Adaptive Active Frequency Drift Islanding Detection for PV Inverters

Khaled Al-Maitah

Electricity Distribution Company (EDCO), Jordan

kmaitah@edco.jo

ABSTRACT. *The penetration level of renewable energy resources (RESs), such as photovoltaic (PV) plant and Wind plant (WP), in the power system is increasing exponentially, such plants connected with grid via inverter. This increasing rises from the attention about the undetected islanding operation. The islanding can be defined, according to IEEE std.1547, as a situation in which part of the power system becomes isolated from the rest of the system.*

Islanding detection methods (IDMs) are divided into passive and active IDM. Among active IDMs, active frequency drift (AFD) is the most IDM applied in the literatures. AFD bases on injecting a distortion waveform to the original waveform of inverter reference current, this to drift the inverter frequency during islanding event to be out of the nominal range. Due to the distortion waveform high harmonics will be injected to the system. Recently, to decrease this harmonic an improved active frequency drift (IAFD) was presented in the literature. IAFD uses a constant step change in in 2nd and 4th quarters of the inverter reference current. IAFD has lower total harmonic distortion (THD) injected to the system compared with conventional AFD.

Since the non-detection zone (NDZ) has been considered as a performance measure for any IDM. The IAFD method did not introduce any improvement in NDZ over the AFD method. Thus, in this paper an adaptive step change is proposed to improve the performance of IAFD method, where a positive feedback of voltage frequency is used in this work to vary the distortion factor of IAFD. The adaption manner of step change enhances in increasing of injected perturbations during islanding event only. Which, it will reduce the NDZ during islanding event and decrease the injected THD in steady state operation. The proposed method has been theoretically analyzed and modeled using MATLAB/Simulink environment. As a result, the proposed method improves the performance of IAFD regard to the non-detection zone (NDZ).

1. Introduction. The penetration level of renewable energy resources (RESs), such as photovoltaic (PV) plant and Wind plant (WP), in the power system is increasing exponentially,

such plants connected with grid via inverter [1], [2]. This increasing rises from the attention about the undetected islanding operation [3]. The islanding can be defined, according to IEEE std.1547 [4], as a situation in which part of the power system becomes isolated from the rest of the system.

The islanding situation was divided into intentional islanding and unintentional islanding. The intentional islanding is doing by operators for urgent and routine maintenance. The unintentional islanding occurs due to fault in the network. If these situations are not detected, serious problems may occur such as manpower safety, protection, and power quality problems [5].

The IEEE Standard 929 [6] and Standard 1547 [4] restrict the normal operation parameters (voltage, frequency, and total harmonic distortion (THD), and specify the allowed time to detect the islanding situations. Additionally, the standards suggest steps and testbed system to test the islanding detection methods (IDM).

IDM for gride-tie inverter can be classified into remote and local methods. Remote methods are those methods which use the communication infrastructure and located at utility level. Remote methods are characterized by high reliability and depend on the communication system reliability, but its implementation is expensive and complex. On the other hand, the local methods are those methods that utilize the measured quantities in the local level and located inside each distributed generation (DG) unit or grid-tie inverter. In more details, the local IDM are further divided to passive and active IDM.

Passive IDM are utilizing the measured parameters (voltage, frequency, active and reactive power, THD, ...etc.), to detect the islanding events, by comparing the measured parameters with predefined threshold values. The under/over frequency (UOF), under/over voltage (UOV), active power variation IDMs were presented in [1], [7], [8]. IDM by reactive power was presented in [9]. Rate of change of frequency IDM was presented in [10]. Voltage with THD IDM was presented in [11]. Power factor variation with voltage IDM was presented in [12]. Although, these methods do not have any impact on the power quality, because there is no control action, it was characterized by large Non-detection zone (NDZ) [5]. NDZs are determinable conditions, IDM may fail to detect islanding situation at those conditions. NDZ has been considered as a performance measure for any IDM.

Active methods were proposed in the literatures to increase the performance of islanding detection. The active methods have lower NDZ compared with passive methods [13]. The operation principle of active methods based on injects a small distortion signal in the system to force at least one of the system parameters out of the normal operation limits during islanding events. Although, the injected distortion causes some of issues in power quality specially for THD, the active methods are the most methods among IDMs reported in the literatures, that because it is effective on the NDZ reducing.

