Synchronization Issues with Irregular Current Injection Islanding Detection Methods in Multi-DG Operation

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***Abstract*—The islanding detection methods that detect an island through injecting high/low frequency currents or negative sequence currents are called irregular current injection methods in this paper. A synchronization issue of such methods is raised in multi-DG (Distributed Generation) operation. This issue requires that the same frequency irregular currents injected by DG units should be in phase to avoid cancelling each other out. If this issue is not handled properly, the effect of such methods is uncontrollable. In view of this, an approach to this issue is proposed in this paper. According to this approach, the terminal voltage of a DG unit is taken as a reference to conduct the irregular current injection, and only parts of the irregular currents whose frequencies are an integer multiple of the frequency of the reference voltage are employed. Finally, experiments and simulations verify the effect of the proposed approach.**

Keywords-current injection; islanding detection; multi-DG; synchronization; terminal voltage reference

I. INTRODUCTION

Along with the growing penetration of DG (Distributed Generation), an anti-islanding function has been generally required. From this, a lot of islanding detection methods have been developed, including local methods, which contain active and passive methods, and remote methods. The active methods are very popular due to their good performance and low cost. The method that injects high/low frequency currents or negative sequence currents, and observes the resultant responses afterwards, is called an irregular current injection islanding detection method in this paper. It is a main active method and will form the main discussion in this paper.

For this method, the injected irregular currents can be divided into positive/negative sequence high frequency currents, positive/negative sequence low frequency currents, and negative sequence fundamental frequency currents. The identification of an island is based on the changes of the irregular voltages excited by the injected irregular currents. By following this route, a second harmonic was injected in [1], [2] and [3]; even harmonics injection was proposed in [4]; a non-characteristic harmonic was used in both [5] and [6], while dual-frequency harmonics were introduced in [5] to cope with the unbalanced grid impedance; inter-harmonics were used in [7] and [8]; asymmetric sub-harmonics, which must contain a negative sequence low frequency component, were injected in [9]; a pulse current was adopted in [10]; and negative sequence currents were adopted in [11]-[13]. On the other hand, the observed objects in these references are also different, even though in some references the same irregular currents were injected. Changes of irregular voltages were directly monitored in [1], [2], [4], [6] and [9]-[12], whereas network impedance was measured by means of the irregular currents and voltages in [3], [5], [7] and [8], and the voltage unbalance factor was measured in [13]. Moreover, irregular voltage injection for islanding detection was proposed in [14]-[20].

However, in multi-DG operation, considering that generally there is no communication between DG units, the phases of the injected irregular currents are irrelevant, by which the irregular currents may cancel each other out and the aggregate irregular currents (magnitude) may become smaller. The smaller irregular currents may cause the resultant irregular voltages to be too small to detect, which will seriously degrade the performance of irregular current injection methods. Accordingly, a synchronization issue comes into being, which requires that the same frequency irregular currents are preferably in phase. This paper will study how to solve this issue without communication.

II. A PROBLEM WITH IRREGULAR CURRENT INJECTION ISLANDING DETECTION METHODS IN MULTI-DG OPERATION

A. Principle of Irregular Current Injection Methods

As shown in Figure 1, the equivalent network impedance $Z_{eq(grid)}$ seen from a DG unit is the parallel impedance of the load and grid impedance (represented by R_g and L_g), while $Z_{eq(island)}$ is the load impedance. Since the grid impedance is much smaller than the load impedance over a certain frequency range, $|Z_{eq(island)}|$ is significantly larger than $|Z_{eq(grid)}|$ [9][21][22]. In this case, irregular current injection methods inject irregular currents into the network and then observe the resultant irregular voltage, by which an island can be identified via a surge of the irregular voltage, the unbalance factor / total harmonic distortion of terminal voltage of a DG unit, the network impedance, or the correlation between the irregular current and voltage.

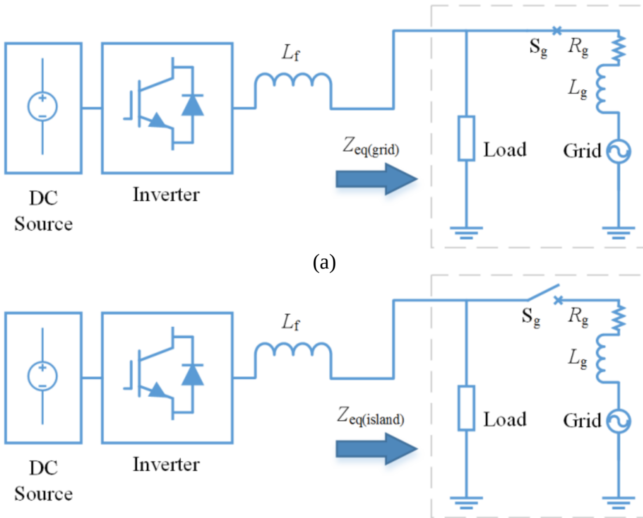


Figure 1. Network impedance seen from an inverter-based DG unit. (a) A grid-connected case. (b) An island case.

B. A Problem in Multi-DG Operation

In multi-DG operation, as shown in Figure2, where all the currents/voltages are irregular currents/voltages with the same frequency, there is the following equation:

$$\dot{U}_{ir} = (\dot{I}_{DG1}+\ldots+\dot{I}_{DGi}+\ldots+\dot{I}_{DGN})Z_{eq(island)} = \dot{I}_{agg\_ir}\, Z_{eq(island)}$$

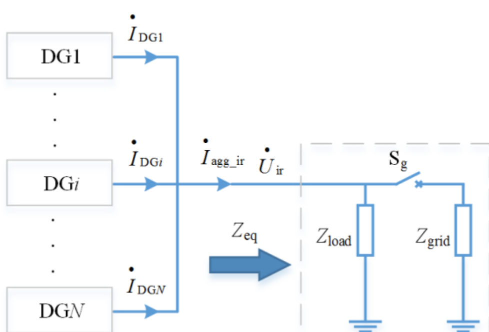


Figure 2. Multi-DG operation.

