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Frequency stability and digital protection coordination of multi-source power system

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Abstract

Nowadays, the interconnection issues of different power plants are interested and must be highlighted, such as the frequency stability and voltage stability, which are a basic principle in the power system operation. Many reasons such as, load shedding, load restoring, and short circuits cause large frequency fluctuations, which threaten the system security and could lead to complete blackouts as well as damages to the system equipment. Hence, this paper proposes a coordination of Load Frequency Control (LFC), which uses an optimized PID controller-based new Moth Swarm algorithm (MSA) and digital under/over frequency relay for a realistic multi-source power system considering different cases study of load shedding and restoring. The digital relay will be energized by the data conversion system under normal and fault conditions. The presented digital frequency relay will cover both over and under frequency conditions. To validate the effect of the proposed coordination, the Egyptian Power System (EPS), which contains three dynamics subsystems, hydro, reheat, and non-reheat power plants, was investigated for the MATLAB/SIMULINK considering the effect of system nonlinearity. The obtained results stated the effectiveness of the proposed coordination to maintain the power system frequency stability and security. Furthermore, the superiority of the under/over digital frequency relay has been approved.

Keywords: Load frequency control, moth swarm algorithm (MSA), digital frequency relay, Egyptian power system (EPS), PID controller

1. Introduction

In recent years, with the continuous developing in electrical loads especially 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 (blackouts), loss of several lines, zone islanding, equipment damaging, transmission line overload, and interfere with system protection schemes [1-2]. Moreover, the frequency control may be difficult in case of any mismatch between electric power generation and load demand [3]. On the other hand, due to the instability problem, there is a risk of tripping the generators or lines because of the distance between the centers of generation and loads [4]. Therefore, the stability and protection coordination issues have become interested and must be highlighted.

There are several studies have dealt with this problem from the control view only such as Fuzzy controller and PID controller based on different algorithms and optimization techniques [5, 6]. Raheel et al. [7] discussed the robustness of the Coefficient Diagram Method (CDM) controller including energy storage system (ESS) like Electric Vehicles (EV) in his control strategy in a small power system. In addition, Princess et al. [8] studied the same issue for the modern power system. However, the structure

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of this control technique in [7, 8] is complicated, as it required more steps to get its parameters. Moreover, R. Hooshmand et al. [9] have presented an optimal design for under-frequency load shedding by using the artificial neural networks. Some researchers handled the frequency stability problem from the protection side such as; Laghariet et al. [10] applied an intelligent computational technique for load shedding of the power system under faulted conditions. Moreover, Komsan and Naowarat. In [11], Komsan discussed the same issue by using the rate of change under frequency relay to improve the load shedding scheme in microgrid systems. Further, W. Freitas et al presented a comparative study of the rate of change of frequency (ROCOF) and vector surge relays for distributed generation applications [12]. However, they faced a very hard task in relays coordination as their design may not detect the islanded conditions within the required time. On the other hand, a few studies have been proposed the coordination of ROCOF and under/over frequency relays such as; Jose Vieira et al. in [13]. However, the presented coordination in [13] did not compensate the frequency fluctuations within the allowable frequency limit due to the action of the relay, which is energized when the system frequency become out of the allowable limit. Such a problem can be overcome by designing the proposed coordination of frequency stability using optimal LFC and digital protection.

This paper presents a coordination of optimal LFC using a new PID controller-based MSA and digital under/over frequency relay for a real hybrid power system in Egypt. This system consists of seven strongly tied zones. It represented as a single area, which comprises of dynamics three subsystems (reheat, non-reheat, and hydropower power plants considering the effect of system nonlinearity. The rest of this paper is organized as follows, the modeling of the studied EPS system presented in section II. The control methodology, which includes a PID controller and MSA technique are described in section III. The principle operation of digital under/over frequency relay is explained in sections IV and V. The simulation results of the proposed coordination which applied to the EPS have been described in section VI. Finally, the last section concludes the results and advantages of the proposed method.

2. EPS Description

The power system presented in this study is a real power system in Egypt. It divided into seven strongly tied zones which are 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 (non-reheat, reheat, and hydropower plants or a combination of each). EPS has more than 180 power plants, moreover it is 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) Hydropower plants contribute almost 14% of the installed capacity. The total generation capacity and peak loads are 35220 MW and 28015 MW respectively according to the annual report of the Egyptian Electricity Holding Company in 2015 [14]. The National Energy Control Center (NECC) in Egypt has advanced a dynamic model of LFC for the EPS in [15]. The National Energy Control Center (NECC) in Egypt estimates the system parameters values which used in the nonlinear model of EPS and independent from the system operation as in Table 1 [16]. However, the other parameters vary with time are depending on the operating conditions. The nominal parameters values are summarized in Table 2. The dynamic equations of EPS are given in [16].