The active IDMs further can be classified according to its target actions to active voltage drift (AVD) method and active frequency drift (AFD) method [14], [15]. In AVD IDM, the injected perturbation will be able to drift the voltage at the point of common coupling (PCC) to activate

the UOV protection relay during islanding events [1]. AFD IDM able to drift the frequency to activate the UOF protection relay during islanding events. AFD method was proposed in [16], [17]. Where, the AFD method has been mathematically analyzed, as a result the NDZ of AFD method highly depends on the load quality factor (Q) and zero conduction time (tz) in the distorted current waveform. The NDZ reduced with large tz. On the other hand, the large value of tz ¬is resulting higher THD. To reduce NDZ, an AFD with positive feedback (AFDPF), which aka as sandia frequency shift (SFS), was proposed in [18], [19]. SFS is expansion of the AFD method [14]. In SFS a positive feedback of frequency of the voltage at PCC is used to change the chopping fraction (Cf). Where, Cf is a function of the frequency deviation between the voltage frequency at PCC and the nominal frequency [18]. An improved active frequency drift (IAFD) with new distortion waveform, based on constant step change in 2nd and 4th quarters of the inverter reference current waveform, was proposed in [13], the IAFD injects 30% less THD compared with conventional AFD, but the authors limit their study in single PV grid connected inverter. To the best of our knowledge, the performance of using of positive feedback of voltage frequency with IAFD did not study in the literatures.

In this paper a modified IAFD method is proposed. The proposed method is extension of IAFD method, where a positive feedback of frequency of the voltage at PCC has been added to the IAFD. This modification enhances the performance of IAFD by further reducing the NDZ and further decreasing of the injected THD to the system at steady state operation. Where, the step change in 2nd and 4th quarters of the inverter reference current waveform will be a function of frequency deviation between the PCC voltage frequency and nominal frequency. The adaption manner of step change enhances in increasing of injected perturbations during islanding event only. Which, it will reduce the NDZ during islanding event and decrease the injected THD in steady state operation.

2. Review of Active Frequency Drift AFD:

For better understand the proposed method, an overview of conventional active frequency drift (AFD) and the improved active frequency drift (IAFD) method were presented in this section. The main principle of conventional AFD bases on injecting a distortion waveform to the original waveform of inverter reference current, that to drift the inverter frequency during islanding event. The original, distorted, and AFD reference current waveforms are shown in Fig.1. By distorted waveform, a permanent drift will be produced to drift the operation frequency toward the resonance frequency of the load and force the frequency to be out of the normal operation limits.
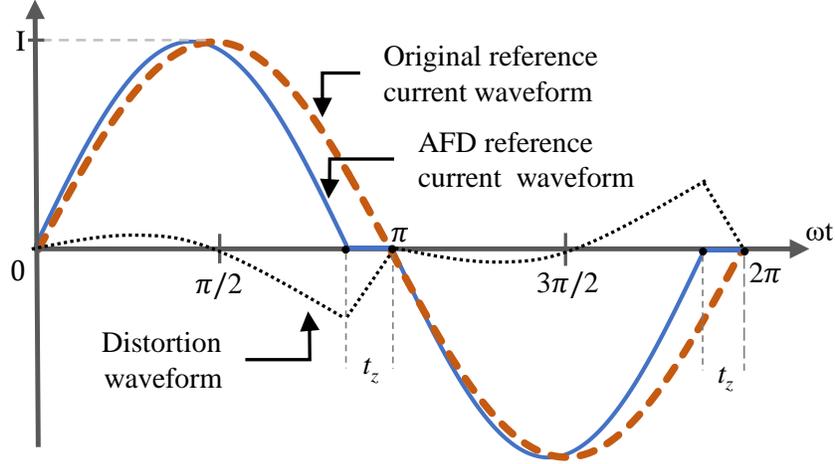
FIGURE.1 Original, AFD, and distortion waveform

The distortion level can be controlled by zero-conduction time (t_z) which can be expressed as chopping fraction (C_f) as in (1), where the greater t_z, the greater C_f hence a larger distortion will be introduced to the reference current.

$$C_f = \frac{t_z}{T} \tag{1}$$

Where, t_z is the zero-conduction time and T is the original signal period (2π). Thus, the reference current of AFD shown in Fig.1 can be expressed as in (2),

$$i_{AFD}(t) = \begin{cases} I\sin(\omega't) & \rightarrow & 0 \leq \omega t \leq \pi\text{-}t_z \\ 0 & \rightarrow & \pi\text{-}t_z \leq \omega t \leq \pi \\ I\sin(\omega't) & \rightarrow & \pi \leq \omega t \leq 2\pi\text{-}t_z \\ 0 & \rightarrow & 2\pi\text{-}t_z \leq \omega t \leq 2\pi \end{cases} \tag{2}$$

