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Islanding Prevention Method for Photovoltaic System by Harmonic Injection Synchronized with Exciting Current Harmonics of Pole Transformer

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Abstract – When large penetration of the distributed generators (DGs) such as photovoltaic (PV) systems is growing up in grid system, it is important to quickly prevent islanding caused by power system fault to ensure electrical safety. We propose a novel active method for islanding prevention by harmonic injection synchronized with the exciting current harmonics of the pole transformer to avoid mutual interference between active signals. We confirm the validity of the proposed method by performing the basic tests of islanding by using a current source superimposed the harmonic active signal. Further, we carry out the simulation using PSCAD/EMTDC, and verify the fast islanding detection.

Keywords: pole transformer, islanding prevention, synchronized injection of harmonic current, harmonic impedance detection

1. Introduction

When large penetration of the distributed generators (DGs) such as photovoltaic (PV) systems is growing up in distribution systems, it is important to quickly prevent islanding caused by power system fault in order to ensure electrical safety.

So far, the various islanding protection methods have been developed practically [1]. The passive methods which detect the small change of frequency or voltage phase angle can not prevent islanding in non detection zone (NDZ) where the frequency and voltage have little change. Another passive method which detects effectively the rapid change of the 3rd harmonic voltage in single phase system is not available to three phase balanced system.

As the countermeasure, the active methods have been used. But, the conventional active methods tend to increase the islanding detection time, because the mutual interference occurs due to asynchronous state between active signals [1]. Moreover, it is required to detect islanding rapidly within 0.2 sec in the case of an intersystem fault between high voltage lines and low voltage lines [2]. But conventional active methods can not satisfy this requirement.

On the other hand, New Energy and Industrial Technology Development Organization (NEDO) in Japan developed a new active islanding detection method for the multiple-inverter of PV system [1] [3]. This method is called “frequency feedback method with step injection function of reactive power (FFB)” and applies positive feedback to the reactive power in the direction of increasing the frequency change. In addition, when the frequency change is within 0.01 Hz, after detecting the change of total harmonic distortion voltage ΔTHD or the fundamental wave voltage, the step injection of the reactive power is conducted in direction of reducing the frequency. However, the step injection function does not operate well when the change of total harmonic distortion voltage ΔTHD is smaller than 1% (2 V). Thus, FFB also has possibility of extending the detection time in NDZ.

In order to solve the above problems, we propose a novel islanding prevention method by the harmonic current injection synchronized with the exciting current harmonics of the pole transformer. Under the grid connecting state, the power conditioning subsystem (PCS) can always inject the k-th harmonic current (k = 3 or 5) used as small active signal synchronized with the exciting current harmonics of the pole transformer. When islanding occurs, PCS changes the active signal amplitude from the first stage (I_{Gk1}) to the second stage (I_{Gk2}) after detecting the k-th harmonic voltage change of more than the threshold value ΔV_{kth}. As the result, PCS can estimate the load impedance for the k-th harmonics (ΔZ_k) to avoid the miss operation of PCS caused

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by power system disturbance, and can detect the islanding reliably.

In this paper, for basic study of propose method, we clarify the synchronized injection method of harmonic active signal and the estimation method of harmonic components of the load impedance. So, we conduct the basic experiment on islanding by using a current source superimposed the harmonic active signal. Further, we carry out the simulation using PSCAD/EMTDC, and verify the fast detection of islanding.

2. Proposed Active Method

2.1 System Configuration

Fig. 1 shows the conceptual block diagram of PCS equipped with the proposed method. We assume that the number of PV systems which are connecting to the grid system are n_G below the secondary winding of the pole transformer. In Fig. 1, one of PV systems is indicated as an example. The proposed active method consists of three parts which are “Estimation of exciting current harmonics phase angle of pole transformer”, “Synchronized injection and amplitude control of active signal” and “Discrimination of islanding state”.

