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A new technique for islanding operation of distribution network connected with mini hydro*

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Abstract: An islanding operation of a distribution network is a topic of interest due to the significant penetration of distributed generation (DG) in a power system network. However, controlling the frequency of an islanded distribution system remains an unresolved issue, especially when the load exceeds the generation. This paper presents a new technique for a successful islanding operation of a distribution network connected with multiple mini hydro based DGs. The proposed technique is based on three main parts. The first part uses an islanding detection technique to detect the islanding event correctly. The second part consists of a power imbalance estimation module (PIEM), which determines the power imbalance between the generation and load demand. The third part consists of a load shedding controller, which receives the power imbalance value and performs load shedding according to load priority. The proposed technique is validated on an 11 kV existing Malaysia distribution network. The simulation results show that the proposed technique is effective in performing a successful islanding operation by shedding a significant number of loads.

Key words: Islanding operation, Mini hydro, Distributed generation (DG), Islanding detection, Load shedding
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1 Introduction

The popularity of distributed generation (DG) has been rapidly increasing over the last decade due to exponential growth in electricity demand and environmental pollution (Golkar and Hajizadeh, 2009; Silva *et al.*, 2012; Ebrahimi *et al.*, 2013; Cheng *et al.*, 2014). Currently, DG has been widely employed as an alternative option for electric power generation, both from power quality and system reliability perspectives. In fact, many power utilities around the world possess significant DG penetration in their distribution networks; e.g., the United States has increased its DG capacity from 9579 MW in 2004 to 22 636 MW in 2008 (EIA, 2009), while the UK has increased its installed DG capacity from 1.2 GW in 1994 to over 12 GW in 2008 (Jenkins *et al.*, 2010). The World Alliance for Decentralized Energy (WADE) presented in its report that in 2004 various developed and developing countries had a significant amount of DG penetration in their distribution networks, varying from 8.9% in Australia to 36% in Germany (WADE, 2006). In addition to this installed DG capacity, the

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countries and utilities are setting up their targets for the future to install DGs. The European Union had set a target to replace 20% of the electricity generated from fossil fuels with renewable energy sources by 2020 (European Union Commission, 2005). In this regard, Malaysia has also set a target to use 6% renewable energy by the end of 2015 and 11% by the end of 2020 (Hashim and Ho, 2011). This increasing interest in renewable energy generation is also supporting DG penetration in the utilities.

A DG is available from different sources, which provide the customers with a wide range of costs and reliability. A DG technology commonly consists of small-scale power generating resources, like small gas turbines, micro turbines, a mini hydro, bio-mass, wind, photovoltaic and fuel cells. A mini hydro power plant (MHPP) based DG is a cost-effective and environment friendly resource for rural electrification schemes (Laghari *et al.*, 2014). Despite all these advantages, the increasing trend of DG penetration in the power system network requires the system configuration to be changed. To fully use the benefits of DGs, certain technical issues need to be addressed, such as islanding detection and control of voltage and frequency. Among them, the islanding condition is one of the most important issues in this context. Islanding is a situation where the distribution network looses grid connection, yet continues to be supplied by the DG connected to it. When islanding occurs in a distribution network, voltage and frequency are severely disturbed due to imbalance between generation and load demand (Walling and Miller, 2002). Furthermore, islanding may cause potential damage to existing equipment, utility liability concerns, and reduction of power reliability and power quality**.**

Due to the above severe consequences of islanding, IEEE Std 929-2000 (IEEE, 2000) has stated that islanding should be prevented and in case of islanding, the DG should detect and disconnect itself from the distribution network within 2 s. However, the benefits of DG will not be fully used if the DG always needs to be disconnected after islanding. With the significant penetration of DG and the expected high penetration level in the near future, the operation of a distribution network in islanded mode will be inevitable. Furthermore, implanting an intentional islanding operation of a distribution network will not only maximize the benefit of DG but also help to improve the reliability of supply to customers. The islanding operation of a distribution network may reduce the congestion of a transmission and distribution network, improve the overall system performance by reducing the power losses, and improve the voltage profiles (AlRashidi and AlHajri, 2011; Biswas *et al.*, 2012). Hence, the islanding operation of a distribution network may be a viable option, provided that the various issues related to it are properly addressed.

