An improved Active Islanding Detection Technology for Grid-connected Solar Photovoltaic System

H. T. Yang, P. C. Peng, T. Y. Tsai, and Y. Y. Hong

Abstract--**Solar photovoltaic (PV) generation has drawn more and more attention since the advent of global warming effects. Among the PV generation systems, the grid-connected system has held the largest percentage of the installations over the past decades. Security about the islanding operation of a grid-connected solar PV system is, therefore, highly concerned. To reduce non-detection zone (NDZ) of islanding operations for different loading conditions, this paper proposes a nonlinear jumping slip-mode frequency shift (NJSMS) method in the voltage-source current-control inverter. The stable operation point (SOP) is avoided through an abrupt phase shifting approach around the load angle. From the extensive simulation and experimental results, the effectiveness of the approach to improve the detection accuracy is demonstrated.**

Keywords: **Islanding Operation, Stable Operating Point, Slip-Mode Frequency Shift, Voltage Source Current Control Inverter.**

I. INTRODUCTION

RENEWABLE energy uses natural resources such as solar, wind, and hydro energy, etc. to generate electricity. Due to relatively little influences on environment in contrast to fossil fuels, like coal, oil, and nuclear energies, renewable energy without warming effects has drawn more and more attention since past decades. In the form of dispersed generations, amount of renewable energy has significantly grown, particularly for the solar PV generations that operate effectively in parallel with utility grids.

However, detection of islanding operation is a significant issue of the PV generation system in parallel with utility grid [1], besides those of synchronization and output control. Islanding operation may result in several serious problems, such as the potential hazard to the line-maintenance crew without knowledge of the energized lines on the load side, as well as damages of power apparatus due to possible mismatch of voltages as grid recovered [1]. To effectively detect occurrence of islanding operation, many detection methods [2-11] have been developed and can generally be categorized into passive and active techniques.

Basically, passive methods [2-5] monitor selected parameters of voltage, frequency, phase displacement, and/or power output as well as rates of their variations. As long as the monitored parameters run out of prescribed normal ranges, islanding condition is formed and an alarm would be issued to cease operation of the dispersed generation system.

Though less cost and efforts required by the passive detection methods, the methods often suffer the difficulties in setting proper normal ranges [3]. Too narrow ranges prescribed for the detection may lead to false alarm with unnecessary disconnection of the solar PV generation from the utility. While wider normal ranges prescribed may fail the passive methods to detect the islanding due to the deemed normal variation of the indices for detection during the islanding operation.

The active methods [6-10] detect the islanding by intentionally introducing small amount of changes or disturbances to the output of inverter in the dispersed system. The response is then monitored to determine if the islanding exists. As the utility grid still connected with stable frequency and voltage, the perturbation introduced would not significantly affect the parameters used for detection. While the utility grid is disconnected from the dispersed system, a small perturbation introduced would be able to affect the parameters for detection to certain degree. By observing pre-defined indices obtained from the resulted parameter variations, the island can be detected.

The active detection methods, such as active frequency drift method (AFD) [6,7], slip-mode frequency-shift method (SMS) [8,9], and differential voltage correlation method (DVC) [10], have been regarded as effective approaches for the islanding detection purpose, even if some issues of NDZs [1] are still needed to be solved under different loading conditions.

The aim of this paper is at proposing an islanding detection technique of NJSMS to improve the existing AFD and SMS methods. In the proposed scheme, through a specially-designed nonlinear function, more perturbation is introduced to the shifting angel in the frequency-slipping process, as the SOP is approached in the existing SMS method. The time needed by the NJSMS method and the accuracy obtained for

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detection of the islanding operation can thus be greatly improved.

The remainder of the article is organized as follows. In Sec. 2, overview of the islanding detection methods, AFD and SMS, are described. Sec. 3 states the proposed improved NJSMS method to fulfill the islanding operation detection. Sec. 4 presents the simulation and experimental results. Finally, the conclusions are given in Sec. 5.