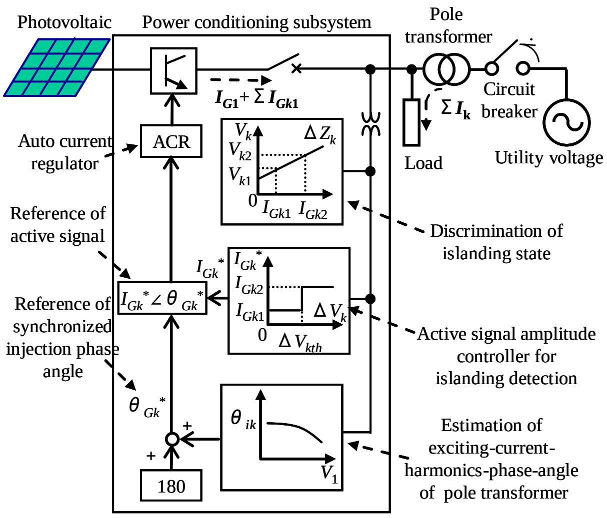


Fig. 1. Conceptual block diagram of proposed method

2.2 Estimation of Exciting Current Harmonics Phase Angle of Pole Transformer

At the residential area, the rated power of the pole transformer is nearly 30 kVA. Table 1 indicates the specification of the pole transformer. Fig. 2 and Fig. 3 show the measurement value on the harmonic characteristics (amplitude I_k and phase angle θ_{ik}) of the exciting current of pole transformer excited by sinusoidal wave voltage whose total harmonic distortion (*THD*) is below 1%. These results mean that the exciting current harmonics can be approximated as the functions of the fundamental wave voltage V_1. Therefore, each PCS can estimate the exciting current harmonics phase angle θ_{ik} of the pole transformer by monitoring V_1 of the line voltage at interconnected terminal.

Table 1. Specifications of Pole Transformer

Rated power	30 kVA
Number of phases and wires	single-phase three-wire (1φ3W)
Primary rated voltage	6600 V
Secondary rated voltage	210/105 V
Rated frequency	50 Hz
Number of turns in the secondary winding (U-V/U-N)	44/22
Secondary resistance (design value)	0.006517 Ω
Secondary leakage reactance (design value)	0.00703 Ω

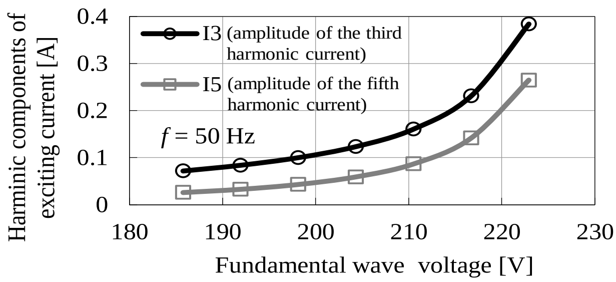


Fig. 2. Harmonic characteristics of pole transformer exciting current

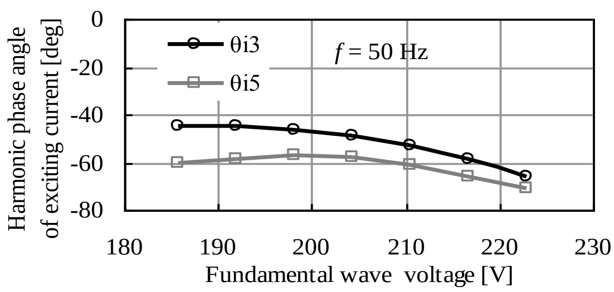
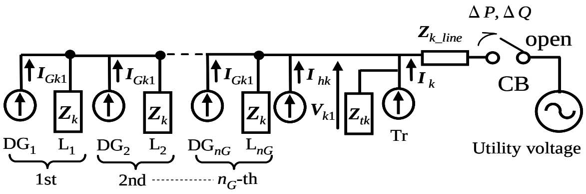


Fig. 3. Phase characteristics of harmonic current of pole transformer exciting current

2.3 Synchronized Injection and Amplitude Control of Active Signal

In Fig.1, PCS can give the reference of active signal (I_{Gk}^*, θ_{Gk}^*) to the auto current regulator (ACR) by using the estimated phase angle θ_{ik}. So, PCS can always inject the k-th harmonic current (k = 3 or 5) which is the active signal I_{Gk1} synchronized to the exciting current harmonics of the pole transformer into the grid system. Taking the power quality into account, I_{Gk1} is set below a few percent of the rated current. The synchronized injection of active signals of each PCS can avoid mutual interference between active signals in the case of large penetration of PV systems.

