Uninterrupted Switching based on VSG Control between Grid-connected and Stand-alone Operation of Single-Phase Grid-Tied Inverter

Kodai Nishikawa[1], Keisuke Kusaka[2] and Jun-ichi Itoh[1]
1 Department of Science of Technology Innovation, Nagaoka University of Technology, Nagaoka, Japan
2 Department of Electrical, Electronics and Information Engineering, Nagaoka University of Technology, Nagaoka, Japan
*E-mail: knishikawa@nagaokaut.ac.jp, kusaka@vos.nagaokaut.ac.jp, itoh@vos.nagaokaut.ac.jp

***Abstract*— This paper proposes an uninterrupted switching method between a grid-connected operation and a stand-alone operation by the output-frequency command switching of a single-phase grid-tied inverter. The proposed switching is characterized by a virtual synchronous generator (VSG) control that switches from a grid-connected operation to a stand-alone operation. The VSG control achieves the uninterrupted switching. However, the VSG control makes a frequency fluctuation during the stand-alone operation. In addition, it is impossible to lock the voltage phase. This is the cause of inrush current at the switching to the grid-connected operation. The proposed switching method uses multiple control systems depending on the operations. A constant voltage constant frequency control is applied to suppress the frequency fluctuation during the stand-alone operation. Moreover, a phase-locked loop is applied to suppress the inrush current at the switching to the grid-connected operation. The proposed switching method is demonstrated by the experiments with a 5-kVA prototype. The experimental result shows that uninterrupted switching is achieved by the proposed switching method.**

Keywords*— *Single-phase inverter, Grid-tied inverter, Stand-alone operation, VSG control

I. INTRODUCTION

In recent years, the introduction of renewable energies such as wind and solar power generation has been expanding. Then, the use of grid-tied inverters has been increasing for a grid-connection of the power generation equipment to the power grid. Grid-tied inverters generally control the output current with a grid connection [1–3]. On the other hand, the inverters control the output voltage by a constant voltage constant frequency (CVCF) control in a stand-alone operation [4–5]. Thus, it is necessary to switch the control between the current control and the voltage control system in order to switch between grid-connected and stand-alone operations. The control switching causes distortions and interruptions of the output voltage.

A virtual synchronous generator (VSG) control is one of the control methods to achieve uninterrupted switching between the grid-connected and stand-alone operations [6–7]. The VSG control not only improves grid stabilities by the simulation of inertia of the synchronous generator [8–12] but also connects to the power grid using the voltage control system. Thus, the control system switching is not required for the operation switching. However, the frequency fluctuation occurs in the output frequency. In addition, the voltage surge occurs in the load voltage. The effect of the frequency fluctuation is an inrush current between the grid-tied inverter and the power grid. The inrush current may occur with switching to the grid-connected operation because the output phase is not locked to the grid phase by a phase-locked loop (PLL). This cause is the impossibility of arbitrary frequency control because the output frequency is controlled according to the power deviation between the power command and the output power. The voltage surge may occur with switching to the stand-alone operation because the voltage of the grid-tied inductance fluctuates due to the sudden change of the inverter output current by the disconnection from the power grid. This cause is the impossibility of the power grid current control because there is the power deviation between the load power and the output power. These power deviations occur because the load power is unknown.

In this paper, the uninterrupted switching method is proposed using the frequency command switching. The proposed method uses multiple voltage control systems corresponding to the operation modes, such as the grid-connected or the stand-alone operation. Thus, arbitrary frequency control is possible. The VSG control is used on the grid-connected operation and the switching to stand-alone operation. The power command of VSG is determined by the supply power from the power grid to the load. Thus, the load voltage surge is decreased at the disconnection from the power grid. The CVCF control is applied to the stand-alone operation. Furthermore, the PLL is applied for the switching from the stand-alone operation to the grid-connected operation. The output frequency is determined within any allowable frequency fluctuation. The uninterrupted switching operation is demonstrated by the proposed method with a 5-kVA prototype.

II. UNINTERRUPTED SWITCHING CONTROL

Figure 1 shows the circuit configuration of a single-phase grid-tied inverter to which the proposed switching method is applied. This circuit has a DC power supply on the input side and supplies power to the load on the output side. In addition, a magnetic contactor (MC) is connected between the load and the power grid on the output side for disconnecting and synchronizing to the power grid.

A. VSG control

Figure 2 shows the synchronous generator model used by the VSG control. The VSG output power P_{out} is controlled to the output power command $P_{command}$ by the voltage controller.

