A Synchronization Control Method for Micro-Grid with Droop Control

Zhongwei Chen, Wei Zhang, Jiuqing Cai, Tao Cai, Zhiqiang Xu and Nana Yan
State Grid Hunan Electric Power Corporation Economical & Technical Research Institute
Changsha 410116, China
School of Electrical and Electronic Engineering, Huazhong University of Science and Technology
Wuhan 430074, China
czw1984joe@163.com

***Abstract*—Micro-grid should be able to operate in both islanding mode and grid-connected mode, but how to transfer smoothly between these two modes is a question. This paper presents a seamless transition strategy for droop-controlled inverters to operate in both islanding and grid-connected modes and transfer smoothly between these two modes.The control principle and pre-synchronization control strategy are introduced in detail, simulation and expertmental results show that the micro-grid inverter can transfer smoothly between islanding mode and grid-connected mode.**

I. INTRODUCTION

With respect to the coordinated integration of DG, the microgrid concept has been developed. Microgrids are power systems that consist of an aggregation of loads, sources and storage elements[1]. Microgrid can assure the distributed power generation system with high quality and high reliability in both grid-connected and islanding operations. Most of the micro sources in the micro-grid system are connected to the micro-grid through interface inverters. Therefore, the control performance of the interface inverter is the key point to maintain the stability of the microgrid.

Many innovative control techniques have been used for stability of the system as well as for proper load sharing. The most common method is the use of droop characteristics for wireless load sharing. Droop-controlled inverter has been presented to operate in both grid-connected and islanding modes. The output power of the droop-controlled inverter in the grid-connected mode may deviate from the operating point because of the fluctuation of the frequency and voltage of the grid. Therefore, the power loop is necessary to be well designed. The frequency and voltage of the microgrid may deviate from the grid in the islanding mode. To ensure the uninterrupted operation of its critical loads,the microgrid must be capable of operating in both the gridconnected mode and the islanded mode and offer a smooth transition between these two modes[2].

The framework of the system is given in this paper. In order to have good dynamic stability, the power loop is designed in detail and a pre-synchronization strategy is proposed to transfer smoothly from the islanding mode to grid-connected mode. Simulation and expertment have been carried out to verify the effectiveness of the pre-synchronization strategy proposed.

II. SYSTEM DESCRIPTION

Fig.1 shows the configuration of the micro-grid considered in this paper. Several DG sources are connected to the load at the point of common coupling (PCC).The Distributed Generation (DG) system is comprised of a dc source and a voltage source inverter. Under normal operational mode, the micro-grid is usually connected to the grid at the point of common coupling (PCC) through a static transfer switch(STS), otherwise it runs in the grid connected mode.

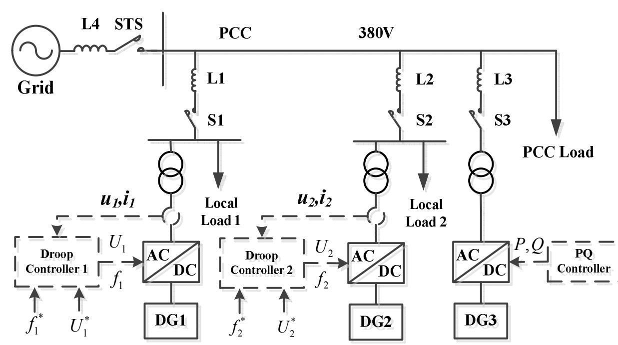

Figure.1 Micro-grid configuration.

The overall control diagram of the droop controlled inverter is shown in Fig. 2. By transferring the three-phase current and voltage into *dq* rotating coordinates, both the instantaneous active and reactive power can be easily calculated. As shown, an outer capacitor voltage feedback PI compensator is used to force the capacitor voltages to track their sinusoidal reference waveforms stiffly with an acceptable low output total harmonic distortion (THD).

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The outputs of this voltage compensator are then fed to an inner capacitor current compensator, acting as the capacitor current reference signals for this inner compensator[3]. Due to the adoption of droop control, there's no need to change the control strategy when the micro-grid transfers between the grid-connected mode and the islanding mode, thus making it easier to achieve smooth transferring and avoiding the voltage fluctuation of AC bus.