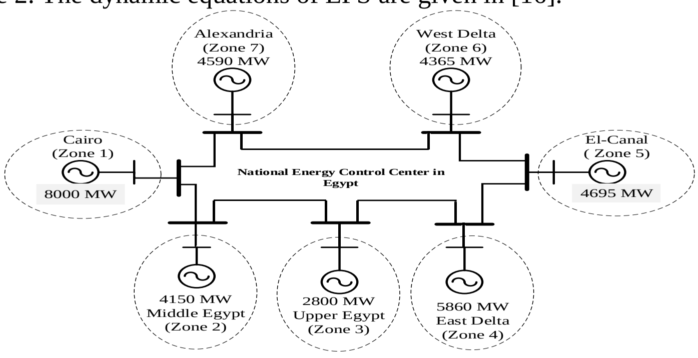

Fig. 1. Typical single-line diagram of Egyptian power system.

Table 1. EPS parameters

Parameter	Value	Parameter	Value
D	0.028 pu (MW/Hz)	T_w	1.0 sec
T_1	*0.4 sec*	m	*0.5 sec*
T_2	*0.4 sec*	R_1	*2.5 Hz/pu MW*
T_3	*90 sec*	R_2	*2.5 Hz/pu MW*
T_d	*5 sec*	R_3	*1.0 Hz/pu MW*
T_h	*6 sec*		

Table 2. Nominal system parameters

Parameter	H	P_{n1}	P_{n2}	P_{n3}
Value	5.7096 pu sec	0.2529 pu	0.6107 pu	0.1364 pu

3. Control Methodology

3.1. PID controller

PID is a proportional, Integral and derivative controller which is one of the earliest industrial controllers. Moreover, most industrial controllers are performed based on PID controller algorithms, particularly at the lowest levels. It is a convenient fractional order structure that has been employed for control purposes as a lead-lag compensator [17]. PID controller has many merits: economic cost, simplicity for parameters tuning, robustness and a successful practical controller which can provide excellent control performance regardless of the perturbations and variations in the system parameters. This controller has been confirmed to be remarkably effective in the regulating of a wide range process according to many types of research such as [6]. However, the PID controller 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 used an intelligent searching method to find the optimum parameters of the PID controller.

3.2. Overview of MSA

In this paper, an intelligent searching method has been adapted to find the optimum parameters of the controller. MSA technique [18] as a fast searching intelligent technique has been modeled to tune the parameters of the PID controller. MSA is a global optimization algorithm based on evolutionary computation technique. It is inspired from the orientation of moths towards moonlight. The available solution of any optimization problem using MSA is performed by the light source position and its fitness is the luminescence intensity of the light source. Furthermore, the proposed method consists of three main groups, the first is called Pathfinders, which is considered a small group of moths over the available space of the optimization. The main target of this group is to guide the locomotion of the main swarm by discriminating the best positions as light sources. Prospectors group is the second one which has a tendency to expatiate in a non-uniform spiral path within the section of the light sources determined by the pathfinders. The last one is the onlookers, this group of moths move directly to the global solution which has been acquired by the prospectors. With MSA, different optimization operators are used to mimicking a set of behavioral patterns of moths in nature, which allows for the flexible and powerful optimizer. Hence, a new dynamic selection strategy of crossover points is proposed based on population diversity to handle the difference vectors Lévy-mutation to force MSA to jump out of stagnation and enhance its exploration ability. In addition, a spiral motion, adaptive Gaussian walks, and a novel associative learning mechanism with immediate memory are implemented to exploit the promising areas in the search space [18]. The new position of i^{th} onlooker moth can be expressed as follows:

$$x_i^{t+1} = x_i^t + \varepsilon_1 + \left[\varepsilon_2 \times best_g^t - \varepsilon_3 \times x_i^t\right] \forall i \in \{1,2,\ldots,n_G\} \quad (1)$$

The best previous position of any onlooker is recorded and is called $best_P$. Another best value that is tracked by a global version of MSA which is the overall best value and called $best_g$. The updating equation can be completed in the form:

$$x_i^{t+1} = x_i^t + 0.001.G\left[x_i^t - x_i^{\min}, x_i^{\max} - x_i^t\right] + (1 - \frac{g}{G}).r_1.(best_p^t - x_i^t) + 2g/G.r_2.(best_g^t - x_i^t) \quad (2)$$

where, $i \in \{1,2,\cdots,nA\}$, $2g/G$ is the social factor, 1-g/G is the cognitive factor and $best_P$ is a light source randomly selected from the new group of pathfinders based on the probability value of its consistent solution. In this study, the main objective of the MSA is to minimize the frequency deviation of EPS LFC through tuning PID controller parameter (K_p, K_i, *and* K_d).

