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An Enhanced Control Strategy for Mitigation of State-Transition Oscillation Phenomena in Grid-Forming Self-Synchronized Converter System with Islanded Power System

Ki Ryong Kim , Sangjung Lee, Jong-Pil Lee and Jaesik Kang * 

Power Conversion System Research Center, Smart Grid Research Division, Korea Electrotechnology Research Institute, Gwangju 61751, Korea; kiryong@keri.re.kr (K.R.K.); lsj8154@keri.re.kr (S.L.); jplee@keri.re.kr (J.-P.L.)

* Correspondence: jskang84@keri.re.kr

Abstract: This paper proposes an enhanced control strategy for mitigating state-transition oscillations in active and reactive power responses of self-synchronized converter system to secure the islanded power system stability. The self-synchronized converter is well known for “grid-forming” that is able to operate to stand-alone mode (SAM) providing grid voltage and frequency without phase synchronization units. Although the grid-forming (GFM) is self-synchronized, the inherent synchronization principle causes system degradation in which should maintain a point of common coupling (PCC) voltage for critical loads as well as transitions from grid-connected mode (GCM) to SAM and vice versa. Therefore, this paper focuses on resolving the inherent oscillatory issues in GFM self-synchronized converter system (especially adopted ‘synchronverter’ principle), and proposes a control strategy for controllability improvement based on stability analysis for smooth state-transition under islanded power system. The efficacy of the proposed control method is verified through a high-fidelity electromagnetic transient (EMT) simulation with case studies on 30 kW synchronverter system and further experimental hardware-in-loop system (HILS) test with Opal-RT (OP-5707) platform.

Keywords: self-synchronized converter; synchronverter; grid-forming converter



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1. Introduction

With increasing interest in environmental pollution (e.g., global warming), domestic and international efforts are underway such as greenhouse gas emissions reduction based on green energy policy by the United Nations Framework Convention on Climate Change (UNFCCC). The Korean government also plans to expand the eco-friendly electric energy production system by 20% until 2030. As a result, distributed generation (DG) based on renewable energy sources (RESs) such as photovoltaic (PV) and wind power has increased in the traditional AC power system. These emerging technologies based on inverter-interfaced generation system for DG have penetrated into the conventional transmission and distribution network, and are changing the philosophy of the electrical energy supply and demand strategy in the power system [1,2].

Although the paradigm-shift in the electrical energy sector had a positive effect on the environmental resolution, it results in challenging issues to weaken the reliability and stability of the existing power system, which relies heavily on synchronous machines (SMs) [3]. It could also cause a higher rate of change of frequency (RoCoF) in the synchronized power system dominated by future power electronic-based generation system with the reduced rotating machines, and an intolerable low frequency drop occurs even owing to small disturbances or fluctuations in the loads. In addition, transient overvoltage and power imbalance conditions may occur [4,5].

In order to address the above technical problems, there have been many studies regarding development of control, operation and design methodology of inverter-interfaced distribution

resources (IIDRs) with conventional AC power system over the past few years [6–15]. For power electronic based applications among the required solutions, GFM converter principle has been an enabler to proliferate the renewable energy resource-based generation system. Ref. [16] has reported that the GFM converter causes post-fault oscillations in active power and voltage responses of grid-connected voltage source converters due to non-ideally tuned controllers, and a combined PLL-based GFM control was developed under grid-following (GFL) converter system for stability improvement [17–20]. An enhanced transient angle stability control of GFM converter based on virtual synchronous generator has been proven as a promising solution to the aforementioned problems introduced by converter interfaced generation [21]. There have also been several issues related with droop coefficient determination and design method in the GFM converter system [22–24]. As a result, for increasing the penetration level of RESs, various virtual synchronous generator (VSG) [6–8], virtual synchronous machine (VISMA) [9,10], and synchronverter [10–15] control strategies have been proposed. These control methods have tried to increase the stability of the grid voltage and frequency by allowing IIDRs to mimic SM characteristics.

The synchronverter introduced in [11,12] is imitated with an intuitive structure of the SM dynamics, which is able to connect to the conventional AC power system without a synchronization unit such as phase-locked loop (PLL). Nevertheless, there has been many challenging issues on stability problems, and thus the control methods are established to enhance the system stability through using virtual impedance technique introduced in [13,14]. These control strategies focus on the interactive problems between the synchronverter and the large power system. In [15], a control method is also proposed to enhance the system stability by employing a damping correction loop to the existing control method, and hence the damping capability of the system has been accomplished. The oscillation damping capability has been an important functionality in the grid-connected power converter system with sustainable energy sources [25]. By the way, the natural control principle of synchronverter with self-synchronization mechanism causes complexities in the internal control structure modification and parameter values adjustment. Despite the insufficient control flexibility, several enhancement methods have been proposed for improving synchronverter system characteristics by adding a cascade control block to conventional control diagram [26–28]. The [26,27] have proposed the method for frequency regulation, especially primary inertial response mentioned in [29], by adjusting the internal hold-filter coefficients while the internal dynamic of synchronverter is slightly modified. The researches have focused on the synchronverter dynamics effect on the frequency of large power system. The [28] has focused on limitation of output current in synchronverter system through a current controller to prevent a power surge phenomenon when the synchronverter should provide an changed active power. With the limitation of output, the current introduced in [28,30] could provide more control capability to reduce harmonic distribution and hence employed repetitive controller in a cascaded control structure.

Although the previous research could improve the self-synchronized system stability and control flexibility, that research is not considered with several important conditions as follows:

1. It should be accounted for under an islanding condition with critical loads requiring a necessary grid service to provide the high quality power generated from RESs, however, the previous research concentrate only on the large grid interconnection condition with other SMs.
2. IIDRs-based generation system should be capable of maintaining and recovering an islanded grid voltage and frequency with SAM operation, GCM operation as well as mode transition.
3. Since the inherent synchronization feature limits the controllability of the synchronverter owing to realization of the mandatory machine dynamics, the GFM self-synchronized converter system is unable to achieve a required coordinated-control scheme that is needed in conventional GFL converter with decoupled current control based on PLL.

4. Power oscillation phenomenon should be mitigated to improve the system stability in power electronic-dominated generation system.
5. Rigorous validation for implementing the proposed control algorithm should be carried out in order to enhance the reliability in practical hardware digital control system.

Therefore, this paper focuses on controllability improvement of the synchronverter system without any modification of the inherent synchronous machine features, and investigates SAM to GCM transition condition with critical loads change in islanded power system that is not considered in previous studies. Furthermore, this research indicates that the practical power system cases cause a power oscillation during load demand changes under the islanded condition. As a result, the synchronverter should need a capability to recover the fluctuating power while providing the system frequency to be more stable than before GCM condition. With consideration of the islanded power system dominated by power electronic-interfaced generation systems, it implies that a power oscillation caused by the load variation affects the synchronverter's high quality performance under SAM condition.

Thus, in this paper, an enhanced control strategy is proposed to mitigate the power oscillation caused by load fluctuations under the islanded power system condition. The enhanced control method for power oscillation reduction developed in this paper could provide a smooth state-transition from SAM to GCM. For enhancing the controllability of the self-synchronized converter system, a reference voltage generated from conventional synchronverter control method should be manipulated through the proposed additional control loop with rigorous stability analysis, and hence the controllability of the synchronverter system could be improved as well as it is possible for other grid service to be equipped in the GFM self-synchronized converter system.

The rest of this paper are organized as follows. Section 2 briefly describes the configuration and operation principle of synchronverter. Section 3 provides a stability analysis result of conventional synchronverter. Section 4 proposes an enhanced transition control method of synchronverter for transient oscillation reduction in active power and voltage responses. Section 5 shows the simulation results comparing with the conventional control method to verify the efficacy of the proposed control method; subsequently, further demonstration under the identical requirement is performed through experimental HILS test in Opal-RT (OP-5707) platform interfaced with lab customized controller based on TMS320F28377D in Section 6. Finally, the conclusions of the study are summarized in Section 7.

2. Fundamental Principle of Synchronverter

This section briefly describes the fundamental operation principle of synchronverter for analyzing an oscillatory phenomenon and developing a proposed control method [11]. In this research, DC link voltage V_{dc} is assumed to be stiff because it is rectified by front-end converter in DG, so that the dynamic generated by the DC link is not considered. 3-phase synchronverter topology consists of two parts; one is the power part and the other is the electronic part depicted in Figure 1.

