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Abstract: Islanding detection in distributed generation (DG) interfaced to the microgrid is a key criterion for safety and power quality of the power system. This study proposes a transient monitoring function (TMF)-based islanding detection technique, which distinguishes between various islanding and non-islanding conditions in an inverter-based DG. Initially, the voltage samples of each phase retrieved at the target DG location are processed through Fourier–Taylor transformation (FTT). The TMF is the difference between the estimated voltage samples regenerated from the FTT and the actual sample values. Finally, the TMF index for islanding detection is computed by combining each phase TMF. Based on simulations carried out in PSCAD/EMTDC environment, the performance of the proposed method is examined in various critical conditions. Therefore, the proposed method provides generalised solution irrespective of active and reactive power mismatch and thus enhancing the non-detection zone. The proposed TMF-based anti-islanding relay is highly efficient and satisfies the speed criteria of the relaying function in performing the task.

1 Introduction

Distributed generation (DG) using renewable sources is an important alternative to meet the growing demands of electricity and reduce the impact on environment of traditional sources. DG meets the customer requirement not only in stand-alone mode but also in grid-connected mode. Therefore, with the increasing penetration of DGs in power grid, their impact on system operation is significant. There is an increased risk of damage to power system, safety hazard for personnel and quality problems of electric service to utility. Since, DG may be connected in parallel and supplying power to grid as well as local loads. Therefore, it must be operated in such manner that they supply power to the network and loads only when utility power supply is on. When DG continues with power supply to distribution network that has been separated from the power system, the mode of operation is called islanding condition. This results in many problems for connected loads as power quality (PQ) problems may be significant in DG interconnection compared to utility, which further causes safety or operational problem. Therefore, immediately after interruption of utility power, all distributed resources (DRs) should be disconnected as soon as possible. Sensing such a condition, when utility power supply is lost, is known as islanding detection [1–7].

Several techniques are used in islanding detection. These can be classified as: passive, active, and communication-based methods. Passive methods detect islanding condition based on variation in parameters such as frequency [8], harmonic detection [9], voltage magnitude [10], and phase jump [11]. Although passive methods do not disturb PQ, in scenarios where the local load power consumption and power generation are matched, the method fails. Besides, as seen in [9], the technique relies on choosing an appropriate threshold value, which depends on monitoring total harmonic distortion and voltage unbalances. This is a tedious and complex task as these signal values are dependent on the system parameters. Moreover, passive techniques exhibit large non-detection zones (NDZs) and thus, fails to operate in lower power mismatch. Another technique used for islanding detection is active islanding detection technique. There are various types of active methods are existing such as slip-mode frequency shift [11], active frequency drift [12], and Sandia frequency [13]. In active method, a perturbation in output current signal is introduced. The active

signal is injected and a change in frequency, magnitude, or phase of voltage at the point of common coupling (PCC) is monitored which is used for islanding detection. Although these methods have small NDZs, but the PQ is degraded as, a perturbation is introduced into the system and response time is large. Further, when active islanding detection techniques are applied to multiple DGs synchronised with the utility, may have difficulties due to averaging effect [14]. Another technique used in islanding detection is communication-based methods [15]. These methods are more exact and robust. This needs a robust communication platform to monitor the microgrid and thus, incur a high price. Hence, it is not economically viable for such application in power systems.

It is seen passive methods such as rate of change of frequency (ROCOF) and vector surge relays are commonly used in islanding detection. Even these methods perform with lower accuracy, but are not as costly as other methods. However, ROCOF method fails in case of low-power imbalance during islanding. Besides, vector surge relays for a specific relay setting and the detection time suffer from the limitation of NDZ [16]. Moreover, hybrid technique, which utilises an average rate of change of voltage (passive method) and real power shift (active method), is proposed in [7]. Although the method is efficient, it takes at least 5 cycles for islanding detection. Recently, an active ROCOF-based islanding detection scheme has been presented in [17] to overcome the shortfall of conventional ROCOF anti-islanding relay. However, the speed of active ROCOF is still high in the order of 12 cycles. Again, the methods such as fuzzy algorithm-based classifier, wavelet transform based a decision tree approach used in [18, 19] for islanding detection. In [19], the paper uses decision tree-based islanding detection method, which extracts threshold values of the system parameters for islanding detection. Although it has almost negligible NDZ but it is unable to capture all islanding events correctly. Among other islanding detection methods, pattern recognition [20] Bayesian classifiers [21] are proposed. Several other methods have been proposed for islanding in DG [22–29].

