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POWER SYSTEMS AND POWER ELECTRONICS

Hybrid parametric islanding detection technique for microgrid system

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Abstract. In microgrid distribution generation (DG) sources are integrated parallelly for the economic and efficient operation of a power system. This integration of DG sources may cause many challenges in a microgrid. The islanding condition is termed a condition in which the DG sources in the microgrid continue to power the load even when the grid is cut off. This islanding situation must be identified as soon as possible to avoid the collapse of the microgrid. This work presents the hybrid islanding detection technique. This technique consists of both active and parametric estimation methods such as slip mode shift frequency (SMS) and exact signal parametric rotational invariance technique (ESPRIT), respectively. This technique will easily distinguish between islanding and non-islanding events even under very low power perturbations. The proposed method also has no power quality impact. The proposed method is tested with UL741 standard test conditions.

Key words: distribution generation; ESPRIT; microgrid; battery energy storage system; islanding.

1. INTRODUCTION

Nowadays the integrated distributed energy sources in the microgrid are inevitable to meet today's power scenario. There are many technical issues associated with the parallel operation of DG sources in microgrids [1]. The most critical issue is the detection of islanding. Islanding should be detected within 2s (as per IEEE 1547 standard) [2]. Otherwise, there may be an equipment failure or hazards to safety personnel. The microgrid should work reliably and be resilient even under islanding conditions. The broad classification of islanding detection is active and passive islanding detection [3, 4]. The active methods involve intentional islanding in which the disturbances are infused into the power system. The parameter analyzed for islanding conditions is voltage signals at the point of common coupling (PCC). The active methods cause power quality deterioration and mainly it is not used for multiple DG integrated systems. The active islanding methods reported in the literature are slip mode frequency shift (SMS), frequency jump, active frequency shift (AFS), variation of active power drift (AFD), Sandia frequency shift, variation of reactive and active power, Sandia voltage shift, etc. The AFD method has a small non-detection zone (NDZ) but increases with an increase in faults and it is not suitable for multiple DG units. The detection time is within 2 s. The SMS has a smaller NDZ, and detection time is also 0.4 s. But this method causes transient instability to the power system. This method is the only method used for multiple inverters and has a low error detection rate [5, 6]. The passive methods detect islanding by measuring the parameters at PCC. The frequency and voltage are measured at PCC under both normal and islanding conditions. The difference between these conditions should be within the threshold value. The value of threshold setting should be taken care of or else there is a problem of detecting other non-islanding events as islanding events and hence leads to false tripping. There is no power quality deterioration in passive methods. The passive detection methods have some limitations such as large NDZ and threshold settings. The passive methods reported in the literature are UVP/OVP, VPJ, etc. The major challenge is large NDZ [7, 8].

Hybrid islanding techniques are reported in the literature to surmount the limitations in the above methods. The hybrid method applies to complex systems. Whenever the active and passive methods are combined, the performance of the whole system is improved to a greater extent. The parametric methods are used for islanding detection in [9, 10]. The parameters such as frequency of oscillation are measured and analyzed to detect islanding. The various parametric methods are ESPRIT, MUSIC, prony, FFT, etc. The ESPRIT method requires two data samples compared to other parametric methods and has good accuracy of detection.

This work presents a novel hybrid islanding detection method combining SMS and ESPRIT. This hybrid technique has the advantages of being used for multiple DG systems, enhanced power quality improvement (ESPRIT), and low NDZ (SMS). Generally, the performance of the islanding technique is analyzed by NDZ, and the factor called quality factor (Q factor) [11]. The NDZ is the interval when the DG unit failed to detect the island. This causes the power mismatch, which is a significant parameter of islanding. The Q factor is the energy dissipation in the RLC circuit. The value of the Q factor is affected by the load. The RLC load has the most effective impact on the Q factor compared to the non-linear load. The Q factor

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is proportional to NDZ. Hence a low Q factor causes low NDZ and vice versa. Therefore, these are the important criteria while designing the islanding detection algorithm.

From the literature review, the research gaps identified are as follows:

- The active islanding method alone causes power quality deterioration and is also not suitable for multiple DG sources.
- The passive islanding techniques have the limitations of large NDZ and annoyance of false tripping. Also, the threshold limit setting is tedious.
  Hence, hybrid islanding techniques incorporating parametric-based methods overcome the limitations.

The major contribution of this work is as follows:

- A novel hybrid islanding detection method combining SMS and ESPRIT is proposed.
- This hybrid technique has the advantages of being used for multiple DG sources, enhanced power quality improvement (ESPRIT), and low NDZ (SMS).
- The proposed method has a lower Q factor compared to other methods and hence low NDZ.
- The NDZ has been analyzed to prove the effectiveness of the proposed strategy.
- The proposed strategy is evaluated in a real-time experiment.