Figure 3 shows the voltage phasor diagram of the model shown in Fig. 2. Equation 1 presents the output current phasor $\dot{I}_{out}$ of the synchronous generator.

$$\frac{\sin\theta - j\left(\left|V_{SG}\right|\cos\theta - \left|V_{Grid}\right|\right)}{\omega L_{SG}} \quad (1),$$

where V_{SG} is an absolute value of the synchronous generator voltage phasor, V_{Grid} is an absolute value of the power grid voltage phasor, θ is a phase difference between V_{SG} and V_{Grid}, ω is an angular frequency of the power grid, L_{SG} is the synchronous inductance of the synchronous generator. Thus, the output active power P and reactive power Q by the synchronous generator is expressed as

$$P = \frac{\left|V_{SG}\right|\left|V_{Grid}\right|\sin\theta}{2\omega L_{SG}} \quad (2),$$

$$Q = \frac{\left|V_{SG}\right|\left|V_{Grid}\right|\cos\theta - \left|V_{Grid}\right|^2}{2\omega L_{SG}} \quad (3).$$

Figure 4 shows the VSG control block diagram for the swing equation of the synchronous generator. The output frequency command is determined from the deviation between the power command value and the output power.

Equation 4 presents the swing equation of the simulated synchronous generator.

$$\frac{d\omega_R}{dt} = \frac{P_{command} - P_{out} - D\left(\omega_R - \omega_{Grid}\right)}{J} \quad (4),$$

where ω_R is an angular frequency of output voltage, ω_{Grid} is an angular frequency of power grid, $P_{command}$ is a power command value, P_{out} is output power, J is the virtual inertia, and D is a damping coefficient.

The phase difference θ is changed by increasing or decreasing the output angular frequency ω_R. The output power is controlled by changing the output angular frequency.

B. Conventional Switching Method

Figure 5 shows the uninterrupted switching method between the grid-connected and stand-alone operation using the VSG control proposed in [7]. The speed regulation factor and the time constant of the governor low-pass filter are expressed δ and T_G, respectively. In the control method of [7], the power command value is switched following the switching between grid-connected and stand-alone operations. In the grid-connected operation and the uninterrupted switching to the stand-alone operation (S_{power} = 1), the inverter outputs the power according to the power command value. In the stand-alone operation (S_{power} = 3), the output frequency

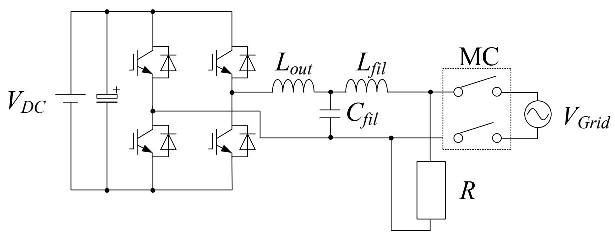


Fig. 1. Circuit configuration of single-phase grid-tied inverter with MC for the operation switching between grid-connected and stand-alone operation.

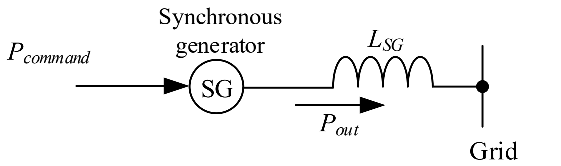


Fig. 2. Synchronous generator model that is connected to a power grid via a grid-tied inductor.

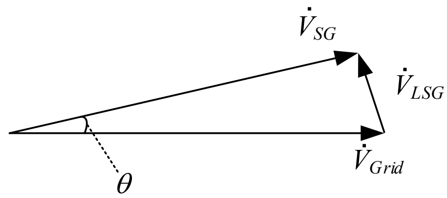


Fig. 3. Voltage phasor diagram of the synchronous generator model.

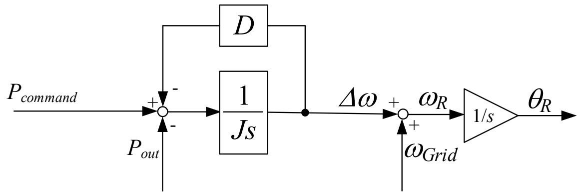


Fig. 4. VSG control block diagram.

changes by the speed regulation rate of the governor according to the difference between the power command value and the output power. Then, a load frequency control is applied to fix the difference from the power grid frequency. In the uninterrupted switching operation from stand-alone operation to grid-connected operation (S_{power} = 2), the output frequency is synchronized to the power grid frequency. At the same time, the power command value is added to $\Delta\omega_R$ for making the moment of phase synchronization for switching to the grid-connected operation.

