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Microgrid dynamic security considering high penetration of renewable energy

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Abstract

This paper presents a coordination strategy of Load Frequency Control (LFC) and digital frequency protection for an islanded microgrid (MG) considering high penetration of Renewable Energy Sources (RESs). In such MGs, the reduction in system inertia due to integration of large amount of RESs causes undesirable influence on MG frequency stability, leading to weakening of the MG. Furthermore, sudden load events, and short circuits caused large frequency fluctuations, which threaten the system security and could lead to complete blackouts as well as damages to the system equipment. Therefore, maintaining the dynamic security in MGs is one of the important challenges, which considered in this paper using a specific design and various data conversion stages of a digital over/under frequency relay (OUFR). The proposed relay will cover both under and over frequency conditions in coordination with LFC operation to protect the MG against high frequency variations. To prove the response of the proposed coordination strategy, a small MG was investigated for the simulation. The proposed coordination method has been tested considering load change, high integration of RESs. Moreover, the sensitivity analysis of the presented technique was examined by varying the penetration level of RESs and reducing the system inertia. The results reveal the effectiveness of the proposed coordination to maintain the power system frequency stability and security. In addition, the superiority of the OUFR has been approved in terms of accuracy and speed response during high disturbances.

Keywords: Digital frequency relay, Load frequency control (LFC), Microgrid, Renewable energy sources (RESs), Dynamic

1 Introduction

In past, several cascaded blackouts happened in electrical power systems due to frequency instability in case of the imbalance between the electrical load and power supply or N-1 contingency [1]. Nowadays, this problem increased after the growing of renewable energy sources (RESs), which have several impacts on the dynamic security of the islanded microgrids (MG). The dynamic security of MG is the ability of electric grid to maintain the system synchronism when subjected to various transient disturbances [2]. Figure 1 shows the dynamic security issues of MG. One of these issues is the lack of system inertia due to the high integration of RESs. Consequently, increase the voltage and frequency fluctuations, loss of generation source, forced load shedding, and short circuit faults [3]. Furthermore, RESs exchange electrical power to MGs through power electronic inverters, which cause higher power fluctuations than the traditional synchronous generators. Hence, if the RESs penetration becomes larger, the islanded MGs might become insecure as the stabilizing in system frequency and voltage is difficult in that situation [4, 5]. Moreover, there will be unbalanced between the generation and load due to the variable nature of RESs. These changes lead to the appearance of challenges for the MG dynamic security such as, nature transient variations in MG. These variations are highly affected by the operation mode of MG whether grid-connected or stand-alone [6, 7]. Moreover, the selection and coordination of conventional protective relays became more complex due to the frequent bidirectional power flow in connection feeders of MGs to utility grids [8, 9]. Regarding to the previous challenges, the stability and protection coordination issues have become interested and must be highlighted. Therefore, this work proposes a

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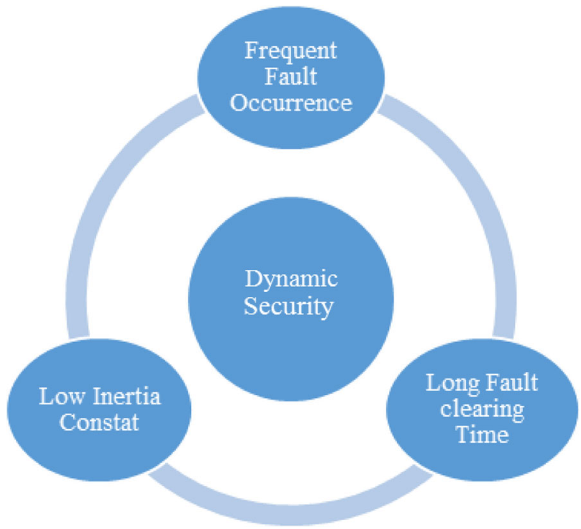

Fig. 1 The microgrid dynamic security issues

coordination of LFC and digital OUFR for maintaining the dynamic security of an islanded MG.

The frequency control and protection of the electrical systems are the two main sides to investigate the dynamic security of the MG system. There are several studies have dealt this problem from the control side such as conventional controllers with different algorithms and optimization techniques [10, 11], intelligent control, (i.e. Fuzzy Logic Control (FLC)) [12, 13], and robust control [14, 15]. X. Tang et al. [16] proposed a novel technique of frequency control, which is V/f droop control (VFDC) and P/Q droop control (PQDC) combined for islanded MG based on different energy storage devices. While, Sedghi and Fakharian [17] used the coordination of robust control and fuzzy technique to address the frequency control issue in [16]. Model Predictive Control (MPC) based LFC for MG based on the coordination of wind turbine and Plug-in Hybrid Electric Vehicles (PHEVs) is proposed in [18] by Jonglak et al. Furthermore, Wang et al. [19] studied and analyzed the voltage security issue for MG using Convolutional Neural Network (CNN).

