Connecting the Home Grid to the Public Grid

Field demonstration of virtual synchronous machines

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Power systems are going through a paradigm shift. More and more distributed energy resources (DERs) and loads are being connected to power systems, mostly through power electronic converters. These power electronic converters can be controlled as virtual synchronous machines (VSMs), leading to a unified interface for grid integration. As a result, all active players in a power system can take part in the regulation of system frequency and voltage in a synchronized and democratized (SYNDEM) manner, significantly simplifying system operation and improving grid stability, reliability, resiliency, security, and sustainability. This article presents a pilot smart home grid at the Llano River Field Station, Texas Tech University Center at Junction, that is built according to the SYNDEM grid architecture. The home grid consists of five DER units, including four 3-kW solar units and one 3-kW wind unit with built-in battery storage in each unit, and one energy bridge for grid connection. The energy bridge has two VSMs connected back-to-back with a common dc bus. All the units are equipped with a self-synchronized universal droop controller (SUDC) with many advanced functions, i.e., black-start, grid-forming, self-synchronization without a phase-locked-loop (PLL), voltage and frequency regulation, power sharing, and power quality control. The home grid can work with or without the public grid, with seamless mode change between grid-tied

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operation and islanded operation. All the functions are achieved without using a communication network; hence, potential cyberattacks can be avoided. Field operation results of the home grid are presented to demonstrate the autonomous operation of the system.

More DERs Are Being Connected to Power Systems

With the development of civilization and the growth of the economy, the demand for electricity is growing rapidly, causing two major global concerns: the energy crisis and environmental problems. As a result, more DERs, such as renewable energy resources like solar and wind, energy storage systems, and electric vehicles, are being connected to power systems. According to the U.S. Department of Energy (DOE), wind energy is targeted to meet 20% of U.S. electricity needs by 2030, and solar energy is targeted to meet 14% of U.S. electricity needs by 2030 and 27% by 2050. Power systems worldwide are going through a paradigm shift from centralized generation to distributed generation.

When a large number of DERs are integrated into a power system, the fundamental problem is how to make sure that all DERs can work together and maintain system stability. This is a great challenge [1] and several potential architectures have been proposed in the literature. The Intergrid [2] adopts the hierarchical nanogrid to microgrid to other grid structure and uses bidirectional power electronic converters as energy control centers to achieve dynamic decoupling of generation, distribution, and consumption. The Integrated Grid [3] expands its scope to integrate DERs into the planning and operation of the grid. An integrated smart grid system [4] is proposed to advocate a synergy of computing and physical resources and envisions a trustworthy middleware providing services to grid applications through message passing and transactions. The Future Renewable Electric Energy Delivery And Management (FREEDM) system [5] envisions operating power systems as an "Energy Internet" or "Internet of Energy."

Adding communication and information networks into power systems is a common trend. Naturally, the added communication systems are expected to provide the infrastructure needed for all power system players to work together, even at low-level controls. This standard scenario, however, could bring serious concerns about reliability and security [6]. If the communication system breaks down, then the whole power system could crash. Moreover, when the number of DERs reaches a certain level, managing the communication network is a challenge. What is even worse is that this opens the door for cyberattacks by anyone, at any time, from anywhere. Therefore, all DERs should have active roles in system regulation to facilitate the organic growth and autonomous operation of future power systems without relying heavily on communication networks [7].

Overview of the SYNDEM Grid Architecture

Most DERs are not compatible with the grid and require power electronic converters for grid integration. For example, wind turbines generate variable ac electricity and solar panels generate variable dc electricity. Similarly, energy storage systems and electric vehicles require power electronic converters for grid integration. Moreover, most of the loads access the grid through power electronic devices. According to the U.S. Electric Power Research Institute, over 50% of electricity is consumed by motors, over 10% is consumed by Internet devices, and about 20% is used in lighting devices. It is well known that motor drives that include a power electronic rectifier at the front end can significantly improve the system efficiency of motor applications, because they can provide accurate voltage needs, e.g., variable-voltage dc power for dc motors and variable-amplitude and variable-frequency ac power for ac motors. Internet devices consume dc power and power electronic rectifiers are needed for the ac-to-dc conversion. There is also a clear trend that LED lights will dominate the lighting market, and they too require power electronic rectifiers to provide dc power. Hence, future power systems will be power electronics based, instead of electric machines based [7], [8].

It is well known that synchronous generators (SGs) or, more generally, SMs, can autonomously synchronize with each other or with the power supply. This has underpinned the growth and operation of power systems for more than 100 years. With DERs and most of the loads being connected to the grid through power electronic converters, they can be controlled to behave like VSMs [9] by embedding the mathematical model of conventional SMs as the core of the controllers for these power electronic converters. They can all possess the synchronization mechanism of the conventional SM with a unified interface for grid integration. This leads to a SYNDEM grid architecture [7], [10], as shown in Figure 1, where all conventional sources, e.g., thermal, hydro, or nuclear power plants, are connected through SMs as normally done without major changes, and all DERs and the majority of loads having power electronic converters are connected through VSMs. All SMs/VSMs under the SYNDEM grid architecture can take part in the regulation of system frequency and voltage autonomously, significantly simplifying system operation and improving grid stability, reliability, resiliency, security, and sustainability.

