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DECENTRALIZED OPTIMAL LFC FOR A REAL HYBRID POWER SYSTEM CONSIDERING RENEWABLE ENERGY SOURCES

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Abstract

This paper proposes a decentralized design of Load Frequency Control (LFC) for a real hybrid power system in Egypt with the integration of Renewable energy Sources (RESs). The Egyptian Power System (EPS) is decomposed into three dynamic subsystems; non-reheat, reheat and hydraulic power plants. Moreover, the physical constraints of the speed governors and turbines (i.e., Governor Deadband (GDB) and Generation Rate Constraints (GRCs)) are taken into consideration. Whereas, each subsystem has its own characteristics compared to the others. Therefore, each subsystem controller has been designed independently to guarantee the stability of the overall closed-loop system. Hence, an optimal PID controller-based Particle Swarm Optimization (PSO) is proposed for every subsystem separately to regulate the frequency and to track the load demands of the EPS. The performance of the proposed decentralized PID controller of each subsystem is compared with the centralized one under variation in loading patterns, system parameters, and RESs penetration level. System modelling and simulation results are carried out using Matlab/Simulink® software. The simulation results reveal the proposed decentralized model gives 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: Decentralized control, Egyptian power system, Load frequency control, Particle swarm optimization (PSO), Renewable energy sources.

1. Introduction

With the continuous development in electrical loads particularly industrial plants and human activities, resulting in an increased number of new transmission lines, power plants, and interconnection between different power systems. This leads to the appearance of the frequency and power oscillations problems as well as tie-line power deviation in the interconnected power system, which may result in disconnection actions, loss of several lines, zone islanding, equipment damaging, transmission line overload, and interfere with system protection schemes [1]. Nowadays, this problem increases after growing the RESs, which have several impacts on the performance of the electrical power systems such as reduction of the overall system inertia that results to increase the frequency and voltage fluctuations [2]. Therefore, the frequency control may be difficult in case of any mismatch between electric power generation and load demand particularly, with penetration growing of RESs (e.g., wind and solar energy), which integrated into the power system. Hence, Load Frequency Control (LFC) 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. Whereas system frequency depends on active power and the system voltage greatly depends on the reactive power. Therefore, the control of power systems can be classified into two fundamental issues. a) Control of the active power along with the frequency, b) control of the reactive power along with the voltage regulation [3].

Various control techniques have been implemented to support frequency stability of power systems [4-9]. Yousef [4] applied an adaptive fuzzy logic approach for frequency control of the multi-area interconnected power system. However, the approach in [4] is dependent on the designer experience to reach the required performance. Garasi et al. [5] focused on applying the LFC scheme to the modern power system and showed the robustness of the Coefficient Diagram Method (CDM) controller. In addition, Ali et al. [6] discussed the same issue for a small power system and involving storage system such as Electric Vehicles (EV) in the control strategy. According to Garasi et al. [5] and Ali et al. [6], however, the drawback of the control technique is a complex structure, which required more steps to find its parameter. El-Saddy et al. [7] obtained the generalized parameter of PID controller based on Ant Colony algorithm for LFC of two area power system. El-Saddy [7] explained that, however, the drawback of the searching technique is needing new programming burdens whenever there is a big change in the system parameters. Kunya and Argin [8] used Model Predictive Control (MPC)-based LFC in the large interconnected power system. Magdy et al. [9] applied the predictive control for frequency control of the multi-source power system. According to Kunya and Argin [8] and Magdy et al. [9], although the predictive control strategy has the advantages of fast response, simple structure, and easy handle system constraints and nonlinearities, it takes more time for the online calculations at each sampling time.

According to the previous studies of the LFC issue, the model of the most powerful systems was considered as thermal power plants (e.g., non-reheat and reheat power plants) or/ and hydropower plants depending on the number of areas [3-8]. However, most of the existing realistic power systems comprise multi-source dynamics generators; thermal, hydro, and gas power plants. Therefore, several types of power plants should be added to the LFC problem to achieve a realistic study as reported in this research. Furthermore, the most studied power system is a linear and simple structure, where it mainly depends on the conventional synchronous generators [3, 4, 7, 8]. However, several RESs should be integrated into the interconnected power system to achieve a more realistic study. Therefore, a few studies have dealt with the effect of incorporation the RESs in the power system that controlled by different LFC strategies. Hasanien [10] used a whale optimization algorithm for obtaining the optimal PID controller parameters in an interconnected modern power system including renewable sources. Ma et al [11] presented Distributed MPC for LFC of multi-area power system considering wind turbines. Therefore, this research presents a real hybrid power system (i.e., The EPS), which includes both conventional generation units (i.e., gas, thermal and hydraulic power plants) with inherent non-linearities and RESs (i.e., wind and solar energy) for studying the LFC problem of such a system.

