Digital coordination strategy of protection and frequency stability for an isolated microgrid

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Abstract: This study presents a digital coordination strategy of load frequency control and over/under-frequency relay (OUFR) protection for an isolated microgrid (MG) considering high penetration of renewable energy sources (RESSs). In such MGs, the reduction in system inertia due to the replacement of traditional generating units with a large amount of RESs causes undesirable influence to MG frequency stability, leading to weakening of the MG. Furthermore, sudden load shedding, load restoring, 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. In order to handle these challenges, this study proposes a specific design of the digital OUFR, which will operate for both conditions of over- and under-frequency in coordination with digital proportional–integration–derivative controller based on mapping technique in discretisation process to protect the MG against high-frequency variations. To prove the effectiveness of the proposed digital coordination strategy, a small MG was investigated for the simulation considering load change and high integration of photovoltaic and wind farm. Moreover, the sensitivity analysis of the presented technique was examined by varying the penetration level of RESs and the system inertia. The results reveal the robustness of the proposed coordination to maintain the MG frequency stability and security. In addition, the superiority of the digital OUFR has been approved in terms of accuracy and speed response during high disturbances.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Δf</td>
<td>frequency deviation of the microgrid, Hz</td>
</tr>
<tr>
<td>D</td>
<td>microgrid damping coefficient, p.u. MW/Hz</td>
</tr>
<tr>
<td>H</td>
<td>microgrid system inertia, p.u. MW s</td>
</tr>
<tr>
<td>Tg</td>
<td>time constant of governor, s</td>
</tr>
<tr>
<td>Ti</td>
<td>time constant of turbine, s</td>
</tr>
<tr>
<td>ΔPc</td>
<td>regulating the system frequency, Hz</td>
</tr>
<tr>
<td>GRC</td>
<td>generation rate constraint, %, p.u.</td>
</tr>
<tr>
<td>R</td>
<td>droop constant, Hz/p.u. MW</td>
</tr>
<tr>
<td>TW</td>
<td>time constant of wind turbines, s</td>
</tr>
<tr>
<td>PV</td>
<td>time constant of solar system, s</td>
</tr>
<tr>
<td>VU</td>
<td>maximum limit of valve gate, p.u. MW</td>
</tr>
<tr>
<td>VL</td>
<td>minimum limit of valve gate, p.u. MW</td>
</tr>
<tr>
<td>oα</td>
<td>synchronous speed</td>
</tr>
<tr>
<td>ΔPM</td>
<td>change in mechanical power</td>
</tr>
<tr>
<td>δ</td>
<td>rotor angle</td>
</tr>
<tr>
<td>ΔPd</td>
<td>change in demand power</td>
</tr>
<tr>
<td>Kg</td>
<td>proportional control variable gain</td>
</tr>
<tr>
<td>Ki</td>
<td>integral control variable gain</td>
</tr>
<tr>
<td>KD</td>
<td>derivative control variable gain</td>
</tr>
<tr>
<td>K</td>
<td>integrator threshold time</td>
</tr>
<tr>
<td>fmax</td>
<td>maximum frequency limit</td>
</tr>
<tr>
<td>fmin</td>
<td>minimum frequency limit</td>
</tr>
</tbody>
</table>