On the other side, the protection systems have changed significantly from the bygone decade and will change continuously as a result of the advancement of technology. Therefore, power systems designers are seeking to apply digital devices to handle the increasing complexity of power system, which improve the cost and usability. Subsequently, the digital technology has appeared in the protection system of microprocessor relays since 1980 and developing to those with communications interfaces in the a990s [20]. Today, digital relays have featured with high speed communication, which helped in replacing wires for safety interlocking, control and also circuit breakers tripping action. Furthermore, there are many applications of digital relays in transmission and generation system protection due to their flexibility, high performance level, and capability of operating under different temperatures compared to the classical electromechanical relays. Therefore, this study focuses on the digital protection device, (e.g. OUFR) to be coordinated with LFC for MG dynamic security. There are several studies have dealt this problem from the short circuit fault side only such as, the optimized time-based coordination of conventional over-current relays; which is the earliest protection technique for utility grids including micro-grids [21]. This method has a limit in its ability of multi-relay protection because of its high sensitivity to components parameters in high fault levels. Sheng et al. [22] presented a multi-agent method depend on assumptions of high fault current levels. However, this method has been developed to island the MG for any fault in the utility grid and also disconnecting most of distributed generations (DGs) for faults within the MG. Furthermore, some studies handled the frequency protection problems such as; Laghariet et al. [23] applied an intelligent computational technique for load shedding of the power system under faulted conditions. Moreover, Komsan and Naowarat [24] discussed the same issue by using the rate of change under frequency relay to improve the load shedding scheme in MGs. Further, Freitas et al. [25] presented a comparative study of the rate of change of frequency (ROCOF) and vector surge relays for distributed generation applications. However, they faced a very hard task in relays coordination as their design may not detect the islanded conditions within the required time. Teimourzadeh et al. [26] introduced a new Region of Attraction (ROA) based protection zone for the detection of MG security status. However, the proposed approach is an efficient index for providing a quick detection of MG security status. Jose Vieira et al. in [27] proposed the coordination of ROCOF and under/over frequency relays. However, this presented coordination has a drawback, which it did not compensate the frequency fluctuations within the allowable frequency limit due to the action of the relay is energized when the system frequency become out of the allowable limit. Such a problem can be overcome by designing the proposed coordination strategy of LFC and digital OUFR for an islanded MG system dynamic security.

According to authors' knowledge, some gaps still need to be filled in the MG dynamic security issue. Therefore, this paper proposes a design of digital over/under frequency relay coordinated with the LFC for the dynamic security of an islanded MG system, which consist of thermal power plant, PV, wind power generation (WPG), and domestic loads. To prove the effectiveness of the proposed coordination in protecting the MG against frequency variations, it has been tested under different scenarios of disturbances such as, high penetration level of RESs, reducing system inertia, and sudden load variations. The remaining of this paper is arranged as follows, Section 2 discusses the problem description. The structure of the studied MG system with the state equations are presented in Section 3. The coordination of control and protection methodology is described in Section 4. Section 5. shows the simulation results of the proposed coordination which applied to the MG. Finally, the last section concludes the results and advantages of the proposed method.

2 Problem formulation

The dynamic security issue is one of the most critical issues, which face the power system designers. Dynamic security refers to the ability of the electrical power system to maintain the synchronism when subjected to a sever trainset disturbance [2]. Therefore, the dynamic security deals with disturbances that impose momentous changes into the system variables. Among these are short-circuit faults, loss of a dominant generation source, and loss of a large load. The system response to these disturbances includes large deviations in the system variables such as voltage magnitudes and angles, generator speed, and system frequency [12]. Hence, the balance between the input mechanical power and the output electrical power is disturbed. And then, the mismatch makes the synchronous generators (SGs) either accelerate or decelerate.

On the other hand, preserving dynamic security is different between the bulk power systems and MGs. In the case of the bulk power systems, the conventional synchronous generators are considered the source of the dynamics. Likewise, in MGs, the RESs are the host of dynamics. Moreover, most of the available methods for preserving the dynamic security of the bulk power systems are considered inefficient for MGs due to these methods are devised based on the features of the bulk power system, which are significant inertia constant and rather slow dynamics. Therefore, this research studies the dynamic security issue in the microgrids. In the MGs, the RESs exchange power to the MGs through inverters/converters. The power electronic interface-based RESs are static devices without any rotating mass so that the associated inertia constant is roughly zero. On the other hand, synchronous generators-based RESs are small-scale generators with noticeably low inertia constants [28]. Such a low inertia constant renders the MGs more vulnerable to the transients than the bulk power systems. Furthermore, the power generation from RESs are unpredictable and variable, results in more fluctuations in power flow and frequency in the MG, which significantly affects the power system operation. Also, the randomly changes in load power demand caused a bad response to the PCC voltage, active, and reactive powers transfer. To solve the dynamic stability problems, it must be determined the effective factors, which steer the MGs toward the insecurity. These factors include a low inertia constant, frequent fault occurrence, and inadequacy of existing protection schemes. Moreover, the performance of the protection system is one the most significant factors which imperils the dynamic security of the μGs. Therefore, the stability and protection coordination issues have become a center of interest especially for power system researchers. Hence, this research proposes an efficient coordination of secondary frequency control (i.e., LFC) and the digital OUFR for an islanded MG security considering high penetration of RESs.

3 System overview and modeling

3.1 Microgrid system

The MG is a small power system, which consisted of Distributed Generators (DGs), domestic loads, energy storage systems (EES), and power conditioning units. The MG is distributed through low voltage distribution systems and the electric power is mainly generated by DGs such as photovoltaic (PV), wind turbines (WT), hydropower plant, fuel cells, etc. This research focuses on the islanded MG, which includes 20 MW of Thermal power plants, 6 MW of a wind farm, 4.5 MW of a solar farm, and 15 MW of domestic loads. The simplified model of an islanded MG with influence of the proposed coordination, the coordination of LFC and digital protection is shown in Fig. 2.

In this study, some physical constraints effects are taken into consideration for modelling the actual islanded MG such as; the speed governor dead band (i.e., backlash) and Generation Rate Constraints (GRC) of power plant. Whereas, backlash is defined as the total magnitude of sustained speed change. All speed governors have a backlash, which is important for primary frequency control in the presence of disturbances. The GRC limits the generation rate of the output power, which is given as 0.2 pu MW/min for non-reheat power plant [29]. In this research, the power variation of the RESs such as; the wind power variation (ΔP_{Wind}), the PV solar power variation (ΔP_{PV}), and the load power variation (ΔP_L) are considered as disturbance signals for islanded MG. The dynamic model of the studied MG system with the proposed coordination strategy as shown in Fig. 3. The nominal parameters values of the studied MG system are indicated in Table 1.