Where $\omega' = \omega\left(\frac{1}{1\text{-}C_f}\right)$

When grid-tie inverter connected with local parallel RLC load and an islanding event is occurred, the operation frequency will drift to the resonance frequency of the local load. Thus, phase angle criteria can be applied ($\theta_{load} = \theta_{AFD}$) as in (3), where $\theta_{AFD} = 0.5\pi C_f$ [16].

$$arg\,[R^{-1} + (j\omega L)^{-1} + j\omega C]^{-1} = 0.5\pi C_f \tag{3}$$

Where the operator arg determine the angle of local load in radian, C_f is the chopping fraction as given in (1). However, this method is effective, but it has a large NDZ for some RLC load combinations, and it injects high harmonics to the system. To overcome these issues a positive feedback was proposed in [16] to vary the chopping fraction (C_f) as in (4).

$$C_f = C_{f_o} + \beta(f_g - f) \tag{4}$$

Where, C_{f_o} is the initial value of chopping fraction, f is the nominal frequency (50 or 60 Hz), f_g is the grid frequency at PCC, and β is the acceleration rate. These improves the NDZ for different load types, but still effect on the power quality by introducing harmonic components. Where according to [20], in AFD, the THD $\approx Q/P \approx C_f$. To drive the frequency out of limit, a

large $\Delta Q/P$ is needed, consequence a large C_f is required, then high harmonics will be injected to the system [21-22].

To decrease the THD produced from AFD an IAFD, that uses different distortion signal, was proposed in [13]. IAFD uses a new distortion waveform, it bases on constant step change in 2nd and 4th quarters of the inverter reference current waveform. The waveforms of original, distorted and IAFD reference current waveforms are shown in Fig.2.
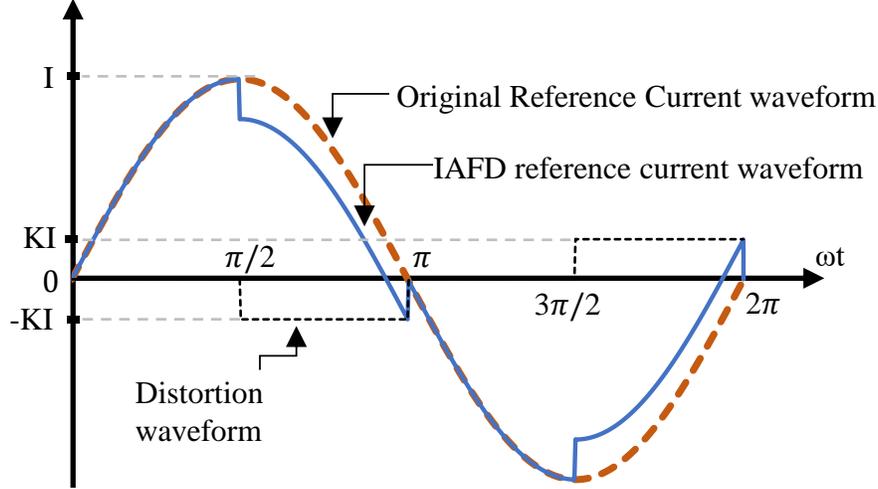

FIGURE.2 Original, IAFD, and distortion waveforms

The reference current waveform of IAFD can be expressed as,

$$i_{IAFD}(t) = \begin{cases} I\sin(\omega t) & \rightarrow & 0 \leq \omega t \leq \pi/2 \\ I\sin(\omega t) - KI & \rightarrow & \pi/2 \leq \omega t \leq \pi \\ I\sin(\omega t) & \rightarrow & \pi \leq \omega t \leq 3\pi/2 \\ I\sin(\omega t) + KI & \rightarrow & 3\pi/2 \leq \omega t \leq 2\pi \end{cases} \tag{5}$$

Where, K is a constant represents the detorsion factor. IAFD method decreases the injected THD to about 30% compared with AFD method. However, according to [13] the THD produced by IAFD is expressed as,

$$\text{THD}_{IAFD} = \sqrt{\frac{K^2 (\pi^2 - 8)}{\pi^2 - 4\pi K + 8K^2}} \tag{6}$$

