Self-Synchronized Synchronverters: Inverters Without a Dedicated Synchronization Unit

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***Abstract*—A synchronverter is an inverter that mimics synchronous generators, which offers a mechanism for power systems to control grid-connected renewable energy and facilitates smart grid integration. Similar to other grid-connected inverters, it needs a dedicated synchronization unit, e.g., a phase-locked loop (PLL), to provide the phase, frequency, and amplitude of the grid voltage as references. In this paper, a radical step is taken to improve the synchronverter as a self-synchronized synchronverter by removing the dedicated synchronization unit. It can automatically synchronize itself with the grid before connection and track the grid frequency after connection. This considerably improves the performance, reduces the complexity, and computational burden of the controller. All the functions of the original synchronverter, such as frequency and voltage regulation, real power, and reactive power control, are maintained. Both simulation and experimental results are presented to validate the control strategy. Experimental results have shown that the proposed control strategy can improve the performance of frequency tracking by more than 65%, the performance of real power control by 83%, and the performance of reactive power control by about 70%.**

***Index Terms*—Droop control, grid connection, microgrid, PLL, renewable energy, smart grid integration, synchronization, synchronverters, virtual synchronous machines.**

I. Introduction

MORE and more renewable energy sources are being connected to power systems, often via dc/ac converters (also called inverters). The most important and basic requirement for such applications is to keep inverters synchronized with the grid before and after being connected to the grid so that 1) an inverter can be connected to the grid and 2) the inverter can feed the right amount of power to the grid even when the grid voltage changes its frequency, phase, and amplitude [1]–[8]. It has been a norm [9] to adopt a synchronization unit, e.g. a phase-locked loop (PLL) and its variants [4], [10]–[15], to make sure that the inverter is synchronized with the grid. This practically adds an outer-loop controller (the synchronization unit) to the inverter controller.

A grid-connected inverter can be controlled as a voltage supply or a current supply. When it is controlled as a voltage supply, the typical control structure is shown in Fig. 1(a). It consists of a synchronization unit to synchronize with the grid, a power loop to regulate the real power and reactive power exchanged with the grid, a voltage loop to regulate the output voltage, and a current loop to control the current. The synchronization unit often needs to provide the frequency and the amplitude, in addition to the phase, of the fundamental component of the grid voltage as the references for the power controller [16]. The negative impact of a synchronization unit on control performance is well known [17], [18]. Moreover, because PLLs are inherently nonlinear and so are the inverter controller and the power system, it is extremely difficult and time-consuming to tune the PLL parameters to achieve satisfactory performance. A slow synchronization unit could directly affect control performance and degrade system stability but a complex synchronization unit, on the other hand, is often computationally intensive, which adds significant burden to the controller. Hence, the synchronization needs to be done quickly and accurately in order to maintain synchronism, which makes the design of the controller and the synchronization unit very challenging because the synchronization unit is often not fast enough with acceptable accuracy and it also takes time for the power and voltage controllers to track the references provided by the synchronization unit as well. When a grid-connected inverter is controlled as a current supply, the output voltage is maintained by the grid and the inverter only regulates the current exchanged with the grid. In this case, the typical control structure is shown in Fig. 1(b). Normally, it does not have a voltage controller; the power controller is often a simple static one as well, which does not require much effort for tuning. Moreover, the synchronization unit is often required to provide the phase of the grid only. Some simple synchronization methods can be adopted and no extra effort is needed to design the synchronization unit. Because of the simplified control structure and the reduced demand on the synchronization unit, it is well known that it is much easier to control a grid-connected inverter as a current supply than to control it as a voltage supply [19]. However, when an inverter is controlled as a current supply, it causes undesirable problems. For example, the controller needs to be changed when the inverter

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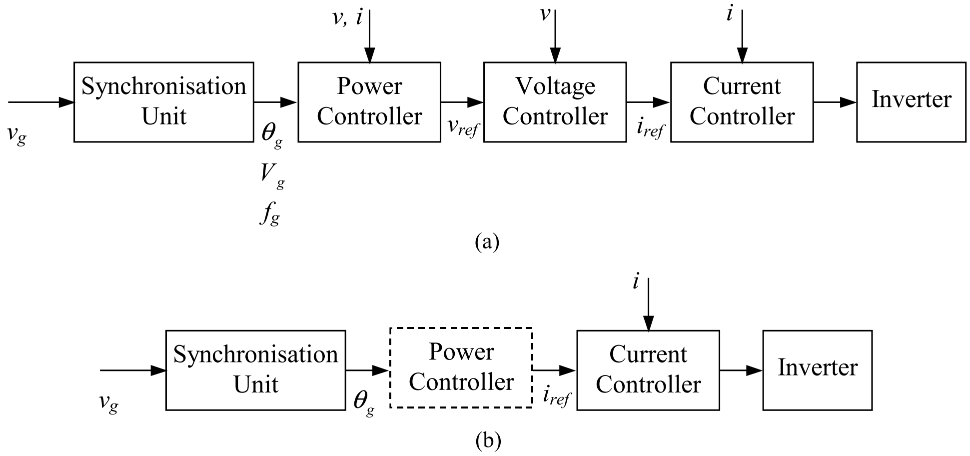

Fig. 1. Typical control structures for a grid-connected inverter. (a) When controlled as a voltage supply. (b) When controlled as a current supply.

is disconnected from the grid to operate in the standalone mode or when the grid is weak because it does not have the capability of regulating the voltage. A current-controlled inverter may also continue injecting currents into the grid when there is a fault on the grid, which might cause excessively high voltage. Moreover, a current-controlled inverter is difficult to take part in the regulation of the grid frequency and voltage, which is a must when the penetration of renewable energy exceeds a certain level. Hence, the industry is increasingly demanding for voltage-controlled inverters and the challenge of achieving fast synchronization cannot be circumvented. A lot of research activities have been done in recent years to increase the speed and accuracy of synchronization [20]–[26] but the problem is still open and it is not fast enough to obtain adequate accuracy. In this paper, a radical step is to be taken, that is, to remove the synchronization unit and embed the synchronization function into the power controller. This removes a nonlinear element from the system, which makes the system operation much easier.

Synchronverters are grid-friendly inverters that mimic synchronous generators [27], [28]. A synchronverter includes the mathematical model of a synchronous machine and behaves in the same way, mathematically, as a synchronous generator to provide a voltage supply. Its controller is in principle a power controller with integrated capability of voltage and frequency regulation so it is able to achieve real power control, reactive power control, frequency regulation, and voltage regulation. Because of the embedded mathematical model, a utility company is able to control a synchronverter in the same way as controlling synchronous generators, which considerably facilitates the grid connection of renewable energy and smart grid integration. Since a synchronous machine is inherently able to synchronize with the grid, it should be possible to integrate the synchronization function into the power controller and make a synchronverter to synchronize with the grid without a dedicated synchronization unit. This could lead to a compact control structure shown in Fig. 2. A current controller is not included there but can be easily added for over-current protection, if needed.

In this paper, the synchronverter strategy is improved to have the capability of synchronizing with the grid by itself without the aid of a dedicated synchronization unit. This takes away a slow element in the closed-loop system consisting of the

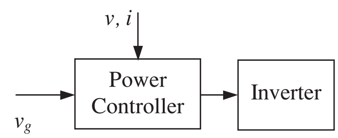

Fig. 2. Compact control structure for a grid-connected inverter, where the functions of synchronization, voltage regulation, and frequency regulation are integrated into the power controller.

synchronization unit, the inverter controller and the power system, and removes a major nonlinear element that affects the speed and accuracy of synchronization. Hence, it widens the system bandwidth, reduces the time needed for synchronization, and improves the accuracy of synchronization, which does not only considerably improve the performance of the system but also reduces the complexity of the overall controller. To the best knowledge of the authors, no control strategy for grid-connected inverters that are not equipped with a dedicated synchronization unit for synchronization both before connection and after connection has been reported in the literature. The closest work along this direction is [6], where an additional PLL is not needed during normal operation but a backup PLL is still needed for synchronization before connection (and also for situations when there are severe faults on the ac side). Simulation and experimental results are provided to demonstrate the excellent performance of the proposed control strategy, both under normal operation and under grid faults.