The paper is organized as follows. The introduction part is subdivided into motivation and background, literature review followed by a contribution of this work. After this brief introduction, the methodology of the proposed system comprising of SMS and ESPRIT is discussed in Section 2. Implementations of the proposed system in the MATLAB SIMULINK environment, as well as results obtained, are discussed in Section 3 and Section 4 discusses the details of the experimental verification. The conclusion and the reference sections follow Section 5.

2. METHODOLOGY

2.1. Sliding mode shift frequency (SMS)

In SMS the feedback given to the phase of the voltage at PCC is positive. This makes the frequency shift. If the islanding occurs in the microgrid system, there is a deviation in the frequency and this deviation may lead to the increase in phase error of the phase locked loop (PLL). Therefore, PLL may lose its reliable operation. This unreliable operation of PLL continues until the phase angle error between the load and the inverter becomes zero [12]. The inverter current is given in equation (1)

$$I_{\text{inv}} = I\sin(\omega t + \theta_{sms}), \tag{1}$$

where

$$\theta_{sms} = \frac{2\pi\theta_m}{360}\sin\left(\frac{\pi f - f_g}{2f_m}\right),$$

θ_m is the phase shift (maximum), f_m is the frequency occurring at θ_m, f_g is the system frequency (50 Hz).

Whenever islanding occurs, there is a drift in the frequency of PCC either in the upward or downward direction. The system is stable whenever the difference between the phase angle of load and inverter is zero. And at this point, the system is stable as shown in equations (2) and (3)

$$\theta_L + \theta_{sms} = 0, \tag{2}$$

$$\theta_L = -\tan^{-1}\left(\omega C - \frac{1}{\omega L}\right). \tag{3}$$

Figure 1 reveals that the intersection point of load and inverter phase angle response to the frequency may either be stable or unstable. The point is moving along with the perturbation, and if it lies within the threshold value, i.e. between 49.5 Hz and 50.5 Hz, then the SMS algorithm is not able to detect the islanding technique. Hence, ESPRIT algorithm is used along with SMS to overcome the limitations of the SMS technique.

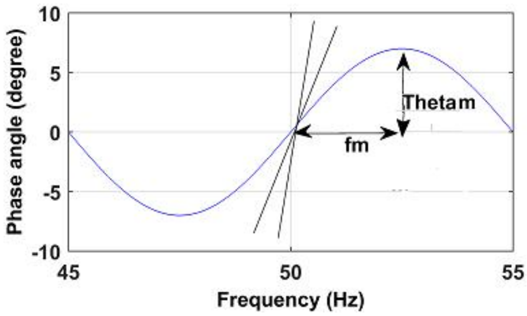

Fig. 1. Frequency V_s phase angle

2.2. ESPRIT

ESPRIT method decomposes signals into sinusoids [13]. The sinusoids are decomposed by finding the autocorrelation mat. This is mathematically represented as

$$x(n) = \sum_{i=1}^{M} Aie^{(\xi i + j\omega i)n + J\varphi i} + z(n), \tag{4}$$

where A is the amplitude, ξ is the damping factor, ω is the frequency, $z(n)$ and is noise.

The ESPRIT algorithm initiates SMS after the threshold level is within the range and the phase angle calculated by SMS is used to calculate the oscillation frequency of the PCC signal as shown in Fig. 2. Depending upon the oscillation frequency, the trip signals are generated. The performance characteristics of different algorithms are shown in Table 1.

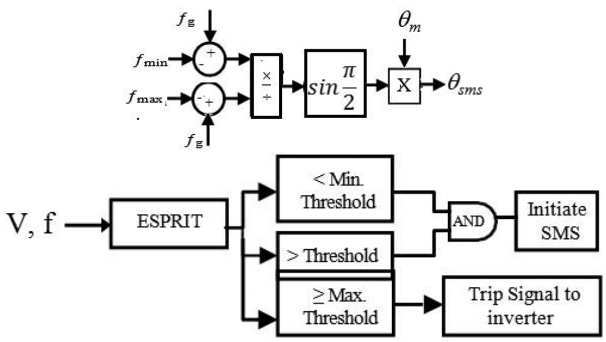

Fig. 2. Proposed hybrid ESPRIT-SMS method

Table 1

Comparison of the performance characteristics of different algorithms

Method	Computational time	Accuracy
FFT	Fast	Low
ESPRIT	Slow	High
SMS	Medium	Medium
ESPRIT-SMS	Fast	High

3. RESULTS AND DISCUSSION

The simulated results are analyzed for different scenarios in MATLAB/SIMULINK. The MATLAB model is shown in Fig. 3.