Fig. 4 shows the distribution system equivalent circuit of k-th harmonic area in islanding. The number of connected DGs and the loads are n_G. The line impedance for the k-th harmonics (Z_{k_line}) in the upper system are very smaller than the load impedance for the k-th harmonics (Z_k) in the low voltage system. So, when each PCS is connecting to the grid system, the change of harmonic voltage does not increase because almost of the active signal I_{Gk1} is absorbed mostly in the upper system.



Tr : Pole transformer (k-th harmonic current source)
Z_{tk} : Exciting impedance for k-th harmonics ($Z_{tk} \gg Z_k$)
Z_k : Each load impedance for k-th harmonics
Z_{k_line} : Line impedance for k-th harmonics
DG_{nG} : Distributed generator of the n_G-th
L_{nG} : Load of the n_G-th
n_G : Number of connected DGs or loads
I_{Gk1} : k-th harmonic current used as active signal of DG at the 1st stage
I_{hk} : The sum of the k-th harmonic current of each load
I_k : k-th harmonic current of pole transformer
V_{k1} : k-th harmonic voltage at the 1st stage injection

Fig. 4. Distribution system equivalent circuit of the k-th harmonic area in islanding

After islanding, the change of harmonic voltage increases because the active signal I_{Gk1} and the exciting current of pole transformer I_k flow into each Z_k. For the sake of simplicity, when we treat islanding in the single phase system, the k-th harmonic voltage V_{k1} and ΔV_k are given by (1), (2), respectively.

$$V_{k1} = (n_G I_{Gk1} + I_k + I_{hk}) \cdot \frac{Z_k}{n_G} \tag{1}$$

$$\Delta V_k = V_{k1} - V_{kbase} \tag{2}$$

where, I_{hk} is the sum of the k-th harmonic current generated by the each load. ΔV_k is the change of the k-th harmonic voltage after islanding. V_{kbase} is the k-th harmonic voltage before islanding. In (1), we neglect the influence of the k-th harmonic impedance of the pole transformer (Z_{tk}), because Z_{tk} is significantly larger than Z_k.

When ΔV_k exceeds the threshold value ΔV_{kth}, PCS changes the active signal amplitude from I_{Gk1} to I_{Gk2}. At the same time, the k-th harmonic voltage also increases from V_{k1} to V_{k2} which is given by (3).

$$V_{k2} = (n_G I_{Gk2} + I_k + I_{hk}) \cdot \frac{Z_k}{n_G} \tag{3}$$

In (3), we assume that I_k, I_{hk} and Z_k are constant until detecting islanding because the detection time is very short from 0.1 sec to 0.2 sec.

2.4 Discrimination of Islanding State

When the increase in harmonic voltage is caused by the grid system disturbance, the miss operation of PCS may occur. In order to protect the miss operation, we introduce the estimation technique on the harmonic impedance of the load. When we subtract (1) from (3), we obtain (4).

$$\Delta Z_k = Z_k = \frac{V_{k2} - V_{k1}}{I_{Gk2} - I_{Gk1}} \tag{4}$$

where, ΔZ_k is the estimation value of the harmonic impedance of the load. Thus, PCS can estimate ΔZ_k by calculating (4). When ΔZ_k is between Z_{kmin} and Z_{kmax}, PCS detects islanding and stops the generation.

2.5 Fast Detection Algorithm of Islanding

Fig. 5 shows the fast detection algorithm of islanding by using proposed method. The detection algorithm consists of three steps. Each step has the timers (T_1, T_W, T_2). T_1 and T_2 are necessary to protect miss operation caused by the grid system disturbance. T_W is needed to detect V_{k2} reliably.

After islanding, when time α has elapsed, PCS detects ΔV_k that has exceeded the threshold value ΔV_{kth}. The time α is around 1-2 cycles, and varies for the load condition and the voltage phase angle at the start of islanding. The net time T_D of islanding detection is given by (5)

$$T_D = T_1 + T_W + T_2 + \alpha \tag{5}$$

When the setting values of these timers are given by the example of Fig. 5, TD is approximately 0.1 sec. Therefore, the fast detection of islanding is possible.

