs installations and hence increase their penetration levels. In addition, power systems would be subjected to unbalance conditions between the energy generation side and the load demands side. These factors impose several challenges for the frequency control and the existing protection schemes in power systems.

To overcome these stability problems, the development of the virtual inertia control (VIC) systems has been proposed and proven themselves as an effective solution for solving the low inertia of RESs-based power systems [4, 5]. In [6] and [7], VIC methods have been proposed to emulate the power system inertia using the conventional controllers, such as proportional-integral (PI) and PI-derivative (PID) controllers. However, these controllers suffer from complex procedures in tuning their parameters. In addition, they are sensitive to the deviations in the power system parameters during disturbances. Consequently, the robustness of the power system is not assured against more perturbations in the system parameters.

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Several advanced control methods have been presented in the literature for controlling virtual inertia of power systems. The model predictive control (MPC) methods have been widely employed for enhancing the frequency regulation of power systems [8]. Fast response and applicability for modern digital controllers are the main features of MPC-based methods. However, the complex calculations, precise modelling, and parameters dependency are the main obstacles for MPC-based methods. In [9], the coefficient diagram method (CDM) has been applied for emulating the VIC for improving the frequency stability of power systems. However, more complicated steps are needed to acquire the parameters of the CDM structure. From another side, the control of wind energy generation systems has been widely employed for improving the frequency regulation and stability of the power system during high wind power integration [10].

In [11], a robust controller based on the H-∞ technique has been proposed for the VIC application in the low-inertia system. In addition, H-∞-based load frequency control (LFC) method has been presented for the hybrid generation system in [12]. This technique can provide a proper dynamic response of power systems. However, its performance is mainly dependent on the expert control designer for selecting the appropriate weight functions. In addition, the required order of the designed state feedback in this type of controller is preferred to be higher than the order of the controlled plant. In addition, complicated computation burdens are needed in H-∞ technique due to the increased system order by the weighting functions.

The support vector machine has been proposed in [13] for designing efficient controllers for automatic generation control (AGC) in multi-area power systems. Additionally, more advanced control method based on fuzzy PID with derivative filters has been presented in [14]; however, the tuning process of the controllers is very complex. The imperialist competitive algorithm has been proposed in [15] for tuning of various fractional-order controllers in two-area microgrids. An event-triggered AGC system has been presented in [16] for multi-area power systems. Moreover, LFC design method based on the D-partition method has been proposed in [17] by employing PI controllers. However, the VIC and the coordination between control and protection devices have not been considered in these methods.

On the other hand, a coordinated control between power system generation supplies and load demand has been developed in the literature. Additionally, the coordination of multi-energy storage sources in a single area and multi-area power systems have been widely studied in the literature [18]. Enhanced frequency regulation, improved dynamic response, and better utilisation of sources are the main benefits of these coordination methods. A control technique considering the state of charge (SoC) of energy storage system (ESS) with wind energy generation has been presented in [19] for the storage system. The SoC is used as a feedback control signal for the ESS to activate pitch control of the wind generator. However, this technique is not appropriate for dealing with the sudden changes in wind power variation, which is a common disturbance in power systems.

A superconducting magnetic energy storage (SMES)-based virtual inertia emulator has been presented in [20]. The SMES as energy storage systems with inertia rate of change of frequency controller has been developed for emulating virtual inertia for power systems. In [21], the authors proposed the coordination of LFC and SMES considering only the wind energy penetration using moth swarm algorithm for optimal PID controller. Moreover, a coordination of VIC and frequency protection has been presented in [22] using the particle swarm optimisation for optimising the conventional PI controller parameters. However, these methods lack the practical model and control of SMES to optimally take the benefit the SMES devices, and complex procedures are needed for tuning the PI and PID controllers. Also, they do not consider the coordination among the control side and the protection action for protective devices.

The fuzzy logic control (FLC) has been widely employed in the literature for enhancing frequency regulation of power systems. In [23], an optimised FLC method for electric vehicles functioning as secondary frequency controllers in two-area power systems has been presented. An adaptive FLC method for LFC control of multi-area power systems has been presented in [24]. Another adaptive FLC has been added to the control loop of the SMES device in [25] to improve the dynamical response of an interconnected power system. Furthermore, FLC-based virtual inertia controller has been presented in [26]. However, the aforementioned control methods lack the counting of the properties of the energy storage supply in addition to the lack of coordination of various control functionalities together and the protection functionalities. A detailed comparison between the main contribution of this study and the literature is shown in Table 1.

Compared with traditional control methods, there are many benefits of using fuzzy logic controllers [27] such as the following:

(i) The FLC can operate at a much wider variety of operating conditions, compared with conventional PI and PID controllers. Moreover, the FLC can deal with the various forms of noise and disturbances, which represent major features of RESs-based power systems.