The rest of this paper is organized as follows. The original synchronverter is reviewed in Section II. The self-synchronized synchronverter is proposed in Section III, with simulation and experimental results presented in Sections IV and V, respectively. The impact of removing the synchronization unit on the complexity of the overall controller and the demand for computational capability is shown in Section VI, followed by conclusions and discussions made in Section VII.

II. Overview of the Synchronverter Technology

A synchronverter is an inverter that mimics a conventional synchronous generator [27], [28]. As a result, grid-connected renewable energy and distributed generation can easily take part in the regulation of system frequency and voltage. A

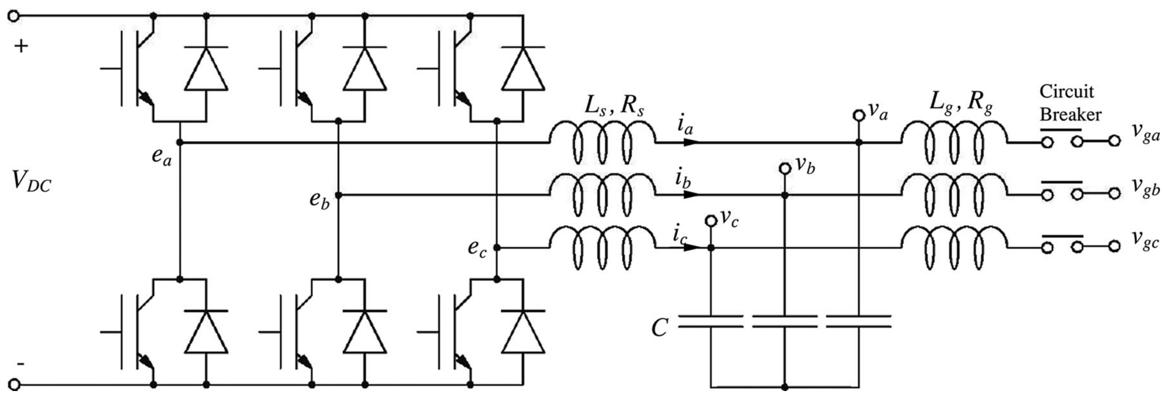

Fig. 3. Power part of a synchronverter.

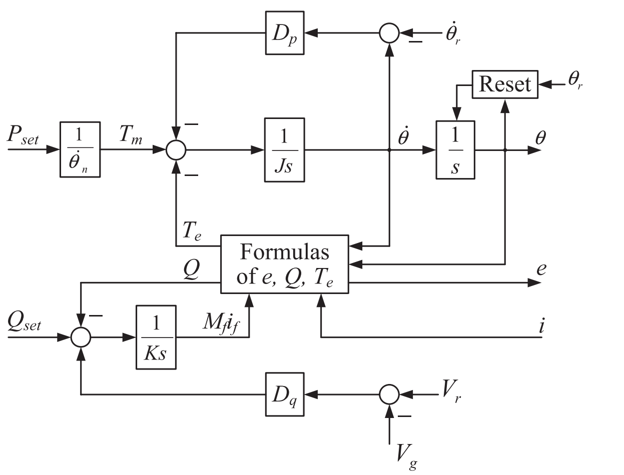

Fig. 4. Electronic part (controller) of a synchronverter, where the provision of the frequency reference $\dot{\theta}_r$, the phase reference θ_r, and the voltage reference V_r, normally via a dedicated synchronization unit, is not shown.

synchronverter consists of a power part, as shown in Fig. 3, and an electronic part, i.e., the controller, as shown in Fig. 4. It is assumed that the dc bus of the synchronverter is constant. Otherwise, a dc-bus voltage controller, together with an energy storage system if needed, can be introduced to maintain the dc-bus voltage constant, e.g., via regulating the reference of the real power for the synchronverter or regulating the power flow into and out of the energy storage system. The controller includes the mathematical model of a three-phase round-rotor synchronous machine described by

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta}) \tag{1}$$

$$T_e = M_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle \tag{2}$$

$$e = \dot{\theta} M_f i_f \widetilde{\sin}\,\theta \tag{3}$$

$$Q = -\dot{\theta} M_f i_f \left\langle i, \widetilde{\cos}\,\theta \right\rangle \tag{4}$$

where T_m, T_e, e, θ, and Q are the mechanical torque applied to the rotor, the electromagnetic torque, the three-phase generated voltage, the rotor angle, and the reactive power, respectively. J is the imaginary moment of inertia of all the parts rotating with the rotor. i_f is the field excitation current and M_f is the maximum mutual inductance between the stator windings and the field winding. $\dot{\theta}$ is the virtual angular speed of the machine and also the frequency of the control signal e sent to the pulse-width modulation (PWM) generator, and i is the stator current (vector) flowing out of the machine. $\widetilde{\sin}\theta$ and $\widetilde{\cos}\theta$ are defined as

$$\widetilde{\sin}\theta = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}, \quad \widetilde{\cos}\theta = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}.$$

In this paper, it is assumed that the number of pairs of poles for each phase is 1 and hence the mechanical speed of the machine is the same as the electrical speed of the electromagnetic field.

Similarly to the control of a synchronous generator, the controller of a synchronverter has two channels: one for the real power and the other for the reactive power. The real power is controlled by a frequency droop control loop, using the (imaginary) mechanical friction coefficient D_p as the feedback gain. This loop regulates the (imaginary) speed $\dot{\theta}$ of the synchronous machine and creates the phase angle θ for the control signal e. The reactive power is controlled by a voltage droop control loop, using the voltage droop coefficient D_q. This loop regulates the field excitation $M_f i_f$, which is proportional to the amplitude of the voltage generated. Hence, the frequency control, voltage control, real power control, and reactive power control are all integrated in one compact controller with only four parameters.

For grid-connected applications, a synchronization unit is needed to provide the grid information for the synchronverter to synchronize with the grid before connection and for the synchronverter to deliver the desired real and reactive powers after connection.

III. Design and Operation of a Self-Synchronized Synchronverter

A. A Synchronous Generator (SG) Connected to an Infinite Bus

The per-phase model of an SG, or a synchronverter, connected to an infinite bus is shown in Fig. 5. The generated real power

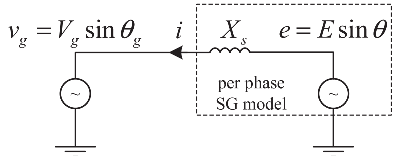

Fig. 5. The per-phase model of an SG connected to an infinite bus.

P and reactive power Q are [3], [29]

$$P = \frac{3V_g E}{2X_s}\sin(\theta - \theta_g) \tag{5}$$

and

$$Q = \frac{3V_g}{2X_s}\left[E\cos(\theta - \theta_g) - V_g\right] \tag{6}$$

where V_g is the amplitude of the infinite bus voltage; E is the induced voltage amplitude of the SG which could be controlled by the exciting current/voltage, or $M_f i_f$ in the case of a synchronverter; θ_g and θ are the phases of the grid voltage and of the SG, respectively; and X_s is the synchronous reactance of the SG. The phase difference

$$\delta = \theta - \theta_g$$

is often called the power angle, which is controlled by the driving torque of the turbine. The factor $\frac{1}{2}$ here is because V_g and E are amplitude values, instead of RMS values.

The voltage V_g and the corresponding phase θ_g of the infinite bus can be used as the references for E and θ to generate the preferred P and Q according to (5) and (6). When the driving torque T_m is increased, δ increases and the real power delivered to the grid increases until the electrical power is equal to the mechanical power supplied by the turbine. The maximum δ that the generator is able to synchronize with the grid is $\frac{\pi}{2}$ rad [3]. If the mechanical power keeps increasing and results in a δ that is larger than $\frac{\pi}{2}$ rad, then the rotor of the SG accelerates and loses synchronization with the grid. This should be avoided.