In addition, the phase angle θ_1 of the fundamental IAFD reference current was expressed in [13] as in (7),

$$\theta_1 = \tan^{-1}\left(\frac{2K}{\pi - 2K}\right) \tag{7}$$

Where, K is a constant represents the detorsion factor. Since the active power and reactive power of sinusoidal waveform are defined as in (8) and (9), respectively, the Q/P ratio can be expressed as in (10),

$$P = V . I_1 .cos(\theta_1) \tag{8}$$
$$Q = V . I_1 .sin(\theta_1) \tag{9}$$

$$\frac{Q}{P} = tan(\theta_1) = \frac{2K}{\pi - 2K} \tag{10}$$

Where, I_1 and θ_1 are the rms value and the phase angle of the fundamental reference current waveform. As a comparison between AFD and IAFD, THD $\approx Q/P$ for AFD, consequence the maximum allowable value of Q/P is (5%) that because THD limitation. On the other hand, based on (10) to produce $Q/P = 5\%$ in IAFD the distortion factor will be $K = 0.075$. Thus, based on (6) the THD will be about 3.4%. In other word, the IAFD success in decrease the THD as compared with conventional AFD.

Regarding to the NDZ, the IAFD method did not introduce any improvement in NDZ over the AFD method, Where the NDZ of IAFD approximately equal to the NDZ of AFD. This has motivated the present work to modify the IAFD to decrease NDZ.

3. The Proposed Method

As stated in the previous section, the distortion waveform in IAFD was a constant step change in 2nd and 4th quarters, where the distortion factor K in IAFD was constant. The proposed method in the present work, a positive feedback of the grid voltage frequency has been used to vary the distortion factor K. Consequently, the distortion factor K is a function of frequency deviation between the grid frequency f_g and nominal frequency f, this can be given as,

$$K(f) = K_o + \beta(f_g - f) \tag{11}$$

Where, K_o is the initial value of distortion factor, β is the accelerating factor of the proposed method, f_g is the grid frequency at PCC, and f is the nominal frequency (50 or 60 Hz). Thus, the phase angle θ_1 of the fundamental reference current will be as,

$$\theta_1 = tan^{-1}\left(\frac{2K(f)}{\pi - 2K(f)}\right) \tag{12}$$

Where, $K(f)$ is the distortion factor as given in (11). The angle of local load can be calculated as,

$$\theta_{load} = tan^{-1}\left(Q_f\left[\frac{f_0}{f} - \frac{f}{f_0}\right]\right) \tag{13}$$

Where, Q_f is the load quality factor. f_0 is the resonance frequency of the load. To determine the NDZ of the proposed method, the phase angle criteria can be applied ($\theta_1 = \theta_{load}$) as,

$$tan^{-1}\left(\frac{2K(f)}{\pi - 2K(f)}\right) = tan^{-1}\left(Q_f\left[\frac{f_0}{f} - \frac{f}{f_0}\right]\right) \tag{14}$$

Thus, after reorganizing the equation (14), the NDZ of the proposed method can be determine by solve the following second order equation,

$$f_o^2 - \frac{2fK(f)}{Q_f(\pi - 2K(f))}f_o - f^2 = 0 \tag{15}$$

Where, $K(f)$ is the distortion factor as given in (11) and f_o is the resonance frequency of load. To calculate the NDZ of the proposed method, the islanding frequency f is first adjusted to a threshold frequency (f_{min} or f_{max}). Then the value of Q_f is varied, and finally the resonant frequency f_o of the load is calculated at the threshold of the NDZ.

