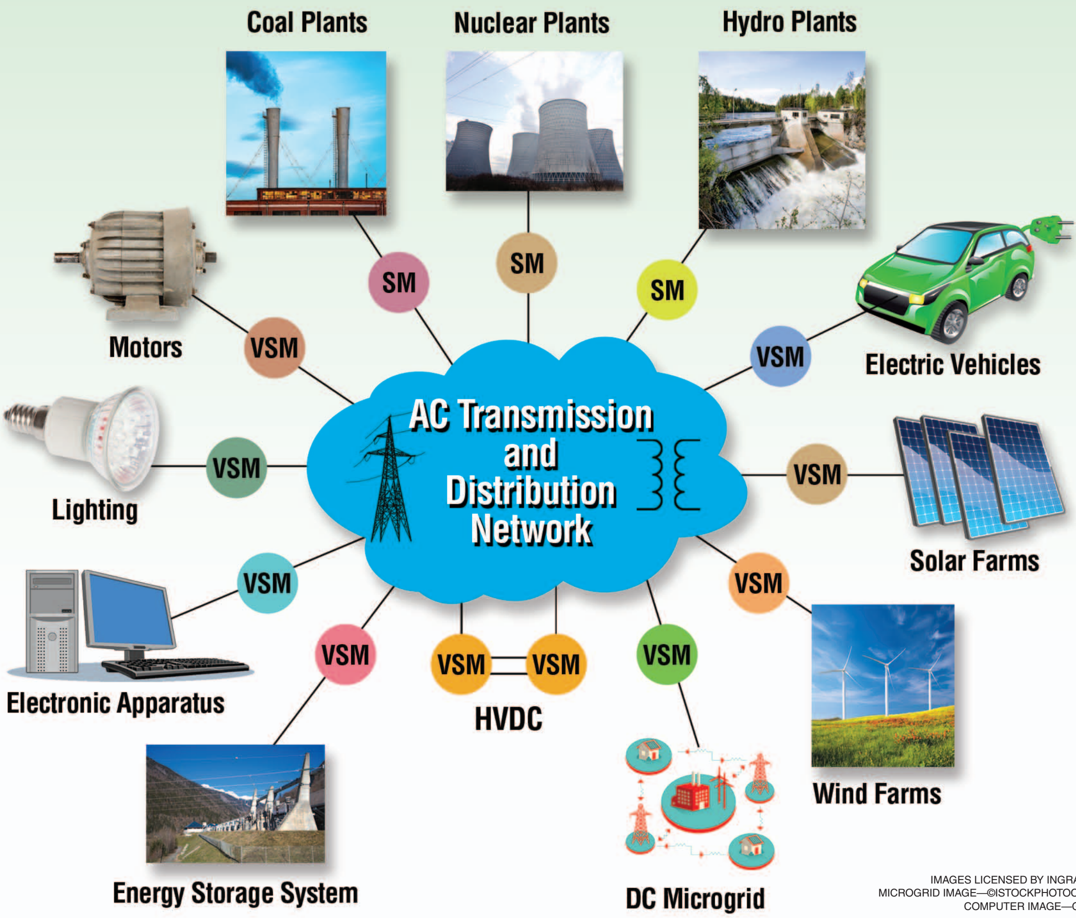
Virtual Synchronous Machines

A unified interface for smart grid integration



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Power systems are going through a paradigm change from centralized generation to distributed generation and further on to smart grids. More and more renewable-energy sources, electric vehicles, energy storage systems, and so forth are being connected to power systems through power electronic converters. Moreover, the majority of loads are expected to connect to the grid through power electronic converters as well. This article shows that these converters, either on the supply side or on the load side, can all be controlled to behave like virtual synchronous machines (VSMs) and possess the dynamics of synchronous machines, providing a unified interface for smart grid integration. Synchroconverter technology and its developments are the focus of this article because the mathematical model of synchronous machines is embedded in the controller of synchronverters to provide close imitation.

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Smart Grid Integration

To deal with an energy crisis and environmental problems, such things as renewable-energy sources, electric vehicles, and energy storage systems are being connected to power systems. The capacity of installed distributed generators (DGs) in power systems is growing rapidly, and a high penetration level is expected in two to three decades. For example, China has set a 15% target for the share of renewable-energy sources by 2020 and over 30% by 2050. The European Union, the United States, and India also have ambitious targets for using DGs and renewable-energy sources.

Most renewable-energy sources are connected to the grid through inverters because the electricity generated by these sources is not compatible with the grid, either with variable amplitude/frequency or in dc. The common control method of wind- or solar-power generators is to maximize the output power generation and then inject all of it to the power grid as current sources. This does not cause a severe power system stability problem when it constitutes a small portion of the grid capacity, because conventional generators can handle system stability. However, as more and more renewable-energy sources are connected to the grid, conventional generators alone can no longer maintain system stability. Moreover, in comparison to conventional power plants, where synchronous machines are adopted, inverter-based DGs have no rotating inertia (rotor) or damping (mechanical friction and damper windings). DGs cannot provide enough inertia and damping to power systems, which makes power systems vulnerable to power dynamics and system faults [1]. Power system stability will be further degraded as the penetration of renewable-energy sources increases, so it is important to address this problem from the beginning when the penetration level of DGs is low.

To solve the problem, researchers worldwide have been seeking different ways to control power electronic converters in power systems to enhance system stability. One very important way is to embed the dynamics and behavior of conventional synchronous machines into power electronic converters as VSMs. Physically they are power electronic converters, but mathematically they are synchronous machines. The VISMA concept [2], one implementation of the VSM, controls the inverter current to follow the current reference generated according to a traditional synchronous machine. In this way, the DGs will mimic the behavior of traditional synchronous machines and provide virtual inertia and damping to the grid. The synchronverter concept [3], another implementation of the VSM, controls the inverter to generate an output voltage via embedding the mathematical model of conventional synchronous generators into the controller of the inverter. A synchronverter has all the major properties of a synchronous machine and can behave in the same way as traditional synchronous generators. The virtual inertia, friction coefficient, field inductance, and mutual inductance of a synchronverter can be flexibly set to design the parameters of a synchronverter according to the grid connected. It is worth noting that VISMAs act like current sources, while synchronverters act like voltage sources. Power systems are dominated by voltage sources, so current sources are inherently not compatible with power systems. Although today's power systems can tolerate some current sources, a large number of current sources could potentially impose serious challenges on power systems operation. Hence, this article focuses on synchronverters to implement VSMs as voltage sources.