The reactive power Q can be regulated by controlling E, according to (6). When θ and E are controlled to be

$$\begin{cases} E = V_g \\ \theta = \theta_g \end{cases} \tag{7}$$

there is no real power or reactive power exchanged between the connected SG and the grid. In other words, if P and Q are controlled to be zero, then the condition (7) is satisfied and the generated voltage e is the same as the grid voltage v_g. This condition is not common in the normal operation of an SG, but when it is satisfied, the SG can be connected to or disconnected from the grid without causing large transient dynamics. This can be used to synchronize a synchronverter with the grid before connection.

B. The Proposed Controller

The proposed controller for a self-synchronized synchronverter is shown in Fig. 6, after making some necessary changes to the core of the synchronverter controller shown in Fig. 4. It

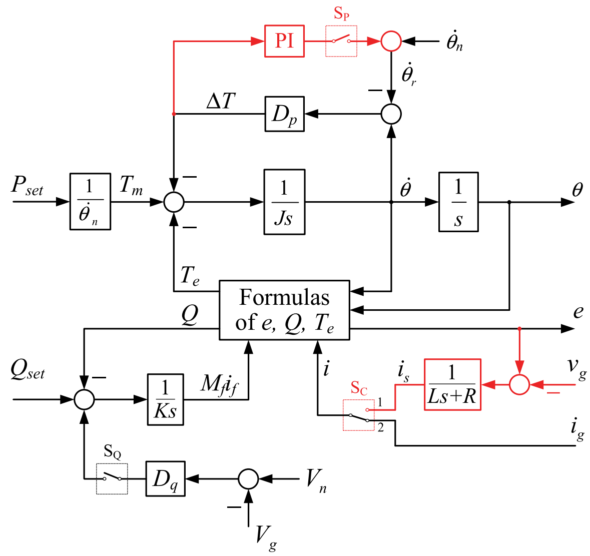

Fig. 6. Proposed controller (electronic part) for a self-synchronized synchronverter.

TABLE I
OPERATION MODES OF A SELF-SYNCHRONIZED SYNCHRONVERTER

Switch S_C	Switch S_P	Switch S_Q	Mode
1	ON	ON	N/A
1	ON	OFF	Self-synchronisation
1	OFF	ON	N/A
1	OFF	OFF	N/A
2	ON	ON	P-mode, Q_D-mode
2	ON	OFF	P-mode, Q-mode
2	OFF	ON	P_D-mode, Q_D-mode
2	OFF	OFF	P_D-mode, Q-mode

is able to be connected to the grid safely and to operate without the need of a dedicated synchronization unit. There are two major changes made: 1) a virtual current i_s generated from the voltage error between e and v_g is added and the current fed into the controller can be either i_s or the grid current i_g; 2) a PI controller is added to regulate the output ΔT of the frequency droop block D_p to be zero and to generate the reference frequency $\dot\theta_r$ for the original synchronverter. In order to facilitate the operation of the self-synchronized synchronverter, three switches S_C, S_P, and S_Q are added to change the operation mode. When Switch S_C is thrown at Position 1 (with S_P turned ON and S_Q turned OFF), the synchronverter is operated under the set mode defined in [28]. If P_{set} and Q_{set} are both 0, then the operation mode is called the self-synchronization mode and the synchronverter is able to synchronize with the grid. When it is synchronized with the grid, the circuit breaker in the power part can be turned on to connect the synchronverter to the grid. When switch S_C is thrown at Position 2, the synchronverter can be operated in four different modes. All the possible operation modes are shown in Table I. In order to safeguard the operation in the self-synchronization mode, S_P can be turned ON and S_Q can be turned OFF automatically whenever switch S_C is thrown at Position 1. In this paper, only the characteristics that are different from the original synchronverter are described, due to the page limit. The details about the original synchronverter, including tuning of parameters, can be found in [28].

C. Operation After Being Connected to the Grid

As mentioned before, the power angle δ of a synchronverter can be controlled by the virtual mechanical torque T_m calculated from the power command $P_{\rm set}$ as

$$T_m = \frac{P_{\rm set}}{\dot\theta} \approx \frac{P_{\rm set}}{\dot\theta_n}$$

where $\dot\theta_n$ is the nominal grid frequency. When S_P is turned ON, ΔT is controlled to be 0 in the steady state via the PI controller. Hence, T_e is the same as T_m and $\dot\theta$ is controlled as

$$\dot\theta = \dot\theta_r = \dot\theta_n + \triangle\dot\theta \tag{8}$$

where $\triangle\dot\theta$ is the output of the PI controller. The power angle δ settles down at a constant value that results in $P = P_{\rm set}$. This operation mode is called the set mode in [28]. In order to differentiate the set mode for real power and reactive power, the set mode for the real power is called the P-mode and the set mode for the reactive power is called the Q-mode in this paper. If $P_{\rm set} = 0$, then $\theta = \theta_g$, in addition to $\dot\theta = \dot\theta_r$. When the switch S_P is turned OFF, the PI controller is taken out of the loop and the synchronverter is operated in the frequency droop mode (called the P_D-mode in this paper, meaning that the real power P is not the same as $P_{\rm set}$ but deviated from $P_{\rm set}$)[1] with the frequency droop coefficient defined as

$$D_p = -\frac{\triangle T}{\triangle\dot\theta} \tag{9}$$

where

$$\triangle\dot\theta = \dot\theta - \dot\theta_n \tag{10}$$

is the frequency deviation of the synchronverter from the nominal frequency. It is also the input to the frequency droop block D_p (because S_P is OFF). This recovers the synchronverter frequency as

$$\dot\theta = \dot\theta_n + \triangle\dot\theta$$

which is the same as (8) but with a different $\triangle\dot\theta$. Actually, in both cases, $\dot\theta$ converges to the grid frequency $\dot\theta_g$ when the power angle δ is less than $\frac{\pi}{2}$ rad, as will be shown below.

According to [28], the time constant $\tau_f = J/D_p$ of the frequency loop is much smaller than the time constant $\tau_v \approx \frac{K}{\dot\theta D_q} \approx \frac{K}{\dot\theta_n D_q}$ of the voltage loop. Therefore, $M_f i_f$ can be assumed constant when considering the dynamics of the frequency loop. Moreover, according to (5), the real power delivered by the synchronverter (or an SG) is proportional to $\sin\delta$. As a result, the electromagnetic torque T_e is proportional to $\sin\delta$. For $\delta \in (-\frac{\pi}{2}, \frac{\pi}{2})$, T_e increases when the power angle δ increases and T_e decreases when the power angle δ decreases. If the grid frequency $\dot\theta_g$ decreases, then the power angle δ and the electromagnetic torque T_e increase. As a result, the input to the integrator block $\frac{1}{Js}$ in Fig. 6 decreases and the synchronverter frequency $\dot\theta$ decreases. The process continues until $\dot\theta = \dot\theta_g$. If the grid frequency increases, then a similar process happens until $\dot\theta = \dot\theta_g$. Hence, the synchronverter frequency $\dot\theta$ automatically converges to the grid frequency $\dot\theta_g$ (when $\delta \in (-\frac{\pi}{2}, \frac{\pi}{2})$) and there is no need to have a synchronization unit to provide $\dot\theta_g$ for the synchronverter as the reference frequency.