In the proposed method the distortion factor K is continuously variated by the acceleration rate β. When the acceleration rate is zero the proposed method becomes an IAFD. However, the NDZ of the proposed IDM versus the quality factor Q_f, with distortion factor $K = 0.105$, nominal frequency $f = 60$ Hz, and difference acceleration rate β, is presented in Fig. 3.
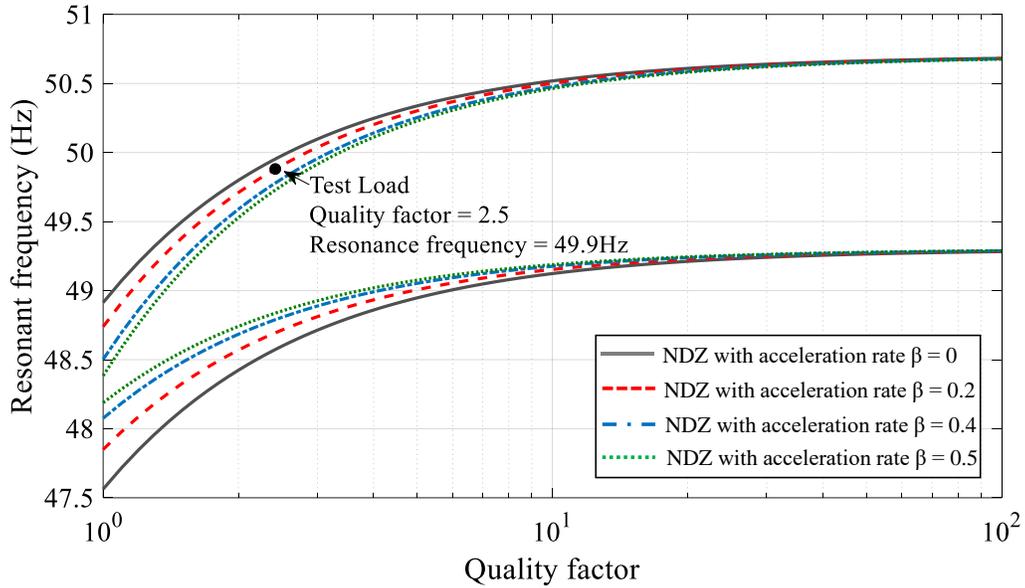

FIGURE. 3. NDZ for the proposed methods with K = 0.105 and difference acceleration rate β.

As seen in Fig.3, the more acceleration rate, the smaller NDZ. By using acceleration rate $β$ zero the NDZ of the proposed method like as the NDZ in IAFD. Additionally, at steady state operation (grid frequency f_g equal to the nominal frequency f) the acceleration term in (11) will be zero, that is mean there no additional THD will be injected in the system. Once the frequency deviated away from the nominal frequency the distortion factor starts to vary in linear manner with frequency deviation, which decrease the NDZ to detect the island situation.

4. Simulation Results

To verify the proposed method, a grid connected single-phase inverter with parallel RLC load has been considered. The power circuit of the test model was presented in Fig.4. the system parameters are listed in Table I. The test model and the proposed method were modeled in MATLAB/Simulink. The inverter was modeled as H-bridge IGBT thyristor with PWM current control. The LCL filter was designed to limit ripple in the inverter output current and to limit the THD to be less than 5%.
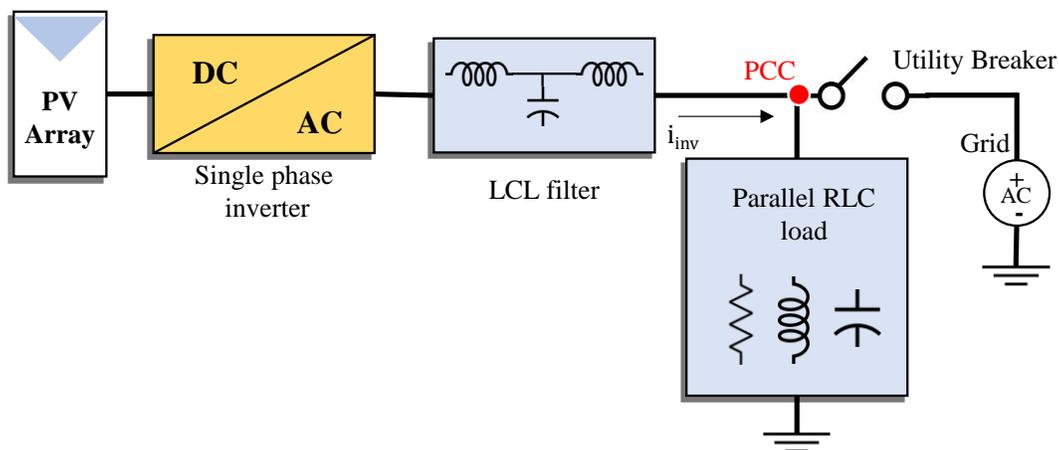
FIGURE. 4. Power circuit of the test model.

