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Smart Grid Research and Educational Kit to Enable the Control of Power Electronic-based Systems from Simulations to Experiments in Hours

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Abstract: Control and power electronics are two major enablers for the paradigm shift of power systems from centralized generation to distributed generation, the electrification of transportation, and the transformation of billions of lives in third-world countries. Experimental validations of control algorithms for these systems play a vital role. However, setting up a suitable experimental system requires time, effort, and a broad range of expertise. This demonstration session aims to help researchers, graduate students, and engineers remove the barriers to go real from simulations to experiments for various power electronic-based systems. It shows that it is possible to obtain experimental results within hours after completing simulations by adopting the SYNDEM Smart Grid Research and Educational Kit, which is a reconfigurable, open-source, multifunctional power electronic converter with the capability of directly downloading codes from Matlab/Simulink. This will maximize the strengths of the control community in developing control algorithms, minimize the efforts on developing hardware systems and programming control algorithms, and improve the efficiency and productivity of research and learning.

Keywords: Control education, smart grid, microgrid, control implementation, hardware-in-the-loop, rapid control prototyping, renewable energy, distributed energy resources (DER), power electronics, electrical drive, wind power, solar power, storage systems, from simulation to experiments.

1. INTRODUCTION

Control and power electronics are two major enablers for the paradigm shift of power systems from centralized generation to distributed generation, the electrification of transportation, and the transformation of billions of lives in third-world countries. For power systems or smart grids, a large number of active units including wind farms, solar farms, DERs, electric vehicles, energy storage systems and flexible loads are being integrated into power systems through power electronic converters (Zhong, 2020; Zhong and Hornik, 2013). This imposes great challenges to the stability, scalability, reliability, security and resiliency of future power systems. Hence, it is vital to develop appropriate control architecture and technologies so that all these different players are able to take part in the regulation of future power systems. For electrification of transportation, power electronic converters are widely used in more-electric aircraft, all-electric ships, electric vehicles, spaceships, and satellites etc. In third-world countries, billions of lives are waiting for low-cost solutions to provide electricity. The control of power electronic converters lies in the heart of these applications and many other areas such as computers, telecommunication, data centers, consumer electronics, lighting, motor drives etc.

While advancing technologies for these applications is important to address the problems, another key is to provide low-cost versatile tools to facilitate the research and development of technologies and to educate next-generation engineers. A lot of education and training on control of power electronics are simulation-based because of the lack of affordable and reconfigurable hardware platform. The emerging of hardware-in-the-loop (HIL) simulation has made it easier to obtain simulation results that are close to real experiments. However, the price of hardware-in-the-loop simulation systems is still high. While these simulations reflect the behavior of real systems to some extent, many practical issues cannot be accurately modeled or studied with simulations. Needless to say, real experiments are the best way to reflect the dynamics and characteristics of real applications and carrying out physical experiments should be an integrated part of training next-generation power electronics engineers and leaders. In order to make this happen, two major challenges need to be overcome: the availability of suitable hardware platforms and the elimination of software coding burden. It usually takes several months for a skilled person to build up an experimental system after several iterations. Furthermore, different topologies usually require different new hardware designs. As to software coding, it is often the job of another person – it is difficult for a hardware engineer to write codes.

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It often takes several months or longer for a beginner to fully understand the programming platform and the target machine. Moreover, code debugging can be very time-consuming. This is particularly true for the control community because of the strengths on developing control algorithms and, relatively, the lack of hardware and software skills.

This demonstration session aims to help researchers, graduate students, and engineers remove the barriers to carry out physical experiments for control of power electronic-based systems. It will demonstrate that it is possible to obtain experimental results within hours after completing simulations by adopting the SYNDEM Smart Grid Research and Educational Kit, which is a multifunctional, reconfigurable, and open-source power electronic converter with the capability of directly downloading codes from Matlab/Simulink. As a result, the two major challenges mentioned above are overcome. In this session, the Smart Grid Research and Educational Kit and its unique features will be presented, together with sample case studies.