This paper focuses on the design of decentralized LFC based on the optimal PID controller, which is optimally designed by the PSO algorithm for improving the frequency stability of the EPS considering RESs. The proposed decentralized controller is designed for each subsystem to regulate the frequency and to track the load demands of the EPS. Where each subsystem of the studied power system is considered as Single-Input Multi-Output (SIMO). The tuning of the PID controller parameters is considered as an optimization problem that is handled by the PSO algorithm. Hence, the contribution of this work includes the following aspects: (i) This paper presents a real hybrid nonlinear power system (i.e., the EPS), which includes both conventional generation units (i.e., thermal, hydro and gas power plants) and RESs (i.e., wind and solar energy) for studying the LFC issue. (ii) This paper proposes a decentralized optimal LFC-based the PID controller, which is optimally designed by the PSO algorithm for frequency stability enhancement of the EPS considering RESs. (iii) The robustness and effectiveness of the proposed decentralized scheme are investigated under variation in loading patterns, loading conditions, system parameters and RESs penetration level.

This paper is an arrangement as follows: Section 2 presents the system configuration including the EPS modelling, the RESs modelling, and the state-space dynamic equations. The proposed control methodology for the EPS and problem formulation are presented in Section 3. Section 4 describes the PSO algorithm-based PID controllers design. The simulation results-based on time demine are discussed in section 5. Finally, the conclusion is given in Section 6.

2. Power System Overview and Modelling

2.1. Dynamic model of EPS

The power system presented in this study is a real hybrid power system in Egypt. It is divided into seven strongly tied zones; Cairo, Middle Egypt, Upper Egypt, East El-Delta, El-Canal, West El-Delta and Alexandria as shown in Fig. 1. Each zone comprises several power plants (i.e., non-reheat, reheat and hydropower plants or a combination of each). The EPS has 180 power plants that are classified into 3 categories: a) Non-reheat turbines represented by gas power plants and a little number of steam power plants. b) Reheat turbines mainly represented by thermal power plants or combined cycle power plants. c) Hydraulic power plants (e.g., High Dam in Aswan city). Recently, RESs such as wind and solar energy have been integrated into the EPS with contribution almost 3% of the installed capacity. However, in the future, the Egyptian Electricity Holding Company (EEHC) aims to increase the electric energy demand from RESs. The total generation capacity and peak loads are 38,000 MW and 29,000 MW respectively according to the annual report of the Egyptian Electricity Holding Company in 2016 [12].

Hence, this research focuses on upgrading the real hybrid power system in Egypt towards a smart grid by merging several RESs. Whereas, the RESs includes wind power with a peak power of 1,140 MW and PV solar power with a peak power of 760 MW. Magdy et al. [9] explained that the National Energy Control Center (NECC) in Egypt has been advanced a dynamic model of Egyptian LFC.

Moreover, this model was rebuild using MATLAB/Simulink with some manipulation, which including the effect of RESs as shown in Fig. 2. The NECC in Egypt estimates the system parameters values, which used in the dynamic model of the EPS as in Table 1. The three subsystems (non-reheat, reheat, and hydraulic power plants) are given for the EPS with inherent nonlinearities, which are speed governor backlash and GRCs of power plants. Backlash is defined as the total magnitude of sustained speed change. All speed governors have a backlash, which is important for the LFC issue in the presence of disturbances.

The GRC limits the generation rate of output power, which is given as 0.2 pu MW/min and 0.1 pu MW/min for non-reheat, and reheat turbines, respectively. However, the actual GRC of a hydropower plant is about 0.5 pu MW/min, which is higher than the generation rate corresponding to any practical disturbance and hence it will be neglected [13].