It is worth emphasizing that all SMs and VSMs have the same intrinsic synchronization mechanism. There is no need to rely on additional communication networks to achieve low-level control, thus avoiding potential cyberattacks. Therefore, the communication network is released from low-level control to focus on high-level functions, e.g., supervisory control and data acquisition (SCADA) system and market operations. The SYNDEM grid architecture is scalable and can be adopted for power systems at different scales, from a single-node system for outdoor recreation or disaster relief, to a multinode system for a household or community grid, and further to a large-scale public grid.

Operating power electronics converters as VSMs does not mean that the flexibility of controlling power electronic converters is lost. VSMs can be controlled to improve inertia responses, power flow control, fault-current limitation, and so on, while being equipped with the synchronization mechanism.

Description of the Home Grid

The Need for Home Grids to Enhance Resiliency

Utility grids, including generation, transmission, and distribution facilities, are vulnerable to disastrous events, i.e., extreme weather or natural disasters. The affected components in these facilities may trigger cascaded failures, which can spread in a quick and wide manner with extensive damages and large power outages. Given the aging electric power infrastructure in the United States, the situation may deteriorate even more quickly on such occasions [11]. For example, in 2012, Hurricane Sandy caused approximately 8 million people to be without access to electric power [12]. Hurricane Irma cut power to nearly two-thirds of Florida's electricity customers [13], and more than a quarter-million people were affected by Texas power outages caused by Hurricane Harvey [14]. Without electricity, other utility infrastructures are affected as well, i.e., water systems, the Internet, and communications. The power outages also cause huge losses to both residential customers and commercial/industrial customers. Based on estimations from the U.S. DOE, the annual cost of weather-related power outages varies from billions to tens of billions of dollars, e.g., from US$45 to US$75 billion in 2008, and from US$27 to US$52 billion in 2012 [15].

To demonstrate how to mitigate power outages caused by extreme weather or disasters, enhance grid resiliency, and accelerate disaster recovery, a pilot smart home was developed at the Llano River Field Station, Texas Tech University Center at Junction, with sustainable power and water supplies, as shown in Figure 2. The home grid is built based on the SYNDEM grid architecture with electricity generated from renewable energy resources, i.e., wind and solar. The storage of electricity is achieved through batteries. This project is expected to demonstrate a new lifestyle, with natural sustainable resources for improved resiliency.

Configuration of the Home Grid

Following the SYNDEM grid architecture, the home grid is designed as illustrated in Figure 3, with its backbone depicted in Figure 4. It consists of five DERs, including four solar units and one wind unit, and one energy bridge. Each solar unit consists of two 1.5-kW strings of solar panels, a built-in battery pack, and a SYNDEM photovoltaic (PV) inverter. The