2. SYNDEM SMART GRID RESEARCH AND EDUCATIONAL KIT

2.1 Overview

The Kit is featured by MathWorks® as a reconfigurable power electronic converter for research and education in smart grids [1]. The Kit can be reconfigured to obtain 10+ different power electronic converters, covering DC/DC converters and single-phase/three-phase DC/AC, AC/DC, and AC/DC/AC converters. As a result, it can be used to quickly set up research, development, and education platforms for different applications, such as solar power integration, wind power integration, machine drives, energy storage systems, and flexible loads. Moreover, there is no need to spend time on coding because it adopts the widely-used Texas Instrument (TI) C2000 ControlCARD and is equipped with the automatic code generation tools of MATLAB®, Simulink®, and TI Code Composer Studio™ (CCS), making it possible to generate experimental results within hours from simulations. It comes with complete interface details and sample implementations, based on which users can easily test their own control algorithms.

The main features of the Kit include

- Reconfigurable to obtain 10+ different power electronic converter topologies
- Capable of directly downloading control codes from Matlab/Simulink
- Ideal for research in smart grid, microgrid, renewable energy, EV, energy storage etc.
- Compatible with utilities around the world with 120 V or 230 V voltage, 5A current
- Versatile communication interfaces, such as RS485 and CAN, for SCADA
- Multiple DAC channels for easy debugging and monitoring of internal states
- Suitable for parallel, grid-tied, or islanded operation with single or multiple kits

Fig. 1. SYNDEM Smart Grid Research and Educational Kit

2.2 Hardware Structure

Each Kit consists of one control board and up to two power boards. Figure 1 shows a picture of the Kit with one power board. The control board is on top of the power board and auxiliary power supplies are located beneath the power board. The Texas Instrument (TI) C2000 ControlCARD is inserted at the back of the control board. The control board has four switches for users to define the functions.

Power Board The power board contains a three-leg IGBT module A1P35S12M3 and its driver circuits, relay, jumper wire connectors, current sensors, voltage sensors, inductors, capacitors, and fuses. The diagram of the main power circuit is shown in Figure 2. The power board accepts PWM signals from the control board through J7/J4 and transfers analogue voltage/current signals to the control board through J2/J3. The IGBT module A1P35S12M3 contains six 1200V 35A devices in three legs with a common positive bus. It has a built-in NTC temperature sensor for thermal protection. There are two DC-bus 470μF 450 V capacitors, $C76$ and $C77$, which can be configured in series or in parallel to meet the requirement of the voltage rating or the capacitance. There are three sets of inductors $L1$, $L2$, and $L3$ and capacitors $C78$, $C79$, $C80$, with two sets reconfigurable. Moreover, inductor $L2$ and Capacitor $C78$ can be placed freely. A relay is included to facilitate grid connection. All the inductor currents and capacitor voltages as well as the DC-bus current and voltage are measured and sent to the control board. In addition, two voltages on the grid side are measured to facilitate grid connection. The power board is also equipped with AC fuses $F2$, $F3$, and $F4$, DC fuse $F1$, NTC thermistors VR1, VR2, and VR3 for protection and a pre-charging resistor $R61$. The power board is also equipped with a standalone 1600 V 35 A three-phase diode bridge with a 470μF 450 V capacitor, making it possible to power the DC bus from an external transformer.

Control Board The control board includes a TI C2000 TMS320F28335 ControlCARD, signal conditioning circuits for AC signals, 22-channel 12 bit ADC, 4-channel 12 bit DAC, 4 switches, 4 LEDs, SPI, RS485 and CAN interfaces, protection circuits, and PWM circuits. Up to two power boards can be connected to one control board. This makes it possible to carry out experiments for two three-phase converters with one controller, e.g., the back-to-back converters in PMSG and DFIG WPGS.

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[1] https://www.mathworks.com/products/connections/product_detail/syndem-smart-grid-kit.html