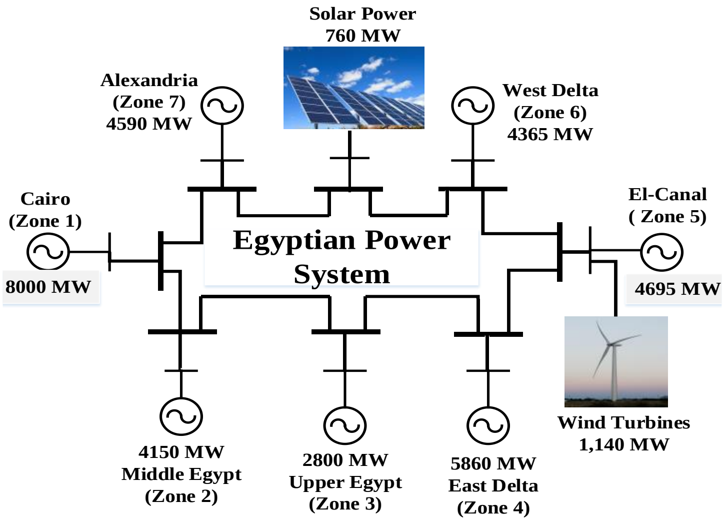

Fig. 1. Typical single-line diagram of EPS.

Table 1. System parameters of the EPS.

Parameter	Value	Parameter	Value	Parameter	Value
D	0.028	T_h	6	R_3	1.0
T_1	0.4	T_w	1.0	H	5.7096
T_2	0.4	m	0.5	P_{n1}	0.2529
T_3	90	R_1	2.5	P_{n2}	0.6107
T_d	5	R_2	2.5	P_{n3}	0.1364

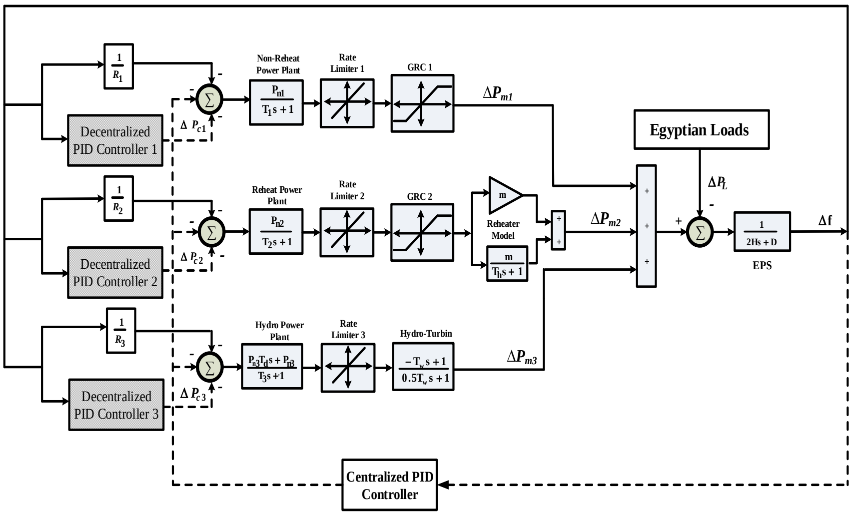

Fig. 2. A nonlinear model of the EPS for seven strongly tied zones with centralized and decentralized schemes.

2.2. Wind power generation

The model of Wind Power Generation System (WPGS) for frequency control is shown in Fig. 3. In the studied model, the wind speed is multiplied by the random speed fluctuation, which derived from the white noise block in Matlab/SIMULINK to estimate the random wind output power fluctuation in the EPS. Based on studies by Kerdphol et al. [14], the mathematical equations of the WPGS are given. In this study, an aggregated wind turbines model, which consists of 380 wind turbine units of 3.0 MW for each unit integrated with the EPS beside the conventional generation units. Magdy et al. [3] explained that the parameters values of each wind turbine unit is taken. The wind turbine output power can be calculated as follows:

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

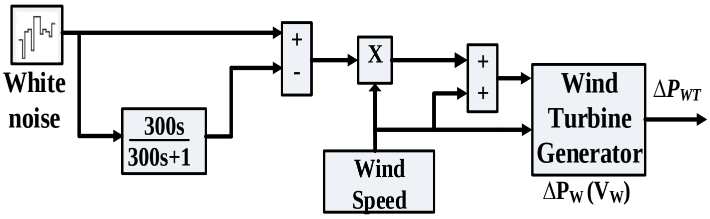

Fig. 3. Model of WPGS using Matlab/Simulink.

