# An Experimental Study on Uninterrupted Switching between Grid-Connected and Isolated Operation of Inverter Power Source

Yuki Kimpara, Muneaki Kurimoto, Yusuke Manabe, Toshihisa Funabashi, Takeyoshi Kato

***Abstract*—This paper develops a controller for Microgrid (MG) to perform uninterrupted switching between grid-connected and isolated operation so that MG can be practically useful even during wide area blackout due to disaster. The proposed method realizes uninterrupted switching by maintaining continuity of the modulation factor of system interconnection inverter and the output voltage phase at the moment of switching. The proposed method is implemented and tested using an experimental setup consisting of a grid simulated voltage source, an inverter power source, and resistive loads. As a result, the MG was uninterruptedly switched to the isolated operation when a significant grid voltage drop continues for a while and switched back to the grid-connected operation when the grid voltage is recovered.**

***Keywords*: Microgrid, Uninterrupted switching, Isolated operation, Grid-connected operation1**

## I. INTRODUCTION

As a result of insufficient electricity supply just after Tohoku earthquake in Japan, Microgrid (MG) has been re-evaluated as self-sufficient power generation [1]. MG is a local energy grid which comprises of distributed generations and loads [2]. It usually operates connected to utility grid, but can operate independently. If MG contains a certain capacity of photovoltaic power generation (PV), MG can continue electricity supply even after the fuel stock for emergency generator is expired when large disturbance occurs [1]. Moreover, MG will be more useful if it can uninterruptedly switch between the grid-connected and isolated operation, because the opportunity losses caused by standstill of electric machines and the costs to introduce Uninterruptible Power Supply (UPS) can be reduced.

The objective of this study is to develop a controller for MG that can perform uninterrupted switching between the grid-connected and isolated operation, and to examine the performance of controller by using an experimental setup. A lot of previous researches focused on developing a method for uninterrupted switching [3]-[7]. However, to the best of the authors' knowledge, the investigation about switching under fault condition is not enough. In [7], a switching method using a Static Switch is investigated in CERTS Microgrid Test Bed. The MG is disconnected from the utility grid when a fault occurs inside the MG for avoiding the negative impact on the utility grid operation. On the other hand, our study focuses on uninterrupted switching to isolated operation when a fault occurs in the utility grid. In order to confirm successful switching without over-current and over-voltage, waveforms of transient voltages and currents caused by switching of operation are observed.

The experimental setup used in this study consists of a several hundred Watts PV, an impedance load, and a 6 kVA voltage source for simulating three-phase voltage drop at grid connection point of MG. A generic mechanical switch instead of a static switch using a power semiconductor device is used as an interface to the utility grid for developing MG with lower investment.

Usually, MG consists of multiple generators and multiple load. The MG used in this study, however, consists of single PV and single load. Although this conformation seems not common practice, this study assumes the situation where the PV in MG can solely supply enough electricity thanks to high-penetration PV in MG and stable and high solar irradiance. The development of integrated control of multiple power sources and consideration of fluctuations in solar irradiance are left as topics for future work.

This paper is organized as follows. First, the experimental setup is explained together with the basic controller for PV inverter in the grid-connected operation. The basic controller is designed to meet the Fault Ride Through (FRT) requirement in which the over current during the grid voltage drop can be avoided and the quick power output recovery after the grid voltage recovery is realized. Then, a controller which can perform uninterrupted switching to the isolated operation and switching back to the grid-connected operation is proposed. Finally, experimental results on the performance of proposed controller are explained.

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Y. Kimpara, and M. Kurimoto are with Department of Electrical Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan (e-mail: kimpara.yuuki@e.mbox.nagoya-u.ac.jp).

Y. Manabe, T. Funabashi, and T. Kato are with Institute of Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan

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## II. Experimental Setup and Basic Control

### A. Experimental Setup

Fig. 1 shows the experimental setup used in this study. The setup consists of a three-phase inverter power source for simulating PV (PV simulator), an impedance load at both side of circuit breaker, and a AC voltage source of 6 kVA for simulating grid (grid simulator).