It is well known that demand response will play an important role in regulating system frequency and voltage. Interestingly, the majority of future loads will connect to the grid through power electronic converters, that is, rectifiers, as well. For example, the widely used motors will be equipped with motor drives, which have rectifiers at the front end; Internet devices will have rectifiers to convert ac into dc; and light-emitting diode (LED) lights will also have rectifiers to convert ac into dc. The synchronverters can be easily applied to operate rectifiers as virtual synchronous motors, simply by changing the mathematical model embedded in the controller from that of synchronous generators to that of synchronous motors. This makes synchronverters a unified interface for smart grid integration.

Similar to other grid-connected converters, the (original) synchronverters also need a dedicated synchronization unit to provide the phase and frequency of the grid voltage, so that synchronverters can be connected to the grid smoothly. Currently, a phase-locked loop (PLL) is the most commonly used synchronization method [4]. However, PLLs are inherently nonlinear, and it is very difficult to tune the parameters. What is worse is that multiple PLLs in a system often compete with each other and cause many problems, for example, reduced performance, increased complexity, and even instability. PLLs are rarely used in current power systems because synchronous machines have the inherent synchronization mechanism and there is no need to rely on external synchronization units to achieve synchronization. The synchronverter is then further improved by removing the dedicated synchronization unit, leading to a self-synchronized synchronverter [5]. A self-synchronized synchronverter can synchronize itself with the power grid automatically before it is connected to the grid, without the need of a dedicated synchronization unit. After it is connected to the grid, it is able to keep synchronized with the grid like a synchronous machine. It is worth noting that the synchronization function is still kept but implemented by the controller itself because of the embedded synchronization mechanism. Similar to synchronverters, self-synchronized synchronverters can also be operated as inverters or rectifiers. The self-synchronization mechanism makes converters fully behave like conventional synchronous machines, which improves the performance, reduces the complexity and computational burden of the controller, and improves stability.

Operation of Inverters as a VSM

As mentioned previously, a synchronverter [3] is an inverter that mimics a conventional synchronous generator. It acts as an interface for smart grid integration. As a result, distributed generation can easily take part in the regulation of system frequency and voltage and provide inertia and damping to the grid, as conventional synchronous generators do.

A synchronverter consists of a power part, which is the same as a conventional power electronic converter depicted in Figure 1(a), and an electronic part, which consists of the sensoring, protection, and control circuits. The controller of a three-phase synchronverter, as shown in Figure 1(b), includes the mathematical model (in red) of a three-phase round-rotor synchronous machine as the core. The back electromotive force e calculated according to the mathematical model is passed through a pulsewidth modulation (PWM) generation block to generate PWM pulses to drive the power semiconductors in Figure 1(a). The currents flowing out of the inductors of the power stage are treated as the stator current i and fed back to the mathematical model. These two-way interactions link the power stage and the controller together.

In current power systems, the frequency is regulated via controlling the real power, and the voltage is regulated via controlling the reactive power, which is often