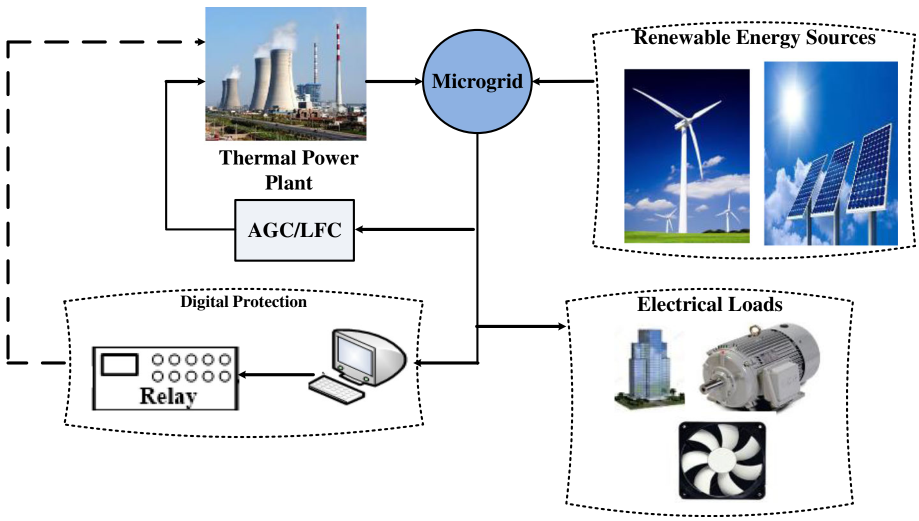

Fig. 2 The studied model of the islanded microgrid with the coordination strategy

3.2 Mathematical model of the proposed microgrid

This section describes the state-space equations of the proposed islanded MG considering high penetration of RESs. The frequency deviation *(Δf)* of the islanded MG considering the effect of penetration of RESs, the primary and secondary control (LFC) can be obtained as:

$$\dot{\Delta} f = \frac{1}{2H}(\Delta P_m + \Delta P_{PV} + \Delta P_{WT} - \Delta P_L) - \frac{D}{2H}{}^{*}\Delta f \quad (1)$$

where,

$$\dot{\Delta} P_g = -\frac{1}{T_g}(\Delta P_g) - \frac{1}{R.T_g}{}^{*}\Delta f + \frac{1}{T_g}(\Delta P_c) \quad (2)$$

$$\dot{\Delta} P_m = -\frac{1}{T_t}(\Delta P_m) + \frac{1}{T_t}(\Delta P_g) \quad (3)$$

$$\dot{\Delta} P_{PV} = -\frac{1}{T_{PV}}(\Delta P_{solar}) - \frac{1}{T_{PV}}(\Delta P_{PV}) \quad (4)$$

$$\dot{\Delta} P_{WT} = -\frac{1}{T_W}(\Delta P_{wind}) - \frac{1}{T_W}(\Delta P_{WT}) \quad (5)$$

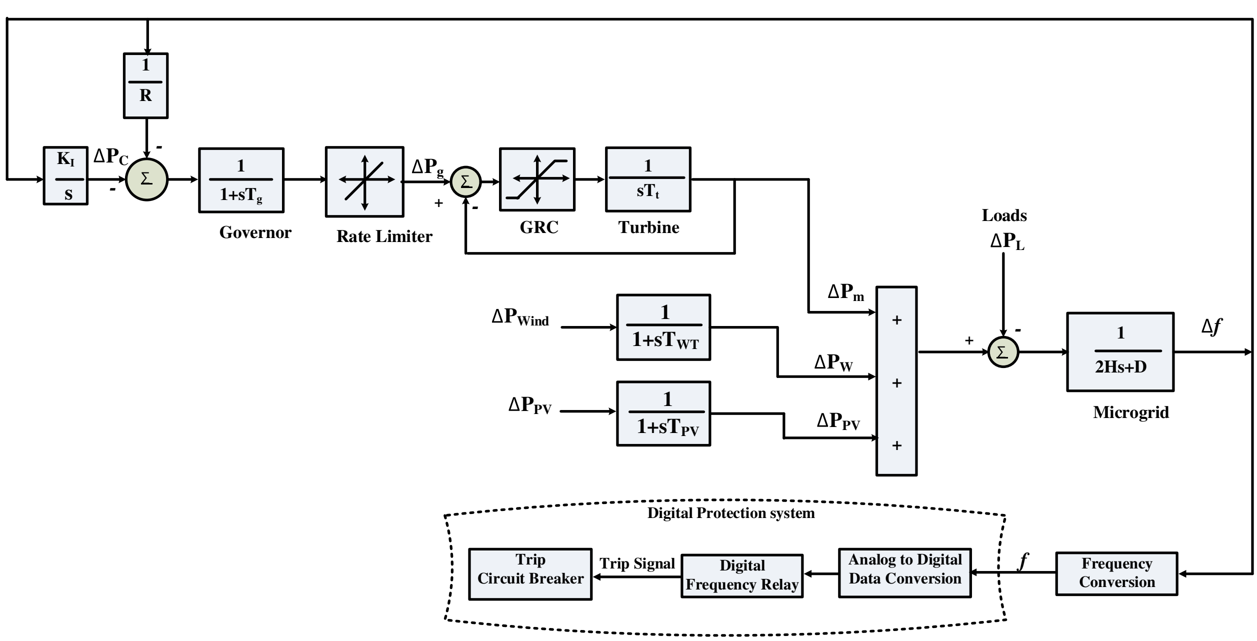

Fig. 3 The dynamic model of the islanded microgrid with the proposed coordination strategy