This paper proposes transient monitoring function (TMF) based an efficient and high-speed islanding detection method, which can be applied to a large number of various critical islanding conditions and non-islanding conditions in DG interfaced to the microgrid. In this paper, a voltage signal is chosen to make the method more

Fig. 1 Moving data window on a target-DG voltage waveform

Fig. 2 Actual and reconstructed signals of a target-DG voltage waveform

reliable and secured against loading conditions. Initially, the voltage signals retrieved at the target DG locations are processed through Fourier–Taylor transformation (FTT). The TMF is the difference between the estimated voltage samples regenerated from the FTT and the actual sample values. Finally, the TMF index (TMFI) for islanding detection is computed by averaging the TMF of each phase. The objective of this paper is as follows:

- To develop high-speed anti-islanding relay algorithm to overcome the shortfall of conventional ROCOF and active ROCOF anti-islanding relay.
- To identify a feature for islanding event using local end information that is effective for various islanding scenarios and to distinguish an islanding condition from non-islanding conditions such as a load and capacitor switching.

This paper is organised in the following way: The proposed technique for an islanding detection in DG is presented in Section 2. Results and analysis of the initial studied system and a standard microgrid structure with different case studies are presented in Section 3. Conclusions followed by discussion and final remarks are presented in Sections 4 and 5, respectively.

2 Proposed technique

The limitations of the existing islanding detection technique discussed in the literature review can be overcome by a proposed alternative solution. In the proposed technique, the TMF is computed using moving data window for a target DG voltage waveform before and during the islanding event as shown in Fig. 1. The algorithm started by estimating the fundamental frequency component of the voltage waveform using least square (LS) method [30–32]. During a pre-fault and non-islanding conditions, the original signal and its reconstruction from the estimated fundamental component match. As shown in Fig. 2, when an islanding event occurs, the target DG voltage waveform changes suddenly, this causes a deviation from the reconstructed signal due to the following:

1. During an islanding instant, the related windows contain both pre and post-islanding data.
2. The added components to the islanding voltage owing to islanding occurrence are not available in the defined model of the signal in the LS approach.

Therefore, by defining a proper TMFI, the transition from a normal operation to an islanding condition can be detected.

2.1 TMF technique

TMF is an index, which measures the difference between the actual signal and the reconstructed (estimated) signal. Here, the estimated signal is obtained by signal estimation explained in the following sections. In other words, TMF is a measure of how accurately a signal has been estimated (in case of normal operation). If we were able to estimate the signal properly, then significant value (above threshold) of the TMF would indicate an islanding condition in the DG interfaced to the microgrid.

The sinusoidal signal described as

$$F(k) = b \cdot \cos(k \cdot \alpha + \beta) \quad (1)$$

where b is the amplitude; α is the $(2\pi/N)$, where N is the number of samples taken per cycle; k is the sample number; β is the phase angle (in radians) of the sinusoidal signal.

Let us consider that

$$\lambda = be^{j\beta} \text{ is a phasor representation of signal} \quad (2)$$

By taking N number of samples per cycle and representing the discrete time signal in terms of phasor and their Taylor–Fourier coefficients (λ and λ^* , where $*$ implies conjugate)

$$F = \begin{bmatrix} F(0) \\ F(1) \\ \vdots \\ F(N) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ e^{j\alpha_1} & e^{-j\alpha_1} \\ \vdots & \vdots \\ e^{j\alpha_1(N-1)} & e^{-j\alpha_1(N-1)} \end{bmatrix} \cdot \begin{bmatrix} 0.5\lambda \\ 0.5\lambda^* \end{bmatrix} = M \cdot P \quad (3)$$

Estimating the coefficients using LSs method:

$$\hat{P} = (M^H \cdot M)^{-1} \cdot M^H \cdot F \quad (4)$$

where

H : Hermitian transpose operator.

Now, using the above estimated phasor $\hat{P}$ if we re-compute the samples giving estimated value of the samples ($\hat{F}$) we get:

$$\hat{F} = M \cdot \hat{P} \quad (5)$$

Since, we have both actual input values and the recalculated sample values, we can calculate the error incurred (Δ):

$$\Delta = F - \hat{F} \quad (6)$$

Using the error of estimation, TMF is calculated as

$$\text{TMF} = \sum_{m=\tau-N}^{m=\tau} |\Delta_m| \quad (7)$$

The TMF index is computed as

$$\text{TMFI}_{\text{INDEX}} = \left(\frac{\text{TMF}(a) + \text{TMF}(b) + \text{TMF}(c)}{3} \right) \quad (8)$$

where $\text{TMF}(a)$, $\text{TMF}(b)$ and, $\text{TMF}(c)$ are TMF of a , b , and c phase, respectively. Fig. 3 depicted the flowchart of the proposed method.