3.1. NDZ analysis

The NDZ is vital criteria to prevent the effectiveness of the proposed method [14, 15]. The NDZ is calculated using the quality factor (QF) and it is expressed using frequency. The NDZ is analyzed by the phase angle of the inverters. The upper bound and lower bound of the NDZ is obtained in equation (5).

$$f_o = \frac{2Q_f f}{2Q_f + \theta_{sms}(f)}, \tag{5}$$

where f_o – frequency of load, Q_f – quality factor, f – nominal frequency, θ_{sms} – the sliding mode shift frequency phase response

If the frequency of loads is $f_o < f_g$, then the stable operating condition is $f < f_g$. Similarly, if the frequency of loads is

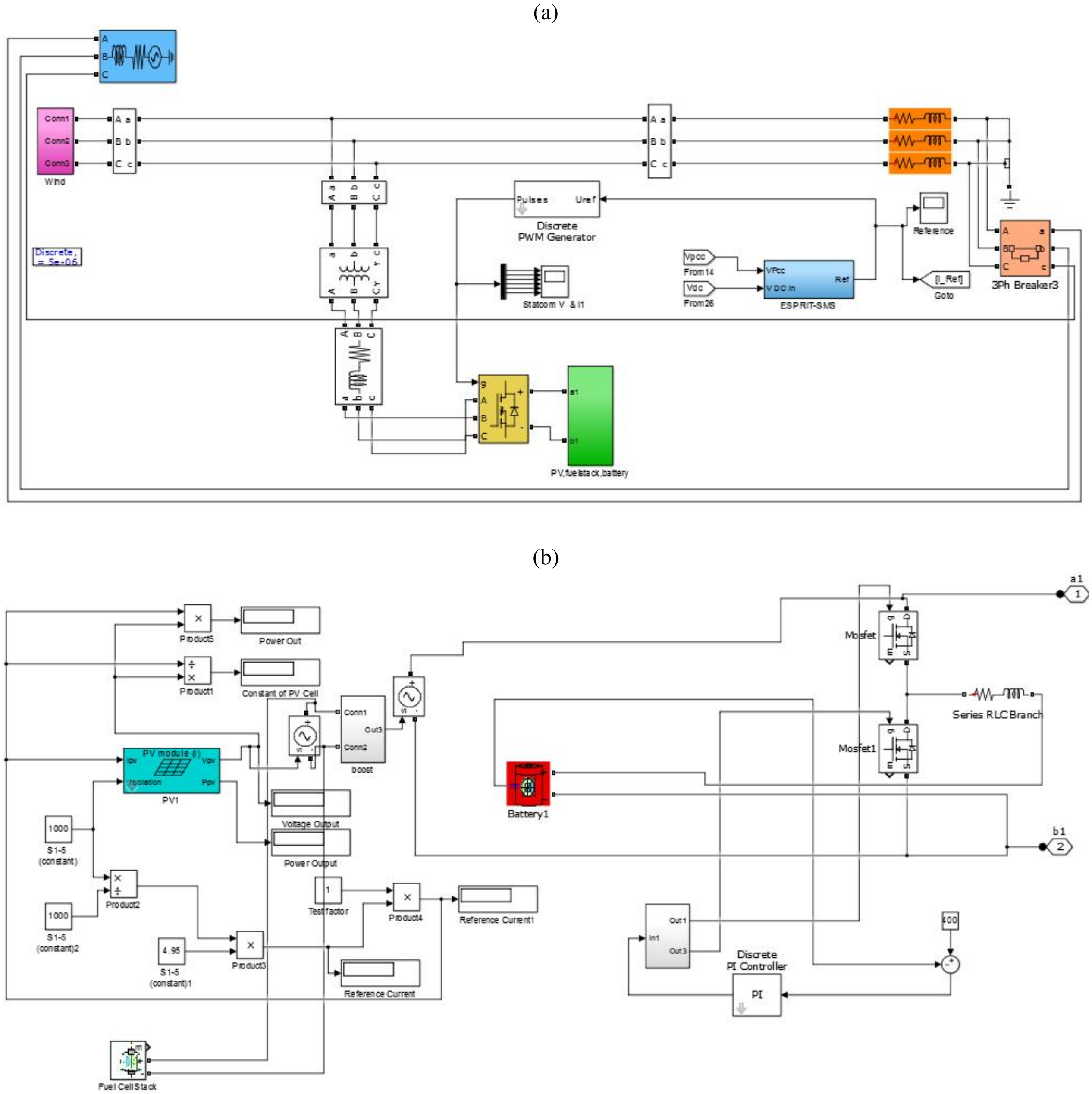

Fig. 3. a) Proposed system b) DG (PV, fuel cell, battery)

$f_o > f_g$, then the stable operating condition is $f > f_g$. Based on the above criteria, the boundary of NDZ is determined.