3.3. Implementation of MSA for PID tuning

PID controller tuning is considered as an optimization problem which is handled by the MSA technique. MSA had superior features such as easy implementation, stable convergence characteristics and it can generate a high-quality solution within a shorter computation time. Moreover, this study develops the MSA which is employed to tune PID gains (K_p, K_i, and K_d) using the model of EPS. Each moth 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, which consists of several component functions as seen in (3). These components are a steady-state error (e_{ss}), peak overshoot (Mp), rise time (Tr), and settling time (Ts). Size of the swarm determines the requirements of global optimization and computation time. The swarm size is the number of moths equals to 50 which are considered enough. However, the selection of MSA parameters decides to a great extent the ability of global minimization. The obtained values of the PID gains controller based on MSA are in Table 3. The evaluation of the objective function is reported in Fig. 2.

$$F = (1 - \exp(-\beta)) \quad (M_P + e_{ss}) + (\exp(-\beta))(T_S - T_R) \quad (3)$$

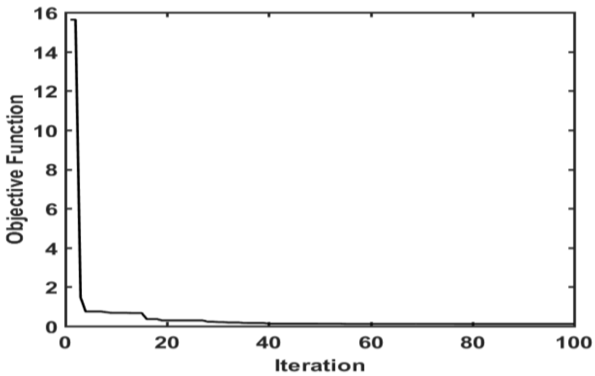

Fig. 2. The evaluation of the objective function on the EPS.

Table 3. PID controller's parameters

Parameter	K_p	K_i	K_d
Value	71.2532	5.9055	6.10758

4. Modeling of Digital Frequency Relay

Owing to the recent developments in the power system, new digital devices are usually utilized. They are widely used in the control and protection of power systems to guarantee sustainable energy. Several kinds of digital devices are used practically in power system protection, such as the digital relay. Recently, there are many applications of digital relays in transmission and generation system protection due to their advantages such as [19]; flexibility, high-performance level, and capability of operating under different temperatures compared to the classical electromechanical relays.

The digital protection system consists of basic components, such as digital relays, digital communication bus, and an optical instrument transformer as shown in Fig. 3. The instrument transformer measures the current and voltage values and then sends the discrete-time data, which obtained from the data conversion system to the digital relay. This relay processes these data using special algorithms based on protection purpose (for example, over/under frequency protection and overcurrent protection). When an abnormal condition is detected, the relay trips a circuit breaker with triggering for an alarm. This work will present the application of the over/under digital frequency relay for the EPS protection. Frequency relay is used to protect the power system against large frequency variations in the case of generation or load loss. Furthermore, it can detect the islanded operation, which occurs due to loss of distributed generation. The loss is detected by measuring the Rate of Change of Frequency (RoCoF). However, RoCoF cannot discriminate between frequency changes because of different disturbances [20]. A comparison of the rate of change of frequency for loss of the main protection is presented in [20].

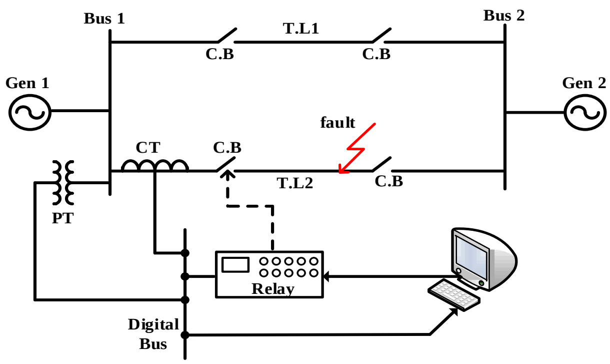

Fig. 3. An example of a digital protection system.