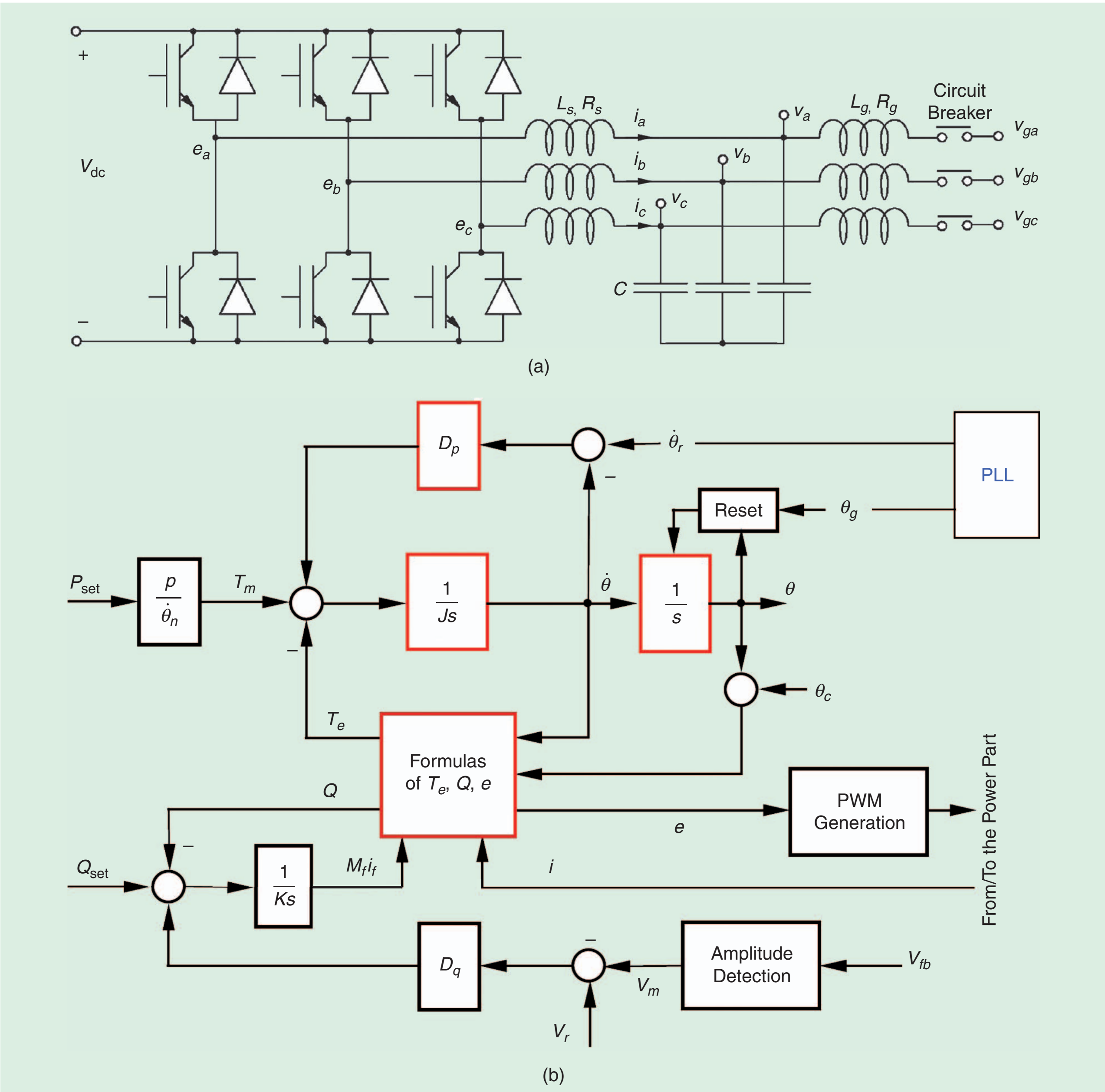

FIG 1 The components of a synchronverter [3]: (a) the power stage and (b) controller.

achieved through frequency droop control and voltage droop control. As shown in Figure 1(b), these matured technologies developed for synchronous machines can be easily adopted to regulate the voltage and the frequency. The mechanical friction coefficient D_p plays the role of the frequency droop coefficient, so there is no need to introduce an additional control loop for frequency droop control. This loop can regulate the frequency/speed $\dot{\theta}$ of the synchronverter and generate the phase angle θ for the back electromotive force e. The reactive power is regulated to generate the field excitation current $M_f i_f$, and a voltage droop control is introduced to control the voltage through the voltage droop coefficient D_q. Hence, the frequency control, voltage control, real power control, and reactive power control are all integrated in one compact controller with only four parameters. It is worth noting that, for grid-connected applications, a dedicated synchronization unit (PLL) is used 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 (i.e., in the set mode) after connection.

The frequency regulation capability of a synchronverter connected to the 50-Hz U.K. public grid is depicted in Figure 2. It can be seen that the synchronverter responded to the varying frequency (in red) very quickly via autonomously changing the real power output. When the frequency increases, the real power is decreased; when the frequency decreases, the real power is increased. Similarly, a synchronverter is able to regulate the voltage autonomously. Note that this controller is so compact and is close to, if not already, the minimal realization of any possible controllers for a grid-tied inverter.

Operation of Rectifiers as a VSM

Various strategies have been proposed to control PWM rectifiers. These strategies can achieve the same major goals, such as high power factor and near-sinusoidal current waveforms [6], [7]. Similar to operating an inverter as a synchronous generator, the mathematical model of synchronous motors can be adopted as the core of the controller for rectifiers, as shown in Figure 3, to operate rectifiers as virtual synchronous motors [8].

The reactive power Q can be controlled to track the reference Q_{ref} through an integrator and generate the field excitation $M_f i_f$ so the power factor can be controlled via setting the reactive power reference. To obtain the unity power factor, the reference value Q_{ref} can be set to zero. Compared to the controller

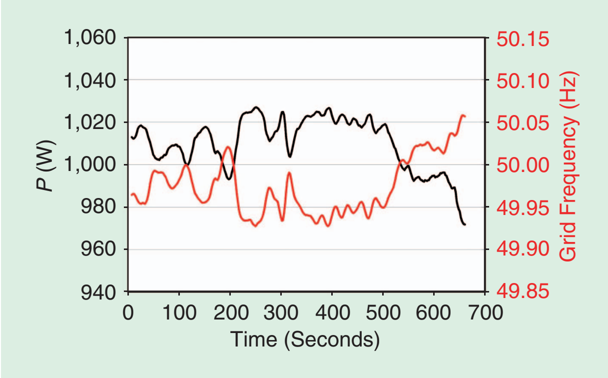

FIG 2 The frequency regulation capability of a synchronverter connected to the U.K. public grid.

for a synchronverter in the "Operation of Inverters as a VSM" section, another loop is added to control the dc-bus voltage through a proportional-integral (PI) controller to generate the virtual torque T_m. Again, a dedicated synchronization unit, which in this case is a sinusoidal tracking algorithm, is adopted for synchronization with the grid.

Figure 4 depicts the simulation results when regulating the dc-bus voltage of a rectifier. The reactive power was set to zero to obtain the unity power factor. The dc-bus voltage was regulated to the reference values, even when the load was changed. The VSM frequency tracked the grid frequency well.

Some Applications

Integration of Wind Power

A common topology for wind-power integration is shown in Figure 5. The wind-power generation system is connected to the grid through a back-to-back converter. Normally, the maximum power extraction from the wind is achieved by controlling the rotor-side converter, and the dc link voltage is controlled by the grid-side converter [9]–[11],

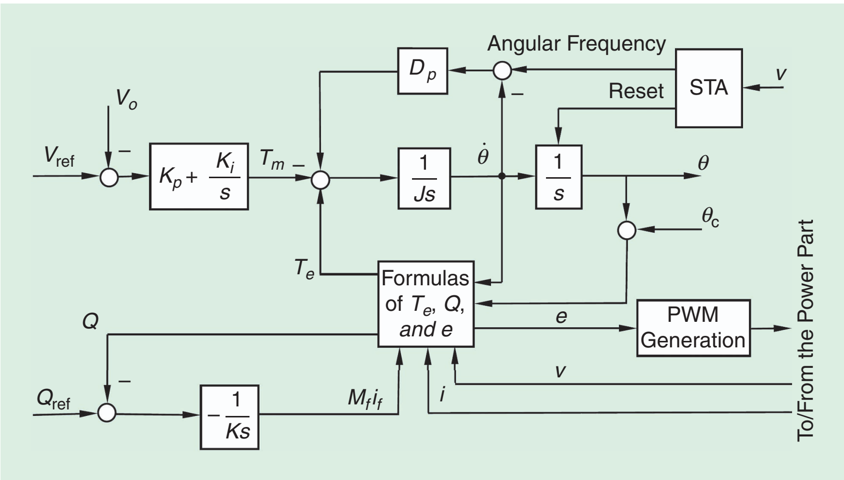

FIG 3 A controller to operate a rectifier as a virtual synchronous motor [8].