II. Overview of the AFD and SMS Methods

The inverter of the grid-connected solar PV generation system is designed to have output of unity power factor with synchronous voltage with grid to supply power to the load. Once the grid is disconnected from the solar PV system (i.e., islanding operation occurs), the phase difference $\Delta\varphi$ between voltage and current of the inverter output is determined by the RLC load and the system frequency f, as expressed below.

$$\Delta\varphi = -\tan^{-1}\left[R\left(2\pi fC - \frac{1}{2\pi fL}\right)\right] \tag{1}$$

The AFD method will shift the frequency f of the inverter to make $\Delta\varphi$ equal to zero to pursue the unity power factor. During the frequency shifting process, if the frequency exceeds the settings of under frequency relay (UFR) or over frequency relay (OFR), the relay would trigger to detect and stop the islanding operation. Otherwise, if the shifted frequency exists within the settings of the relays, there would be a SOP. Similar to the AFD method, the SMS method changes the phase angle θ_{SMS} of the output current with the frequency shifting as indicated in (2) to have more robust detection capabilities.

$$\theta_{SMS}[t] = \theta_m \cdot \sin\left(\frac{\pi}{2} \cdot \frac{f_v[t-1] - f_g}{f_m - f_g}\right) \tag{2}$$

where f_g is the grid frequency (60 Hz used as in this paper), f_v is the frequency of the inverter output voltage, and f_m is the corresponding frequency of the given maximum phase shift θ_m. In general, deviations from the grid frequency ($f_m - f_g$) is given as ± 3 Hz and $\theta_m = 10°$, which will be employed in the subsequent descriptions.

However, due to existence of the SOPs in the AFD and SMS methods, they would fail to detect the islanding operation. For example, the frequency of the SOP under certain loads would be those with $\Delta\varphi = 0$ for the AFD method and $\Delta\varphi + \theta_{SMS} = 0$, for the SMS method before the UFR or OFR triggers, as shown Fig. 1. As a result, the detection methods fail.

III. Nonlinear Jumping Slim Mode Frequency Shift Method

In this paper, the proposed NJSMS method is used to solve

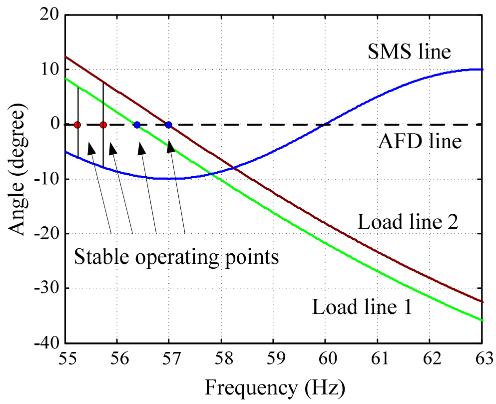


Fig. 1. SOPs with AFD and SMS methods.

the existing problems of the SMS method due to being trapped at the SOP and failing to detect the islanding operation. Based on the SMS method, the proposed NJSMS changes the phase angle of the frequency-shifting function in an abrupt manner around the SOP. It means that if an extra much larger angle is added on the regular phase angle around the SOP while keeping the same angle variation in the frequency regions away from the SOP, the problem of being trapped at the SOP would be avoided. To achieve this, a nonlinear exponential component θ_{aux} is added into the shifting angle of the inverter current output, as expressed in (3).

$$\theta_{NJSMS}[t] = \theta_m \cdot \sin\left(\frac{\pi}{2} \cdot \frac{f_v[t-1] - f_g}{f_m - f_g}\right) + \theta_{aux}[t] \tag{3}$$

where θ_{aux} is a nonlinear shifting component in the form below.

$$\theta_{aux}[t] = k \cdot e^{x[t]} \tag{4}$$

$$x[t] = -\left|\theta_{Load}[t] + \theta_{NJSMS}[t-1]\right| \tag{5}$$

where k is a constant; θ_{Load} is the load angle, and θ_{NJSMS} is the shift angle of the proposed NJSMS method.