When unintentional islanding occurs, the distribution network is disconnected from the main grid through a circuit breaker operation. The islanding area can be based on a substation, and one or more distribution feeders. After islanding identification, the power generation must be capable of maintaining stability, reliability, and power quality, ensuring customers voltage and frequency in an acceptable range. Otherwise, it may cause the islanded network to experience blackouts. In case of unintentional islanding, intentional or controlled islanding may be used as a preventive strategy to minimize the losses caused by unintentional islanding (Aghamohammadi and Shahmohammadi, 2012). Intentional islanding is the process of intentionally splitting the grid into separate controllable islands (Pahwa *et al.*, 2013). In such a situation, each island region should have sufficient generation to supply its loads in order to remain operative.

Realizing the benefit of intentional islanding, the IEEE 1547 group has developed a draft series of guides referred to as the 'P1547.4 Draft Guide for Design, Operation and Integration of a Distributed Resource Island System' with an electric power system (Basso and DeBlasio, 2004). This document will serve as a guide for practicing an intentional islanding operation in an electric power system. In addition to this draft, several other international standards have been developed that can be used as guidelines by utilities or independent power producers (IPPs) to perform an intentional islanding operation within an electrical power system, such as IEEE Std 929-2000.i, IEEE Std 242-2001, UL 1741, and IEEE Std C37.95-2002 (IEEE, 2000; 2001; 2002; UL, 2001). In this regard, there have been research efforts in intentional islanding operations. Several studies have been performed for the feasibility of islanding operations of different countries or regions, such as the United

Kingdom (Chowdhury *et al.*, 2011), Carolina (Gooding *et al.*, 2014), Thailand (Fuangfoo *et al.*, 2007), India (Joshi and Pindoriya, 2013), Colombia (Carvajal Quintero *et al.*, 2012), Brazil (Londero *et al.*, 2010), and Denmark (Chen *et al.*, 2008).

For a successful islanding operation of a distribution network connected with DG, two important issues are required. The first step would be to detect the islanding phenomenon. This requires an efficient islanding detection technique to detect the islanding event in order to operate the DG in islanding mode. This issue is very important, as failing to accurately detect islanding may cause failure in the operation of the whole distribution network. Secondly, during islanding, when a distribution system operating at maximum power is islanded, the frequency will go down if the total load is more than the total generation. Hence, an efficient load shedding technique is required to shed an optimal amount of load in order to stabilize the frequency. The under frequency load shedding (UFLS) technique is commonly applied to avoid this blackout (Vasquez-Arnez *et al.*, 2014). In such a situation, optimal load shedding is important for a successful islanding operation, because the improper and non-optimal load shedding based on conventional UFLS techniques has led to a high number of power blackouts (Laghari *et al.*, 2013a). In this paper we use the islanding detection technique and propose an adaptive load shedding technique to perform load shedding, in order to stabilize the frequency to its nominal value during the islanding operation.

2 Methodology

2.1 Description of the proposed technique

The description of the proposed technique is illustrated in Fig. 1.

The proposed technique consists mainly of three parts. In the first part, the proposed technique uses an islanding detection technique to detect the islanding event correctly. The islanding detection technique is based on the rate of change in reactive power and a load connecting strategy to detect islanding within the system. For a large power mismatch, islanding is detected based on the rate of change in reactive power ($\mathrm{d}Q/\mathrm{d}t$). If the measured $\mathrm{d}Q/\mathrm{d}t$ is higher than the threshold value, then islanding is detected. However, for a small power mismatch, the $\mathrm{d}Q/\mathrm{d}t$ initiates a load connecting strategy, which in turn alters the load on the distribution network. This addition of load will further change the rate of change in reactive power. This load variation in the distribution network causes a variation in the $\mathrm{d}Q/\mathrm{d}t$, which is used to distinguish islanding and other events. The main concept behind this load connecting strategy is that in grid connected mode the addition of load will cause a small variation in $\mathrm{d}Q/\mathrm{d}t$. However, in islanded mode, the system will observe a large $\mathrm{d}Q/\mathrm{d}t$, which will lead to detection of islanding. The details of this technique can be found in Laghari *et al.* (2013b).