2.1. Power Part

The power part is composed of the general 3-phase voltage source inverter (VSI) as shown in Figure 1. The VSI consists a 3-phase half-bridge type using IGBTs, which is identical with general 2-level inverter topology. As illustrated in Figure 1, the synchronverter could be implemented without a significant topology modification.

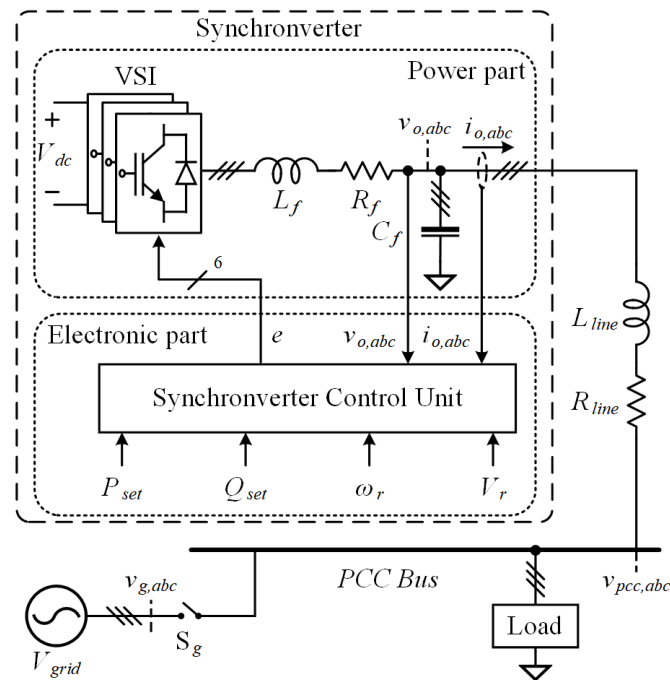


Figure 1. Block diagram of synchronverter topology.

L_f , R_f and C_f represent filter inductance, equivalent resistance and filter capacitance, respectively. L_{line} and R_{line} are the line inductance and line resistance at PCC bus. $v_{o,abc}$ represents the synchronverter output voltage, and $i_{o,abc}$ are the output current. e is the synchronverter reference voltage such as SM's electromotive force (EMF) by rotor movement. $v_{pcc,abc}$ and $v_{g,abc}$ represent PCC bus voltage and grid voltage, respectively. P_{set} and Q_{set} refer to the setting values of active power and reactive power. V_r and ω_r are the required droop voltage and angular frequency, which refer to the reference voltage and frequency of the synchronverter, respectively.

2.2. Electronic Part

Figure 2 is the synchronverter control block diagram as an electronic part corresponding to the synchronverter control unit in Figure 1. J is the rotor moment of inertia, D_p is the damping (frequency droop) coefficient, D_v is the voltage droop coefficient and K is the regulating factor of reactive power. $M_f i_f$ stands for virtual rotor flux linkage. T_m is a mechanical torque, selected by dividing ω_r from P_{set} , which is used as a torque reference and T_e is the electromagnetic torque which is obtained by dividing the output power by the output angular frequency. ω and θ are the output angular frequency and phase angle of the synchronverter, respectively.

The main principle of synchronverter control and operation is based on the following equations.

$$P = \omega \cdot M_f i_f \cdot \langle \mathbf{i}_o \cdot \mathbf{sin}\theta \rangle \quad (1)$$

$$Q = -\omega \cdot M_f i_f \cdot \langle \mathbf{i}_o \cdot \mathbf{cos}\theta \rangle \quad (2)$$

$$e = \omega \cdot M_f i_f \cdot \mathbf{sin}\theta \quad (3)$$

where $\langle \mathbf{A} \cdot \mathbf{B} \rangle$ means the inner product of its components. $\mathbf{i}_o$ is the 3-phase inverter output current (i.e., $i_{o,abc}$). $\mathbf{sin}\theta$, and $\mathbf{cos}\theta$ are 3-phase sine and cosine waveforms, respectively.

where, ΔQ is the amount of reactive power variation and ΔV_o is the deviation of output voltage. K is chosen as

$$K = \tau_v \cdot \omega_r \cdot D_q \quad (10)$$

where τ_v is the voltage loop time constant. According to (4) and (8), active power and reactive power could be independently controlled with both APL and RPL.

3. Analysis of Transient Oscillation Phenomenon in Synchronverter System

The control principle of synchronverter is based on SM's dynamics as an attribute for natural synchronism phenomenon by active power flow between synchronverter and power grid, such as an infinite bus. As seen in the control block diagram in Figure 2 and defined in Section 2, all parameters are dominated by SM's characteristics, which implies that critical parameter values to determine the internal dynamics of synchronverter is selected during an initial design procedure for capacity, time constant and inertia moment, etc. In other words, flexibly controllable parts are limited in the conventional algorithm, and thus the entire system stability highly depends on external passive components (e.g., inverter output filters, line impedances, loads, etc). The transfer function of the synchronverter system could be expressed as follows

$$G_{\text{synchronverter}}(s) = \frac{v_o(s)}{v_i(s)} = \frac{As^2 + Bs + C}{Ds^4 + Es^3 + Fs^2 + Gs + H} \quad (11)$$

where the coefficients are described in Appendix A.1.

Based on (11), Figure 3 is the root-loci of synchronverter control method under an islanded condition and indicates the pole-zero map for 4 cases of (i) no-load (red), (ii) 10 kW load (blue), (iii) 20 kW load (green) and (iv) rated load (30 kW, pink).

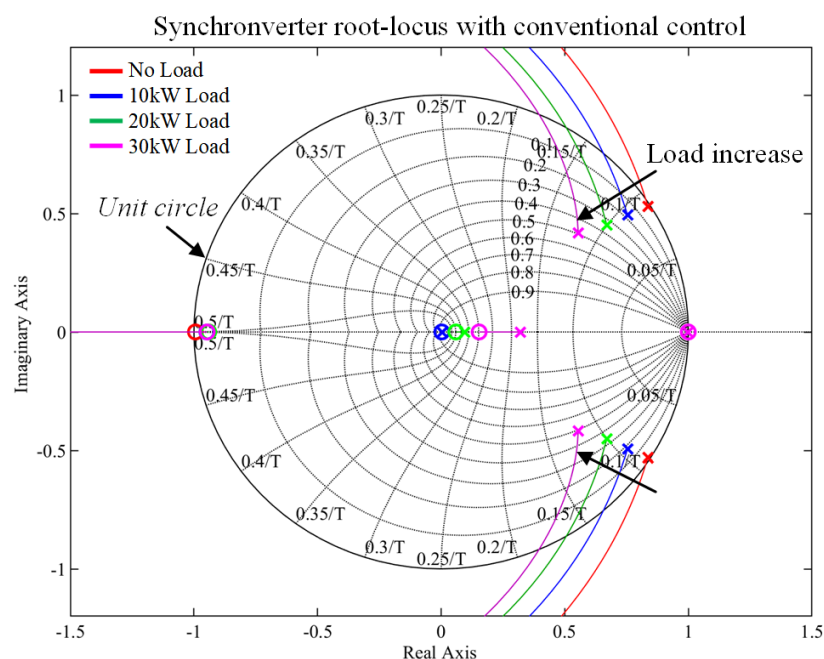


Figure 3. Root-locus of conventional synchronverter control method in islanded power system.

In islanded power system, IIDR-based synchronverter system should provide active power to critical loads that could be abruptly changed depending on consumers. In Figure 3, it is observed that the position of the pole approaches to unit circle line along with the load decrease from full-load to light-load, and the rate of the exponentially decaying is increased; damping ratio is decreased. It implies that load variations have a highly impact

on an internal dynamic of synchronverter system under islanded power system with a limited controllability.

The synchronverter system depicted in Figure 1 could be replaced with a simplified circuit diagram illustrated in Figure 4a. For transient simulation to replicate load variations under an islanded grid in order to demonstrate the stability analysis result, a mechanical switch as shown in Figure 4a is installed as a component for realizing the load change condition. When the load changes (i.e., the switch is closed), it could be found that a transient state is generated.