2.3. Solar irradiation power

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. Moreover, fluctuating PV solar power causes large frequency and voltage deviations, which threatening the system frequency stability. Hence, the power fluctuations from PV solar power generation units can be estimated by considering the deviation from the uniform and non-uniform insolation as shown in Fig. 4. The standard deviation is multiplied by the original random output fluctuation, which generated from the white noise block in Matlab/SIMULINK to simulate the real-time PV solar power fluctuation [15]. The solar power deviation is simulated close to an actual solar power change by the following function.

$$\Delta P_{Solar} = 0.6\sqrt{P_{Solar}} \tag{2}$$

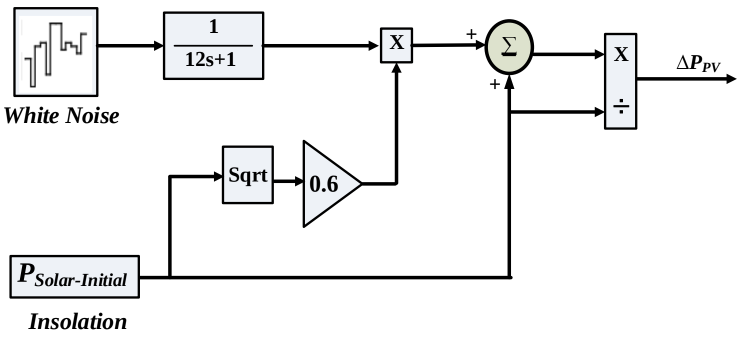

Fig. 4. Model of PV solar power using Matlab/Simulink.

2.4. Mathematical model of EPS

The dynamic equations of the EPS from Fig. 2 can be derived and written in the state variable form as follows:

$$\dot{X} = AX + BU + EW \tag{3}$$

$$Y = CX + DU + FW \tag{4}$$

where

$$A = \begin{bmatrix} -\frac{D}{2H} & \frac{1}{2H} & \frac{1}{2H} & 0 & \frac{1}{2H} & 0 \\ -a_1 & -\frac{1}{T_1} & 0 & 0 & 0 & 0 \\ -ma_2 & 0 & -\frac{1}{T_h} & b_1 & 0 & 0 \\ -a_2 & 0 & 0 & -\frac{1}{T_2} & 0 & 0 \\ (-2b_2D + 2a_3) & 2b_2 & 2b_2 & 0 & (2b_2 - \frac{2}{T_w}) & (\frac{2}{T_w} + \frac{2}{T_3}) \\ (b_2D - a_3) & -b_2 & -b_2 & 0 & -b_2 & -\frac{1}{T_3} \end{bmatrix}$$

$$C = [\,1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\,]\ , \qquad U = [\Delta P_c]\ , \qquad W = [\Delta P_L]$$

The state variables of matrices are:

$$a_1 = \frac{P_{n1}}{T_1R_1}, \quad a_2 = \frac{P_{n2}}{T_2R_2}, \quad a_3 = \frac{P_{n3}}{T_3R_3}, \quad a_4 = \frac{T_d}{2H}, \quad b_1 = \frac{2m}{T_h} - \frac{m}{T_2}, \quad b_2 = a_3a_4$$

$$B = \begin{bmatrix} 0 \\ -\frac{P_{n1}}{T_1} \\ -\frac{m*P_{n2}}{T_2} \\ -\frac{P_{n2}}{T_2} \\ \frac{2*P_{n3}}{T_3} \\ -\frac{P_{n3}}{T_3} \end{bmatrix}, \quad E = \begin{bmatrix} -\frac{1}{2H} \\ 0 \\ 0 \\ 0 \\ -2b_2 \\ b_2 \end{bmatrix}, \quad X = \begin{bmatrix} \Delta f \\ \Delta P_{g1} \\ \Delta p_{m2} \\ \Delta p_{g2} \\ \Delta P_{m3} \\ \Delta P_{g3} \end{bmatrix}, \quad D = [0], \quad F = [0]$$

3. Control Methodology and Problem Formulation

In this study, the control strategy of the proposed control schemes is based on the PID controller for frequency control of the EPS considering RESs. The PID controller has three design gains, which are the proportional gain (*Kp*), the integral gain (K_i), and the derivative gain (K_d). Its transfer function can be expressed as follows:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{5}$$

Despite all the advantages of a 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 [16, 17]. Therefore, this research uses the PSO algorithm to find the optimum parameters of the PID controller for minimizing the system frequency deviation. Therefore, the Integral of Squared-Error (ISE) is used as an objective function of the proposed optimization technique and can be formulated as follows:

$$ISE = \int_0^{tsim} (\Delta f)^2 \, dt \tag{6}$$

where (Δf) is the frequency deviation of the EPS and t_{sim} is the simulation time to execute one run. The proposed PSO technique 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.