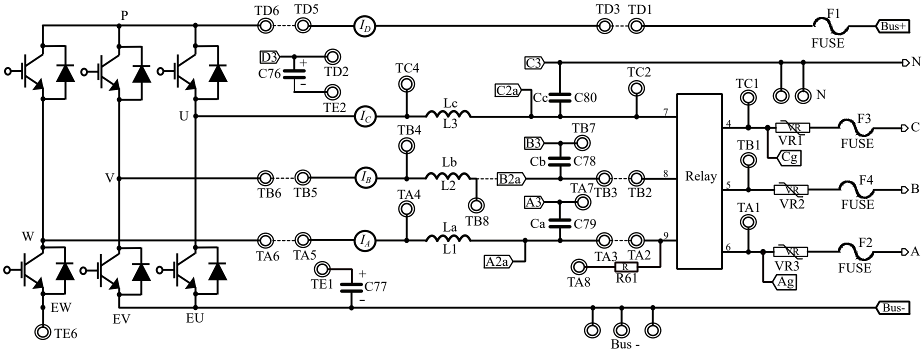
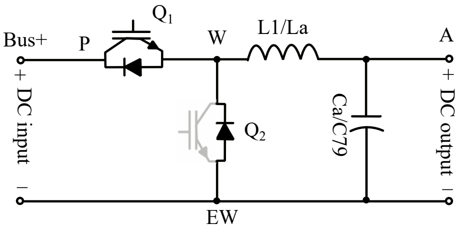
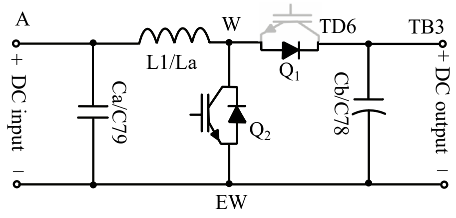


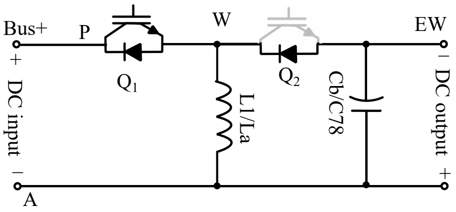
Fig. 2. SYNDEM Smart Grid Research and Educational Kit: Main power circuit



(a) Buck (step-down) converter

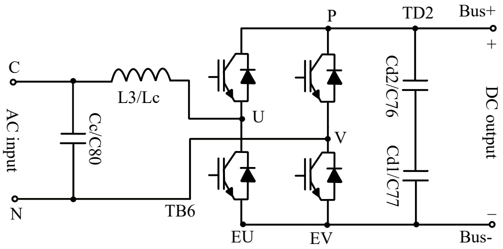


(b) Boost (step-up) converter

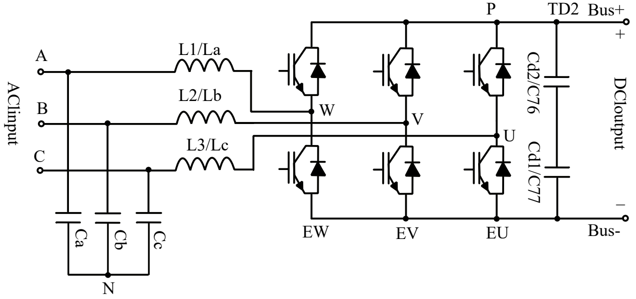


(c) Buck-boost converter

Fig. 3. Implementation of DC-DC converters



(a) Single-phase rectifier



(b) Three-phase rectifier

Fig. 4. Implementation of PWM-controlled rectifiers

2.3 *Sample Conversion Topologies*

The Kit can be reconfigured into different converter topologies for various applications, such as solar power, wind power, energy storage system, motor drives, electric vehicles, and flexible loads. Some sample topologies are outlined below.

DC-DC Converters DC-DC converters are used to change the voltage level of a DC source to another level that is suitable for the load connected. A DC-DC converter can be designed to increase the voltage, decrease the voltage, or both. The ratio between the output voltage and the input voltage is called the conversion ratio. When the conversion ratio is lower than 1, the converter is called a buck (step-down) converter; when the conversion ratio is higher than 1, the converter is called a boost (step-up) converter; when the conversion ratio can be higher and lower than 1, then the converter is called a buck-boost converter. The SYNDEM Kit can be adopted to realize all these three types of DC-DC converters. Figure 3 shows some implementations.

Uncontrolled Rectifiers Because of the diodes in the IGBT module, it is easy to implement uncontrolled rectifiers with the SYNDEM Kit. It is also possible to use the standalone three-phase bridge rectifier for this purpose. When the system is configured as an uncontrolled rectifier, no PWM control command is needed from the control board. A command signal can be given to operate the relay.

PWM-controlled Rectifiers The SYNDEM Kit can be configured to form a single-phase or three-phase PWM-controlled rectifier, as shown in Figure 4. The circuit configurations of these PWM-controlled rectifiers can also be used for single-phase/three-phase uncontrolled rectifiers, with the main difference being that the switches are not controlled through PWM signals from the DSP.