The output power during stand-alone operation is determined by the required power of the load in the VSG control. The output frequency fluctuates because there is a power difference between the output power command and the output power. Thus, an additional control system is required to suppress fluctuations, such as the load frequency control used by the conventional method. In addition, the output frequency is not directly controlled by the conventional control method. It is impossible to fix the output voltage phase with the power grid when

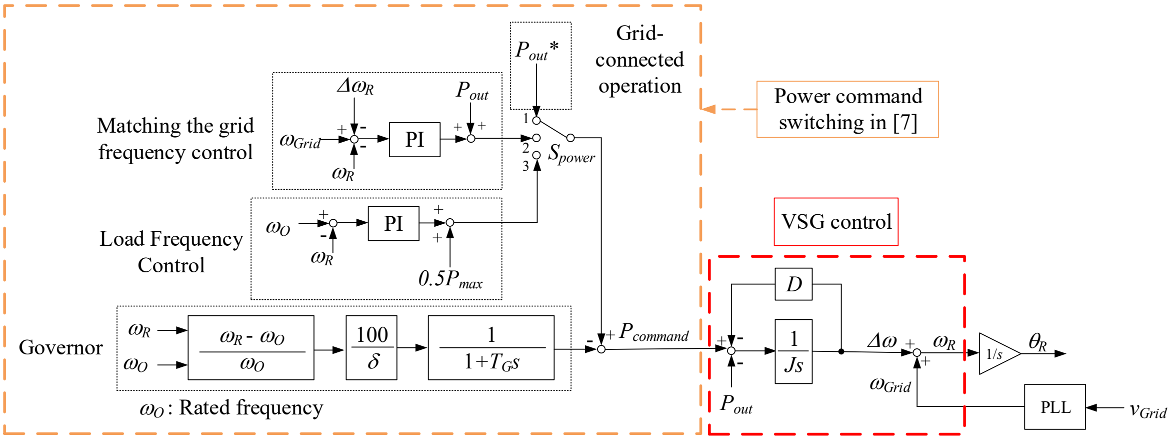


Fig. 5. Conventional uninterrupted switching method between the grid-connected operation and the stand-alone operation in [7] using the output power command switching.

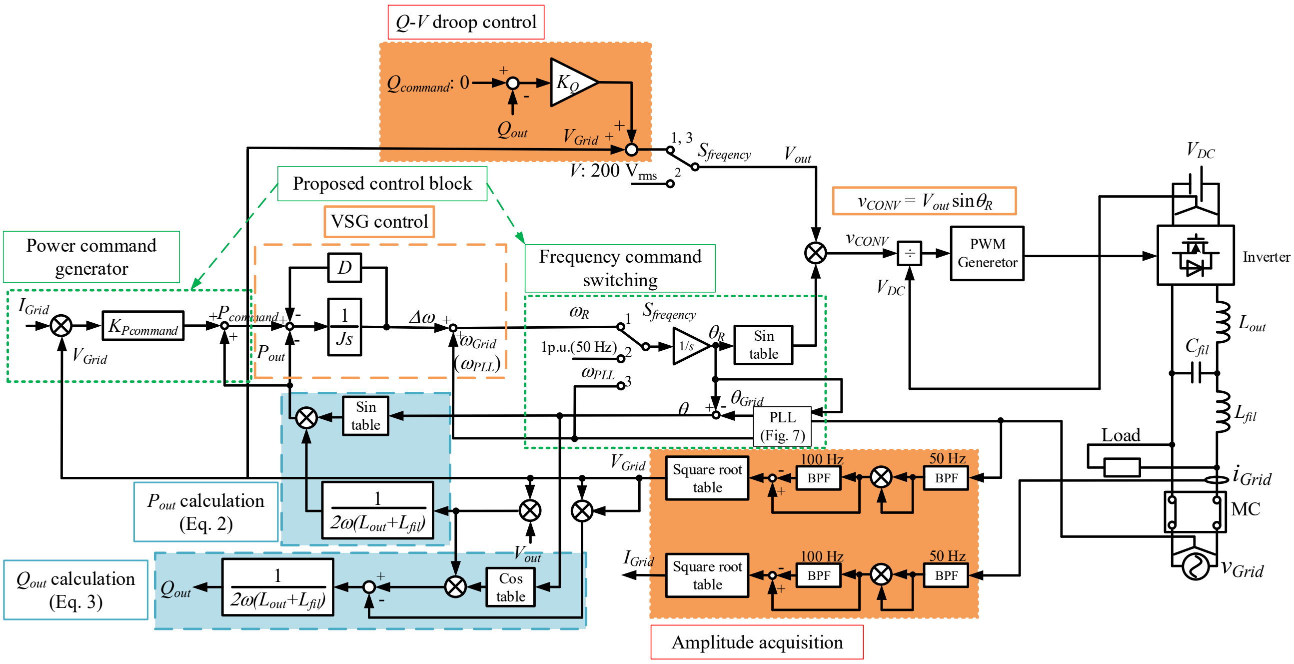


Fig. 6. Experimental control block diagram with proposed uninterrupted switching method using the frequency command switching and the power command generator.

