2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia
June 2-5, 2012, Harbin, China

Anti-Islanding Detection Method Using Negative Sequence Voltage

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Abstract— **This paper presents an active Anti-Islanding Detection (AID) method using Negative Sequence Voltage (NSV) injection to electrical grid through a three-phase photovoltaic (PV) inverters. Because islanding operation mode can cause a variety of problems, the islanding detection of grid-connected PV inverter is the mandatory feature. The islanding mode is detected by measuring the magnitude of Negative Sequence Impedance (NSI) calculated by the negative sequence voltage and current at the point of common coupling (PCC). Simulation and experiment are performed to verify the effectiveness of the proposed method which can detect the islanding mode in the specified time. The test has been done in accordance with the condition on IEEE Std 929-2000.**

Keywords-anti-islanding detection; negative sequence voltage injection; photovoltaic systems

I. INTRODUCTION

The islanding of photovoltaic (PV) system is a condition in which a portion of the utility system that contains both load and distributed resources including PV inverter remains energized while isolated from the remainder of the utility system [1].

Islanding mode can cause variety of problems such as safety issues, damage to loads, reclosing problem and so on [2]. As grid-connected inverter cannot control voltage and frequency of grid in islanding mode, the grid voltage and frequency might be fluctuated. This can results in unrecoverable damages to loads. In islanding mode, grid synchronization is also impossible because of no standard grid voltage. And, due to out-of-phase of the voltage of the isolated grid to the utility grid, at the recloser operation, it is difficult to synchronize the isolated grid to the utility grid, and the grid may be re-tripped due to over current fault.

Because islanding can be a threat to the grid operation, Anti-Islanding Detection (AID) is mandatory feature for grid-connected PV inverters. The PV inverter must detect islanding and cease to energize the grid in the specified time.

For avoiding islanding, AID algorithms have been developed and several of them are commercialized. These algorithms may be divided into passive methods and active methods [3].

Passive methods are based on monitoring grid parameters. The relay of voltage and frequency such as OUF (Over or Under Frequency)/OUV (Over or Under Voltage) is simple way to detect islanding. Islanding can be avoided by monitoring voltage and frequency which are not within the acceptable range. The phase jump or variation of harmonics also can be used for the detection of the islanding operation [4].

Active methods perturb grid by PV inverter and observe reaction of grid parameters. This can be divided in two types. The first type of active method uses positive feedback which results in instability of the grid at islanding operation. The positive feedback to power references or, phase angle of current is activated in islanding, and frequency or voltage instability would be followed [3-6]. The frequency drift methods (FDMs) are representative methods, such as active-frequency drift (AFD) method, slip-mode frequency shift (SMS) and Sandia-frequency shift (SFS) [2, 7]. The second type of active method injects signal to grid and observes reaction of system parameters [8-10]. The current or voltage can be used as a signal for the injection. As the current is injected, after islanding, voltage which is made by injected components can be sensed. As high frequency voltage is injected, grid impedance can be estimated and this can be used as an indicator for islanding detection.

In this paper, active AID method available to three-phase PV system is proposed. Proposed method extracts symmetric components used in analyzing three-phase power systems, especially negative sequence components. Islanding can be detected by observation of the negative sequence impedance at point of common coupling (PCC) which is reaction made by injecting negative sequence voltage. The proposed method is analyzed by negative sequence equivalent circuit. The performance of proposed algorithms is verified by the simulation and experiment.