Considering that generally there is no communication between DG units, the phases of these irregular currents are irrelevant, for which reason $\dot{I}_{DG1}$, $\dot{I}_{DG2}$, ... may cancel each other out and $\dot{I}_{agg\_ir}$ may become smaller on the basis of these injected irregular currents. If $\dot{I}_{agg\_ir}$ is so small that the following relationship is true, where U_{th_i} denotes the threshold of the DGi unit used to determine an island event, the island will not be detected by the DGi unit. This is exactly the problem with irregular current injection methods in multi-DG operation.

$$U_{ir}=I_{agg\_ir}|Z_{eq(island)}|<U_{th\_i}$$

To overcome this problem, the irregular currents should have similar phases, and the optimal situation is that they are in phase. In this manner, the synchronization issue on how to make these irregular currents be in phase arises.

III. An Approach to the Synchronization Issue

As mentioned above, since there is no communication between DG units, a reference that is common to all the DG units can be used to conduct the irregular currents injection. Throughout the measurable quantities, grid voltage is a natural reference quantity, and presents as the terminal voltage of a DG unit. By referencing the terminal voltage, if all the irregular currents are injected in the same injection pattern, a synchronization is available.

A. Injection Pattern

In this paper, an irregular current is injected in this pattern: the first zero phase (based on a sine function) of the irregular current i_{ir} lags a zero phase of the terminal voltage u_{tm} (i.e., reference voltage) by T_{lag} (time), which is less than the periods of both i_{ir} and u_{tm}, as shown in Figure 3. Since the frequency of terminal voltages of DG units (fundamental frequency) is likely to be different from that of the irregular currents, T_{lag} is characterized by time rather than angle. Furthermore, it is found that other injection patterns can actually be attributed to this pattern as long as they are based on a terminal voltage reference.

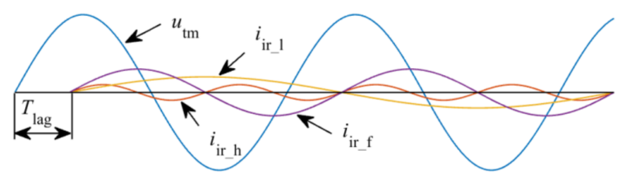


Figure 3. Injected pattern of the irregular currents. u_{tm}: terminal voltage; i_{ir_h}: high frequency current; i_{ir_l}: low frequency current; i_{ir_f}: negative sequence fundamental frequency current.

B. Generally Usable Frequencies for Irregular Currents

We take the DG1 and DG2 units in Figure 2 for an example to analyze below.

1) High Frequency Currents: If i_{DG1} is injected earlier than i_{DG2}, as shown in Figure 4, to ensure that i_{DG1} and i_{DG2} are in phase the equation below should be met, where T_{Pu} and T_{Piir} are the periods of the terminal voltage and irregular currents, respectively, and, both m_u and m_{iir} are positive integers and $m_u < m_{iir}$.

$$m_u T_{Pu}=m_{iir} T_{Piir} \tag{1}$$

The above equation can be rewritten as follows, where f_u and f_{iir} are the frequencies of the terminal voltage and irregular currents, respectively, i.e., $1/T_{Pu}$ and $1/T_{Piir}$. From

Figure 4, m_u may be any positive integer. Considering that f_u is actually certain, a f_{iir} is usable if there is always a proper m_{iir} (positive integer) to enable the following equation to be established for each value of m_u (i.e., each positive integer).

$$f_{iir}/f_u = m_{iir}/m_u \tag{2}$$

Accordingly, the aggregate usable f_{iir} can be expressed as the following set.

$$\{f_{iir} \mid f_{iir}=f_u m_{iir},\ m_{iir} \text{ is an integer greater than } 1\} \cap \{f_{iir} \mid f_{iir}=f_u m_{iir}/2,\ m_{iir} \text{ is an integer greater than } 2\} \cap \ldots \cap \{f_{iir} \mid f_{iir}=f_u m_{iir}/h,\ m_{iir} \text{ is an integer greater than } h\} \cap \ldots$$

According to the result of the above expression, the usable f_{iir} for high frequency currents can be obtained as follows, where k is an integer greater than 1.

$$f_{iir} = k f_u \tag{3}$$

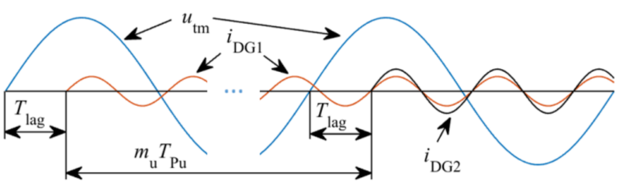


Figure 4. High frequency currents injection.

2) Low Frequency Currents: In the same case as above, as shown in Figure 5(a), (1) and (2) should still be satisfied, where both m_u and m_{iir} are positive integers and $m_u > m_{iir}$, and then it means $m_u \neq 1$. m_u means that i_{DG2} starts to be injected later than i_{DG1} for $m_u T_{Pu}$. Hence, it may be any positive integer, including 1, which contradicts the preceding $m_u \neq 1$. In other words, if i_{DG2} starts to be injected later than i_{DG1} for T_{Pu}, i_{DG1} and i_{DG2} cannot be in phase. On the other hand, for any given f_{iir}, due to $f_{iir}/f_u < 1$ and according to (2), it cannot be ensured that m_{iir} is an integer for each value of m_u, which contradicts the previous limitation that m_{iir} is a positive integer. Consequently, low frequency currents are unsuitable as injected currents. Figure 5(b) shows an example.