Table 1 Islanded microgrid parameters

Parameter	Value	Parameter	Value	Parameter	Value
D	0.015	T_{WT}	1.5	V_U	0.3
H	0.083	T_{PV}	1.8	V_L	−0.3
T_g	0.1	K_I	0.05	GRC	20%
T_t	0.4	R	2.4	f	50

The dynamic equations of the studied hybrid power system can be derived and written in the state variable form as follows:

$$\dot{X} = AX + BU + EW \tag{6}$$

$$Y = CX + DU + FW \tag{7}$$

where, ΔP_{wind}, ΔP_{solar}, and ΔP_L are the wind power, solar power, and load power variations, respectively. These variations are considered as the MG disturbance signals. While, the damping (D) and the inertia (H) are the uncertainty parameters. ΔPm is the thermal power deviation, and ΔP_g is the governor power deviation. The complete state-space model of the presented MG considering high RESs penetration level can be obtained through the state variables and definitions from (1) to (7). The linearized state-space model of the MG from Fig. 3 is as in (8) and (9).

4 The proposed coordination strategy

4.1 Frequency control of an islanded microgrid

The power system frequency may have high variations if there is no longer balance between the generation and load demand. The normal frequency deviations can affect the power systems efficiency and reliability, while large deviations can destroy the equipment, overload transmission lines and cause interference with the system protection. Therefore, the frequency control is divided into three main operations based on the size of the frequency deviations. The frequency deviation ranges and their control actions are shown in Table 2. Whereas, the normal frequency deviations up to Δf_1, the power requirement is balanced by attenuating these deviations by the governor natural autonomous, which named primary control. If the frequency deviations more than Δf_1 up to Δf_2, the secondary control (i.e. LFC) must recover the system frequency to its steady-state condition within the limits of standard time deviations. However, in case of large frequency deviations such as Δf_3 and over, which lead to imbalances in active power during the fault periods, the LFC cannot maintain the system frequency. In that situation, the protection devices (i.e. frequency relays) may be activated and trip generators. This action will interrupt power system supply. Hence, there must be an accurate coordination of LFC or emergency control and protection scheme.

Table 2 Frequency and control/protection actions

Frequency deviation	Condition	Action
Δf1 (0.3 Hz)	No contingency or load event	Primary Control
Δf2 (1 Hz)	Generation /Load event	Secondary Control
Δf3 > (2 Hz)	Large Separation event	Protection operation

4.2 Protection scheme

4.2.1 Modelling of digital frequency relay

The frequency relay is a member of the protection devices group. It is used to protect the power system from a blackout in case of load loss, generation loss, or N-1 emergency. Furthermore, it is used in the MG network to detect the islanding operation, which occurs in case of DGs because of losing of mains [30]. Moreover, the main threat occurs when a DG reconnected to the rest of the system without synchronizing operation at first. In the past, DGs are directly disconnected from the system due to over or under frequency problems. Recently, the continuous operation of DGs to supply domestic loads in islanded condition become necessary. Therefore, the use of digital relays has spread and become more widely used in the MGs as the digital relays can change their settings according to the abnormality conditions. Furthermore, recently, there are many applications of digital relays in transmission and generation system protection due to their advantages such as; flexibility, high performance level, and capability of operating under different temperatures compared to the classical electromechanical relays [4, 31]. The digital relay is a basic component in the digital protection system, which includes optical instrument transformer and a digital communication bus as shown in Fig. 4. The current and voltage values are measured by the instrument transformer and sends the discrete-time data obtained from the data conversion system to the digital relay, which processes the data using algorithms such as for over/

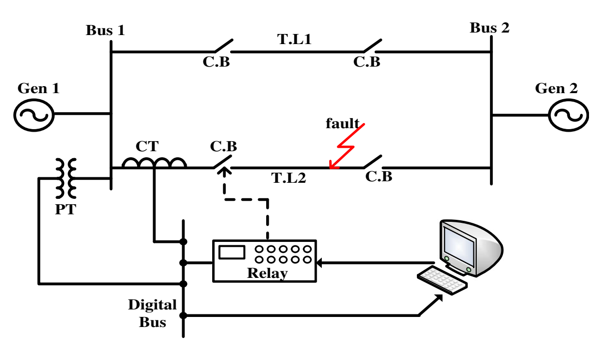

Fig. 4 A simplified digital protection system

under frequency protection and overcurrent protection. When an abnormal condition is detected, the relay trips a circuit breaker and make triggering for an alarm.

$$\dot{X} = \begin{bmatrix} -\frac{D}{2H} & 0 & \frac{1}{2H} & \frac{1}{2H} & \frac{1}{2H} \\ -\frac{1}{RT_g} & -\frac{1}{T_g} & 0 & 0 & 0 \\ 0 & \frac{1}{T_t} & -\frac{1}{T_t} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{WT}} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{PV}} \end{bmatrix} * \begin{bmatrix} \Delta f \\ \Delta P_g \\ \Delta P_m \\ \Delta P_{WT} \\ \Delta P_{PV} \end{bmatrix} + \begin{bmatrix} -\frac{1}{2H} & 0 \\ 0 & \frac{1}{T_g} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} * \begin{bmatrix} \Delta P_L \\ \Delta P_C \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -\frac{1}{T_{WT}} & 0 \\ 0 & -\frac{1}{T_{PV}} \end{bmatrix} * \begin{bmatrix} \Delta P_{wind} \\ \Delta P_{solar} \end{bmatrix} \quad (8)$$

$$Y = [1\ 0\ 0\ 0\ 0] * \begin{bmatrix} \Delta f \\ \Delta P_g \\ \Delta P_m \\ \Delta P_{WT} \\ \Delta P_{PV} \end{bmatrix} + [0\quad 0] * \begin{bmatrix} \Delta P_L \\ \Delta P_C \end{bmatrix} + [0\quad 0] * \begin{bmatrix} \Delta P_{wind} \\ \Delta P_{solar} \end{bmatrix} \quad (9)$$