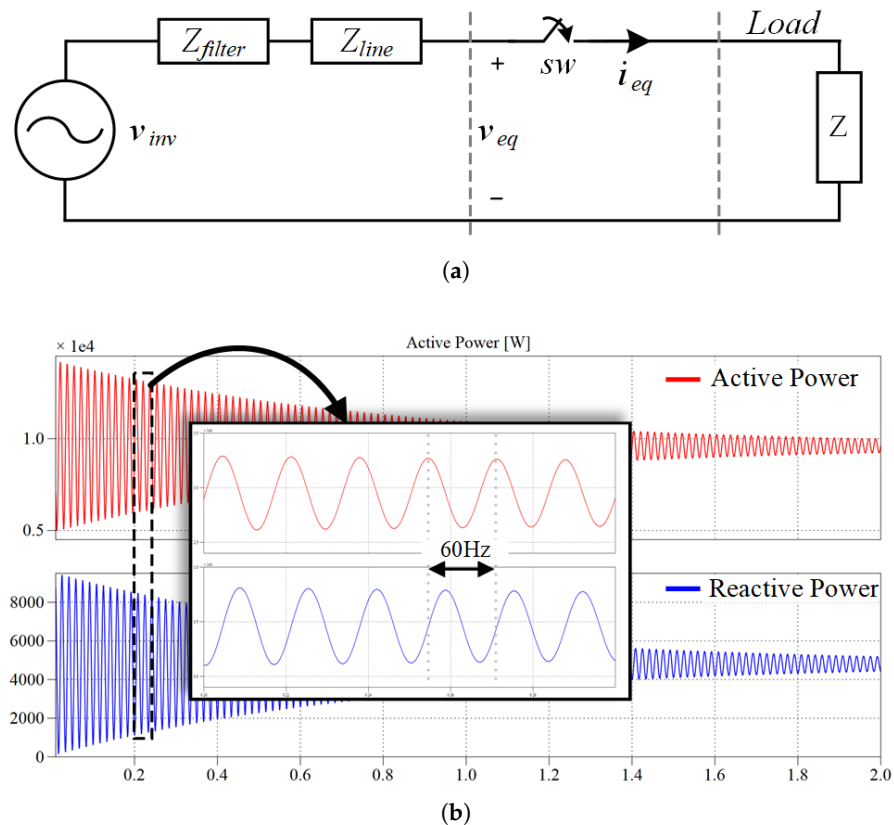


Figure 4. (a) Simplified synchronverter system circuit diagram and (b) power oscillation occurred in islanded power system during load variation.

Using differential equations [31], the equivalent voltage and current are obtained as

$$\begin{aligned} \mathbf{v}_{eq} &= V_m \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \\ \mathbf{i}_{eq} &= \frac{V_m}{Z} \begin{bmatrix} \sin(\omega t - \varphi) \\ \sin(\omega t - \varphi - \frac{2\pi}{3}) \\ \sin(\omega t - \varphi + \frac{2\pi}{3}) \end{bmatrix} - \frac{V_m}{Z} e^{-\frac{R}{L}t} \begin{bmatrix} \sin(-\varphi) \\ \sin(-\varphi - \frac{2\pi}{3}) \\ \sin(-\varphi + \frac{2\pi}{3}) \end{bmatrix} \end{aligned} \quad (12)$$

where, $Z = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}$, and $\varphi = \tan^{-1}\left(\frac{R}{X_L}\right)$. By using (12), the active and reactive power could be derived as follows

$$\begin{aligned} p_{eq} &= K \cos(\omega t - \varphi) e^{-\frac{R}{L}t} + L \\ q_{eq} &= M \sin\left(\omega t - \frac{\pi}{6}\right) e^{-\frac{R}{L}t} + N \end{aligned} \quad (13)$$

where, the coefficient corresponding to (13) can be found in Appendix A.2.

Transient state is expressed by the frequency component and the exponential function. Figure 4b shows the results of active and reactive power oscillation generated in the load change conditions and is well matched with further detailed simulation results included in next section with detailed EMT simulation and experimental HILS test. As a result, a transient oscillatory phenomenon occurs in active and reactive power when a load condition is changed under islanded power system relying on conventional synchronverter control algorithm.

In summary, this analytic result indicates that the fundamental synchronization principle of synchronverter causes a serious transient oscillation and there is no control-freedom for stability improvement, and hence the GFM self-synchronized converter system lacks of grid stabilizing capability, which should rely on other smart devices for such an ancillary service. Furthermore, the power oscillation would cause a life shortening problem due to an excess the allowable current even with overcurrent limit in terms of hardware system.

4. Enhanced Control Method of Synchronverter System for Transient Oscillation Mitigation

For aforementioned inevitable transient oscillation in active and reactive power responses of synchronverter system, an additional control scheme should be required owing to a lack of a degree of freedom (DOF). Thus, in this research, an additional compensating control loop is developed and then is capable of reducing the generated oscillation in active and reactive power. Figure 5 shows the modified synchronverter control block diagram from Figure 2 as a conventional control method. For enhancing a DOF, the output EMF value (e) is manipulated through the additional control loop that is called to double loop voltage controller. In order to decouple the AC component by synchronous reference frame, dq-axis frame is employed to distinguish the active and reactive components, and is possible to design stable controller by stability criterion. As a result, the proposed control block is able to reproduce a compensated output EMF value (e^*) as shown in Figure 5.

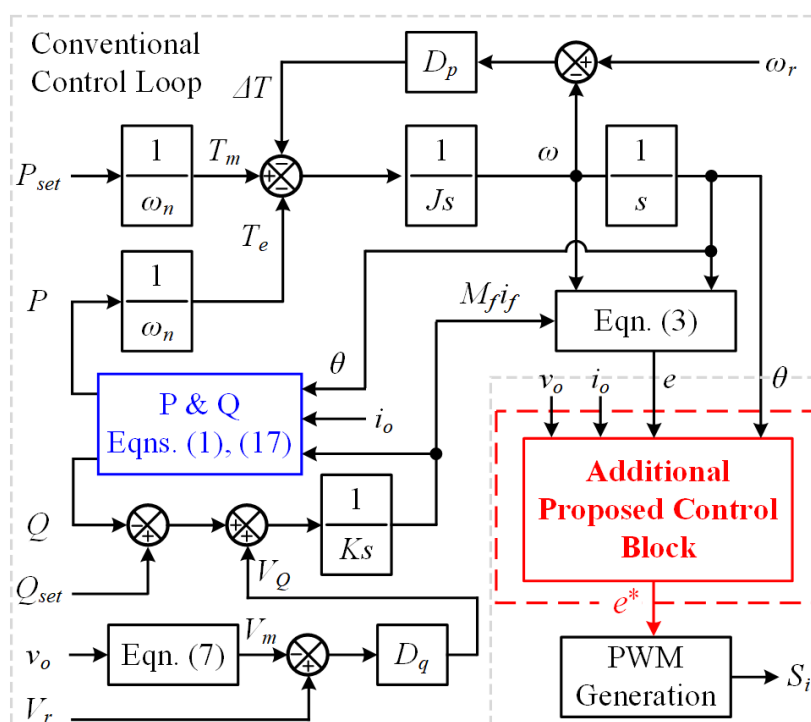


Figure 5. Proposed control block diagram for enhancing the synchronverter dynamics from SAM to GCM transition.

Compared with the conventional synchronverter control method, the added control block could provide a DOF without any modified synchronization principle. Figure 6 indicates detailed the block diagram of additional proposed control block shown in Figure 5. Three-phase information of conventional output EMF (e), inverter output current (i_o) and inverter output voltage (v_o) are used to make the reproduced output EMF value (e^*), and to mitigate a transient oscillatory phenomenon in islanded power system. The dq-axis components were used to feedback control loop, since the rotational coordinate system is advantageous in terms of exploiting a flexible current control and elaborating a stable control design.

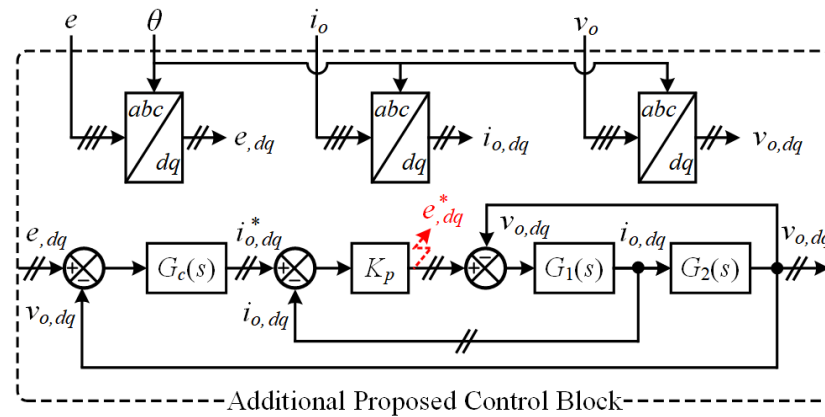


Figure 6. Block diagram of additional proposed control block.