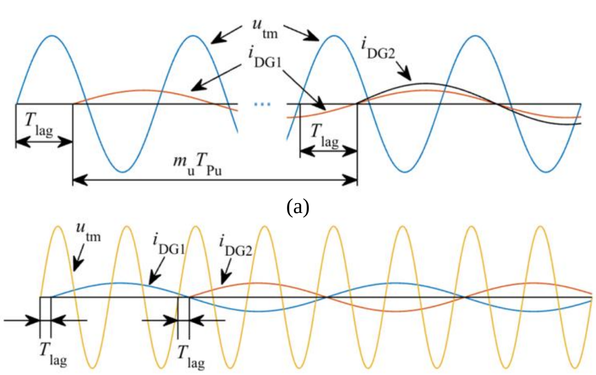


Figure 5. Low frequency currents injection. (a) General diagram where i_{DG1} is in phase with i_{DG2}. (b) An example where i_{DG1} and i_{DG2} are out of phase.

3) Negative Sequence Fundamental Frequency Currents: Such currents only exist in three-phase systems. As shown in Figure 6, as above, (2) should still be satisfied, where both m_u and m_{iir} are positive integers. In this condition, f_{iir} is equal to f_u, and for each value of m_u, as long as m_{iir} is taken as this value as well, (2) can be satisfied. Hence, negative sequence fundamental frequency currents are usable at present.

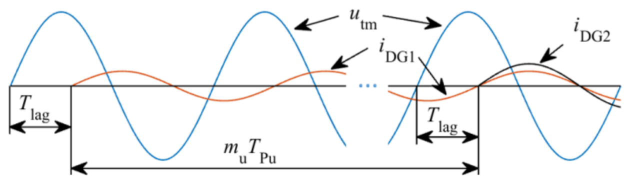


Figure 6. Negative sequence fundamental frequency currents injection.

The following will only focus on the usable irregular currents derived above.

C. Applications in Three-Phase DG Units

For three-phase DG units, the referenced terminal voltages of irregular currents i_{ira}, i_{irb} and i_{irc} are line voltages (i.e., phase-to-phase voltage) u_{ab}, u_{bc} and u_{ca}, respectively, and T_{lag} is appointed as T_a, T_b and T_c, respectively.

The time interval between a zero phase of the reference voltage and the zero phase of an irregular current immediately after it is defined as the zero phase interval in this paper, and every zero phase of the reference voltage corresponds to a zero phase interval of the irregular current, which is represented by bold solid lines in Figure 7(a). For any irregular current, its first zero phase interval must be equal to T_{lag}, and for those whose frequencies are an integer multiple of the frequency of the reference voltage, i.e., the usable irregular currents derived in the previous subsection, all of their zero phase intervals are the same and equal to their T_{lag}, as shown in Figure 7(a). From the definition of zero phase interval, the positive sequence irregular currents injection is shown in Figure 7(b). Accordingly, the equations below can be established, where m_{p1} and m_{p2} are non-negative integers, and each non-negative integer may be the value of m_{p1} and m_{p2}.

$$\begin{cases} T_b = T_a + T_{Piir}/3 + m_{p1} T_{Piir} - T_{Pu}/3 \\ T_c = T_a + T_{Pu}/3 - T_{Piir}/3 - m_{p2} T_{Piir} \end{cases} \tag{4}$$

The negative sequence irregular currents injection is shown in Figure 7(c). As above, (5) can be derived for such currents, where m_{n1} and m_{n2} are non-negative integers, and each non-negative integer may be the value of m_{n1} and m_{n2}.

$$\begin{cases} T_b = T_a + m_{n1} T_{Piir} - T_{Pu}/3 - T_{Piir}/3 \\ T_c = T_a + T_{Pu}/3 + T_{Piir}/3 - m_{n2} T_{Piir} \end{cases} \tag{5}$$

Equations (4) and (5) indicate that, for irregular currents, T_b and T_c are determined by T_a. Thus, for a three-phase DG unit only T_a needs to be set.

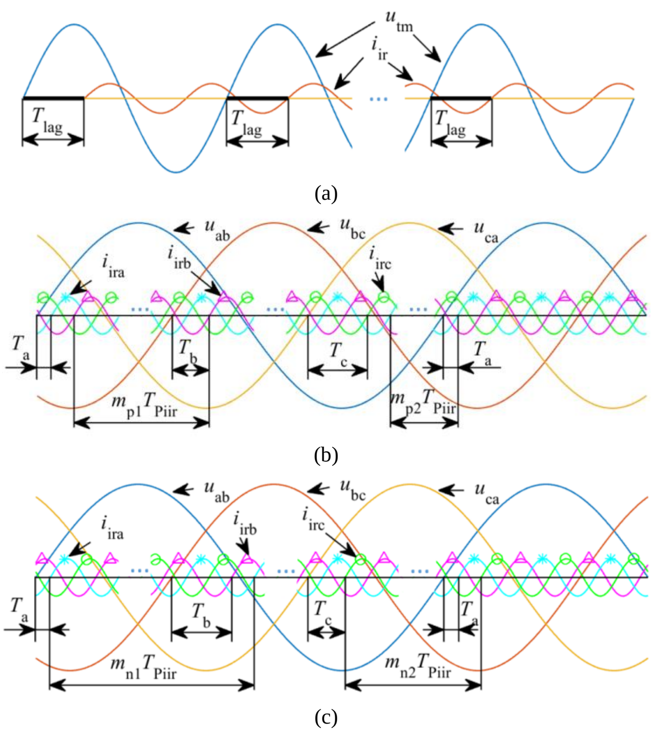


Figure 7. Definition of zero phase interval and three-phase currents injection. (a) Zero phase intervals represented by bold solid lines. (b) Positive sequence irregular currents. (c) Negative sequence irregular currents.