II. PROPOSED ANTI-ISLANDG METHOD

A. *Injecting Negative Sequence Voltage to Grid*

The Negative Sequence Voltage (NSV) is synthesized and injected to grid by PV inverter. Based on the negative sequence reference frame, a constant dc voltage is injected. In Fig. 1, several reference d-q frame are shown, namely stationary *d-q*

978-1-4577-2087-1/11/$26.00@2012 IEEE

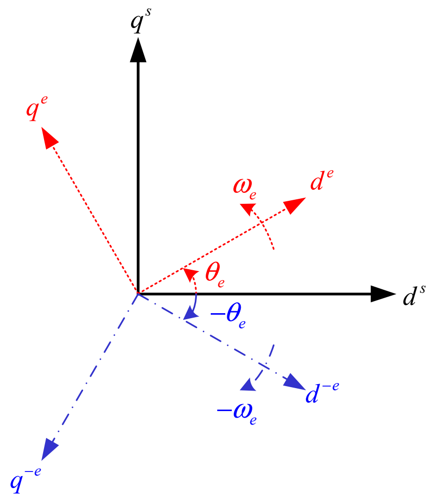


Figure 1. Synchronous reference frame and negative reference frame

frame denoted as $d^S - q^S$, positive sequence synchronous *d-q* frame as $d^e - q^e$, and negative sequence synchronous *d-q* frame as $d^{-e} - q^{-e}$. The negative sequence frame rotates at the same speed of synchronous reference frame but opposite direction. The NSV can be written in complex vector form like (1). The NSV can be represented as (2) in stationary reference frame. This NSV on stationary reference frame can be added to output of current controller, or voltage reference represented on stationary reference frame. Equation (3) represents final voltage reference synthesized by inverter including a NSV.

$$\vec{V}^{-e}_{dq,neg} = V^{-e}_{d,neg} + jV^{-e}_{q,neg} = V_{neg,inj} + j \cdot 0 \tag{1}$$

$$\vec{V}^{s}_{dq,neg} = \vec{V}^{-e}_{dq,neg} e^{-j\theta} = V_{neg,inj} e^{-j\theta} \tag{2}$$

$$\vec{V}^{s*}_{dq} = \vec{V}^{s*}_{dq,CC} + \vec{V}^{s}_{dq,neg} \tag{3}$$

In previous researches for the second type of active AID, the current and voltage signals are injected to the grid. The method based on the injection of current needs additional current regulator for the signal injection. The design and tuning of the regulator is not a trivial one. If high frequency voltage or current is injected, the resonant frequency of the controller and the resonant frequency of over-all grid should be considered. However, the resonant frequency of the grid is difficult to estimate and varying according to the grid operating conditions. Furthermore, the AID methods based on high frequency injection is vulnerable to load contain capacitor. Especially, the test load for islanding provided by international standard such as IEEE Std 929-2000 is composed by paralleled RLC load. Because the capacitor in test load acts as short circuit path for high frequency injected signal, in result, the performance of injection is decreased and the performance of the detection of the islanding is degraded.

If the NSV is injected by VSI, the voltage intended can be synthesized directly. Then, there is no need to consist of additional regulator for injection. Because the frequency of the NSV is grid frequency, consideration for resonant frequency of the control system or the grid can be alleviated. The effect of injection is also not affected to the capacitor of load.

B. *Estimation of Negative Sequence Impedance*

After the NSV is injected to grid, the Negative Sequence Impedance (NSI) at PCC is monitored. The islanding mode can be detected by variation of the magnitude of NSI. The magnitude of NSI can be calculated by the magnitude of the ratio of the negative sequence voltage to the negative sequence current at PCC as (4).

$$\left|\vec{Z}_{pcc,neg}\right| = \left|\frac{\vec{V}_{pcc,neg}}{\vec{I}_{pcc,neg}}\right| \tag{3}$$

where $\vec{Z}_{pcc,neg}$, $\vec{V}_{pcc,neg}$, $\vec{I}_{pcc,neg}$ stands for negative sequence impedance, negative sequence voltage and negative sequence current at PCC. To reject nuisance trip, moving average can be used to (4).

The symmetric components can be calculated from voltage and current at PCC by (5) and (6).

$$\mathbf{V}_{012} = \begin{bmatrix} V_{ab0} \\ V_{ab1} \\ V_{ab2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \mathbf{a} & \mathbf{a}^2 \\ 1 & \mathbf{a}^2 & \mathbf{a} \end{bmatrix}\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \tag{5}$$

$$\mathbf{I}_{012} = \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \mathbf{a} & \mathbf{a}^2 \\ 1 & \mathbf{a}^2 & \mathbf{a} \end{bmatrix}\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} \tag{6}$$

where $\mathbf{a} = e^{j\frac{2}{3}\pi}$, and each subscript 0, 1, 2 stands for zero sequence components, positive sequence components and negative sequence components, respectively.