switching from the stand-alone operation to the grid-connected operation. Thus, it is necessary to switch when the output voltage phase is synchronized with the power grid. An inrush current is caused by the voltage difference between the output voltage and the power grid voltage at the moment of synchronization. The voltage difference occurs because there is a delay in the synchronization with the power grid due to the use of MC.

C. Proposed switching method

Figure 6 shows the control system of the single-phase grid-tied inverter with the proposed uninterrupted switching method using the output frequency command switching. In the conventional method, the output power command is switched at the time of the operation switching. Hence, there are the problems such as the output frequency fluctuation during the stand-alone operation and that phase synchronization is not possible during synchronizing. The output frequency command is directly switched according to the operation in the proposed method. Thus, the suppression of the output frequency fluctuation and the phase synchronization are achieved.

The explanation of each operation is described below.

(i) Output power control during grid-connected operation and switching to stand-alone operation ($S_{frequency} = 1$)

The output power is controlled by VSG control. In this case, the power command value $P_{command}$ is expressed as follows from the grid current amplitude I_{Grid} and the phase difference between the grid voltage and the output voltage.

$$P_{command} = K_{Pcommand}\left|I_{Grid}\right|\left|V_{Grid}\right| + \frac{\left|V_{out}\right|\left|V_{Grid}\right|}{2\pi f_{Grid}\left(L_{out}+L_{fil}\right)}\sin\theta \quad (5),$$

where $K_{Pcommand}$ is the gain that makes the product of current and voltage to power, V_{Grid} is the grid voltage amplitude, f_{Grid} is the power grid frequency, L_{out} is a grid-tied inductance, L_{fil} is a filter inductance, and θ is the phase difference between the power grid and the output voltage.

The output current of the inverter cancels the grid current i_{Grid} because $P_{command}$ is kept constant and the phase difference θ is increased. This $P_{command}$ makes it possible to suppress the voltage surge that occurs when the load is disconnected from the power grid.

(ii) Output voltage control during stand-alone operation ($S_{frequency} = 2$)

The output voltage command of the inverter is determined by a constant output frequency and a constant voltage amplitude during stand-alone operation. The voltage is output without frequency fluctuation due to the effect of VSG control.

(iii) Switching from stand-alone operation to grid-connected operation ($S_{frequency} = 3$)

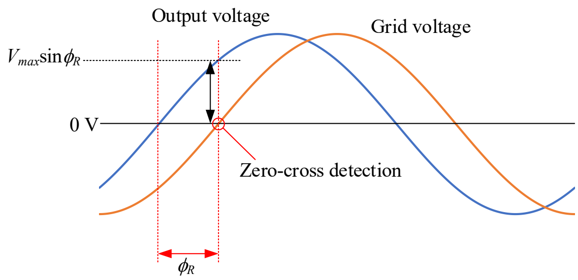
There is a phase difference between the inverter output voltage and the grid voltage since the inverter is not synchronized with the power grid during stand-alone operation. Hence, it is necessary to synchronize the phase of the inverter output voltage during switching from stand-alone operation to grid-connected operation. In the proposed method, phase synchronization is achieved by using a zero-crossing detection-based PLL.

Figure 7 shows the block diagram of the frequency command generation using the zero-crossing detection PLL. The zero-crossing detection-based PLL shown in Figure 7 (a) detects the zero-crossing of the grid voltage and obtains the phase difference ϕ_R from the output voltage phase during stand-alone operation. The phase is synchronized by generating the output frequency so that the phase difference becomes zero using the PI controller shown in Figure 7 (b). Thus, it is not necessary to turn on the MC in a moment when the phases of the output voltage and the grid voltage overlap as in the conventional method. The MC operation delay is not a problem for the uninterrupted switching.