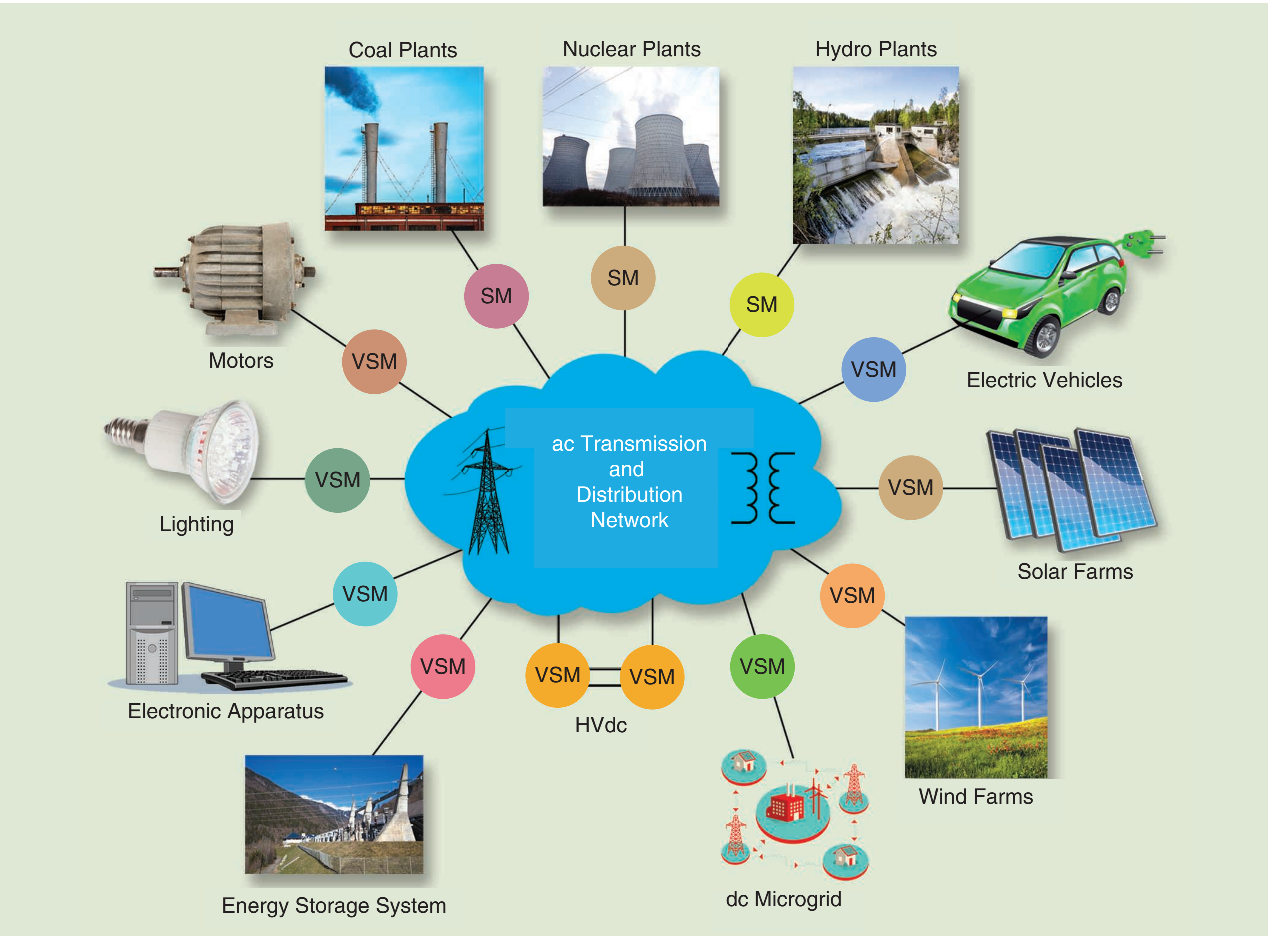

FIG 1 The SYNDEM grid architecture [7], [9], [10]. HVdc: high-voltage dc.

rated voltage of each PV string is 162.5 V. Each battery pack contains 18 rechargeable lead-acid batteries [12 V at 20 ampere hours (Ah) each] in series. The battery packs store energy when the load demand is less than generation, and they release energy when the load demand is more than generation. The PV inverters extract the maximum electricity from the solar panels and maintain the stability of the home grid collectively, with the battery pack as a buffer. The wind unit has a similar design as the solar units but with a 3-kW wind turbine. The major function of the energy bridge is to act as the system backup when the renewable resources and the battery storage are insufficient to power the home. The home grid can be connected to or disconnected from the public grid through the energy bridge, which consists of two interconnected back-to-back inverters with a common dc bus. All six units are ac coupled together to power the household loads. Because the inverters have a single phase, an isolation transformer has been adopted to generate a split-phase ac grid. The home grid can operate independently without the public grid, thereby enhancing resilience.

FIG 2 A smart home field at the Llano River Field Station, Texas Tech University Center at Junction.

Underlying Control Technology

The core control algorithm for implementing the VSM is the SUDC [16], as shown in Figure 5. This controller has three major operation modes: self-synchronization, set, and droop. In the self-synchronization mode, S_P and S_Q are OFF, and a virtual current i_s is generated by the voltage difference between the inverter output voltage v_o and the grid voltage v_g with S_C at position s. This regulates the real power P and reactive power Q to be zero and forces v_o to be the same as v_g, i.e., to synchronize v_o with the grid voltage v_g. The dedicated PLL that is often needed for grid-connected or parallel-operated inverters is removed. Once the synchronization is achieved, the inverter can be connected and then operated in the droop mode or the set mode. In the droop mode, both S_P and S_Q are ON, and S_C is at position g. It can provide the droop

