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Supplementary Frequency Control in a High-penetration Real Power System by Renewables Using SMES Application

In modern power systems, the penetration level of Renewable Energy Sources (RESs) is strikingly increasing. Where, many synchronous generators are being replaced by the RESs-based the power electronic devices, this will reduce the overall system inertia. Moreover, the intermittent nature of the RESs causes several control problems such as frequency/voltage instability problem. Hence, these disturbances threaten preservation the power system stability and can lead to system collapse. In addition, the secondary frequency control action (i.e., Load Frequency Control (LFC)) will not be sufficient to maintain the system frequency close to its scheduled value. Therefore, this paper proposes an application of Superconducting Magnetic Energy Storage (SMES) system based on an optimal PID controller, which is optimally designed by the Particle Swarm Optimization (PSO) to enhance the frequency stability of modern power systems due to high RESs penetration. From the perspective of the LFC, the proposed controlled SMES can be used as a feedback controller with the aim of supporting the frequency control loops for frequency stability enhancement of the power systems. Moreover, the effectiveness of the proposed control strategy is tested and verified through a real hybrid power system in Egypt (i.e., Egyptian Power System (EPS)) that includes thermal, gas, hydraulic power plants, wind, and solar energy. The obtained simulation results by Matlab/Simulink software reveal that the proposed control strategy achieved superior dynamic responses satisfying the LFC requirements in all test scenarios. Consequently, the frequency stability is improved regarding peak undershoot, peak overshoot, and settling time.

Keywords: Renewable energy sources, Superconducting magnetic energy storage, Egyptian power system, Frequency control, Particle swarm optimization.

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1. Introduction

Nowadays, due to the complexity of power systems and the high penetration of Renewable Energy Sources (RESs), research on the Load Frequency Control (LFC) is more challenging. Where the complexity of modern power system renders the traditional LFC strategies more challenging since most of the existing power grids are geographically dispersed. Additionally, the vitality request on the energy is relentlessly expanding and new kinds of energy sources must be found to cover the future demands since the traditional sources are going to be exhausted. Therefore, owing to the recent developments in power systems, widespread growth in utilizing the RESs such as solar, wind, and geothermal has become inevitable. However, the majority of RESs outputs such as photovoltaic, and wind generation are often uncertain because of natural conditions and meteorological [1]. Furthermore, the RESs exchange the electrical power to the power grids through power electronic devices (i.e., inverters and converters), which reduce the overall system inertia. Consequently, the inverter

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based RESs will cause high frequency/voltage fluctuations compared to the conventional generation units [2]. Therefore, the frequency control may be difficult in case of any mismatch between electric power generation and load demand, particularly, with the high penetration level of RESs (e.g., wind and solar energy). The LFC strategy is considered as one of the most important control strategies in the power system, which maintains the system frequency and the power variations at their standard values.

Various control techniques have been presented in the literature review of the LFC issue for different power systems [3-5], [7-10], [12-16]. Among them, Model Predictive Control (MPC) was applied in [3], and Distributed MPC (DMPC) was applied in [4, 5]. However, the predictive control strategy has some of the drawbacks such as it takes more time for the online calculations at each sampling time [6]. Also, sliding mode control [7], Radial Basis Function Neural Network (RBF NNs) [8], Fuzzy Logic Controller (FLC) [9], and Artificial Neural Network (ANN) technique [10] were demonstrated in the literature to achieve the goal. Although the control strategies [7-10] gave a good dynamic response, they suffer from many drawbacks such as; its dependency on the designer's experience and need long computational time. On the other hand, real-world LFC is performed based on Proportional-Integral-Derivative (PID) due to its low cost, simple structure, robustness and a successful practical controller [11]. However, the process of finding the optimal PID controller parameters is considered one of the most challenges that face the power system designers. Therefore, several optimization algorithms were used to find the optimal parameters of the PID controller in the LFC loop such as Whale Optimization Algorithm [12], Particle Swarm Optimization (PSO) [13], Symbiotic Organisms Search (SOS) [14], cuckoo optimization algorithm [15], Grey Wolf Optimization (GWO) [16] and so on.

Based on most of the published research works on the LFC issue, the studied power systems are modelled as thermal power plants (e.g., non-reheat and reheat power plants) or/ and hydraulic power plants depending on the number of areas [3-16]. Nevertheless, most of the existing realistic power systems comprise of multi-source dynamics generators; thermal, hydraulic and gas power plants. Therefore, several types of power plants should be added in the LFC issue to achieve a realistic study as reported in our previous researches [17, 18]. On the other hand, based on the previous studies, the effects of high-level penetration of the RESs have not been considered for frequency stability analysis. Therefore, several types of RESs with high penetration levels should be added to the analysis of the LFC issue for achievement more accurate studies for today's power systems as reported in this research. Moreover, with increasing the power from the RESs, it becomes much important to look at techniques to store this energy. Where there are several Energy storage systems (ESSs) such as Superconducting Magnetic Energy Storage (SMES), electric batteries, fuel cells, and others, which should be considered within the design of the power grid. Thus, the ESS can be used for storing the excess energy from RESs, in addition, discharging the stored energy to the grid as needed, depending on demand [19].