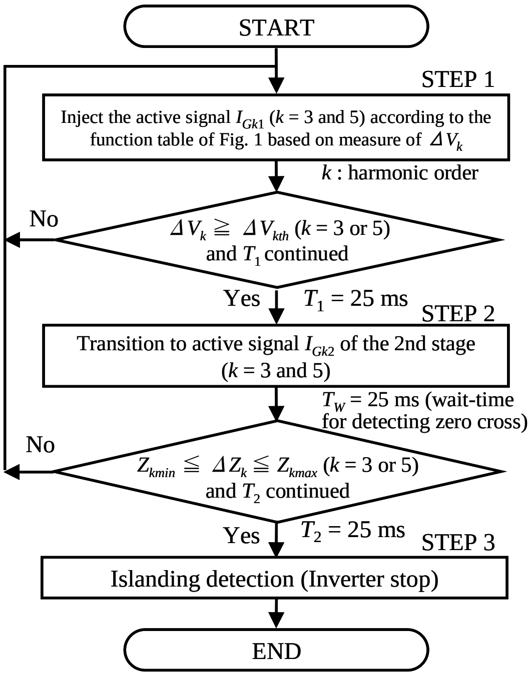


Fig. 5. Flow diagram of proposed islanding detection algorithm

3. Experimental Method

Through the following basic experiment in islanding, we clarify the synchronized injection method of harmonic active signal and the estimation method of the load impedance for the k-th harmonics.

3.1 Experimental Circuit

Fig. 6 shows the experimental circuit. The current source J_G superimposed the harmonic active signal is treated as a current controlled type inverter for PV system.

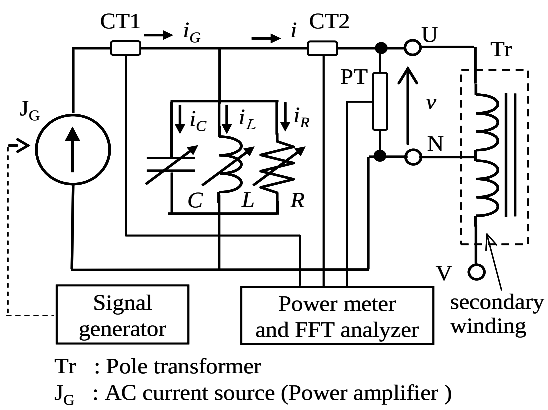


Fig. 6. Experimental circuit

3.2 Experimental Common Conditions

Table 2 shows the experimental common conditions for "Active signal injection test" and "Estimation test of load impedance for the k-th harmonics".

Table 2. Experimental common conditions

Item	Conditions
Fundamental voltage V_1 (U-N)	105 V
Fundamental frequency f	50 Hz
Rated power of the current source	2 kVA
Rated current of the current source	20 Arms
Rate of output power of the current source	20%, 50%, 100%
Power factor of the current source	1.0
Quality factor : Q_f	1.0

We adjust the RLC resonant load to satisfy the condition of (6) and Table 2.

$$P_G \cdot Q_f = (P_R + P_{tr}) \cdot Q_f = Q_C = | Q_L + Q_{tr} | \qquad (6)$$

where, P_G is the output power of the current source. Q_f is the quality factor [4]. P_R is the active power of the resistor R. P_{tr} is the iron loss of the pole transformer. Q_C is the reactive power of the capacitor C. Q_L is the reactive power of the inductor L. Q_{tr} is the reactive power of the pole transformer. Z_k is given by (7).

$$Z_k = \left\{ \frac{1}{R} + j\left(k\omega C - \frac{1}{k\omega L} \right) \right\}^{-1} \qquad (7)$$

3.3 Active Signal Injection Test

Table 3 shows the conditions for "Active signal injection test". The amplitude of each active signal is equal to the exciting current harmonics of the pole transformer.

Table 3. Active signal injection test conditions

Item		Conditions
Amplitude of active signal: I_{Gk}	k = 3	0.33 Arms
	k = 5	0.18 Arms
Injection phase angle of active signal : θ_{Gk} (k = 3 or 5)		from 0 to 360 ° (Increments of 30 °)

3.4 Estimation Test of Load Impedance for the k-th Harmonics

Table 4 shows the for the estimation test conditions of load impedance for the k-th harmonics. We assume that the positive direction of θ_{ik} is inflow and the positive direction of θ_{Gk} is outflow.