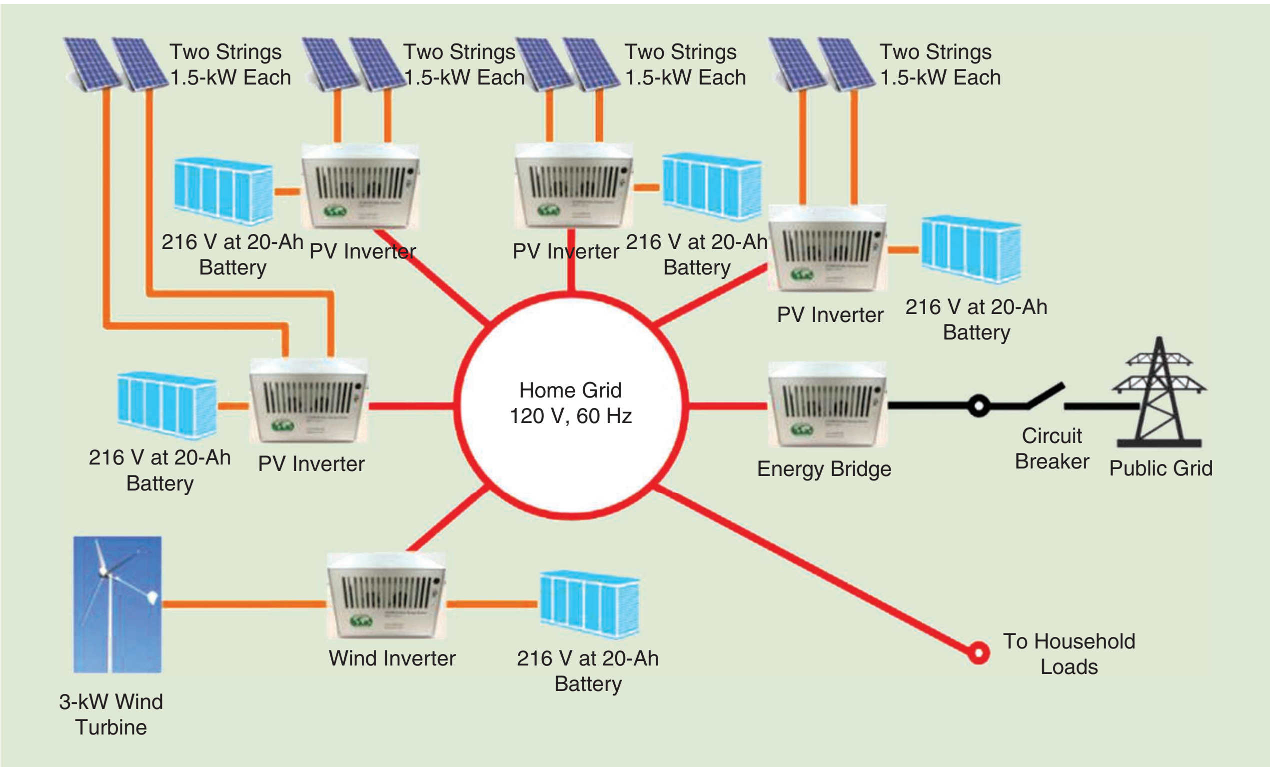

FIG 3 A single-line diagram of the home grid.

functions of the real power with respect to the voltage and the reactive power with respect to the frequency to regulate the voltage and the frequency. The system can also black-start without the public grid. With the voltage feedback into the droop design, accurate load sharing of both real power and reactive power, and power balance, can be achieved. In the set mode, S_P and S_Q are OFF, and S_C is at position g, the desired power P_{set} and Q_{set} can be exchanged with the public grid with accurate power regulation.

The same technology is adopted for the public-grid side VSM of the SYNDEM energy bridge, making it possible to synchronize the energy bridge with the public grid while the home-grid loads are in operation and to achieve seamless mode change between grid-tied operation and islanded operation for the home grid. To achieve the maximum power acquisition from the renewables, maximum power point tracking algorithms are embedded into the solar and wind inverters.

Results From Field Operations

The home grid reliably operates to support the smart home under different scenarios. Four typical cases are selected and presented to demonstrate the autonomous operation of the system.

Black-Start and Grid-Forming

The black-start and grid-forming capabilities are demonstrated with the results shown in Figure 6. The isolation transformer and some household loads, e.g., lights, laptops, and so on are initially connected to the home grid. At $t = 2$ s, PV inverter I starts to form the grid to supply electricity to household loads, as shown in Figure 6(a). The peak-to-peak output voltage of PV Inverter I is around 340 V, which corresponds to 120 V root mean square (RMS). The corresponding current of PV Inverter I is shown in Figure 6(a) as well. The current has some transients initially, mainly caused by the initialization of the isolation transformer, but it quickly settles down. At around $t = 6$ s, PV Inverter II synchronizes with the home grid and then connects to it. After the connection of PV Inverter II, the current of PV Inverter I decreases, and the current of PV Inverter II increases to the same value of PV Inverter I, due to the power sharing mechanism. Figure 6(b) shows the zoomed-in results at around $t = 10$ s. The two inverters have very consistent voltages and currents and work together to stabilize the grid. There are some harmonics in the output currents of both inverters that is caused by the nonlinearity of the isolation transformer and the household loads. Note that both inverters share the

FIG 4 The backbone of the home grid that contains five SYNDEM inverters, one energy bridge, and battery packs.