θ-converters The SYNDEM Kit can be used to implement other rectification topologies, for example, the θ-converter proposed in (Zhong and Ming, 2016). The configuration of the θ-converter is shown in Figure 5, which is a single-phase bridge converter that looks like the symbol θ. It has a common AC and DC ground, which reduces common-mode voltages and leakage currents. The DC-bus capacitor $C77$ provides a direct

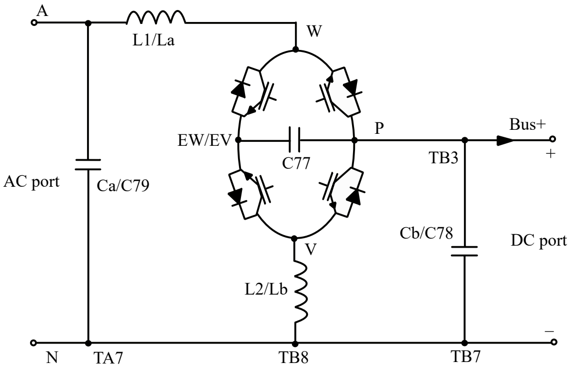


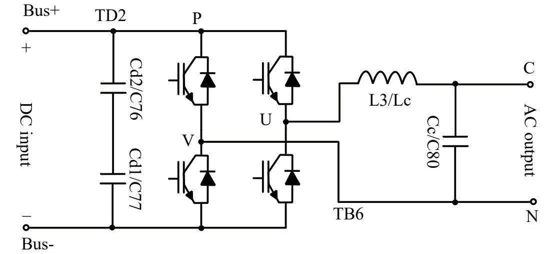
Fig. 5. Implementation of the θ-converter

path for the double-frequency ripple current inherently existing in single-phase converters to return continuously. The output capacitor $C78$ only deals with switching ripples so it can be chosen small. Moreover, the DC-bus capacitor $C77$ is designed to store the system ripple energy with large voltage ripples. As a result, its capacitance can be reduced as well. The θ-converter offers more advantages than a conventional bridge converter because its two legs are controlled independently; see (Zhong and Ming, 2016) for details. The inductor $L2/Lb$ can also be connected between P and Bus+ to form an improved θ-converter.

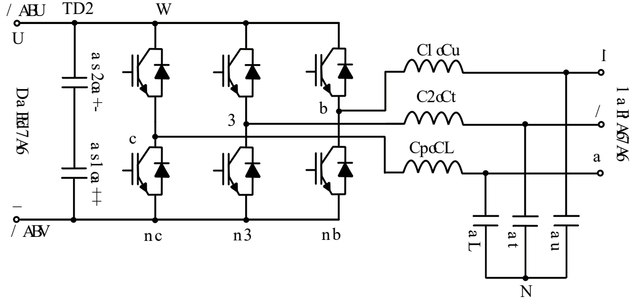
Inverters An inverter converts an DC source into an AC output. According to the type of the DC supply, there are current-source inverters (CSI) and voltage-source inverters (VSI). Typically, an inverter is a VSI if there is a large capacitor across the DC bus and is a CSI if there is a large inductor in series with the DC supply. The SYNDEM Kit can be configured as VSI for single-phase and three-phase applications, as shown in Figure 6. Depending on the control algorithm implemented, the output of the inverter can be current-controlled or voltage-controlled. Both control methods can be implemented with the SYNDEM Kit because there are sensors to measure the output voltage and the output current. The inverter can be operated in the islanded mode or in the grid-connected mode. If it is operated in the grid-connected mode, the voltage on the grid side is available for synchronization. Once it is synchronized, the relay can be turned ON.

DC-DC-AC Converters Some applications require DC-DC and DC-AC two-stage conversion. For example, a solar power system often needs a DC-DC converter on the PV side to step up the voltage before conversion into AC with a DC-AC converter. The SYNDEM Kit can be configured to implement this DC-DC-AC conversion, as shown in Figure 7. Two separate controllers but inside the same ControlCard are needed for the DC-DC converter and the DC-AC inverter, respectively.