In some cases, due to misoperation or missing relevant information, the phase symbols of a DG unit may not match that of the grid, while the phase sequence is matched, as shown in Figure 8, which is called a phase symbol fault in this paper. This situation is acceptable from a generation point of view and is almost impossible to be perceived by the DG unit itself. Thereupon, it is hoped that irregular current injection islanding detection methods can also tolerate this fault. In other words, the irregular currents injected into the same phase of a grid must still be in phase. For example, for i_{ira1}, i_{irc2} and i_{irb3}, their actual reference voltage is u_{ab} of the grid, and their T_{lag} is T_a, T_c and T_b, respectively. For them to be in phase, (6) should be met. For other irregular currents in Figure 8, (6) can still be derived.

$$T_a = T_b = T_c \tag{6}$$

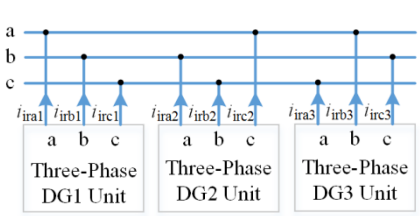


Figure 8. Three-phase DG units with a phase symbol fault.

By combining (4), (5) and (6), the usable frequencies for three-phase irregular currents can be derived, as shown in (7), where m is a positive integer. (7) reflects that when considering the phase symbol fault, the totality of usable frequencies will decrease on the basis of the usable frequencies mentioned in the previous subsection. Meanwhile, it reveals that negative sequence fundamental frequency currents are no longer usable, since the right side of the lower equation in (7) cannot be f_u.

$$\begin{cases} f_{iir} = (3m+1) f_u, \text{ for positive sequence irregular currents} \\ f_{iir} = (3m-1) f_u, \text{ for negative sequence irregular currents} \end{cases} \tag{7}$$

D. *Applications in Single-Phase DG Unit*

As shown in Figure 9, generally, for ease of use, the parameters of a single-phase DG unit do not need to be modified when the phase it is connected to is changed. Accordingly, for single-phase DG units, their T_{lag} must be the same to make the injected irregular currents be in phase regardless of which phase they are connected to. Thereupon, their T_{lag} is specially appointed as T_l. Since the reference voltages of i_{irs1} and i_{ira} are phase voltage (i.e., phase-to-ground voltage) u_{an} and line voltage u_{ab}, respectively, and u_{an} lags u_{ab} by π/6 rad, to make i_{irs1} and i_{ira} be in phase, T_l must satisfy (8), where m_a is the integer that makes $0 \le T_l < T_{Piir}$. For the other irregular currents in Figure 9, the two equations after (8) must be met, where m_b and m_c are also the integers that make $0 \le T_l < T_{Piir}$. And it can be found that the three equations below must still be met even if there is a phase symbol fault with the DG4 unit. As mentioned before, only T_a needs to be set for a three-phase DG unit, and for a single-phase DG unit only T_l needs to be set. Therefore, (8) should be met when setting T_a and T_l.

$$T_l = T_a - T_{Pu}/12 + m_a T_{Piir} \tag{8}$$

$$T_l = T_b - T_{Pu}/12 + m_b T_{Piir}$$

$$T_l = T_c - T_{Pu}/12 + m_c T_{Piir}$$

By combining (4), (5) and the above three equations, the usable frequencies for single-phase irregular currents can be derived, as shown in (7) (ignore the phase sequence).

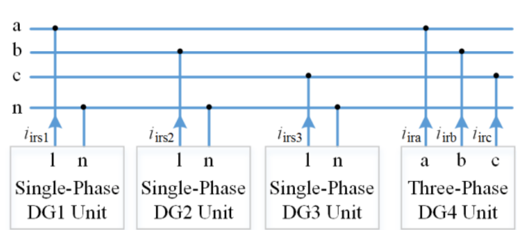


Figure 9. Hybrid generation comprising single-phase DG and three-phase DG.

It has been found that only parts of the frequencies shown in (3) are usable for three-phase irregular currents and single-phase irregular currents in order to achieve synchronization, as shown in Figure 10. And the rest of the frequencies contained in (3), i.e., $3mf_u$, will not be employed by three-phase irregular currents. Thus, it seems that they can be employed by a single-phase irregular current, for there is no synchronization issue between the currents at different frequencies. The following will study whether this is practicable.

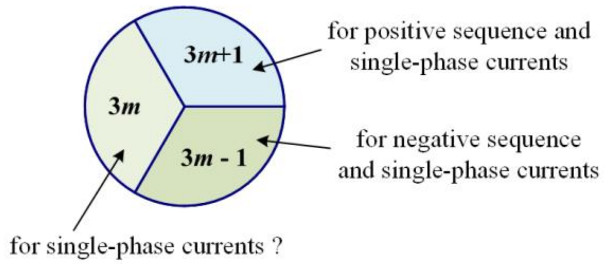


Figure 10. Integer orders larger than 1.