(ii) The FLC can achieve more smooth frequency regulation at the existence of various disturbances in the power system. In addition, the FLC can achieve a faster response, which is crucial for the virtual inertia controllers.

(iii) The implementation of the FLC is cheap and it can be programmed using low-cost digital controllers. Furthermore, the FLC represents a rule-based control system, which does not require experienced persons.

The main contributions in this study can be summarised as the following:

(i) A VIC strategy using SMES has been presented. The incorporation of the fast charge/discharge of SMES devices, compared to other ESSs, with the governor action and LFC to enhance the power system stability regarding the
The realistic Egyptian power system (EPS) is selected as a case study for evaluating the proposed control and coordination strategy. The simulation results and discussions for the selected case study are presented in Section 4. Finally, Section 5 presents the conclusion of this study.

## 2 SYSTEM CONFIGURATION

### 2.1 The selected case study

The realistic Egyptian power system (EPS) is selected as a case study for evaluating the proposed control and coordination methods. Each zone includes one or more power plants of different generation sources such as thermal, hydraulic, coal, and natural gas power plants. The conventional generation sources are classified into reheat, non-reheat, and hydropower plants. With the advantageous location of Egypt, the government is targeting to increase the penetration levels of renewable energy in the EPS. The most appropriate RESs for the Egyptian weather are solar and wind power generation. The government plan is aiming at increasing the penetration level of RESs to about 30%–40% of the total generation by the year 2035 and up to 65% by the year 2050. Therefore, promoting the EPS acts more challenges for the Egyptian engineers and designers as the existing control and protection schemes may not be enough to withstand this increase in RESs penetration.

A schematic diagram of the power system elements of the typical power system is shown in Figure 1. There are two main generation resources including conventional generation sources and RESs. The electrical loads are mainly residential and industrial loads. Additionally, energy storage systems are employed for smoothing the generation-side and load-side fluctuations. The control centre performs two main functions including the control and the protection functions. The dynamical modelling of the selected case study is shown in Figure 2. In the selected EPS case study, a centralised PID controller is employed for performing the secondary frequency control. The participation of each of the non-reheat thermal power plant, reheat thermal power plant, and the hydropower plant is determined by $P_{e1}$, $P_{e2}$ and $P_{e3}$, respectively.

Therefore, this study proposed a new coordination of LFC and SMES based on fuzzy controller in addition to the digital frequency relay (DFR) to preserve the dynamic stability of the EPS considering the future updating of increasing RESs and loads. The control functions are classified into VIC, primary frequency control, and secondary frequency control functionalities. Coordinated operation of these functions is crucial for robust operation of the power system. From another side, the main protection functions are the over-frequency (OF) and under-frequency (UF) protection functionalities. The detection of abnormal OF and UF operation at predefined levels requires tripping the circuit-breaker relays of the power system. Additional coordination is required between the control and protection functions for reliable operation of the power system.

### 2.2 Mathematical model of the system

This section presents the state-space modelling of the studied microgrid. The block diagram of the transfer function for the various elements in the studied system is shown in Figure 2. The justification of the various symbols is included in the nomenclature part. The frequency deviation ($\Delta f$) of the overall power system considering the effect of penetration of RESs, SMES, the

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**TABLE 1** Comparison between the proposed method with the existing methods in the literature

| Reference | Energy storage type, model | Control method | Protection and control coordination | Renewable energy sources type | Minimum stable inertia level | Case study |
|-----------|---------------------------|----------------|-------------------------------------|------------------------------|-----------------------------|------------|
| [8]       | Not specified, first-order model | Model predictive control | Not considered                  | Only wind                   | Till 25% of normal inertia  | MG         |
| [20]      | Superconducting magnetic energy storage (SMES), dynamic model | The derivative control ($d\Delta f/dt$) | Not considered                  | Wind and PV                 | Till 50% of normal inertia  | MG         |
| [21]      | SMES, first-order model | Proportional-integral (PI) controller tuned using moth swarm algorithm | Not considered                  | Only wind                   | Till 50% of normal inertia  | EPS        |
| [22]      | Not specified, first-order model | PI tuned using particle swarm optimisation | Considered                      | Wind and PV                 | Till 30% of normal inertia  | MG         |
| [26]      | Not specified, first-order model | Robust fuzzy logic control (FLC) | Not considered                  | Wind and PV                 | Till 30% of normal inertia  | MG         |
| Proposed  | SMES, new practical model | Adaptive FLC | Considered                      | Wind and PV                 | Till 25% of normal inertia  | EPS        |