With increasing the penetration level of the RESs into the power systems, it will be caused higher frequency deviations as well as the secondary frequency control may fail to maintain the system frequency. Therefore, from the perspective of the LFC, the ESS can be used as a feedback controller in the aim of supporting the frequency control loops for frequency stabilization. Among many ESSs, SMES technology is most suited for improved frequency stability in power systems, due to its outstanding advantages such as fast response, high efficiency, and long lifetime [20]. The SMES technology has been considered in the design of several power systems [21-24]. However, the effect of the dynamic contribution of SMES technology has not been considered yet for frequency stability analysis of multi-source power system during high-level RESs penetration and contingencies.

Based on the above analysis, this paper presents a real hybrid power system (i.e., the EPS), which includes both conventional generation units (i.e., thermal, gas and hydraulic power plants) and RESs (i.e., wind and solar energy) for studying the LFC problem due to high-level RESs penetration. Moreover, the effects of the physical constraints such as Generation Rate Constraints (GRCs) of power plants and speed governor deadband (backlash) are taken into consideration. Therefore, this paper proposes a new coordinated control strategy between the secondary frequency control loop (i.e., LFC) and the SMES (i.e., supplementary LFC) using the optimal PID controller-based the PSO algorithm for frequency stability improvement of the EPS with high-level RESs penetration. This paper is organized as follows: The notation used throughout the paper is stated in 2. The description of the studied power system considering RESs and SMES unit is considered in section 3. Section 4 provides the proposed control methodology based on an optimization technique for design the coordinated control strategy. The simulation results and discussion based on time-domain are performed in section 5. Finally, the conclusion is outlined in section 6.

2. Notation

The notation used throughout the paper is stated below.

D	System damping coefficient (pu MW/Hz)
H	Equivalent inertia constant (pu sec)
T_1	The valve time constant of the non-reheat plant (sec)
T_2	The steam valve time constant of the reheat plant (sec)
T_3	Water valve time constant of the hydraulic power plant (sec)
T_d	The dashpot time constant of the hydraulic power plant speed governor (sec)
T_h	The time constant of reheat thermal plant (sec)
T_w	Water starting time in hydro intake (sec)
ΔP_L	Load variation (MW pu)
m	The fraction of turbine power (intermediate pressure section)
R_1	Governor speed regulation non-reheat plant (Hz/pu MW)
R_2	Governor speed regulation reheat plant (Hz/pu MW)
R_3	Governor speed regulation hydraulic power plant (Hz/pu MW)
P_{n1}	Nominal rated Power output for the non-reheat plant (MW pu)
P_{n2}	Nominal rated Power output for reheat plant (MW pu)
P_{n3}	Nominal rated Power output for the hydro plant (MW pu)
ΔP_{c1}	Regulating the system frequency of the non-reheat plant (Hz)
ΔP_{c2}	Regulating the system frequency of the reheat plant (Hz)
ΔP_{c3}	Regulating the system frequency of the hydraulic power plant (Hz)
K_{SMES}	SMES variable gain
T_{SMES}	SMES time constant (sec)
T_{WT}	Wind turbine time constant (sec)
$\mathrm{T_{PV}}$	Solar system time constant (sec)
w	Inertia weight factor
rand ()	A random number between 0 and 1
x_{id}^{n}	The current position of particle i at iteration n
v_{id}^{n}	The velocity of particle i at iteration n

c_1, c_2	Acceleration constant
n	Number of iterations
P_{id}^{n}	pbest of particle i at iteration n
P_{gd}^{n}	gbest of particle i at iteration n

3. System Configuration and Modelling

3.1. Dynamic model of the EPS

The studied power system is a real hybrid power system in Egypt, which has 180 power plants. Moreover, the power plants are classified into 3 categories: a) Non-reheat power plants represented by gas turbine power plants and a few numbers of steam power plants. b) Reheat power plants mainly represented by thermal power plants or combined cycle power plants. c) Hydraulic power plants (e.g., High Dam in Aswan city). Recently, the RESs (i.e., wind and solar energy) have been included into the EPS by 3% of the installed capacity according to the annual report of the Egyptian Electricity Holding Company (EEHC) in 2016 [25]. However, the Egyptian government aims to increase the penetration level of the RESs to reach 20% of the total capacity by 2020. Where the total generation capacity of the conventional generators and peak loads in the EPS are 38,000 MW and 29,000 MW respectively [25]. Hence, this research focuses on upgrading the real hybrid power system in Egypt towards smart grid via integrating high-level RESs penetration, and SMES technology for facing the future challenges, which are expected to integrate more and more RESs. Whereas, the RESs includes wind power with a peak power of 3,000 MW and PV solar power with a peak power of 1,600 MW. The base of the system frequency is 50 Hz, while the power base is 38,000MW. Therefore, the dynamic model of the EPS with the proposed coordination scheme is shown in Fig. 1, and the system parameters are given in [13]. In order to save space, we only provide a brief discussion about the modelling of the EPS. Interested readers can find detailed information in [13, 17].