MG consists of PV and an impedance load of 400 W. As shown in Fig.1, PV simulator consists of an inverter (or Power Conditioning System (PCS) in other words), DC power source and parallel connected a set of series diodes to realize an I-V characteristic of PV module. The power output of PV simulator can be controlled ranging 0 – 600 W.

On the grid side, the terminal voltage of grid simulator is controlled by a computer to simulate voltage drop caused by a short circuit fault in the grid. The instantaneous drop of voltage amplitude can be controlled, while the phase of the voltage drop is out of control. Magnetic contactor (MC) is used as circuit breaker. The MC is controlled by the PCS to disconnect MG from the grid and reconnect MG to the grid according to the voltage on grid side.

### B. Basic controller for PCS in grid connected operation

PCS used in the PV simulator consists of system interconnection inverter and DC/DC converter as shown in Fig. 1. Fig. 2 shows the block diagram of controllers of system interconnection inverter controller and DC/DC converter in the grid connected operation. The DC/DC converter controller performs maximum power point tracking (MPPT). The inverter controller maintains the DC voltage at 365V. The PCS output voltage is synchronized to the grid voltage by using phase locked loop (PLL).

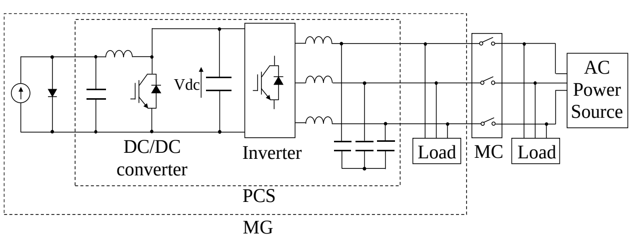
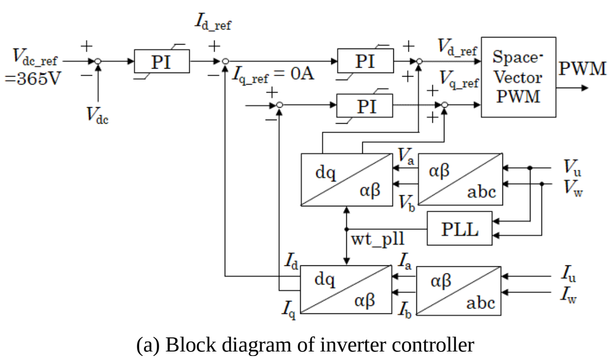
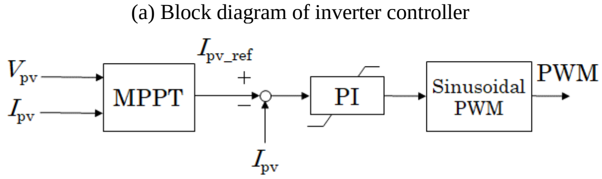


Fig. 1. Experimental setup



(a) Block diagram of inverter controller



(b) Block diagram of converter controller

Fig. 2. Controller for grid-connected operation

The inverter controller for grid-connected mode is equipped with an active islanding detector which can prevent MG from unintentionally continuing the grid-connected operation when MG is disconnected from the grid due to a grid fault. The active islanding detector injects the reactive current of 5 Hz square waveform with 5% amplitude of active current. When MG is disconnected from the grid, frequency fluctuates due to the injection of reactive power. If average absolute frequency deviation is over 0.75Hz for 0.5sec, the MG is switched to isolated operation mode. Detection of islanding operation is one of the conditions when PCS is switched to isolated operation, besides under voltage detection.

PCS is equipped with FRT capability. As described below, FRT capability is sophisticated by avoiding overcurrent during the voltage drop, and enhancing power output recovery by using time-varying change in the gain of PI controller.