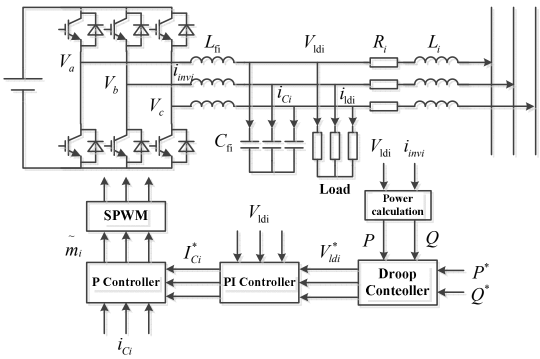


Figure.2 Overall control structure of the inverter.

III. CONTROL STRATEGY

Fig. 3 depicts the equivalent circuit of one single-phase inverter derived from Thévenin's theorem[4]. In this figure, $U_s\angle\delta$ is the inverter open-circuit voltage, $E\angle 0°$is the common ac bus voltage, $R + jX$ is the impedance of the inverter system.

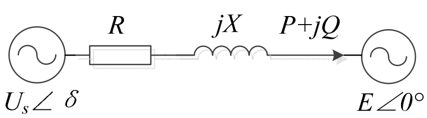


Figure 3. Equivalent circuit of a parallel inverter.

The phase value δ is usually very small, so we can get $sin\delta=\delta$, $cos\delta=1$.When the output impedance of the inverter is inductive, the active and reactive powers are:

$$P=\frac{EU_s\delta}{X} \qquad Q=\frac{E(U_s-E)}{X} \tag{1}$$

It is shown that the value of the reactive power here is constant with any variation of the power angle δ; however the value of the active power increases when the power angle δ increases, and it is mainly decided by the power angle δ. So it is feasible to control the active power and the reactive power of the inverter by controlling the power angle and the output voltage, respectively.

A. Power Control Loop

In the droop control, the relationship between the frequency of the output voltage f and the output power P can be reasonably represented by the following equations:

$$f=f_n-\frac{P-P_n}{a} \qquad V=E_n-\frac{Q-Q_n}{b} \tag{2}$$

where a and b are the droop coefficients, f_n is the synchronous frequency, V is the magnitude of the converter output voltage and $f$is its frequency, while P and Q respectively denote the active and reactive power supplied by the converter. Thus the frequency and the voltage are being controlled by the active and reactive power output of the DG sources.

The droop coefficients can be calculated by the following equations:

$$a=\frac{P_{\max}-P_n}{f_n-f_{\min}}, \quad b=\frac{Q_{\max}-Q_n}{E_n-E_{\min}} \tag{3}$$

where P_{max} and Q_{max} are the maximum permitted output active power and reactive power of the inverter, P_n and Q_n are the normal output active power and reactive power of the inverter, f_{min} and E_{min} are the minimum permitted frequency and voltage of the inverter, respectively.

The power control loop is shown in Fig.4, and the voltage and current decoupling control diagram is shown in Fig. 5.

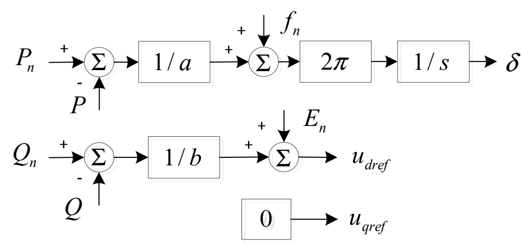


Figure.4 Power control loop

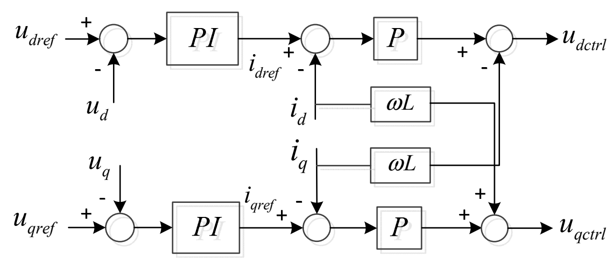


Figure.5 Voltage and current dual-loop.