The NDZ of the ESPRIT-SMS method is shown in Fig. 4. The proposed system detects the islanding condition when the $QF < 2.8$. Figure 4 reveals that the proposed system has a lower NDZ. Figure 4 shows the NDZ with different operating frequencies of 50.5 Hz and 49.5 Hz. Even for the high QF, i.e. $QF = 2.8$, the proposed method has no NDZ and avoids unwanted tripping. For $QF = 2.5$, the proposed system detects islanding with no NDZ.

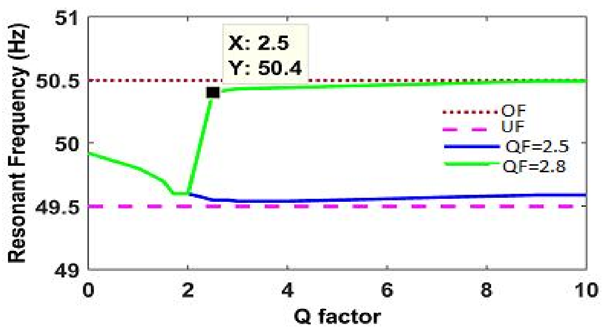

Fig. 4. NDZ of the proposed method

Scenario 1. Power mismatch

In this scenario, the real and reactive power is decreased or increases gradually to analyze the system for islanding and non-islanding condition. The islanding condition is detected by a change in voltage and frequency.

1. The real power is gradually increased to $+5\%$, $+10\%$, $+20\%$ of actual real power.
2. The reactive power is gradually reduced to -5%, -10%, -20% of actual reactive power.

The effect of power mismatch is analyzed by a change in frequency. The change in frequency and voltage cannot be noticed by conventional relays as the controller tries to compensate for the real and reactive power. At $t = 0.2$ s, the active power increases to 5% of actual real power by inserting a resistive load. The frequency is changed beyond the threshold limits of maximum and minimum frequency (i.e. 50.5 Hz and 49.5 Hz). The active power is gradually increased to 10% and 20%. Figure 5 shows the active power changes. Figure 6 shows the frequency of the PCC voltage for the real power mismatch.

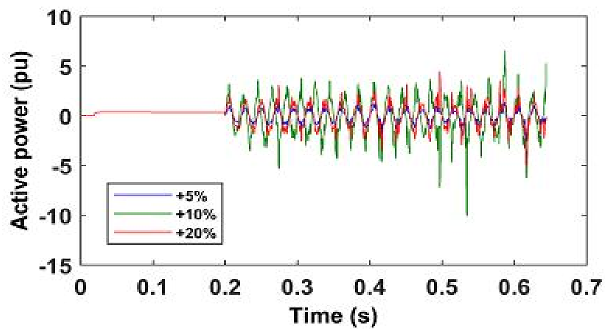

Fig. 5. Active power changes at $t = 0.2$ s

When the power mismatch occurs, the ESPRIT algorithm estimates the oscillation frequency and checks whether it is within the threshold value. If it is beyond the threshold value, the algorithm trips the breaker for islanding the DG unit. If the oscillation frequency is within the threshold, then the SMS method is initiated to find the phase angle and it is used by PLL to calculate the frequency for the ESPRIT method. Figure 5 reveals that the islanding occurs at 0.2 s and the proposed algorithm is detected at 0.25 s and generates a trip signal at 0.28 s (protection time). Hence it detects the islanding within 0.05 sec. The detection time of the other algorithm is shown in Table 2.

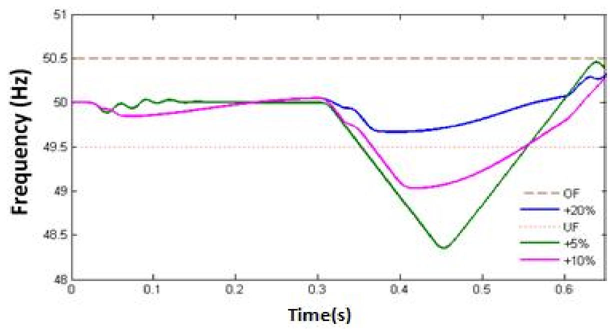

Fig. 6. Frequency changes due to active power mismatch

Similarly for reactive power mismatch the actual reactive power is gradually reduced to 5%, 10% and 20% by changing load. The reactive power variation and frequency of the PCC voltage for reactive power mismatch is shown in Figs. 7, 8 respectively. The islanding detected at 0.28 s. Hence the detection time is 0.08s for -20% power mismatch.