MG, microgrid; PV, photovoltaic.
primary and secondary control (LFC) can be obtained as

\[
\Delta f = \frac{1}{2Hs + D_s}\left( \Delta P_{m1} + \Delta P_{m2} + \Delta P_{m3} + \Delta P_W + \Delta P_{PV} \right) - \Delta P_{SMES} - \Delta P_L \tag{1}
\]

The conventional generation includes non-reheat thermal power plant ($\Delta P_{m1}$), reheat thermal power plant ($\Delta P_{m2}$), and hydropower plant ($\Delta P_{m3}$). The total power of the conventional generation ($\Delta P_m$) can be modelled as the following:

\[
\Delta P_m = \Delta P_{m1} + \Delta P_{m2} + \Delta P_{m3} \tag{2}
\]

First, the non-reheat thermal power plant can be modelled as the following:

\[
\Delta P_{m1} = \Delta P_{g1} \frac{1}{T_{s1} + 1} \tag{3}
\]

Second, the reheat thermal power plant can be modelled as the following:

\[
\Delta P_{m2} = \Delta P_{g2} \frac{1}{T_{s2} + 1} \tag{5}
\]

\[
\Delta P_{g2} = \Delta P_{g2} \left( \frac{K_{s2} + 1}{T_{s2} + 1} \right) \tag{6}
\]
Third, the hydropower plant can be modelled as the following:

\[
\Delta P_{w3} = \frac{P_{a3}}{T_{g3} f + 1} \left( -\frac{1}{R_3} \Delta f - \Delta P_c \right) \tag{8}
\]

\[
\Delta P_{\beta3} = \Delta P_{w3} T_{g3} f + 1 \tag{9}
\]

\[
\Delta P_{\beta3} = \frac{P_{a3}}{T_{g3} f + 1} \left( -\frac{1}{R_3} \Delta f - \Delta P_c \right) \tag{10}
\]

The regulating system frequency (\(\Delta P_c\)) is a function of PID secondary controller and the area control error (ACE), where \(ACE = \beta \Delta f\), as the following [7]:

\[
\Delta P_c = -K_p - K_i \int ACE - K_d \frac{d}{dt} ACE \tag{11}
\]

The wind and PV renewable powers are considered in the selected case study. They are usually modelled using first-order transfer function with unity gain and the corresponding time constants (\(T_{w7}\)) and (\(T_{PV}\)) for the wind and PV generation, respectively, as the following:

\[
\Delta P_w = \frac{1}{sT_{w7} + 1} (\Delta P_{\text{wind}}) \tag{12}
\]

\[
\Delta P_{PM} = \frac{1}{sT_{PV} + 1} (\Delta P_{\text{PV}}) \tag{13}
\]

The various modelled generation and loads in the selected case study as in Equations (1) to (13) can be employed for deriving the dynamic equations for the selected case study. The state-space description of the studied system is as follows:

\[
\dot{x} = Ax + Bu + B_1w
\]

\[
y = Cx
\]

where \(x, y, w, \) and \(u\) are vectors representing the system states, output states, disturbances, and control variables, respectively, in the frequency model of the selected case study. The control variables in the proposed method include \(\Delta P_a\) and \(\Delta P_{\text{MES}}\), which is obtained by the proposed FLC method as will be described in Section 3.1, whereas \(A, B_1, B_2,\) and \(C\) represent the corresponding matrices of the linearised modelled system. The elements of the state space can be modelled as follows:

\[
x = [\Delta f, \Delta P_{a1}, \Delta P_{\beta3}, \Delta P_{w3}, \Delta P_{\beta3}, \Delta P_{w3}, \Delta P_{\beta3}, \Delta P_{a3}]^T
\]

\[
w = [\Delta P_a, \Delta P_{PM}]^T
\]

\[
u = [\Delta P_a, \Delta P_{\text{MES}}]^T
\]

The matrices \(A, B_1, B_2,\) and \(C\) for the linearised state space of the selected case study can be described as following:
The proposed SMES model and control system for the power system is shown in Figure 3. It consists of a three-phase transformer, voltage source converter (VSC) using an insulated-gate bipolar transistor triggered with pulse width modulation, and DC-link capacitor. The heart of the SMES unit is the superconducting coil (SC), which is connected to the AC grid through a power conversion system (PCS), which includes an inverter/DC-DC chopper. The SC is charged from the grid during the normal operation to a set value. After charging the SC, it can conduct the supporting current with the electromagnetic field. During SMES operation, the SC should be immersed in liquid helium at 4.2 K in an insulated vacuum cryostat to maintain it in the superconducting state. Whenever there is a fluctuation in the system power during a disturbance, the discharging starts immediately through the PCS to the utility grid. The control system can restore the power system to an equilibrium condition, and the SC charges again to its steady-state value.