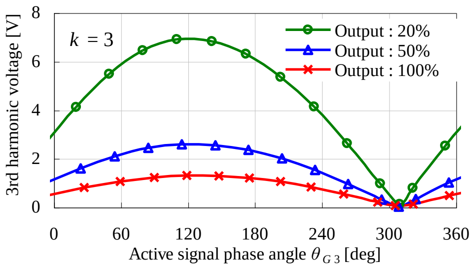
Table 4. Estimation test conditions of load impedance for the k-th harmonics

Item	Conditions
Amplitude of active signal: I_{Gk} (k = 3 or 5)	from 0 to 1 Arms (Increments of 0.2 Arms)
Injection phase angle of active signal : θ_{Gk}	$\theta_{Gk} = \theta_{ik} + 180°$

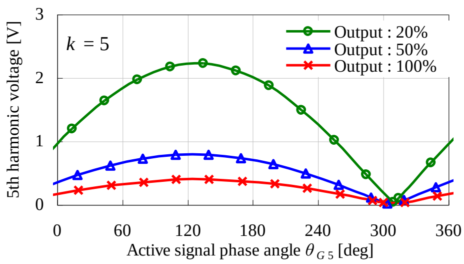
4. Experimental Results

4.1 Active Signal Injection Test

Fig. 7 shows the test results. In all test cases, the harmonic voltage (k = 3 or 5) has the maximum value at around 130° of the injection phase angle of the active signal (θ_{Gk}), and has the minimum value at around 310° of θ_{Gk}. The reason for this is that the mutual interference occurs between the active signal (I_{Gk}) and the exciting current harmonics of the pole transformer (I_k).



(a) Characteristics of 3rd harmonic voltage



(b) Characteristics of 5th harmonic voltage

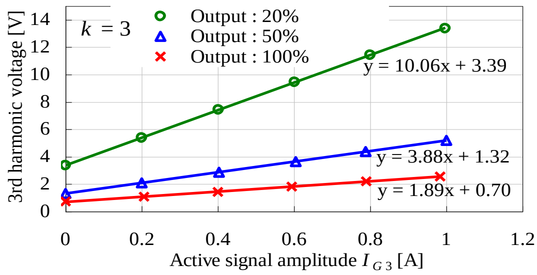
Fig. 7. Harmonic voltage vs. active signal phase angle

When V_k becomes the maximum value at θ_{Gk}, θ_{Gk} corresponds to synchronized phase angle. According to Fig. 3, when V_1 is 210 V (105 V at U-N phase), θ_{ik} is -53° (k = 3) or -61° (k = 5). The positive direction of θ_{Gk} is outflow. Considering that the positive direction of θ_{ik} is inflow, relation between θ_{Gk} and θ_{ik} at the maximum point of V_k is represented by (8).

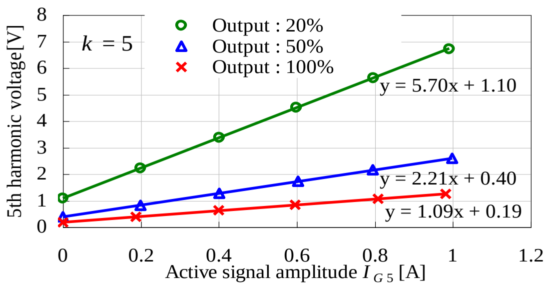
$$\theta_{Gk} = \theta_{ik} + 180 \qquad (8)$$

4.2 Estimation Test of Load Impedance for the k-th Harmonics

Fig. 8 shows the test results. In all test cases, when the active signal amplitude increases, the harmonic voltage also increases linearly. In Fig. 8, the linear approximated equations (such as $y = ax + b$) by the least squares method are also indicated. The slope (a) corresponds to the estimation value ΔZ_k which is defined by (4). The estimation value ΔZ_k (= a) is compared with the measured value Z_k given by (7).