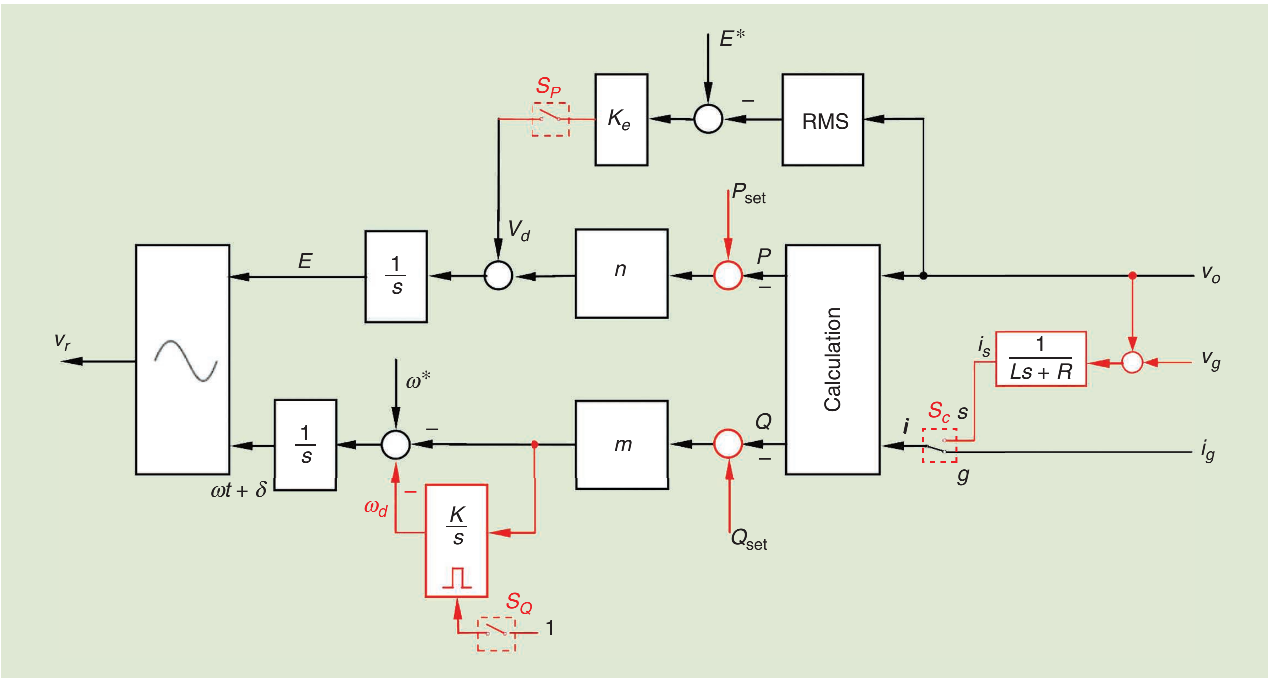

FIG 5 The self-synchronized universal droop controller [16].

harmonic currents well. At t = 15 s, a large resistive load is added to the system, the currents of both inverters increase, as shown in Figure 6(a). The zoomed-in results at around t = 18 s are shown in Figure 6(c). With the connection of the resistive load, the current quality is improved. The voltage quality is improved as well. Both inverters continue sharing the current well after the load change.

From Islanded to Grid-Tied Operation

The connection of the energy bridge to the public grid is demonstrated with the results shown in Figure 7. The public grid is always ON. At t = 10 s, the energy bridge starts to synchronize with the public grid. There is some initial current in the energy-bridge current (i.e., the inductor current) during the synchronization stage, as shown in Figure 7(a), which is caused by the filter capacitor. The energy bridge is connected to the public grid at about t = 10.4 s. Simultaneously, the energy bridge also connects and delivers power to the home grid, causing an increase of the energy-bridge current because some power is sent to the home grid. The corresponding public-grid current increases as well. The zoomed-in results at around t = 18 s are shown in Figure 7(b). The energy-bridge voltage at the public-grid side is synchronized with the public-grid voltage with almost the same phase angle due to the intrinsic synchronization mechanism of the VSM. The public-grid current is similar to the energy-bridge current because the filter capacitor is small.

Seamless Mode Change When the Public Grid Is Lost and Recovered

The results are shown in Figure 8. Initially, the home grid is in continuous operation in the islanded mode with the public grid ON. At t = 2 s, the energy bridge starts to connect the home grid to the public grid and the home grid enters into the grid-tied operation mode, as shown in Figure 8(a). It absorbs power from the public grid and delivers power to the home grid, with the energy-bridge output current at the home-grid side determined by the load on the home grid according to the droop function. The public-grid current increases accordingly to keep the power balance of the common dc bus of the back-to-back converters. At about t = 8 s, the public grid is lost, and the energy bridge immediately shuts down. Both the public-grid current and the energy-bridge current become zero. The home grid enters into the islanded mode and is not affected by the loss of the public grid. When the public grid is recovered at about t = 14 s, the energy bridge is resynchronized with the public grid and the home grid before autonomously connecting the home grid to the public grid. Figure 8(b) shows the zoomed-in results at around t = 18 s. The home-grid voltage is different from the public-grid voltage, demonstrating the independent operation of the home grid from the public grid. The energy-bridge output current has some harmonics that are caused by the split-phase isolation transformer and the