### C. Switching Process of Grid Connected / Isolated Operation of MG and Related Controllers

According to FRT requirements in Japan, a grid-connected PV is required to continue the operation for a short disturbance. However, a grid-connected PV must be disconnected from the utility grid when disturbance is longer than 300 ms [8]. Assuming that the FRT requirements is applied to MG including multiple power sources, this study develops controller for MG to realize disconnection from grid, uninterrupted switching to the isolated operation, and the reconnection to grid when the disturbance is cleared. At this moment, this study so far is the case of simple MG with single power source, investigation into MG including multiple power sources will be investigated in the future.

Fig. 3 shows the flowchart of the whole switching process. Usually, MG continues power supply in the grid-connected operation. When the voltage drop occurs but the residual voltage is kept at 20% or higher, MG must continue the power supply. In the proposed controller, the limiter of output current is temporarily activated so that the overcurrent is prevented. Then, the grid voltage is recovered within 300 ms, the power output of MG is required to recover quickly. To perform this, this study proposes the time varying proportional gain of PI controller at leftmost in Fig. 2 (a) described in Section 3.

On the other hand, if the grid voltage is not recovered within 300 ms, MG is disconnected and switched to the isolated operation. To perform uninterrupted switching, this study proposes a novel controller described in Section 4.

When the grid frequency and voltage are recovered to the normal range, MG is reconnected to the grid by adjusting the phase difference between both sides of circuit breaker within ±5°.

## III. Adaptation to FRT Requirements

### A. Overcurrent Protection

When PV continues the grid-connected operation during short-circuit, an overcurrent may occur. In this study, therefore, the controller is modified so that a current limiter is temporarily activated when the output current exceeding the limit level is detected. In order to decide the limit level, PCS always records the average value of *d*-axis output current at 50 ms interval. When the voltage drop occurs, the limiter of output current is temporally activated and reference of d-axis output current is limited to the observed level of 500-550 ms before the voltage drop. If DC/DC converter continues MPPT while the limiter is activated, DC input voltage to inverter ($V_{dc}$) rises because the power input would exceed the output. Therefore, DC/DC converter controller which performs MPPT is switched to controller to maintain $V_{dc}$ at 365V as shown in Fig. 4. This overcurrent protection is activated when line voltage of grid is under 160V and deactivated when grid voltage gets higher than 160V.