The proposed controller preserves the reactive power control channel of the original synchronverter, with the added Switch S_Q to turn ON/OFF the voltage droop function. When S_Q is OFF, $M_f i_f$ is generated from the tracking error between $Q_{\rm set}$ and Q by the integrator with the gain $1/K$. Therefore, the generated reactive power Q tracks the set-point $Q_{\rm set}$ without any error in the steady state regardless of the voltage difference between V_n and V_g. This operation mode is the set mode for the reactive power, called the Q-mode in this paper. When the Switch S_Q is ON, the voltage droop function is enabled and the voltage error $\triangle V = V_n - V_g$ is taken into account while generating $M_f i_f$. Hence, the reactive power Q does not track $Q_{\rm set}$ exactly but with a steady-state error $\triangle Q = Q_{\rm set} - Q$ that is determined by the voltage error $\triangle V$ governed by the voltage droop coefficient

$$D_q = -\frac{\triangle Q}{\triangle V}.$$

This operation mode is the voltage droop mode and is called the Q_D-mode in this paper, meaning that the reactive power is not the same as $Q_{\rm set}$ but deviated from $Q_{\rm set}$.

D. Synchronization Before Connecting to the Grid

Before the synchronverter is connected to the grid, its generated voltage e (strictly speaking, v) must be synchronized with the grid voltage v_g. Moreover, the amplitude E is also required to be equal to the amplitude V_g and the phase sequence of e and v_g must be the same as well. For a conventional SG, a synchroscope is often used to measure the phase difference between e and v_g so that the mechanical torque is adjusted accordingly to synchronize the SG with the grid. For grid-connected inverters, PLLs are often adopted to measure the phase of the grid voltage so that the generated voltage is locked with the grid voltage.

As mentioned before, the proposed controller shown in Fig. 6 is able to operate the synchronverter under the set mode with $P_{\rm set} = 0$ and $Q_{\rm set} = 0$. As a result, the condition (7) can be satisfied when it is connected to the grid. However, the current i_g flowing through the grid inductor is 0 until the circuit breaker is turned on, and hence, no regulation process could happen. In order to mimic the process of connecting a physical machine to the grid, a virtual per-phase inductor $Ls + R$ is introduced to connect the synchronverter with the grid and the resulting current

$$i_s = \frac{1}{Ls + R}(e - v_g)$$

can be used to replace i_g for feedback so that T_e and Q can be calculated according to (2) and (4). This allows the synchronverter to operate in the P-mode for the real power with $P_{\rm set} = 0$ and in the Q-mode for the reactive power with $Q_{\rm set} = 0$ so that the generated voltage e is synchronized with the grid voltage

[1]This means the PI controller is active only in the self-synchronization mode and the set mode (P-mode) but not in the droop mode (P_D-mode).

TABLE II
PARAMETERS USED IN SIMULATIONS AND EXPERIMENTS

Parameters	Values	Parameters	Values
L_s	0.45 mH	f_n	50 Hz
R_s	0.135 Ω	V_n	$12\sqrt{2}$ V
C	22 μF	DC-link voltage	42 V
R	1000 Ω	L	0.2 mH
rated power	100 VA	R	0.05 Ω
L_g	0.15 mH	K_p	0.5
R_g	0.045 Ω	K_i	20

v_g. The only difference is that the (virtual) current i_s, instead of the grid current i_g, is routed into the controller via the switch S_C thrown at Position 1. Since the current i_s is not physical, the inductance L and resistance R of the virtual synchronous reactance X_s can be chosen within a wide range. Small values lead to a large transient current i_s to speed up the synchronization process before connection. However, too small L and R may cause oscillations in the frequency estimated. Normally, the L and R can be chosen slightly smaller than the corresponding values of L_s and R_s. Moreover, the ratio $\frac{R}{L}$ defines the cut-off frequency of the filter $\frac{1}{sL+R}$, which determines the capability of filtering out the harmonics in the voltage v_g.

When the virtual current i_s is driven to zero, the synchronverter is synchronized with the grid. Then, the circuit breaker can be turned on at any time to connect the synchronverter to the grid. When the circuit breaker is turned on, the Switch S_C should be turned to Position 2 so that the real current i_g is routed into the controller for normal operation. After the synchronverter is connected to the grid, the switches S_P and S_Q can be turned ON/OFF to achieve any operation mode shown in Table I.

IV. SIMULATION RESULTS

The proposed control strategy was verified with simulations carried out in MATLAB 7.9/Simulink/SimPowerSystems, with the parameters given in Table II. The solver used was ode23 with the maximum step size of 0.1 ms. The inverter was connected to the grid via a step-up transformer, which allows an equivalent comparable experimental setup at low voltages for safety reasons. Similar to the implementation in [28], $D_p = 0.2026$ was chosen so that a drop of 0.5% in the frequency (from the nominal frequency f_n) causes the torque (hence, the power) to increase by 100% (of the nominal power) and the voltage droop coefficient was chosen as $D_q = 117.88$ so that a drop of 5% in the voltage requires the increase of 100% reactive power. The time constants for the droop control loops were chosen to be $\tau_f = 0.002$ s and $\tau_v = 0.02$ s.

A. Normal Operation

The simulation was started at $t = 0$ s, with switch S_C at Position 1, S_P turned ON, S_Q turned OFF, and the circuit breaker turned OFF, i.e., in the self-synchronization mode with $P_{\text{set}} = 0$ and $Q_{\text{set}} = 0$. The grid voltage was set to be 2% higher than the nominal value. The synchronverter synchronized itself with the grid very quickly. At $t = 2.0$ s, the circuit breaker was turned ON and S_C was switched to Position 2. The set-point for the real power $P_{\text{set}} = 80$ was applied at $t = 5$ s and the set-point for the reactive power $Q_{\text{set}} = 60$ Var was applied at $t = 10$ s. The grid frequency was stepped up to $f = 50.1$ Hz (i.e. increased by 0.2%) at $t = 15$ s. The P_D-mode was enabled at $t = 20$ s by turning S_P OFF and the Q_D-mode was enabled at $t = 25$ s by turning S_Q ON. The grid frequency was changed back to 50 Hz at $t = 30$ s and the simulation was stopped at $t = 35$ s. The system responses are shown in Fig. 7.

The synchronverter was operated in the self-synchronization mode at first to synchronize itself with the grid. The virtual current i_s was replaced with the real current i_g as soon as the synchronverter was connected to the grid. The transition between the two currents was very smooth, with P and Q well maintained at zero before and after connection. There was small dynamics at the moment of connection (mainly because of the filter). After the connection, regardless of the set-points P_{set} and Q_{set} applied and the modes of operation, the synchronverter tracked the grid frequency very well without any problem, even when the frequency stepped up by 0.1 Hz at $t = 15$ s. Note again that no dedicated synchronization unit was adopted in the controller and the frequency f is the internal frequency of the synchronverter. There are transient peaks in the frequency curve at each event, as shown in Fig. 7(a) and (b). This is expected, similar to the change of the speed of a synchronous machine when the operating condition is changed.

The operation modes of the original synchronverter were preserved well. The system under the set mode (i.e., the P-mode and the Q-mode) had reasonable responses with small overshoot and zero steady-state error. The frequency was also tracked well in the droop modes, but the real power and reactive power changed with the grid frequency, as expected. When the P_D-mode was enabled and the frequency was increased to $f_g = 50.1$ Hz, the real power dropped by 40 W, i.e., $\frac{0.2\%}{0.5\%} = 40\%$ of the nominal value, because the frequency f_g at that time was 0.2% higher than f_n. The power quickly jumped back to the set-point when f_g returned to the nominal frequency f_n. Similarly, the reactive power also dropped by 40 Var, i.e., $\frac{2\%}{5\%} = 40\%$ of the nominal value, when the Q_D-mode was enabled because the grid voltage V_g was 2% higher than the nominal value V_n.

The voltages v and v_g and their difference around the connection time are shown in Fig. 8, with Phase b taken as an example. Before connection, the difference was about 100 mV peak to peak, which was very small, and there was no problem to connect it to the grid.