Single-phase DG units are likely to be evenly distributed on the three-phase lines. Accordingly, as shown in Figure 9, it can be assumed that i_{irs1}, i_{irs2} and i_{irs3} are equal or approximately equal in magnitude, by which there injection can be drawn as shown in Figure 11, where i_{irs1} leads i_{irs2} by T_{12} (time), i_{irs2} leads i_{irs3} by T_{23}, and m_s is a non-negative integer. From Figure 11, the equation below can be obtained.

$$m_s T_{Piir} + T_{12} = T_{Pu}/3$$

It can be rewritten as

$$T_{12} = [f_{iir}/(3f_u) - m_s] T_{Piir}$$

Considering $0 \le T_{12} < T_{Piir}$, the result below can be obtained when substituting $f_{iir}=3mf_u$ into the above equation. And for T_{23}, the same result can be obtained. These results reveal that if i_{irs1}, i_{irs2} and i_{irs3} are at the frequencies of $3mf_u$, they will be in phase and then present as a set of zero sequence currents in the grid. However, here the zero sequence currents are bothersome in the grid. For example, they may affect zero-sequence relay [23]. Therefore, the frequencies of $3mf_u$ are not recommended to single-phase irregular currents.

$$T_{12} = 0$$

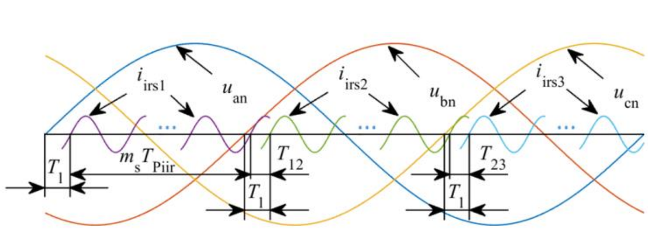


Figure 11. Three single-phase currents injected into a three-phase system.

In conclusion, for the proposed approach, in order to be robust and affect grids as little as possible, only the irregular currents whose frequencies are selected according to Table I are usable.

TABLE I. USABLE HARMONIC ORDERS FOR IRREGULAR CURRENTS

Irregular currents	Usable orders
Three-phase positive sequence currents	$3m+1$
Three-phase negative sequence currents	$3m - 1$
Single-phase currents	$3m \pm 1$

In this table m is a positive integer.

IV. SETTING OF T_{lag}

T_{lag} (T_a and T_l) has been proposed from the start and must be unified. However, regarding the setting of T_a and T_l, besides the mandatory requirement shown in (8), there is no more conclusion. In fact, no effect index has been found to be relevant to T_a and T_l up to now, and therefore it is difficult to say which value is optimal. Accordingly, at present the only way is to specify values for them artificially, e.g., specified by the grid code makers. For example, T_a and T_l can be set as follows.

$$\begin{cases} T_a = T_{Pu}/12 \\ T_l = 0 \end{cases} \quad (9)$$

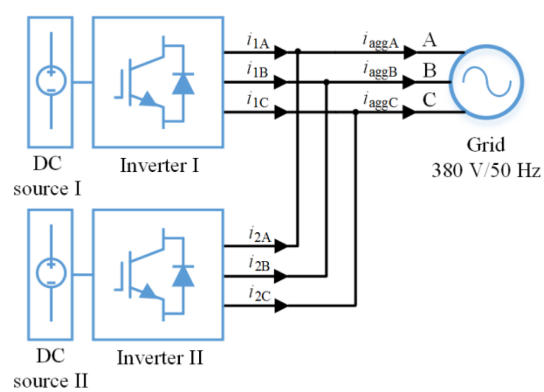
V. EXPERIMENTS AND SIMULATIONS

In both the experiments and simulations, T_a and T_l are set in accordance with (9).

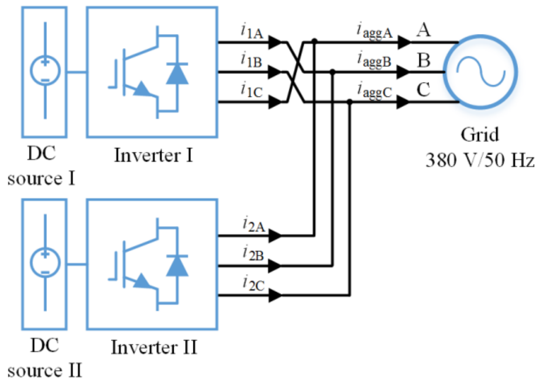
A. Experiments

The following experiments are based on normal generation. Thus, the irregular currents have to be extracted from the measured currents offline through filtering out the components at other frequencies and the components of the opposite phase sequence at the same frequency [24].

1) Synchronization Tests under a Normal Connection: The normal connection means that there is no phase symbol fault, as shown in Figure 12(a). Both the inverters are based on unity power factor control, and a fundamental current of 5 A (amplitude) is output by inverter I, while another fundamental current of 3.5 A is output by inverter II.



(a)



(b)

Figure 12. Synchronization tests based on two inverters. (a) Normal connection. (b) A scenario that inverter I has a phase symbol fault.

a) Positive sequence 200 Hz irregular current: An irregular current of 0.8 A (amplitude) and another of 0.5 A are injected into the grid by inverter I and inverter II, respectively. The experimental results are shown in Figure 13.