(a)Characteristics of 3rd harmonic voltage



(b) Characteristics of 5th harmonic voltage

Fig. 8. Harmonic voltage vs. active signal amplitude

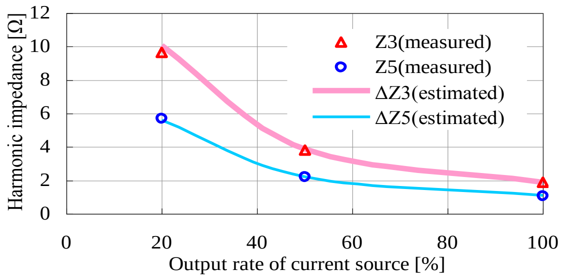


Fig. 9. Harmonic impedance vs. output rate of current source

As shown in Fig. 9, the estimation value ΔZ_k agreed well with the measured value Z_k. These results mean that the proposed method can estimate the harmonic impedance of the load with high accuracy.

5. Verification of Fast Islanding Detection by Simulation

5.1 Simulation Model for Grid Connected Inverter

Fig. 10 shows the block diagram of simulation model for single-phase grid-connected inverter. In order to simplify the model, we treat the inverter as a current source which has the control systems, because the inverter for PV system is generally used the fast current controlled type [5]. The islanding detection function is the proposed method. The inverter's rated power is 4 kW, the rated voltage is 200 V, and the frequency is 50 Hz.

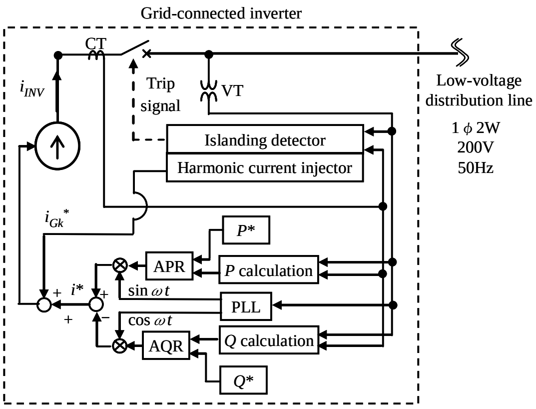


Fig. 10. Block diagram of simulation model for single phase grid-connected inverter

5.2 Simulation Conditions

Fig. 11 shows the islanding detection test circuit. As the basic study, we treat the worst condition for the islanding detection. That is, the power flow (ΔP and ΔQ) at the circuit breaker (CB) is equal to 0 %.

Table 5 - 8 show the simulation conditions. The load is the parallel *RLC* resonant circuit whose quality factor Q_f is 1 or 3 [4] [6]. As shown in Fig.2 and Fig. 3, the pole transformer whose rated power is 30 kVA is connected to the test circuit and generates the excitation current.

5.3 Simulation Result in Case 1 (Q_f = 1)

Fig. 12 shows the simulation result in Case 1. HID detects islanding at 98.4 ms through the following processes. First, when the time is 0 ms, the circuit breaker opens and islanding starts. When the time is 23 ms, the changes of harmonic voltage ΔV_k become 1.51 V (k = 3) and 1.41 V (k = 5), and are over the threshold values ΔV_{kth} which are 1.2 V (0.6 %).

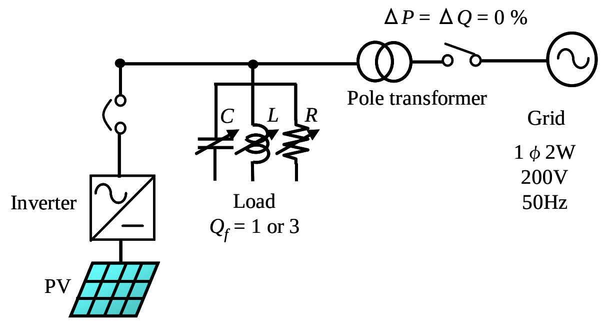


Fig. 11. Simulation test circuit for islanding detection

Table 5. Simulation test conditions

Contents	Conditions	
Case Number	Case 1	Case 2
Q_f : Quality factor	1.0	3.0
Inverter output power	100% (4 kW)	
Power factor of inverter	1.0	

Table 6. Setting of Active Signal Amplitude

Contents	Conditions
Active signal amplitude of inverter (1st injection) I_{Gk1}	I_{G31} = 1.5%, I_{G51} = 3.0%
Active signal amplitude of inverter (2nd injection) I_{Gk2}	I_{G32} = 3.0%, I_{G52} = 6.0%