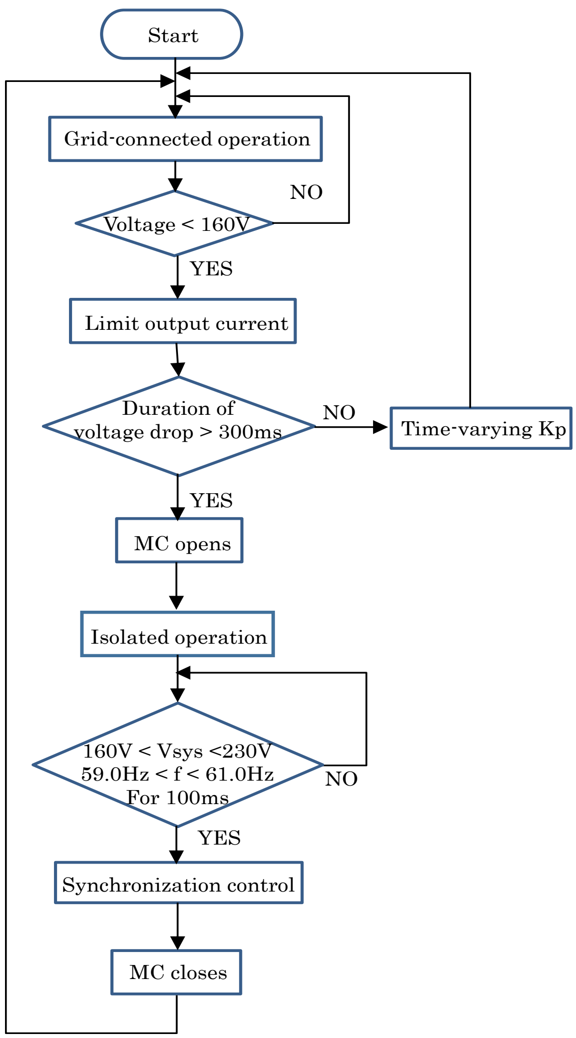



Fig. 3. Flowchart of switching process

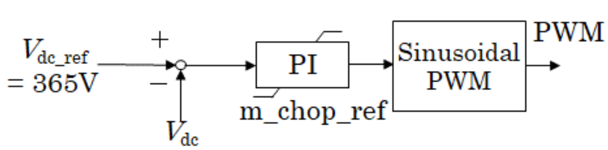



Fig. 4. DC/DC converter controller during voltage drop

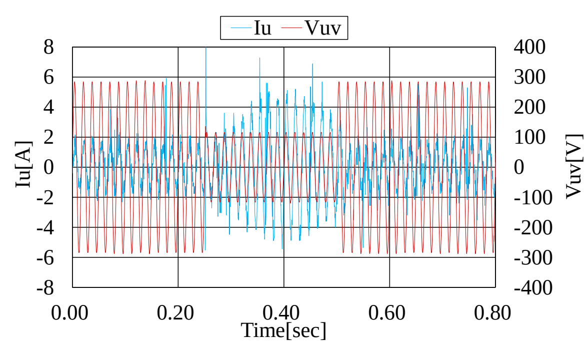
The effect of this overcurrent protection method is examined by experiment which simulates three-phase short-circuit. As shown in Fig. 5 (a), the result without the overcurrent limiter shows that the output current considerably increases during voltage drop. On the other hand as shown in Fig. 5 (b), the result with the overcurrent limiter shows that current level is maintained even during voltage drop.

### B. Time-Varying Proportional gain of PI controller

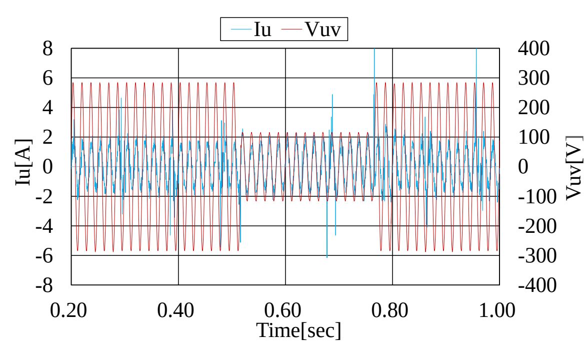
When the grid voltage is recovered within 300 ms, the power output of PCS has to recover quickly. For this purpose, the proportional gain $K_p$ of leftmost PI controller shown in Fig. 2 (a) should be relatively small. On the other hand, for prioritizing the stable operation in steady state, $K_p$ should be relatively small, which may result in a long time for the power output recovery and be hard to satisfy FRT requirements.

By changing $K_p$, this study examined the power output recovery performance. The target voltage of the AC voltage source is dropped to 20% of the rated voltage for 250 ms. The transition time of voltage drop and voltage recovery are 1ms.

As an example, result in power output when $K_p$ = 0.15 and $K_p$ = 0.6 is shown in Fig. 6. Before the voltage drop, the power output slightly fluctuates at 5Hz due to reactive power injection described above. During the voltage drop, power output is suppressed. As shown in Fig. 6 (a), when $K_p$ = 0.15, after the voltage is recovered at around 0.85 sec, the power output is recovered but fluctuating by about 100 W for a few seconds. The reason for the fluctuation is small $K_p$. On the other hand, when $K_p$ = 0.6 is selected to prioritize quick power output recovery, power output is recovered very quickly without the




(a) Without overcurrent protection




(b) With overcurrent protection

Fig. 5. Experimental result

fluctuation, as shown in Fig. 6 (b). However, power output is unstable including short-term fluctuation even in the steady state.