The SMES is the preferred solution among the various types of ESSs to resolve the problems caused by changing weather and load capacity. During the charging/discharging processes, SMES systems have a quick time delay, high efficiency, high power density, quick response, and long service lifespan [28, 29]. In comparison to the other ESSs, there are many advantages of SMES [30], which are as follows:

1. The SMES operates through the direct storage of electrical energy in a superconducting belt, which enables access time in milliseconds.
2. The duration and number of charges/discharges have almost no influence on the lifetime of SMES. Therefore, SMES benefits the long lifetime superiority over the other existing energy storage systems.
3. The SMES has high efficiency and it can achieve up to 98% charge/discharge efficiency.
4. Due to its low power loss, the SMES unit is highly efficient.
5. Electric currents in the coil encounter almost no resistance and the unit has no moving parts.

The simplified dynamic model of the SMES system is employed to study the performance of the frequency response as presented in Figure 4 [31]. The system frequency deviation (Δf) is the input signal of the SMES model to generate the required power to the system (ΔP_{SMES}). By neglecting the transformer and converter losses, the inductor voltage deviation (ΔE_L) and inductor current deviation (ΔI_L) can be calculated as follows:

\[ \Delta E_L = \frac{K_{SMES}}{T_{DC}} + 1 \Delta f - K_{id} \Delta I_d, \quad \text{and} \quad \Delta I_L = \frac{\Delta E_L}{sL} \]  

where \( T_{DC} \), \( K_{SMES} \), \( L \), \( K_{id} \) are the converter time delay, the gain of SMES control loop, coil inductance, the feedback gain of \( \Delta I_d \), respectively. The SMES active power deviation \( \Delta P_{SMES} \) can be expressed by considering the coil rated current \( (I_{d0}) \) and \( \Delta E_L \), as follows:

\[ \Delta P_{SMES} = (\Delta I_d + I_{d0}) \Delta E_L \]  

2.3 SMES model

SMES basic configuration for the power system is shown in Figure 3. It consists of a three-phase transformer, voltage source converter (VSC) using an insulated-gate bipolar transistor triggered with pulse width modulation, and DC-link capacitor. The heart of the SMES unit is the superconducting coil (SC), which is connected to the AC grid through a power conversion system (PCS), which includes an inverter/DC-DC chopper. The SC is charged from the grid during the normal operation to a set value. After charging the SC, it can conduct the supporting current with the electromagnetic field. During SMES operation, the SC should be immersed in liquid helium at 4.2 K in an insulated vacuum cryostat to maintain it in the superconducting state. Whenever there is a fluctuation in the system power during a disturbance, the discharging starts immediately through the PCS to the utility grid. The control system can restore the power system to an equilibrium condition, and the SC charges again to its steady-state value.

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\[ \Delta E_L = \frac{K_{SMES}}{T_{DC}} + 1 \Delta f - K_{id} \Delta I_d, \quad \text{and} \quad \Delta I_L = \frac{\Delta E_L}{sL} \]  

where \( T_{DC} \), \( K_{SMES} \), \( L \), \( K_{id} \) are the converter time delay, the gain of SMES control loop, coil inductance, the feedback gain of \( \Delta I_d \), respectively. The SMES active power deviation \( \Delta P_{SMES} \) can be expressed by considering the coil rated current \( (I_{d0}) \) and \( \Delta E_L \), as follows:

\[ \Delta P_{SMES} = (\Delta I_d + I_{d0}) \Delta E_L \]  

3 THE PROPOSED COORDINATION OF FLC-SMES/DFR

3.1 The proposed SMES model and control

Figure 5 describes the proposed SMES model based on FLC. This model considers all SMES modes of operation as well as the initial condition of SMES node as the following:
Charging mode of operation: In this mode, SMES charges power from EPS when the value of duty cycle $D$ (the output of FLC) is larger than 0.5 and less than or equal to 1.0 (i.e. $0.5 < D \leq 1.0$). The complete equations for this mode can be summarised as follows:

$$E_{ismo} = 0.5I_{ismo}^2 t_{ismo}$$ (19)
$$V_{ismo} = (2D - 1) \cdot V_{DC}$$ (20)
$$P_{ismo} = V_{ismo} \cdot I_{ismo}$$ (21)
$$E_{ismo} = E_{ismo} + \int_0^t P_{ismo} dt$$ (22)

where $E_{ismo}$, $E_{ismo}$, $I_{ismo}$, $I_{ismo}$, $V_{ismo}$, $P_{ismo}$, $V_{DC}$ are the initial SMES energy, the current SMES stored energy, initial SMES coil current, the updated SMES current, SMES coil inductance, SMES coil voltage, output SMES active power, and the voltage across DC capacitor linked between SMES chopper circuit and SMES VSC, respectively.