Considering the EPS presented in Fig. 1, the mechanical power P_M is balanced with the demand power P_d according to swing equation as given in (4) at steady state. The rotor angle δ and the rotor speed ω of the generator are constant. When an imbalance occurs due to a disturbance, the frequency deviations start to due to the transients of the generator.

$$\begin{cases} \dfrac{2H}{\omega_o}\dfrac{d\omega}{dt} = P_M - P_d = \Delta P_{sys} \\ \dfrac{d\delta}{dt} = \omega - \omega_o \end{cases} \tag{4}$$

Where,

$$\Delta P_M = \Delta P_m + \Delta P_W + \Delta P_{PV} \tag{5}$$

The rotor speed can be calculated from (4) as:

$$\omega = \frac{\omega_o \Delta P_{sys}}{2H} t + \omega_o \tag{6}$$

By substituting $(\omega = \omega_o + \Delta\omega)$ in (6):

$$\omega_o + \Delta\omega = \frac{\omega_o \Delta P_{sys}}{2H} t + \omega_o \Rightarrow \quad \Delta\omega = \frac{\omega_o \Delta P_{sys}}{2H} t \tag{7}$$

where ω_o=f_o, and $\Delta\omega$=Δf.

Hence the relation between the frequency deviations (Δf), the detection time (t), and integrator value (K) can be calculated from the following equation:

$$\Delta f = \frac{f_o \Delta P_{sys}}{2H} t \tag{8}$$

where f_o is the system frequency, H is the micro-grid system inertia, and ΔP_{sys} is the system power change.

The proposed digital relay can be adjusted by the time-delay of the integrator. Therefore, the frequency deviations must persevere during a previous specific time for energizing the relay. The delay time setting is calculated as:

$$t = \frac{2H\Delta f}{f_o \Delta P_{sys}} + K \tag{9}$$

In this study, the digital frequency relay process will be coordinated with the LFC action to maintain the power system stability. The digital relay system consists of the frequency measurement unit, which measures the system frequency and converts it to a discrete-time signal through the data conversion unit. Further, it contains a frequency detection element, which sends a tripping action to the circuit breaker in case of frequency disturbance as shown in the block diagram of the digital frequency relay implementation of Fig. 4.

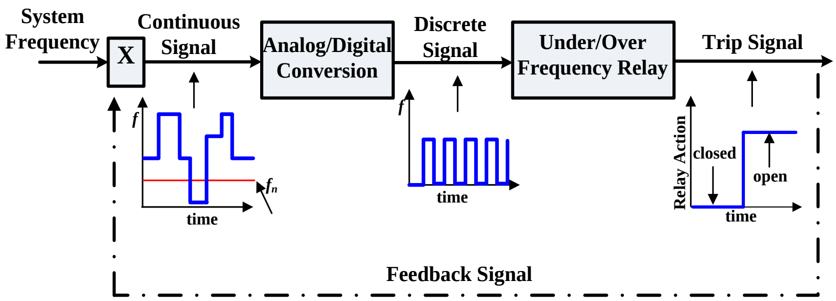

Fig. 4. The logic block diagram of the proposed digital frequency relay.

5. Principal Operation of Digital Frequency Relay

The computational modeling of the proposed digital frequency relay in this study is represented in Fig. 5. Where, the system frequency f is measured and then compared with over/under frequency limit (f_{max}<f<f_{min}). If the frequency is over or under the allowable limits, the integrator output is compared with its threshold value (K=5sec). If the detected value of the integrator output exceeds the set value, a trip action will occur by the digital relay to take a decision, such as disconnecting load or generation unit. On the other hand, if the integrator output value is lower than the set value, while the system frequency is out of relay range. The relay does not energize and the control system will restore the system stability by readjusting the system frequency to (f_o=50Hz). The international grid code for the frequency relay setting is seen in Table 4 [21]. This code could be set to other values based on country standards. The whole operation of the coordination of digital frequency relay and the LFC is concluded in the flowchart in Fig. 6.

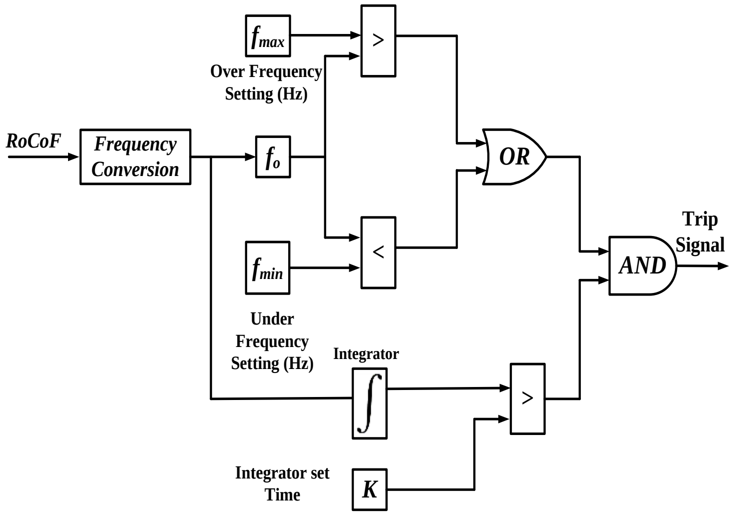

Fig. 5. The computational model of digital frequency relay.