IV. PRE-SYNCHRONIZATION CONTROL STRATEGY

Smooth transferring between the grid-connected mode and the islanding mode is one of the key technologies of micro-grid operation. Smooth transferring means that the voltage phase, the amplitude and frequency of the micro-grid does not change suddenly at the transition moment. As a result of the adoption of the droop control, it is unnecessary to change the control strategy at the moment of transferring, thus contributing to the achievement of smooth transferring.

A. Islanding Mode to Grid-connected Mode

When the micro-grid is re-linked to the grid directly, there may be huge transient current, resulting in damage to the equipment. In order to ensure the smooth transferring between the islanding mode and the grid-connected mode, certain presynchronization measures must be taken before grid-connected. A pre-synchronization control strategy of the micro-grid inverter based on the droop control is proposed in this article.

Synchronization can be achieved by aligning the voltage phasors at the microgrid and utility ends of the STS separation device, and can conveniently be implemented by adding two separate synchronization compensators to the external real and reactive power control loops, as shown in the dashed frames of Figs. 6(a)(b). Inputs to these synchronization compensators are the magnitude and phase of the two voltage phasors at both ends of the STS shown in Fig.1, and their outputs are fed to the real and reactive power loops to make the voltage phasor at the microgrid end tracks the phasor at the utility end closely (both in magnitude and frequency). Once synchronized and upon closing the STS separation device, the synchronization compensators must be deactivated by setting their outputs to zero so as not to interfere with the proper operation of the real and reactive power control loops in the grid-connected mode.

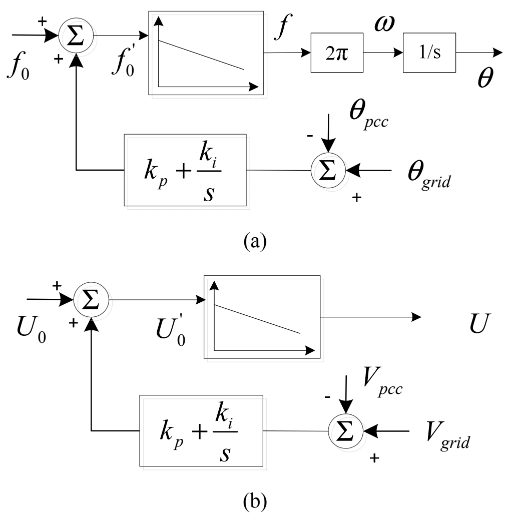


Figure.6 Real power and reactive power compensator with synchronization function.

The operating principle of the real power compensator is shown in Fig. 7(a), when the microgrid operates in the islanding mode, the power outputs of both DG systems must immediately be raised in accordance with their individual droop characteristics, to supply power to all critical loads within the micro-grid adequately at a reduced steady-state frequency of f. DG1 and DG2 are operating at point A and B, and the power outputs of both DG systems are P_1 and P_2, respectively. When the real power compensator is added to the power loop, the frequency reference will increace or reduce, making the P-f droop curve move up or move down in the dynamic process. When the phase error of the two voltage phasors at both ends of the STS reaches zero, the output of the synchronization compensator is zero with DG1 and DG2 operating at point A' and B'. The operating principle of the reactive power compensator is shown in Fig. 7(b), it is similar to that of the real power compensator. Fig.8 shows the control process of the pre-synchronization.