In order to realize quick power output recovery after the grid voltage recovery together with stable operation during the usual operation, the proposed controller temporarily uses time-varying $K_p$ to leftmost PI controller in Fig. 2 (a) for 100 ms after the grid voltage recovery. When voltage of d-axis becomes larger than 160V, grid voltage is regarded as recovered. Setting of $K_p$ is shown in Table I. $K_p$ is set large value (= 0.6) just after voltage recovery (0 – 60 ms) to achieve quick power output recovery. Then, $K_p$ is gradually decreased to default level (= 0.15) to realize stable operation.

Fig. 6 (a) shows the power output using time-varying $K_p$ together with fixed $K_p$ = 0.15, the power output is recovered quickly to stable operation in steady state without fluctuation. On the other hand as shown in Fig. 6 (b), the short-term fluctuation due to large $K_p$ is eliminated. As a result, the controller using time-varying $K_p$ performs quick output recovery while realizing stable operation.

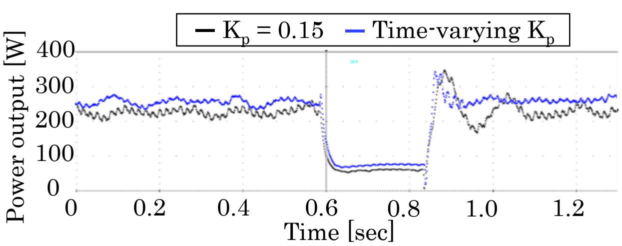
## IV. Switching from Grid-Connected Operation to Isolated Operation

### A. Controller

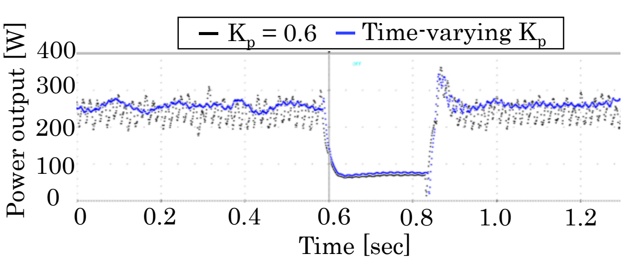
According to FRT requirements, MG must stop grid connected operation when short-circuit continues for more than 300 ms [8]. In this study, a controller which automatically disconnects MG from grid and switch MG to the isolated operation is developed.

TABLE.I
SETTING OF $K_P$ AFTER VOLTAGE RECOVERY

| Elapsed time from voltage recovery [ms] | $K_p$ |
|---|---|
| 0 - 60 | 0.6 |
| 60 - 80 | 0.4 |
| 80 - 100 | 0.2 |
| 100 - | 0.15 (Default) |




(a) With fixed $K_p$ (0.15) and time-varying $K_p$




(b) With fixed $K_p$ (0.6) time-varying $K_p$

Fig. 6. Power output recovery after grid voltage recovery

The converter controller in the isolated operation is the same as that during voltage drop shown in Fig. 4, which maintains $V_{dc}$ at 365V. Fig. 7 shows the developed inverter controller in the isolated operation, which maintains the output line voltage at 200V. The phase and frequency of PCS output voltage is determined based on the internal counter which creates 60Hz clock. Fig. 8 shows a conceptual diagram of the switching process. In the grid-connected operation before the voltage drop, the internal counter is calculated based on the measured line voltage between U and V phases. After the operation is changed from the isolated mode to the grid-connected mode, the internal counter is created in controller of PCS. At the instant of changing to the isolated operation, the internal counter value is set at the value in the grid-connected operation. The modulation factor of inverter and output voltage phase are also set at the value at the instant of changing to the isolated operation. As shown in Fig. 8, all three phases are switched to the isolated operation mode simultaneously.

In the experimental test, MC starts to open when the line voltage under 160V continues for 300 ms. Then, by waiting for 20 ms for MC to be completely opened, the controller for PCS is switched to the isolated operation.