The $G_c(s)$ is proportional-integral (PI) controller for sustaining PCC voltage and compensating a dynamic for reactive power part in conventional synchronverter system, which is as follows

$$G_c(s) = K_{p,cv} + \frac{K_{i,cv}}{s} \quad (14)$$

where $K_{p,cv}$, $K_{i,cv}$ are proportional gain and integral gain of PI controller, respectively. The outer voltage loop could be accomplished with a facile design method.

In Figure 6, K_p is a proportional gain for inner current control loop. The proportional control serves to mitigate the power oscillation associated with conventional synchronverter controller. The magnitude of the corrective action by K_p is reduced as the controlled variable approaches the set point. $G_1(s)$, and $G_2(s)$ are plant models to establish transfer function for the inner current loop and the outer voltage loop, which are expressed by

$$G_1(s) = \frac{i_o(s)}{v_i(s)} = \frac{Is^3 + Js^2 + Ks + L}{Ms^4 + Ns^3 + Os^2 + Ps + Q} \quad (15)$$

$$G_2(s) = \frac{v_o(s)}{i_o(s)} = \frac{Rs^2 + Ss + T}{Us^3 + Vs^2 + Xs + Y} \quad (16)$$

where the coefficients are described in Appendix A.3.

For examining a stability of the synchronverter control system, root-locus diagram is shown in Figure 7. Comparing with Figure 3, where the position of the root is changed only by the load condition, it can be confirmed that the position of the root is changed according to the gain of the controller as well as the load condition. In other words, the over-damping or under-damping operating region of the synchronverter system can be flexibly adjusted, which means that the internal dynamics of the synchronverter system can be flexibly adjusted. Therefore, it is confirmed that oscillatory issues in active and reactive power responses could be alleviated by the additional controller with the natural synchronism.

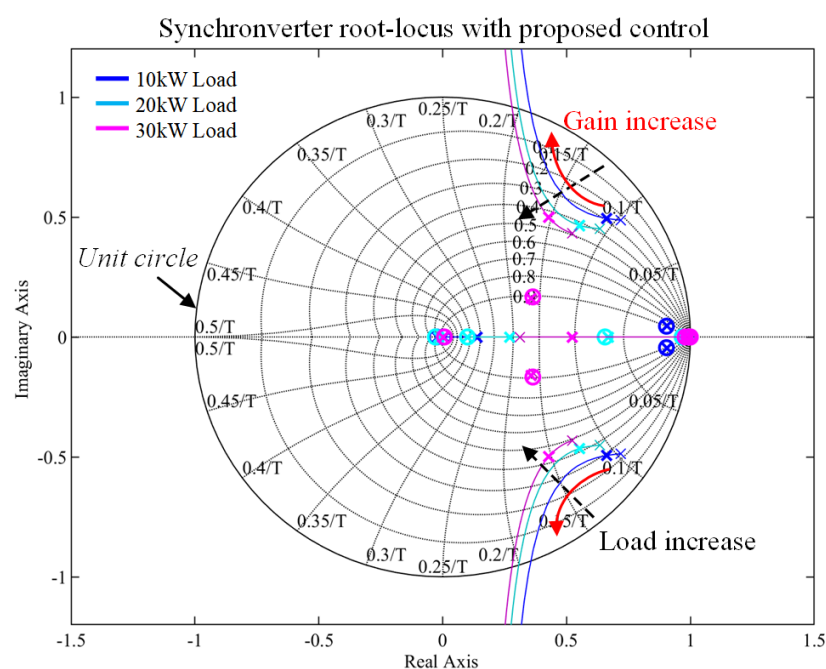


Figure 7. Root-locus of proposed control algorithm.

Moreover, in the proposed control block diagram, an instantaneous reactive power equation is employed to increase the accuracy of measured reactive power as follows.

$$Q = \frac{1}{\sqrt{3}} \{ (v_{o,b} - v_{o,c})i_{o,a} + (v_{o,c} - v_{o,a})i_{o,b} + (v_{o,a} - v_{o,b})i_{o,c} \} \quad (17)$$

Since the calculated reactive power by (2) causes a difference between supply and demand side under a constant impedance loading condition of static polynomial (ZIP) load, instantaneous calculation method of reactive power is more beneficial under islanded power system to maintain the PCC voltage.

5. Simulation Results

The improved control principle of synchronverter is verified under islanded power system condition with the simulation parameters defined in Table 1, and entire system configuration is established to replicate both SAM and GCM through an isolating switch (S_g) as shown in Figure 1. Synchronverter proposed in the initial paper has been developed as an enabler to operate with other electrical machines in securing the power system stability, and hence it is assumed that a generation resource and constant PQ load through an aggregation are included in the system topology without certain complicated network and multiple converters. This research is to focus on investigation of a specific relationship between loading condition and controller's variables and then achieves the power oscillation damping capability under load changes in 100% dominated-power electronic generation system on islanding power system. The synchronverter has a rated power of (30+j10) kVA and is operated at 6.0kHz switching frequency.

The damping coefficient (D_p) is calculated by (5). Since the load fluctuations are taken into account in islanded operation conditions, the output torque difference is set the 100% change rate and the frequency change rate to 0.5% according to limitation of frequency change. The voltage droop coefficient (D_q) is calculated by (9). The voltage fluctuation rate to 5% according to provide stable power. The J and K values is set with consideration of the time constant for frequency (τ_f) and voltage (τ_v) according to (6) and (10).

Table 1. Specific parameters of simulation.

Parameter	Symbol	Value	Description
Rated Power	S	$(30 + j10)$ kVA	
Switching Frequency	f_{sw}	6.0 kHz	
Sampling Frequency	f_{samp}	6.0 kHz	
Reference Voltage (rms)	V_r	220.0 V	
Angular Frequency	ω_r	376.991 rad/s	
Filter inductance	L_f	0.45 mH	
Filter resistance	R_f	0.135 Ω	
Filter capacitance	C_f	60.0 μ F	
Line inductance	L_{line}	0.15 mH	
Line resistance	R_{line}	0.045 Ω	
Load1	Z_{load1}	$(15 + j5)$ kVA	
Load2	Z_{load2}	$(30 + j10)$ kVA	
Damping coefficient	D_p	42.2172	Calculated from Equation (5)
Voltage droop coefficient	D_q	642.8243	Calculated from Equation (9)
Frequency time constant	τ_f	0.002 s	
Voltage time constant	τ_v	0.02 s	
Momentum of inertia	J	0.0844	Calculated from Equation (6)
Reactive regulating coefficient	K	4846.78	Calculated from Equation (10)

A case concerning load step change is carried out for transient oscillation issues according to power system requirements under islanded grid. Figure 8 shows simulation results with the conventional synchronverter control and proposed control method under only resistive load condition. Until 1.0 s, half of loading condition is maintained and the load step change occurs at 1.0 s from 15 kW to 30 kW. The conventional synchronverter algorithm has a characteristic of fast response with stable performance and proposed algorithm provides a smooth transient response to the load. It implies that a position of poles could be moved through tuning the parameters of the external controller and the synchronverter system could be over-damped against from an oscillatory mode.

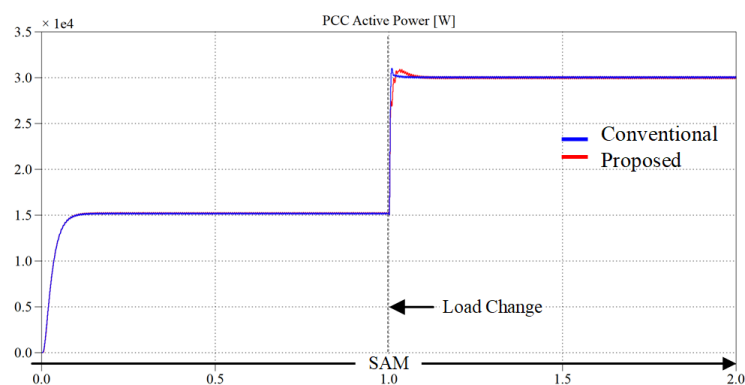
**Figure 8.** Simulation results of conventional (blue line) and proposed (red line) synchronverter control dynamic under only resistive load condition with load step change.