In (3), as $x[t-1] \approx 0$, i.e., around the SOP, $\theta_{aux}[t-1]$ would equal nearly to k. The phase θ_{NJSMS} still has a shifting angle k in the inverter current output during the frequency-shifting process that would avoid the detection scheme staying at the SOP. Oppositely, the angle of $\theta_{aux}[t-1]$ added can be ignored as the frequency shifts away from the SOP with $x[t-1] \neq 0$ or the frequency as the same as the grid frequency.

To verify the effectiveness of the proposed technique, numerical results are obtained from both simulations and experiments under different scenarios. The testing cases consist of loading conditions with diverse quality factors as islanding operations happen while the grid-connected system disconnects. Examined are also the impacts of disturbances of different power-quality events on the performance of islanding detection. As shown in the testing results, effectiveness of the proposed approach to reduce non-detection zone and improve the detection accuracy is proved.

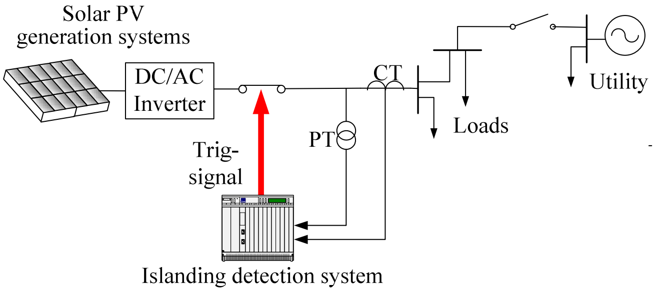


Fig. 2. Schematic diagram for the utility-connected solar PV generation system

TABLE I
SIMULATION LOADS IN DIFFERENT QUALITY FACTOR

Load	Resistance (Ohm)	Capacitance (F)	Inductance (H)	Quality Factor
A	14.4	5×10^{-1}	1.408×10^{-5}	0.076
B	14.4	1×10^{-1}	7.04×10^{-5}	0.382
C	14.4	1×10^{-2}	7.04×10^{-4}	3.82
D	14.4	1×10^{-3}	7.04×10^{-3}	38.2
E	14.4	1×10^{-4}	7.04×10^{-2}	381.2

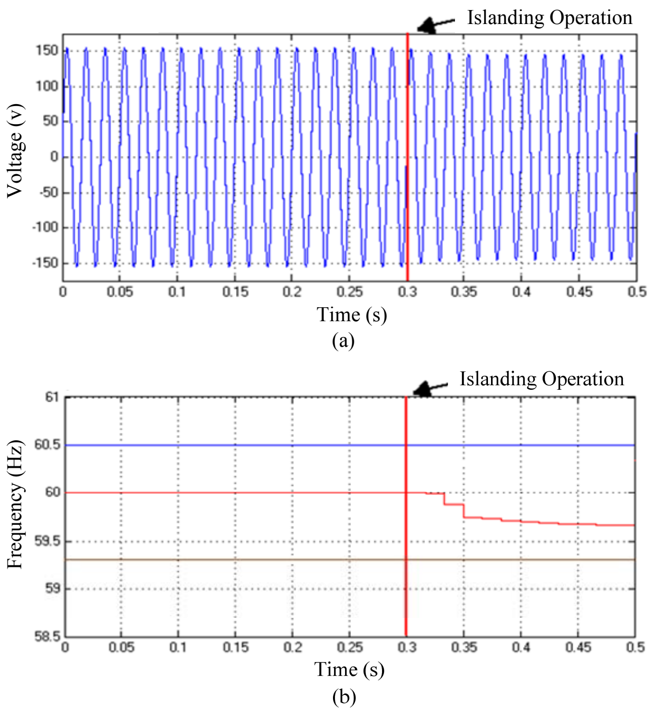


Fig. 3. Load C test using AFD method: (a) load voltage (b) frequency curve.

IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the proposed approach for the islanding detection of the solar PV generation systems as schematically shown in Fig. 2, both simulation and experimental results were used. Following the simulations, practical experiments were conducted to validate the proposed NJSMS islanding detection method.