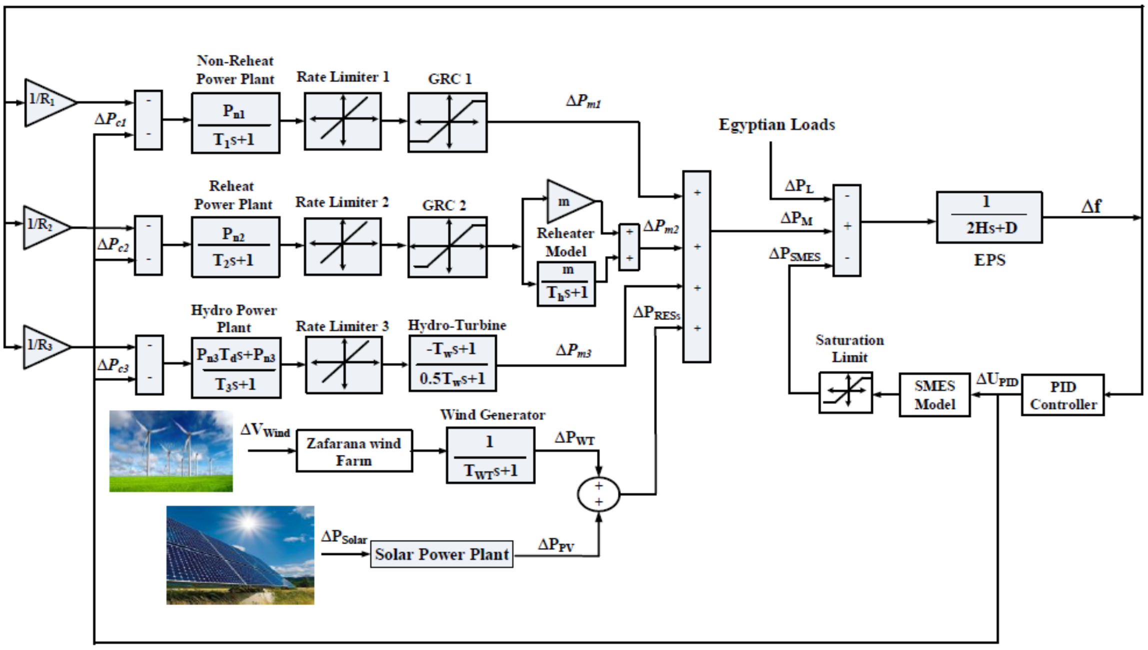

Fig. 1 A nonlinear model of the EPS for seven strongly tied zones considering RESs and SMES technology.

3.2. Wind power plant

The mathematical model of the mechanical power from the wind turbine model can be written as follows [12]:

$$P_m = \frac{1}{2}\rho A_T V_W^3 C_P(\lambda,\beta) \tag{1}$$

Where ρ is air density (Kg/m^3), A$_T$ is the rotor swept area (m^2), V$_W$ is the rated wind speed (m/s) and C$_P$ represents the power coefficient of the rotor blades, which can be termed by the following equation :

$$C_P(\lambda,\beta) = 0.5 * (\lambda_I - 0.022\beta^2 - 5.6) * e^{-0.17\lambda_I}$$

$$\lambda_I = \frac{3600R}{1609\lambda}\ ,\ \lambda = \frac{\omega_B R}{V_W} \tag{2}$$

Where β is the pitch angle, λ corresponds to the optimal tip-speed ratio (TSR), λ_I is the intermittent TSR, and ω_B is the rotational blade speed (rad/s).

This study uses GAMESA wind turbine, which is installed at Zafarana location in Egypt. The details of this wind turbine are given in the Appendix [26]. Furthermore, for achieving a realistic study, real wind speed data that was extracted from Zafarana location in Egypt for one day are used [14]. In that case, the rated wind speed was 16 m/s. In this study, the EPS includes a combined model of the wind farm, which are 1340 wind turbine units of 850-KW for each unit beside the conventional generation units (as a future planning of the EPS). The wind generator is modeled as a first-order transfer function of a unity gain and 0.3 sec time constant (T$_{WT}$) as shown in Fig. 1. Therefore, the real output wind power from the wind farm is shown in Fig. 2.