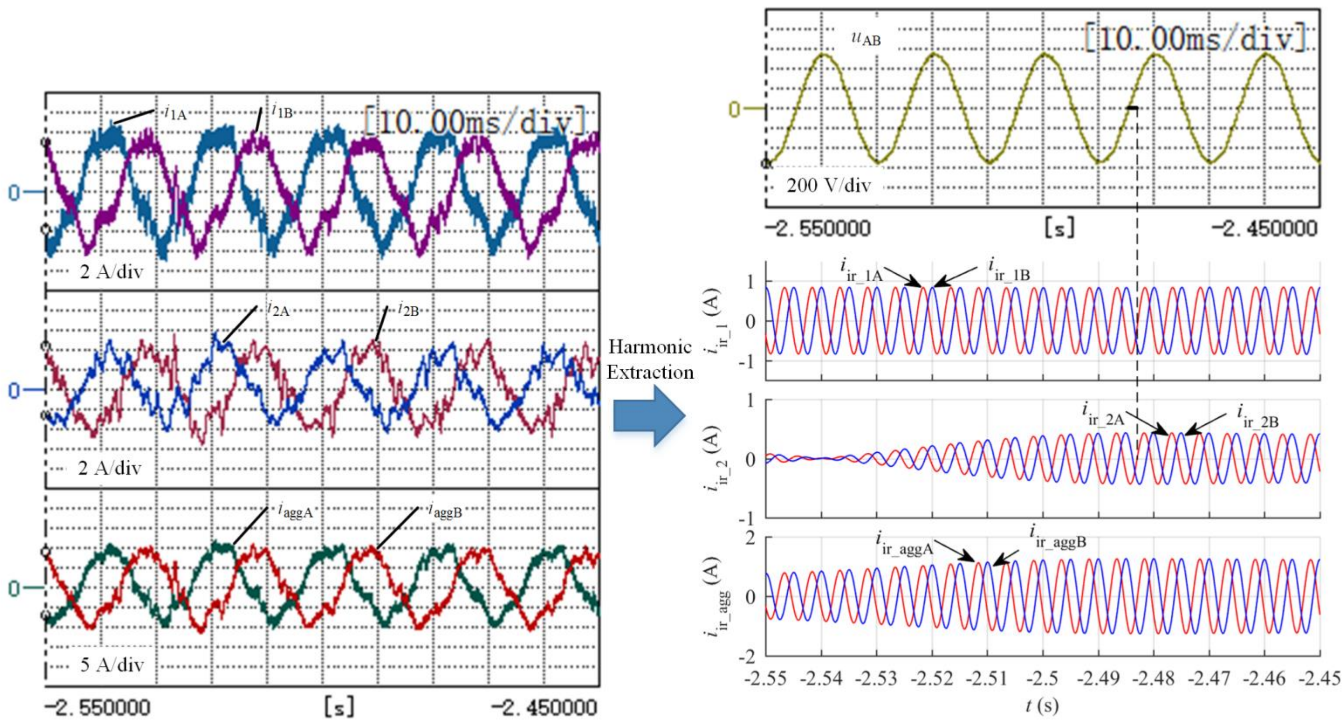


Figure 13. Waveforms before and after the injection of positive sequence 200 Hz irregular current of inverter II

According to the demonstration in subsection III-C, all the zero phase intervals of both i_{ir_1A} and i_{ir_2A} are equal to T_a. Therefore, i_{ir_2A} will be in phase with i_{ir_1A} whenever it is injected, for which reason i_{ir_aggA} increases after the injection of i_{ir_2A}. Therefore, this irregular current is usable.

b) Negative sequence 50 Hz irregular current: The size of the irregular current is the same as that in a). The experimental results are shown in Figure 14.

As this case is similar to a) with respect to the frequency of the irregular current, i_{ir_2A} is in phase with i_{ir_1A} while i_{ir_aggA} still increases. Thereupon, this irregular current is usable under a normal connection.

2) Synchronization Tests under a Phase Symbol Fault: In this test, there is a phase symbol fault with inverter I, as shown in Figure 12(b). The output fundamental currents are the same as those in 1).

a) Positive sequence 200 Hz irregular current: The size of the irregular current is the same as that in a) of 1). The experimental results are shown in Figure 15.

Since the reference voltage of both i_{ir_1C} and i_{ir_2A} is u_{AB} and both of their zero phase intervals are equal to T_a, they are in phase and i_{ir_aggA} must increase. Therefore, this irregular current is still usable.

b) Negative sequence 50 Hz irregular current: The size of the irregular current is the same as that in a) of 1). The experimental results are shown in Figure 16.