Table 4. Frequency relay settings

Nominal Frequency (f)	*Frequency Relay*	*Limit*	*Threshold Time*
50	Over Under	f_{max} =51 Hz f_{min} =49 Hz	*K*=5 sec

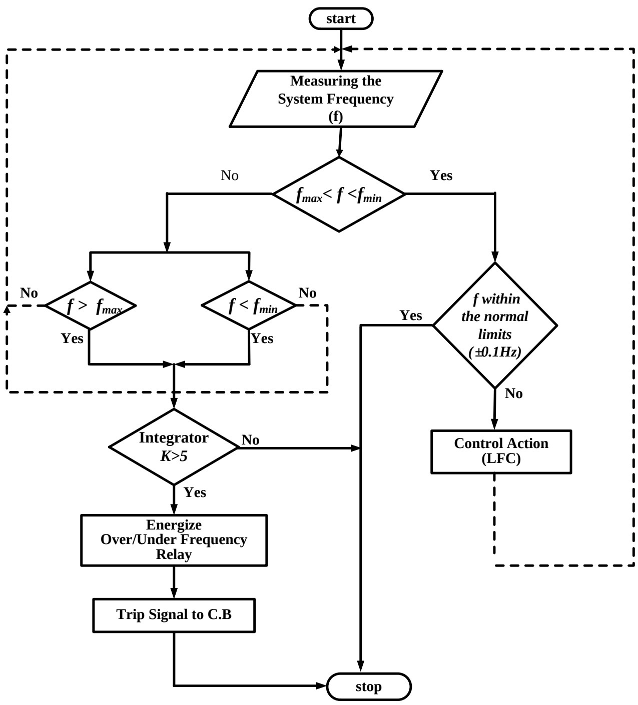

Fig. 6. Flowchart of the proposed coordination.

6. Results and Discussion

Simulation results and analysis are carried out on the EPS model with the effect of system nonlinearity as shown in Fig. 7. The GRC limits of the generation rate 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 [21]. The proposed coordination is tested under different cases of load shedding and restoring. Each case has some different scenarios and the simulation time of each one is 5 minutes. The studied scenarios on the EPS are as the follows:

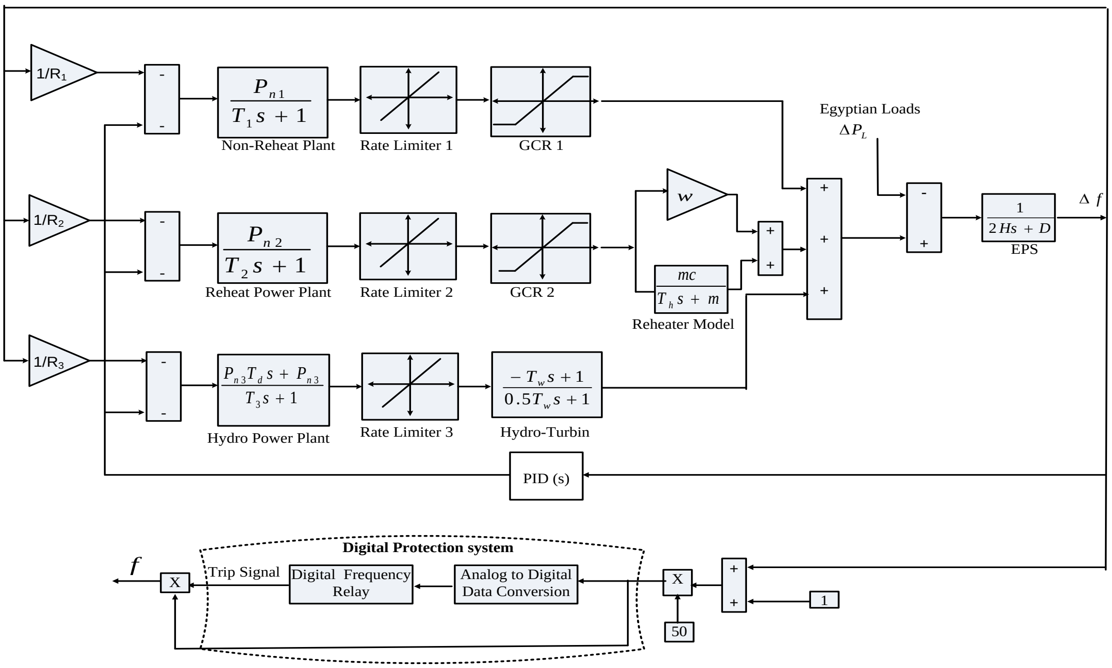

Fig. 7. A nonlinear model of the Egyptian power system (EPS).