A. Simulations for Different Quality Factors

Table I shows the five different loads, A, B, …, and E, used in the simulations. Tests of inductive loads, capacitive

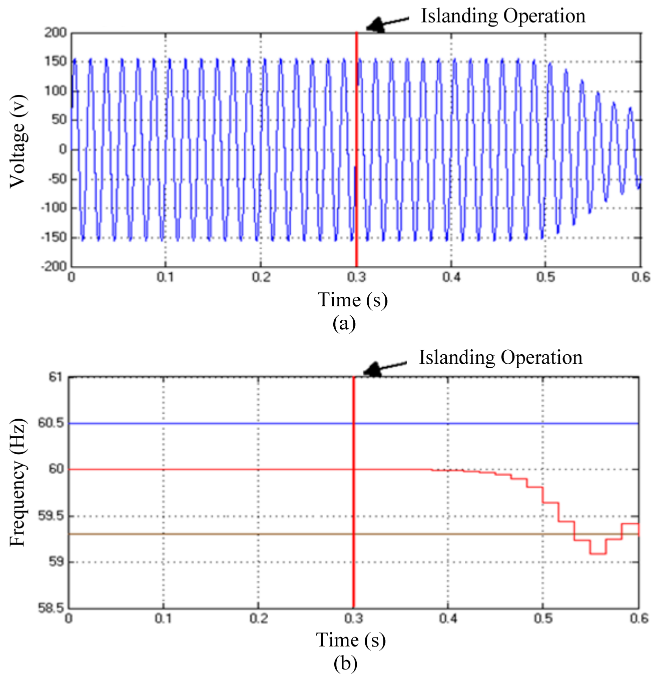


Fig. 4. Load C test using SMS method: (a) load voltage (b) frequency curve.

loads as well as islanding detection under diverse PQ disturbances have been studied for the five different loads in Table I. Described in the following subsections are the detailed simulation results by using the load C and the analyses for loads of different quality factors.

(i) Simulation Results

Simulation results by using Load C in Table I were obtained and demonstrated via three different methods, AFD, SMS, and the proposed NJSMS methods. Assuming the islanding operation occurs at 0.3 sec, Fig. 3 shows the results of the AFD based islanding detection method. The load voltage is displayed in Fig. 3(a) and Fig. 3(b) exhibits the frequency shifted from 60Hz to 59.75Hz (SOPs) and the islanding detection fails.

Fig. 4 shows the results of SMS based islanding detection approach. Islanding operation was supposed to occur at 0.3 sec, as shown in Fig. 4(a). Fig. 4(b) exhibits the frequency variations before and after the islanding operation. The frequency variation runs out of the relay setting and triggers the relay. However, the time needed to detect the occurrence of the islanding operation is 0.53 sec, which is more than 0.5 sec of the standard required in IEEE-929 [11]. As a comparison to the results of SMS method, the proposed NJSMS method increases the variation by the nonlinear function with an exponential component and detects the islanding less than 0.5 sec, as shown in Fig. 5.

(ii) Analyses for Different Quality Factors

Quality factor, Q_f, is defined as two pi times the ratio of the maximum stored energy to the energy dissipated per cycle at a given frequency. When the islanding operation occurs, it would result in the inverter shifting its operating frequency to

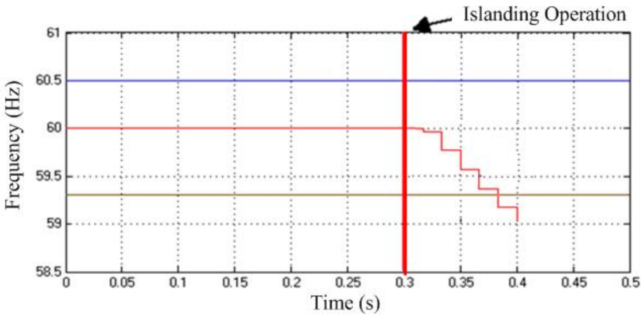


Fig. 5. Load C test using NJSMS method.