### B. Experimental Result

In order to validate the switching from the grid-connected to isolated operation, a three-phase voltage drop which lasts for 350 ms is simulated by the grid simulator. The transition time of voltage drop and voltage recovery are 1ms. Sensitive analysis regarding residual voltage and power output of PCS is conducted. Power output of PCS before the voltage drop varied from 400 W to 600 W and residual voltage varied from 5% to 50%.

As an example, Fig. 9 shows the experimental result with 600W PCS power output and 5% residual voltage. The line

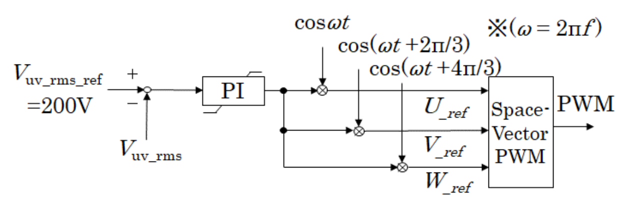



Fig. 7. Block diagram of inverter controller for isolated operation

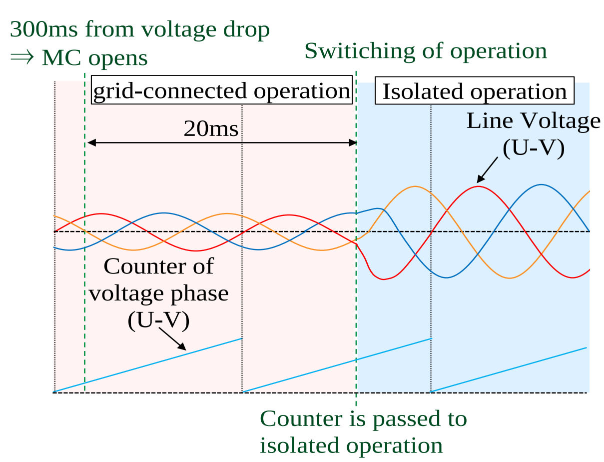



Fig. 8. Conceptual diagram of switching to isolated operation

voltage of MG (U-V) drops at 0.85 sec and the voltage drop continues. At 1.25 sec, after the voltage drop continues for 300 ms, the control signal of MC is turned off and MC starts to open. 20 ms later, the PCS controller is switched to isolated operation. As a result, the line voltage is recovered quickly after switching as shown in Fig. 9.

Uninterrupted switching was successfully performed in different conditions regarding voltage drop and PCS power output. The voltage recovery is slower as the power output before voltage drop is smaller. The reason is as follows. The output current during voltage drop is limited by the over current limiter at most to the current before the voltage drop. Therefore, when the PCS supplies small power output before the voltage drop, the deviation of power from the 400W load in isolated operation is large, resulting in longer time for changing the operation point after the voltage recovery.

Study so far is the case of simple MG which have single power source; however, real MG usually has several power sources. As a future work, the investigation into such MG is required. If MG have multiple power sources, the controller has to be changed in order to cooperate with these sources. One of the cooperative controls is master-slave control. A power source becomes a master and it decides frequency and voltage level. The other sources become slaves and follow the frequency and voltage level of master. Development of switching method for MG which has multiple power sources and performs cooperative control can be a future work.