Discharging mode of operation: In this mode, SMES discharges its power to EPS when the value of $D$ changes between 0.0 to 0.5 (i.e. $0.0 \leq D < 0.5$). All equations for this mode are listed as follows:

$$V_{ismo} = (2D - 1) \cdot V_{DC}$$ (23)
$$P_{ismo} = V_{ismo} \cdot I_{ismo}$$ (24)
$$E_{ismo} = E_{ismo} + \int_0^t P_{ismo} dt$$ (25)

Standby mode of operation: SMES operates without either charging or discharging energy to or EPS, respectively, in this mode. The value of $D$ is equal to 0.5. The equations which define this mode are as follows:

$$\begin{cases} I_{ismo} = \text{Constant} \\ V_{ismo} = 0.0 \\ P_{ismo} = 0.0 \end{cases}$$ (26)
$$E_{ismo} = 0.5I_{ismo}^2 L_{ismo}$$ (27)

A Gaussian-type mode is used to design inputs and output membership function, which indicates good and fast response during a sharp variation in both inputs and output variables [32, 33]. Figure 6 displays the complete process and the rule tables of the designed FLC technique. The inputs of FLC are frequency deviation ($\Delta f$) and the derivative of frequency deviation ($d(\Delta f)/dt$). $D$ is considered the output variable of the FLC. The initial current value of the proposed SMES in the selected case study is 4 kA and SMES inductance is 0.5 H.

3.2 Proposed setting for the DFR

The implemented DFR consists mainly of three main stages, namely, the analogue-to-digital (ADC) conversion, detection, and reconfiguration stages. Figure 7 shows the three stages and waveforms of each stage. In the ADC stage, the measured frequency through the frequency measurement unit is sampled...
FIGURE 6  Complete procedures of the FLC process. $\text{BigN}$ = big negative, $\text{Neg.}$ = negative, $\text{Pos.}$ = positive, $\text{BigP}$ = big positive, $\text{FatD}$ = fast discharge, $\text{Dis.}$ = discharge, $\text{Not}$ = no action, $\text{Charg.}$ = charge, $\text{FastC}$ = fast charge

FIGURE 7  The implementation stages of the digital frequency relay system

and converted to digital waveform suitable for digital manipulation.

The second stage of the implemented DFR is the frequency detection element, which receives the digital frequency signal from the ADC stage. In this stage, the received digital frequency signal is compared with the frequency limits of the DFR ($f_{\text{max}} = 51 \text{ Hz} < f < f_{\text{min}} = 49 \text{ Hz}$) as per the European grid code for the islanded mode [34]. The counter begins to count the cycles when the measured frequency is out of the DFR limits. A threshold is set in order to distinguish the short duration UF and OF limits. When the counted error cycles reach the predefined threshold, a trip signal is generated and sent to the third stage of the reconfiguration stage. Therefore, in order to energise the relay and send a trip signal to the circuit breaker, there are two conditions that have to be met together. The first condition is that the system frequency exceeds the permissible limits of the OF and UF settings, whereas the second condition is that the counter output magnitude is larger than the threshold value ($K > \text{threshold (1 s)}$). The third stage is the reconfiguration stage, which receives the detection enable signal and its type. Then, the reconfiguration stage determines the appropriate control action, including the disconnection of power system elements, load management and/or shedding, and so forth. The proposed construction of the DFR is suitable for the implementation by an intelligent electronic device using microprocessor-based technology.

3.3  Proposed control and protection coordination method

Figure 8 shows the proposed coordination strategy between control functionalities together and with the protection scheme. The protection strategy is activated when the measured frequency exceeds the limits for the predefined time duration. Afterwards, the reconfiguration strategy is enabled, and suitable protection action is applied. From another side, there are three control units for the control functionalities. These control units are the virtual inertia, the primary frequency, and the secondary control units. They are applied in a coordinated manner in order to maintain stable system frequency during the power system transients.

In the proposed coordination strategy, the VIC unit takes the charge and responsibility for mitigating sudden power mismatches at 1 to 10 s range. Thence, it accounts for the first balancing strategy for achieving power balance between
generations and loads. Afterwards, the primary frequency control unit is in charge for the stabilisation of the power system frequency to steady state in time range of 10 to 30 s. The third stage is the secondary frequency control unit, which is accounting for the recovery of the power system frequency to the nominal value within the time range between 10 to 30 min.

The proposed control method and the SMES device participate in stabilising the power system against disturbances, whereas the RESs and load demands in the selected case study do not participate in the frequency regulation. The added functionality of inertia control in addition to the coordinated operation of control and protection units helps to maintain stable and continuously available power systems. The absence of coordination in traditional control and protection systems may lead to more shutdown of the power system in addition to unstable operation.