2.2 Error analysis on the proposed method

In real-time scenario, noise is an unwanted part of any signal and might affect the accuracy of any method. Equation (9) presents the sinusoidal signal (1) with variable amplitude and phase to zero mean Gaussian noise (ξ)

$$F(k) = b \cdot \cos(k \cdot \alpha + \beta) + \xi(k) \quad (9)$$

Fig. 3 Flowchart of proposed scheme

Fig. 4 Errors in phasor estimation

Fig. 5 Power distribution network with 4-DG units

Therefore, the matrix form of noisy signal (9) for N samples written below

$$F = M \cdot P + E \quad (10)$$

where,

$$E = [\xi(0), \xi(1), \xi(2), \dots, \xi(N-1)]$$

F , M , and P defined in the previous section.

By assuming $\sigma^2 \cdot I$ is covariance matrix of noise (η), where σ^2 is the variance of zero mean Gaussian noise (ξ) and I is the unit

matrix. Equation (10) solved using LS technique [30] and final derived solution is given as

$$\hat{P} = (M^H \cdot \eta^{-1} \cdot M)^{-1} \cdot M^H \cdot \eta^{-1} \cdot F \quad (11)$$

$$E((\hat{P} - P) \cdot (\hat{P} - P)^T) = (M^H \cdot \eta^{-1} \cdot M)^{-1} \quad (12)$$

Equation (12) has been used for computing covariance matrix phasor estimation error. The performance of proposed approach depends on the window length. The longer the window length, the lower the error but with decrease in the response time and processing speed. Therefore, the signal is sampled at seven different sampling rates: 8, 16, 32, 64, 128, 256, and 512 times per cycle. The signal samples are created with appropriately modelled noise input for 1000 cycles, and 1000 estimates of the phasor values are calculated. Fig. 4 shows the error in standard deviation with a change of the variance and the number of sample per cycle. In this paper, 64 samples per cycle (sampling rate of 3.84 kHz) are chosen, which measures the low error and a good processing speed.

3 Results and analysis of the proposed method

3.1 Initial test system [5, 6]

The line diagram of power distribution network with four DG units is shown in Fig. 5. The base frequency and power are 60 Hz and 10 MVA, respectively. The system under study consists of four DG units (three wind farms (WFs)) and one emergency diesel generator (EDG), which are connected to the utility through a PCC. The DG units are situated at a distance of 20 km from PCC and the microgrid is operated at 25 kV. The system details are given in [5, 6].

3.2 Islanding detection challenges of ROCOF

Commonly, ROCOF-based anti-islanding relays are used for islanding detection. The mathematical expression of ROCOF-based anti-islanding relay given as

$$\text{ROCOF} = \frac{1}{N} \sum_{m=1}^N \left| \frac{df}{dt}(m) \right| \quad (13)$$

where

$$\frac{df}{dt}(m) = \frac{f(t_m) - f(t_m - \Delta t)}{\Delta t}$$

$N = ((\Delta t)/(T_s))$ (N is the number of samples in a given window of Δt)

$$\frac{df}{dt} = \frac{P_D - P_L}{2 \times (\text{DG rating}) \times H} \times f_0 \quad (14)$$

where

P_D = DG output power

P_L = load power

H = inertia constant

f_0 = fundamental frequency

From (14), it is observed that the operation of the ROCOF-based anti-islanding relays depends mainly on dynamic change in the frequency (df/dt) during islanding due to the power mismatch between the generation and the load. Thus, if the difference between P_D and P_L is low subsequent to islanding, the dynamic change in frequency becomes very low, i.e. system frequency does not change subsequent to islanding. Therefore, the ROCOF relay

Fig. 6 Islanding detection challenges

(a) ROCOF-based anti-islanding relay performance for various loading condition during pre and post loss of mains (LOM), (b) dv/dt -based anti-islanding relay performance during reactive power mismatch

Fig. 7 Three-phase voltage waveform of a target DG-1 during islanding (MCB tripped) and non-islanding condition (other DG tripping)

will not respond and the islanding goes undetected. The line diagram of the power distribution network is shown in Fig. 5. The ROCOF-based anti-islanding relay response under different loading conditions is shown in Fig. 6a. Islanding is initiated at 10 s and it can be seen from Fig. 6a that the setting of threshold on the ROCOF (say 0.5 to 1 Hz/s: standard) fails to detect the islanding during low-power mismatch. Similarly, islanding is performed at 8 s and it can be seen from Fig. 6b that with setting a threshold on the dv/dt -based anti-islanding relay, i.e. 0.1 p.u./s, fails to detect islanding during low reactive power mismatch. Therefore, a technique, which takes care of these shortcomings and performs well by reducing the NDZ, is mandated.

3.3 Studied islanding conditions in initial system

For experimentation, a target DG is chosen. The voltage signals retrieved at the target DG during the islanding and non-islanding condition (other disturbances) are retrieved. The relays for each target DG is placed at the end of the DG. For example, for CBD_1,

the relay is placed at DG-1. This relay collects the voltage signals. These signals are analysed and used for detecting whether the condition is an islanding or a non-islanding condition. TMFI is used for this purpose, as described in Section 2.