1 Introduction

In past, several cascaded blackouts happened in electrical power systems due to frequency instability in the case of the imbalance between the electrical load and power supply or N−1 contingency [1]. Nowadays, this problem increased after the growth of renewable energy sources (RESSs) which have several impacts on the performance of the isolated microgrids (MGs) such as the reduction in system inertia. Consequently, it increases the voltage and frequency fluctuations [2]. Furthermore, the RESs exchange electrical power to MGs through power electronic inverters, which cause higher power fluctuations than the traditional synchronous generators. Therefore, if the RESs penetration becomes larger, the isolated MGs might become insecure as the stabilising in system frequency and voltage is difficult in that situation [3, 4]. Moreover, there will be unbalance between the generation and load due to the variable nature of RESs. These changes lead to the appearance of high-integration of photovoltaic and wind farm. Moreover, frequency and voltage is difficult in that situation [3, 4]. Furthermore, there will be unbalance between the generation and load due to the variable nature of RESs. These changes lead to the appearance of high-frequency variations. To prove the effectiveness of the proposed digital coordination strategy, a small MG was investigated for the simulation considering load change and high integration of photovoltaic and wind farm. Moreover, the sensitivity analysis of the presented technique was examined by varying the penetration level of RESs and the system inertia. The results reveal the robustness of the proposed coordination to maintain the MG frequency stability and security. In addition, the superiority of the digital OUFR has been approved in terms of accuracy and speed response during high disturbances.
controllers become more appealing to replace analogue controllers in different power systems. Using digital control systems reduces the implementation cost and increase the reliability of control system [10]. Therefore, many digital devices have been used in electrical power systems such as digital proportional–integration–derivative (PID) controller, digital power system stabiliser (PSS), digital automatic voltage regulator, and digital protection devices, i.e. digital over/under frequency relay (OUFR). There are two approaches for designing digital control systems [11]. The first one is the direct digital design approach, which converts the analogue plant to discrete and then defines a digital controller for the discretised plant. The second approach is the digital redesigns approach [12, 13], which designs a good analogue controller for the analogue plant and then carry out the digital redesign for the good designed analogue controller. This paper is focusing on the second approach, which is indirect design approach due to: (i) it is more realistic to carry out the design of the continuous-time controller, and (ii) it is easy for selecting the sampling time which can be selected after defining the continuous-time closed loop bandwidth.

According to the most recent researches, frequency regulation issue of an islanded MGs utilises several types of control strategies: such as conventional controller with different algorithms and optimisation techniques [14, 15], intelligent control, i.e. fuzzy logic control [16, 17], and robust control [18, 19]. Tang et al. [20] proposed a novel technique of frequency control, which is \( \frac{V}{f} \) droop control and \( \frac{P}{Q} \) droop control combined for islanded MG based on different energy storage devices. While, Sedghi and Fakharian [21] used the coordination of robust control and fuzzy technique to address the studied issue in [20]. Model predictive control (MPC)-based load frequency control (LFC) for MG based on the coordination of wind turbine and plug-in hybrid electric vehicles (PHEVs) is proposed in [22] by Pahasa and Ngamroo. While, application of discrete-time controllers to power system was reported in several types of research [23–27]. Shabib and Hori [23] presented a discrete-time model of continuous-time PSS for the transient stability of single machine infinite bus utilising Tustin’s discretisation method. However, this model of digital PSS withstands the large disturbances for small sampling intervals, which needs to hardware devices with a high cost. Rafiee et al. [24] applied a new digital redesign approach for the conventional PSS discretisation based on the optimal matching of the continuous-time closed loop. The new approach which is used in [24] is called plant input mapping (PIM) method. Whereas the optimisation problem is solved by sampled data control theory. Moreover, Shabib et al. [25, 26] used the same technique for discretisation continuous-time conventional controllers for a single machine power system to guarantee the stability of any sampling rate. While Rabahch and Hori [27] modified this technique to reduce the order of PIM controllers for making it a global digital design method. However, the main drawback of the PIM controller design which was used in [24–27] is depending on the model of the studied power system.

On the other hand, several studies have dealt this problem from the short-circuit fault side only, such as the optimised time-based coordination of conventional over-current relays; which is the earliest protection technique for utility grids including MGs [28]. 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. [29] presented a multi-agent method depending 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 the distributed generations (DGs) for faults within the MG. Furthermore, some studies handled the frequency protection problems such as relay coordination did not compensate the frequency fluctuations within the allowable frequency limit. Such a problem can be overcome by designing the proposed coordination of frequency stability using digital LFC and digital OUFR.

This paper will present the design of digital OUFR coordinated with the digital LFC for a small MG system, which consists 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 load shedding/restoring. The rest of this paper is organised as follows: Section 2 discusses the problem description. The structure of the studied MG system with the state equations is 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 description

Since the power generation from RESs is unpredictable and variable, results in more fluctuations in power flow and frequency in the MG, which significantly affects the power system operation. Therefore, the high penetration of RESs makes the situation in MG worse because of the low inertia and small time constant of the system; consequently, creating a difficulty in stabilising system frequency and voltage, causing the weakening of MG stability and resiliency. Moreover, the randomly changes in load power demand caused a bad response to the point of common coupling voltage, active, and reactive powers transfer. Hence, a severe frequency deviation in the presence of high RESs power fluctuations has an adverse impact on the control performance parameters and may cause energising of under/over-frequency relay and disconnect some loads and generation parts of the MG system. Therefore, the stability and protection coordination issues have become a centre of interest, especially for power system researchers.