TABLE 1. SYSTEM PARAMETERS

Parameter	Value
DC Voltage	400 V
AC grid voltage	300 V
Grid frequency f	50 Hz
Switching frequency fs	10kHz
L_1 for LCL filter	4.06mH
L_2 for LCL filter	4.35mH
C for LCL filter	6.01µF
Initial distortion factor Ko	0.105
Accelerating factor β	0.05
Test load	$f_o = 49.9$Hz, $Q_f = 2.5$

The voltage waveform at PCC and inverter output current at normal operation (without islanding) are presented in Fig. 5 (a) and (b), respectively. It observed that the inverter output current is distorted based on the proposed method. Where, at normal operation the distortion factor K is equal to the initial distortion factor ($K_o = 0.105$), that because there is no deviation between the voltage frequency at PCC and the grid nominal frequency.
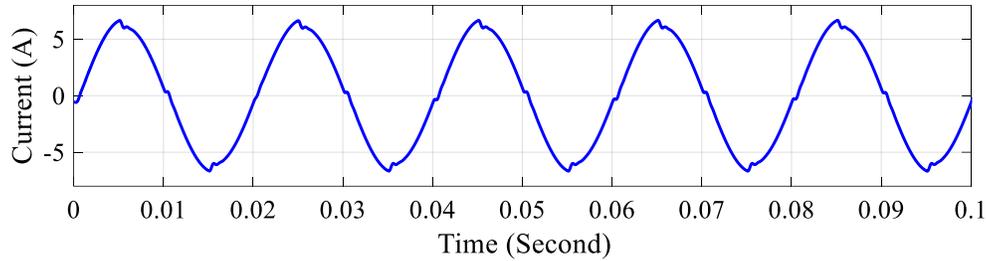
(a)
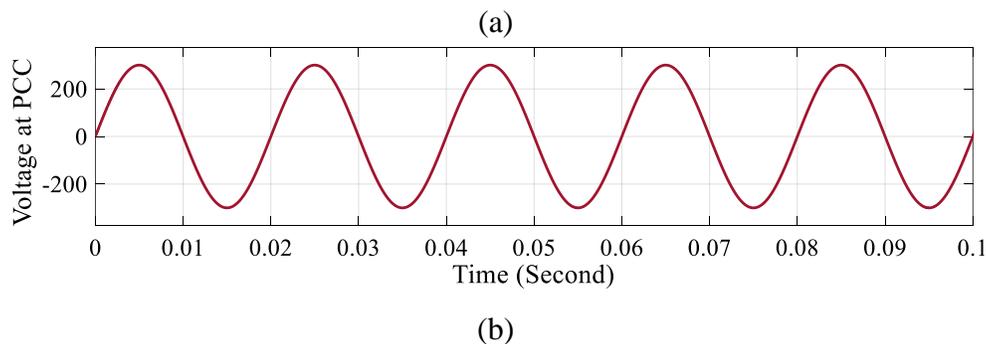
(b)

FIGURE. 5. Voltage and current at normal operation with proposed method: (a) voltage waveform at PCC (b) inverter output current.

The spectrum of inverter output current waveform is presented in Fig.6. It is observed that the THD was 4.9%, that because the used distortion factor was (0.105). However, the THD for various values of distortion factors K are presented in Fig.7. It is observed that, the maximum allowable initial distortion value is about 0.105, which produce THD about 5%.
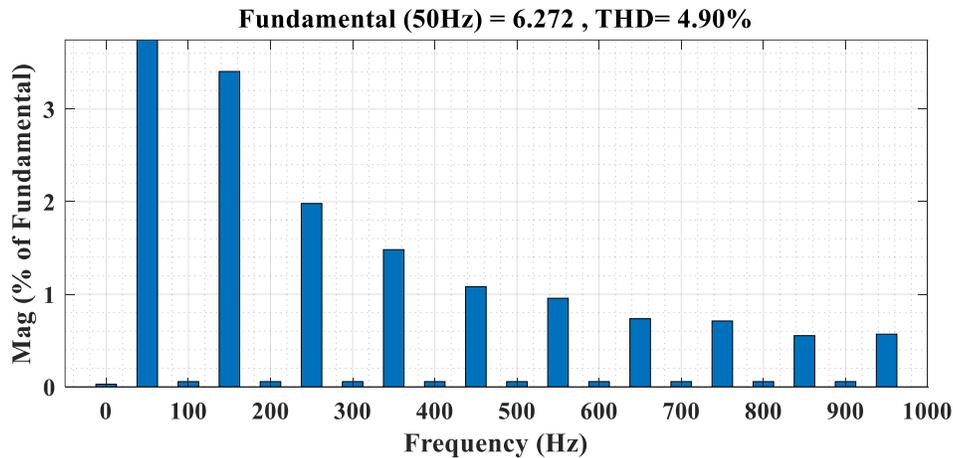