Figure 9 shows the simulation results with parallel R-L load condition to inject the oscillatory mode in the system. The overall simulation progress is shown in Figure 9a. The load change is occurred in 1.0 s and the synchronization mode is started at 2.0 s. After synchronization is completed (conventional is 7.1 s, and proposed is 6.1 s), the synchronverter operation mode is changed from SAM to GCM. A sudden problem occurs in the grid system, the isolation switch is opened and the operation mode is changed from GCM to SAM at 9.0 s. After 9.0 second, the synchronverter continues to operate in SAM, and when the grid is restored, the synchronverter operates in synchronization mode again and prepares to be connected to the grid as can be seen in 2.0 s. Through the control method

proposed in this paper, the effect of reducing power oscillation can be confirmed in the vicinity of 1.0 second when the load changes, and an enlarged view of this part is shown in Figure 9b. A severe power oscillation occurs in active and reactive power when comparing with Figure 8 and the result are well matched with the analytic result through simple circuit topology in Figure 4b; 40.37% and 26.15% of peak to peak oscillation magnitude is reduced in active power response and reactive power response respectively.

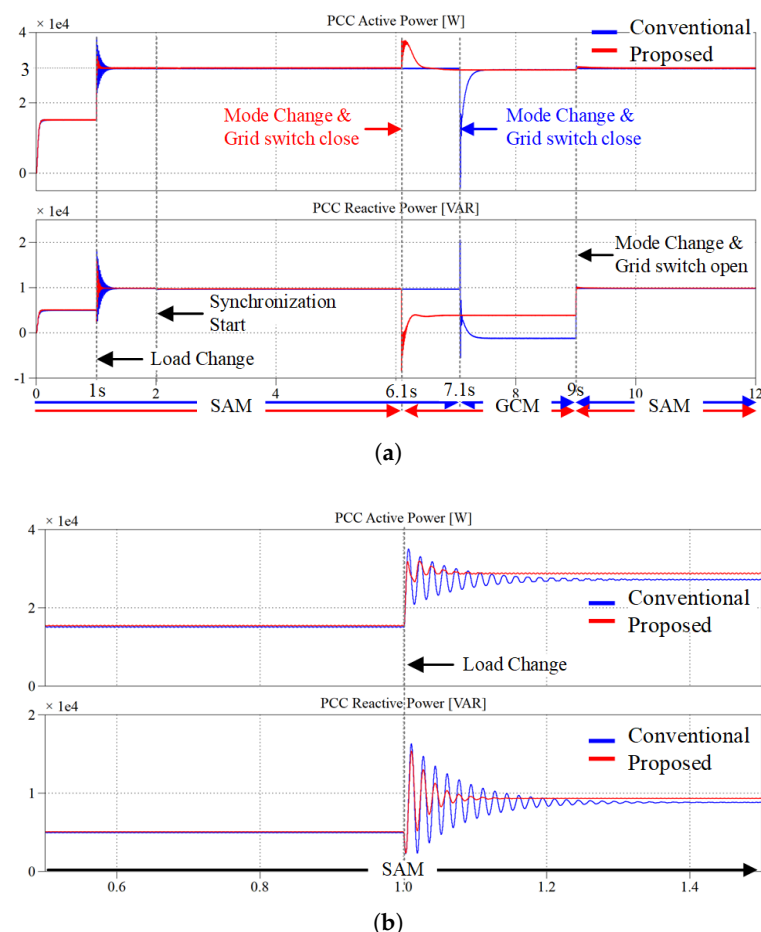


Figure 9. Simulation result of conventional (blue line) and proposed (red line) synchronverter control method with parallel R-L load condition from SAM to GCM (a) overall sequence, (b) load change.

The power oscillation may cause an instability in multiple interfaced converters system. Also, it damages life shortening of critical loads and further causes serious destruction of synchronverter system. On the other hand, the synchronverter with the proposed control strategy is able to significantly reduce the serious oscillation in the active and reactive power responses as shown in Figure 9. As a result, the proposed control could provide a stable operation under critical load step change cases in islanded power system through an enhanced and flexible controllability in a limited DOF of self-synchronization GFM converter.

In the case of synchronization, there are many commonly use synchronization methods [12,32]. One is using a virtual current method, which based on the magnitude and phase angle difference between grid voltage and output voltage through the virtual impedance [12], and the other is a method of matching by adjusting the output voltage phase information by comparing the grid voltage [32]. In this paper, the latter one is conducted to GCM transition with a grid voltage synchronization for a smoothly interconnection. After grid synchronization is completed with a negligible disturbance, the synchronverter operation mode is changed from SAM to GCM, while the critical loads are still connected, and thus active power is continuously delivered from it.

In both the conventional and the proposed method, it is obtained that a manageable transient state occurs when the synchronverter operation mode is switched. However, as shown in Figure 9a, the active and reactive power fluctuation in the proposed method is less generated than that of the conventional method, and it is confirmed that there was little difference in performance between the proposed method and the conventional method in the part where the mode was changed (i.e., GCM to SAM) due to the occurrence of a grid system problem. As a result, the proposed control method is more beneficial in islanded grid with critical loads.

6. Experimental Results from Hardware-in-Loop System (HILS) Test with Real-Time Simulator

6.1. Hardware-in-Loop System (HILS) Setup

HILS based experimental setup is shown in Figure 10. The actual experimental environment is configured as shown in Figure 10a. The AC grid and converter system are modeled in Op-5707 of Opal-RT simulator [33], and modeled synchronverter is controlled by external DSP hardware board (TMS320F28377) [34]. For interfacing, the Opal-RT model is transferred to the external control board. The all HILS setup is illustrated in the simplified block diagram of Figure 10b.

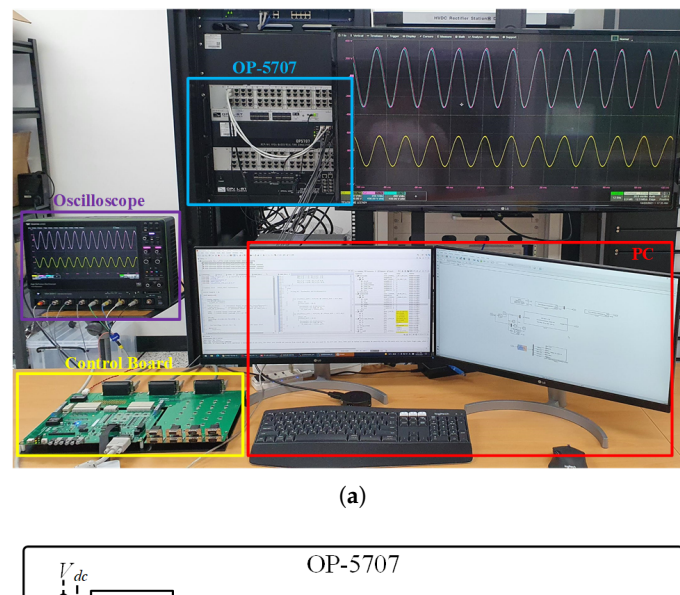


Figure 10. (a) Configuration of HILS based experimental setup, and (b) simplified HILS experiment block diagram.

6.2. Experimental Results with HILS Test

Based on the simulation results of Section 5, HILS based experiments are conducted. First, the experimental results under the only resistive load condition is shown in Figure 11, and Figure 11a indicate the results by the conventional control, and the proposed control. Comparing with Figure 8 by ideal simulation condition, the transient result could be similarly obtained.