3 System configuration

3.1 Structure of MG

The MG is a small power system, which contains DG units, 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), hydro units, fuel cells etc. This research focuses on the isolated MG (base of 20 MW), which includes 15 MW of domestic loads, 20 MW of thermal power plant, 6 MW of a wind farm, and 4.5 MW of a solar farm as shown in Fig. 1.

In this study, the effects of the physical constraints such as generation rate constraints (GRC) of power plant and speed governor dead band (blackash) are taken into consideration for modelling the actual islanded MG. Whereas blackash is defined as the total magnitude of sustained speed change. All speed governors have a blackash, which is important for primary frequency control in the presence of disturbances. The GRC limits the generation rate of output power which is given as 0.2 p.u. MW/min for the non-reheat power plant. The \( P_U \) and \( P_L \) are the maximum and minimum limits that restrict the rate of the valve-gate closing or opening speed [18]. In this research, the power variation of RESs such as the wind power variation (\( \Delta P_{\text{wind}} \)) and the PV solar power variation (\( \Delta P_{\text{PV}} \)), and the load power variation (\( \Delta P_L \)) are considered as disturbance signals for islanded MG. The dynamic model of the studied MG system is shown in Fig. 2. The MG nominal parameters values are shown in Table 1.
3.2 Mathematical model of the islanded MG

The different subsystems of the islanded MG in Fig. 2 can be described below.

3.2.1 Governor model: The speed governor adjusts the turbine gate to return the frequency to its nominal value. The governor is modelled by a first-order function of a unity gain and time constant ($T_g$)

$$TF_g = \frac{K_g}{1 + sT_g}$$  \hspace{1cm} (1)

where the governor with speed-droop ($1/R$) represents the primary frequency control of governor action.

3.2.2 Turbine model: The turbine model considered in this study is a steam turbine, which represents a first-order transfer function as this relation:

$$TF_t = \frac{1}{1 + sT_t}$$  \hspace{1cm} (2)

In order to get an accurate perception of the actual MG, this paper considers the non-linear model; that is considering various effects of physical system dynamics, including the GRC and maximum/minimum turbine limits [2].

### Table 1  Islanded MG parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>0.015</td>
<td>$T_{PV}$</td>
<td>1.8</td>
</tr>
<tr>
<td>$h$</td>
<td>0.083</td>
<td>$R$</td>
<td>204</td>
</tr>
<tr>
<td>$T_g$</td>
<td>0.1</td>
<td>GRC</td>
<td>20%</td>
</tr>
<tr>
<td>$T_l$</td>
<td>0.4</td>
<td>$V_U$</td>
<td>0.3</td>
</tr>
<tr>
<td>$T_{WT}$</td>
<td>1.5</td>
<td>$V_L$</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

Fig. 1 Islanded MG system with digital coordination strategy

Fig. 2 Dynamic model of the islanded MG with the proposed coordination
3.2.3 Rotating mass and load: This block represents the machine mechanically dynamic loop, which is modelled by a first-order transfer function of a system inertia constant \( (H) \) and damping coefficient \( (D) \) as seen in the following equation:

\[
TF_e = \frac{\Delta P}{2H + D}
\]  

(3)

3.2.4 Wind power system: This study uses an aggregated model to form the wind farm as large capacity induction generator. The generator is modelled by a given first-order lag transfer function with a unity gain and time constant \( (T_{WT}) \), neglecting all nonlinearities, as given below:

\[
TF_{WTO} = \frac{\Delta P_w}{\Delta P_{Wwind}} = \frac{1}{1 + sT_{WT}}
\]  

(4)