Table 7. Threshold values for islanding detection

Q_f	k	ΔV_{kth}	Z_{kmin}	Z_{kmax}
1	3	0.6%	2.5 Ω	11 Ω
	5	0.6%	1.5 Ω	11 Ω
3	3	0.15%	0.5 Ω	11 Ω
	5	0.15%	0.3 Ω	11 Ω

Table 8. Setting of Islanding detection timer

T_1	25 ms
T_W	25 ms
T_2	25 ms

The islanding detection timer T_1 starts to count the continued time. Since ΔV_k (k = 3 or 5) continued to be over ΔV_{kth}, the active signal changes from the 1st stage (I_{Gk1}) to the 2nd stage (I_{Gk2}) at the time 48 ms (STEP 2). Thus, I_{G3} changes from 1.5% (0.3 A) to 3.0% (0.6 A), and

I_{G5} changes from 3 % (0.6 A) to 6 % (1.2 A). The harmonic voltage are growing by increasing the active signal amplitude. After the wait-time T_W (25 ms) is elapsed, the changes of the harmonic voltage are almost stable at the time 73 ms, and the estimation of the load impedance for the k-th harmonics ΔZ_k starts. By using (4), ΔZ_3 and ΔZ_5 were estimated to be 3.60 Ω and 2.02 Ω, respectively.

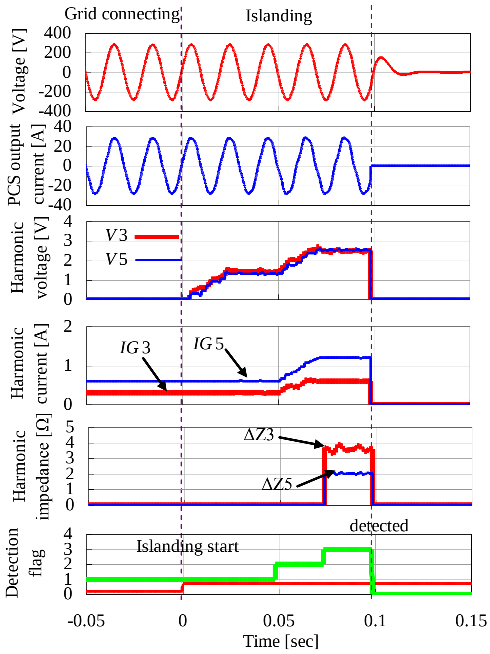


Fig. 12. Simulation result in Case 1 (Q_f = 1)

5.4 Simulation Result in Case 2(Q_f = 3)

Fig. 13 shows the simulation results in Case 2. In Fig. 13, PCS can also detect islanding quickly within 0.1 sec.

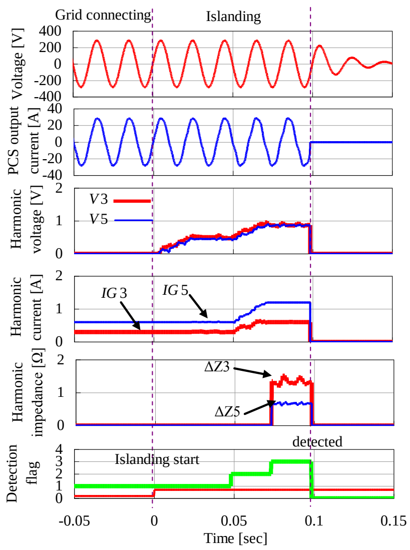


Fig. 13. Simulation result in Case 2 (Q_f = 3)

The harmonic voltage V_k and the load impedance for the k-th harmonics ΔZ_k are smaller than that of Case 1, because the active signals are absorbed to the large LC resonant circuit (Q_f = 3). However, as shown in Table.7, since the detection thresholds are set to the lower adequate values, PCS can detect islanding quickly within 0.1 sec.

6. Conclusion

We proposed a novel islanding prevention method by the harmonic current injection synchronized to the exciting current harmonics of the pole transformer. By the basic experiment and the simulation, we presented the feasibility of detecting the islanding quickly and reliably, even if quality factor of resonant circuit is significantly large (Q_f = 3). And this proposed method is applicable to the islanding detection system under clustered installation of PV systems because mutual interference does not occur due to synchronous state between active signals.

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