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A Highly Integrated and Reconfigurable Microgrid Testbed with Hybrid Distributed Energy Sources

Chengshan Wang, *Senior Member, IEEE*, Xianshen Yang, Zhen Wu, Yanbo Che, Li Guo, *Member, IEEE*, Shuhuai Zhang, and Yixin Liu

***Abstract*—A highly integrated and reconfigurable microgrid testbed is presented in this paper. The microgrid testbed contains various distributed generation units and diverse energy storage systems. Apart from electrical power, it can also provide energy in forms of hydrogen and thermal energy. The topology of this testbed is very flexible with different combinations of buses and feeders. The deployment of hybrid distributed energy sources and the highly reconfigurable structure are available to meet different research requirements. Extensive experiments have been carried out to provide verification for microgrid research and guides for microgrid projects. Some experimental results are shown in this paper in several aspects of microgrid research, including performance evaluation of distributed energy sources, verification of control schemes in ac/dc hybrid microgrid, investigation of fault transients, and feasibility of protection schemes.**

***Index Terms*—Distributed energy sources, microgrid, testbed, voltage control.**

I. Introduction

RENEWABLE energy applications will be the feasible solution for energy scarcity and environmental problems as a result of the rapid advancement of global economic growth. Microgrid is presented as one of the most effective forms integrating renewable energy sources (RESs) with the utility grid. It can mitigate the adverse effects of RESs performance, offers highly reliable electrical power supply, and enhances energy efficiency of power system. Therefore, it becomes an attractive alternative that has drawn significant attention all over the world. Large number of research works on microgrid are being actively carried out in several aspects, e.g., coordinated control [1], energy management [2], and protection [3]. To promote the development of microgrid research and extend its engineering applications, a microgrid testbed embedded with different distributed generations (DGs) and energy storage systems (ESSs) is necessary to simulate real microgrid projects.

During last decade, there are many microgrid testbeds and demonstration projects established successively in different countries. In North America, Consortium for Electric Reliability Technology Solutions microgrid testbed consists of three feeders with loads and three micro-turbines to demonstrate the ease of integrating distributed energy sources into a microgrid, with the functions of peer-to-peer and plug-and-play [4]. The National Renewable Energy Laboratory has conducted various researches on hybrid power system integration and microgrids. They focus on characteristics and status assessing of stand-alone hybrid power systems incorporating photovoltaic (PV) generation in the USA, and also supports the progression of IEEE P1547.4 Draft Guide [5]. The Distributed Energy Technologies Laboratory at Sandia National Laboratories has supported diverse renewable system tests [6]. Meanwhile, with the cooperation of governments and enterprises, some demonstration projects, such as distributed utility integration test, Mad River Microgrid, Nemiah Valley Microgrid, and Ramea Microgrid, have been constructed in USA and Canada [7]–[9].

In Europe, several microgrid testbeds have been built in the frame of the European project "Microgrids." The microgrid in National Technical University of Athens, including PV systems, controllable loads and wind turbine, is specially designed in single-phase structure, and a multiagent system technology is developed to estimate the effect of power flow adjustment and energy consumption. DeMoTec microgrid testbed in Germany mainly concentrates on electrification with RESs using modularly expandable and grid-compatible hybrid power supply system [10]. In addition, other leading laboratories and research institutes have founded the association of DERlab to boost their cooperation in the EU microgrid projects, which include Armines microgrid in France, Austrian Institute of Technology testing laboratory in Austrian, Technical University of Denmark Electrical Engineering in Denmark, etc. [11]–[13].

In Asia, the development of microgrid testbeds become yearly mature, and promotes practical microgrid projects. In Japan, New Energy and Industrial Technology Development Organization is founded by the Japanese government [14], [15], which leads the construction of several microgrid demonstrations such as microgrid projects in Aichi, Kyoto, etc. In China, microgrid testbeds and demonstrations have also been developed vigorously. The microgrid testbed constructed in Hefei University of Technology is a typical microgrid with multiDG, including hardware and software design scheme that conforms to IEC61970 standards [16]. An integrated microgrid laboratory system has been established in Zhejiang Electric Power Test and Research

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The authors are with the School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China (e-mail: cswang@tju.edu.cn).