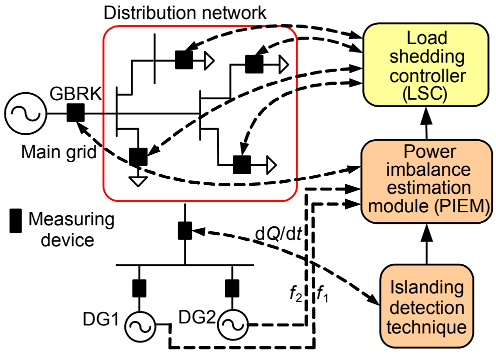

Fig. 1 Layout of the proposed technique

When the islanding detection technique detects islanding correctly, it sends a signal to the power imbalance estimation module (PIEM). PIEM uses the frequency, $\mathrm{d}f/\mathrm{d}t$, as the input and estimates the power imbalance during that event. PIEM, after estimating the power imbalance, sends the signal to the load shedding controller (LSC) to shed the loads according to load priority in order to stabilize the frequency. In this work we assume that the distribution network is equipped with reliable monitoring devices and a fast communication system for transmitting data.

2.2 Mathematical modeling of the proposed technique

As mentioned, the first part uses the islanding detection technique based on $\mathrm{d}Q/\mathrm{d}t$ and the load connecting strategy to detect an islanding event. After the islanding event is detected, the signal is sent to PIEM. PIEM monitors the frequency every half cycle. In grid connected mode, PIEM follows the grid frequency. However, during the islanding operation, PIEM determines the frequency of the equivalent inertial center f_c as follows (Terzija, 2006):

$$f_\mathrm{c}=\sum_{i=1}^{N}H_i f_i \Big/ \sum_{i=1}^{N}H_i, \tag{1}$$

where H_i is the inertia constant of the ith DG (in s), f_i is the frequency of the ith DG (in Hz), and N is the number of DGs.

PIEM estimates the power imbalance using a power swing equation. The ith generator swing equation for N machines can be expressed as (Saadat, 1999)

$$\Delta P=2\sum_{i=1}^{N}\frac{H_i}{f_\mathrm{n}}\frac{\mathrm{d}f_\mathrm{COI}}{\mathrm{d}t}, \tag{2}$$

where f_COI is the center of inertia frequency (in Hz), f_n is the rated frequency (in Hz), and ΔP is the power imbalance.

PIEM, after estimating the power imbalance, checks the frequency threshold. The Malaysia Tenaga Nasional Berhad (TNB) utility has the standard frequency threshold of 49.5 Hz to begin the load shedding scheme. If the frequency goes below this threshold, PIEM sends the signal to LSC to start load shedding. To avoid load shedding due to small disturbances, a threshold ΔP_th is introduced. The value set for this threshold is 50 kW. If the estimated amount exceeds ΔP_th, the proposed technique starts load shedding; otherwise, the DG unit remains operating without requiring any load shedding. The proposed technique uses a delay time of 100 ms according to practical considerations (Anderson and Mirheydar, 1992; IEEE, 2003). The proposed algorithm performs load shedding in a single step. Fig. 2 shows the flow chart of the proposed technique.

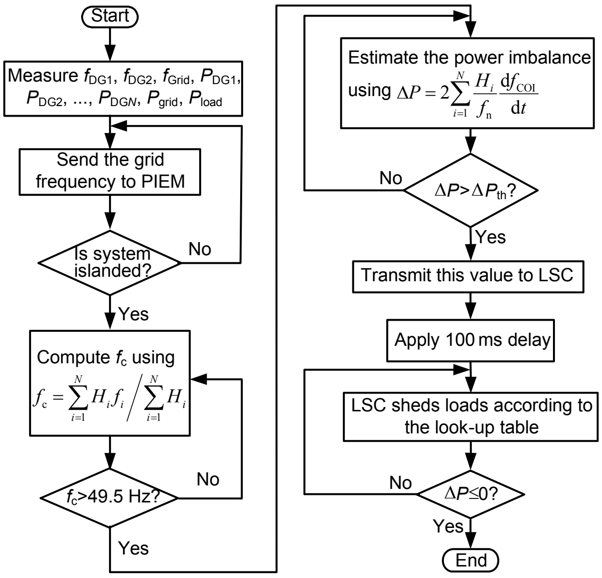

Fig. 2 Flow chart of the proposed technique

3 Test system modeling

The test system used for validation of the proposed technique is part of an existing 11 kV Malaysia distribution network as shown in Fig. 3. The transmission grid is connected to the distribution network via step-down transformers (132 kV/11 kV), rated