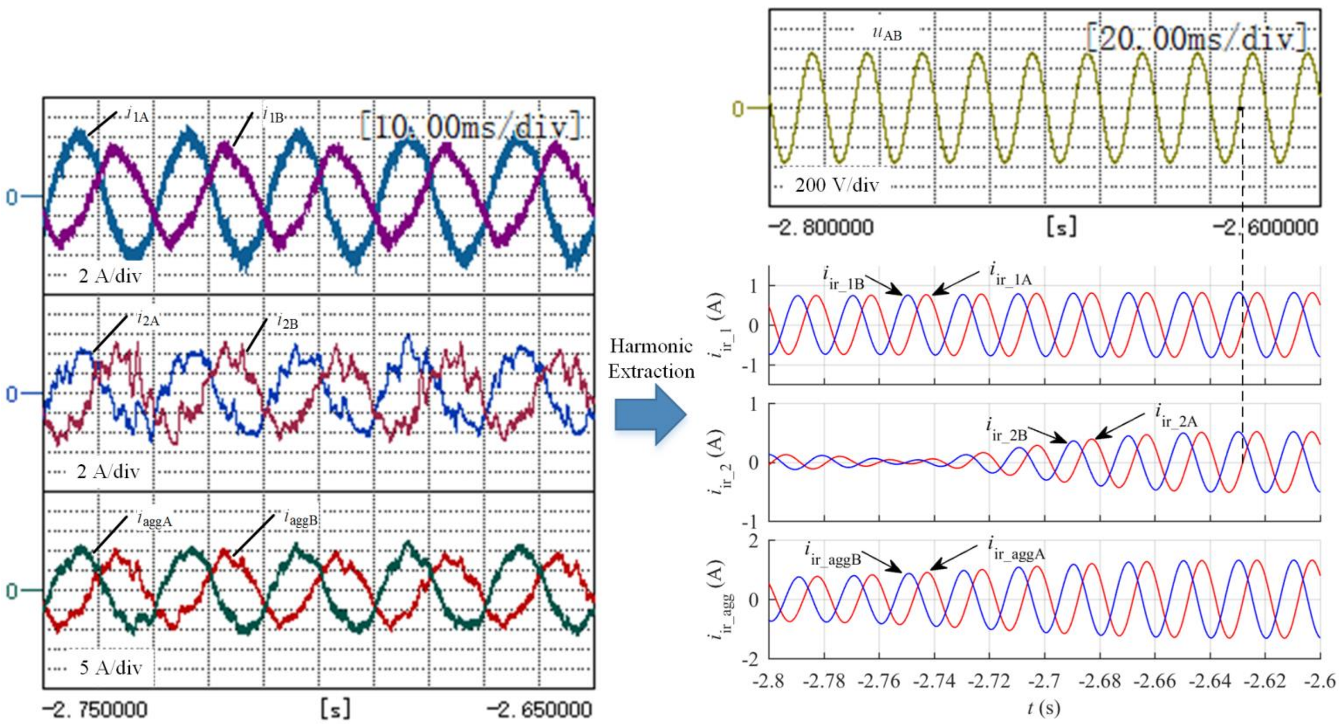


Figure 14. Waveforms before and after the injection of negative sequence 50 Hz irregular current of inverter II.

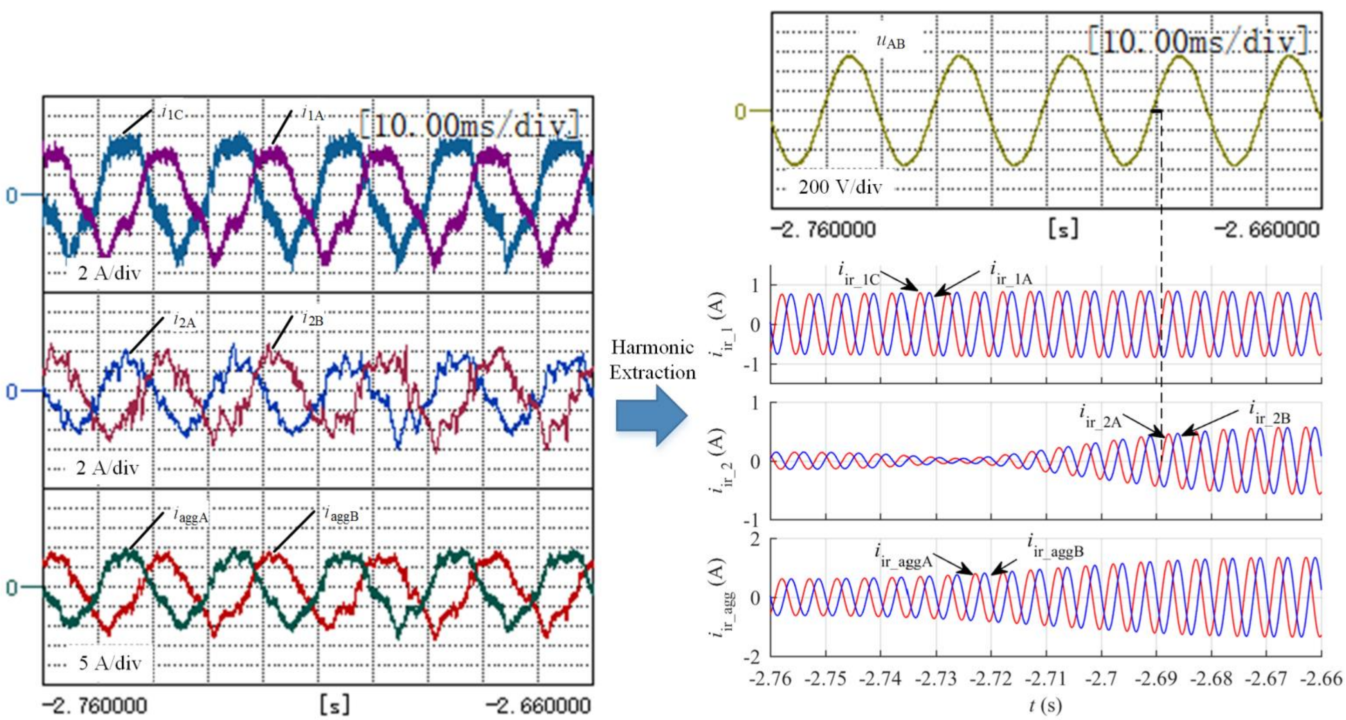


Figure 15. Waveforms before and after the injection of positive sequence 200 Hz irregular current of inverter II.

The reference voltage of both i_{ir_1C} and i_{ir_2A} is still u_{AB}, while their zero phase intervals are distinctly different. Thus, they cannot be in phase and i_{ir_aggA} decreases. It means that this irregular current is unusable under a phase symbol fault.

In conclusion, the above tests conclude that only the positive sequence 200 Hz irregular current is usable, which is consistent with the conclusion in Table I.