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Institute, integrating with a diesel generator as backup power source and flywheel ESS for fast power balancing. Some experiments on control, protection have been carried out [17].

The microgrid testbed proposed in this paper is known as the Tianjin University microgrid testbed (TUMT). It is a highly integrated and reconfigurable microgrid testbed with distinctive features of.

1) The incorporation of multiple energy carriers, e.g., electricity, hydrogen, natural gas, heat, and multiple DGs, such as PVs; wind turbines; combined cooling, heating, and power system (CCHP); proton exchange membrane fuel cell (PEMFC); and different kinds of ESSs, etc.
2) Some converters have been specifically designed for the easy integration of different types of DGs, and the control strategies of the converters are open to researchers. Thus, researchers are able to use the existing strategies or develop their own strategies.
3) Various topologies of the TUMT are capable of meeting different research requirements in ac microgrids or in ac/dc microgrids.

The TUMT is dedicated for physical simulation and experimental research on microgrids. Based on the above-mention features, theoretical and experimental researches on DGs and microgrids are to be carried out, including: 1) the combined modeling and operation analysis of multiple energy carriers; 2) coordinated control and energy management of microgrid from an integrated view of energy systems containing multiple energy carriers, instead of focusing on electricity; 3) studies on interaction between microgrid and distribution network; and 4) the verification of microgrid protection schemes in different fault transients. Extensive research works have been conducted within the TUMT, as well as some microgrid projects such as Dongfushan microgrid [18].

The rest of this paper is organized as follows. In Section II, the composition and topologies of the TUMT are presented in detail, including testbed topologies, facilities utilized in the TUMT, classification of test structures, and the modular centralized management system (CMS). In Section III, several experimental studies are discussed. Finally, the conclusion is given in Section IV.

II. Composition and Structure of the TUMT

A. Topologies of the TUMT

The TUMT is a low voltage (LV) ac microgrid testbed, coupled to local LV grid (0.4 kV) via a three-winding power transformer. To be specific, six buses and six feeders constitute the main topology of testbed. In each bus, several switches with current transformers and potential transformers have been installed and provide unified electric interfaces to access DGs, ESSs, or loads. Buses are connected by feeders, and the parameters of feeders can be adjusted flexibly to emulate power cables in real microgrids with different lengths or types.

The topologies of testbed can be reconfigured flexibly by changing the combinations and selections of buses and feeders. Hybrid DGs and ESSs can also be connected to the microgrid optionally in each topology. The total number of the topologies with practical value is about 40 in the TUMT. The topology in Fig. 1 is type 1 indicated in Table I, and some other topology sketches are also shown in Table I.

Topologies in Table I are mainly aimed at studying the practical microgrids with various topologies, e.g., nonradial topology of type 15 is more appropriate for the verification of power control and sharing strategy for power electronic interfaced DG units connected to the same bus [19]. Note, that the process of topology reconfiguration is conducted offline. For example, the connecting change of feeder L5 from bus E to bus C in Fig. 1 will fulfill the reconfigurability from type 1 to type 3 in Table I.

B. Hybrid Distributed Energy Sources in the TUMT

Renewable energy applications involve several different subjects of study such as chemistry and thermodynamics, and integrate multidisciplinary research efforts. In the TUMT, there are various DGs and ESSs, including fixed PV systems, dual-axis solar tracking PV system, wind turbines, PEMFC, CCHP, vanadium redox flow battery (VRB), flywheel, ultracapacitor, and compressed air energy storage (CAES) system, etc. Apart from electrical power, there are other energy forms, such as hydrogen, heating, etc. The total rated capacity of DGs is 113 kVA and ESSs is 308 kWh. The details are summarized in Table II, and will be fully discussed below.