4. Optimal PID Controllers Design Based on PSO Algorithm

4.1. Overview of particle swarm optimization

Kennedy and Eberhart [18] first introduced the PSO in 1995. It is a global optimization algorithm based on evolutionary computation technique. The basic operation principle of PSO is developed on a swarm of fish schooling, birds flocking and so on. The birds are either dispersed or go together from one place to another for searching of their food. Furthermore, one of them can discover the place where the food can be found due to the transmitting information by other birds at any time while searching for the food [19]. In the PSO algorithm, instead of using evolutionary operators, individuals called particle are used. Therefore, a swarm consist of several particles, each particle represents a potential to the problem. Each particle in PSO flies in the search space according to its own flying experience and its companion flying experience. Each particle is treated as a particle in D-dimension search space. The particle position represented X_i, the best previous position of any particle is recorded, and this value is called p_{best}. Another best value that is tracked by a global version of the PSO, which is the overall best value and called g_{best} [20]. The velocity of particle i is represented by V_i and all particles are updated according to the following equations:

$$v_{id}^{n+1} = w.V_{id}^{n} + c_1.rand().(P_{id}^{n} - X_{id}^{n}) + c_2.rand().\left(P_{gd}^{n} - X_{id}^{n}\right) \tag{7}$$

$$x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n+1} \tag{8}$$

Equations (7) and (8) are used to calculate the new velocity and new position of each particle according to its previous values. In this study, the main objective of the PSO algorithm is to minimize the frequency deviation of the EPS through tuning PID controller parameters (*Kp*, *Ki*, and *Kd*).

4.2. Implementation of PSO for PID tuning

PID controller tuning is considered as an optimization problem that is handled by the PSO algorithm. The PSO had superior features such as; easy implementation, stable convergence characteristics and it can generate a high-quality solution within shorter computation time [19]. Moreover, this study develops the PSO, which is employed to tune PID gains (*Kp*, *Ki*, and *Kd*) using the model of the EPS in Fig. 2. Each particle in the search space introduced a probable solution for PID gains, which are a 3-dimensional problem. The performance of the probable solution point is determined by a fitness function in Eq. (6). Where the size of the swarm determines the requirements of global optimization and computation time. Therefore, according to the trials, the PSO algorithm parameters are given in Table 2, which are used for verifying the performance of PSO-PID controllers.

The EPS has three dynamic subsystems; non-reheat, reheat and hydraulic power plants. In addition, RESs (i.e., wind and solar power) is integrated into the EPS. The response of each subsystem is different from each other. Therefore, the optimal decentralized PID controller based on PSO algorithm has been designed for every subsystem separately to regulate the frequency and to track the load. The obtained values of decentralized PID controllers' parameters based on the PSO technique are given in Table 3.

On the other hand, the optimal centralized PID controller-based PSO is used to make a fair comparison with the optimal decentralized model for stabilizing the EPS frequency considering RESs. Moreover, the main idea behind combining the three controllers in one centralized controller is to simplify the optimization process and to compare the performance of both schemes. The obtained values of the centralized PID controllers based on PSO technique are given in Table 4.

Table 2. PSO parameters.

Parameter	N	C_1	C_2	W
Value	50	0.12	1.2	0.9

Table 3. Decentralized PID controllers' parameters for every subsystem.

Type of subsystem	PID parameter		
	K_p	K_i	K_d
Non-reheat power plant	26.537	16.312	-0.508
Reheat power plant	9.682	0.806	18.730
Hydro power plant	38.537	18.1430	0.101

Table 4. Centralized PID controller's parameters for overall system.

Overall EPS	PID parameter		
	K_p	K_i	K_d
Centralized controller	71.2532	5.9055	6.10758

5. Simulation Results and Discussion

The detailed model of the EPS considering RESs is built using Matlab/ Simulink model to validate the effectiveness of the proposed decentralized LFC scheme under the nature variety of the RESs (i.e., disturbances), random load variation, and system parameters variations (i.e., system uncertainties). Moreover, the code of the PSO algorithm (i.e., M-file) is interfaced with the EPS model to perform the optimization process. The dynamic response of the studied power system with the control schemes is obtained and evaluated under different operating conditions through the following scenarios:

5.1. Scenario 1. Performance evaluation of the EPS without RESs

In this scenario, the effectiveness of the proposed control strategy is investigated by implementing different conventional load patterns. Moreover, the system performance with the proposed decentralized controllers based on PSO algorithm is tested and compared with the system performance with the optimal centralized controller. This comparison is evaluated under different load patterns as follows:

Case A: In this case, the EPS with the proposed control schemes are tested by implementation a Step Load Perturbation (SLP) of 15% during the period from 200 s to 800 s. Figure 5 shows the frequency deviation of the EPS with the proposed control schemes. From Fig. 5, it has been noticed that the system response with the proposed decentralized control scheme is faster, has a lower steady-state error, and better damped than the centralized control scheme. On the other hand, the system response with centralized control cannot dampen the frequency fluctuations at the large disturbance.