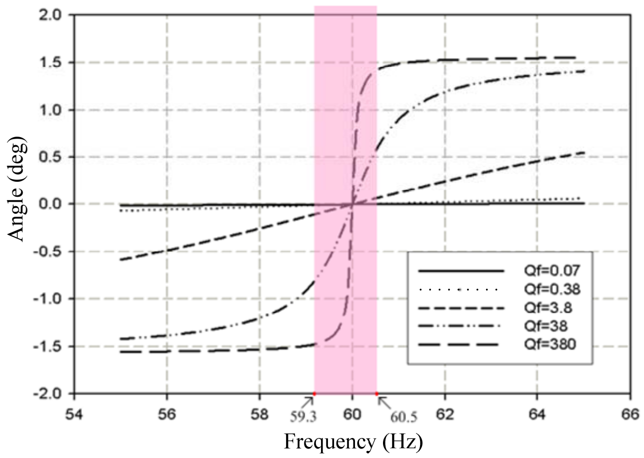


Fig. 6. Test results of different quality factors using AFD method.

TABLE II

θ_{SMS} AND S_{SMS} IN THREE FREQUENCY INTERVALS

Frequency Interval		θ_{SMS} (deg)	S_{SMS} (deg/Hz)
I	59.9 ~ 60	0.52	1
	60 ~ 60.1	-0.52	
II	59.3 ~ 59.8	2.58	3.34
	60.2 ~ 60.5	-3.58	
III	57 ~ 59.2	10	4.167
	60.6 ~ 63	-10	

the resonance frequency to have unity power factor. Loads of different quality factors have different resonance frequencies and represent different load characteristics as frequency shifts. As a result, distinct quality factors thus would influence the effectiveness of the islanding detection methods.

For instance in Fig. 6, suppose the resonance frequency and the detection range of relay are, respectively, set at 60Hz and above 60.5 or below 59.3Hz [11]. Fig. 6 demonstrates the angle variation versus the frequency shifting for RLC loads with different quality factors. The AFD method shifts the frequency f of the inverter to make the load angle $\Delta\varphi$ equal to zero. As a consequence, compared with the angle variation curves in Fig. 6., the islanding detection of AFD method would fail, as the angle variation by the AFD method versus frequency is less than that of load angle, especially for higher quality factors. The shaded area of the relay settings would become the NDZ of the AFD method as shown in Fig. 6.

As shown in Fig. 7, suppose the frequency span within the

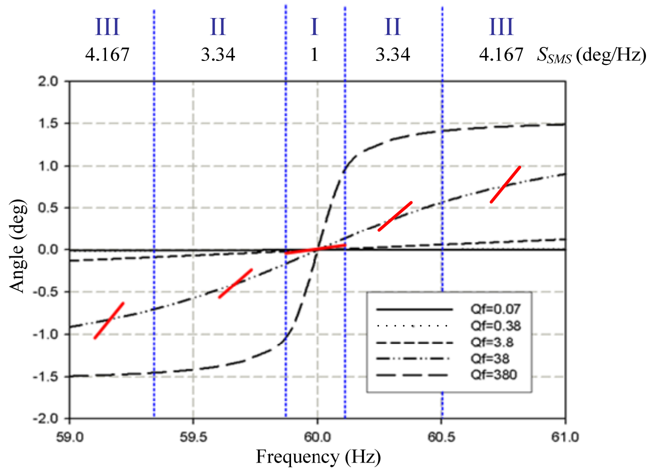


Fig. 7. Test results of different quality factors using SMS method.