4 | SIMULATION RESULTS AND ANALYSIS

4.1 | Single-area EPS

The studied EPS case study contains reheat, non-reheat, and hydropower plants with a total generation capacity 38,000 MW, base peak loads of 29,000 MW, and system frequency of 50 Hz based on the annual report of the Egyptian Electricity Holding Company [35]. This system is presented by the National Energy Control Centre in Egypt [36]. It has been rebuilt using MATLAB software with some manipulation to include the new integration of RESs and the coordination of SMES and DFR. Table 2 summarises the nominal system parameters [36]. This system is tested in the presence of wind power of about 8750 MW and solar power of 5700 MW as shown in Figure 9, in addition to load variations as shown in Figure 10 for a simulation time of 20 min. To investigate the dynamic security of this system by using the proposed coordination of FLC-SMES and DFR, four scenarios are applied. The generation rate constraints limit the generation rate of output power. The main objective of this research is to investigate the studied system performance under the power variation of RESs such as the wind power, the PV solar power and the load power variations ($\Delta P_{L}$) as.
**TABLE 3** Disturbance operating conditions for the simulation study

| Source       | Starting | Stopping | Size (pu) |
|--------------|----------|----------|-----------|
| Industrial load | 300 s    | –        | 0.22      |
| Residential load | Initial | 800 s    | 0.12      |
| Wind power   | 600 s    | –        | 0.23      |
| PV           | Initial  | –        | 0.15      |

**FIGURE 11** The frequency response for scenario A (100% of default system inertia)

disturbance signals. Table 3 summarises these disturbance conditions during the simulation period.

### 4.1.1 Scenario A

In this scenario, the performance of EPS is tested without changing the system inertia level (i.e. 100% of default system inertia). Figure 11 shows the frequency response of the EPS under the sequence of operating conditions as shown in Table 3. The EPS could not withstand its stability at the first step of a disturbance at 300 s at the instant of connecting the industrial load, where the frequency deviation exceeds the allowable limits. Hence, the DFR is energised in that case, and then a trip signal is sent to the circuit breaker. While the simplified SMES model can dampen the frequency oscillations under the acceptable limits, the frequency oscillates at the instant of wind farm connection (at 600 s), the maximum and minimum frequency deviations are 0.5 and 0.39 Hz, respectively. The frequency takes a long settling time to return to its stable operating point. On the contrary, by installing the proposed modified SMES based-FLC, the frequency changes within 0.1 and 0.13 Hz during the undershoot and overshoot variations, respectively. The frequency returns rapidly to steady-state value without the necessity of DFR action. Therefore, the proposed coordination method plays an efficient role in maintaining the EPS dynamic security, compared to the other two cases.

### 4.1.2 Scenario B

In this scenario, the EPS system is subjected to the same operating conditions of Table 3 besides reducing the system inertia to 55% of the default system inertia level. The EPS failed to restore its frequency stability only in the case of the conventional controller (without using SMES), where the frequency deviation increases over the allowable limits. This, in turn, leads to the DFR being energised and send a trip signal to the circuit breaker because the integrator value ($K$) exceeds its threshold value at the industrial load connection (at 300 s) as shown in Figure 12, while the impact of the simplified SMES model on the system performance under the same conditions can restore the system frequency at different disturbance instants, such as at 300, 600, and 800 sc. In this case, the maximum and minimum frequency deviations are 0.85 and 0.64 Hz, respectively. However, the utilisation of modified SMES-based FLC with EPS can significantly reduce the maximum and minimum frequency deviations to 0.14 and 0.11 Hz, respectively, and restore the frequency to its normal state rapidly.

### 4.1.3 Scenario C

The effectiveness of the proposed coordination strategy is approved in this scenario, whereas the EPS is estimated under the situation of low system inertia (35% of default system inertia), with the default parameters and multiple operation conditions of wind power, PV solar power variations, and load disturbance profile as summarised in Table 3. Figure 13 shows that the EPS can operate within the stable region at 300 s in both cases of simplified SMES and FLC-SMES models. However, during the wind power insertion period (i.e. at 600 s), EPS could not withstand in stable operation in case of the simplified SMES model, and thus the DFR operates and sends a trip signal to the circuit breaker. On the other hand, the proposed FLC-SMES has the ability to readjust the frequency variation (0.15 Hz in overshoot and 0.11 Hz in undershoot variations).
to its normal value during the events of insertion/rejection for both loads and wind power generation. Hence, the proposed coordination can effectively solve the maloperation problem of the DFR in the other two cases without the necessity of readjusting the integrator setting of the DFR.