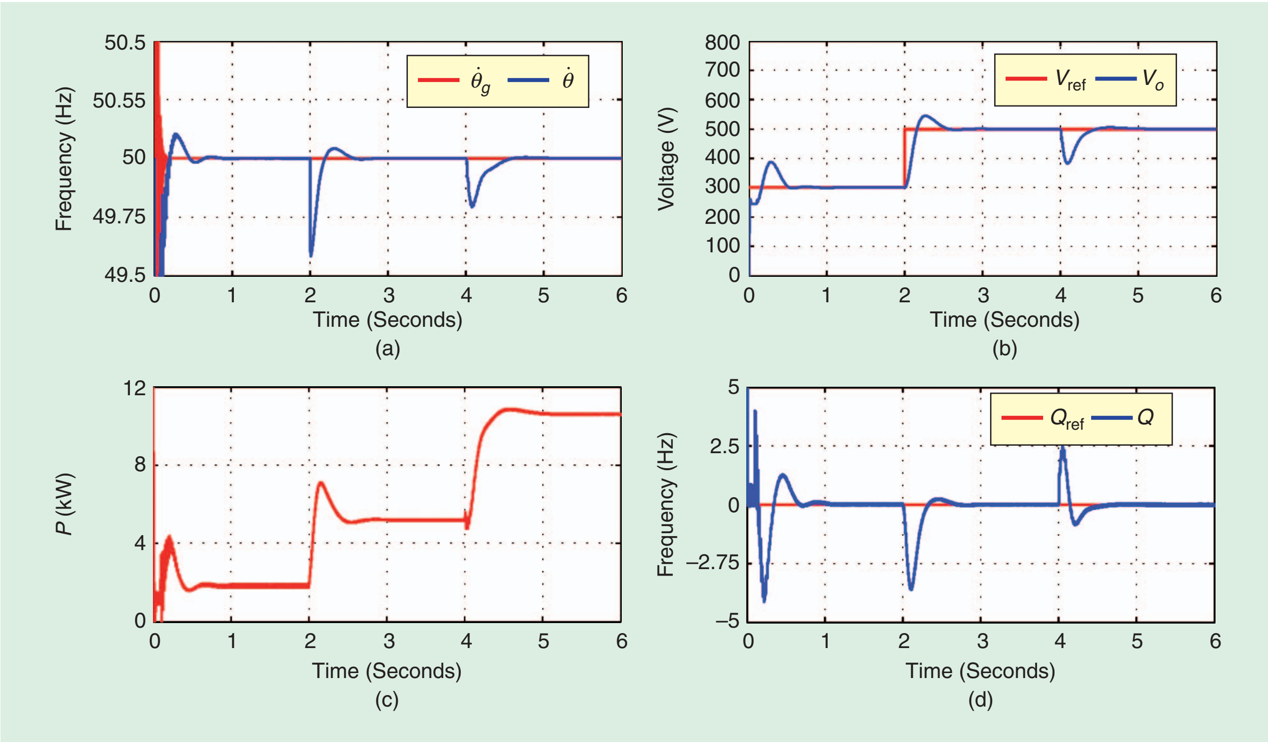

FIG 4 **The simulation results of a rectifier operated as a VSM [8]. (a) Frequency. (b) V_{ref} and V_o (V). (c) P (W). (d) Q (Var).**

mainly based on the vector control approach in the d-q reference frame. However, vector control techniques are very sensitive to parameter variations and mismatches because of the decoupling terms used for achieving the desired field orientation. The VSM technologies described in the "Operation of Inverters as a VSM" and "Operation of Rectifiers as a VSM" sections can be adopted to integrate wind energy, because the back-to-back converter consists of a rectifier and an inverter [12].

The rotor-side converter can be operated as a virtual synchronous motor, as shown in Figure 6, because it receives power from the permanent magnet synchronous generator (PMSG) at the ac side and injects it to the dc link. The main tasks of the rotor-side converter are to regulate the dc link voltage to the desired level and to achieve unity power factor operation at the ac side. In contrast to the existing vector control techniques, the synchronverter technology is completely independent from the parameters of the PMSG, providing significant advantages.

The grid-side converter can be operated as a virtual synchronous generator to inject real and reactive power to the grid, as shown in Figure 7. The main tasks of the grid-side converter are to achieve maximum power point tracking (MPPT), that is, maximum power extraction from the wind, and also to regulate the reactive power. As a result, the whole system behaves as a rotor–generator/motor–generator system, which leads to a compact and effective system with the potential of utilizing the inertia of the wind turbine.

Figure 8 shows the real-time simulation results of the rotor-side performance of such a system. Note that the dc-bus voltage is always maintained around the desired value, even when the wind speed changed at 6 seconds.

Integration of Solar Power

A VSM control strategy can also be applied to the integration of solar power. In [13], a synchronverter-based single-phase transformerless photovoltaic (PV) inverter is proposed. The topology of the inverter is shown in Figure 9. The PV inverter can be formed by adding a neutral leg into the conventional half-bridge inverter. The added neutral leg consists of two switches and one inductor. The two switches are connected in series and then put between the positive and negative poles of the dc bus. The neutral inductor is put between the midpoint of the switches

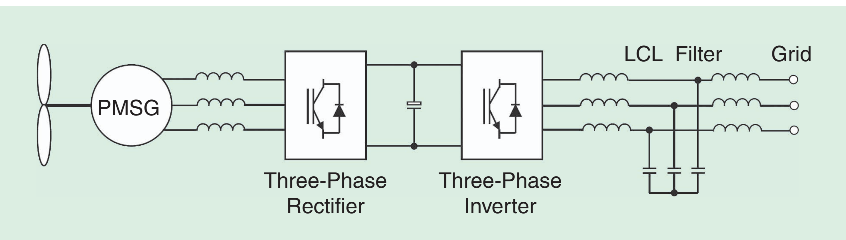

FIG 5 **The connection of a wind-power generation system to the grid through a back-to-back converter.**

and the midpoint of the split capacitors. The main objectives of the neutral leg are to balance the voltages of the capacitors and to provide a return path for the dc input current. At the same time, the inverter leg is used to generate an ac output voltage with high power quality and to control the reactive and active power exchange between the PV and the grid.