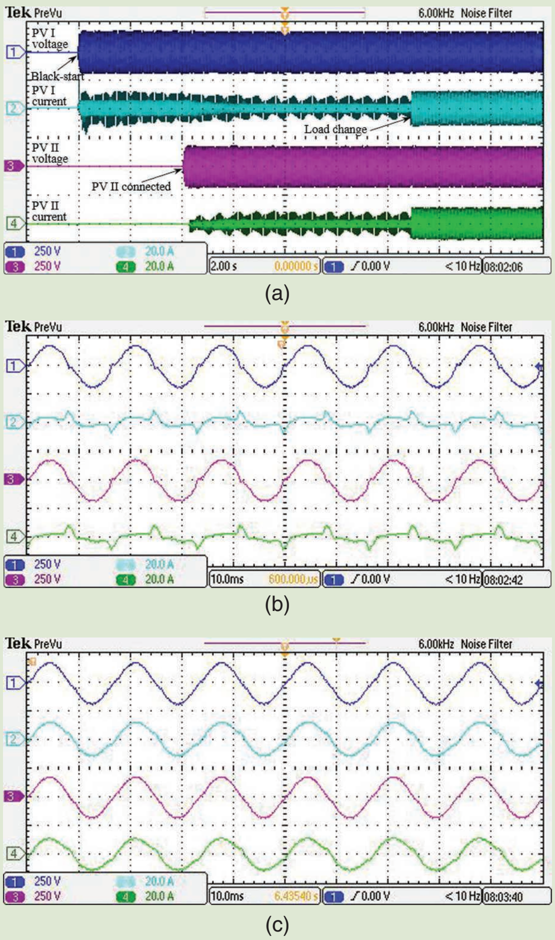

FIG 6 Black-start and grid-forming capabilities: (a) whole process and zoomed-in results at around (b) t = 10 s and (c) t = 18 s.

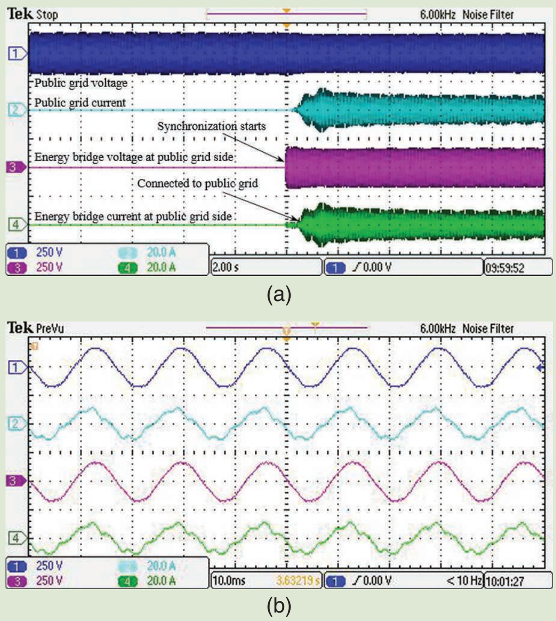

FIG 7 The connection of the energy bridge from islanded to grid-tied operation: (a) whole process and (b) zoomed-in results at around t = 18 s.

nonlinear loads in the home grid. The home grid can seamlessly change the operation mode between grid-tied and islanded modes and maintain independent operation regardless of the presence of the public grid.

Voltage/Frequency Regulation and Power Sharing

In this case, all renewable units work together to power the home grid, with the results shown in Figure 9. All data are sent out by the SYNDEM inverters and recorded by a PC through an RS485 channel. Initially, the home grid is connected to the transformer and some household loads. With the capabilities of the black-start and the synchronization discussed in the section "Black-Start and Grid-Forming," PV Inverter I starts to form the grid and other units are then connected one by one with PV Inverter II at about at t = 6 min, PV Inverter III at about t = 11 min, PV Inverter IV at about t = 17 min, and Wind Inverter at about t = 22 min, as shown in Figure 9(a). All connected inverters can share the real power and reactive power well, as shown in Figure 9(a) and (c). At about t = 25 min, an electric fan is turned ON, causing the increase of the reactive power and the real power. At about t = 38 min, a large load is added to the system, resulting in the increase of the real power and the decrease of the reactive power. It is evident that all connected inverters can continue to share the loads during the load change. The home grid voltage and frequency are well regulated during the whole normal operation, as shown in Figure 9(b) and (d), with voltage variations of less than 1.8 V and frequency variations of less than 0.005 Hz because all inverters work together to regulate both voltage and frequency collectively without relying on a communication network.

Lessons Learned

Many lessons were learned from the field trial. The three major lessons learned involve the extremely high nonlinearity of the transformer, the high nonlinearity of the household loads, and the large inrush current of the air-conditioning unit.