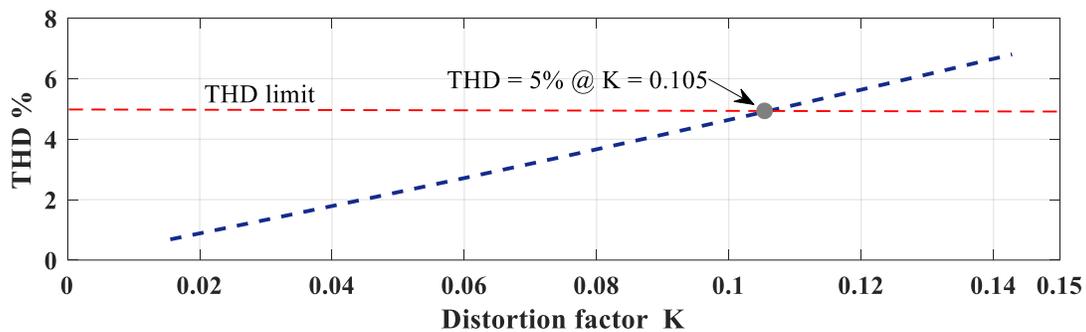FIGURE. 6. spectrum of the inverter output current.

FIGURE. 7. THD for various versus the distortion factor.

To verify the NDZ of the proposed method, a test load with quality factor 2.5 and resonance frequency 49.9 Hz has been considered. As shown in Fig. 3, the test load is in the NDZ of the IAFD, and it is out of the NDZ of the proposed method.

An islanding situation is simulated at 0.2 second of the simulation time by open the utility breaker in Fig.4. The inverter output current, voltage at PCC, and the frequency of at the PCC

has been presented in Fig.8 (a), (b), and (c). it is observed the inverter current has small distortion due to the distortion signal of the proposed method. From Fig.4 (c), the frequency at PCC start to decrease at about 0.21 second due to the proposed method, and the frequency reached to the frequency limit (49.3 Hz) at about 0.25 second.
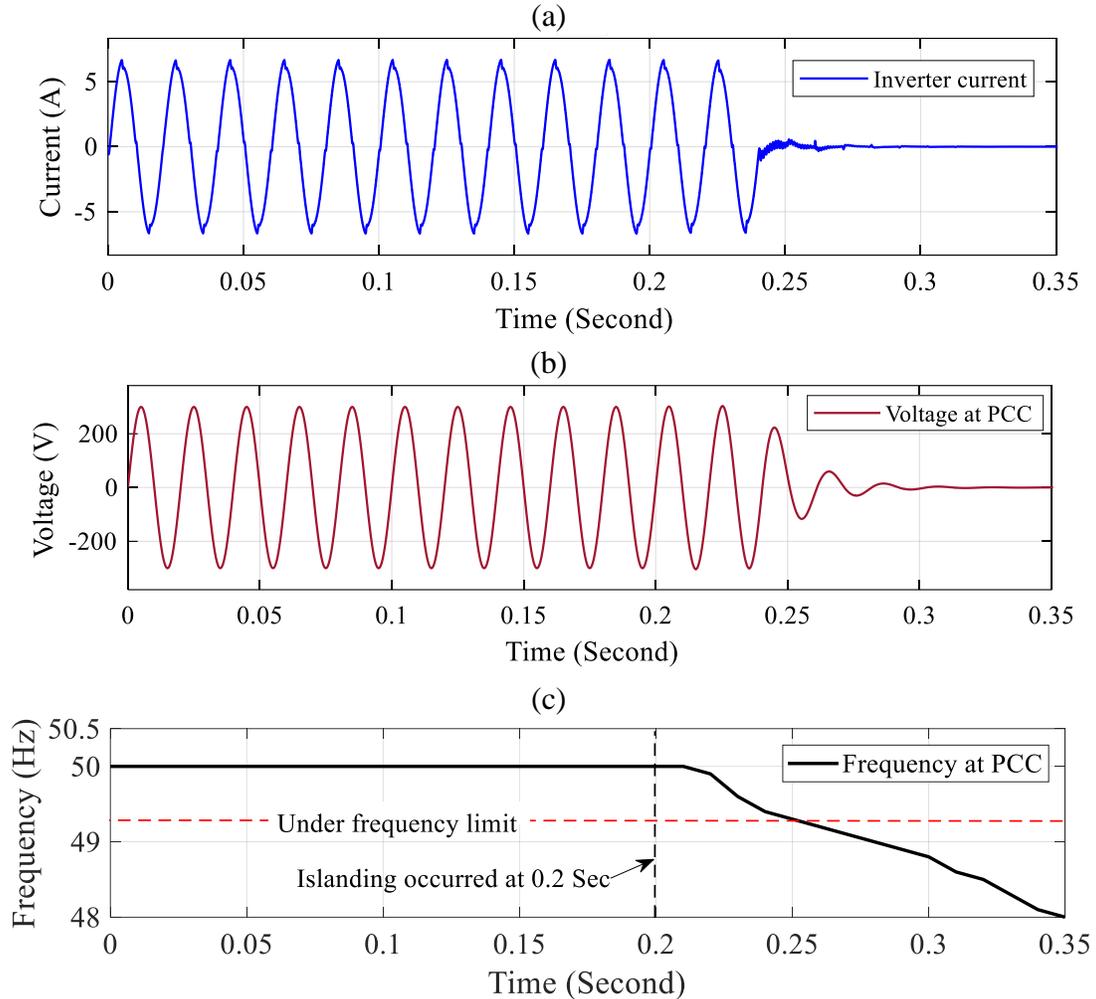