In order to compare the performance with the original synchronverter, a three-phase PLL was adopted to provide the grid frequency and the simulation was repeated. After a great deal of effort was made to tune the PLL parameters, the best performance achieved was shown in Fig. 9. The overshoots of the frequency were quite similar. The frequency of the original synchronverter reached 15.1 Hz quicker than the self-synchronized synchronverter but it had a long oscillatory tail and took much longer to settle down. The frequency of the self-synchronized synchronverter settled down within 1 s but the frequency of the original synchronverter had noticeable errors even after 5 s. Because the frequency in a real power system changes all the time,

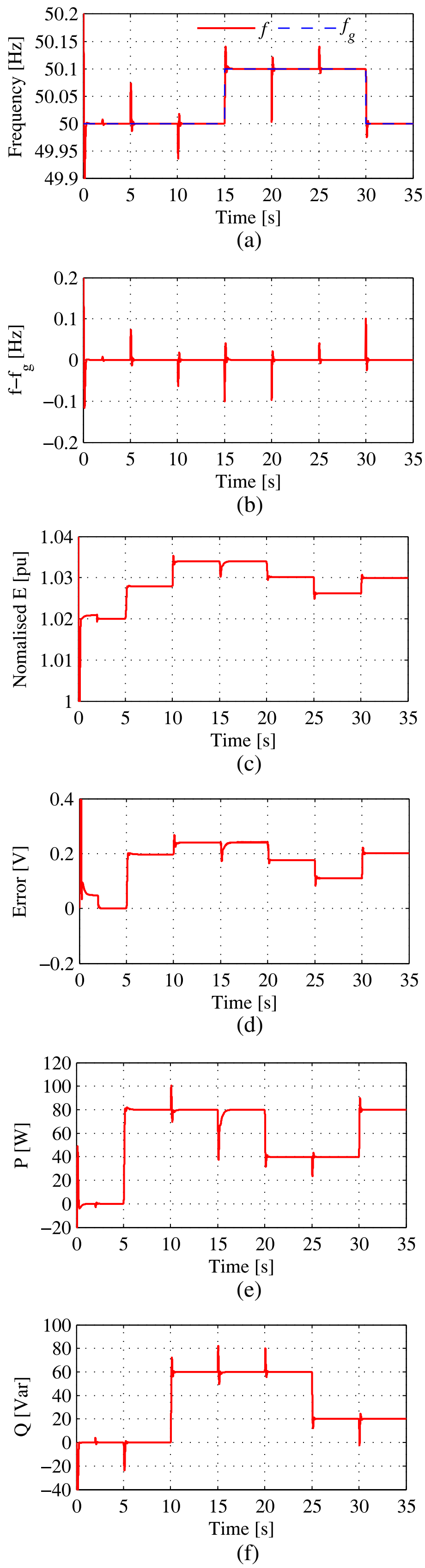

Fig. 7. Simulation results: under normal operation. (a) Synchronverter frequency f and the grid frequency f_g. (b) Frequency tracking error $f - f_g$. (c) Amplitude E of the generated voltage e. (d) Amplitude of $v - v_g$. (e) Real power. (f) Reactive power.

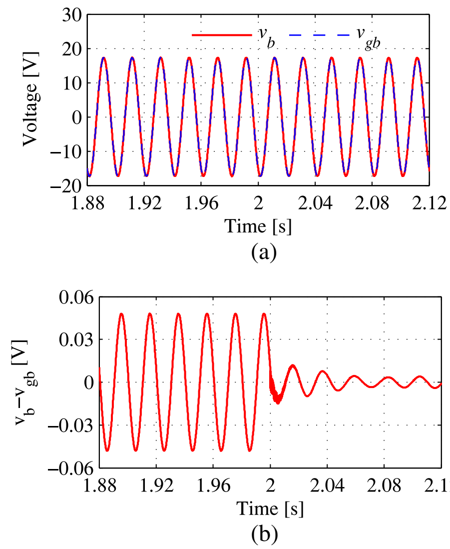

Fig. 8. Simulation results: Voltages around the connection time. (a) v_b and v_{gb}. (b) $v_b - v_{gb}$.

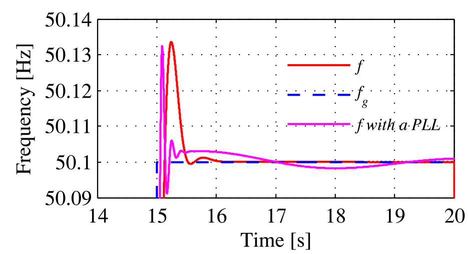

Fig. 9. Comparison of the frequencies of the self-synchronized synchronverter (f) and the original synchronverter with a PLL (f with a PLL).

the long tail of errors will accumulate, which could lead to large tracking error in the frequency.

In order to demonstrate the dynamic performance of the synchronverter, the responses when the grid frequency increased by 0.1 Hz at 15 s and returned to normal at 30 s are shown in Fig. 10. Note that during the former case, the PI controller to generate the reference frequency $\dot{\theta}_r$ was active (S_P was ON) but during the latter case, the PI controller was not active (S_P was OFF). This led to different response speeds. Moreover, the currents did not change much in the formal case because the synchronverter was operated in the set mode but the currents changed significantly in the latter case because the synchronverter was operated in the droop mode. There were no noticeable changes in the voltage amplitude in both cases.

B. Operation Under Grid Faults

In order to demonstrate the performance of the self-synchronized synchronverter under grid faults, two simulations were carried out. One is when the grid had a 50% voltage dip and the other is when the grid had a 1% frequency drop. Each fault happened at 36 s and lasted for 0.1 s, respectively. Everything remained the same as those under the normal operation, apart from that the impedance of the feeder was considered explicitly as 1.35 mH and 0.405 Ω.

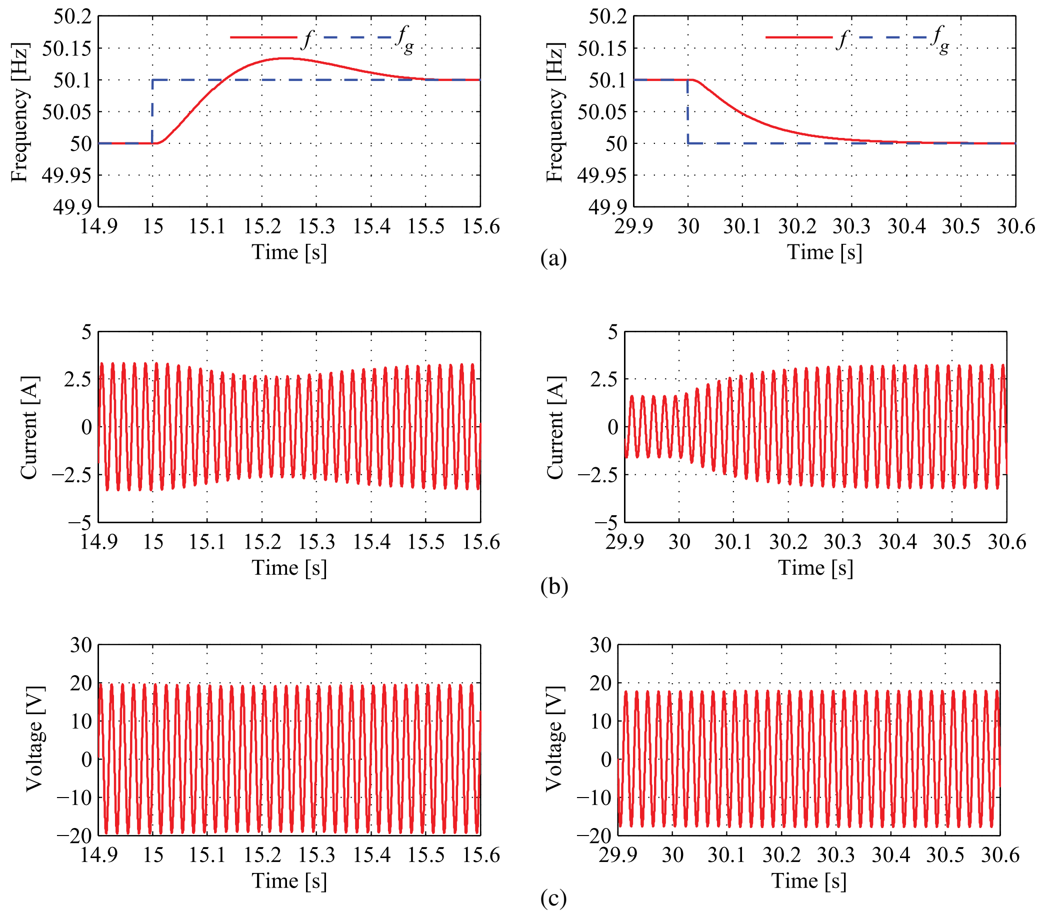

Fig. 10. Dynamic performance: when the grid frequency increased by 0.1 Hz at 15 s and returned to normal at 30 s. (a) Synchronverter frequency f and the grid frequency f_g. (b) Output current of Phase a. (c) Output voltage of Phase a.