The negative sequence components of voltage and current can be extracted as (7) and (8).

$$\begin{bmatrix} V_{ab2} \\ V_{bc2} \\ V_{ca2} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}V_{ab} + \frac{1}{2\sqrt{3}} j\left(V_{ca} - V_{bc}\right) \\ -V_{ab2} - V_{ca2} \\ \frac{1}{2}V_{ca} + \frac{1}{2\sqrt{3}} j\left(V_{bc} - V_{ab}\right) \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} I_a + \frac{1}{2\sqrt{3}} j \left(I_c - I_b \right) \\ -I_{a2} - I_{c2} \\ \frac{1}{2} I_c + \frac{1}{2\sqrt{3}} j \left(I_b - I_a \right) \end{bmatrix} \tag{8}$$

The complex number j, which means 90 degree leading to original signal, can be realized by all-pass filter [11].

$$j \rightarrow \frac{s - \omega_n}{s + \omega_n} \tag{9}$$

C. Anti-Islanding Detection

As mentioned, the NSI at PCC can be used for an indicator of islanding operation. In this section, the negative sequence equivalent circuit is used for analyzing the variation of the NSI according to the operating condition.

In Fig. 2 (a), a circuit diagram is shown, where a three-phase PV inverter is connected to the grid through a harmonic filter and transformer. The three-phase PV inverter synthesizes the NSV, and can be modeled as voltage source in negative sequence equivalent circuit. As the ideal grid produces only positive sequence voltage, it is assumed that negative sequence does not exist. The parameters of the passive components in negative sequence equivalent circuit are the same to that of the components in positive sequence. The LCL filter can be installed as the harmonic filter and the filter can be modeled simply as L filter in grid frequency. The transformer can be modeled as an additional reactor to the filter. Fig. 2 (b) presents the negative sequence equivalent circuit under above considerations.

1) Grid-connected operation

In normal operating mode- where the grid is connected- because the load impedance is much larger than the grid impedance, equivalent circuit in Fig. 2 (b) can be simplified as Fig. 3 (a). In this case, the NSI at PCC is equal to grid impedance as (10).

$$\left| \vec{Z}_{pcc,neg} \right| = \left| \frac{\vec{V}_{pcc,neg}}{\vec{I}_{pcc,neg}} \right| = \left| \vec{Z}_g \right| \tag{10}$$

2) Islanding operation

In islanding mode, the grid is disconnected and grid impedance can't be observed at PCC. Equivalent circuit in Fig. 2 (b) becomes one in Fig. 3 (b). The NSI is equal to load impedance as (11). As mentioned above, because the load impedance is larger than grid impedance in islanding mode, the NSI becomes larger than the NSI in normal mode. By this variation, islanding mode can be easily detected by PV inverter.