FIGURE. 8. (a) Inverter output current at islanding event. (b) voltage at PCC. (c) frequency at islanding event

From voltage and current measurements Fig (a) and (b), the islanding is properly detected by the proposed method. As a comparison between the proposed method and IAFD method, the test load located in the NDZ of the IAFD, that mean the IAFD unable to detect the islanding situation at that load. On the other hand, the proposed method able to detect the islanding at that load.

In the proposed method, the distortion factor is adaptive. The variation of distortion factor during the islanding event has been presented in Fig.9. It is observed that, the initial value of distortion factor was 0.105, and it starts varying at 0.2 second. Where, according to proposed method the distortion factor increases with frequency deviation.
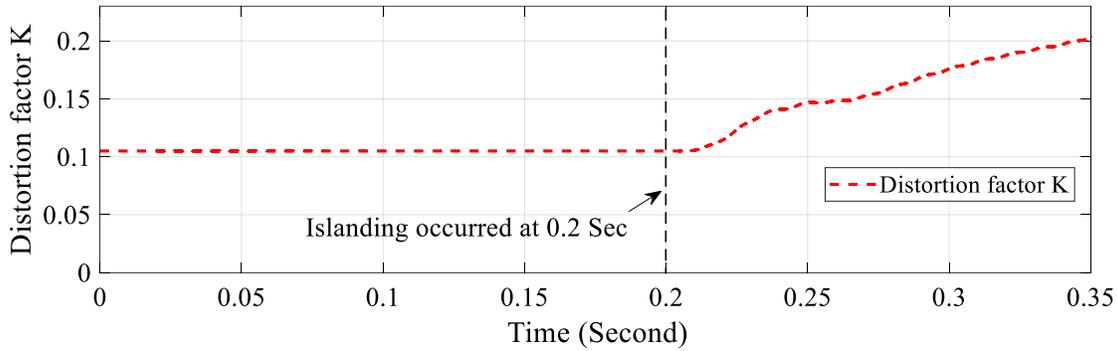
FIGURE. 9. The variation of distortion factor for proposed method.

Based on the simulation results, the proposed method successfully improved the performance of IAFD islanding detection method by decreasing the NDZ. Additionally, the proposed method does not inject any additional harmonics over the IAFD at steady state operation.

5. Conclusion

In this paper, a modified IAFD method was proposed. A positive feedback of frequency of the voltage at PCC was added to vary the injected perturbation, that to improve the performance of the IAFD. The adaption manner of distortion signal enhances in increasing the injected perturbations during islanding event only. Which reduced the NDZ during islanding event and decreased the injected THD in steady state operation. The proposed method was modeled in MATALB/Simulink environment, and it was tested in testbed system as suggested in IEEE Standard 929 [6] and Standard 1547 [4]. As a result, the proposed method successfully improved the performance of IAFD method by decreasing the NDZ. The proposed method could be enhanced farther by choosing the optimal values of initial distortion factor K_o and acceleration factor β, this could be as a future work of the presented study.

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