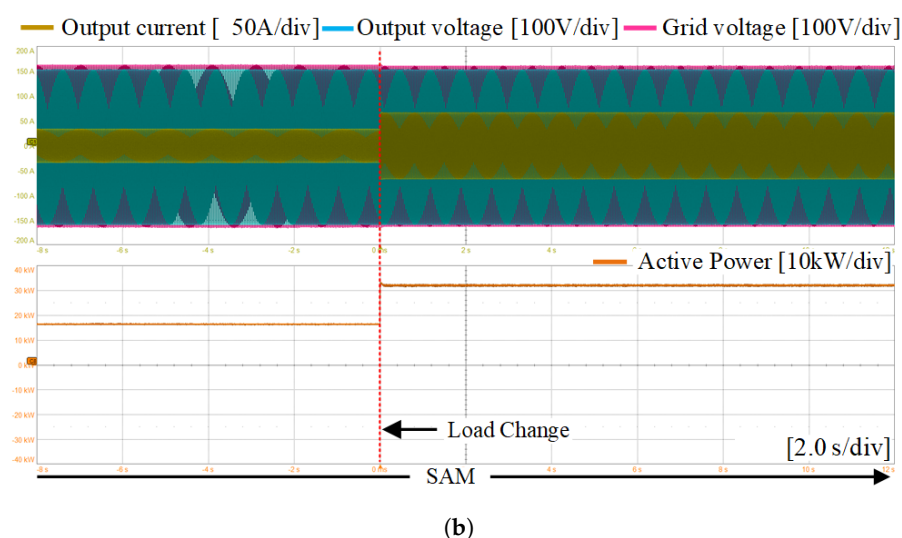
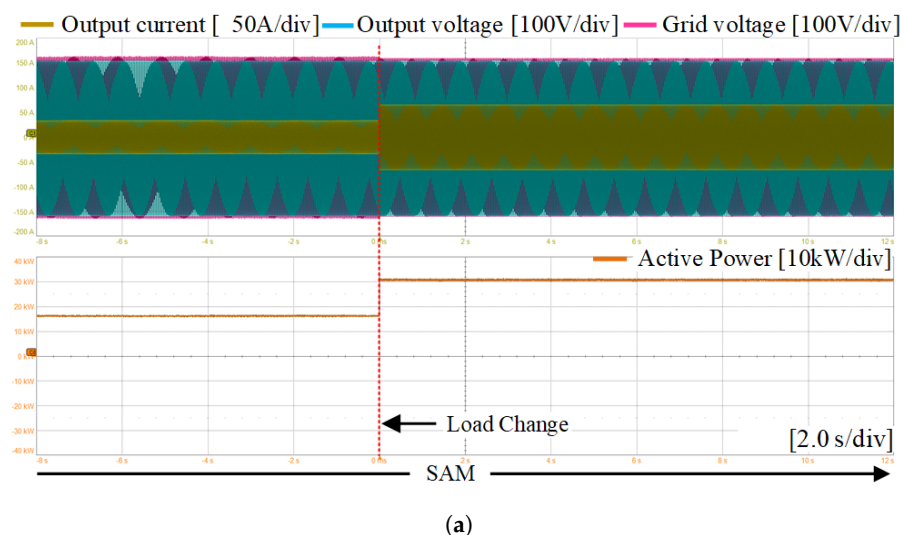


Figure 11. HILS based experimental results with only resistive load condition (a) conventional (b) proposed control method.

Figure 12 shows HILS based experimental results by the conventional synchronverter control algorithm. Figure 12a indicates the entire sequence in which (i) the loads are increased, (iii) the operation mode of the synchronverter is changed after (ii) grid synchronization for preparing a connection to AC power system is completed, (iv) the synchronverter operation mode is converted due to a problem in the grid system.

Figure 12b is an enlarged view of the point at which the load step change occurs in Figure 12a. When the load changes, the large active and reactive power fluctuations could be identified. Figure 12c is also an enlarged view of the time when the mode change occurs on the state that the phase matching between the AC grid and the synchronverter output voltage for the synchronization is made. Comparing with Figure 12b, it shows that the phase difference between the grid voltage and the output voltage of the synchronverter is

well matched, and it is observed that a large transient occurs when the operation mode is switched from SAM to GCM. When the grid system problem occurs, the synchronverter changes its operation mode from GCM to SAM as shown in Figure 12d, and it could be seen that the operation mode conversion without any major problems.

Figure 13 shows the experimental results using the proposed control algorithm. Figure 13a shows the overall experimental procedure, and Figure 13b shows the experimental result of load increase. Comparing with Figure 12b, it could be achieved that the fluctuation amplitude in transient state is decreased by 57.1% for active power and 37.5% for reactive power, respectively. Figure 13c shows the experimental result during operation mode transfer, and compared with Figure 12c, it is also achieved that the transient phenomenon during operation mode transition is greatly reduced. Compared with Figure 12d, Figure 13d was confirmed to change the mode from GCM to SAM without a significant difference. Therefore, the proposed control method is more beneficial when the loads change in islanded grid condition.

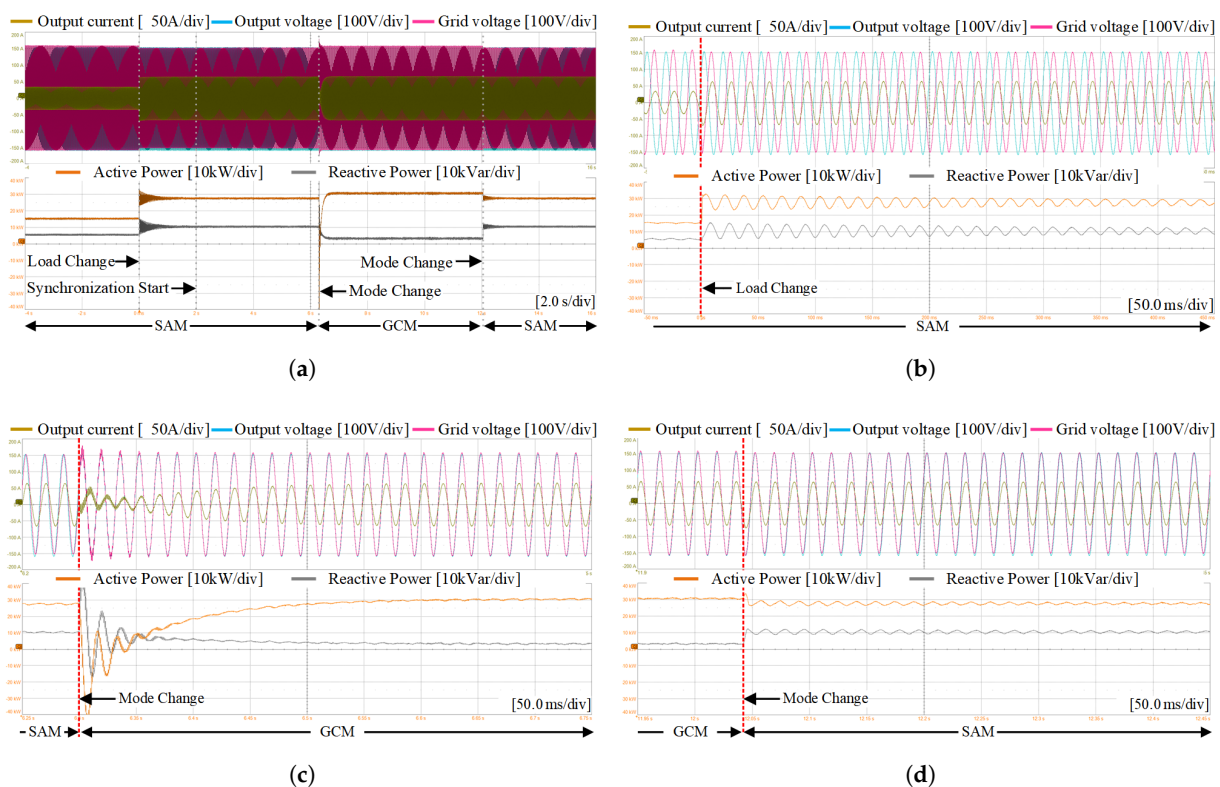


Figure 12. HILS based experimental results of conventional control method with parallel R-L load condition (a) overall sequence, (b) load step change, (c) SAM to GCM transition, (d) GCM to SAM transition.