The simulation results when the grid frequency dropped by 1% for 0.1 s are shown in the left column of Fig. 11. The synchronverter frequency dropped and then recovered, following the grid frequency. The output current increased and then returned back to normal. It is worth noting that the current was not excessively high. There was no noticeable change in the amplitude of the output voltage.

The simulation results when the grid voltage dropped by 50% for 0.1 s are shown in the right column of Fig. 11. When the grid fault happened, the output current increased immediately and when the fault was removed, the output current decreased immediately and returned to normal. The maximum current is about 3.5 times of the normal current, which is acceptable because power inverters are often designed to cope with excessive over-currents for a short period. The frequency dropped by 0.1 Hz during the fault and then recovered after the fault was removed. The output voltage decreased accordingly but recovered very quickly. Although the frequency took about 0.2 s to return to normal, the voltage and current returned to normal within 0.1 s after the fault was removed.

It is worth emphasizing that, during the two faults described above, the synchronverter demonstrated excellent fault ride-through capability although the PI controller introduced to provide the grid frequency was not active (because the synchronverter was working in the droop mode). This is due to the inherent self-synchronization mechanism of the controller based on the mathematical model of synchronous machines.

V. Experimental Results

The proposed strategy was also tested with an experimental synchronverter. For safety reasons, this was a low-power low-voltage system but it was enough to demonstrate the technology and to compare with the simulation results. The operating concept is not limited to low voltage and power levels and can be easily scaled up for high-power high-voltage applications. The parameters used in the experimental setup are roughly the same as those used in the simulations given in Table II. The synchronverter was connected to a three-phase 400 V 50-Hz grid via a circuit breaker and a step-up transformer. The sampling frequency of the controller was 5 kHz and the switching frequency was 15 kHz.

The experiments were carried out according to the following sequence of actions:

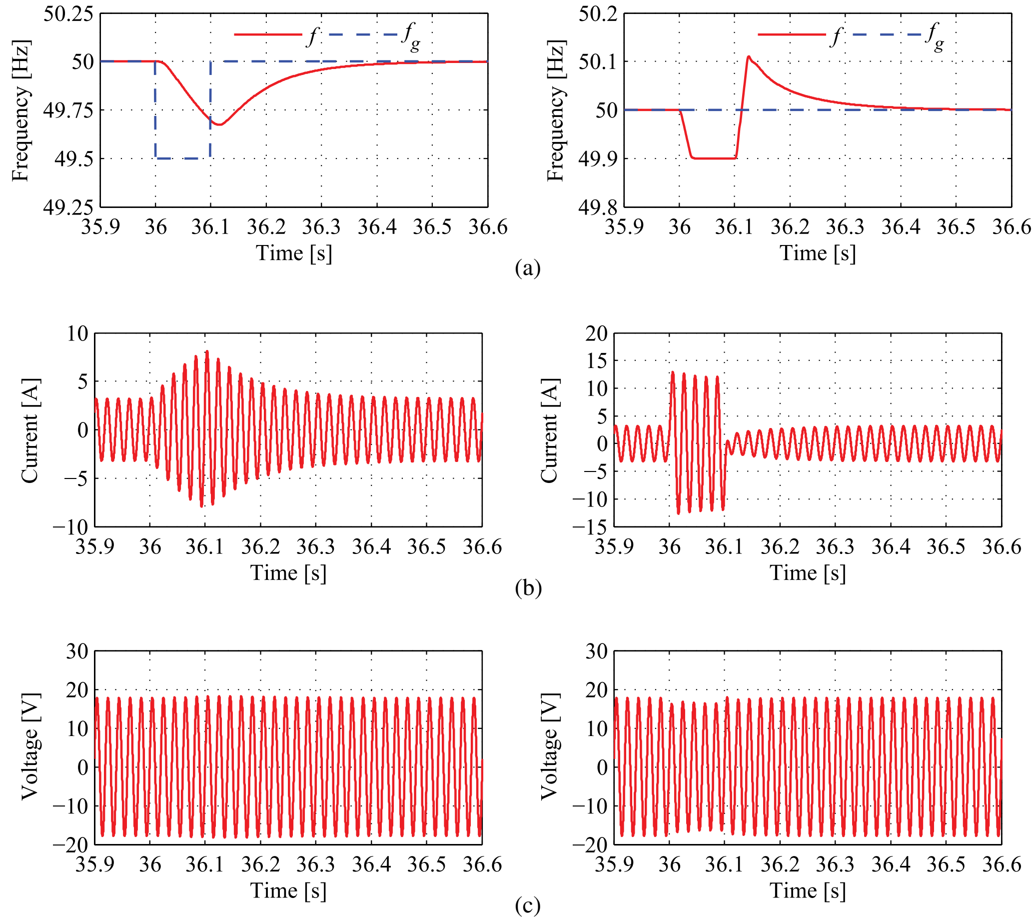

Fig. 11. Simulation results under grid faults: when the grid frequency dropped by 1% (left column) and when the grid voltage dropped by 50% (right column) at 36 s for 0.1 s. (a) Synchronverter frequency f and the grid frequency f_g. (b) Output current of Phase a. (c) Output voltage of Phase a.

1) starting the system with the IGBT switched off in the self-synchronization mode (S_C: 1; S_P: ON; and S_Q: OFF) with $P_{\text{set}} = 0$ and $Q_{\text{set}} = 0$;
2) starting the IGBT, roughly at $t = 5$ s;
3) turning the circuit breaker on and switching S_C to Position 2, roughly at $t = 10$ s;
4) applying $P_{\text{set}} = 60$ W, roughly at $t = 20$ s;
5) applying $Q_{\text{set}} = 20$ Var, roughly at $t = 30$ s;
6) turning S_P OFF to enable the P_D-mode, roughly at $t =$ 40 s;
7) turning S_Q ON to enable the Q_D-mode, roughly at $t =$ 50 s;
8) stopping data acquisition at $t = 60$ s.

In order to demonstrate the frequency tracking performance of the self-synchronized synchronverter, a three-phase PLL block from Simulink/SimPowerSystems was used to obtain the grid frequency f_g for comparison. Note that the PLL was not used for control purposes. Many experiments were done, but only two typical cases are shown here.