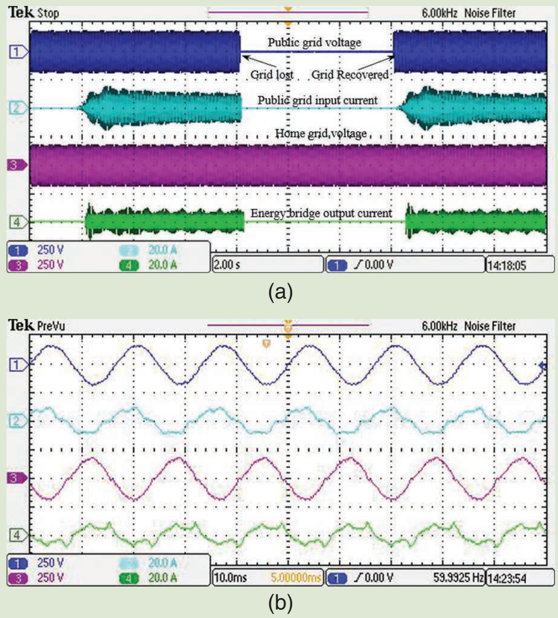

FIG 8 The seamless mode change of the home grid when the public grid is lost and recovered: (a) whole process and (b) zoomed-in results at around t = 18 s.

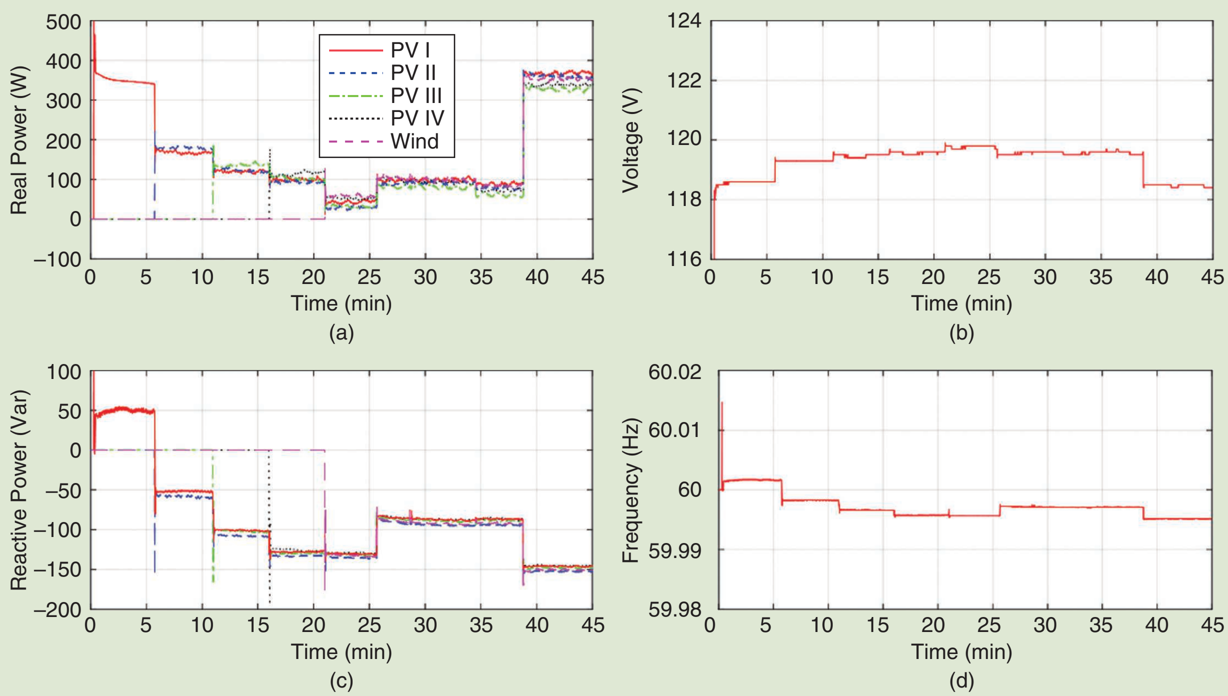

FIG 9 The power sharing and regulation of voltage and frequency grids: (a) real power, (b) voltage, (c) reactive power, and (d) frequency.

Figure 10(a) shows the grid voltage and the transformer current when the transformer is connected to the public grid without a load connected. The transformer current includes very large harmonics, which normally results in high total harmonic distortion (THD) in the voltage. Figure 10(b) shows the inverter voltage and the transformer current when the transformer is connected to one inverter without a load connected. Even with such excessive high current harmonics, the SYNDEM inverters can maintain good voltage quality due to their low impedance. With more inverters added into the system, the voltage quality is improved significantly. Figure 10(c) shows the case when two inverters are connected together to feed the transformer. The voltage quality is improved, and the two inverters share the current harmonics well. Note that the scales of Figure 10(a) are twice of those in Figure 10(b) and (c).