$$\left| \vec{Z}_{pcc,neg} \right| = \left| \vec{Z}_{load} \right| \tag{11}$$

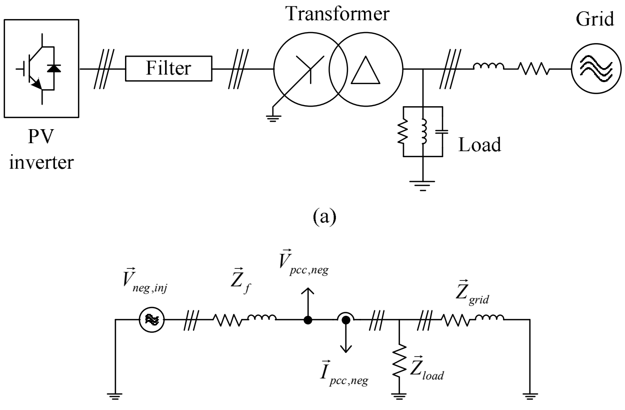


Figure 2. (a) Grid-connected PV system
(b) Negative sequence equivalent circuit

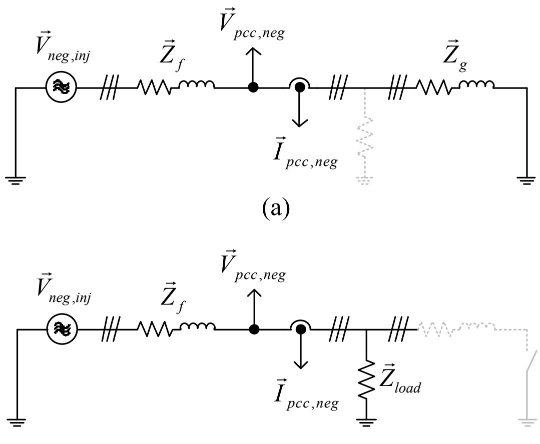


Figure 3. Negative sequence equivalent circuit
(a) Normal operation (b) Islanding

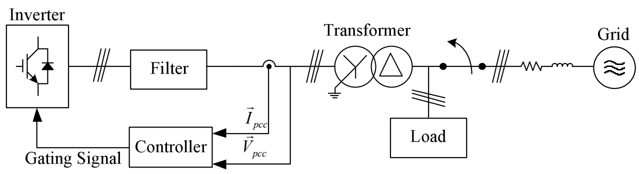


Figure 4. System configuration

The variation of the NSI from (10) to (11) can be used as the indicator of the islanding operation.

III. Simulation and Experiment Results

A. System Configuration

System which is used in simulation is depicted in Fig. 4. A 5kW PWM voltage source inverter is used for grid connection, and islanding load is designed to fit to IEEE Std. 929-2000. The grid side line-to-line voltage set as $220V_{rms}$ and the inverter side line-to-line voltage set as $140V_{rms}$. Grid impedance is set as 5% of base impedance. The magnitude of the NSV injected is set as 1% of rated inverter side line-to-line voltage.

When current is controlled by the conventional PI controller with bandwidth above 120Hz on positive sequence synchronous *d-q* frame, the reaction of injection, that is, the negative sequence current can be alleviated. The negative sequence components of current, which appears 120Hz AC component on the positive sequence synchronous *d-q* frame, can be regulated by controller. If the negative sequence components are processed as shown in Fig. 5, the effect of the negative sequence injection would not be alleviated.

B. *Simulation Results*

The local load in islanding operation is simulated by three phase parallel RLC circuit in Y-connection. The parameter is set according to IEEE Std 929-2000. For 5kW set, the resistance is set as 9.68Ω, the inductance is set as 10.27mH and the capacitance is set as 685.1µF.

In Fig. 6, a simulation result in the PV system with two-level voltage source inverter is shown. At 1.5 second, by opening the grid side circuit breaker, the islanding occurred. Before the islanding, the negative sequence impedance is almost equal to grid impedance as described in (10). After islanding, that is, the input current of grid side is blocked, the negative sequence impedance increases. After saturation, impedance value became equal to impedance of load by (11). The equivalent impedance of islanding load specified in standards equals to resistance of load. The resistance which is estimated in inverter side after islanding is 3.92Ω because of considering turn ratio of transformer.

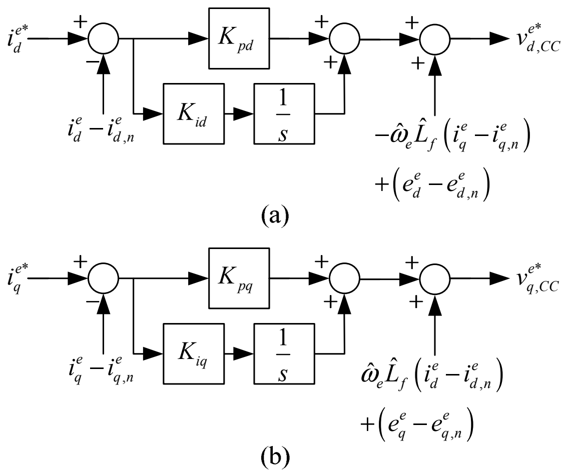


Figure 5. Current controller subtracting negative sequence component (a) *d*-axis current controller (b) *q*-axis current controller