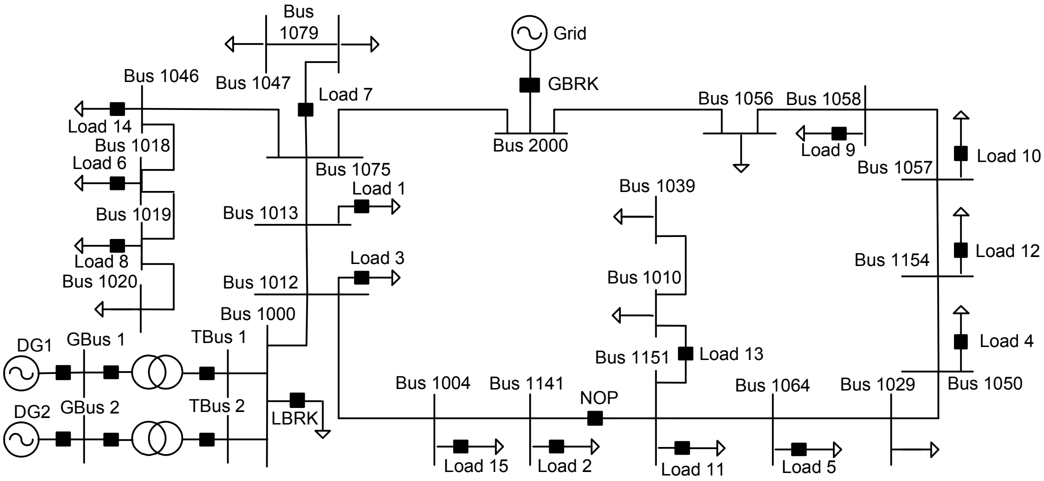

Fig. 3 Schematic of the test system

30 MV·A, and islanding is simulated by opening the circuit breaker (GBRK) of bus 2000. The distribution network is supplied by two mini hydro DG units and the grid. Each mini hydro DG has a capacity of 2 MV·A (maximum power dispatch is 1.8 MW). The test system is modeled in the PSCAD/EMTDC library.

The standard model for the exciter, governor, and hydraulic turbine provided in the PSCAD/EMTDC library is used in this study. The IEEE type AC1A excitation standard model is chosen (Table 1). The governor consists of a PID controller including pilot and servo dynamics models (Table 2). The hydraulic turbine is considered as a non-elastic water column without surge tank (Table 3). The distribution network consists of 27 buses and 20 lumped loads. The loads in the distribution network are prioritized into three categories: vital, semi-vital, and non-vital. Non-vital loads have the lowest priority and will be shed first, followed by semi-vital and vital loads. This load priority is created on the active power value of each load. Table 4 shows the power consumption of each load and its priority.

Table 1 Exciter parameters

Parameter	Value
Voltage regulator time constant, T_C	0 s
Voltage regulator time constant, T_B	0 s
Voltage regulator gain, K_A	400 p.u.
Voltage regulator time constant, T_A	0.02 s
Maximum regulator limit, V_{AMAX}	14.5 p.u.
Minimum regulator limit, V_{AMIN}	−14.5 p.u.
Maximum regulator limit, V_{RMAX}	6.03 p.u.
Excitation stabilizer gain, K_F	0.03 p.u.
Excitation stabilizer time constant, T_F	1 s
Exciter time constant, T_E	0.8 s
Exciter control system gain, K_E	1 p.u.
Rectifier loading factor, K_C	0.2 p.u.
Demagnetizing factor, K_D	0.38 p.u.
Maximum regulator limit, V_{RMIN}	−5.43 p.u.