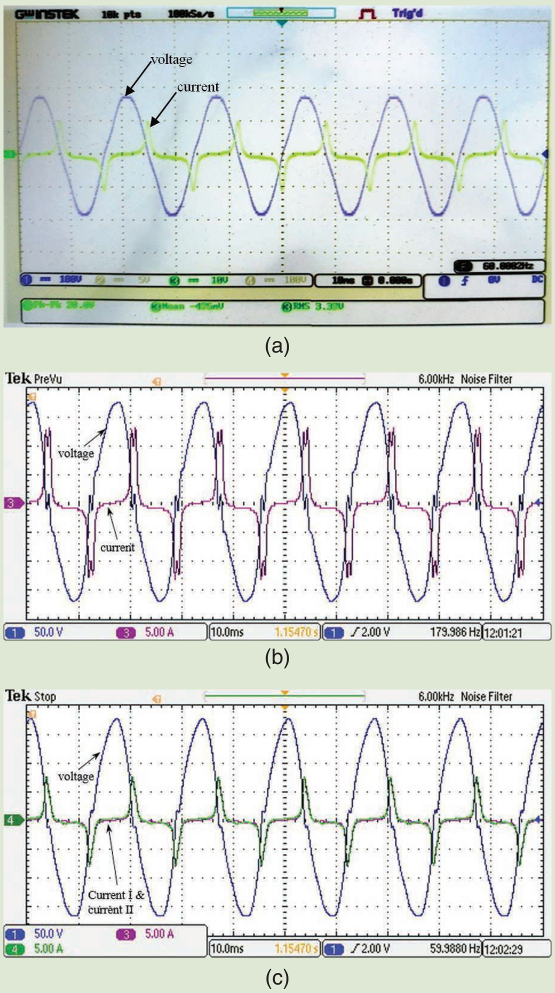

FIG 10 The nonlinearity of the transformer: (a) the transformer is connected to the public grid without a load, (b) the transformer is connected to one inverter without a load, and (c) two inverters are connected together to feed the transformer.

Figure 11 shows the home grid voltage and the split-phase currents of the household loads. The current of the phase with the isolation transformer contains significant harmonics due to the transformer, but the current of the phase without the transformer also contains visible harmonics. Although the current quality is very bad, the SYNDEM inverters are able to maintain good voltage quality with low THD.

Figure 12 shows the large inrush current when turning ON the air conditioning unit that is measured when connected to the public grid. This is far beyond the designed capacity of the home grid and current protection is triggered to avoid any damage. An inrush current limiter is added to the air-conditioning to suppress the inrush current. In the future, if the power electronic converters in air-conditioning units are operated as VSMs, then this kind of inrush current can be avoided.

Conclusions

In this article, a home grid based on the SYNDEM grid architecture and developed for a smart home at the Llano River Field Station, Texas Tech University Center at Junction, was demonstrated. The home grid contains four solar units, one wind unit, and one energy bridge. The autonomous operation of the home grid to achieve tight voltage and frequency regulation was demonstrated without relying on a communication network. Many advanced functions, i.e., black-start, grid-forming, self-synchronization, voltage and frequency regulation, power sharing, power

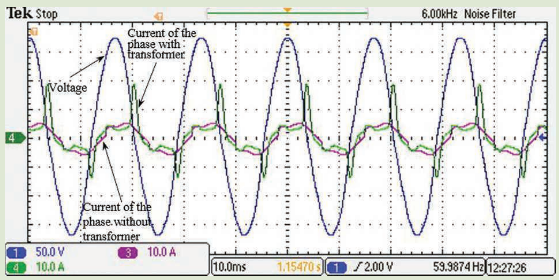

FIG 11 The nonlinearity of household loads.

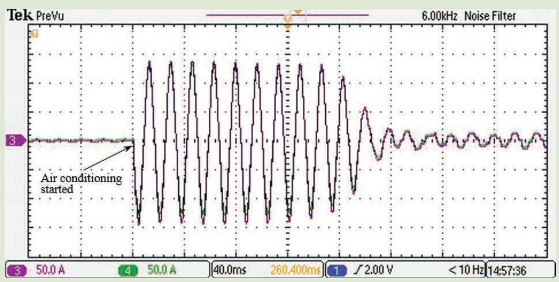

FIG 12 The large inrush current of the air-conditioning.

quality control, and power balance, were demonstrated through field tests. The home grid can operate with or without the public grid, with a seamless mode change between grid-tied operation and islanded operation. Some unexpected problems, i.e., the high nonlinearity of the isolation transformer, the high nonlinearity of household loads, and the large inrush current of air-conditioning units, were presented as well. The field trial demonstrated the favorable integration of DERs without relying on communication networks while improving grid stability, reliability, security, resiliency, and sustainability.

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