## V. Switching from Isolated Operation to Grid-Connected Operation

### A. Controller

After the grid voltage is recovered, MG in the isolated

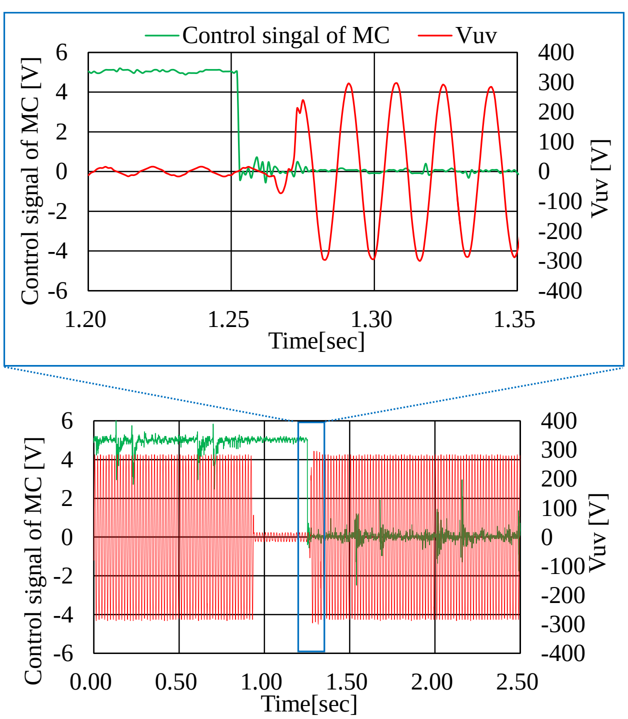


Fig. 9. Experimental result of switching to isolated operation

operation should be reconnected to grid in order to resume electricity supply to all electricity load in MG. When reconnecting MG, the voltage at circuit breaker (or MC) on MG side must be in phase with that on grid side in order to realize smooth transition from the isolated operation to the grid-connected operation. However, during the isolated operation previously described, the voltage phase on MG side and grid side may be different because the frequency based on internal clock of PCS can be different from the grid frequency. Therefore, automatic switching from the isolated operation to the grid-connected operation with synchronization control is developed. In the practical situation, the voltage at MC's terminal on MG side must be synchronized to the grid side voltage. In the experimental test, however, the voltage at load terminal inside MG is controlled to synchronize to the grid side voltage, because the phase difference between these two terminals would be small due to no large reactive component between two terminals.

MG is controlled to start reconnection when line voltage on grid side is recovered between 160 V and 230 V and frequency is recovered between 59.0 Hz and 61.0 Hz for 100 ms. For the purpose of synchronization, if the voltage phase on MG side lags more than 2.4° to the grid side voltage, the frequency of PV is changed to 60.4 Hz and if the voltage phase on MG side leads more than 2.4°, the frequency is changed to 59.6 Hz, as shown in Fig. 10. When the phase difference is within 5° for 50 ms, the MC starts to reclose. 20 ms later, when MC has completely closed, controllers for PCS are switched to the grid-connected operation. At the same time, output voltage phase and modulation factor of system interconnection inverter which are used in the isolated operation are passed to the grid-connected operation.

### B. Experimental Result

The controller for switching back to the grid-connected operation is validated experimentally, in the case with the fault condition of 50% voltage drop for 10 sec. The transition time of voltage drop and voltage recovery are 1ms. Firstly, when MG performs the grid-connected operation before the voltage drop, the voltage phase difference is almost zero. However, after the voltage drop occurs and MG switches to the isolated operation at about 7 sec, the phase difference starts to vary continuously due to difference of frequency. After the gird voltage is recovered and synchronization control is activated at 16 sec, the phase difference gradually decreased and became smaller than 5°. As a result, MC was closed, resulting in successful reconnection at 21 sec. Fig. 11 shows waveforms of voltages and current for 100 ms around the reconnection.

As shown in Fig. 11 (a), the phase difference is smaller than 5° when MG is closed at 50 ms. Fig. 11 (b) shows U phase and V phase current of PCS output increases after switching to the grid-connected operation because converter resumes MPPT and input from PV is increased. However, at the instant of reconnection, the voltage does not rise sharply, therefore, reconnection is completed safely.