To illustrate whether a condition is islanding or non-islanding, we take an example. Let, DG-1 be our target DG for this illustration and the islanding conditions for DG-1 as a target DG will necessitates:

- Tripping of main circuit breaker (MCB) for islanding conditions.
- Opening of breakers between the power system and DG-1, i.e. opening circuit breaker named CBD_1.
- Loss of distribution lines (DL-1) of the power distribution network.

In a similar way, the non-islanding conditions for DG-1 as target DG will necessitates:

- Tripping of other DGs apart from the target DG (DG-1). This includes opening of circuit breakers CBD_2, CBD_3 and CBD_4 individually.
- Loss of distribution lines of the distribution network (DL-2, DL-3 or DL-4).

The three-phase voltage signals measured at target DG-1 during islanding occurs at 10 s due to tripping of the MCB as shown in Fig. 7. The three-phase voltage signals are sampled from the secondary side of the voltage transformer, and normalised by the peak value of the rated secondary voltage. The normalised voltage of each phase is then process through TMF algorithm. The voltage waveform during non-islanding condition for DG-1 due to tripping of circuit breaker CBD_2 (DG-2 tripped) is also shown in Fig. 7. It has been observed from Fig. 8 that the TMF for each phase and the TMFI is very low during normal condition and non-islanding condition compared to the islanding condition which starts at 10 s. Thus, the proposed anti-islanding relay algorithm works successfully. Similarly, other different islanding and non-islanding conditions are tested as presented in the next section.

3.4 Performance of the proposed anti-islanding relay during different power imbalance

The ROCOF and dv/dt relays used to detect islanding event in DG interfaced to the microgrid. However, speed of both methods slow down drastically in case of low active and reactive power mismatch (below 16%) during islanding as shown in Fig. 9. Fig. 9 depicts the computed TMFI at DG-1 for the islanding detection with active power mismatch of $\pm 1\%$ to $\pm 20\%$ and reactive power mismatch is $\pm 1\%$ to $\pm 5\%$ against the non-islanding condition of load switching (L1) at $t = 8$ s. From Fig. 9, it is observed that TMFI is able to detect islanding condition effectively at with high speed and different power mismatch.

3.5 NDZ of the proposed method

The NDZ concept is an index to evaluate the performance of islanding protection [27]. In different types of DG, NDZs are of different shapes. In synchronous generator-based systems, the NDZ of the voltage function is influenced by reactive power imbalance (Fig. 10a), which at the same time defines the top and bottom boundaries, and also by active power imbalance level to a lesser degree [28]. Meanwhile, active power mismatch determines the performance of frequency function, which results in the left and right boundaries. This performance index is defined by power imbalance (measured at distribution system PCC) and plotted in ΔP - ΔQ space as shown in Fig. 10. As for the inverter-based systems, the size of the NDZ, in terms of active power and reactive power mismatch at PCC, depends on the inverter control strategy. For a constant power control strategy, the following relationships define the boundary limits of the NDZ [27]:

Fig. 8 TMF for each phase and TMFI during islanding(MCB tripped) and non-islanding condition(DG-2 tripped)

Fig. 9 TMFI during various power mismatches and load switching

$$\left(\frac{V}{V_{\max}}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{V}{V_{\min}}\right)^2 - 1 \quad (15)$$

$$Q_f \left(1 - \left(\frac{f}{f_{\min}}\right)^2\right) \leq \frac{\Delta Q}{Q} \leq Q_f \left(1 - \left(\frac{f}{f_{\max}}\right)^2\right) \quad (16)$$

where $V_{\max}$ is the maximum limit of over voltage, $V_{\min}$ is the minimum limit of under voltage, $f_{\max}$ is the maximum limit of over frequency, $f_{\min}$ is the minimum limit of under frequency, Q_f is the quality factor, V is the rated voltage, f is the rated frequency, P is

the active power, Q is the reactive power, ΔP is the active power mismatch, and ΔQ is the reactive power mismatch.

By putting typical values of standard parameters as given in Table 1 in the above (15) and (16), it becomes

$$-17.36\% \leq \frac{\Delta P}{P} \leq 29.13\% \quad (17)$$

$$-5.94\% \leq \frac{\Delta Q}{Q} \leq 4.11\% \quad (18)$$

Equations (17) and (18) show the typical values of NDZ in terms of active and reactive power mismatch for over/under voltage and over/under frequency-based methods. Therefore, the method proposed in this paper has been tested with small power mismatches, that is inside NDZ of voltage and frequency relay. The NDZ of the TMFI-based method is $\leq \pm 1\%$ which is much less than NDZ of OV/UV and OF/UF method. The NDZ of the proposed method depicted in Fig. 11.