Case B: In this case, the comparison between the two models is represented by using a series of step load changes with random magnitudes to test the robustness and effectiveness of the proposed decentralized controllers. From Fig. 6, the simulation results concluded that the proposed decentralized controllers' model gives robust stability and has a faster settling time than the centralized controller model. While the system response with the centralized controller design oscillates to such an extent that it is not satisfactory. In contrast, it gives satisfactory performance in the case of applying the slight load change.

Case C: In this case, the robustness of the proposed decentralized control scheme is evaluated under system parameters variation (i.e., system uncertainties) for two operating conditions of the EPS as reported in Table 5. Moreover, a ramp load change has been applied to the EPS as shown in Fig. 7. The simulation results concluded that favourable results have been obtained from the proposed decentralized control scheme. On the other hand, the system response with the centralized controller design oscillates violently to such an extent that it is not acceptable.

The performance specification; Maximum Overshoot (MOS), Maximum Undershoot (MUS) and maximum settling time (T_S) of the EPS with the proposed decentralized and centralized control schemes for this scenario have been compared in Table 6.

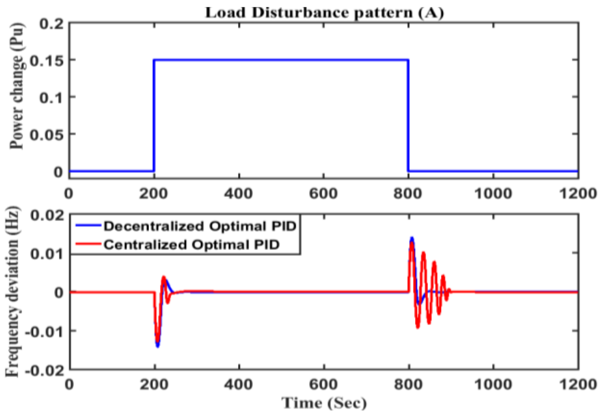

Fig. 5. Frequency deviation of EPS, case A-scenario 1.

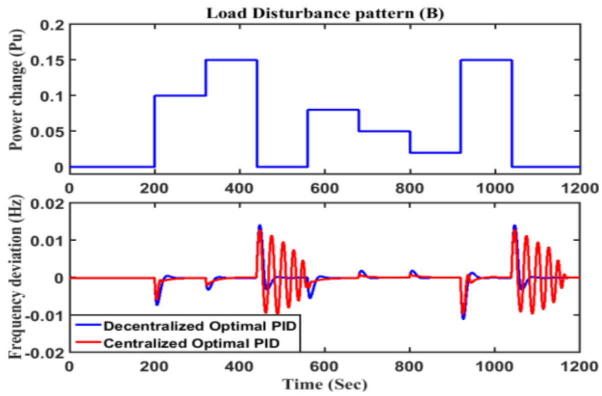

Fig. 6. Frequency deviation of EPS, case B-scenario 1.

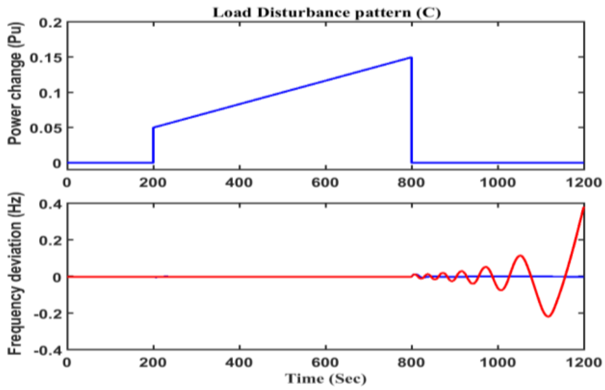

Fig. 7. Frequency deviation of EPS, case C-scenario 1.

Table 5. Two operation conditions of the EPS.

Parameter	H	P_{n1}	P_{n2}	P_{n3}
Case C	6.1452	0.3335	0.5455	0.1210
Base value	5.7096	0.2529	0.6107	0.1364

Table 6. Performance specification of the EPS for scenario 1.