4 Simulation results and discussion

The proposed strategy is validated on the test system with various events, such as islanding at a large power mismatch, islanding at a moderate power

Table 2 Governor parameters

Parameter	Value
Proportional gain, K_P	2 p.u.
Integral gain, K_I	0.35 p.u.
Derivative gain, K_D	0.9 p.u.
Permanent droop, R_P	0.04 p.u.
Pilot servomotor time constant, T_A	0.05 s
Gate servomotor gain, T_C	0.2 s
Gate servomotor time constant, T_D	0.2 s
Maximum gate opening	0.16 p.u./s
Maximum gate closing	0.16 p.u./s
Dead band value	0
Maximum gate position	1 p.u.
Minimum gate position	0 p.u.

Table 3 Hydraulic turbine parameters

Parameter	Value
Water starting time, T_W	2 s
Penstock head loss coefficient, f_P	0.02 p.u.
Turbine damping constant, D	0.5
Initial output power	0.7 p.u.
Initial operating head	1 p.u.
Rated output power	1 p.u.

Table 4 Load ranking table

Bus No.	P (MW)	Q (Mvar)	Load ranked	Load category	Bus No.	P (MW)	Q (Mvar)	Load ranked	Load category
1013	0.070	0.030	Load 1	Non-vital	1057	0.200	0.090	Load 10	Semi-vital
1141	0.080	0.040	Load 2	Non-vital	1151	0.215	0.080	Load 11	Semi-vital
1012	0.080	0.050	Load 3	Non-vital	1154	0.220	0.070	Load 12	Semi-vital
1050	0.100	0.050	Load 4	Non-vital	1010, 1039	0.220	0.058	Load 13	Semi-vital
1064	0.150	0.080	Load 5	Non-vital	1046	0.235	0.090	Load 14	Semi-vital
1018	0.175	0.070	Load 6	Non-vital	1004	0.250	0.085	Load 15	Semi-vital
1047, 1079	0.180	0.070	Load 7	Non-vital	1020	0.275	0.100	Load 16	Vital
1019	0.190	0.100	Load 8	Non-vital	1056	0.330	0.150	Load 17	Vital
1058	0.190	0.080	Load 9	Semi-vital	1029	0.350	0.140	Load 18	Vital

mismatch, islanding at a small power mismatch, and a load increment case, to further validate the effectiveness of the proposed scheme. All of these events are simulated at t=5 s. When the dQ/dt is greater than 1 Mvar/s, the islanding detection technique is activated. It measures the dQ/dt for 0.1 s; if the measured value for this time is greater than 35 Mvar/s, then the island is detected without the initialization of the load connecting strategy.

On the contrary, the islanding detection technique starts a load connecting strategy and measures the dQ/dt for 0.15 s. If the measured dQ/dt is greater than 13 Mvar/s, then islanding is detected; otherwise, no islanding is detected and the system will continue to run without requiring any load to be shed. The details of this technique can be found in Laghari *et al.* (2013b).

4.1 Islanding at a large power mismatch

In this case, intentional islanding at a large power mismatch of 1 MW between generation and load demand is simulated. The total load demand in this case is 4.6 MW and 1.4 Mvar, from which 3.6 MW and 1.4 Mvar are supplied by both mini hydro DGs and 1 MW is supplied by the grid. When the grid is disconnected, the proposed algorithm is activated to perform the islanding operation successfully. The dQ/dt response for islanding detection is shown in Figs. 4a and 4b.

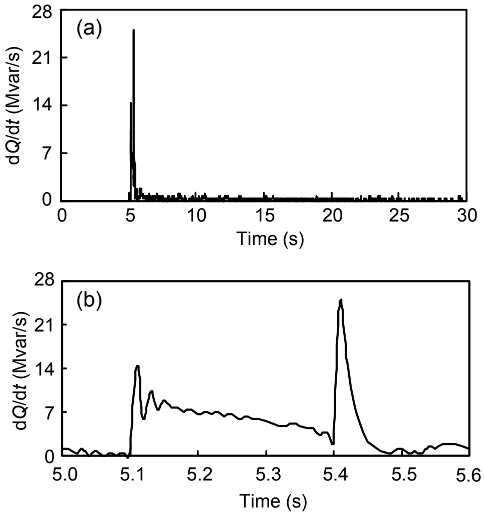

Fig. 4 Islanding detection at a large power mismatch (a) and the magnified view (b)

Figs. 4a and 4b show that when islanding is performed at t=5 s, the dQ/dt measured at 5.1 s has a value of 14.2 Mvar/s, smaller than 35 Mvar/s. Hence, the load connecting strategy is activated and dQ/dt is again measured at 5.4 s, which has a value of 24.6 Mvar/s, greater than 13 Mvar/s; hence, islanding is detected successfully and the signal is sent to PIEM. PIEM checks the frequency limit of 49.5 Hz and estimates the power imbalance using a power swing equation. After the power imbalance is estimated, this value is sent to LSC. LSC performs load shedding to enable a successful islanding operation. Figs. 5a and 5b show the frequency and power responses for this case, respectively.