Considering the islanded MG presented in Fig. 3, at steady state the mechanical power PM of the DGs is balanced with the load power P_d according to swing equation as given in (10). Hence the rotor angle δ and the rotor speed ω of the DG are constant. When a disturbance occurs causing power imbalance, the system frequency starts to deviate due to the transients of DG.

$$\begin{cases} \frac{2H}{\omega_o}\frac{d\omega}{dt} = P_M - P_d = \Delta P_{sys} \\ \frac{d\delta}{dt} = \omega - \omega_o \end{cases} \quad (10)$$

where,

$$\Delta P_M = \Delta P_m + \Delta P_W + \Delta P_{PV} \quad (11)$$

The rotor speed (ω) can be calculate from (10) as:

$$\omega = \frac{\omega_o \Delta P_{sys}}{2H} t + \omega_o \quad (12)$$

By substituting the system angular speed ($\omega = \omega o + \Delta\omega$) in (12):

$$\omega_o + \Delta\omega = \frac{\omega_o \Delta P_{sys}}{2H} t + \omega_o \Rightarrow \quad \Delta\omega = \frac{\omega_o \Delta P_{sys}}{2H} t \quad (13)$$

where, $\omega_o = f_o$, and $\Delta\omega = \Delta f$.

Hence the relationship between the frequency deviations (Δf) for relay setting, the power change ΔP_{sys} and the detection time (t) can be represented by (14).

$$\Delta f = \frac{f_o \Delta P_{sys}}{2H} t \quad (14)$$

The digital OUFR can be adjusted with the integrator (time-delay settings). In this condition, the deviations of system frequency must persist during a pre-defined time interval for energizing the relay. Hence, the delay time setting can present as:

$$t = \frac{2H\Delta f}{f_o \Delta P_{sys}} + K \quad (15)$$

In this study, the digital over/under frequency relay (OUFR) coordinated with the digital LFC to maintain the stability of the MG system as shown in Fig. 3. The digital frequency protection system consists of two main parts; the first part, measures the system frequency and convert it to a discrete-time signal via data conversion unit, and the second part, is a frequency detection element, which sends a tripping action to the circuit breaker in case of under /over frequency as shown in Fig. 5, which is the logic diagram for the digital frequency relay implementation.

4.2.2 Principal operation of digital frequency relay

The implemented digital OUFR model in this study is presented in Fig. 6. Whereas, 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 limit. Then, the integrator output is compared with threshold time (K = 5 s), which is the set value. If the value of the integrator output exceeds the set value, a trip action will occur by the digital relay sent to the circuit breaker to disconnect the variable load or disconnect DG. On the other hand, if the integrator output value doesn't exceed the magnitude K, while the system frequency is out of relay setting. The OUFR does not energize and the digital LFC system will restore the MG stability and readjust the system frequency to (f_0 = 50 Hz). The OUFR setting is given in Table 3 according to the European grid code of islanded mode [29].

The limits of the digital frequency relay are depended on the European codes and could be set to other values

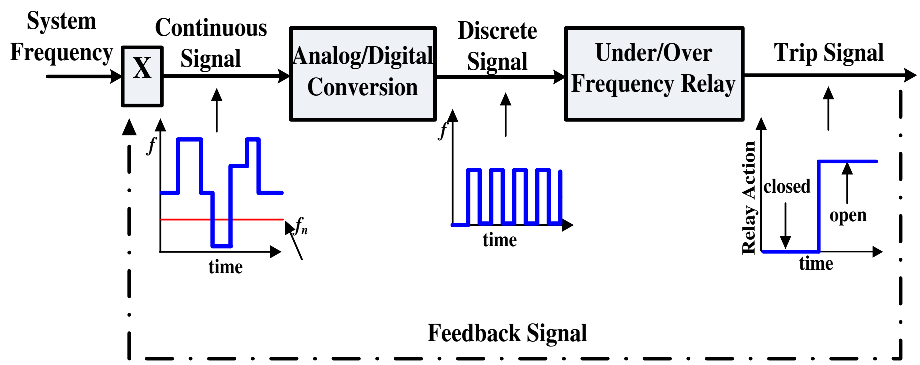

Fig. 5 A simplified block diagram of digital OUFR

based on country standards. The operation of the digital OUFR is concluded in the flowchart in Fig. 7.

5 Results and discussion

The studied islanded MG considering RESs is build using Matlab/ Simulink model. The dynamic response of the studied MG with the proposed coordination strategy is evaluated and tested under variation in loading patterns, loading conditions, system parameters (i.e., system uncertainty), and RESs penetration levels, which are know the important characteristics of an actual MG. The islanded MG is tested in the presence of high fluctuated wind power and low fluctuated solar power as shown in Fig. 8. Whereas, the wind power (i.e., high fluctuated wind power) is connected to the islanded MG at time t = 500 s, while the solar PV power is connected at time t = 0 s. Then, the wind power, solar irradiation power, and load demand are assigned as the disturbance sources to the islanded MG To verify its dynamic security, which is the main target of this research.