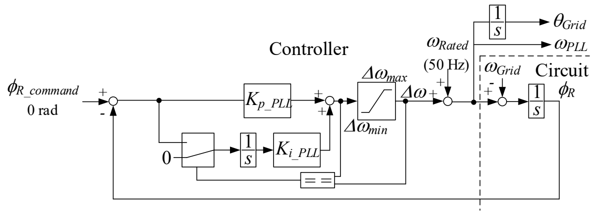
Assuming that the power grid frequency is constant, the time required for phase synchronization is mainly determined by the proportional gain and the allowable frequency fluctuation. The allowable frequency fluctuation $\Delta\omega_{max}$ $\Delta\omega_{min}$ is determined by the assumed load condition. The operating time in the region where the proportional controller output is saturated Δt_{diff_psat} is expressed as

$$\Delta t_{diff\_psat} = \frac{1}{f_{Grid}} \frac{\phi_0 - \phi_{border}}{\Delta\phi_{psat}} \qquad (6),$$

where ϕ_0 is the initial phase difference between the output voltage and the power grid voltage at the moment of the synchronization start, ϕ_{border} is the boundary phase difference of whether the proportional controller output is saturated and $\Delta\phi_{psat}$ is the amount of change in the phase difference per cycle of the power grid frequency. The boundary phase difference ϕ_{border} and the amount of change in the phase difference per cycle $\Delta\phi_{psat}$ are expressed such as



(a) Conceptual diagram



(b) Control block

Fig. 7. Frequency command generation method by the zero-cross detection-based PLL.

$$\phi_{border} = \frac{\Delta\omega_{max}}{K_{p\_PLL}} \qquad (7),$$

$$\Delta\phi_{psat} = \frac{\Delta\omega_{max} + \omega_{Rated} - \omega_{Grid}}{f_{Grid}} \qquad (8),$$

where K_{p_PLL} is the proportional gain of the PLL and ω_{Rated} is the rated angular frequency of the power grid. The operating time in the region where the integral controller is working Δt_{diff_pi} is estimated by the proportional gain. In this case, the amount of change in the phase difference per cycle $\Delta\phi_{pi}$ is expressed as

$$\Delta\phi_{pi} = \frac{K_{p\_PLL}\phi_R + \omega_{Rated} - \omega_{Grid}}{f_{Grid}} \qquad (9).$$

The operation of (9) is repeated N times until the phase difference θ reaches the phase synchronization threshold $\theta_{Thereshold}$. The operating time Δt_{diff_small} is expressed as

$$\Delta t_{diff\_pi} = \frac{N}{f_{Grid}} \qquad (10).$$

The estimated operation time is the sum of Δt_{diff_psat} and Δt_{diff_pi}.

The amplitude values of the power grid voltage and current are acquired only for the 50 Hz component using a bandpass filter (BPF). The output voltage command is determined by the amplitude and phase. The output voltage is controlled by an open-loop voltage controller. The procedure for switching from the start of the grid-connected operation to the stand-alone operation is as shown below.

(1) The power grid frequency and phase is obtained by PLL.

(2) The operation of the grid-tied inverter is started with the $S_{frequency}$ being one at the moment when the power grid phase becomes zero rad.

(3) $S_{frequency}$ is switched from one to two at the moment when the current amplitude of the power grid I_{Grid} becomes equal to or less than the switching threshold value $I_{Grid\_Threshold}$. The operation is switched to the stand-alone operation.
(4) The MC is turned off.
In this procedure, the reason why the operation starts at zero rad is to prevent the inrush current caused by the voltage difference from the power grid voltage.

The procedure for switching from the stand-alone operation to the grid-connected operation is shown below.
(1) $S_{frequency}$ is switched from two to three. The output voltage phase and the output frequency are synchronized with the power grid by PLL.
(2) The MC is turned on at the moment when the phase difference with the grid voltage θ becomes equal to or less than the threshold value $\theta_{Threshold}$.

III. EXPERIMENTAL RESULT

Table 1 shows the experimental conditions, and Table 2 shows the control parameters. The switching operations from grid-connected to stand-alone operation and from stand-alone to grid-connected operation are confirmed with the 5-kVA prototype with the proposed switching method.

A. Switching from grid-connected operation to stand-alone operation

Figure 9 shows the waveforms when the operation is switched to a stand-alone operation. Before the inverter operation starts, the power is supplied to the load from the power grid. The grid current i_{Grid} corresponds to the load.

The inverter is connected to the grid and starts supplying power to the load. The waveform shows that the inverter output current starts to increase at the zero crossing of the grid voltage. Thus, the inverter starts operation at the grid phase of zero rad. Also, the grid current amplitude is reduced as the inverter output current amplitude increases.

Next, the MC turns off and switches to stand-alone operation when the grid current i_{Grid} is reduced to the threshold $I_{Grid\_Threshold}$. However, the amplitude of the grid current is less than 5 A, which is the threshold of the grid current amplitude about 40 ms before the turn-off signal is output. This is due to an error in the current amplitude detection.