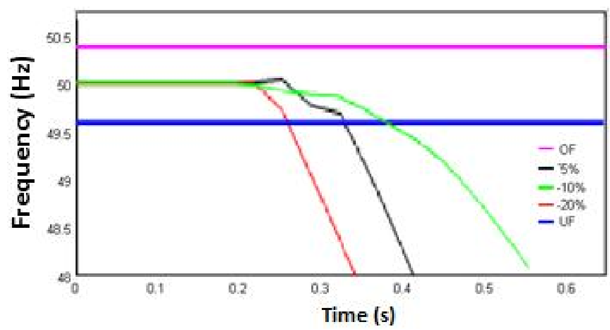

Fig. 7. Reactive power changes at $t = 0.2$ s

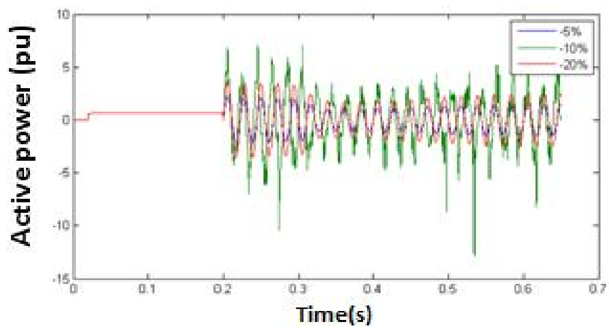

Fig. 8. Frequency changes due to reactive power mismatch

Table 2
Detection and protection time of different islanding techniques under power mismatch

Scenario	Cases	Voltage frequency protection	Detection time			Protection time by ESPRIT-SMS
			SMS	ESPRIT	ESPRIT-SMS	
Active power mismatch	+5%	0.15 s	0.28 s	0.09 s	0.05 s	0.08 s
	+10%	0.16 s	0.19 s	0.11 s	0.06 s	0.09 s
	+20%	0.16 s	0.23 s	0.14 s	0.08 s	0.11 s
Reactive power mismatch	-5%	0.15 s	0.28 s	0.09 s	0.05 s	0.08 s
	–10%	0.16 s	0.19 s	0.11 s	0.06 s	0.12 s
	–20%	0.16 s	0.23 s	0.14 s	0.08 s	0.12 s

Scenario 2. Influence of *Q* factor

The Q factor is measured using the relation between reactive power consumption and output DG power [16]. The load parameters for different QFs are shown in Table 3. As per IEEE standards, the detection of islanding is effective only when the Q factor is in the range of $1 < \text{QF} < 2.5$. The islanding is detected when the Q factor changes even under zero power mismatch as shown in Fig. 9 and the protection time for different algorithms is shown in Table 4.

Table 3
Load parameters for different QF

Q_f	R (kΩ)	$L(H)$	C (μF)
1	5.123	6.34	0.92
1.5	4.654	2.32	2.33
1.7	4.654	3.23	1.34
2	4.564	2.24	1.63
2.5	4.565	2.53	1.72

Table 4
Detection and protection time of different islanding techniques under varying Q factors

Scenario	Q factor	Voltage frequency protection	SMS	ESPRIT	ESPRIT-SMS
Q factor variation with RLC load	1	0.13 s	0.22 s	0.1 s	0.09 s
	1.5	0.13 s	0.16 s	0. 11 s	0.08 s
	1.7	0.13 s	0.16 s	0.12 s	0.09 s
	2	0.13 s	0.17s	0.13 s	0.09 s
	2.5	0.15 s	0.19 s	0.12 s	0.11s

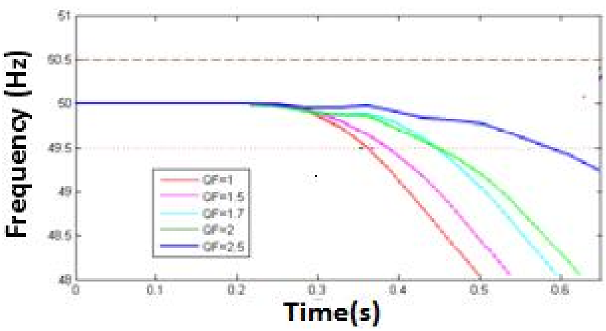

Fig. 9. Frequency variation for varying Q_f

Scenario 3. Non-islanding event

Capacitor switching

To analyze the non-islanding event, the capacitor banks of 10 kVAR and 20 kVAR are inserted suddenly at $t = 0.2$ s and rejected at $t = 0.5$ s. There is an oscillation in frequency when the capacitor is switching ON and OFF. The change in frequency is considered as islanding by conventional techniques and leads to false tripping [15]. The proposed algorithm detects the change in frequency and checks whether it is within the threshold value. If it is within the threshold value, then the SMS technique is initiated to detect the islanding. Figure 10 shows the load current, and it clearly reveals that the capacitor switching event does not initiate the false tripping. Figure 11 shows the frequency of PCC voltage for capacitor switching.