To investigate the dynamic security of the islanded MG by using the proposed coordination of LFC and digital OUFR, four scenarios are applied on the MG as follows:

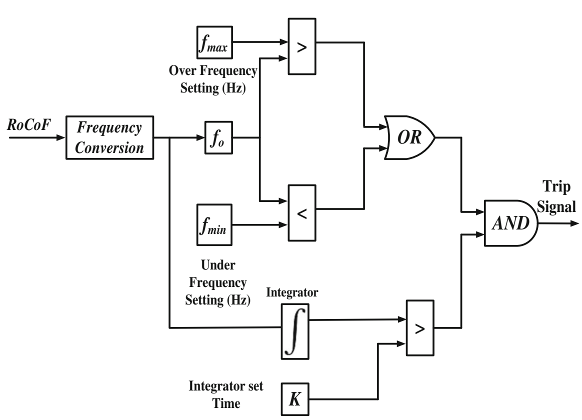

Fig. 6 The computational model of the digital OUFR

5.1 Scenario A

In this scenario, the robustness of the proposed coordination for the dynamic security of the islanded MG is evaluated by implementing the random domestic load variations as shown in Fig. 9(a). In addition, connecting the high fluctuated wind power and low fluctuated solar power at time t = 500 s, t = 0, respectively. In this case, the variation of the system frequency is within the second type of frequency deviations (Δf_2). Figure 9(c) shows the frequency response of the studied islanded MG. Although, the dynamic response fluctuates beyond the allowable frequency limits at 600 s when shedding of a large load, the LFC can readjust the frequency to its normal value and the digital frequency relay does not trip as seen in Fig. 9(b). This is because the integrator output value does not exceed the set value. Therefore, the LFC succeeded to readjust the frequency to its normal value. This scenario proves the effectiveness of the LFC as it can adjust the frequency to its normal value in all five stages of this scenario without needs to protection action.

5.2 Scenario B

In this scenario, the islanded MG is subjected to the power change under different load disturbance profile as shown in Fig. 10(a) as well as the power fluctuations from the wind and the PV power. The LFC can handled the frequency deviations and succeed to maintain the dynamic security of the MG frequency during the first load change at time t = 300 s and connecting of wind farm at 500 s as seen in Fig. 10(c). Hence, there is no need for relay action. On the other hand, the digital LFC was unable to control the

Table 3 Frequency relay settings

Nominal frequency	Frequency relay	Limit	Threshold time
50 Hz	Over	f_{max} = 51 Hz	K = 5 s
	Under	f_{min} = 49 Hz	

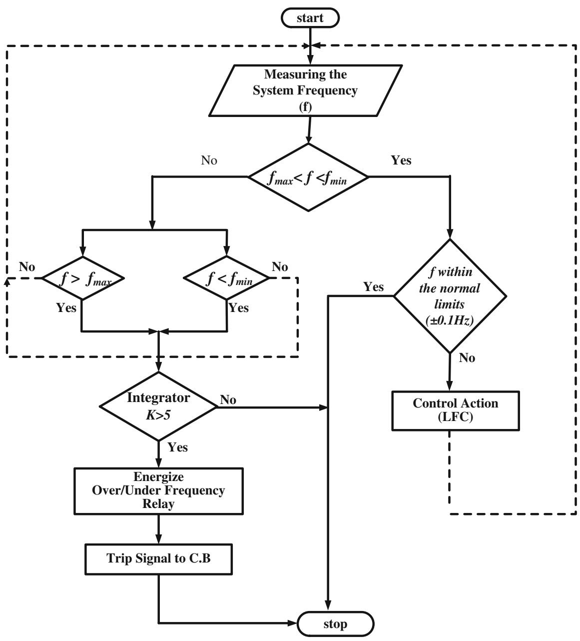

Fig. 7 Flowchart of the proposed coordination

frequency when the heavy load of 40% is applied at time t = 700 s as the system frequency fluctuated out of the given digital relay setting limits. Furthermore, the integrator output exceeds the integrator set time K. Therefore, the digital relay is energized and sending a trip signal to the generator circuit breaker. And then, the action of the digital OUFR is observed in this scenario as shown in Fig. 10(b).