To make the PV inverter grid friendly, the inverter leg is controlled to be a synchronverter. There are two operating modes for the operation of the single-phase synchronverter (SPSV): the islanded mode and the grid-connected mode. In the islanded mode, the SPSV generates the nominal voltage at the nominal frequency. The real power and reactive power generated depend on the local load connected (when radiation is high enough). In the grid-connected mode, the SPSV could be controlled to generate the required amount of both real and reactive power to take part in the grid frequency and voltage regulation or to generate the power set by the reference values.

Figure 10 shows the real-time simulation results of such a system, where the grid frequency increased to 50.02 Hz at $t = 4$ seconds and the grid voltage decreased by 2% at $t = 5$ seconds. The real power and reactive power automatically changed according to the change of the frequency and the voltage. Note that the MPPT was not included in the simulation for brevity.

Removal of PLLs

As discussed in the "Smart Grid Integration" section, it is crucial for DGs to synchronize with the grid before connection and after connection. This is often achieved by adding a dedicated synchronization unit, for example, PLLs, to the controller. However, PLLs suffer from nonlinear structure, time-consuming tuning, and slow performance, all of which bring many problems to grid-connected inverters, for example, instability [14]. Because of the inherent synchronization mechanism of synchronous machines

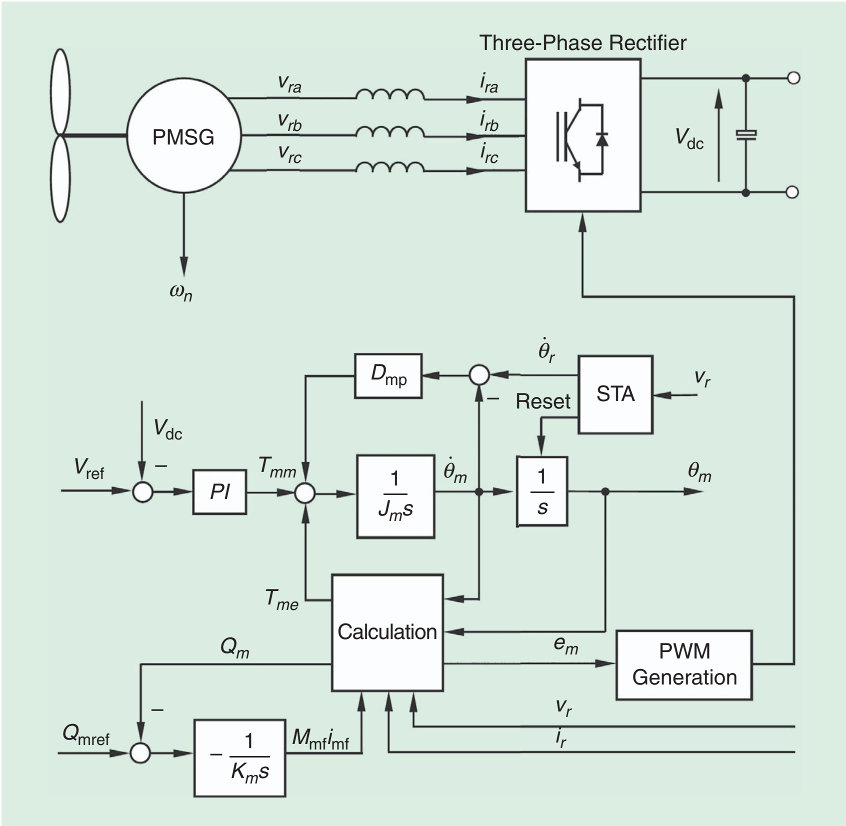

FIG 6 A controller for the rotor-side converter in Figure 5 [12].

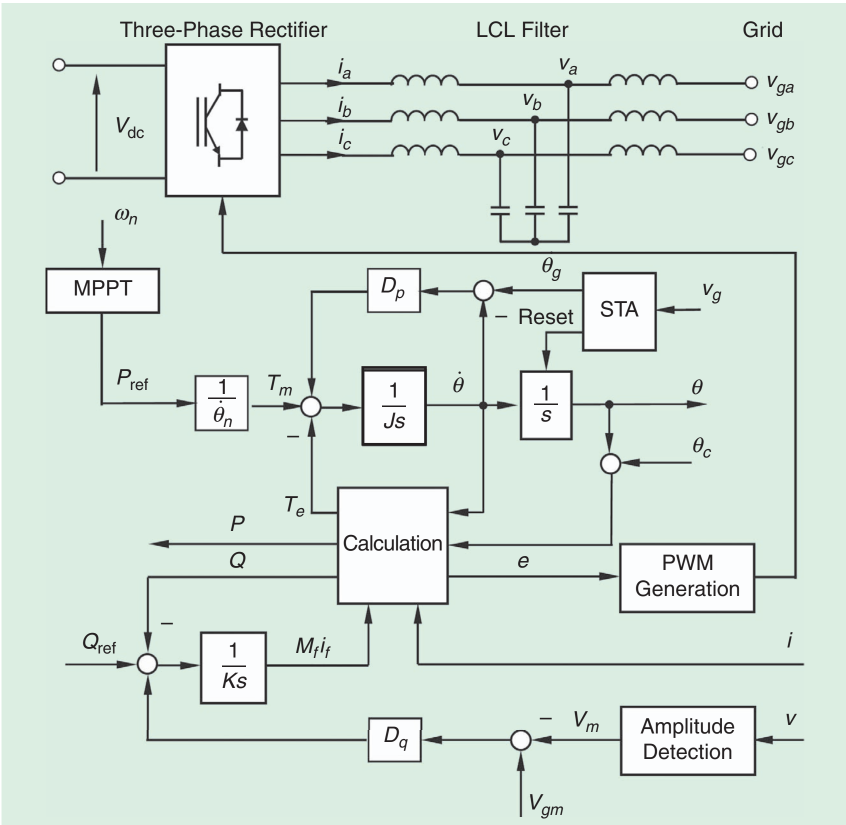

FIG 7 A controller for the grid-side converter in Figure 5 [12].