B. Switching from stand-alone operation to grid-connected operation

Figure 10 shows the waveforms when the operation is switched to a grid-connected operation. The output voltage phase is not synchronized with the phase of the grid voltage during stand-alone operation. Then, a synchronization operation is performed by PLL. After the phase synchronization, the MC is turned on to switch grid-tied operation and supply power to the load by the power grid. In Figure 10 (a), the output current is reduced to almost zero amperes by the switching operation. This is because the phase difference between the grid voltage

Table 1. Experimental condition.

Rated Power	P_{rated}	5 kVA
DC-link voltage	V_{DC}	350 V
Grid voltage	V_{Grid}	200 V_{RMS}
Utility frequency	f_{Grid}	50 Hz
Switching frequency	f_{SW}	10 kHz
Grid-tied inductor	L_{out}	2 mH
Filter inductor	L_{fil}	340 μH
Filter capacitor	C_{fil}	6 μF
Percent impedance	%Z	7.9%
Percent admitance	%Y	1.5%

Table 2. Controller parameter.

Damping coefficient	D	0.048 J/rad
Vertual Inertia	J	0.055 kgm^2
Q-V droop gain	K_Q	0.1 V/var
Power command generator gain	$K_{Pcommand}$	0.5p.u.
Threshold of grid current	$I_{Grid\_Threshold}$	5 A
Threshold of phase different	$\theta_{Threshold}$	0.015 rad
PLL PI gain	K_{p_PLL}	62.8 s^{-1}
	K_{i_PLL}	987 s^{-1}
Rated grid frequency	ω_{Rated}	100π rad/s
Allowable frequency fluctuation	$\Delta\omega_{max}$	2π rad/s
	$\Delta\omega_{min}$	-2π rad/s

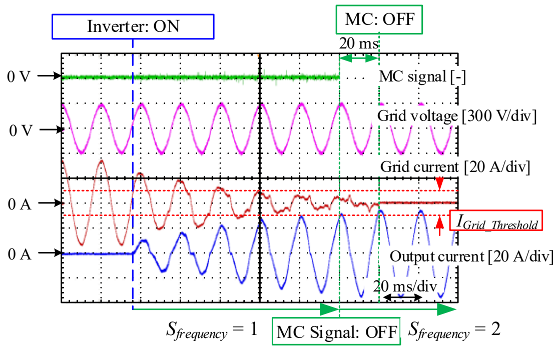
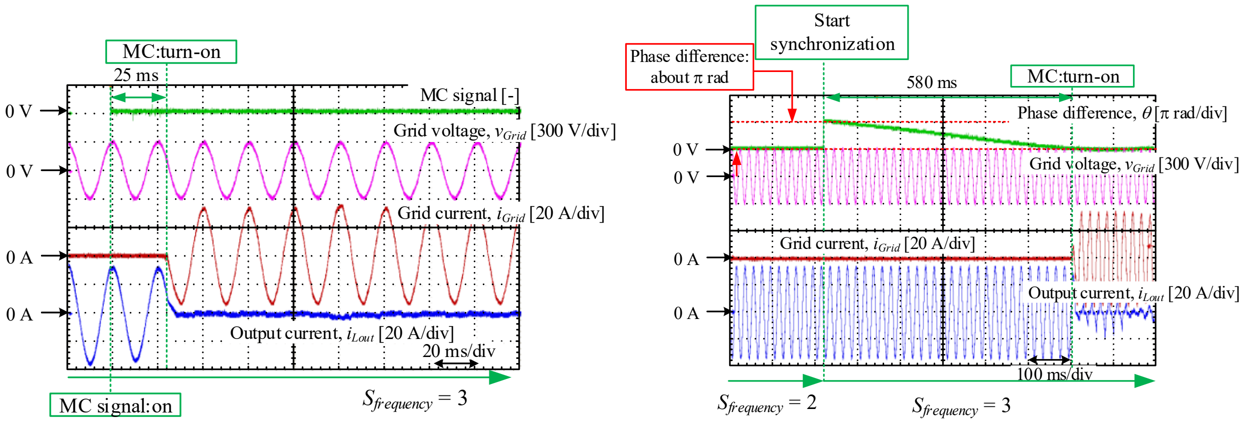


Fig. 9. Switching operation waveform from the grid-connected operation to the stand-alone operation.

and the output voltage is around zero rad. It takes 25 ms from the time the turn-on signal is output to the MC to the time it turns on. However, the phase synchronization by PLL makes it possible to switch to the grid-connection without inrush current due to phase difference. In Figure 10 (b), the synchronization is completed in about 580 millisecond after the start of synchronization under the condition that there is a phase difference of about π rad. when the PLL synchronization is started.