TABLE III

θ_{NJSMS} AND S_{NJSMS} IN THREE FREQUENCY INTERVAL ($k = 4$)

Frequency Interval		θ_{NJSMS} (deg)	S_{NJSMS} (deg/Hz)
I (x=0.1)	59.9 ~ 60	0.52 +3.62	5.2
	60 ~ 60.1	-0.52+3.62	
II (x=0.64)	59.3 ~ 59.8	2.5+2.1	6.08
	60.2 ~ 60.5	-3.5+2.1	
III (x=∞)	57 ~ 59.2	-10	4.167
	60.6 ~ 63	10	

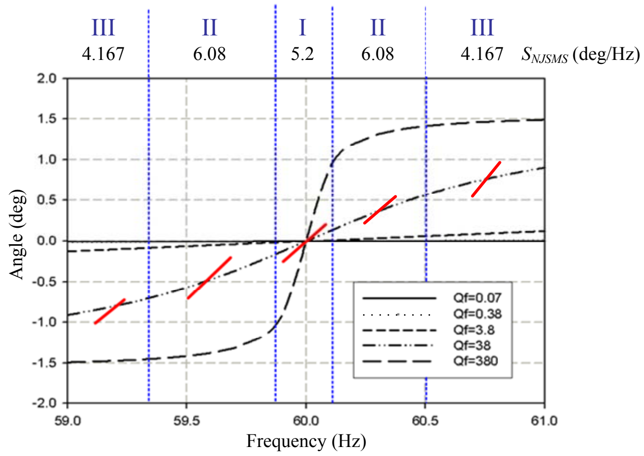
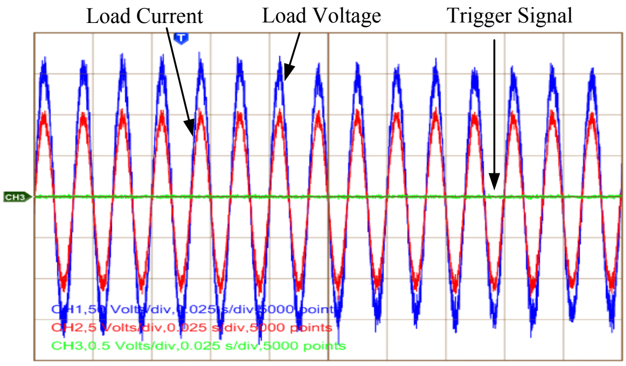


Fig. 8. Test results of different quality factors using NJSMS method.

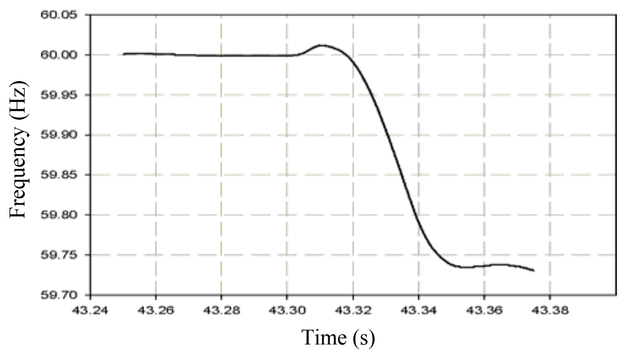
maximal frequency f_m was divided into three intervals around the assumed SOP of 60Hz. The corresponding θ_{SMS} and the average variation rate (deg/Hz), S_{SMS}, of θ_{SMS} in the respective intervals can be calculated in (2) as given in Table II. It is noted that the average variation rate in interval I by using the SMS method is less than the variation rate of load angle for the quality factor larger than or equal to 38. Consequently, the islanding detection would fail due to being trapped at the SOP. Table II and Figs. 7 reveals that the NDZ of SMS method is the shaded area for the loads of quality factor larger than or equal to 38.

TABLE IV
LOAD AND SYSTEM PARAMETERS

Parameters of the Load Used		
	Load F	Load G
R	15.1Ω	15.03Ω
L	15.59mH	1mH
C	455μF	7000 μF
Q_f	2.58	39.782
Resonance Frequency	59.74 Hz	60.154 Hz
System Parameters		
Voltage	110V（rms）	
Frequency	60 Hz	



(a)



(b)