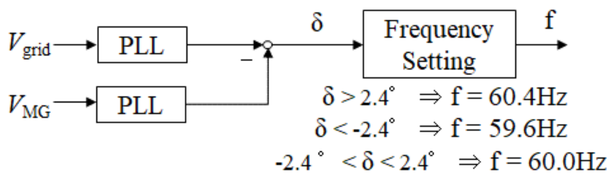
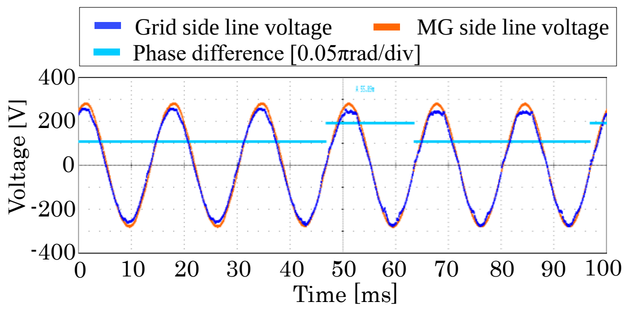
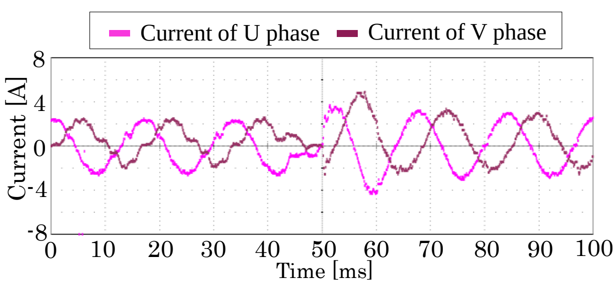



Fig. 10. Conceptual diagram of synchronization control




(a) MG side voltage, grid side voltage and phase difference




(b) PCS output current (U phase and V phase)

Fig. 11. Experimental result of reconnection

## VI. Conclusion

In this paper, uninterrupted switching method between the grid-connected and isolated operation for MG is developed. As for the grid-connected operation, FRT requirements are satisfied due to overcurrent protection and time varying $K_p$. Switching to the isolated operation is successfully completed by passing over the phase and inverter's modulation factor of the gird-connected operation. Switching to the grid-connected operation is also completed safely thanks to synchronization control which avoids overcurrent in connection.

## VII. Acknowledgement

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## VIII. References

[1] Keiichi Hirose, Toyonari Shimakage, James T.Reilly, Hiroshi Irie, "The Sendai Microgrid Operational Experience in the Aftermath of the Tohoku Earthquake: A Case Study", NEDO, Case Studies of Smart Community Demonstration Project. Available: http://www.nedo.go.jp/content/ 100516763.pdf, 2013.

[2] Keiichi Hirose, Tadatoshi Babasaki, "Smart Power Supply Systems for Mission Critical Facilities", IEICE Transactions on Communications, vol. E95.B, No. 3, pp.325-332, 2012.

[3] R. H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, and J. Roy, "CERTS Microgrid Laboratory Test Bed", IEEE Transactions on Power Delivery, vol. 26, issue. 1, pp.325-332, Jan.2011.

[4] Kimio Morino, Atsushi Denda, Kazuhiro Sato, Eisuke Shimoda, Takayuki Sugimoto, Hiroyuki Kihara, Yuji Yamamoto, Toshihiro Yamane and Kei Furukawa, "Demonstration Tests of the Smart Grid at the Office Building in City of Albuquerque", Available: http://www.shimz.co.jp/tw/sit/report/vol92/pdf/92_016.pdf

[5] J. Rocabert, A. Luna, I. Candela, P. Rodriguez, "Seamless disconnection and reconnection transients for Micro-Grids", International Conference on Renewable Energies and Power Quality, Santiago de Compostela, Spain, 2012.

[6] Yunwei Li, Mahinda Vilathgamuwa, Poh Chiang Loh, "Design, Analysis, and Real-Time Testing of a Controller for Multibus Microgrid System", IEEE Transactions on Power Electronics, vol. 19, issue. 5, pp/1195-1204, Sept.2004.

[7] D. Klapp and H. Vollkommer, "Aoolication of an intelligent static switch to the point of common coupling to satisfy IEEE 1547 compliance", presented at the IEEE Power ENG. Soc. General Meeting Tampa, Jun, 2007.

[8] *Grid-interconnection Code [2013 supplement revision]*, JEAC 9701-2012, Mar. 2013.