3.6 Threshold setting of the proposed method

Fig. 12a shows the TMFI of target DG-3 during islanding condition due to tripping of the MCB at 5.5 s. TMFI for 40 and 20 dB noise with islanding condition mismatch computed and presented in Fig. 12a. In case of a normal operation, the TMFI value will be very low and stays high during islanding condition. Considering the fact that there would be some error of estimation in the estimated signal from the original signal, the threshold value was set to 0.5 in this paper. To obtain TMFI threshold, the contamination of the harmonics and noise is considered. Fig. 12b shows the computed TMFI at DG-1 when a capacitor bank is added in DG-1 and switched on at $t = 8$ s. It has been observed that the TMFI is able to detect an islanding condition effectively with a high speed of $\pm 5\%$ of the power mismatch.

3.7 Validations on the standard microgrid model [6]

The validation of the proposed method is done for a microgrid model shown in Fig. 13a with 7-DGs ((DG-1, DG-2, DG-4, and DG-7 are WFs, whereas DG-3, DG-5, and DG-6 are EDGs each with 9 MW capacity). The base frequency is 60 Hz and the base power is 5000 MVA (short-circuit MVA of the utility). The microgrid operates at 25 kV and each line is 20 km long. The other per unit parameters are the same as those of the initial sample test system (Fig. 5). The complete load data is given in the Appendix.

The performance of the proposed technique for an islanding condition in the standard utility-based microgrid model is shown in Fig. 13a. The islanding is created by switching off the main circuit breaker (i.e. MCB-off) at 20 s. Fig. 13b shows the TMFI for islanding condition with $\pm 15\%$ active and $\pm 5\%$ reactive power mismatch at DG-2 and DG-6. Similarly, Fig. 13c shows the TMFI for an islanding condition (MCB cut-off at 21 s) with a $\pm 16\%$ active and $\pm 4\%$ reactive power mismatch at DG-1 and DG-7. It is observed that the islanding detection is highly effective based on a set threshold on TMFI at different target DG locations irrespective of active and reactive power mismatch at the lower end and thus, reducing the NDZ.

4 Discussion

4.1 Case study on microgrid system according to IEEE standard 399

The basic system configuration and its parameters were extracted from the benchmark system of the IEEE Standard 399 [22] as shown in Fig. 14a, with some modifications to allow autonomous MG operation. The system is composed of a 13.8 kV distribution feeders and the MG is connected to the main grid through a 69 kV transmission line. The main grid is a network with 1000 MVA short-circuit capacity and an X/R ratio of 22.2. The 13.8 kV distribution substation is equipped with a three-phase, 1.5-MVAR, fixed shunt-capacitor bank. The system also includes two DG units: DG1 (5 MVA) and DG2 (2.5 MVA) on feeders F1 and F3,

Fig. 10 Non-detection zones
(a) Synchronous generator, (b) Inverter-based systems

Fig. 11 NDZ of the proposed method

Fig. 12 Validation on TMFI index in critical scenario
(a) TMFI during noisy condition with DG-3 in islanding condition, (b) TMFI during islanding and capacitor bank switching

Table 1 Typical value of standard parameter

Parameter	Value	Parameter	Value
V	1 p.u.	V _{min}	0.88 p.u.
f	60 Hz	f _{max}	60.5 Hz
Q _f	2.5	f _{min}	59.3 Hz
V _{max}	1.1 p.u.	detection time	<2 s

respectively. The DG1 is a synchronous rotating machine equipped with excitation and governor control systems. The DG2 is a dispatchable source with voltage-source converter and power electronic interface. Therefore, it has adequate capability to meet the real/reactive power controlling commands independently, within the pre-specified limits, in different conditions. Loads are supplied through three radial feeders of the system. More details of the system parameters can be found in [23].

The DG control scheme is shown in Fig. 14b. The DG interface has two sets of controllers: (i) for power regulation and (ii) for current regulation [24]. When the circuit breaker (B1) is closed, the two DGs along with their local loads are connecting to the main grid. When the circuit breaker (B1) is opened, islanding occurs, and the DGs along with their local loads form the islanding. In this situation, islanding condition should be detected and the required proceedings should be accomplished. At $t = 15$ s, the circuit breaker (B1) is opened and two DGs with local loads are separated from the main grid and islanding condition occurs. Fig. 14c shows TMFI during islanding condition for DG1 and DG2 with $\pm 50\%$ load variation (L3). It has been observed that the TMFI is able to detect an islanding condition effectively. Although the rate-of-false detection in the testing set is zero, it should be noted that the system resulted in false alarm (false detection of non-islanding condition) when a double contingency was simulated. This double contingency was a combination of (i) the tripping of the largest DR within the DG other than the target one under maximum system loading condition and (ii) increase of the loading of L3 by 200%. While the probability of occurrence of such contingencies is very low, false alarm in general, could be reduced by new setting value of $TMFI_{INDEX}$ to cover all possible operating states.