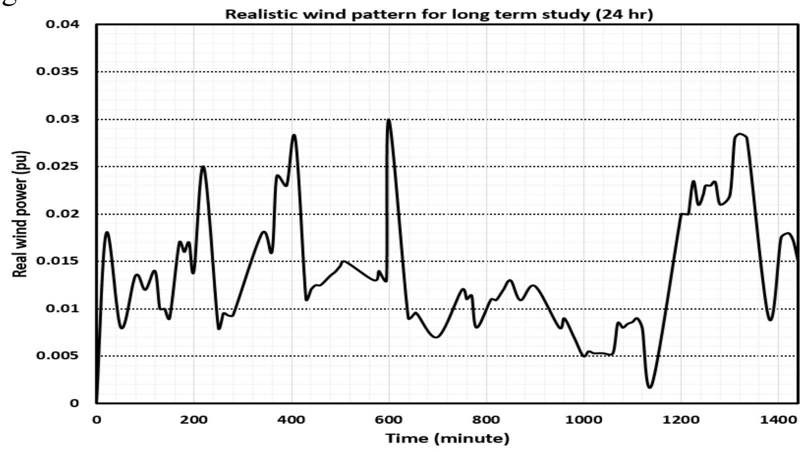

Fig. 2 The real power of Zafarana wind farm.

3.3. Solar irradiation power plant

The solar power generation can be represented by an equivalent PV generation plant whose rating is equal to the sum of the ratings of the individual PV generating units. Whereas, the output power of the PV generation system is irregular due to depending on weather conditions. Hence, the power fluctuations from the PV solar power generation units can be estimated by considering the deviation from the uniform and non-uniform insolation as shown in Fig. 3. To obtain an accurate power output profile of a PV solar irradiation model in the EPS, the original random output fluctuation that can be modelled by the white noise block in Matlab program is multiplied by the standard deviation, which is assumed by the following [27]:

$$\Delta P_{Solar} = 0.6\sqrt{P_{Solar}} \tag{3}$$

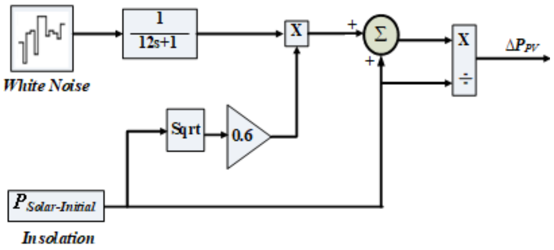

Fig. 3 The model of PV solar power generation system using Matlab /Simulink.

3.4. Frequency control based on SMES technology

The frequency control loops can be represented as three subcategories; primary frequency control, secondary frequency control and supplementary frequency control. The primary frequency control damps the system frequency deviation for few seconds (i.e., 30 sec) after occurrence the disturbance. Where, the power requirement is balanced by attenuating these deviations (i.e., the governor natural autonomous). While, the secondary frequency control (i.e., LFC) stabilizes the frequency to its nominal value for a time from few seconds to few minutes after the disturbance [28]. On the other hand, with upgrading the electric networks by utilizing several RESs can be caused a rapid frequency changes and maybe the LFC system fails to recover frequency. Hence, the role of the supplementary frequency control emerges as the last option for stabilization of the system frequency and decreasing the risk before energizing the protection devices. Thus, this study proposes a coordinated control strategy of the LFC and SMES system to address the LFC issue in renewable power systems. Where the controlled SMES is used as a feedback controller in the aim of supporting the frequency control loops for frequency stabilization of the EPS considering high RESs penetration. Moreover, by using the proposed coordinated control strategy, the speed damping of system frequency is considerably increased.

The SMES technology is one of the most important ESSs due to it has many merits such as fast response, high efficiency, and long lifetime compared to other ESSs. Moreover, it storages the power in the magnetic coil, which made from a superconducting material with nearly zero loss of energy [23]. This makes it a preferable choice for an energy storage solution in different power systems, which are integrated with RESs. In this study, the SMES technology is used as frequency stabilizer (i.e., auxiliary LFC), which can charge and discharge electrical power from/to the grid with very short time considering the SMES power limits. Hence, the proposed coordinated control strategy between the controlled SMES and the LFC is applied in the EPS considering high-level RESs penetration to enhance the frequency stability. The linearized model representation of SMES such a control scheme is shown in Fig. 4. The SMES device is modelled by a first-order transfer function of 6 variable gain (K_{SMES}) and 0.03 s time constant (T_{SMES}). The SMES parameters obtained using trial-and-error method.

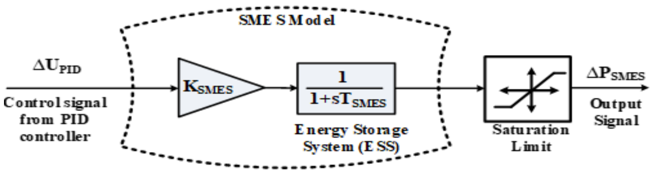

Fig. 4 Dynamic structure of the controller SMES.