Fig. 5a shows that by applying load shedding the DG frequency drops to 48.76 Hz and then is restored to the nominal value. For this case, the proposed technique sheds loads up to the 8th load ranked, since the total magnitude of eight loads is 1.025 MW, which is slightly greater than 1.0 MW power imbalance. Hence, the frequency has a smaller overshoot. DG units can supply 3.6 MW load after the grid has been disconnected (Fig. 5b). Thus, the proposed technique enables a successful islanding operation of the distribution network at a large power mismatch.

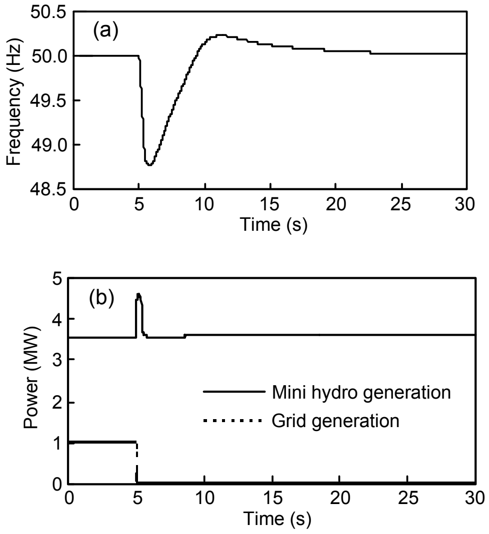

Fig. 5 Frequency response for an islanding event at a large power mismatch (a) and the power graph (b)

4.2 Islanding at a moderate power mismatch

In this case, intentional islanding at a moderate power mismatch of 0.5 MW between generation and load demand is simulated. The total load demand in this case is 4.1 MW and 1.4 Mvar, from which 3.6 MW and 1.4 Mvar are supplied by both mini hydro DGs and 0.5 MW is supplied by the grid.

When the grid is disconnected, the proposed algorithm is activated to perform the islanding operation successfully. The dQ/dt response for islanding detection is shown in Figs. 6a and 6b. When islanding is performed at t=5 s, the dQ/dt measured at 5.1 s has a value of 13.7 Mvar/s, smaller than 35 Mvar/s.

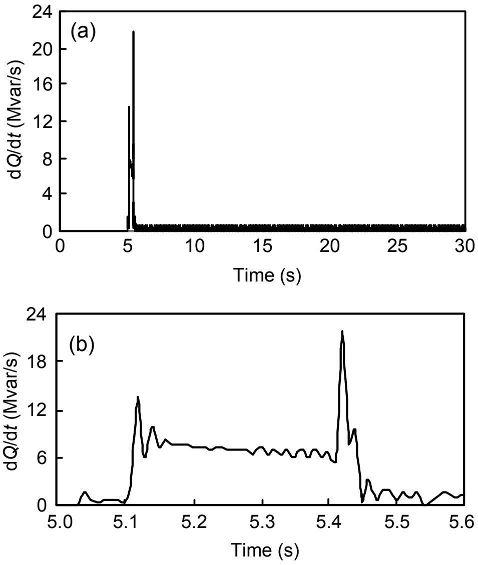

Fig. 6 Islanding detection at a moderate power mismatch (a) and the magnified view (b)

Hence, the load connecting strategy is activated and dQ/dt is again measured at 5.4 s, which has a value of 21.64 Mvar/s. The dQ/dt measured is greater than 13 Mvar/s; hence, islanding is detected successfully and the signal is sent to PIEM. PIEM checks the frequency limit of 49.5 Hz, estimates the power imbalance, and sends the signal to LSC. LSC performs load shedding to enable a successful islanding operation. The frequency and power responses for this case are shown in Figs. 7a and 7b, respectively.