4.2 Real-time realisation of the proposed algorithm and islanding detection time calculation

The proposed algorithm has been tested on RTDS platform using GTNET-SKT (Socket) protocol. The SKT protocol is provided as a means to communicate with the RTDS using TCP or UDP sockets (GTNETx2 card). The SKT protocol represents both integer and floating-point numbers as 4 bytes in the packet. Floating-point numbers are single precision (32 bit) and are represented using IEEE754 format. The number of points and type of each point (integer or float) are defined in the SKT component in RSCAD/Draft. The maximum size for a packet corresponds to 300 data points (update rate 1000 Hz) or 1200 bytes. Most utility DG interconnection regulations, which are usually guided by the IEEE Standards 1547-2003 [1], require disconnection of DGs within 2 s in an event of loss of the mains. The on-line real-time realisation architecture of the proposed method is depicted in Fig. 15. The islanding detection time calculation of the proposed method in real time as per (19) is around 55 ms

$$\begin{aligned}
 &\text{islanding detection time} \\
 &= \text{phasor computation time (16.67 ms)} \\
 &+ \text{response time (33.33 ms)} \\
 &+ \text{programme execution time (34 ns)} \\
 &+ \text{propagation delay (5 ms)} \approx 55 \text{ ms}
 \end{aligned} \tag{19}$$

4.3 Comparative assessments with existing wavelet-based transient method

The proposed method compares with wavelet singular entropy-based index (WSEI) method [6]. The quality of wavelet transient index (WSEI) calculations can be degraded by the presence of noise in practical environments, and it is one of the major challengers in implementing transient-based relays. The effect of measurement noise on the wavelet-based algorithms can be reduced through denoising techniques [25, 26], but this may compromise the speed of detection. As the calculation of TMFI requires utilisation of phasor estimation algorithm and model transform, therefore practical implementation of the proposed

Fig. 13 Validation on standard microgrid model

(a) Standard microgrid model [6], (b) TMFI during islanding with $\pm 15\%$ active and $\pm 5\%$ reactive power mismatch, (c) TMFI during islanding with $\pm 16\%$ active and $\pm 4\%$ reactive power mismatch

scheme is easier compared to the schemes based on wavelet transform [6]/artificial intelligence [20] (see Fig. 16).

4.4 Overall summary

The percentage of power mismatch during islanding is a serious concern for the existing ROCOF and dv/dt -based anti-islanding relay. The detailed analysis with a different power mismatch is presented in Section 3. During power mismatch $> 18\%$, the threshold for ROCOF is $0.5\text{--}1\text{ Hz/s}$ (standard practice) and for dv/dt is 0.1 p.u./s . However, the speed of the existing ROCOF and dv/dt -based anti-islanding relay drastically slows down during power mismatch $< 16\%$. Also, the set threshold of ROCOF-based anti-islanding relay fails to operate during lower power imbalance. Therefore, a TMF-based islanding detection method is proposed to overcome the shortfall of ROCOF and dv/dt -based anti-islanding relay. The TMF starts with estimating the fundamental frequency component of the voltage waveform by moving use of the LS method. During steady state, the actual signal is match its reconstruction. Again, when an islanding occurs, the target DG voltage waveform changes, and causes deviation from the reconstructed waveform because during islanding instant, the related windows contain both pre- and post-islanding data.

Fig. 14 Validation on IEEE standard 399 model

(a) System studied according to IEEE standard 399, (b) Block diagram of constant power controlled mode of operation, (c) TMFI-based anti-islanding relay performance during pre- and post-islanding condition with standard $\pm 50\%$ load variation (L3)

Therefore, the added components to the islanding voltage data owing to islanding occurrence are not available in the defined model of the signal in the LS approach. In this way, by defining a proper TMFI i.e. $TMFI_{INDEX}$, this transition from normal operation to islanding condition can be detected effectively.

While performing the experiment with the proposed TMF-based anti-islanding relay, it has been noticed that TMF detects an islanding condition with a wide variation of the operating parameter during islanding. The proposed method provides generalised solution with an irrespective of the power mismatch. Also, the proposed method is able to detect islanding event during a low power imbalance, whereas the existing ROCOF-based anti-islanding relay fails to operate during low-power imbalances. Recently, an active ROCOF-based anti-islanding relay concept has been presented to overcome the shortcoming of the existing ROCOF-based anti-islanding relay. The speed (detection time) of the proposed method is 55 ms to detect the islanding situation, it operates fast and hence, its time of operation is equally compatible as per IEEE 1547 standards ($< 2\text{ s}$). The NDZ of the proposed method is less than $\pm 1\%$ power mismatch as depicted in Fig. 12. The NDZ area of the proposed method is much less than the existing OV/UV and OF/UF method. The proposed islanding