4. Control Strategy and Problem Formulation

In this study, the control strategy of the proposed coordination between secondary frequency control (i.e., LFC) and controlled SMES (i.e., supplementary frequency control) is based on the optimal PID controller the EPS considering RESs. The PID controller gains are a proportional gain (Kp), integral gain (Ki) and derivative gain (Kd). Its transfer function can be expressed as follows:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{4}$$

Despite all the advantages of the PID controller, it suffers from a complicated process of parameters tuning based on trial and error method. In such a case, the robustness of the system is not guaranteed against further perturbations in the system parameters. Therefore, this research uses PSO algorithm to find the optimum parameters of the PID controller for minimizing the system frequency deviation. In this study, the integral of squared-error (ISE) is used as a fitness function that is the objective function of the proposed optimization technique and can be formulated as follows:

$$ISE = \int_0^{tsim} (\Delta f)^2 \, dt \tag{5}$$

where (Δf) is the frequency deviation of the EPS and t_{sim} is the simulation time to execute one run. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PID controller parameter bounds. So, minimize the objective function (ISE) subject to:

$$\left[K_{p,i,d}^{Min} \leq K_{p,i,d} \leq K_{p,i,d}^{Max}\right]$$

Therefore, the proposed PSO algorithm is applied in the EPS to obtain the minimum value of the objective function (i.e., system frequency deviation) through getting on the optimal parameters of the PID controller. It is worth mentioning that, the PID controller of the LFC is designed off-line during the planning stage and then put into online action to control of power system operation during load disturbances [29, 30]. Therefore, the PID controller parameters are adjusted for different load scenarios before putting into operation [29]. Accordingly, the task of PID controller design, which is treated as a planning manner, is executed off-line using the proposed PSO algorithm before the PID controller of the LFC is put into operation. Further information for the PSO can be found in [31-34]. Hence, the optimum parameters of the designed PID controller are K_p=72.001, K_i=6.015, K_d=5.856, which produce the optimal control signal to the SMES unit for given a compensation active power to the set-point of the studied EPS during high-level RESs penetration and contingencies. Typical ranges of the optimized parameters of the designed PID controller are selected between 0 and 100, which are chosen after exhaustive trial and errors.

5. Simulation Results and Discussion

The proposed coordinated control strategy of the secondary frequency control loop (i.e., LFC) and the supplementary frequency regulation (i.e., controlled SMES) based on the optimal PID controller in the EPS concerning RESs (i.e., Wind and solar Power) has been designed to support the frequency stability. Moreover, the performance of the proposed coordinated control strategy is compared with both; the optimal LFC with/without the uncontrollable SMES unit under different load profiles, wind and solar power fluctuations, and system parameters variations (i.e., system uncertainties). The studied power system is a novel power system, which includes both conventional generating units and RESs. The conventional generation units comprise steam power plants (i.e., reheat and non-reheat turbines), gas power stations (i.e., non-reheat turbines), and hydraulic power plants, with inherent nonlinearities that are GDB and the GRCs of power plants.

The Simulation results of the studied power system are performed and analyzed using Matlab/SIMULINK® software to validate the effectiveness and robustness of the proposed coordinated control strategy under the nature variety of the RESs, random load variation, and system parameters variations (i.e., system uncertainties). The code of the PSO as an m-file is interfaced with the model of the EPS to execute the optimization process. The EPS is tested in the presence of wind and solar power variations. Where, this research uses real wind speed data that extracted from Zafarana location in Egypt for one day, which has been taken from [14]. Thus, the actual power output of this wind farm is illustrated in Fig. 2, where it fluctuates at its rated value of 0.0301 pu. In addition, it is clear that the real wind power fluctuates randomly due to the nature of wind speed at the Zafarana location (120 km South of Suez on the Red Sea) in Egypt. However, as a future planning, this research uses two wind farms with peak power of 2280 MW, which is tested to validate the robustness of the proposed coordinated control strategy to enhance the frequency stability. Therefore, the fluctuated wind power of the wind farms at the Zafarana location in Egypt is switched on to the EPS at time t=800 minute, while the fluctuated solar power as shown in Fig. 5 is connected at time t=0 minute. Hence, the dynamic response of the EPS considering RESs with the different control strategies are obtained under different operational scenarios and the simulation time of each one for one day (i.e., long-term study).

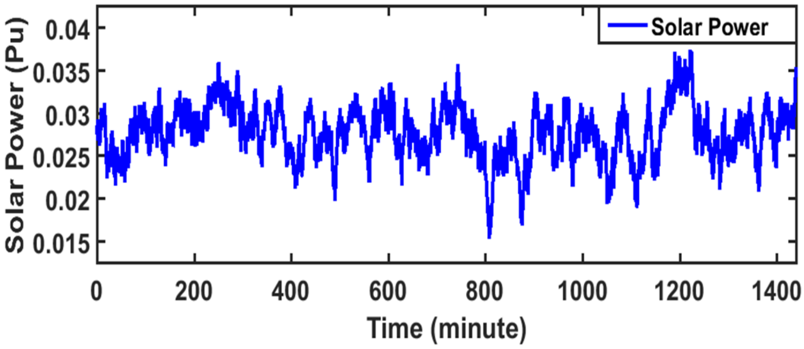

Fig. 5 Power variation pattern of solar power generation.