Fig. 7a shows that, by applying load shedding, the DG frequency drops to 49.25 Hz and then is restored to the nominal value. For this case the proposed technique sheds loads up to the 5th load ranked and DG units can supply 3.6 MW load after the grid has been disconnected (Fig. 7b). Thus, the proposed technique enables a successful islanding operation of the distribution network at a moderate power mismatch.

4.3 Islanding at a very small power mismatch

In this case, intentional islanding performed at a very small power mismatch of 0.03 MW between generation and load demand is simulated. The total load demand in this case is 3.63 MW and 1.4 Mvar, from which 3.6 MW and 1.4 Mvar are supplied by both mini hydro DGs and 0.03 MW is supplied by the grid. The dQ/dt response for islanding detection is shown in Figs. 8a and 8b. When islanding is performed at t=5 s, the dQ/dt measured at 5.1 s has a value of 3.3 Mvar/s, which is smaller than 35 Mvar/s. Hence, the load connecting strategy is activated and dQ/dt is again measured at 5.4 s, which has a value of 16.3 Mvar/s. The dQ/dt measured is greater than 13 Mvar/s; hence, islanding is detected successfully and the signal is sent to PIEM. The frequency and power responses for this case are shown in Figs. 9a and 9b, respectively.

Fig. 9a shows that the DG frequency has not dropped below 49.5 Hz. The threshold frequency is set to 49.5 Hz to initiate the UFLS scheme. This shows that for this case, load shedding is not required. Thus, the proposed load shedding algorithm does not perform any load shedding, and the system frequency is restored to its nominal value without any load shedding. The power graph is as shown in Fig. 9b. Thus, the proposed technique enables a successful islanding operation of the distribution network at a small power mismatch.

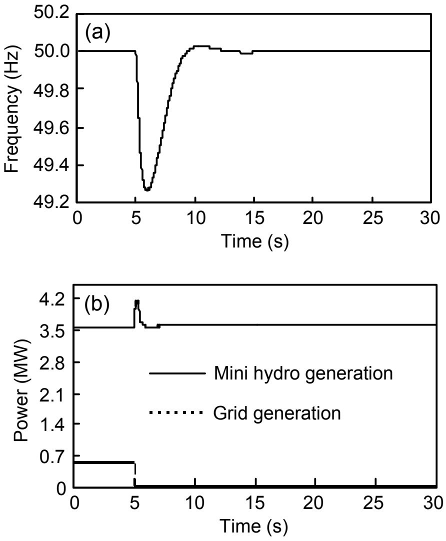

Fig. 7 Frequency response for an islanding event at a moderate power mismatch (a) and the power graph (b)

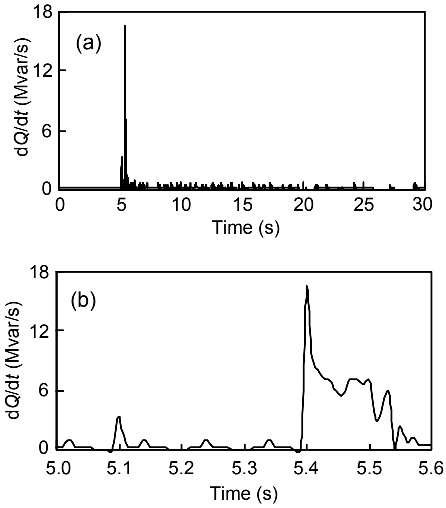

Fig. 8 Islanding detection at a small power mismatch (a) and the magnified view (b)

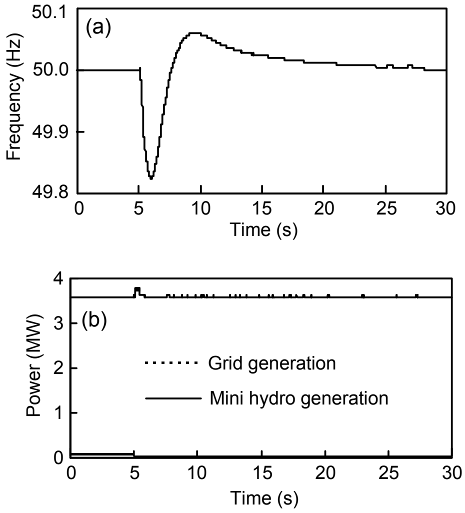

Fig. 9 Frequency response for an islanding event at a small power mismatch (a) and the power graph (b)