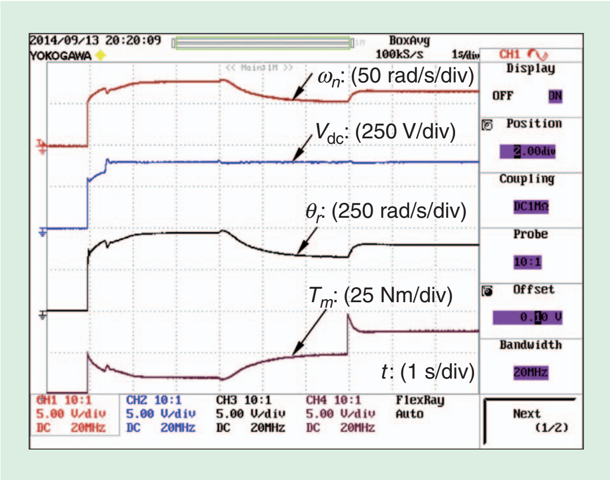

FIG 8 The rotor-side performance of a wind-power system [12].

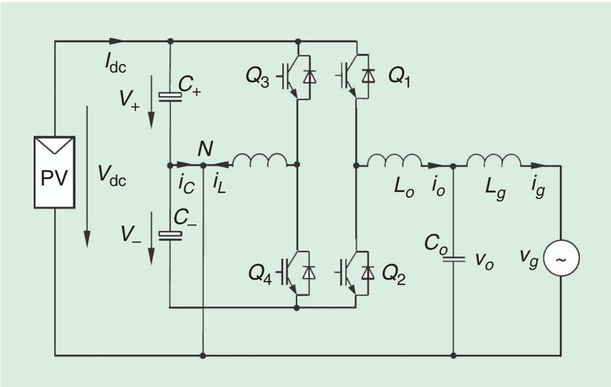

FIG 9 The topology of a synchronverter-based transformerless PV inverter [13].

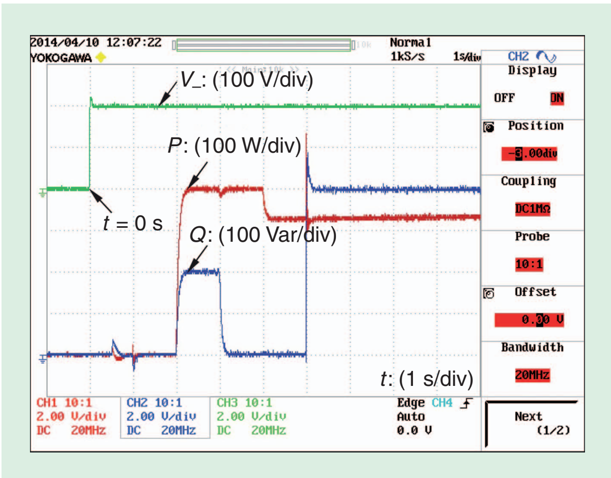

FIG 10 The simulation results of a synchronverter-based transformerless PV inverter [13].

embedded into synchronverters, it is possible to remove the dedicated synchronization unit while achieving synchronization before and after connection to the grid to improve performance and reduce computational burden.

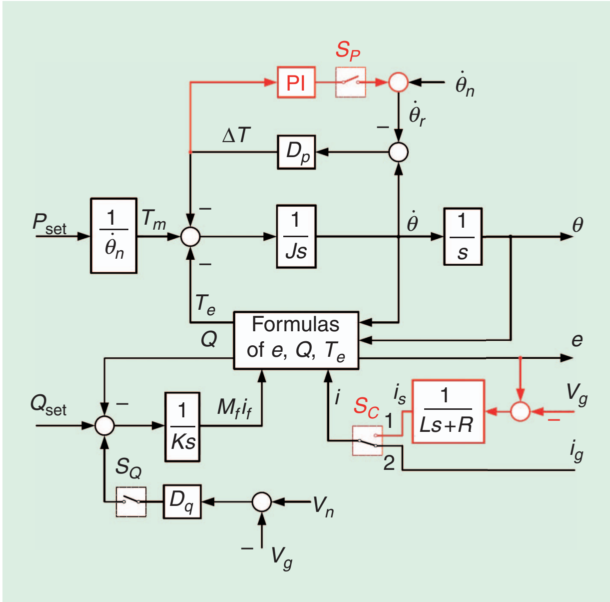

FIG 11 The controller for a self-synchronized synchronverter [5].

Inverters Without a Dedicated Synchronization Unit

The controller for a self-synchronized synchronverter [5] is shown in Figure 11. A virtual current i_s generated from the voltage difference between e and v_g is added to the synchronverter controller shown in Figure 1(b), and the current fed into the controller can be either i_s or the grid current i_g. 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. Moreover, the PLL is removed. 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 to send the reference real power and reactive power to the grid [3]. If P_{set} and Q_{set} are both 0, the synchronverter is operated in the self-synchronization mode. When the virtual current i_s is driven to zero, which means e is equal to v_g, the synchronverter is synchronized with the grid and can be connected to the grid by turning ON the circuit breaker in the power part. When switch S_C is at position 2, the synchronverter can be operated in different modes.

After being connected to the grid, 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, which results in $P = P_{\text{set}}$. This operation mode is called the *set mode*. To differentiate the set mode for real power and reactive power, the set mode for real power is denoted the P mode and the set mode for reactive power is denoted the Q mode. 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, denoted the P_D mode. Similarly, the voltage droop mode is denoted the Q_D mode. All the possible operation modes are shown in Table 1.

Figure 12 depicts the experimental results of a self-synchronized synchronverter with the grid frequency lower than 50 Hz. It can be seen that the synchronverter frequency is much smoother than the grid frequency obtained by a PLL, which means the performance is much worse if a PLL is adopted to provide the frequency reference.