4.1.4 Scenario D

In this scenario, the reliability of EPS is studied under the situation of very low system inertia (25% of default system inertia) with the same operation condition listed in Table 3. Due to the extreme reduction of system inertia, the EPS could not withstand in stable operation in the case without using SMES and utilizing a simplified SMES mode. In this critical scenario, in both the above-mentioned two cases, the system frequency comes out of the adjustable limits and exceeds the threshold value of the integrator gain $K$ as presented in Figure 14. Therefore, the DFR sends a trip signal with a quick response at the first disturbance event (at 300 s) to protect the equipment from failure. On the contrary, by utilizing the proposed FLC-SMES model, the system frequency can

![Figure 13](image1.png)  
**FIGURE 13** The frequency response for scenario C (35% of default system inertia)

![Figure 14](image2.png)  
**FIGURE 14** The frequency response of the Egyptian power system (EPS) for scenario D (25% of default system inertia)

![Figure 15](image3.png)  
**FIGURE 15** Comparison of FLC and proportional-integral-derivative controllers

| Scenarios          | Variations                  | Max. overshoot (Hz) | Min. undershoot (Hz) | Overshoot | Undershoot |
|--------------------|-----------------------------|---------------------|----------------------|-----------|------------|
| Scenario A        | Simplified SMES model       | 0.5                 | 0.39                 | 80        | 66.7       |
|                    | Proposed FLC-SMES           | 0.1                 | 0.13                 |           |            |
| Scenario B        | Simplified SMES model       | 0.85                | 0.64                 | 83.5      | 82.8       |
|                    | Proposed FLC-SMES           | 0.14                | 0.11                 |           |            |
| Scenario C        | Simplified SMES model       | 1.3                 | Dropped to zero      | 88.5      | 99.8       |
|                    | Proposed FLC-SMES           | 0.15                | 0.11                 |           |            |
| Scenario D        | Simplified SMES model       | –                   | Dropped to zero      | –         | 99.8       |
|                    | Proposed FLC-SMES           | 0.15                | 0.11                 |           |            |

**TABLE 4** Proposed method improvement in frequency deviation comparing with a simplified SMES model
significantly dampen during all disturbance events after extreme over/undershoot variations (i.e. 0.15 Hz overshoot and 0.11 Hz undershoot).

Moreover, Figure 15 shows the superiority of the proposed FLC-SMES, compared to the optimal PID controller. It is clear that the FLC technique can provide a satisfactory performance in restoring the system frequency against different disturbances in terms of maximum overshoot and maximum undershoot and with minimum settling time, whereas the PID-SMES suffers from elongated damped fluctuations at all instants of disruptions especially during the wind generation connection at \( t = 600 \text{ s} \).

Table 4 summarises the improvement in frequency deviation after using the proposed FLC-SMES in comparison with a simplified SMES model. It is clear that a good enhancement of the EPS frequency response is achieved in all scenarios by installing the proposed FLC-SMES model. Moreover, the stability of EPS can be quickly returned due to the operation of very low system inertia. The improvement index \( (IP) \) can be calculated as follows:

\[
IP = \frac{d f_{\text{sim.}} - d f_{\text{prop.}}}{d f_{\text{sim.}}} \% \quad (28)
\]

where \( d f_{\text{sim.}} \) and \( d f_{\text{prop.}} \) represent the value of maximum overshoot/minimum undershoot frequency variations at using a simplified SMES model and maximum overshoot/minimum undershoot after installing the proposed FLC-SMES, respectively.

4.2 Two-area EPS

To validate the effectiveness of the proposed coordinated scheme of FLC-SMES and the DFR, it has been extended to the interconnected power system. For a large multi-area power system, it is very difficult to keep the tie-line power at their arranged values in case of large disturbances, which could disseminate quickly via the whole system resulting in a cascade tripping of units due to loss of system stability. Hence, this section presents the multi-area EPS, whereas the first area includes the same generation units of the previous case study, and the second area consists of the main reheat, non-reheat, and hydropower plants beside the solar power plant. Figure 16 illustrates the schematic diagram of the two-area interconnected EPS. The all nominal data of the two-area EPS are included in Table 2. The studied two-area EPS is tested under the conditions of high system inertia (at 100% of its nominal value) and low system inertia (25% of its nominal value) to represent the consider-

| Area 1 | Source | Starting | Stopping | Size (pu) |
|-------|--------|----------|----------|-----------|
| Industrial load | 300 s | – | 0.22 |
| Residential load | Initial | 800 s | 0.12 |
| Wind power | 600 s | – | 0.23 |
| PV | Initial | – | 0.15 |

| Area 2 | Source | Starting | Stopping | Size (pu) |
|-------|--------|----------|----------|-----------|
| Industrial load | Initial | – | 0.22 |
| Residential load | Initial | – | 0.12 |
| PV | Initial | – | 0.15 |