Scenario A: A step load perturbation (SLP) of 10% Pu amplitude is applied to the EPS as shown in Fig. 6. Moreover, the wind and solar power fluctuations are applied to the EPS at time t=800 minute, and 0 minute, respectively. Fig. 6 concluded that the system performance with the dynamic contribution of the SMES unit can improve the frequency response and reduce transient deviation compared to the system performance without the SMES system. On the other hand, the proposed SMES-based the optimal PID controller achieved a superior performance and more reduction of the frequency excursions (Δf) and the RESs fluctuations than other strategies. Moreover, the proposed control strategy could properly maintain the frequency deviation within ±0.0002 Hz while the optimal LFC with/without SME (i.e., uncontrollable unit) gives the frequency deviation of about ±0.005 Hz and ±0.006 Hz, respectively. Also, the SMES energy is fastly discharged and charged according to the EPS needing by the proposed coordinated control strategy as shown in Fig. 7. Hence, the frequency stability of the EPS considering RESs has been achieved using the proposed coordinated control strategy.

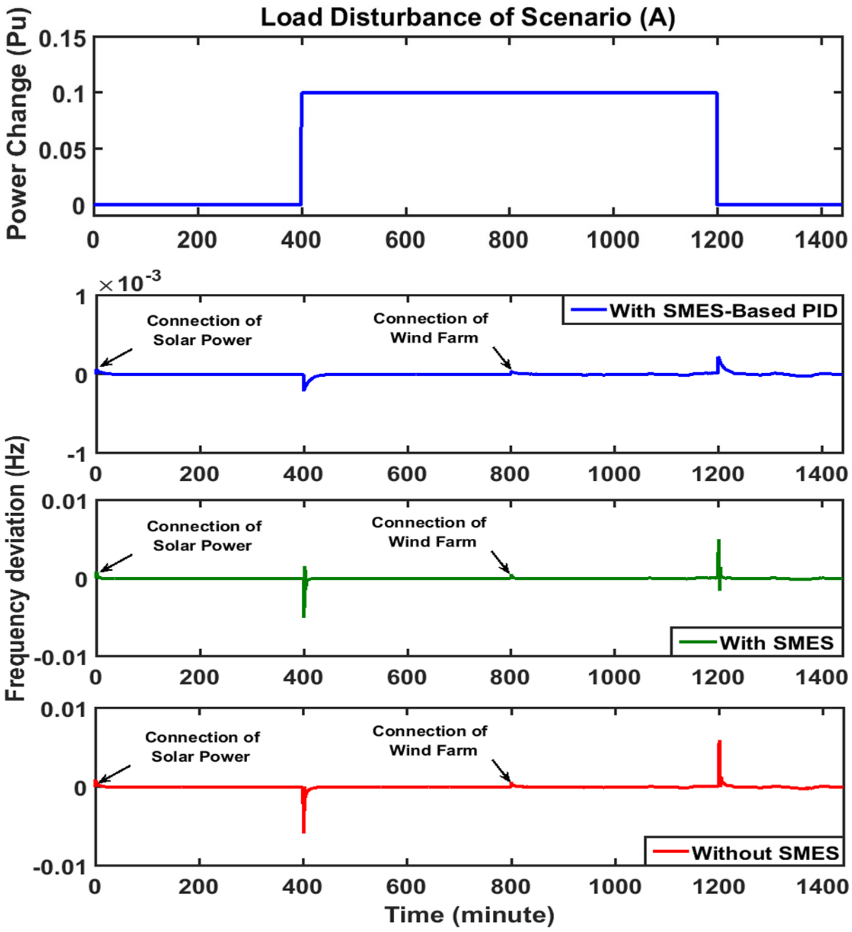

Fig. 6 The frequency deviation of the EPS for scenario A.

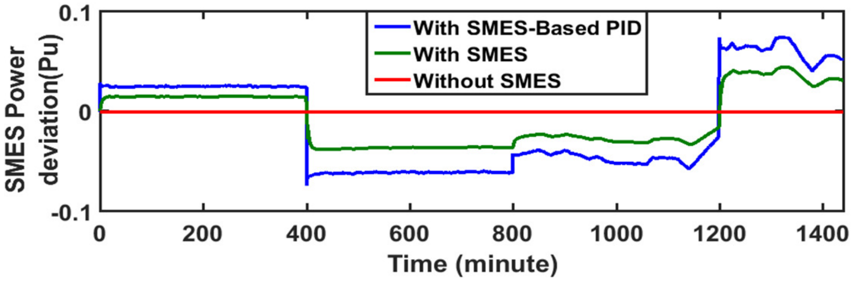

Fig. 7 SMES power deviation in the EPS for scenario A.

Scenario B: A series of load disturbance with random magnitudes during the period from 200 minute to 1400 minute is applied to the EPS considering RESs as depicted in Fig. 8. It can be seen that the desired result has been obtained from the proposed coordinated control strategy, which is more effective in handling the sudden load variation of the EPS compared to the other strategies. Moreover, The SMES power is highly discharged by the proposed coordinated control strategy, which leads to reducing the needed power from the conventional generation units as shown in Fig. 9. Therefore, the proposed coordinated control strategy between the secondary frequency control (i.e., LFC) and the controlled SMES is robust to compensate the load variation and the fluctuation power from the RESs (i.e., wind and solar energy) and hence it has been overcome on the disturbances, which may be imperiled the system dynamic security.