Fig. 15 Validation on real-time digital simulator (RTDS)

(a) Overall architecture in real-time testing platform and, (b) GTNET-SKT block used for real-time interfacing with personal computer

As the proposed scheme requires less than three and half cycles to detect the islanding situation, it operates fast and hence, its time of operation is equally compatible as per IEEE 1547 standards

Fig. 16 Comparative assessments of WSEI [6] and TMFI-based anti-islanding relay

detection technique has the following advantages over the existing one:

1. The proposed scheme is capable to detect islanding situation with low mismatch of active/reactive power.
2. As the calculation of TMFI requires utilisation of phasor estimation algorithm and model transform, practical implementation of the proposed scheme is easier than the schemes based on wavelet transform/artificial intelligence.
3. The proposed scheme remains stable during non-islanding situation and hence, avoids nuisance tripping.
4. As the proposed scheme requires less than three and half cycle to detect islanding situation, it operates rapidly and hence, its time of operation is equally compatible as per IEEE 1547 standards.

5 Conclusion

This paper presents a TMF-based high-speed islanding detection for microgrids with high penetration of DGs. The proposed TMFI

clearly distinguishes the islanding events from non-islanding ones under considerations of wide variations in system conditions. The speed of the proposed TMF-based anti-islanding relay is highly improved considering different power mismatch, which is the great advantage over existing active ROCOF-based anti-islanding relay. Further, the performance of the proposed TMF-based index for islanding detection under wide range of power mismatch improves the NDZ of the proposed scheme. Validation on RTDS platform enhances the applicability of the proposed scheme in real-world scenario.

6 References

- [1] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems: IEEE Std. 1547-2003, July 2003
- [2] IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources With Electric Power Systems: IEEE Std. 1547.1, July 2005
- [3] IEEE Draft Application Guide for IEEE Standard 1547: Interconnecting Distributed Resources With Electric Power Systems, IEEE P1547.2/D10, March 2008
- [4] IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected With Electric Power Systems: IEEE 1547.3, November 2007
- [5] Samui, A., Samantaray, S.R.: 'Assessment of ROCFAD relay for islanding detection in distributed generation', *IEEE Trans. Smart Grid*, 2011, **2**, (2), pp. 391–398
- [6] Samui, A., Samantaray, S.R.: 'Wavelet singular entropy-based islanding detection in distributed generation', *IEEE Trans. Power Deliv.*, 2013, **28**, (1), pp. 411–418
- [7] Mahat, P., Chen, Z., Bak-Jensen, B.: 'A hybrid islanding detection technique using average rate of voltage change and real power shift', *IEEE Trans. Power Deliv.*, 2009, **24**, (2), pp. 764–771
- [8] Vieira, J.C.M., Freitas, W., Xu, W., et al.: 'Performance of frequency relays for distributed generation protection', *IEEE Trans. Power Deliv.*, 2006, **21**, (3), pp. 1120–1127
- [9] Jang, S.I., Kim, K.H.: 'An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current', *IEEE Trans. Power Deliv.*, 2004, **19**, (2), pp. 745–752
- [10] Vieira, J.C.M., Correa, D.S., Freitas, W., et al.: 'Performance curves of voltage relays for islanding detection of distributed generators', *IEEE Trans. Power Syst.*, 2005, **20**, (3), pp. 1660–1662
- [11] Singam Hui, L.Y.: 'Assessing SMS and PID schemes of antiislanding with varying quality factor'. Proc. IEEE Power Energy Conf., Putra Jaya, Malaysia, November 2006, pp. 196–201
- [12] Yafouai, A., Wu, B., Kouro, S.: 'Improved active frequency drift antiislanding detection method for grid connected photovoltaic systems', *IEEE Trans. Power Electron.*, 2012, **27**, (5), pp. 2367–2375
- [13] Zeineldin, H.H., Salama, M.M.A.: 'Impact of load frequency dependence on the NDZ and performance of the SFS islanding detection method', *IEEE Trans. Ind. Electron.*, 2011, **58**, (1), pp. 139–146
- [14] Lopes, L.A.C., Zhang, Y.Z.: 'Islanding detection assessment of multiinverter systems with active frequency drifting methods', *IEEE Trans. Power Deliv.*, 2008, **23**, (1), pp. 480–486
- [15] Ropp, M.E., Aaker, K., Haigh, J., et al.: 'Using power line carrier communications to prevent islanding'. Proc. 28th IEEE Rec. Photovoltaic Specialists Conf., 2000, pp. 1675–1678
- [16] Freitas, W., Xu, W., Affonso, C.M., et al.: 'Comparative analysis between ROCOF and vector surge relays for distributed generation applications', *IEEE Trans. Power Deliv.*, 2005, **20**, (2), pt. 2, pp. 1315–1324
- [17] Gupta, P., Bhatia, R.S., Jain, D.K.: 'Active ROCOF relay for islanding detection', *IEEE Trans. Power Deliv.*, 2017, **32**, (1), pp. 420–429
- [18] Pigazo, A., Liserre, M., Mastromauro, R.A., et al.: 'Wavelet-based islanding detection in grid-connected PV systems', *IEEE Trans. Ind. Electron.*, 2009, **56**, (11), pp. 4445–4455
- [19] El-Arroudi, K., Joos, G., Kamwa, I., et al.: 'Intelligent-based approach to islanding detection in distributed generation', *IEEE Trans. Power Deliv.*, 2007, **22**, (2), pp. 828–835
- [20] Lidula, N.W.A., Rajapakse, A.D.: 'A pattern recognition approach for detecting power islands using transient signals-part I: design and implementation', *IEEE Trans. Power Deliv.*, 2010, **25**, (4), pp. 3070–3077
- [21] Najj, W.K.A., Zeineldin, H.H., Alaboudy, A.H.K., et al.: 'A Bayesian passive islanding detection method for inverter-based distributed generation using ESPRIT', *IEEE Trans. Power Deliv.*, 2011, **26**, (4), pp. 2687–2696
- [22] Katiraei, F., Iravani, M.R., Lehn, P.W.: 'Micro-grid autonomous operation during and subsequent to islanding process', *IEEE Trans. Power Deliv.*, 2005, **20**, (1), pp. 248–258
- [23] Zeineldin, H.H., Kirtley, J.L.Jr.: 'A simple technique for islanding detection with negligible non-detection zone', *IEEE Trans. Power Deliv.*, 2009, **24**, (2), pp. 779–786
- [24] Karimi, H., Nikkhajoei, H., Reza, I.: 'Control of an electronically-coupled distributed resource unit subsequent to an islanding event', *IEEE Trans. Power Deliv.*, 2008, **23**, (1), pp. 493–501
- [25] Dwivedi, U.D., Singh, S.N.: 'A wavelet-based de-noising technique for improved monitoring and characterization of power quality disturbances', *Elect. Power Compon. Syst.*, 2009, **37**, (7), pp. 753–769