Table 5 Operation condition of the multi-area Egyptian power system

4.2.1 Case 1

In this scenario, the performance of the multi-area EPS with the proposed coordinated frequency control and protection is tested under the natural fluctuations of the RESs. A high fluctuated wind power of 0.23 pu is installed in area 1 and connected at time \( t = 600 \text{ s} \), while a solar generation of 0.15 pu is connected in area 2 at the initial time as shown in Table 5. Figure 17 displays the frequency and tie-power deviations in areas 1 and 2 of the studied two-area EPS with different control strategies. It is clear that the proposed FLC-SMES can provide satisfactory performance in restoring the system frequency against different disturbances at the instants of abrupt connection/disconnection of the loads at 300 and 800 s as well as the insertion of wind generation unit at 600 s, where \( f_1 = 49.9, 50.21, 50.1 \text{ Hz at 300, 600, and 800 s, respectively} \) whereas the PID-SMES indicated a severe change along the disturbances periods \( f_1 = 49.5, 50.6, 50.24 \text{ Hz at 300, 600, and 800 s, respectively} \), with large settling times, which leads to an unstable solution in damping the system frequency deviation as shown in Figures 17(a) and (b). Furthermore, the developed FLC-SMES displayed its ability to effectively enhance the change in tie-line power between the two areas compared to other techniques as depicted in Figure 17(c). It is also found that by applying FLC-SMES, not only the frequency and tie-power transient are damped but they also settled down in less time in comparison with PID-SMES.

4.2.2 Case 2

The effectiveness and robustness of the proposed coordinated FLC-SMES and DFR protection technique are tested in an extreme case, where the system inertia is reduced to 25% of the default system inertia considering the same assumed various disturbances of load and RESs as noted in Table 5. Figure 18 shows that applying the PID-SMES can return the frequency oscillations to its normal value at the first time of disturbance at \( t = 300 \text{ s} \) after it went down to \( f_1 = 49.13 \text{ Hz and } f_2 = 49.6 \text{ Hz as shown in Figure 18(a). However, it suffers from high-frequency overshoot at the connection of the wind
A generation unit at $t = 600$ s, where the EPS frequency violated the allowable limits ($f_i = 51.07$ Hz). Although the EPS frequency varied out of the given protection range at this moment, the DFR does not trip. This is because the integrator output value does not exceed the set value ($K$). On the other hand, the proposed FLC-SMES improved the overall transient EPS performance as shown in Figures 18(a) to (c) in terms of maximum overshoot and undershoot as well as the rise and settling times throughout the three times of load and wind power disturbances under the low-inertia effect without the need for DFR action. Therefore, it can be demonstrated that the FLC-SMES is the robustness method for the EPS over the PID-SMES method.
5 | CONCLUSION

This study has presented a new coordination strategy among the control functionalities and the control functionalities for low-inertia power systems. The coordination strategy includes the LFC, SMES as virtual inertia emulator, and the digital frequency protection. Moreover, a more practical modelling and new FLC method have been developed for the SMES to emulate the virtual inertia characteristics. The EPS has been selected as a case study for investigating the proposed system. The results proved the superior performance of the proposed system for enhancing the security and stability for the studied power system, considering high penetration of RESs and insertion/rejection of loads. The results have demonstrated that the proposed FLC-SMES has achieved frequency stability robustly in the presence of high wind/PV power penetration, different load power fluctuations, and different levels of system inertia in all cases of the studied scenarios. The system stability is preserved in the obtained results with the reduction of the system inertia until 25% of its nominal value. Moreover, the employed practical model and FLC method have helped at smooth and fast regulation of the system frequency, compared to the simplified first-order model in the literature. The new proposed coordination strategy has achieved proper cooperative operation of the control and protection functionalities of the control centre. The proposed coordination strategy with the FLC-SMES model can significantly reduce the spikes in the frequency during the overshoot and undershoot peaks as well as return to the steady-state value with short settling time. In the selected case study, the improvement of the frequency spikes reduction exceeds 50% over the conventional method for all tested scenarios.

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NOMENCLATURE

Δf frequency deviation of the system (Hz)
Dc system damping coefficient (pu MW/Hz)
H system inertia (pu MW s)
T1 salve time constant of non-reheat plant (s)
T2 steam valve time constant of reheat plant (s)
T3 water valve time constant hydro plant (s)
T4 dashpot time constant of hydro plant speed governor (s)
T5 time constant of reheat thermal plant (s)
Tw water starting time in hydro intake (s)
ΔP1 load variation (pu)
R1 governor speed regulation non-reheat plant (Hz/pu MW)
R2 governor speed regulation reheat plant (Hz/pu MW)
P1 nominal rated power output for non-reheat plant (pu)
P2 nominal rated power output for reheat plant (pu)
P3 nominal rated power output for hydro plant (pu)
ΔPr regulating of the system frequency (Hz)
β bias factor (pu MW/Hz)
T12 sync. coefficient of tie-line
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