4.4 Load increment of 0.5 MW in grid connected mode

In this case, a load increment of 0.5 MW is simulated at bus 1012 of the distribution network operating in grid connected mode. Before load increment, the total load demand in this case is 3.6 MW and 1.4 Mvar, which is supplied by both mini hydro DGs. However, when a load increment of 0.5 MW occurs, the total load demand is 4.1 MW and 1.4 Mvar, from which 3.6 MW and 1.4 Mvar are supplied by both mini hydro DGs and 0.5 MW is supplied by the grid. The dQ/dt response for islanding detection is shown in Figs. 10a and 10b. When the load increment occurs at t=5 s, the dQ/dt measured at 5.1 s has a value of 5.92 Mvar/s, smaller than 35 Mvar/s. Hence, the load connecting strategy is activated and dQ/dt is again measured at 5.4 s, which has a value of 3.83 Mvar/s, smaller than 13 Mvar/s. Hence, no islanding is detected. The frequency and power responses for this case are shown in Figs. 11a and 11b, respectively.

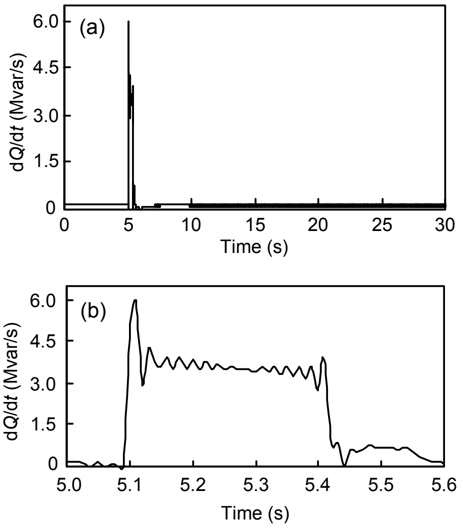

Fig. 10 Islanding detection for a 0.5 MW load increment case (a) and the magnified view (b)

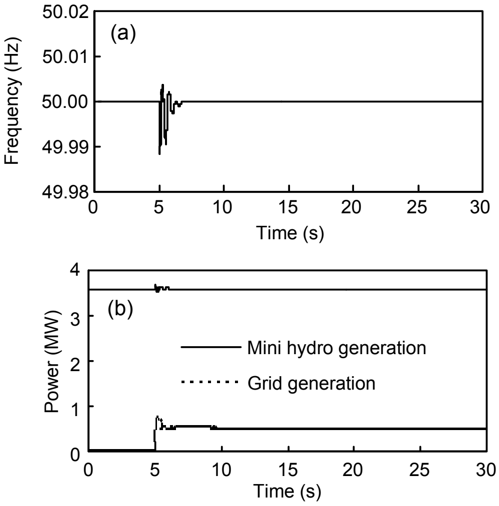

Fig. 11 Frequency response for a load increment of 0.5 MW (a) and the power graph (b)

Fig. 11a shows that the frequency has not dropped below 49.5 Hz. Hence, no load shedding is required. Thus, the proposed load shedding algorithm does not perform any load shedding. The system frequency for this case recovers to the nominal value without any load shedding. Thus, the proposed technique clearly distinguishes between islanding and the load increment event.

Simulation results show that the proposed technique enables a successful islanding operation of the distribution network. The islanding detection technique efficiently distinguishes between islanding and other events and the proposed load shedding technique performs suitable load shedding to stabilize the frequency to its nominal value.

5 Conclusions

We have proposed a new technique for a successful islanding operation of the distribution network connected with multiple mini hydro DGs. The proposed technique uses an islanding detection technique to detect the islanding event, and a load shedding technique to stabilize the frequency to its nominal value. The load shedding technique is developed using frequency, d*f*/d*t*, and load priority. The robustness of the proposed technique has been investigated for different islanding cases, such as islanding at a large power mismatch, moderate power mismatch, very small power mismatch, and in a load increment case. Simulation results show that the proposed strategy is effective in performing a successful islanding operation of a distribution network.

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