3.2.5 Solar PV system: The model of solar power is presented as a disturbance source to the islanded MG. Therefore, it is modelled by a simple linear first-order lag of a unity gain and time constant \( (T_{PV}) \):

\[
TF_{PV} = \frac{\Delta P_{PV}}{\Delta P_{solar}} = \frac{1}{1 + sT_{PV}}
\]  

(5)

Hence, the overall generator–load dynamic relation between the net power and the frequency deviation \( (\Delta f) \) can be obtained as

\[
\dot{\Delta f} = \frac{1}{2H}(\Delta P_m + \Delta P_{PV} + \Delta P_{WT} - \Delta P_L) - \frac{D}{2H} \ast \Delta f
\]  

(6)

where

\[
\dot{\Delta P}_g = -\frac{1}{T_g} (\Delta P_g) - \frac{1}{T_{ WT}} \ast \Delta f + \frac{1}{T_{ PV}} (\Delta P_c)
\]  

(7)

\[
\dot{\Delta P}_m = -\frac{1}{T_i} (\Delta P_m) + \frac{1}{T_i} (\Delta P_c)
\]  

(8)

\[
\dot{\Delta P}_{PV} = -\frac{1}{T_{PV}} (\Delta P_{solar}) - \frac{1}{T_{PV}} (\Delta P_{PV})
\]  

(9)

\[
\dot{\Delta P}_{WT} = -\frac{1}{T_w} (\Delta P_{wind}) - \frac{1}{T_w} (\Delta P_{WT})
\]  

(10)

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

\[
\dot{X} = AX + BU + EW
\]  

(11)

\[
Y = CX + DU + FW
\]  

(12)

where \( \Delta P_{wind}, \Delta P_{solar}, \) and \( \Delta P_L \) are the wind power variation, solar power variation, and load power variation, respectively. These variations are considered as the MG disturbance signals. While the damping \( (D) \) and the inertia \( (H) \) are the uncertainty parameters. \( \Delta f \) is the frequency deviation, \( \Delta P_m \) is the thermal power deviation, and \( \Delta P_g \) 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 (4) to (10). The linearised state-space model of the MG from Fig. 2 is as in (13) and (14)
difference method, (ii) backward difference method, and (iii) bilinear transformation method or in practice, called Tustin’s method [34]. This study focuses on the last approach due to its advantages compared to other approaches such as easy for implementation and convergence to analogue one. Moreover, in this technique, the left-hand side of the S-plane is mapped within the unit circle in the Z-plane. The discrete-time PID controller approximation is obtained for the transfer function of continuous-time PID controller simply by replacing S-domain to Z-domain, according to this relation

\[
s = \frac{1}{T} \ln z = \frac{z - 1}{T/2(z + 1)}
\]

where \( T \) is the sampling interval of the discrete-time system, which is selected as \( T = 0.01 \) s for this study. The design parameters of the digital PID controller are given in Table 3.

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 the case of load/generation loss, or \( N-1 \) emergency. Furthermore, it is used in the MG network to detect the islanding operation, which occurs in the case of DGs because of losing of mains [35]. Moreover, the main threat occurs when a DG reconnected to the rest of the system without synchronising 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 becomes necessary. Therefore, the use of digital relays has spread and become more widely used in 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 [4] flexibility, high-performance level, and capability of operating under different temperatures compared to the classical electromechanical relays [36]. The digital relay is a basic component of the digital protection system, which includes optical instrument transformer and a digital communication bus as shown in Fig. 3. The current and voltage values are measured by the instrument transformer, and send the discrete-time data obtained from the data conversion system to the digital relay, which processes the data using algorithms such as for over/under-frequency protection and overcurrent protection. When an abnormal condition is detected, the relay trips a circuit breaker.