Single-phase AC-DC-AC Back-to-Back Converters The SYNDEM Kit can be used to implement AC-DC and DC-AC back-to-back conversion. As shown in Figure 8, the implementation only needs three legs, with a common neutral point provided by the θ-converter. The three legs are controlled independently.



(a) Single-phase inverter



(b) Three-phase inverter

Fig. 6. Implementation of inverters

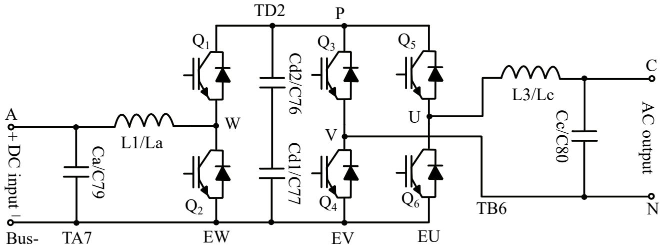


Fig. 7. Implementation of a DC-DC-AC converter

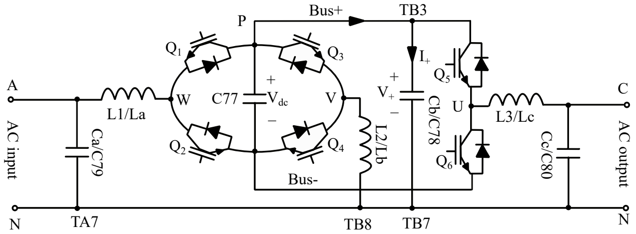


Fig. 8. Implementation of a single-phase back-to-back converter

Three-phase AC-DC-AC Back-to-Back Converters Three-phase applications, such as wind power systems, frequency converters, and machine drives, often require three-phase back-to-back converters. One SYNDEM Kit plus an additional power board can be used to form such a three-phase back-to-back converter, as shown in Figure 9. Both power boards can be controlled through one control board.

3. SAMPLE APPLICATIONS

3.1 A Grid-tied Inverter System

A grid-tied inverter system is constructed with the SYNDEM Kit, with the configuration shown in Figure 10(a). It is a single-phase inverter fed by a DC source. The inverter is connected through an external switch S_2 to a local AC bus, which is connected to the grid through another external switch S_1. A local load is connected to the local AC bus.

The wiring illustration and the schematic diagram for the configuration are shown in Figures 10(b) and 10(c), which use four on-board voltage and current sensors: the voltage sensor across $C78$ to measure the AC grid voltage; the voltage sensor across

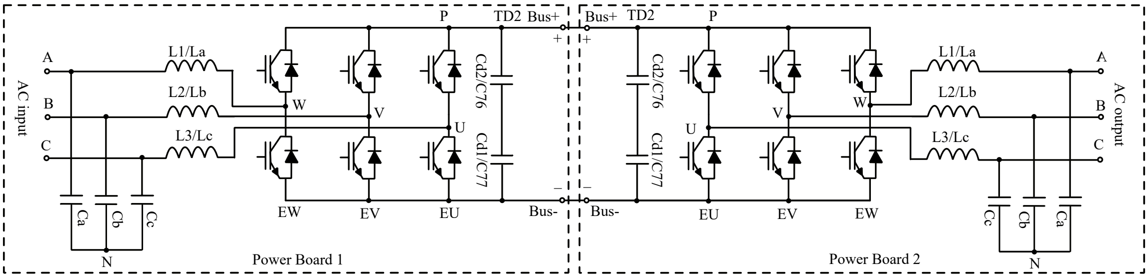
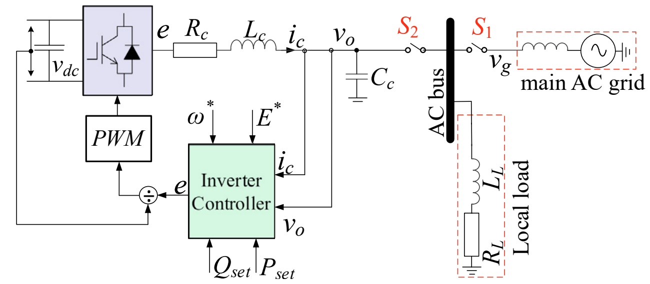
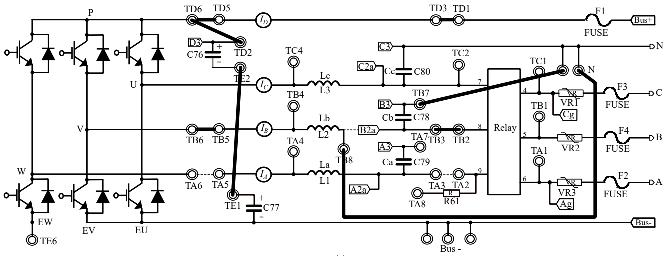