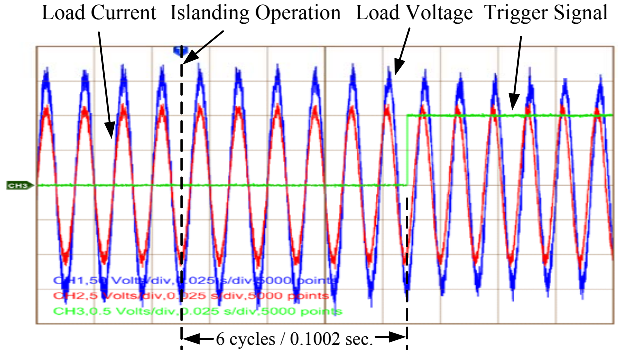
Fig. 9. Testing results of Load F by using AFD method: (a) voltage and current (b) frequency

As a contrast, Table III and Fig. 8 show the results of the proposed NJSMS method which increases the variation rate of θ_{NJSMS} to frequency around the SOP. Therefore, the proposed NJSMS method still can detect the islanding operation for the load with the quality factor as high as 38. The NDZ of the NJSMS method is thus less than the NDZ of SMS method for loads of higher quality factors.

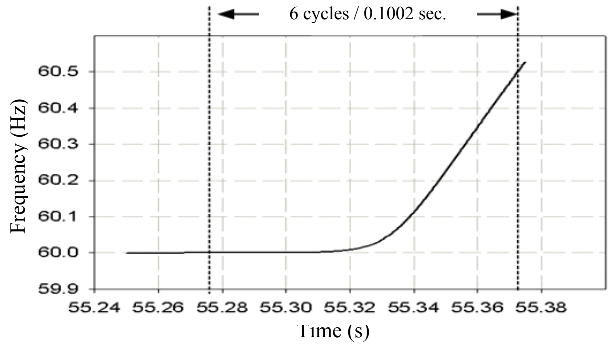
B. Experimental Results

Following the simulations, practical experiments were conducted to validate the proposed NJSMS based islanding detection approach. The solar PV generation system used in the tests consists of a utility-connected 1 kW PV system with loads of different quality factors as shown in Table IV.

Shown in Fig. 9-11 are the testing results for Load F with $Q_f = 2.58$ by using AFD, SMS, and proposed NJSMS methods. The islanding detection time needed is 0.1002 sec. and 0.0925 sec., i.e., 6 cycles and 5.5 cycles, for the SMS and NJSMS methods, respectively. However, for the AFD method,

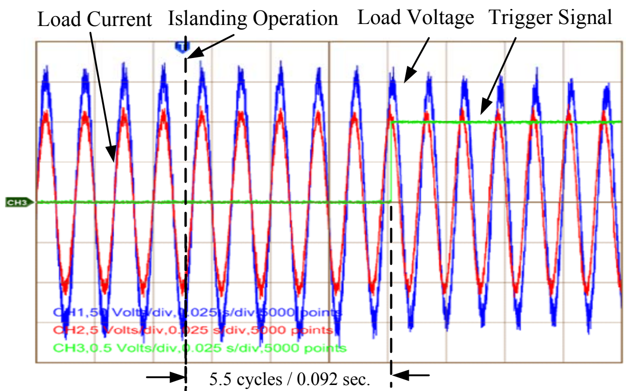


(a)

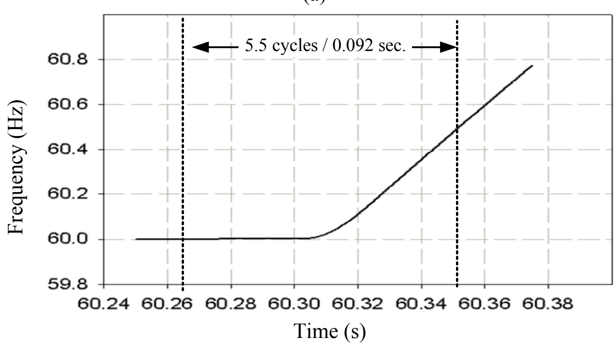


(b)

Fig. 10. Testing results of Load F by using SMS method: (a) voltage and current (b) frequency



(a)



(b)