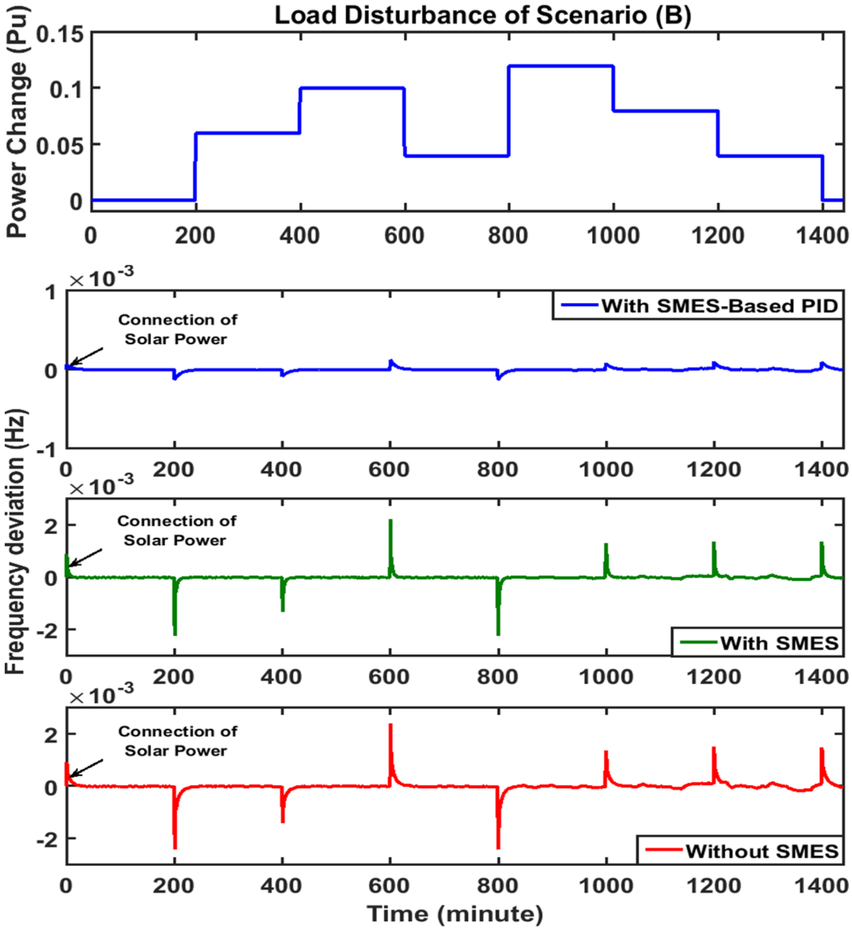

Fig. 8 The frequency deviation of the EPS for scenario B.

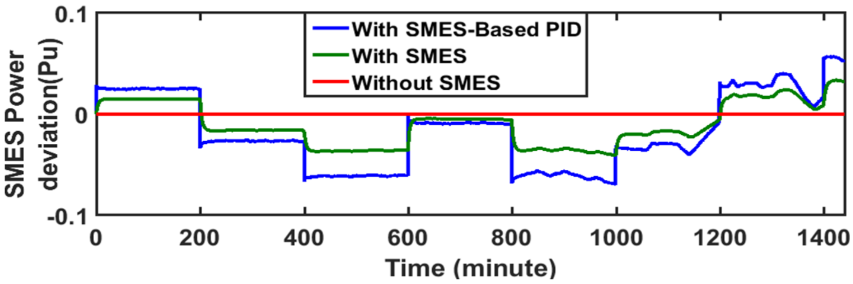

Fig. 9 SMES power deviation in the EPS for scenario B.

Scenario C: In this scenario, the proposed coordinated control strategy is validated in the extreme scenario by implementation high fluctuated random load change (e.g., industrial load) with the random magnitude, as well as the fluctuations of wind and solar power. Fig. 10 clears that the frequency response is affected by the load power variation and the fluctuations power from the RESS. The targeted power system (i.e., the EPS) without the dynamic contribution of SMES unit has obtained a frequency deviation of about ±0.009 Hz while the EPS with the dynamic contribution of SMES unit maintains the frequency deviation within ±0.006 Hz. On the other hand, the proposed controlled SMES-based the optimal PID controller could maintain the frequency deviation within ±0.0003Hz. Moreover, the SMES power is significantly discharged by the proposed control strategy to regulate the frequency and track the load demands of the EPS as shown in Fig. 11. it is clear that the best result is obtained from the proposed coordinated control strategy.