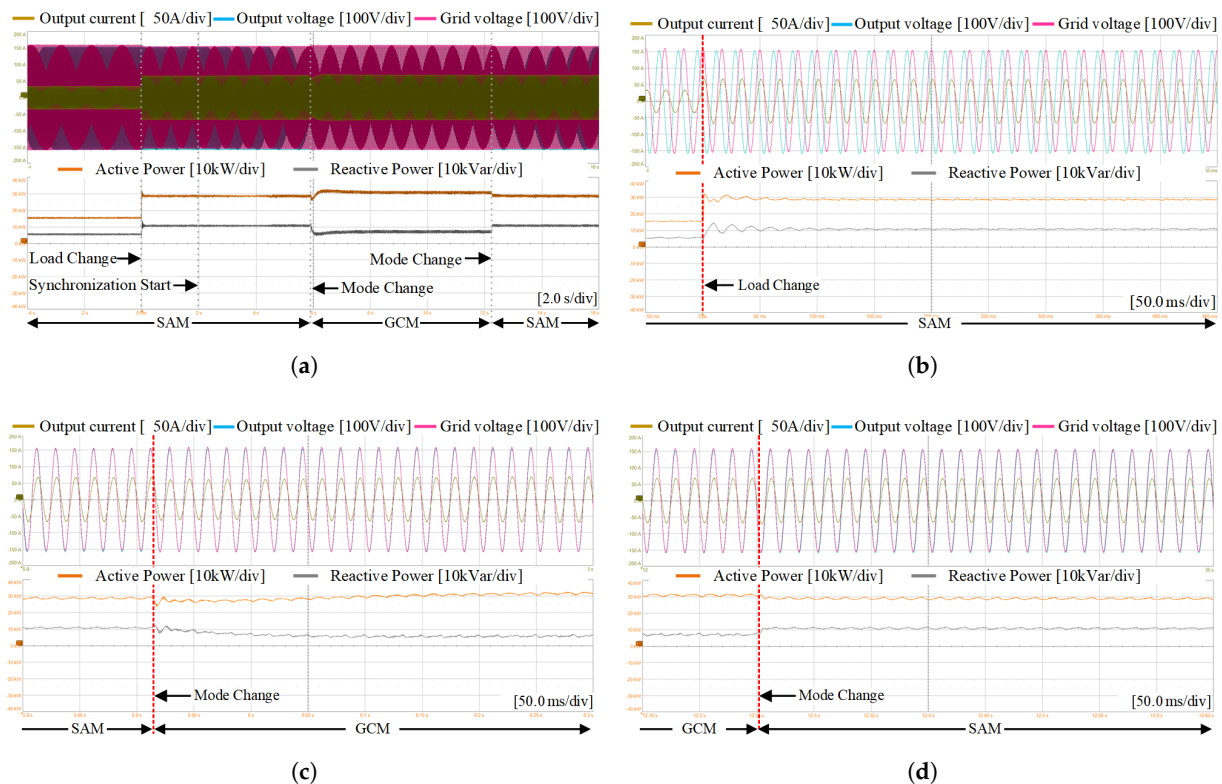


Figure 13. HILS based experimental results of proposed control method with parallel R-L load condition (a) overall sequence, (b) load step change, (c) SAM to GCM transition, (d) GCM to SAM transition.

7. Discussion and Conclusions

An enhanced control strategy of the synchronverter was proposed to reduce the power oscillation phenomenon caused by load fluctuations in the islanded power system. Also, a stability analysis was conducted for inspecting the internal dynamics of the synchronverter system and designing the control algorithm. The efficacy of the proposed control was validated by rigorous EMT simulations, and HILS based experimentations, which showed that the oscillatory problems in active and reactive power responses were resolved, and the power fluctuations were significantly reduced through the proposed control method compared to the conventional control method.

For future research based on this study results, it will be expanded to multiple synchronverter parallel operation and also conducted on power sharing among the multiple synchronverters with the improved control method under the islanded power system, including critical loads. Recent power systems are rapidly changing toward both GFL and GFM converter combined hybrid networks [35–38], so we should analyze the power system issue related with GFL and GFM for future grid and continue to research in this regards.

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Abbreviations

The following abbreviations are used in this manuscript:

GFL	Grid-Following
GFM	Grid-Forming
PCC	Point of Common Coupling
GCM	Grid-Connected Mode
SAM	Stand-Alone Mode
EMT	Electromagnetic Transient
HILS	Hardware-In-Loop System
UNFCCC	United Nations Framework Convention on Climate Change
DG	Distributed Generation
PV	Photovoltaic
RES	Renewable Energy Source
DER	Distributed Energy Resource
MG	Microgrid
SM	Synchronous Machine
VISMA	Virtual Synchronous Machine
VSG	Virtual Synchronous Generator
IIDR	Inverter-Interfaced Distribution Resource
PLL	Phase-Locked Loop
EMF	Electromotive Force
APL	Active Power Loop
RPL	Reactive Power Loop
VSI	Voltage Source Inverter
RoCoF	Rate of Change of Frequency

Appendix A

Appendix A.1

$$\begin{aligned}
 A &= L_L L_{line} \\
 B &= (L_L + L_{line}) R_d R_L + L_L R_{line} \\
 C &= R_d R_{line} \\
 D &= R_d L_L C_f L_f L_{line} E = L_f L_L L_{line} + (R_d L_f R_{line} + R_f L_{line} + R_L L_L) L_L C_f \\
 F &= C_f L_f (R_L R_{line} + R_f R_{line}) + R_L C_f (R_f L_L + R_f L_{line}) + L_L L_{line} (R_f + R_d) \\
 &\quad + L_f L_L (R_{line} + R_d) + L_f R_L (L_L + L_{line}) \\
 G &= (L_f R_L + L_L R_f) R_{line} + (L_L + L_{line}) R_f R_L + (R_L + R_L) L_L \\
 &\quad + (R_d L_L + R_f R_L C_f) R_{line} + (L_f + L_{line}) R_L \\
 H &= (R_f + 1) R_L R_{line} + R_f R_L
 \end{aligned}$$

Appendix A.2

$$\begin{aligned}
 v_a(t) &= V_m \sin(\omega t) \\
 v_b(t) &= V_m \sin(\omega t - \frac{2\pi}{3}) \\
 v_c(t) &= V_m \sin(\omega t + \frac{2\pi}{3}) \\
 i_a(t) &= \frac{V_m}{Z} \sin(\omega t - \varphi) - \frac{V_m}{Z} \sin(-\varphi) e^{-\frac{R}{L}t}
 \end{aligned}$$

$$\begin{aligned}
i_b(t) &= \frac{V_m}{Z} \sin(\omega t - \varphi - \frac{2\pi}{3}) - \frac{V_m}{Z} \sin(-\varphi - \frac{2\pi}{3}) \\
i_c(t) &= \frac{V_m}{Z} \sin(\omega t - \varphi + \frac{2\pi}{3}) - \frac{V_m}{Z} \sin(-\varphi + \frac{2\pi}{3}) \\
p(t) &= v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) \\
&= \frac{3}{2} \frac{V_m^2}{Z} \cos(\omega t - \varphi) e^{-\frac{R}{L}t} + \frac{3}{2} \frac{V_m^2}{Z} \cos(-\varphi) \\
K &= \frac{3}{2} \frac{V_m^2}{Z} \\
L &= \frac{3}{2} \frac{V_m^2}{Z} \cos(-\varphi) \\
q(t) &= \frac{1}{\sqrt{3}} ((v_a(t) - v_b(t))i_c(t) + (v_b(t) - v_c(t))i_a(t) + (v_c(t) - v_a(t))i_b(t)) \\
&= -\frac{3V_m^2}{Z} \sin(\omega t + \frac{\pi}{6}) e^{-\frac{R}{L}t} + \frac{V_m^2}{2Z} \sin(-\varphi) \\
M &= -\frac{3V_m^2}{2Z} \\
N &= \frac{V_m^2}{2Z} \sin(-\varphi)
\end{aligned}$$

Appendix A.3

$$\begin{aligned}
I &= R_d L_L C_f L_{line} \\
J &= (R_d C_f R_{line}) L_L + (L_L + L_{line}) R_L C_f \\
K &= (R_{line} + R_L + R_d) L_L + (L_{line} + R_{line} C_f) R_L \\
L &= (R_{line} + 1) R_L \\
M &= R_d L_L C_f L_{line} \\
N &= (L_L R_{line} R_d + R_f L_{line} + L_L R_L + R_L L_{line}) L_f C_f + (L_f + R_f L_{line}) L_L L_{line} \\
O &= (R_d L_f + R_L C_f) L_L + (R_f L_L + R_d L_L + R_L C_f) L_{line} + (L_f + R_f C_f) L_L R_{line} \\
&\quad + R_L C_f L_f R_{line} \\
P &= (R_f R_{line} + R_d R_{line} + 2R_L + R_f) L_L + (C_f R_{line} + 2L_{line} + L_f) R_L \\
Q &= (1 + 2R_{line}) R_L \\
R &= R_d L_L L_{line} \\
S &= (R_L + R_{line}) L_L R_d + R_d L_{line} R_L \\
T &= R_d R_{line} R_L \\
U &= C_f L_L L_{line} R_d \\
V &= (L_{line} + C_f R_d R_L + C_f R_d R_{line}) L_L + C_f L_L L_{line} R_d \\
W &= (R_d + R_L + R_{line}) L_L + (L_{line} + C_f R_d R_{line}) R_L \\
X &= (R_d + R_{line}) R_L
\end{aligned}$$

References

1. Dreidy, M.; Mokhlis, H.; Mekhilef, S. Inertia response and frequency control techniques for renewable energy sources: A review. *Renew. Sustain. Energy Rev.* **2017**, *69*, 144–155. [\[CrossRef\]](#)
2. Shuai, Z. Microgrid stability: Classification and a review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 167–179. [\[CrossRef\]](#)
3. van Wessenbeeck, M.P.N.; de Haan, S.W.H.; Varela, P.; Visscher, K. Grid tied converter with virtual kinetic storage. In Proceedings of the 2009 IEEE Bucharest PowerTech, Bucharest, Romania, 28 June–2 July 2009.
4. Fernández-Guillamón, A.; Gómez-Lázaro, E.; Muljadi, E.; Molina-García, Á. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109369. [\[CrossRef\]](#)
5. Seneviratne, C.; Frequency, C. Response due to a large generator loss with the increasing penetration of wind/PV generation: A literature review. *Renew. Sustain. Energy Rev.* **2016**, *57*, 659–668. [\[CrossRef\]](#)
6. Driesen, J.; Visscher, K. Virtual synchronous generators. In Proceedings of the 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008.
7. Ma, Y.; Cao, W.; Yang, L.; Wang, F.F.; Tolbert, L.M. Virtual synchronous generator control of full converter wind turbines with short-term energy storage. *IEEE Trans. Ind. Electron.* **2017**, *64*, 8821–8831. [\[CrossRef\]](#)
8. Sakimoto, K.; Miura, Y.; Ise, T. Stabilization of a power system with a distributed generators by a virtual synchronous generator function. In Proceedings of the International Conference on Power Electronics (ICPE) ECCE Asia, Jeju, Korea, 30 May–3 June 2011.