Considering the islanded MG presented in Fig. 2, at steady state, the mechanical power \( P_M \) of the DGs is balanced with the load power \( P_L \) according to swing equation as given in (16). Hence, the rotor angle \( \delta \) and the rotor speed \( \omega \) of DG are constant. When a disturbance occurs causing power imbalance, the system frequency starts to deviate due to the transients of DG

\[
\frac{2H}{\omega_0} \frac{d\omega}{dt} = P_M - P_d = \Delta P_{sys}
\]

where

\[
\Delta P_M = \Delta P_{in} + \Delta P_W + \Delta P_{PV}
\]

The rotor speed \( \omega \) can be calculated from (16) as

\[
\omega = \frac{\omega_0 \Delta P_{sys}}{2H} + \omega_0
\]

By substituting the system angular speed \( \omega = \omega_0 + \Delta \omega \) in (18):

\[
\omega_0 + \Delta \omega = \frac{\omega_0 \Delta P_{sys}}{2H} + \omega_0 \Rightarrow \Delta \omega = \frac{\omega_0 \Delta P_{sys}}{2H}
\]

Hence, the relationship between the frequency deviations (\( \Delta f \)) for relay setting, the power change \( \Delta P_{sys} \), and the detection time (\( t \)) can be represented by the following equation:

\[
\Delta f = \frac{f_0 \Delta P_{sys}}{2H}
\]

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 energising the relay. Hence, the delay time setting can present as

\[
t = \frac{2H \Delta f}{f_0 \Delta P_{sys}} + K
\]

The digital frequency protection system consists of two main parts: the first part, measures the system frequency and converts 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 the case of under/over-frequency as shown in Fig. 4 of the logic diagram for the digital frequency relay, which can be implemented by using microprocessor-based technology. Therefore, the presented OUFR is considered a simple intelligent electronic device (IED) as it combines the main functions of protection, control, monitoring, metering, and communications [37].

4.2.2 Principal operation of digital frequency relay: The implemented digital OUFR model in this study is presented in Fig. 5. 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 \( \tau \), which is the set value. If the value of the integrator output exceeds the set value, a trip action will occur by

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Frequency operation and control/protection actions</th>
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<tbody>
<tr>
<td>Frequency deviation</td>
<td>Condition</td>
</tr>
<tr>
<td>( \Delta f_1 ) (0.3 Hz)</td>
<td>no contingency or load event</td>
</tr>
<tr>
<td>( \Delta f_2 ) (1 Hz)</td>
<td>generation/load event</td>
</tr>
<tr>
<td>( \Delta f_3 &gt; (2 \text{ Hz}) )</td>
<td>large separation event</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>PID controller’s parameters for the MG</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID parameters</td>
<td>( K_p )</td>
</tr>
<tr>
<td>( 9.68204 )</td>
<td>( 0.806941 )</td>
</tr>
</tbody>
</table>
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 does not exceed the magnitude $K$, while the system frequency is out of relay setting. The OUFR does not energise and the digital LFC system will restore the MG stability and readjust the system frequency to $(f_o = 50\,\text{Hz})$. The OUFR setting is given in Table 4 according to the European grid code of islanded mode and could be set to other values based on country standards [38]. The operation of the digital OUFR is concluded in the flowchart in Fig. 6.

5 Results and discussion

The proposed digital coordination of LFC and OUFR protection is tested on the single-line diagram of the islanded MG in Fig. 7 under the nature variety RESs, random load variation, and system parameters variations, which are known to be the important characteristics of an actual MG. The simulation results and analysis of the islanded MG frequency during multiple changes in WPG, solar power, domestic loads (i.e. disturbances), system inertia, and parameters (i.e. uncertainties) are carried out using the MATLAB/Simulink. The wind power of a 25% (5 MW) from the system base is integrated to the islanded MG at 500 s, while the PV solar power of 15% (3 MW) from the system base is connected from the initial time. The islanded MG is tested in the presence of high fluctuated wind power and low fluctuated solar power shown in Fig. 8 for a simulation time of 15 min.

To investigate the effectiveness of the proposed digital coordination on the islanded MG frequency response, five several scenarios are applied on the MG as described below.
5.1 Scenario A

In this scenario, the effectiveness of the proposed digital coordination for the islanded MG is evaluated by implementing the random domestic load variations as shown in Fig. 9a. In addition to connecting the high fluctuated wind power and low fluctuated solar power. In this case, the variation of the system frequency is the second type of frequency deviation ($\Delta f_2$) and within the limits of the digital relay. The digital frequency relay does not trip as seen in Fig. 9b due to the integrator output value does not exceed the set value. Therefore, the digital LFC succeeded to readjust the frequency to its normal value as shown in Fig. 9c. This case proves the effectiveness of the digital LFC as it can adjust the frequency to its normal value in all five stages of this scenario without need to protection action.