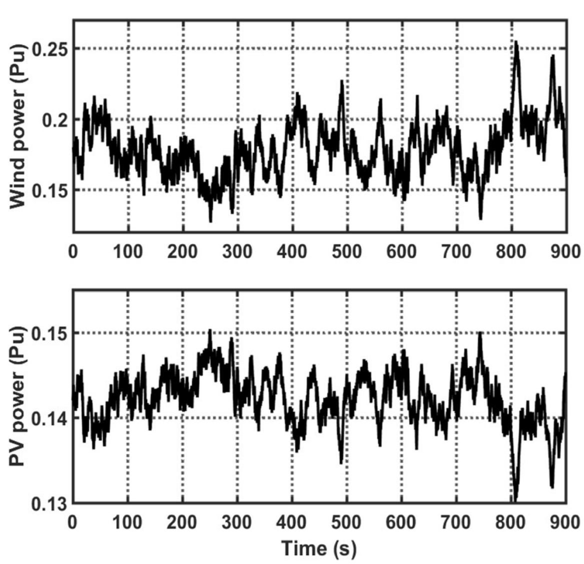

Fig. 8 Multiple disturbances in wind power and solar irradiation power

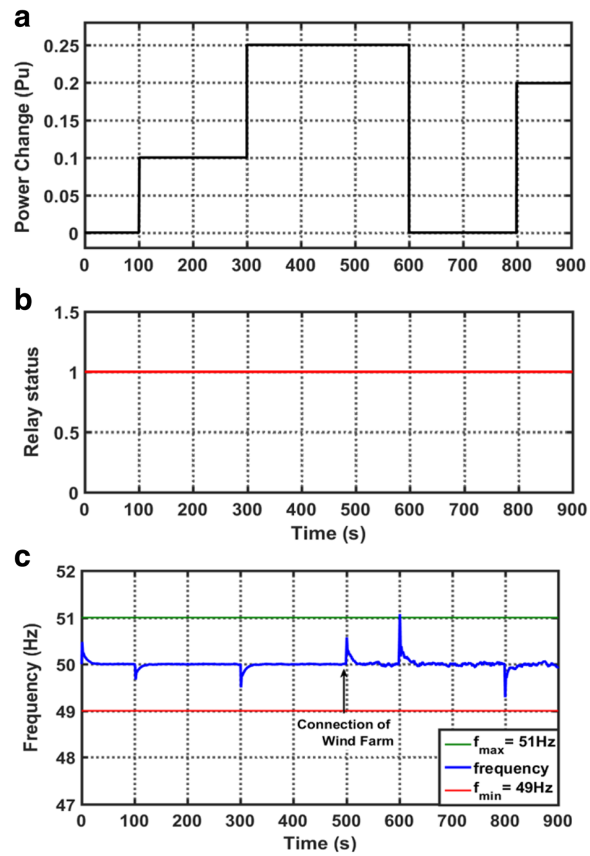

Fig. 9 Case A (**a**) Load disturbance, (**b**) Relay status, (**c**) Frequency response of MG

5.3 Scenario C

In this scenario, the dynamic security of the islanded MG with the proposed coordination strategy is evaluated under variation in wind power penetration levels (i.e., 25%, 30%, and 35% pu), which are tested respectively at time t = 500 s. Moreover, the load disturbance profile of scenario (B) is applied to the studied MG as in Fig. 11(a).

The secondary control (i.e., LFC) can restore the frequency to its steady-state value at the first load disturbance at time t = 300 s, while it cannot withstand the change of system frequency caused by high wind penetration (i.e., 35% pu) as noted in Fig. 11(c). Therefore, the digital OUFR sent a trip signal to the generator circuit breaker at that time as shown in Fig. 11(b), whereas the integrator output exceeds the threshold value of 5 s. Hence, the effectiveness of the proposed coordination is approved for the MG dynamic security.

5.4 Scenario D

The islanded MG is assumed to have the default parameters and the microgrid is estimated under the situation of half of default system inertia (50% of default system inertia) with multiple operation conditions of

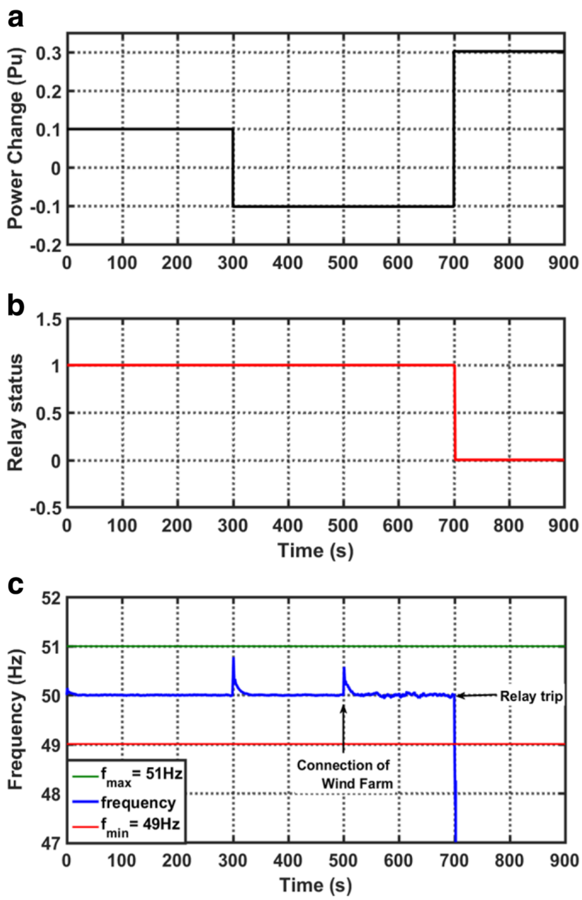

Fig. 10 Case B (**a**) Load disturbance, (**b**) Relay status, (**c**) Frequency response of MG

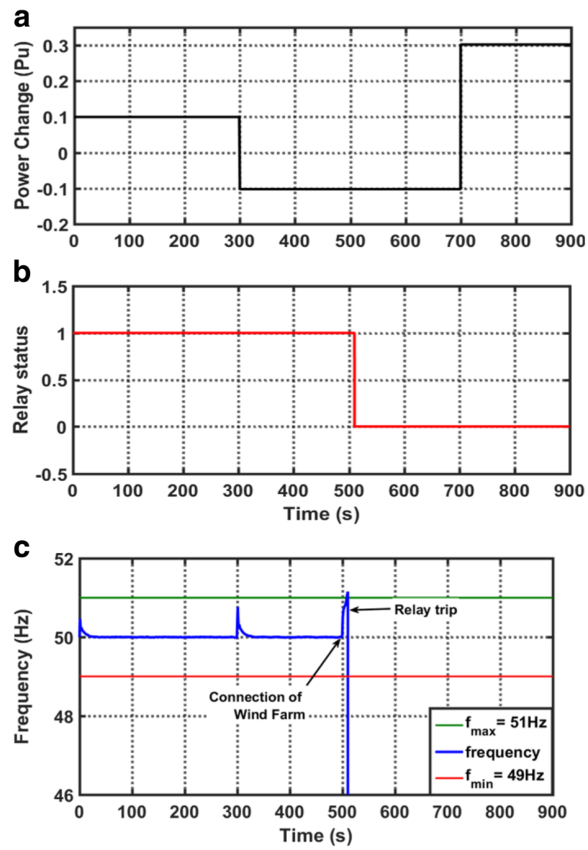

Fig. 11 Case C (**a**) Load disturbance, (**b**) Relay status, (**c**) Frequency response of MG