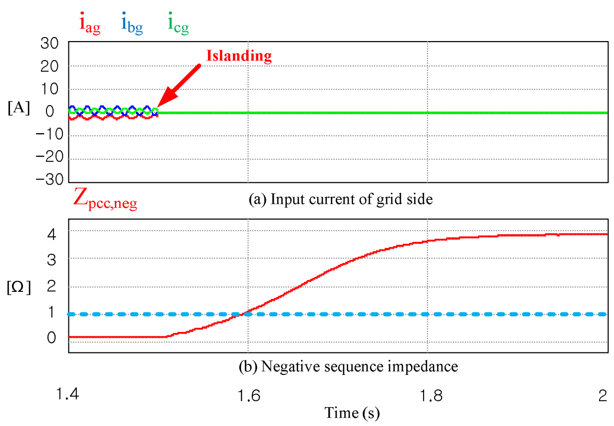


Figure 6. Simulation results of 5kW set (a) Input current of grid side (b) Negative sequence impedance

C. *Experiment Results*

In Fig. 7, an experimental setup for islanding test is shown. The condition of experimental setup was almost equal to simulation. For simulating islanding, circuit breaker is used. The two-level voltage source inverter is used for PV inverter and the three-phase reactor is used for filter. The inductance is 1.5mH. The islanding load was set similar to simulation

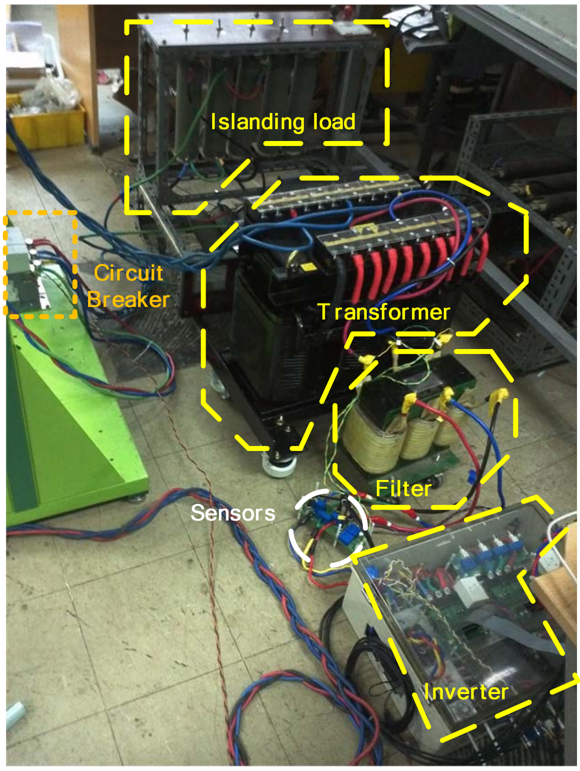


Figure 7. Experimental setup (5kW)

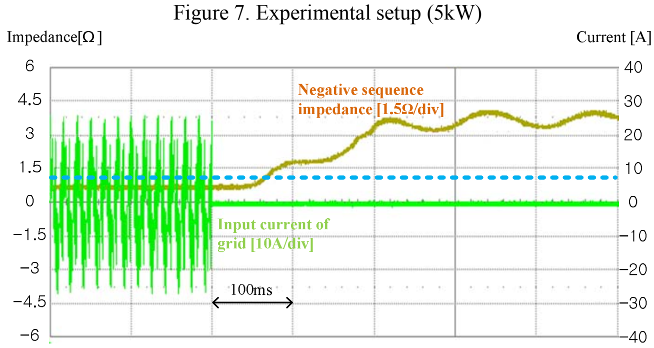


Figure 8. Experiment results (5kW)

condition and three phase parallel RLC circuit was used. The magnitude of the NSV injected is set as 1% of rated inverter side line-to-line voltage.