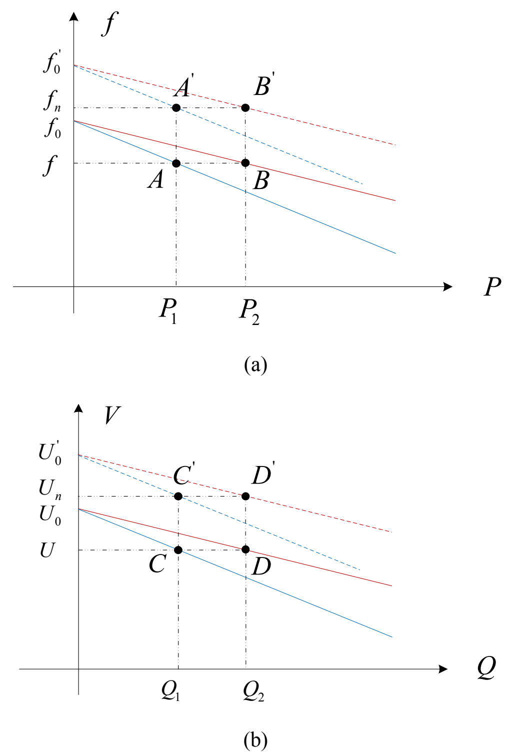


Figure.7 Operating principle of the synchronization compensator .

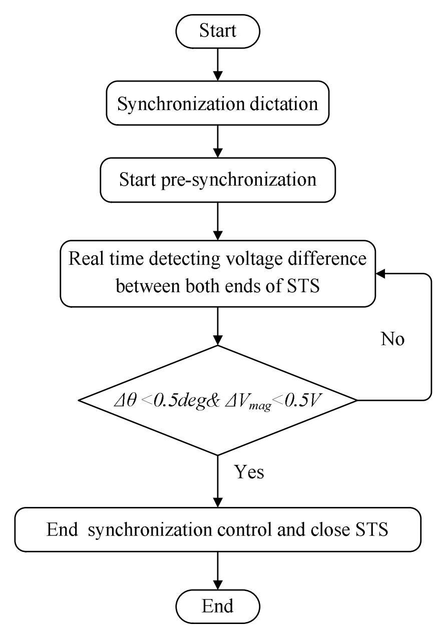


Figure.8 Control process of the pre-synchronization

B. *Grid-connected Mode to Islanding Mode*

The frequency and amplitude of the voltage of the inverter agree with the grid if the inverter operates in the grid-connected mode. The inverter continues to operate in accordance with the droop characteristics, when the inverter transfers to islanding mode from grid-connecten mode. There're only minor variations on the frequency and amplitude of the output voltage. And the phase does not change suddenly, thus achieving the smooth transferring between two modes.

V. Simulation And Experimental Validation

Simulation and experiment are made in this paper to verify the synchronization method. Fig.1 shows the configuration of the micro-grid researched in MATLAB, the system parameters is shown in the Table.I. The Distributed Generation (DG) system is comprised of a dc source and a voltage source inverter, the droop-control method introduced above is adopted to DG1 and DG2, constant power control is adopted to DG3.

Table.I Parameters of the micro-grid.

Parameters		Simulations
DG1 and DG2	Inverter filter inductance	1.5mH
	Inverter filter capacitance	300uF
	DC link voltage	800V
DG3	Inverter filter inductance	1.5mH
	Inverter filter capacitance	25uF
	DC link voltage	800V
	Parameters of L_1,L_2,L_3,L_4	(0.01Ω 0.2mH)
	RMS line voltage of *PCC*	380V
	Parameters of load 1,2,3	(50kW 10kVar)
Power loop control parameters	f_n , E_n	(50Hz, 311V)
	P_n , Q_n	(50kW, 10kVar)
	$1/a_1$, $1/b_1$	(1e-5, 5e-5)
	$1/a_2$, $1/b_2$	(1e-5, 5e-5)
Synchronization compensator	Real power loop(k_p ,k_i)	(7, 0.2)
	Reactive power loop(k_p ,k_i)	(50, 10)

A. Transfer from Islanding Mode to Grid-connected Mode

t=0-0.5s: Start DG1 and DG2 in the islanding mode until the micro-grid reaches steady state (P=150kW,Q=30kVar);