Table 1. The 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-synchronization
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

Rectifiers Without a Dedicated Synchronization Unit

Like synchronverters, a self-synchronized synchronverter can also be operated as a rectifier [15]. The controller for three-phase PWM-controlled rectifiers is shown in Figure 13. Compared to Figure 3, similarly, three major changes are made: 1) a virtual current i_s generated from the error between the grid voltage v and the control signal e is introduced, and the current fed into the controller can be either the virtual current i_s or the grid current i; 2) the synchronization unit to provide the grid frequency reference and the reset signal is removed from the controller; and 3) a PI controller is added to generate the reference frequency/speed $\dot{\theta}_r$ for the virtual synchronous motor while driving the error between the reference speed $\dot{\theta}_r$ and the virtual speed $\dot{\theta}$ to zero.

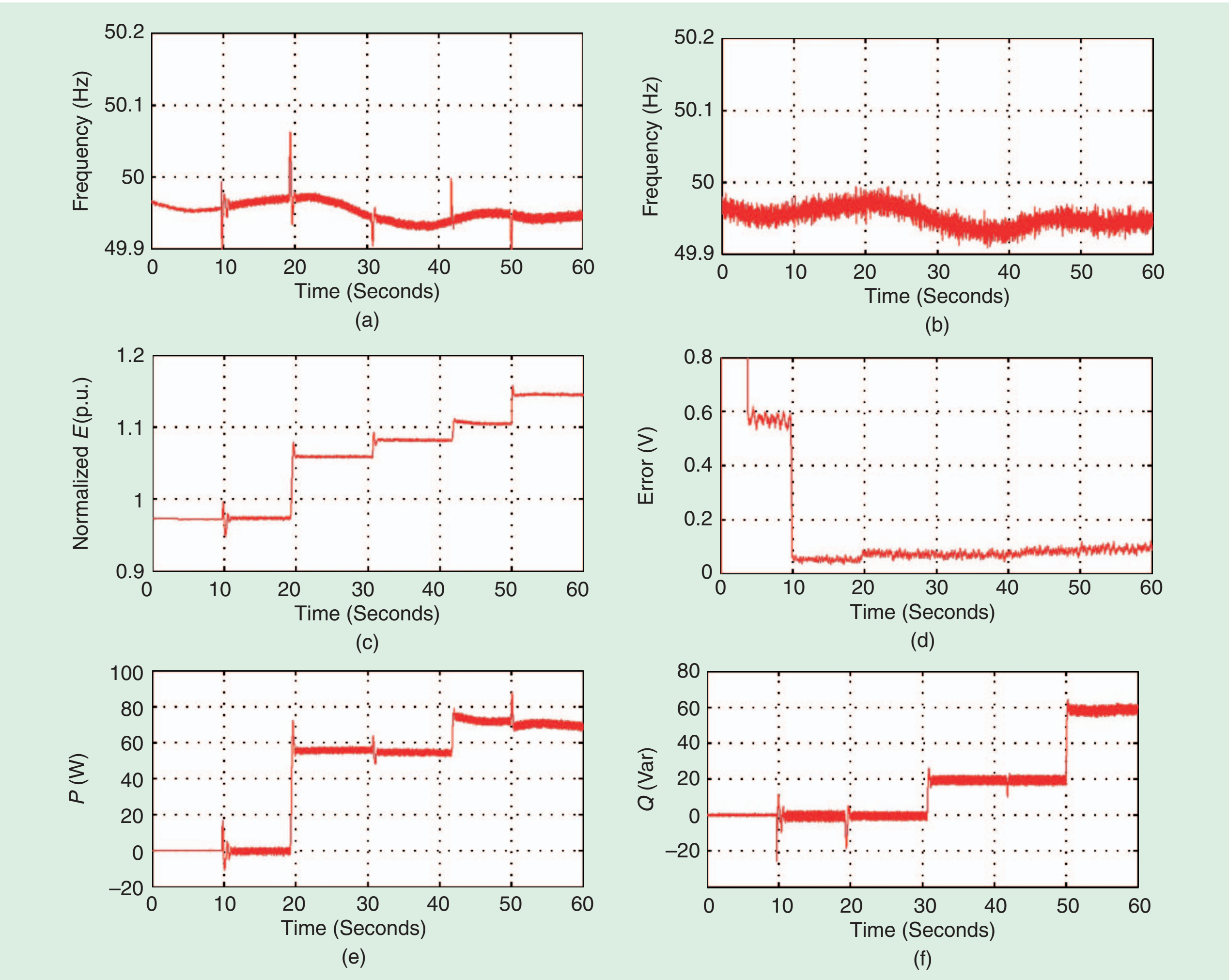

FIG 12 The experimental results of a self-synchronized synchronverter [5]. (a) The synchronverter frequency f. (b) The grid frequency f_g from a three-phase PLL for comparison (not used for control). (c) The amplitude E of the generated voltage e. (d) The amplitude of $v-v_g$. (e) The real power at the terminal. (f) The reactive power at the terminal.

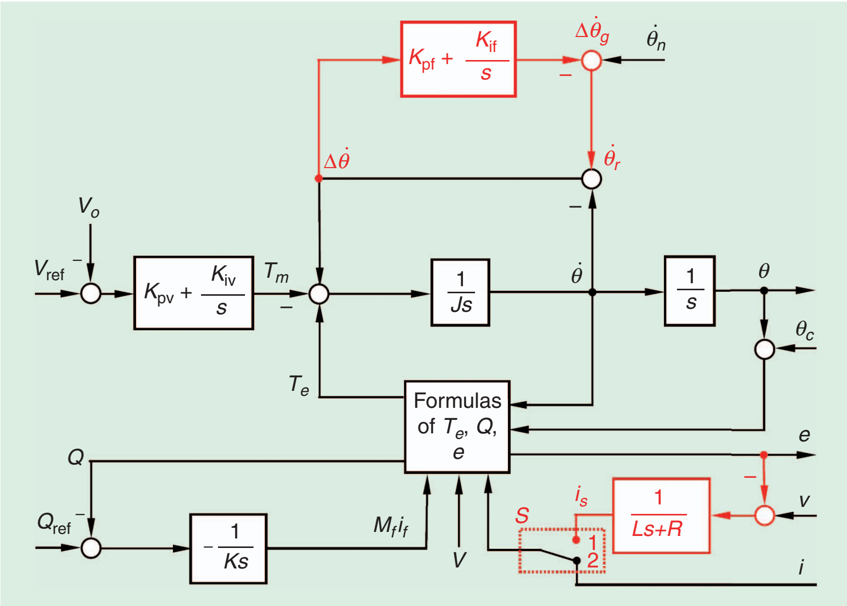

FIG 13 The controller of rectifiers without a dedicated synchronization unit [15].