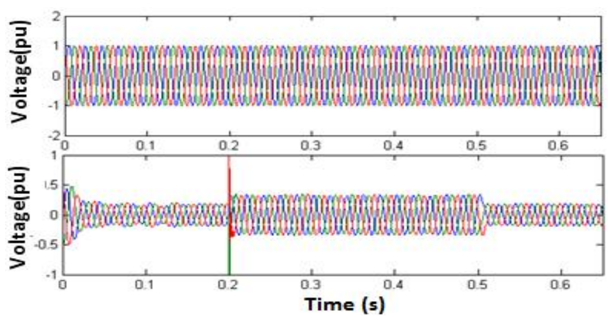

Fig. 10. Voltage and current at PCC for capacitor switching

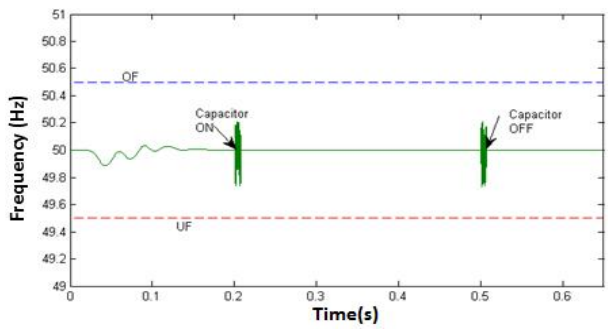

Fig. 11. Frequency for Capacitor switching

Load switching

Load switching influences the PCC voltage and frequency. This is not an islanding event and hence the islanding detection technique can clearly differentiate between islanding and non-islanding events. At $t = 0.2$ s, a load of 20 kVA is suddenly injected and removed at 0.5 s as shown in Fig. 12. The frequency is changed only at that transient second as shown in Fig. 13. The proposed algorithm is a non-islanding event, i.e. load switching and avoids false tripping.

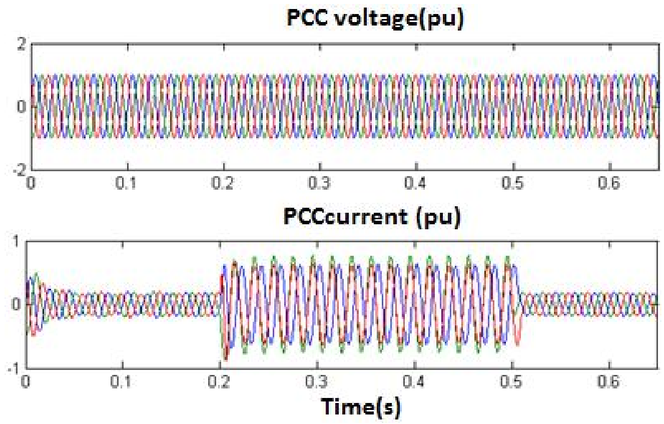

Fig. 12. Voltage and current at PCC for load switching

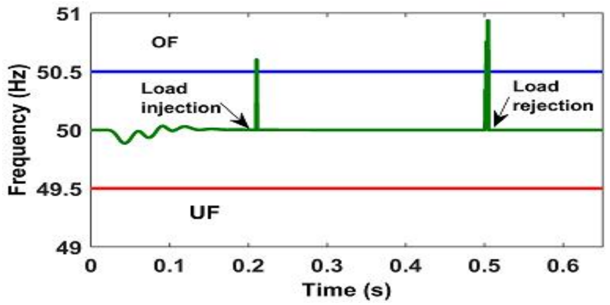

Fig. 13. Frequency for load switching

The simulation results clearly reveal that the ESPRIT-SMS islanding method detects islanding conditions effectively compared to other methods. This method also has a low impact on power quality compared to other active methods. The NDZ is also small compared to other methods. The detection time is also low compared to other methods. The THD of the current at PCC is compared for SMS and ESPRIT-SMS in Figs. 14 and 15, respectively. Figures 14 and 15 show that the THD is lower compared to other active islanding detection methods.