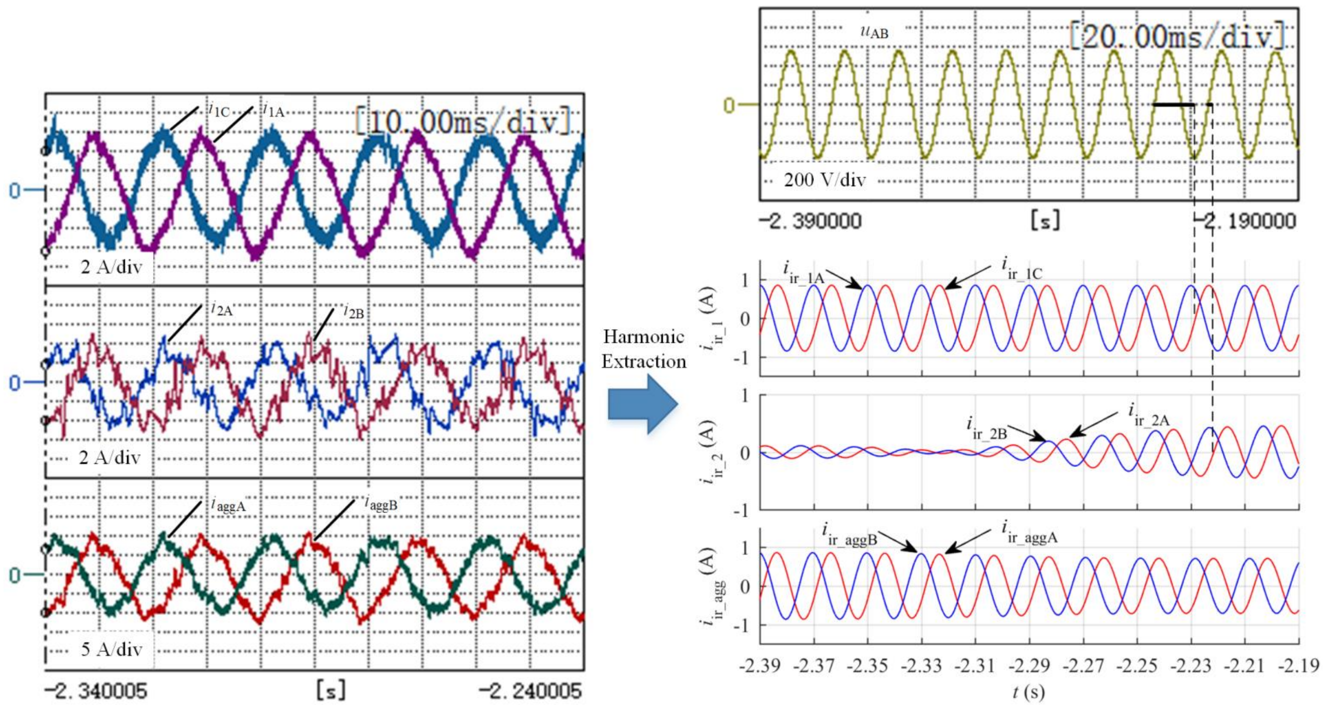
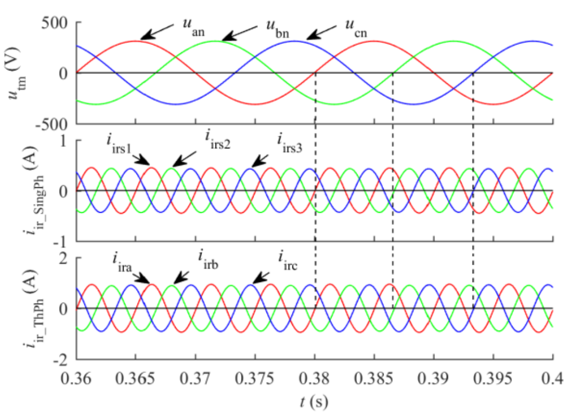
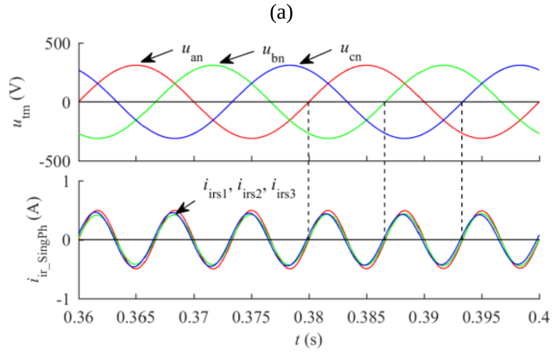


Figure 16. Waveforms before and after the injection of negative sequence 50 Hz irregular current of inverter II.

B. Simulations



(a)



(b)

Figure 17. Irregular currents of inverter-based three single-phase DG units and a three-phase DG unit. (a) 200 Hz irregular currents (positive sequence for the three-phase DG unit). (b) 150 Hz irregular currents

The simulations in this paper are based on Matlab/Simulink. The test is based on Figure 9, where the three single-phase DG units inject irregular currents of the same magnitude (0.5 A) into the grid (represented by a 380 V/50 Hz source), while the three-phase DG unit injects irregular currents of 1 A. As above, the irregular currents are still extracted from the measured currents, as shown in Figure 17, where i_{ir_ThPh} and i_{ir_SingPh} represent three-phase and single-phase irregular currents, respectively.

Figure. 17(a) shows that when Table I is obeyed, i_{irs1}, i_{irs2} and i_{irs3} will be in phase with i_{ira}, i_{irb} and i_{irc} respectively and present as positive sequence in the grid. Figure 17(b) shows that when the frequency of 150 Hz (one of the orders of 3*m*) is adopted, i_{irs1}, i_{irs2} and i_{irs3} indeed present as zero sequence currents. The results validate the conclusions in subsection III-D.

VI. Conclusion

In response to the synchronization issue with irregular current injection islanding detection methods, this paper proposes an approach under consideration that there is generally no communication between the DG units. According to this approach, first, the terminal voltage of a DG unit is taken for reference to conduct the irregular current injection. Then, it is found that only parts of the frequencies that are an integer multiple of the frequency of the reference voltage are usable, or can be employed.

Furthermore, this approach is better to be employed by as many manufacturers and users as possible, or the performance of irregular current injection methods may not increase. However, this approach shows that the optimal effect of irregular current injection methods without communication can be made available.

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