6.1. Scenario A

In the first scenario, 12% of the load is added at 50 sec; then it is shed at 100 sec, later on, further 20% of the load is applied at 150 sec as shown in Fig. 8. Although the system frequency exceeds the allowable limits of under-frequency during this case, the digital frequency relay does not trip as seen in Fig. 8 due to the integrator output value does not exceed the set value.

Therefore, LFC succeeded to readjust the frequency to its normal value as shown in Fig. 9. This case proves the effectiveness of the proposed optimal LFC which used PID controller-based MSA as it can adjust the frequency to its normal value in all three stages of this scenario without needs to protection action.

6.2. Scenario B

In this scenario, the load disturbance is greater than the previous case; whereas a 20% of the load is added at 100 sec then it followed by adding another 25% of the load at 200 sec in addition to the base load and the relay is observed. Fig. 10 represents the power change and relay status under different load conditions. In the first load change (added 20% of the load), the frequency fluctuations are not within the allowable frequency limits. However, the value of the integrator output does not exceed the set value.

Hence, the control action returned the frequency to the stable case without any action from the protection side. On the other hand, when a heavy load applied to the EPS, the digital frequency relay tripped the system. Fig. 11 shows the performance of the frequency in the two stages of scenario B.

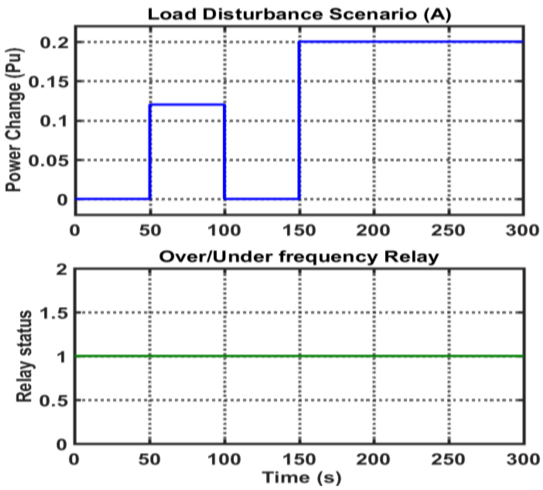

Fig. 8. Load Disturbance and Relay Status of Case A.

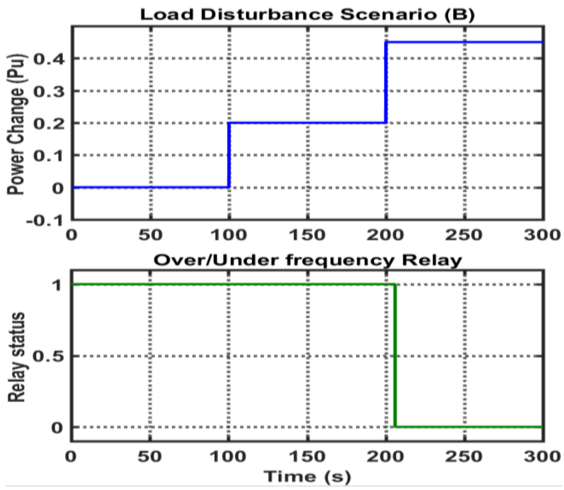

Fig. 10. Load Disturbance and Relay Status of Case B.

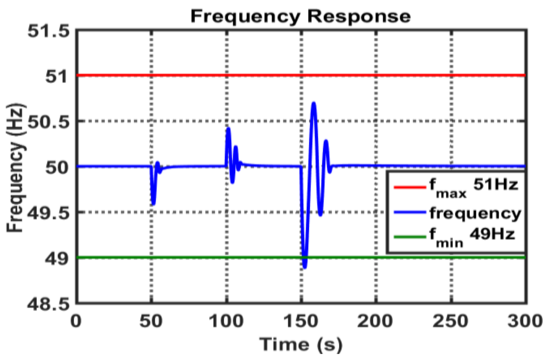

Fig. 9. The Frequency response of EPS for Case A.