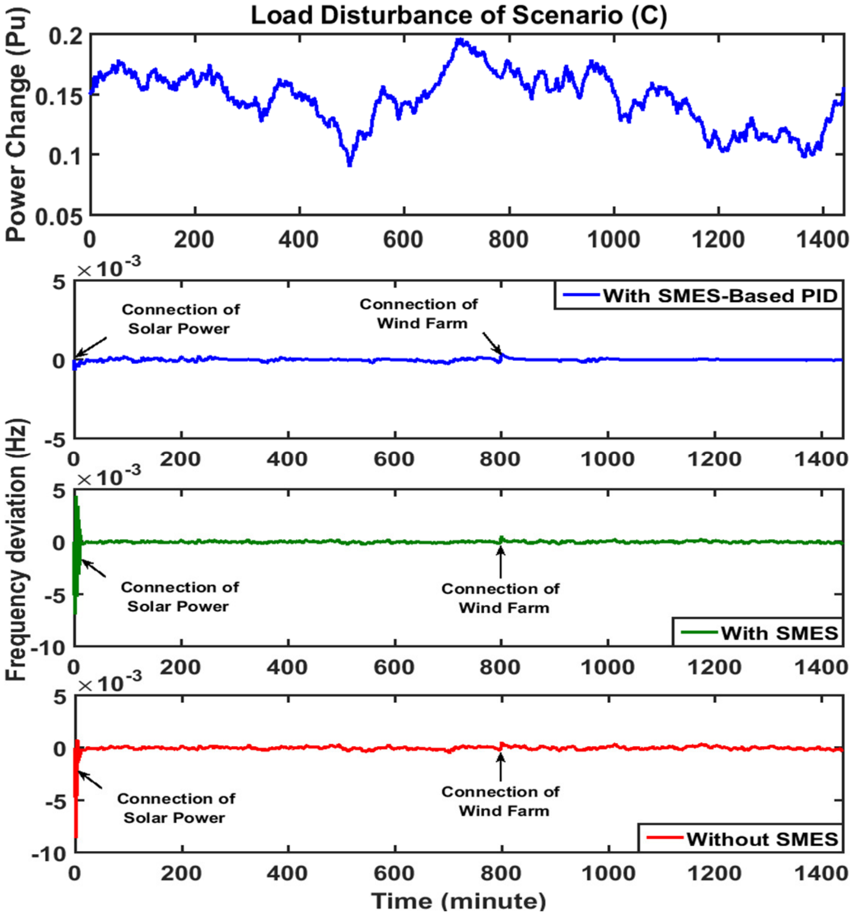

Fig. 10 The frequency deviation of the EPS for scenario C.

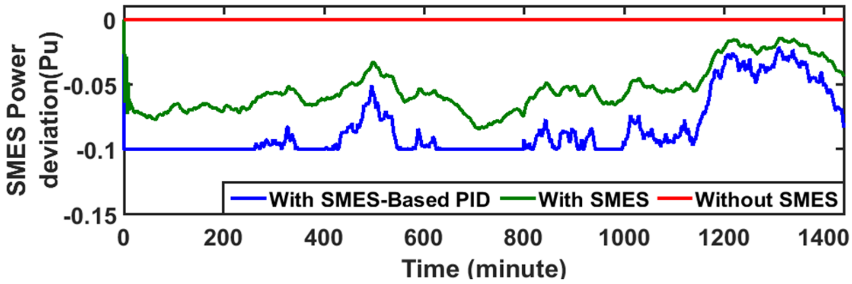

Fig. 11 SMES power deviation in the EPS for scenario C.

6. Conclusion

With rapidly growing of Renewable Energy Sources (RESs) in modern power systems, these power systems are become more susceptible to the disturbances than the conventional power systems due to decreasing the system inertia that results from replacing the synchronous generators with the RESs. Therefore, the modern power systems are facing some of the disturbances (e.g., frequency/voltage fluctuations) that threaten the preservation of frequency stability. Therefore, this paper proposes an effective coordinated control strategy of the LFC and SMES (i.e., supplementary frequency controller) using the optimal PID controller, which is optimally designed by the PSO algorithm for frequency stability enhancement of the Egyptian power system (EPS) considering high RESs penetration. The EPS includes both conventional generating units (i.e., steam, gas, and hydraulic power plants) and RESs (i.e., wind and solar energy) considering inherent nonlinearities, which are GDB and the GRCs of power plants. To prove the effectiveness of the proposed coordinated control strategy, the EPS was tested under variation in load profiles, RESs power fluctuations, and system parameters. The simulations results showed that the EPS with the proposed controlled SMES-based the optimal PID controller achieved a robust stability in terms of peaks overshoot, peaks undershoot, and settling time. Whereas, the optimal LFC system with/without the SMES model (i.e., uncontrollable SMES) could not endure the large frequency deviation that due to reduction of system inertia, thus could not maintain stability. Hence, the proposed coordinated control strategy will ensure an avoidance of power system instability and system collapse owing to high-level RESs integration.

7. Appendix [26]

Wind Turbine model: manufacturer: GAMESA (Spain), model: G52/850, rated power: 850 KW, rotor diameter: 52 m, swept area: 2.124 m2, Cut-in wind speed 4 m/s, Rated wind speed 16 m/s, Cut-off wind speed 25 m/s, maximum generator output speed 1900 rpm, and output voltage 690 V.

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