5.2 Scenario B

In this scenario, the MG system is subjected to the power change under different load disturbance profiles as shown in Fig. 10a besides the power fluctuations from wind and PV sources. The digital LFC can handle the frequency deviations and succeed to restore the MG frequency to its normal value during the first load change at 300 s and the instant of wind farm connection at 500 s as seen in Fig. 10c. Hence, there is no need for relay action. On the other hand, the digital LFC was unable to control the frequency when the heavy load of 40% is applied at 700 s as the system frequency fluctuated beyond the digital relay setting limits. In addition, the integrator output exceeds the integrator set time $K$. Therefore, the digital relay is energised and sending a trip signal to the generator circuit breaker in this case as shown in Fig. 10b.

5.3 Scenario C

In this case, the islanded MG behaviour is tested implementing the same profile of load disturbance as the previous scenario as
depicted in Fig. 11a. However, the penetration of wind power increased to 35% (7 MW) from the system base. It integrated to the MG at 500 s. The digital LFC has the ability to control and restore the frequency to its steady-state value at the first load disturbance at 300 s, while it cannot withstand the change of system frequency caused by high wind penetration at 500 s as noted in Fig. 11c. Hence, the digital OUFR sent a trip signal to the generator circuit breaker at that time as shown in Fig. 11b, whereas the integrator output exceeds the threshold value of 5 s. Hence, the effectiveness of the proposed coordination is approved.

5.4 Scenario D

To evaluate the behaviour of the MG under the system uncertainties, the MG is tested under the situation of half of the system inertia (50% of the default value) with multiple operating conditions of wind power and PV power, and load disturbance profile as shown in Fig. 12a. The effect of half system inertia through the proposed digital coordination of LFC and OUFR is investigated. The frequency fluctuations increased in this case with high deviation as depicted in Fig. 12c. Although the frequency deviations are not within the allowable frequency limits at 500, 600, and 800 s, respectively, the digital LFC can readjust the frequency to its normal value. This happens due to the value of the integrator output does not exceed the threshold value. Hence, the digital LFC action returned the frequency to the nominal value without interfering the digital protection side as seen in Fig. 12b.

5.5 Scenario E

The effectiveness of the proposed digital coordination is approved in this extreme scenario. Whereas the MG system inertia behaviour is tested by implementing the same profile of load disturbance as the previous scenario as depicted in Fig. 13a. Moreover, the MG system inertia is decreased (40% of the default system inertia), with the same conditions of wind power and PV solar power variations.

The digital LFC can withstand the fluctuations and return the frequency to its nominal value at 100, 300, and 500 s, respectively, as shown in Fig. 13c of the MG frequency response. However, it failed to restore the system frequency in the fourth stage at 600 s with more load shed due to the two conditions for energising the OUFR are achieved; the system frequency is beyond the allowable frequency control limits and the integrator output reaches quickly to the threshold value (5 s). Hence, the digital frequency relay trips quickly in this scenario to maintain the equipment from damage as shown in Fig. 13b.

6 Conclusion

This paper proposed a digital coordination strategy of LFC-based mapping technique and OUFR protection for an islanded MG system security considering high penetration of RESs. This coordination strategy is proposed for supporting the frequency stability and protecting the isolated MG against high-frequency deviations, which increased recently due to the high penetration of RESs, random load variations, and system uncertainty. These changes threaten the MG system security and can lead to cascading outages.

The simulation results proved that the proposed digital coordination of LFC and frequency relay has achieved an effective performance for maintaining the system frequency at nominal value. Whereas the digital LFC succeeded to readjust the frequency deviations to its allowable limits under different conditions of transients, load disturbances, and RESs penetration. However, in some cases of large disturbances and high RESs penetration, the
digital LFC cannot maintain the frequency stability as the frequency fluctuates beyond the normal limits. In that case, the digital frequency relay will trip the generation unit. Furthermore, the results confirmed that the digital OUFR has superiority in terms of accuracy, sensitivity, and wide range controlling.

7 References