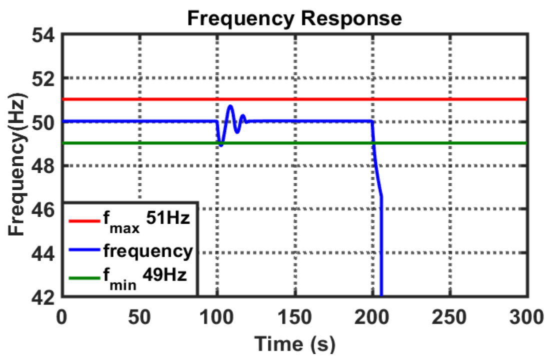

Fig. 11. The frequency response of EPS for Case B.

6.3. Scenario C

In the third scenario, the behavior of the proposed optimal LFC and digital protection coordination is tested under shedding loads conditions. Fig. 12 shows that 20% of the load is switched off at 100 sec, followed by another 20% of the load shedding at 200 sec. The control action of optimal LFC overcomes the first change in frequency at 100 sec instant. However, it cannot handle the change of system frequency when a huge load applied at 200 sec. therefore, the digital frequency relay (as an over frequency relay in this case) trips the system at that time as shown in Fig. 12 whereas the integrator output exceeds the threshold value of 5. Hence, the effectiveness of the proposed coordination is proved; the frequency behavior is depicted in Fig. 13.

6.4. Scenario D

In this case, the optimal LFC has the ability to readjust the frequency variation to its normal value at three times of load disturbances, firstly 10% of the load is added at 50 sec then it is shed at 100 sec followed by adding 20% of the load from 150 to 200 sec as shown in Fig. 14. However, the load shedding at 200 sec leads to obtaining large frequency fluctuations and the controller could not reset the frequency to the normal value. Moreover, the integrator reached quickly and exceeded the threshold value of 5sec. Therefore, the digital frequency relay trips the system as seen in Fig. 14. In the last case of a load change, the frequency exceeded the allowable limits which are used for designing the digital relay. The change in the system frequency under the load shedding and restoring can be observed in Fig. 15.

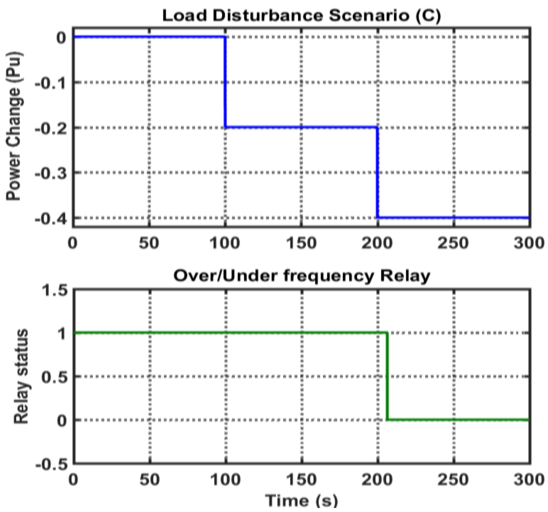

Fig. 12. Load Disturbance and Relay Status of Case C.

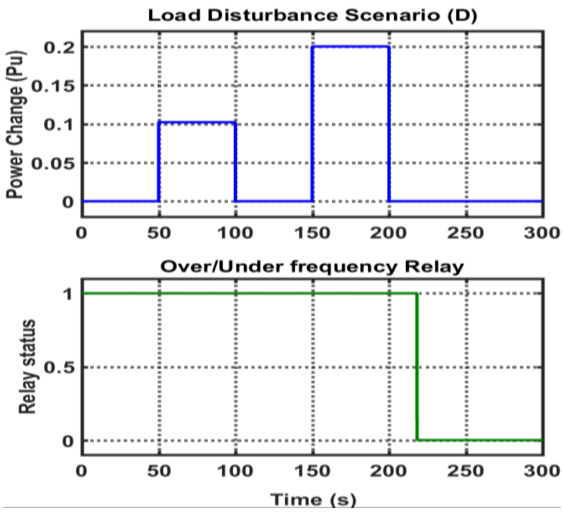

Fig. 14. Load Disturbance and Relay Status of Case D.

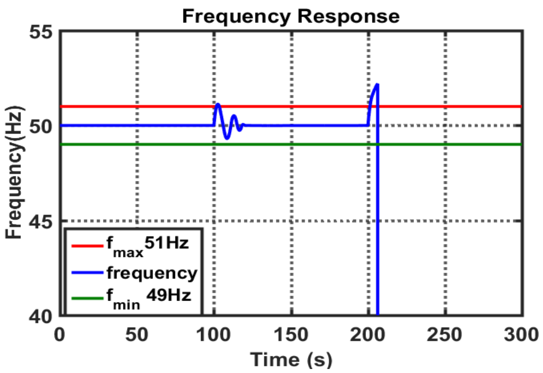

Fig. 13. The frequency response of EPS for Case C.