Case	Decentralized controller			Centralized controller		
	MUS	MOS	Ts (s)	MUS	MOS	Ts (s)
A	0.014	0.014	17.412	0.0127	0.0128	43.585
B	0.011	0.014	16.576	0.010	0.0128	37.076
C	0.0054	0.012	18.764	0.218	0.3816	-

5.2. Scenario 2. Performance evaluation of the EPS including RESs uncertainty

In this scenario, the effectiveness of the proposed control schemes is tested and evaluated under variation in loading conditions, system inertia (i.e., uncertainties), and nature of the RESs, which are known the important characteristics of an actual power system. The EPS is tested in the presence of the wind and solar power fluctuations shown in Fig. 8, and also high random load variation (i.e., industrial loads), and low random load variation (i.e., residential load) shown in Fig. 9. This scenario is divided into three sub-scenarios, which are implemented under the assumed multiple operating conditions in Table 7.

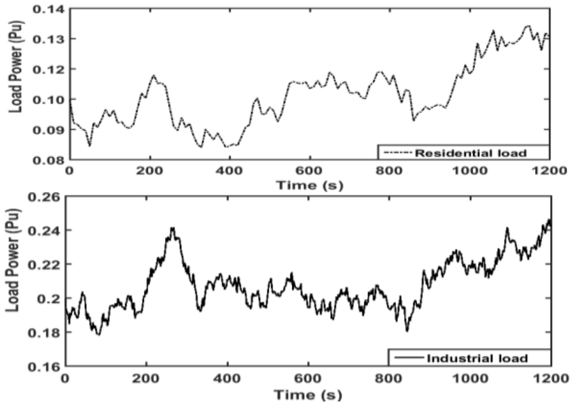

Fig. 8. Random load deviations of case studies in scenario 2.

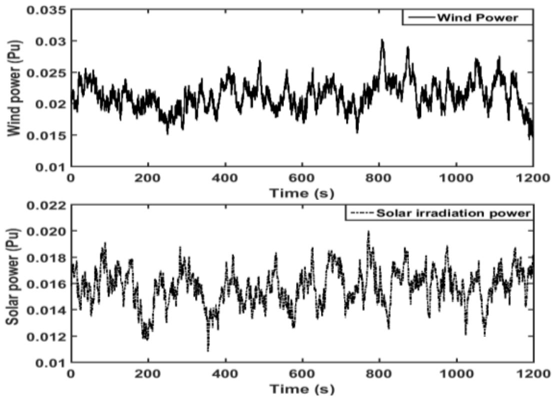

Fig. 9. Wind and solar power fluctuations of case studies in scenario 2.

Case A: In this case, the studied EPS is operated under the situation of 100% of default system inertia as well as implementing the multiple operating conditions in Table 7. The frequency deviation of the EPS with the two control schemes is shown in Fig. 10. It can be seen that the favourable result has been obtained from the proposed decentralized control scheme.

Case B: To perform an extreme test scenario, the studied power system is examined under the situation of reduction the system inertia to 75% from its initial value with the multiple operating conditions in Table 7. Figure 11 shows that the proposed control scheme can provide a smooth and secure frequency performance during the multiple operation conditions of the EPS. On the other hand, the system performance with the centralized controller design oscillates to such an extent that it is not satisfactory during connection of industrial load at time t = 300 s.

Case C: In this case, the EPS is tested under a drastic change in the operating condition, the studied system is operated under the situation of 50% of default system inertia as well as implementing the multiple operating conditions in Table 7. From Fig. 12, the simulation results concluded that the frequency is fluctuating more with high deviation, whereas, the studied system with the centralized control scheme oscillates to such an extent that it is not acceptable. While the proposed decentralized scheme can reduce and stabilize the frequency deviation of the EPS and give robustness to the system subjected to uncertainties.

The performance specification like MOS, MUS, and T_S of the EPS with the proposed decentralized and centralized control schemes for this scenario have been compared in Table 8.

Table 7. Multiple operating conditions of the studied power system.

Disturbance source	Starting time (s)	Stopping time (s)	Size (pu)
Industrial load	300 s	-	0.25
Residential load	Initial	800 s	0.13
Wind farm	600 s	-	0.03
Solar power plant	Initial	-	0.02

Table 8. Performance specification of the EPS for scenario 2.

Case	System inertia	Decentralized controller			Centralized controller		
		MUS	MOS	T_S (s)	MUS	MOS	T_S (s)
A	100 %	0.023	0.009	24	0.025	0.012	46
B	75 %	0.031	0.012	24	0.033	0.025	53
C	50 %	0.045	0.021	20	-	-	-

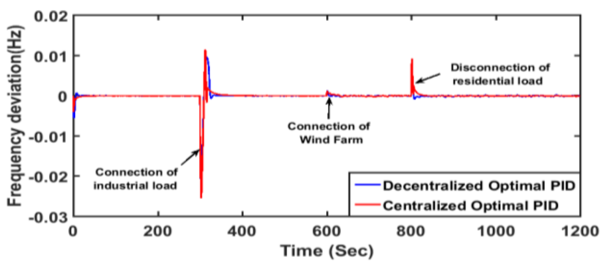

Fig. 10. Frequency deviation of EPS, case A-scenario 2.