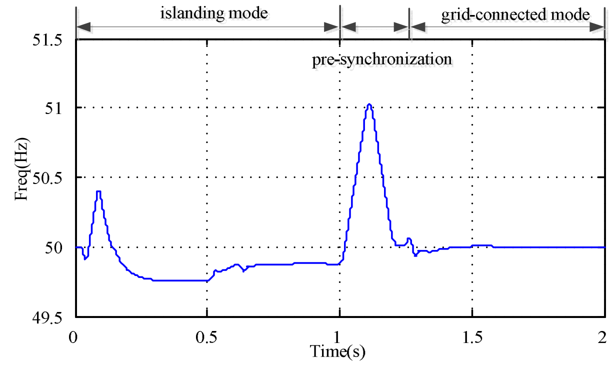
t=0.5s: Start DG3 and the power output of DG3 is 25kW;

t=1s: Start the signal of the pre-synchronization;

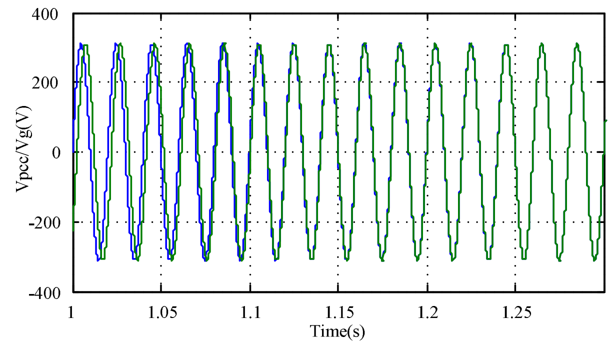
t=1.25s: Complete the process of pre-synchronization;

t=1.25-2s: Operate in the gridconnected mode (P=150kW, Q=30kVar).

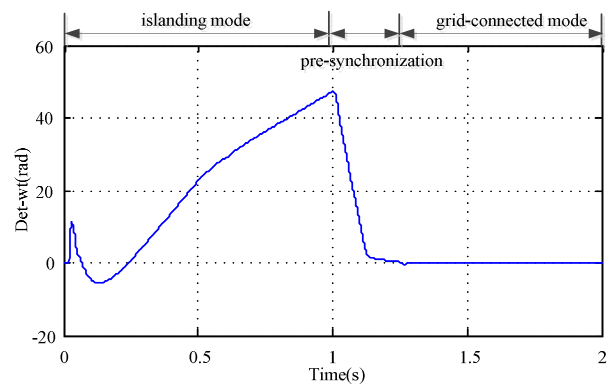
Fig.9 shows the simulation results for pre-synchronization, Fig.9(a), Fig.9(b), Fig.9(c) are the simulation results of PCC frequency, the A phase voltage waveform at both ends of the STS and the phase error of them, respectively. As can be seen from the figure, the synchronous tracking process spents only 0.25s. Therefore, the pre-synchronization strategy is fast and effective.



(a)



(b)



(c)

Figure.9 Simulation results for pre-synchronization

Fig.10 shows the output voltage and current waves of DG1/DG2 when the micro-grid transfer from islanding mode to grid-connected mode, Fig.11(a) shows the output power of DG1/DG2, Fig.11(b) shows the output power of DG3, we can see that when DG3 is connected to the micro-grid, the output power of DG1/DG2 will reduce automatically to maintain the power balance of the microgrid. The output of DG1/DG2 will reduce again because the synchronization compensator quits running after 2s, and the grid will delivery active power of 25kW to the microgrid.

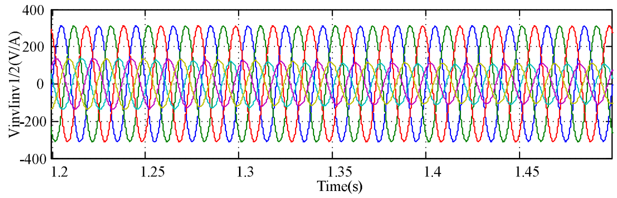


Figure.10 The output voltage and current waves of DG1/DG2

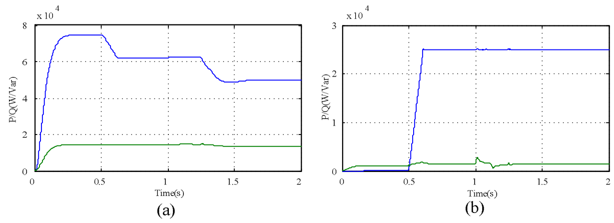


Figure.11 The output power of DG1/DG2 and DG3

From the two figures, we can see that the grid current and output current increase to the given value smoothly, without the appearance of huge transient current. Therefore, the microgrid transfers from islanding mode to grid-connected mode smoothly.