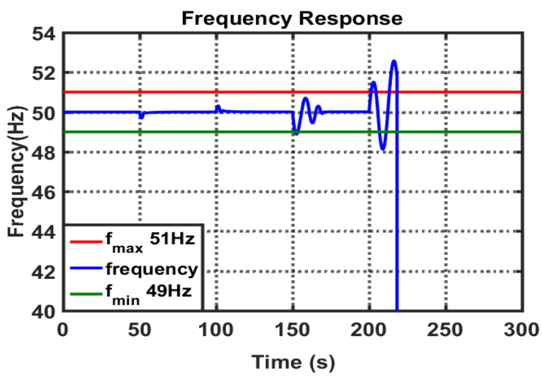

Fig. 15. The frequency response of EPS for Case D.

6.5. Scenario E

In the last scenario, the robustness of the proposed coordination technique against series changes in loads has been tested as depicted in Fig. 16. It is clearly shown in Fig. 17 that the optimal LFC can maintain the frequency stability of the EPS under different cases of transient and permanent conditions from 50 sec to 200 sec. However, at 230 sec, the load disturbance is huge and permanent results that the frequency value was not within the control limits. Hence, the digital frequency relay action became necessary to protect the electrical system. Fig. 16 shows the action of the under-frequency relay, which trips after the integrator exceeded its threshold value.

Results proved that a high-performance of coordination of protection and control unit for application in the EPS was developed. The proposed coordination succeeded in maintaining the protection and control functions at all times by eliminating the power-system faults or prevents the spreading.

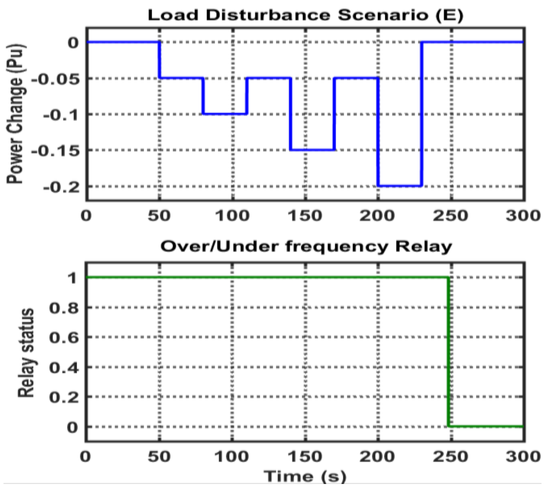

Fig. 16. Load Disturbance and Relay Status of Case E.

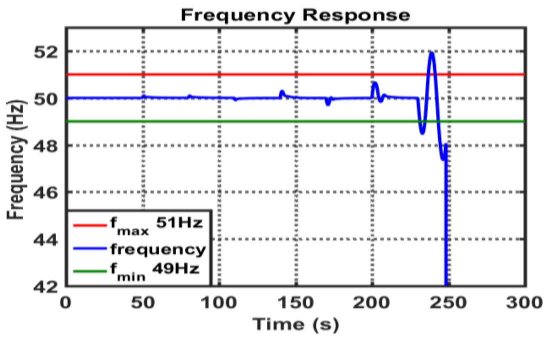

Fig. 17. The frequency response of EPS for Case E.

7. Conclusion

This article has presented a novel coordination of optimal LFC using PID controller-based on MSA and digital over/under frequency relay for the real power system protection (e.g. power system in Egypt). The Egyptian Power System (EPS) contains three subsystems; non-reheat, reheat, and hydropower plants with inherent nonlinearities. A recently developed hybrid algorithm namely Moth Swarm Algorithm (MSA) has been applied to optimize the PID controller parameters with the aim of frequency regulation. To prove the effectiveness of the proposed control/protection coordination, the EPS has been subjected to different scenarios of load disturbances as case studies.

The simulations results proved that the proposed coordination of optimal LFC and digital frequency relay achieved an effective performance for maintaining the system frequency at 50 HZ. Whereas, the LFC succeeded to readjust the frequency fluctuations to its normal value under different conditions of transients and permanent load disturbances. However, in the case of large disturbances, LFC cannot maintain the frequency stability and the frequency exceeding the normal limits. Moreover, the value of the integrator output exceeds the set value. Hence, the relay will trip the system. Furthermore, the results confirmed that the digital relay has superiority relay in terms of accuracy and sensitivity and wide range controlling. Application of the proposed coordination will be applied in the microgrid system as a future scope of this work considering renewable energy sources and islanded issues.

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