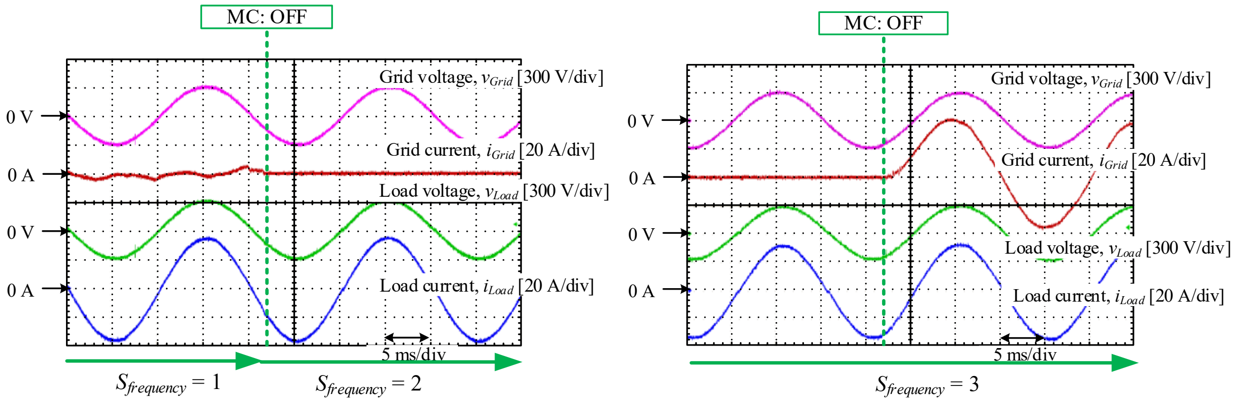
C. Uninterrupted switching

Figure 11 shows the waveforms during operation switching with the load voltage v_{Load}. The power is supplied to the load continuously after the MC is turned



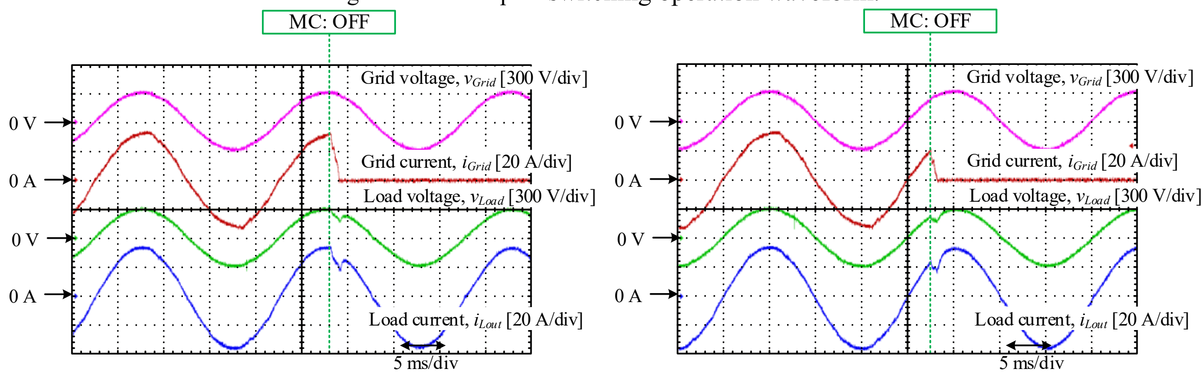
(a) Switching to the grid-connected operation (b) Phase synchronization control by the PLL

Fig. 10. Switching operation waveform from the stand-alone operation to the grid-connected operation.



(a) Switching to the stand-alone operation (b) Switching to the grid-connected operation

Fig. 11. Uninterrupted switching operation waveform.



(a) Grid current value at MC turn-off is 35 A (b) Grid current value at MC turn-off is 20 A

Fig. 12. Comparison of the load voltage surge by the difference current at MC turn-off.

on or off. The load voltage waveform at the moment of switching is used to confirm uninterrupted switching. Figure 11 (a) shows that there is no surge or interruption in the load voltage at the moment of switching from grid-connected to stand-alone operation. Similarly, Figure 11 (b) shows that there is no surge or interruption in the load voltage at the moment of switching from grid-connected to stand-alone operation.

Figure 12 shows the load voltage surge without surge reduction power command at the moment of switching from grid-connected to stand-alone operation. In Figure 12 (a), the voltage surge value is about 90 V. In Figure 12 (b), the voltage surge value is about 60 V. It is checked that a large load surge voltage is generated when the grid current is not reduced.