wind power, PV solar power variations, and load disturbance profile as depicted in Fig. 12(a). The effect of half microgrid inertia through the proposed coordination of LFC and digital OUFR is investigated for the microgrid dynamic security. Figure 12(c) shows the frequency fluctuations of the studied microgrid. Whereas, the LFC could withstand the fluctuations and return the frequency to its nominal value at initial time, and 100 s. However, it fails to restore the system frequency at 300 s with more load shed due to the two conditions for energizing the digital OUFR are achieved, which are the system frequency beyond the allowable frequency control limits, and the integrator output reaches quickly to the threshold value (5 s). Hence, the digital protection device quickly trips the generation units in this scenario to maintain the equipments from damage as shown in Fig. 12(b).

6 Conclusion

This paper proposed a coordination strategy of Load Frequency Control (LFC) and digital Over/Under Frequency Relay (OUFR) protection for an islanded microgrid system security considering high penetration of RESs. This coordination strategy is proposed for supporting the frequency stability and protecting the islanded MG against high-frequency deviations, which increased recently due to high penetration of (RESs), random load variations, and system uncertainty. These changes threaten the MG dynamic security and can cause under/over frequency relaying and disconnect some loads and generations, which may lead to cascading failure and system collapse. The simulations results proved that the proposed coordination has been achieved an effective performance for maintaining the MG dynamic security. Whereas, the LFC has been succeeded to readjust the frequency deviations to its allowable limits under different conditions of transients, load disturbances, and RESs penetration levels. However, in some cases of large disturbances and high RESs penetration, the LFC cannot maintain the frequency stability as the frequency fluctuates beyond the normal limits. In that case, the digital frequency relay trips the generation units. Furthermore, the results confirmed that the digital OUFR has superiority in terms of accuracy, sensitivity and wide range controlling.

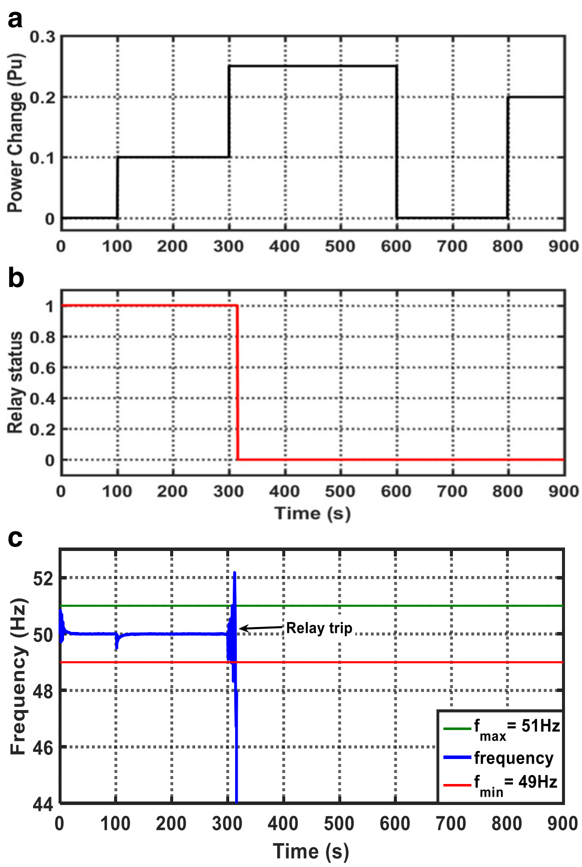

Fig. 12 Case D (**a**) Load disturbance, (**b**) Relay status, (**c**) Frequency response of MG

7 Nomenclature

LFC Load frequency control
MG Microgrid
Δf Frequency deviation of the microgrid (Hz)
D Microgrid damping coefficient (pu MW/Hz)
H Microgrid system inertia (pu MW sec)
T_g Time constant of governor (sec)
T_t Time constant of turbine (sec)
ΔP_C Regulating the system frequency (Hz)
GRC Generation Rate Constraint, % (pu)
R Droop constant (Hz/pu MW)
T_{WT} Time constant of wind turbines (sec)
T_{PV} Time constant of solar system (sec)
RES Renewable energy sources
OUFR Over/Under frequency relay
V_U Maximum limit of valve gate (pu MW)
V_L Minimum limit of valve gate (pu MW)
ΔP_M Change in Mechanical power
δ Rotor Angle
ΔP_d Change in demand power
K_I Integral control variable gain
K Integrator set time
F_{max} Maximum frequency limit
f_{min} Minimum frequency limit
ω_o Synchronous speed

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Authors' contributions
Emad Mohamed carried out the all simulation analysis, the design of the digital frequency relay, and wrote the paper. Gaber Magdy helped in the control part of load frequency control for the microgrid system. Gaber Shabib participated in the sequence alignment and renewable energy sources specifications. Adel Abdelbasit participated in some statistical analysis like the state space modeling of the islanded microgrid. Yasunori Mitani conceived of the study, and participated in its design and coordination and revised the draft of the manuscript. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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