Fig. 11. Load F test using proposed NJSMS method: (a) voltage and current (b) frequency

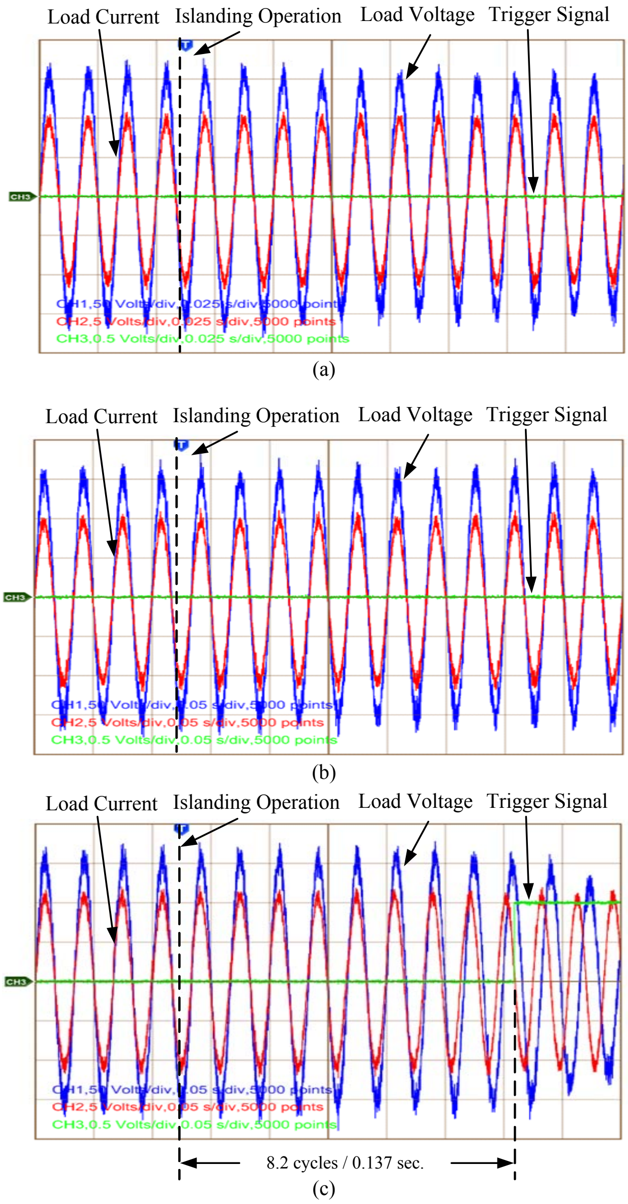


Fig. 12. Load G test using the AFD (a) , the SMS (b) and the proposed NJSMS method (c).

the frequency was shifted from 60Hz to 59.74Hz (the SOP). As a result, the islanding operation cannot be detected by using the AFD method, as shown in Fig. 9.

Fig. 12 shows the detection results of the AFD, the SMS and the the proposed NJSMS method for Load G with the higher quality factor of 39.782 as listed in Table IV. The results reveal that the proposed NJSMS can detect the occurrence of the islanding operation in 0.137 sec (8.2 cycles), which is less than 0.5 sec required by IEEE-929 [11], in comparison to the facts that the AFD and the SMS failed to detect the islanding operation, as shown in Fig. 12.

V. Conclusions

An improved islanding detection technique through the NJSMS method has been proposed in this paper to improve the existing methods for a grid-connected solar PV system. A specially designed exponential function was introduced to the phase angle of the frequency shifting process in the inverter current output. The problem of being trapped at the SOP was thus overcome through the proposed approach. The proposed NJSMS method has been tested through various simulations and experiments with loads of different quality factors. The time and accuracy for the islanding detection have been ameliorated as presented in the numerical results. In the practical experiments on the grid-connected 1 kW solar PV system, the proposed NJSMS method was validated by reliably detecting the occurrence of the islanding operation within 0.137 sec, which is less than 0.5 sec required by the IEEE Standard.

VI. Acknowledgments

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