- [26] Yang, H.-T., Liao, C.-C.: 'A de-noising scheme for enhancing wavelet-based power quality monitoring system', *IEEE Trans. Power Deliv.*, 2001, **16**, (3), pp. 353–360
- [27] Ye, Z., Kolwalkar, A., Zhang, Y., *et al.*: 'Evaluation of anti-islanding schemes based on nondetection zone concept', *IEEE Trans. Power Electron.*, 2004, **19**, (5), pp. 1171–1176
- [28] Vieira, J., Freitas, W., Xu, W., *et al.*: 'An investigation on the nondetection zones of synchronous distributed generation anti-islanding protection', *IEEE Trans. Power Deliv.*, 2008, **23**, (2), pp. 593–600
- [29] Pham, J.-P., Denboer, N., Lidula, N.W.A., *et al.*: 'Hardware implementation of an islanding detection approach based on current and voltage transients'. Proc. IEEE Elect. Power Energy Conf., October 4, 2011, pp. 152–157
- [30] Phadke, A.G., Thorp, J.S.: '2' in *synchronized phasor measurements and their applications* (Springer, New York, 2008), pp. 39–45
- [31] Khodaparast, J., Khederzadeh, M.: 'Three-phase fault detection during power swing by transient monitor', *IEEE Trans. Power Syst.*, 2015, **30**, (5), pp. 2558–2565
- [32] Sadeghkhani, I., Hamedani Golshan, M.E., Mehrizi-Sani, A., *et al.*: 'Transient monitoring function-based fault detection for inverter-interfaced microgrids', *IEEE Trans. Smart Grid*, 2016, **9**, (3), pp. 2097–2107

7 Appendix

The distributed load pattern for Fig. 13a given below
Load in MW(P) are

$$\begin{aligned}
 L_1 = L_8 = 2.5; L_2 = L_3 = L_5 = L_6 = L_9 = L_{11} = 4; \\
 L_4 = L_7 = 3.5; L_{10} = 3; L_{D1} = L_{D7} = 3.5; L_{D2} = L_{D3} = 3; \\
 L_{D4} = 4; L_{D5} = 2.5; L_{D6} = 4
 \end{aligned}$$

Load in MVar(Q) are

$$\begin{aligned}
 L_1 = L_8 = 0.5; L_4 = L_7 = 0.7; L_{10} = 0.6; \\
 L_2 = L_3 = L_5 = L_6 = L_9 = L_{11} = 0.8; \\
 L_{D1} = L_{D7} = 0.7; L_{D2} = L_{D3} = 0.6; \\
 L_{D4} = 0.8; L_{D5} = 0.5; L_{D6} = 0.8
 \end{aligned}$$