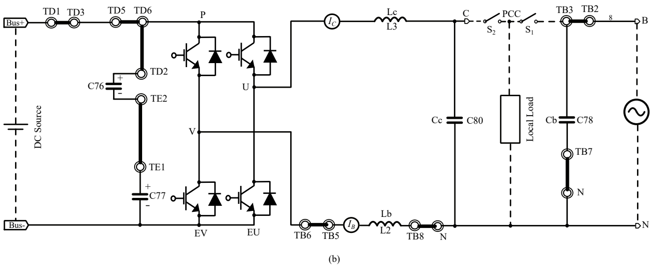
Fig. 9. Implementation of a three-phase back-to-back converter



(a) Illustrative structure



(b) Wiring illustration with the SYNDEM Kit power circuit



(c) Schematic diagram

Fig. 10. A grid-tied system

the capacitor $C80$ to measure the output voltage v_o; a current sensor to measure the current flowing through inductor $L3$; and a voltage sensor to measure the voltage between Bus+ and Bus-. The wiring procedures are to:

- Connect Bus+: TD1 – TD3 and TD5 – TD6,
- Connect the DC-bus capacitor: TD6 – TD2 and TE2 – TE1,
- Connect the neutral line: TB6 – TB5, TB8 – N and TB7 – N,
- Connect the phase line: TB3 – TB2,
- Connect the DC-source: between Bus+ and Bus-,
- Connect the AC grid: between B and N,
- Insert switches S_1 and S_2: between C and TB3,
- Connect the local load: between PCC and N.

The self-synchronized universal droop controller (Zhong et al., 2016) together with additional functions such as islanding detection are implemented in MATLAB/Simulink and directly downloaded to the DSP for execution.

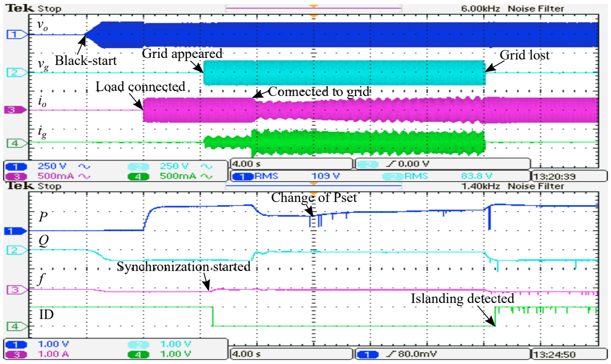


Fig. 11. Experimental results from the grid-tied system in Fig. 10 equipped with a SYNDEM Smart Grid Research and Educational Kit

Figure 11 shows the experimental results covering black-start, connecting local loads, grid appearance and detection, synchronizing and connecting to the grid, changing the operation condition, loss of the grid, and islanding detection etc., with details described below:

1) the VSM started from black at about $t = 4$ s: the inverter voltage v_o was established gradually and smoothly. The reactive power Q decreased from 0 because of the filter capacitor and, consequently, the frequency f decreased slightly. Because there was no voltage present on the grid side, the relay was turned ON to pass the generated voltage to the terminal C;

2) the switch S_2 was turned ON to connect a local load about 290 W at about $t = 8$ s: the output current i_o and the real power P increased while the inverter voltage v_o decreased slightly because of the load effect. Note that P and Q are calculated according to the filter inductor current instead of the output current i_o at the terminal;

3) the AC grid voltage v_g appeared at about $t = 12$ s: the grid current i_g became non-zero because there was a capacitor $C78$ on the grid side. The inverter detected the presence of the grid voltage and the islanding detection signal ID changed from 1 (no grid) to 0 (grid present). The VSM autonomously started synchronizing with the grid, without causing noticeable changes in v_o and i_o. It can be seen that the frequency f increased and became close to the grid frequency;