These results show that the uninterruptible switching between grid-connected and stand-alone operations is achieved by the proposed method by switching the output frequency command.

IV. CONCLUSION

In this paper, the uninterrupted switching method is proposed using the frequency command switching for the purpose of supplying power to the load at the operation swathing without interruption. The proposed method uses multiple voltage control systems such as the VSG control and the CVCF control. It solves the problems of the conventional VSG control, such as the frequency fluctuation during the stand-alone operation and phase synchronization at switching to the grid-connected operation. In addition, the inrush current due to a grid-connected delay of MC is prevented. The uninterrupted switching of the proposed method is demonstrated by 5-kVA prototype verification.

In the future, we will study the application of this method to nonlinear loads.

REFERENCES

[1] K. Kusaka, N. Takaoka, T. Sakuraba, H. Watanabe and Jun-ichi Itoh, “Single-Phase AC Grid-Tied Inverter with Buck-Type Active Power Decoupling Circuit Operated in Discontinuous Current Mode”, IEEJ Journal of Industry Applications, Vol. 10, NO. 3, pp. 292‑302, 2021

[2] S. U. Hasan, H. A. Hassan, M. J. Scott, Y. P. Siwakoti, G. Town and F, Blaabjerg, “Common-Ground Transformerless Inverter with Virtual DC Bus Concept for Single-Phase PV Systems”, IEEJ Journal of Industry Applications, Vol. 9, No. 5, pp. 538‑548, 2020

[3] A. Shawky, M. A. Sayed, T. Takeshita, “Analysis and Experimentation of Modular Differential Inverter Utilizing SEPIC Modules and SIC Devices for Grid Connected Applications”, IEEJ Journal of Industry Applications, Vol. 9, No. 5, pp. 573‑583, 2020

[4] D. S. Ochs, B. Mirafzal, and Pedram Sotoodeh, “A Method of Seamless Transitions Between Grid-Tied and Stand-Alone Modes of Operation for Utility-Interactive Three-Phase Inverters”, IEEE Transactions on Industry Applications, Vol. 50, No. 3, pp.1934‑1941, 2014

[5] Z. Yao, L. Xiao and Y. Yan, "Seamless Transfer of Single-Phase Grid-Interactive Inverters Between Grid-Connected and Stand-Alone Modes," *IEEE Transactions on Power Electronics*, vol. 25, No. 6, pp. 1597-1603, 2010

[6] Z. Peng, J. Wang, Y. Dai, Y. Wen, Z. John Shen, Z. Li, and D. Bi, “Improved Virtual Synchronous Generator Control Strategy for Seamless Switching”, 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1003‑1007

[7] C. Lung, T. Shintai, H. Kakigano, Y. Miura and T. Ise: “Control Scheme of Uninterrupted Switching using a Virtual Synchronous Generator between Stand-Alone and Grid-Connected Operation of a Distributed Generation System for Houses”, IEEJ Transactions PE, Vol.133, No.5, pp.430‑438, 2013

[8] Y. Hirase, O. Noro, E. Yoshimura, H. Nakagawa, K. Sakimoto and Y. Shindo, "Virtual Synchronous Generator Control with Double Decoupled Synchronous Reference Frame for Single-Phase Inverter", IEEJ Journal of Industry Applications, Vol.4, No.3, pp. 143‑151, 2014

[9] X. Xiong, C. Wu and F. Blaabjcrg, “An improved Synchronization Stability Method of Virtual Synchronous Generators Based on Frequency Feedforward on Reactive Power Control Loop”, IEEE Transactions on Power electronics, Vol. 36, No. 8, pp. 9136‑9148, 2021

[10] Z. Shuai, C. Shen, X. Liu, Z. Li and J. Shen, “Transient Angle Stability of Virtual Synchronous Generators Using Lyapunov’s Direct Method”, IEEE Transactions on Smart Grid, Vol. 10, No. 4 pp. 4648‑4661, 2019

[11] H. Cheng, Z. Shuai, C. Shen, X. Liu, Z. Li and J. Shen, “Transient Angle Stability of Paralleled Synchronous and Virtual Synchronous Generators in Islanded Microgrids”, IEEE Transactions on Power Electronics, Vol. 35, No. 8, pp. 8751‑8765, 2020

[12] X. Xiong, C. Wu, G. Hu, D. Pan, F. Blaabjerg, “Transient Damping Method for Improving the Synchronization Stability of Virtual Synchronous Generators”, IEEE Transactions on Power Electronics, Vol. 36, No. 7, pp. 7820‑7831, 2021