9. D'Arco, S.; Suul, J.A.; Fosso, O.B. Small-signal modelling and parametric sensitivity of a virtual synchronous machine. In Proceedings of the Power Systems Computation Conference (PSCC), Wroclaw, Poland, 18–22 August 2014.
10. Beck, H.P.; Hesse, R. Virtual synchronous machine. In Proceedings of the International Conference on Electrical Power Quality and Utilisation (EPQU), Barcelona, Spain, 9–11 October 2007.
11. Zhong, Q.; Weiss, G. Synchronverters: Inverters that mimic synchronous generators. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1259–1267. [\[CrossRef\]](#)
12. Zhong, Q.; Nguyen, P.; Ma, Z.; Sheng, W. Self-synchronized synchronverters: Inverters without a dedicated synchronization unit. *IEEE Trans. Power Electron.* **2014**, *29*, 617–630. [\[CrossRef\]](#)
13. Natarajan, V.; Weiss, G. Synchronverters with better stability due to virtual inductors, virtual capacitors, and anti-windup. *IEEE Trans. Ind. Electron.* **2017**, *64*, 5994–6004. [\[CrossRef\]](#)
14. Tebib, A.; Boudour, M. Optimal design of synchronverter virtual capacitor to achieve capacitive output impedance. In Proceedings of the International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, 28–31 October 2018.
15. Dong, S.; Chen, Y.C. Adjusting synchronverter dynamic response speed via damping correction loop. *IEEE Trans. Energy Convers.* **2017**, *32*, 608–619. [\[CrossRef\]](#)
16. Me, S.P.; Zabihi, S.; Blaabjerg, F.; Bahrani, B. Adaptive Virtual Resistance for Post-fault Oscillation Damping in Grid-forming Inverters. *IEEE Trans. Power Electronics* **2021**. [\[CrossRef\]](#)
17. Harnefors, L.; Schweizer, M.; Kukkola, J.; Routimo, M.; Hinkkanen, M.; Wang, X. Generic PLL-Based Grid-Forming Control. *IEEE Trans. Power Electron.* **2022**, *37*, 1201–1204. [\[CrossRef\]](#)
18. Gong, H.; Wang, X.; Harnefors, L. Rethinking Current Controller Design for PLL-Synchronized VSCs in Weak Grids. *IEEE Trans. Power Electron.* **2022**, *37*, 1369–1381. [\[CrossRef\]](#)
19. Alassi, A.; Ahmed, K.; Egea-Alvarez, A.; Foote, C. Modified Grid-forming Converter Control for Black-Start and Grid-Synchronization Applications. In Proceedings of the International Universities Power Engineering Conference (UPEC), Middlesbrough, UK, 7–10 September 2021.
20. Li, Y.; Du, Z. Stabilizing Condition of Grid-Connected VSC as Affected by Phase Locked Loop (PLL). *IEEE Trans. Power Deliv.* **2021**. [\[CrossRef\]](#)
21. Chen, M.; Zhou, D.; Blaabjerg, F. Enhanced Transient Angle Stability Control of Grid-Forming Converter Based on Virtual Synchronous Generator. *IEEE Trans. Ind. Electron.* **2021**. [\[CrossRef\]](#)
22. Kong, L.; Xue, Y.; Qiao, L.; Wang, F.F. Angle Droop Design for Grid-Forming Inverters Considering Impacts of Virtual Impedance Control. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 10–14 October 2021.
23. Chen, M.; Zhou, D.; Tayyebi, A.; Prieto-Araujo, E.; D'orfler, F.; Blaabjerg, F. Generalized Multivariable Grid-Forming Control Design for Power Converters. 2021. Available online: <https://arxiv.org/abs/2109.06982> (accessed on 14 September 2021).
24. Rathnayake, D.B.; Akrami, M.; Phurailatpam, C.; Me, S.P.; Hadavi, S.; Jayasinghe, G.; Zabihi, S.; Bahrani, B. Grid Forming Inverter Modeling, Control, and Applications. *IEEE Access* **2021**, *9*, 114781–114807. [\[CrossRef\]](#)
25. Nikolaev, N.; Dimitrov, K.; Rangelov, Y. A Comprehensive Review of Small-Signal Stability and Power Oscillation Damping through Photovoltaic Inverters. *Energies* **2021**, *14*, 7372. [\[CrossRef\]](#)
26. Li, H.; Zhang, X.; Shao, T.; Zheng, T.Q. Flexible Inertia Optimization for Single-Phase Voltage Source Inverter Based on Hold Filter. *IEEE J. Emerg. Sel. Top. Power Electron.* **2019**, *7*, 1300–1310. [\[CrossRef\]](#)
27. Li, H.; Zhang, X.; Shao, T.; Zheng, T.Q. Study on the inertia optimization of grid-friendly single-phase synchronverter. In Proceedings of the IEEE Energy Conversion Congress Exposition (ECCE), Cincinnati, OH, USA, 1–5 October 2017.
28. Younis, T.; Ismeil, M.; Hussain, E.K.; Orabi, M. Single-phase self-synchronized synchronverter with current-limiting capability. In Proceedings of the International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 27–29 December 2016.
29. Qi, Y.; Deng, H.; Liu, X.; Tang, Y. Synthetic Inertia Control of Grid-Connected Inverter Considering the Synchronization Dynamics. *IEEE Trans. Power Electron.* **2022**, *37*, 1411–1421. [\[CrossRef\]](#)
30. Roldán-Pérez, J.; Rodríguez-Cabero, A.; Prodanovic, M. Parallel current-controlled synchronverters for voltage and frequency regulation in weak grids. In Proceedings of the The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018), Liverpool, UK, 17–19 April 2018.
31. Najm, F.N. *Circuit Simulation*; Wiley-IEEE Press: Hoboken, NJ, USA, 2010.
32. Kim, K.; Oh, C.; Kim, T.; Lee, J.; Kim, H. Implementation of a Smart Power Conditioning System for Energy Storage System with a Novel Seamless Transfer Strategy. *Energies* **2018**, *11*, 1108. [\[CrossRef\]](#)
33. Op5700 User Manual. Available online: <https://manualzz.com/doc/29448289/op5700-user-manual---opal-rt> (accessed on 1 March 2016).
34. TMS320F2837xD Dual-Core Microcontrollers Datasheet (Rev. O). Available online: <https://www.ti.com/product/TMS320F28377D> (accessed on 1 February 2021).
35. Xue, Y.; Wang, G.; Zhang, Z.; Xu, Z. Mechanism analysis and mitigation strategies for oscillatory instability of synchronous generators affected by voltage source converters. *IET Gener. Transm. Distrib.* **2021**, 1–16. [\[CrossRef\]](#)
36. Zuo, Y.; Yuan, Z.; Sossan, F.; Zecchino, A.; Cherkaoui, R.; Paolone, M. Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids. *Sustain. Energy Grids Netw.* **2021**, *27*, 100496. [\[CrossRef\]](#)

-
37. Kenyon, R.W.; Sajadi, A.; Hoke, A.; Hodge, B.-M. Open-Source PSCAD Grid-Following and Grid-Forming Inverters and A Benchmark for Zero-Inertia Power System Simulations. In Proceedings of the IEEE Kansas Power and Energy Conference, Manhattan, KS, USA, 19–20 April 2021.
 38. Pattabiraman, D.; Lasseter, R.H.; Jahns, T.M. Comparison of Grid Following and Grid Forming Control for a High Inverter Penetration Power System. In Proceedings of the IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018.