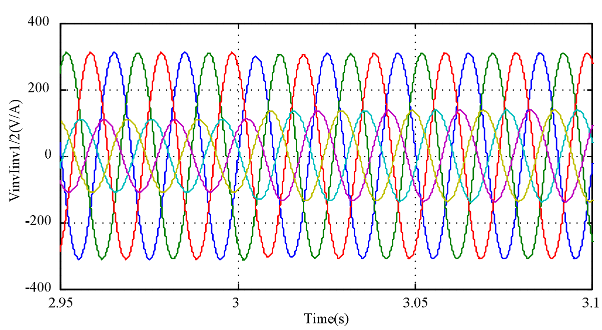
B. Transfer from Grid-connected Mode to Islanding Mode

t=2.5-3s: Operate in the grid-connected mode (*P*=150kW, *Q*=30kVar);

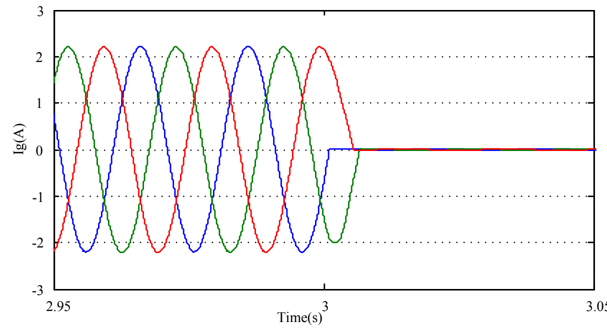
t=3s: Turn off the switch at PCC;

t=3-3.5s: Operate in the islanding mode (*P*=150kW, *Q*=30kVar).

Fig12(a)(b) shows the output voltage and current waves of DG1/DG2 and the grid current when the micro-grid transfer from islanding mode to grid-connected mode. We can see that when unintentional islanding occurs, the output power of DG1/DG2 will increace automatically to maintain the power balance of the micro-grid, and there're no transient current and fluctuation on the voltage during the transferring. Thus the micro-grid achieves smooth transferring from gridconnected to islanding mode.



(a)



(b)

Figure.12 The output voltage and current waves of DG1/DG2 and the grid current

Fig.13 shows the experimental device of parallel-connected PCS controlled by digital signal processor (TMS320F2812), maximum power is limited by the experimental conditions. Fig.14(a) shows the experimental results for inverter output power P/Q, output voltage U_a, and grid current i_{ga} in the smooth transferring from the islanding mode to the grid-connected mode. Fig.14(b) shows the experimental results in the smooth transferring from the grid-connected mode to the islanding mode. The active and reactive power P/Q are calculated by the data from the oscilloscope.

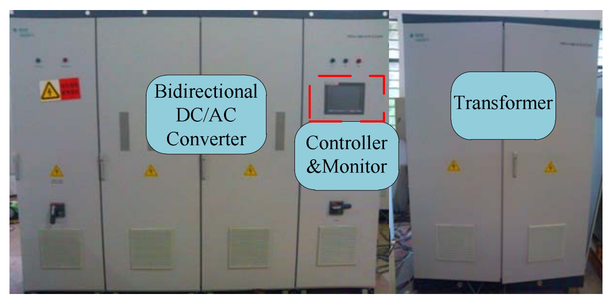
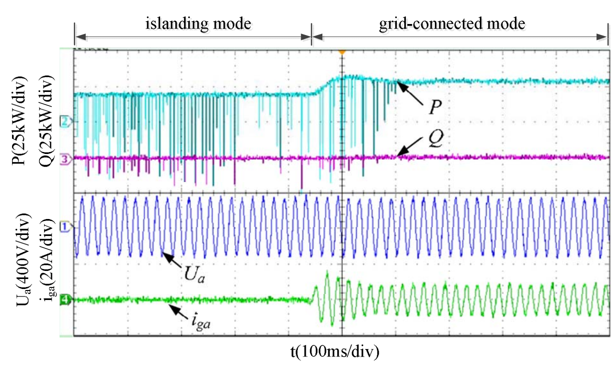
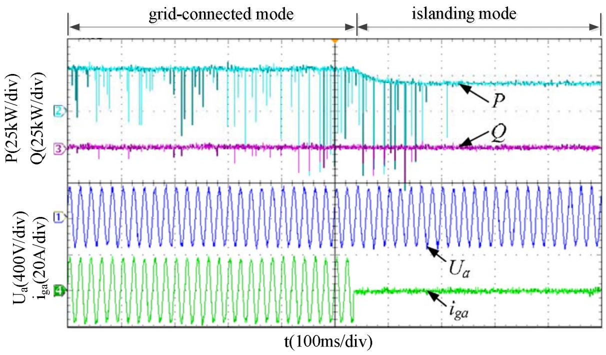