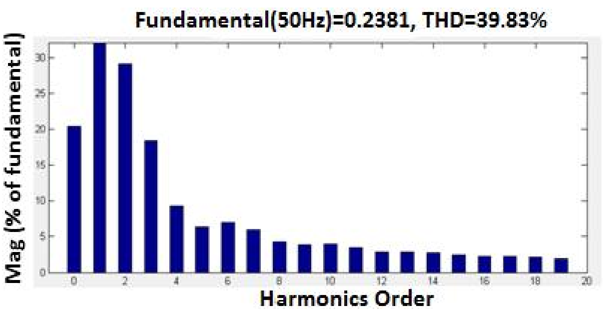

Fig. 14. THD of PCC current for SMS method

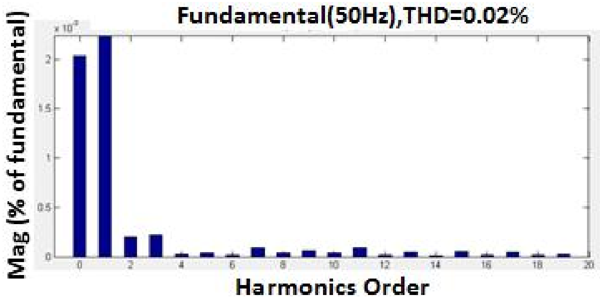

Fig. 15. THD of PCC current for ESPRIT-SMS method

Scenario 4. Multiple distributed generators

The three DG units are considered in this work to evaluate the performance of the proposed system. The scenario considered is shown in Table 5. The islanding happens at 0.15 s. This is a complicated system as it involves three DG units [17]. The cause of islanding is the loss of synchronization of DG units when operated in parallel. The proposed technique detects it as a non-islanding event and the load is not disconnected from the system as shown in Fig. 16.

Table 5
Multiple DG units

DGs	Power at inverter	Power at load	
DG1	20 kW	20 kW	Islanding happened at 0.15 s.
DG2	20 kW	10 kW	
G3	20 kW	10 kW	

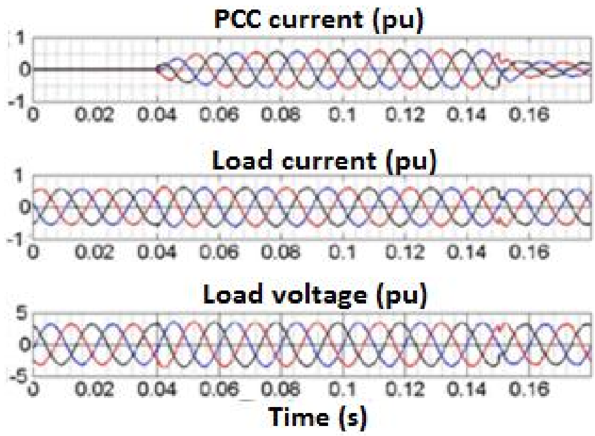

Fig. 16. Voltage and current for multiple DG unit operation

The islanding occurs when the DG source wind is disconnected at 0.1 s as shown in Fig. 17. The impedance at the PCC also changes due to the disconnection of the wind source. The ESPRIT-SMS estimates the oscillation frequency as 2 Hz. Hence it is an islanding event. The ESPRIT-SMS detects this islanding event and disconnects the grid. The protection time is 0.06 s, and it is within 2 s as per IEEE 5147 standard.