self-synchronization mode in the self-synchronized synchronverter, during the uncontrolled mode, Q_{ref} should set at zero, and the dc-bus voltage loop should be disabled. A virtual current i_s is introduced in the controller during the uncontrolled mode to make sure that the control signal e is synchronized with the grid voltage v. After the synchronization, the switches can be turned on at any time to operate the rectifier in the PWM-controlled mode. In the PWM-controlled mode, not only should switch S be turned to position 2, but also the Q loop and the dc-bus voltage loop should be enabled at the same time. T_m is generated from the dc-bus voltage PI controller to regulate the output voltage V_o. The reactive power Q can be controlled to track the reference reactive power Q_{ref}. By feeding the difference between the grid frequency and the rectifier frequency through a PI controller, the rectifier could track the grid frequency well.

It is well known that a three-phase PWM-controlled rectifier consists of six switches with antiparallel diodes. When all the switches are OFF, the three-phase PWM-controlled rectifier works as an uncontrolled rectifier. This is denoted the *uncontrolled mode*. When the switches are operated, it is called the *PWM-controlled mode*. In the uncontrolled mode, before turning on the switches, the control signals e must be synchronized with the grid voltage v, with the same phase sequence. Similar to the

The simulation results from a rectifier without a dedicated synchronization unit are shown in Figure 14. The rectifier tracked the grid frequency very well. Moreover, the output voltage and the reactive power tracked their references quickly and accurately under different operational conditions, respectively.

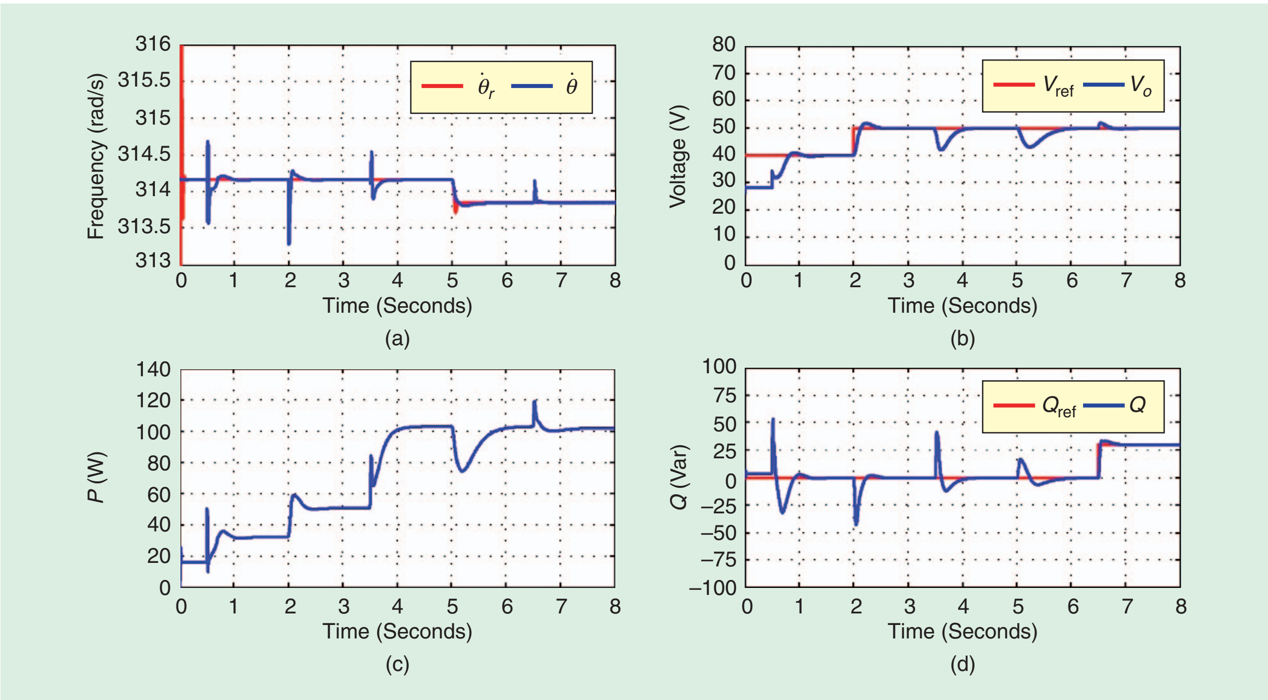

FIG 14 The simulation results from a rectifier without a dedicated synchronization unit [15]. (a) Frequency (rad/s). (b) DC-bus voltage (V). (c) Real power (W). (d) Reactive power (Var).

Conclusions

This article has shown that power electronic converters, both inverters and rectifiers, can be operated to behave like virtual synchronous machines. Moreover, the dedicated synchronization unit that has been deemed indispensable for grid-connected converters can be removed. This leads to a unified interface for smart grid integration and a simple architecture for next-generation smart grids. The application to the integration of wind and solar power is given as an example. Other applications include vehicle-to-grid systems [16] and static synchronous compensators [17], etc. It is worth mentioning that the VSM offers the dynamics and synchronization mechanism of synchronous machines to facilitate the self-balancing of real power and reactive power. The actual energy needed to support the grid comes from the energy stored in the system, for example, in large motors, wind turbines, and energy storage systems. While, in this article, the VSMs are implemented based on the synchronverter technology to facilitate the presentation, another (actually better) way is to adopt the robust droop control technology [18], which is universal for converters with different impedances. A more systematic treatment on this topic can be found in [19], and various aspects about control of power electronic inverters can be found in [20]. Live discussions and future updates are available via joining the LinkedIn group at https://www.linkedin.com/groups/7061909.

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