Figure.13 Experimental device of parallel-connected PCSs.



(a)



(b)

Figure.14 Experimental results for inverter output power P/Q, output voltage U_a, grid current i_{ga}.

As can be seen from the figures, there're no transient current and fluctuation on the voltage during the transferring. Thus the micro-grid achieves smooth transferring between the gridconnected mode and the islanding mode.

VI. VI. CONCLUSION

The control principle of droop-control and design of the power loop are analysised detailedly in this paper. A pre-synchronization strategy is proposed to achieve seamless transfer from the islanding mode to the grid connected mode, and the operating principle of the synchronization compensator is analysised in detail. Finally, simulation and expertmental results are given to verify the effectiveness of the droop control strategy for micro-grid inverter.

REFERENCES

[1] Vandoorn, T.L.; Meersman, B.; De Kooning, J.D.M.; Vandevelde, L., "Transition From Islanded to Grid-Connected Mode of Microgrids With Voltage-Based Droop Control," Power Systems, IEEE Transactions on , vol.28, no.3, pp.2545,2553, Aug. 2013

[2] Chia-tse Lee; Ruei-Pei Jiang; Po-tai Cheng, "A Grid Synchronization Method for Droop-Controlled Distributed Energy Resource Converters," Industry Applications, IEEE Transactions on , vol.49, no.2, pp.954,962, March-April 2013

[3] Yunwei Li, Poh Chiang Loh, "Design, Analysis, and Real-Time Testing of a Controller for Multibus Microgrid System," IEEE Transactions on Power Electronics, vol.19, No.5, September 2004, pp.1195-1024.

[4] Josep M.Guerrero, José Matas, Luis García de Vicuña, "Wireless-Control Strategy for Parallel Operation of Distributed-Generation Inverters," IEEE Transactions on Industrial Electronics, vol.53, No.5, October 2006, pp.1461-1470.

[5] Vasquez, J.C.; Guerrero, J.M.; Luna, A.; Rodriguez, P.; Teodorescu, R., "Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes," Industrial Electronics, IEEE Transactions on , vol.56, no.10, pp.4088,4096, Oct. 2009

[6] Wei Yao; Min Chen; Matas, J.; Guerrero, J.M.; Zhao-ming Qian, "Design and Analysis of the Droop Control Method for Parallel Inverters Considering the Impact of the Complex Impedance on the Power Sharing," Industrial Electronics, IEEE Transactions on , vol.58, no.2, pp.576,588, Feb. 2011

[7] Vandoorn, T.L.; Meersman, B.; De Kooning, J.D.M.; Vandevelde, L., "Transition From Islanded to Grid-Connected Mode of Microgrids With Voltage-Based Droop Control," Power Systems, IEEE Transactions on , vol.28, no.3, pp.2545,2553, Aug. 2013

[8] Changhee Cho; Jin-Hong Jeon; Jong-Yul Kim; Soonman Kwon; Kyongyop Park; Sungshin Kim, "Active Synchronizing Control of a Microgrid," Power Electronics, IEEE Transactions on , vol.26, no.12, pp.3707,3719, Dec. 2011