A. Case 1: When the Grid Frequency Was Lower Than 50 Hz

The responses of the system when the grid frequency was lower than 50 Hz are shown in the left column of Fig. 12. The self-synchronized synchronverter tracked the grid frequency very well before the connection, with achieved peak–peak ripples of around 0.0053 Hz. However, the grid frequency obtained from the PLL had peak–peak ripples of around 0.035 Hz. If it was adopted to provide the reference for the power controller, the smallest achievable ripples would be larger than 0.035 Hz, which means the self-synchronized synchronverter has significantly improved the performance of frequency tracking, by almost six times. There are transient changes in the frequency shown in Fig. 12(a). This is similar to the change of the speed of a synchronous machine when the operational condition is changed. There were small transient responses at the connection time, but they were quickly settled down after the connection. The responses at all actions were very smooth and the frequency was tracked well, with achieved peak–peak ripples of around 0.011 Hz. The frequency ripples nearly doubled after connection but it was still three times better than that was obtained from the PLL. In the set mode, the real and reactive power followed the reference set-points. Note that the real power shown was the actual power sent to the grid from the synchronverter, which was a little less than the set-point because there was a small loss on the internal resistance of the inductors.[2] When the P_D-mode was enabled at about 42 s, the real power immediately

[2]The real power measured with the voltage e instead of v_g, which showed accurate real power in the experiments, was not recorded due to a mistake in

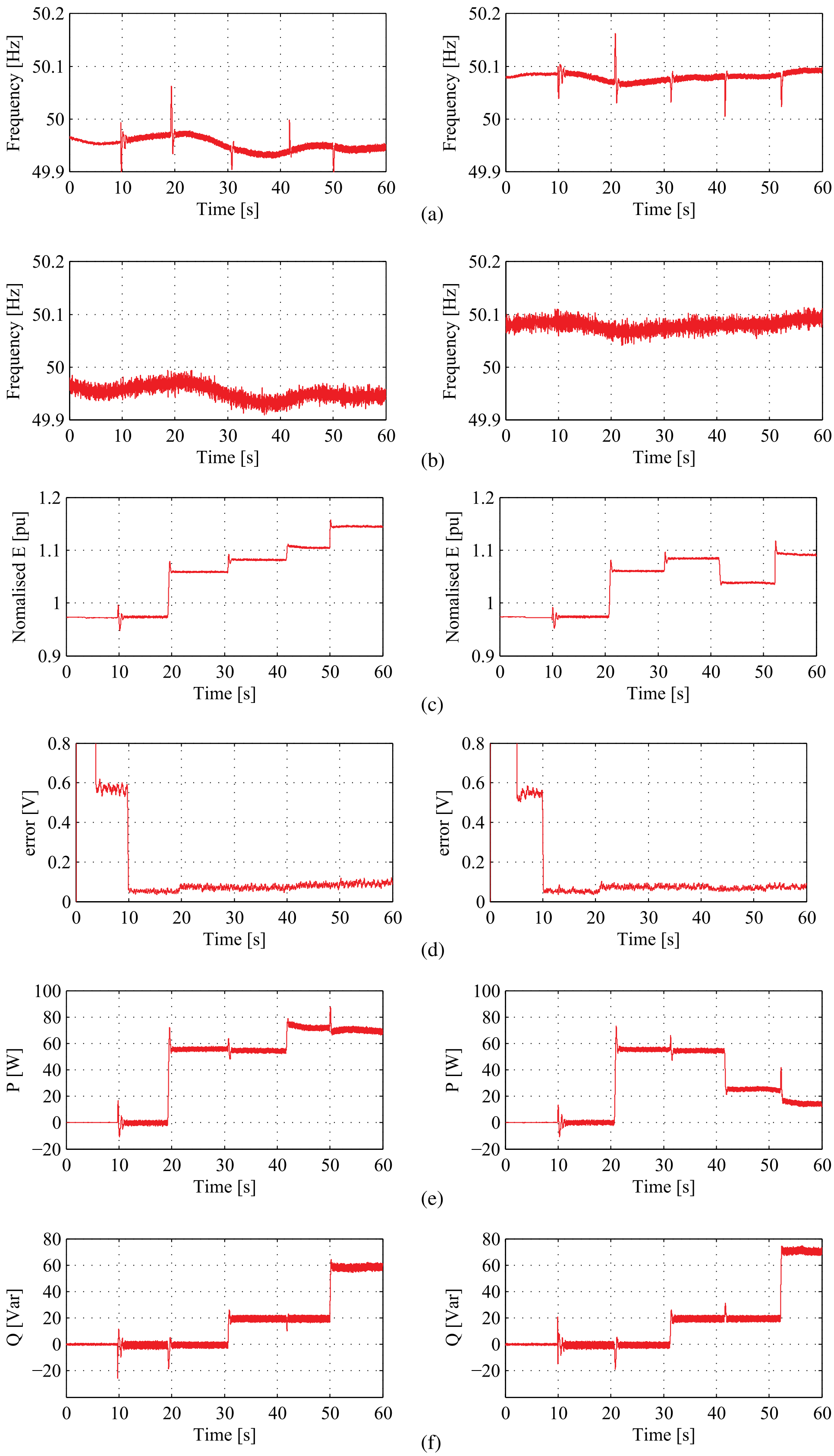

Fig. 12. Experimental results. When the grid frequency was lower than 50 Hz (left column) and higher than 50 Hz (right column). (a) Synchronverter frequency f. (b) Grid frequency f_g from a three-phase PLL for comparison. (c) Amplitude E of the generated voltage e. (d) Amplitude of $v - v_g$. (e) Real power at the terminal. (f) Reactive power at the terminal.

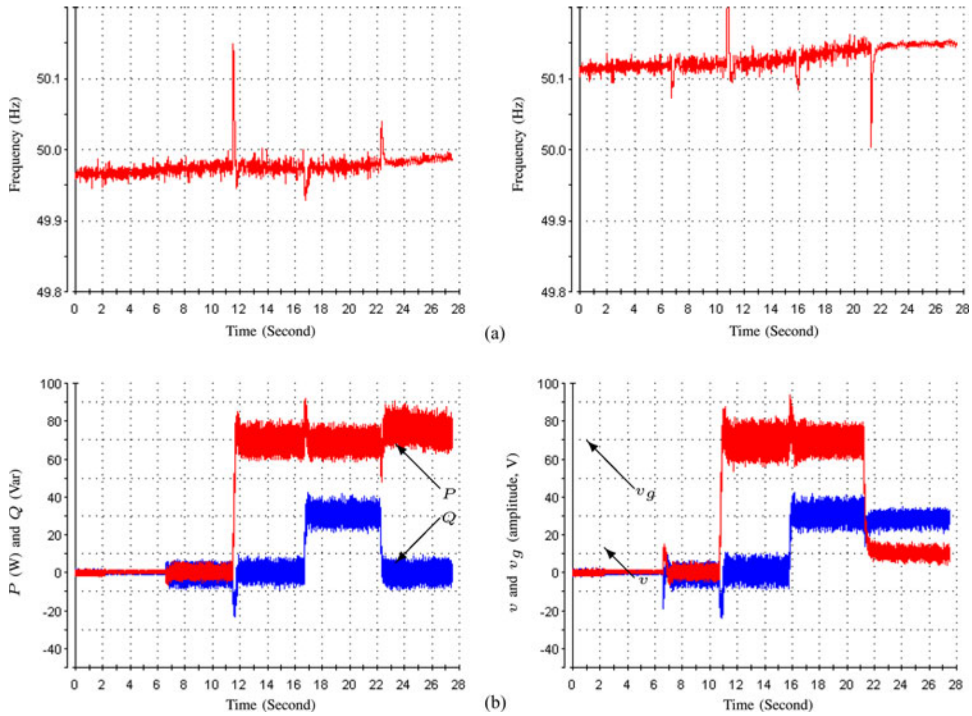

Fig. 13. Experimental results of the original synchronverter presented in [28] for comparison: when the grid frequency was lower than 50 Hz (left column) and higher than 50 Hz (right column). (a) Synchronverter frequency. (b) P and Q.

increased to the new steady state, which also changed with the grid frequency as expected.

During the experiment, the grid voltage V_g was about 98% of the nominal voltage V_n as tracked by E before $t = 20$ s. The set-point of Q was chosen to be as small as 20 Var so that in the Q_D-mode the synchronverter would not generate excessive reactive power that could cause over-currents. The response of the reactive power generated was stable and smooth. When the Q_D mode was enabled at about $t \approx 50$ s, the reactive power increased by about 40 Var, as expected because of the low V_g.