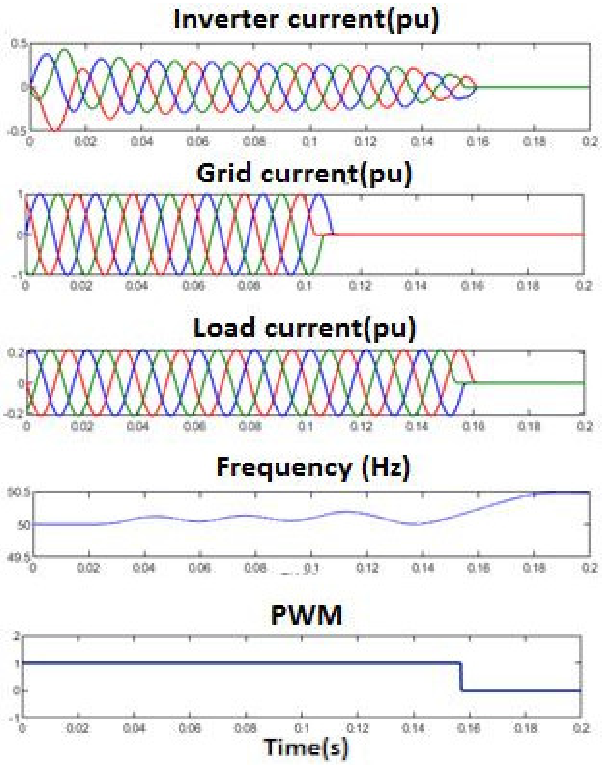

Fig. 17. Voltage and current when DG wind is disconnected

4. EXPERIMENTAL RESULTS

The proposed ESPRIT-SMS method is implemented in the 1 kW inverter with a grid simulator. The controller and islanding detection algorithm is implemented in HIL simulation, and the switching signals are sent to the inverter through the HIL coder. The islanding is initiated by changing the Q factor by varying the reactive power. Figure 18 shows the PCC voltage and current. The islanding happens at 0.4 s, there is no change in frequency as shown in Fig. 19 after islanding. Hence the conventional SMS failed to detect islanding under varying Q factors. Figure 20 shows the PCC voltage and current under islanding conditions happen at 0.4 s. The proposed algorithm detects the islanding and disconnected from the system at 0.6 s. ESPRIT-SMS gives encouraging results in detecting islanding within the required time.

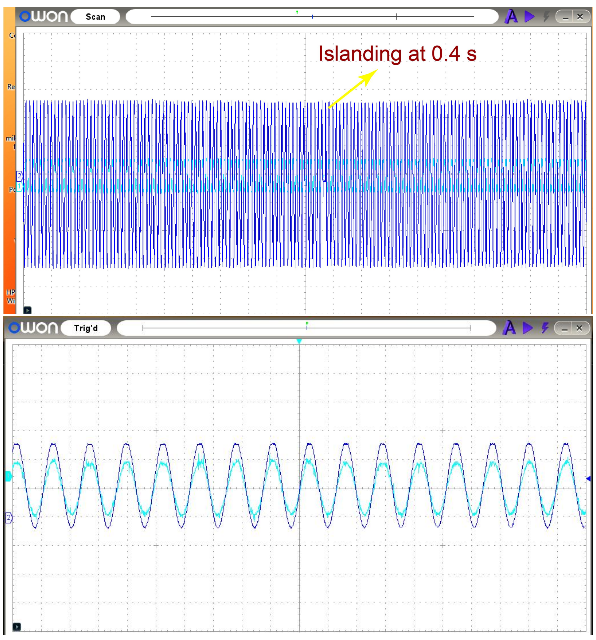

Fig. 18. PCC Voltage and current for SMS technique

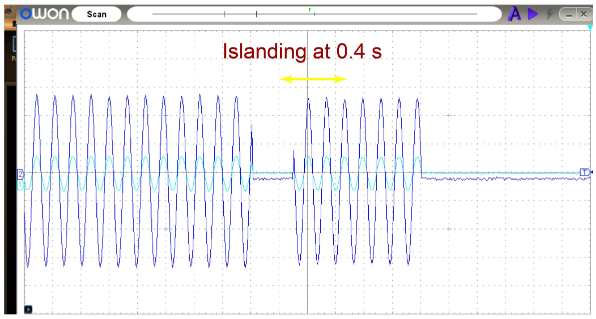

Fig. 19. Load voltage and current for SMS technique

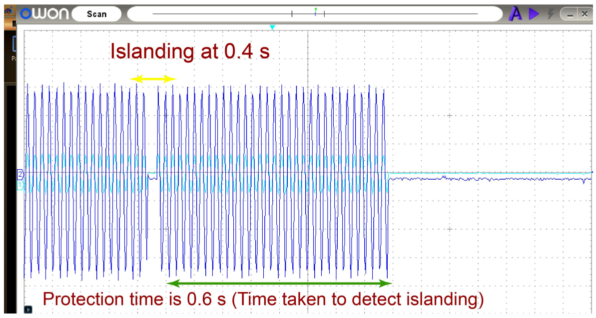

Fig. 20. PCC voltage and current of the inverter $Q = 2.5$ using ESPRIT-SMS

5. CONCLUSION

The hybridization of active and parametric passive islanding detection methods, i.e ESPRIT-SMS is anticipated in this work. This method reduces the impact of power quality deterioration compared to active methods. This method also has a small NDZ compared to other passive methods. This method is also used for multiple DG systems. This is the main advantage of the proposed method. This method also analyses the effect of a quality factor on islanding detection and properly distinguishes between islanding and non- islanding events. The analysis is performed by load switching and capacitor switching scenarios. Therefore, the proposed hybrid method reduces the limitations and disadvantages of active and passive methods. This method also detects islanding with less time compared to other islanding detection methods and satisfies the UL741 standard test conditions.

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