4) the switch S_1 was turned ON to connect the system to the grid after reaching synchronization, at about $t = 16$ s: there was no noticeable change in the inverter voltage v_o or the grid voltage v_g, meaning that the grid connection was seamless. The grid took some load over, causing the output current i_o to decrease

Fig. 12. Texas Tech SYNDEM Microgrid built up with eight SYNDEM Smart Grid Research and Educational Kits

and the grid current i_g to increase. Note that P was higher than $P_{set} = 100$ W because the load drew some power from the grid and the inverter voltage was lower than the rated voltage;

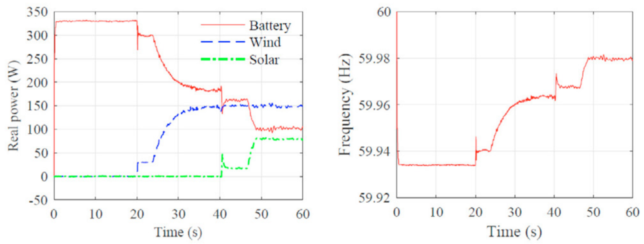
5) the real power set-point P_{set} of the VSM was increased to $P_{set} = 200$ W at about $t = 20$ s: there was no noticeable change in v_o. The output current i_o and real power P increased accordingly. Less power was drawn from the grid and P became close to P_{set};

6) the grid was lost at about $t = 32$ s: the full load was reverted back to the VSM and i_g (and v_g) became 0. The VSM detected the islanding after a short period of delay, as designed, and disconnected from the grid. There was no noticeable change in the inverter voltage v_o, meaning that the load was not affected by the loss of the grid.

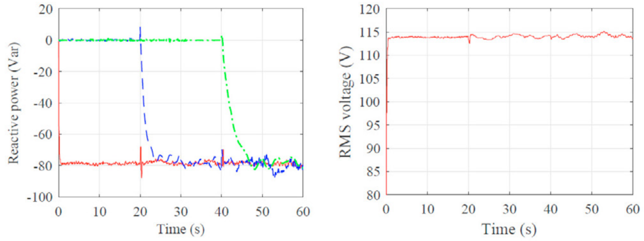
3.2 An 8-node SYNDEM Smart Grid Testbed

Because of the versatile reconfigurability of the Kit, it can be adopted to quickly build up physical smart grid testing facilities. Figure 12 shows such a SYNDEM Microgrid facility established at Texas Tech University.

This microgrid consists of renewable resources (including a wind turbine emulator and a solar system emulator), energy storage system (batteries), a traditional generator, a utility grid interface, and two flexible loads. The sources and loads are integrated through eight open-source SYNDEM Smart Grid Research and Educational Kits connected on a common AC bus. The set-up of the system was very quick so that the focus was able to be paid on developing advanced control algorithms to guarantee an autonomous, robust, and stable operation for the microgrid. Figure 13 shows the experimental results when the battery node, the wind node, and the solar node are connected one by one to the system. This 100% power electronic converters-based microgrid is able to maintain the frequency and voltage within tight ranges around the nominal frequency and the nominal voltage. A video about the system and its operation can be found at www.syndem.com. For the SYNDEM (meaning synchronized and democratized) grid architecture, the readers are referred to (Zhong, 2020, 2017).



(a) Real power of sources (b) Frequency



(c) Reactive power of sources (d) Voltage

Fig. 13. Experimental results from the microgrid in Fig. 12

4. CONCLUSIONS

In this paper, the SYNDEM Smart Grid Research and Educational Kit, which is a reconfigurable, open-source, multifunctional power electronic converter with the capability of directly downloading codes from Matlab/Simulink, is introduced with the aim of helping researchers, graduate students, and engineers remove the barriers to go real from simulations to experiments for various power electronic-based systems. This removes two major challenges, i.e., the lack of suitable hardware platforms and the burden of software coding, faced by the control community in carrying out experiments for power and energy systems. This makes it possible to quickly obtain experimental results after completing simulations. The kit is expected to maximize the strengths of the control community in developing control algorithms and minimize the efforts on developing hardware systems and programming the algorithms, which will significantly improve the efficiency and productivity of research and learning. The kit can be adopted for lab-bench systems as well as standalone research projects. While the kit is developed for power and energy related applications, it can be applied to the research and education of other control systems as well because of its versatile interfaces and computational power.

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