Some experimental results from the original synchronverter equipped with a PLL presented in [28] when the grid frequency was lower than 50 Hz are shown in the left column of Fig. 13 for comparison. Although the experiments were done slightly differently, it can be seen that the original synchronverter equipped with a PLL had caused frequency ripples of around 0.037 Hz, which means the performance of frequency tracking has been improved by 70% after removing the PLL. This leads to much smaller ripples in the real power and reactive power, from around 21.3 W and 19.6 Var obtained from the original synchronverter with a PLL to around 3.7 W and 6.1 Var obtained from the self-synchronized synchronverter, in addition to the considerably simplified controller. The performance of real power control and reactive power control has been improved by 83% and 69%, respectively, which is very significant.

The Phase-b voltages and their difference around the connection time are shown in the left column of Fig. 14. The voltage v_b was synchronized with the grid voltage v_{gb} with a small error before the connection.

B. Case 2: When the Grid Frequency Was Higher Than 50 Hz

The results when the grid frequency was higher than 50 Hz are shown in the right column of Fig. 12. There was not much difference in the responses before the droop modes were enabled, compared to the previous case. The frequency was tracked well and the set-points for the real power and reactive power were followed with smooth transition and small overshoots. When the P_D-mode was enabled, the generated active power reduced quickly to a new steady state, which also changed with the frequency. This was expected because the grid frequency f_g was higher than 50 Hz. The grid voltage level V_g in this case was slightly smaller than that in the previous case and was about $97.5\% V_n$. Therefore, when the Q_D-mode was enabled at about 50 s, the reactive power generated increased by about 50 Var.

Some experimental results from the original synchronverter equipped with a PLL presented in [28] when the grid frequency was higher than 50 Hz are shown in the right column of Fig. 13 for comparison. Again, although the experiments were done slightly differently, it can be seen that the proposed self-synchronized synchronverter offers much better performance of frequency tracking, which leads to much smaller ripples in the real power and reactive power, in addition to the considerably simplified controller. The proposed self-synchronized synchronverter achieved frequency ripples of around 0.012 Hz but the original synchronverter equipped with a PLL had caused frequency ripples of around 0.035 Hz, which means the performance of frequency tracking has been improved by 66%. This

the experiment and the experimental setup is no longer available for doing the experiments again because of a recent job move.

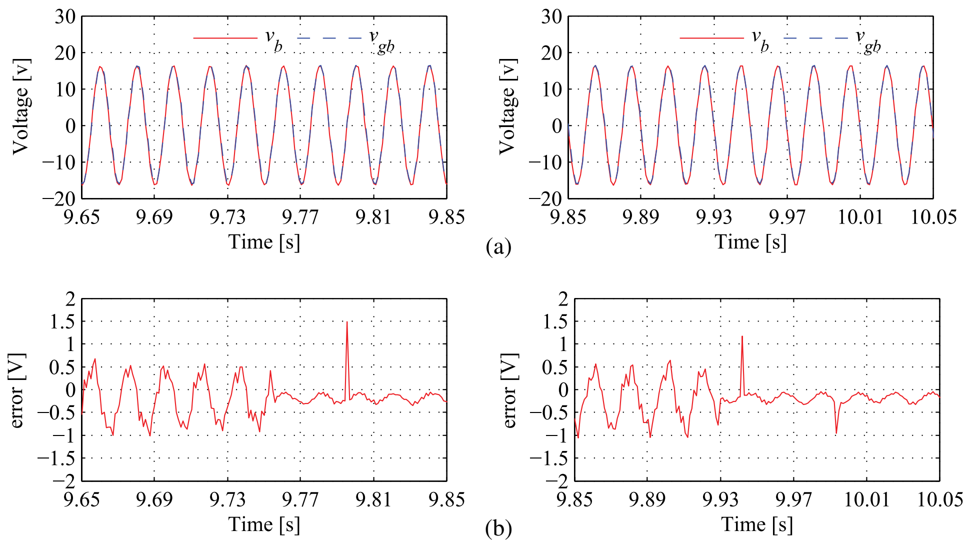

Fig. 14. Voltage difference around the connection time: when the grid frequency was lower than 50 Hz (left column) and higher than 50 Hz (right column). (a) v_b and v_{gb}. (b) $v_b - v_{gb}$.

TABLE III
IMPACT ON THE COMPLEXITY OF THE OVERALL CONTROLLER AND THE DEMAND FOR THE COMPUTATIONAL CAPABILITY

	Code size (Bytes)	Average TET (μs)
Power part only	44112	1.64
With the original synchronverter	60753	4.66
With the self-synchronised synchronverter	48920	4.08
Net value of the original controller	16641	3.02
Net value of the self-synchronised controller	4808	2.44
Improvement	71.1%	19.2%

leads to much smaller ripples in the real power and reactive power, from around 24.6 W and 18.5 Var obtained from the original synchronverter with a PLL to around 3.9 W and 5.3 Var obtained from the self-synchronized synchronverter. The performance of real power control and reactive power control has been improved by 84% and 71%, respectively, which is again very significant.

The Phase-b voltages and their difference around the connection time are shown in the right column of Fig. 14. Again, the voltage v_b was synchronized with the grid voltage v_{gb} with a small error before the connection.

VI. Impact of Removing the Synchronization Unit

Both simulations and experiments have demonstrated that it is possible to operate a grid-connected inverter without a dedicated synchronization unit. The synchronization function can be embedded into the controller itself. It has been shown by the experimental results that the performance of frequency tracking can be improved by more than 65%, the performance of real power control by 83%, and the performance of reactive power control by about 70%.

In order to demonstrate the impact of removing the synchronization unit on the complexity of the overall controller and the demand for the computational capability of the microcontroller adopted to implement the controller, the original synchronverter and the proposed self-synchronized synchronverter, together with a three-phase inverter, a three-phase LCL filter connected to the grid (i.e., the power part shown in Fig. 3), are built in MATLAB 7.9/Simulink/SimPowerSystems and implemented with a xPC target[3] running on a Intel Core i7 3.2GHz CPU with 4GB DDR3 RAM. The code sizes and the average TET (target execution time) are shown in Table III. The code size is reduced by 71.1% and the average target execution time is shortened by 19.2%. It is not a surprise that the code size has been reduced significantly because a three-phase PLL is a very complex system, including a $abc/dq0$ transformation, an automatic gain control block for each phase, a variable-frequency mean value block, a second-order filter, and other simple blocks. There are in total 11 integrators, seven variable delay blocks, and two trigonometric function blocks. It is more complicated than the synchronverter itself. Hence, removing the dedicated synchronization unit also reduces the development cost and improves the software reliability.

[3]The details of the xPC target are xPC version 4.2 (R2009b); compiler Open Watcom 1.7; fix-step 20-kHz sampling time; solver ode3.

VII. Conclusion and Discussions

A self-synchronized synchronverter has been proposed, implemented, and tested so that there is no need to incorporate a dedicated synchronization unit for synchronization purposes. This leads to much improved performance, simplified controller, reduced demand for computational power, reduced development cost and effort, and improved software reliability. It is able to synchronize itself with the grid before connection and to track the grid frequency automatically after connection. Moreover, it is able to operate in different modes as the original synchronverter but without the need of a dedicated synchronization unit to provide the grid frequency as the reference frequency. Both simulation and experimental results are presented to validate the strategy. Experimental results have shown that the proposed control strategy can improve the performance of frequency tracking by more than 65%, the performance of real power control by 83%, and the performance of reactive power control by about 70%.

The focus of the paper is to demonstrate the feasibility of removing the synchronization unit that has been believed to be a must-have component for grid-connected inverters, based on the synchronverter concept developed recently. Whether it can be extended to other types of controllers for grid-connected inverters is an interesting question. In principle, if a controller has the capability of synchronization, then it should be possible to find a way to remove the synchronization unit. For example, the power-synchronization controller proposed in [6] has the capability of synchronization during normal operation, so it should be able to remove the backup PLL as well. Some other aspects of this strategy, e.g., the operation under unbalanced and distorted grid voltages, should be further investigated as well. Some of these issues can be tackled by adopting existing strategies, e.g., those described in [1].

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