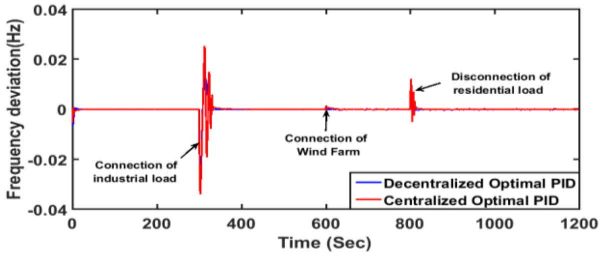

Fig. 11. Frequency deviation of EPS, case B-scenario 2.

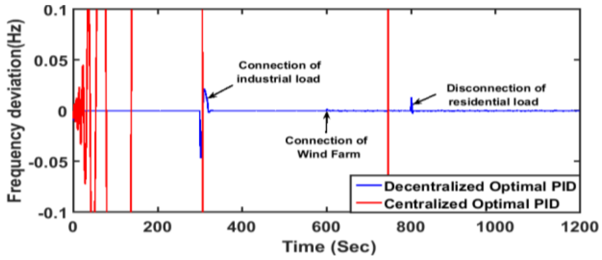

Fig. 12. Frequency deviation of EPS, case C-scenario 2.

6. Conclusion

This research has presented a real hybrid power system in Egypt, which includes both conventional generation units (i.e., gas, thermal and hydraulic power plants) and Renewable Energy Sources (i.e., wind and solar energy) for studying the Load Frequency Control (LFC) issue. Therefore, this paper has proposed a decentralized LFC scheme for each subsystem of the Egyptian Power System (EPS) independently to guarantee the stability of the overall closed-loop system. Where each subsystem of the EPS has its own characteristics compared to the others. Hence, the proposed decentralized LFC has been based on the PID controllers that were optimally designed by the Particle Swarm Optimization (PSO) algorithm. The performance of the proposed decentralized control scheme of each subsystem is compared to the centralized one under variation in loading conditions, loading patterns, system parameters and RESs penetration level. The EPS considering RESs is tested using the nonlinear simulation by Matlab/SIMULINK software®. The obtained results reveal the superior robustness of the proposed decentralized controller against different load disturbance patterns, RESs fluctuations, and EPS uncertainties. Although the centralized controller gives satisfactory performance in case of applying a slight load change, it oscillates to such an extent that it is not satisfactory in case of applying large load disturbance.

Nomenclatures

A_T	Rotor swept area, m^2
C_1, C_2	Acceleration constant
C_P	Power coefficient of the rotor blades
D	System damping coefficient of the area, pu MW/Hz
H	Equivalent inertia constant, pu s
m	Fraction of turbine power (intermediate pressure section)

N	Number of iterations
P_{id}^{n}	p_{best} of particle i at iteration n
P_{gd}^{n}	g_{best} of particle i at iteration n
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
P_{Solar}	Output power of the solar power, W
P_W	Output power of the wind turbine, W
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 hydro plant, Hz/pu MW
rand ()	Random number between 0 and 1
T_1	Valve time constant of the non-reheat plant, s
T_2	Steam valve time constant of reheat plant, s
T_3	Water valve time constant hydro plant, s
T_d	Dashpot time constant of hydro plant speed governor, s
T_h	Time constant of reheat thermal plant, s
T_w	Water starting time in hydro intake, s
W	Inertia weight factor
V_W	Rated wind speed, m/s
v_{id}^{n}	Velocity of particle i at iteration n
x_{id}^{n}	Current position of particle i at iteration n

Greek Symbols

Δf	Frequency deviation of the area, Hz
ΔP_{c1}	Regulating system frequency of non-reheat plant, Hz
ΔP_{c2}	Regulating system frequency of reheat plant, Hz
ΔP_{c3}	Regulating system frequency of hydro plant, Hz
ΔP_L	Load variation, MW pu
β	Pitch angle
λ	Tip-speed ratio (TSR)
ρ	Air density, kg/m^3

Abbreviations

EPS	Egyptian Power System
LFC	Load Frequency Control
PSO	Particle Swarm Optimization
RESs	Renewable Energy Sources
WPGS	Wind Power Generation System

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