In Fig. 8, the result of anti-islanding detection according to the proposed method is shown. After input current of grid side is blocked, the NSI increased and became almost equal to 3.92Ω. By the proposed method with negative sequence voltage injection, the impedance estimation is working well as the simulation result.

The dot line represents threshold for detection of the islanding operation. In both results of simulation and experiment show that the islanding can be detected less than 100ms. The proposed method can detect the islanding within limited time specified by IEEE Std 929-2000.

The proposed algorithm is not affected by type of PV inverter or filter. To verify this, another 1kW experiment setup was tested. In this setup, the three-level inverter is used for PV inverter and the LCL type is used for filter. The resonant frequency of LCL-filter is designed considering injection frequency in the case of injecting high frequency component. Because the frequency of negative sequence component is equal to grid frequency, the proposed method doesn't affect to design the resonant frequency of LCL-filter. The transformer was not used in this experimental setup and the line-to-line voltage of grid is $140V_{rms}$.

In this 1kW system, islanding load tester equipment is used for islanding load. According to IEEE Std 929-2000, the islanding tester equipment operated so that the power flowing into the load was solely supplied by the inverter.

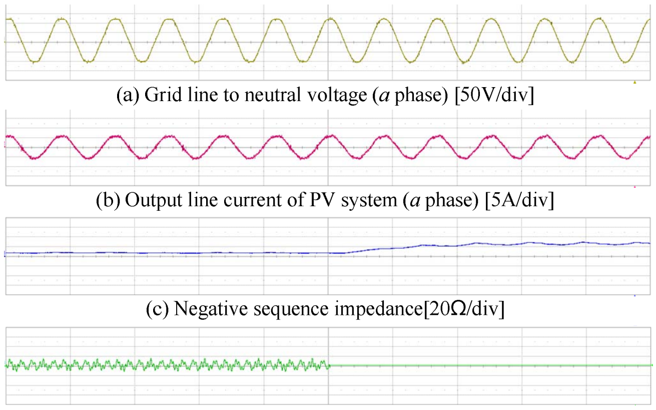
In Fig 9, the result is shown. After input current of grid side is blocked, the islanding occurred. After islanding, the NSI increases and is saturated almost equal to 21Ω. As a result, the islanding can be detected less than 60ms. The expected value of NSI in 1kW system is 19.2Ω according to IEEE Std 929-2000 and the NSI estimated almost same to expected value.

IV. Conclusion

In this paper, an active anti-islanding detection method using negative sequence component has been proposed. The negative sequence voltage is injected to grid by PWM voltage source inverter and the estimated negative sequence impedance of PCC is used as an indicator for detecting islanding mode. The injection of negative sequence voltage is implemented by injecting DC voltage in negative sequence *d-q* reference frame. The magnitude of negative sequence impedance is obtained from the ratio of negative sequence voltage to negative sequence current at PCC. To minimize the side effect of the negative voltage injection, the current regulator of inverter has been modified.

For analyzing variation of the NSI, negative sequence equivalent circuit is introduced. In normal operation, the NSI is equal to grid impedance. In islanding mode, the NSI is large enough to differentiate the islanding operation from normal operation. Based on this variation, islanding can be detected.

The performance of the proposed method is verified by simulation and experimental test. In 5kW PV system, the RLC parallel load condition of the test is set similar to IEEE Std 929-2000. The simulation and experimental results, both, reveals the satisfactory identification of islanding operation within 100ms, which is less than the time specified in the regulation. In 1kW PV system, it is verified that the proposed method is not affected by type of the PV inverter or filter.



(a) Grid line to neutral voltage (*a* phase) [50V/div]

(b) Output line current of PV system (*a* phase) [5A/div]

(c) Negative sequence impedance[20Ω/div]

(d) Input current of grid [5A/div]

Figure 9. Experiment results (1kW)
(time: 20ms/div)

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