As shown in Table II, there are three types of PV panels installed on the building roof, namely monocrystalline silicon PV panels, polycrystalline silicon PV panels, and thin film PV panels. The peak power of the three fixed PV panel sets is 30 kW in total, and 10 kW of each. For comparison purposes, different connection structures are adopted in the three PV systems. Specifically, PV panels of the thin film PV system are connected to the testbed via a three-phase inverter and an isolation transformer. Another type of three-phase inverter is adopted in polycrystalline Si PV system, and is connected to the microgrid by a step-up transformer. In monocrystalline Si PV system, three single-phase inverters are deployed. In addition, lead-acid batteries are installed in both two crystalline-Si PV systems.

Likewise, the peak power of the dual-axis solar tracking PV system is also 10 kW. The control schemes embedded in the system controller is mainly based on altitude and azimuth angular position of the sun in order to make PV panel face in the direction of maximum irradiation to boost the efficiency.

Apart from PV systems, eight wind turbines with permanent magnet synchronous generators (PMSGs) are installed on the building roof. These wind turbines can be divided into two kinds, namely vertical-axis type and horizontal-axis type. The rate power of each generator is 1 kW. Moreover, six of them constitute two three-phase generation systems, and the other two are connected to single-phase lines of testbed via back-to-back converters. They have better availability in low wind speed circumstances and smaller energy loss, but require more intricate control strategies.

The wind power simulation system for doubly-fed induction generator (DFIG) consists of a DFIG, a prime motor, converters, and control system. The prime motor is adopted to simulate the wind turbines that drive the DFIG, and its

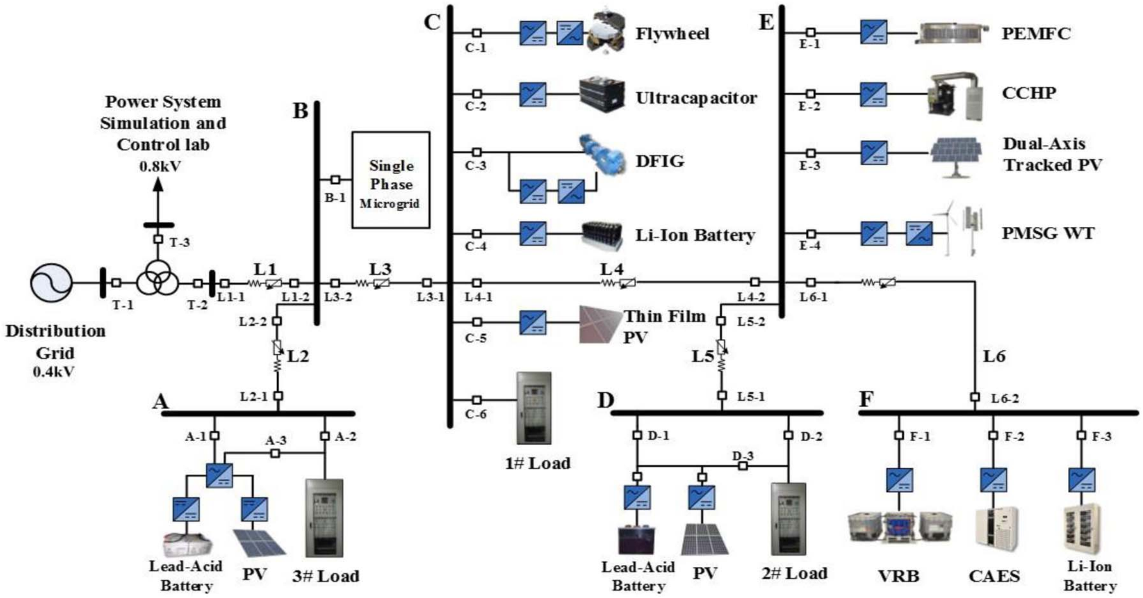


Fig. 1. Typical topology of the TUMT.

TABLE I
SOME TOPOLOGY SKETCHES IN THE TUMT

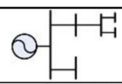
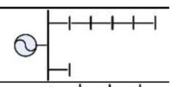
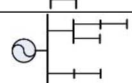
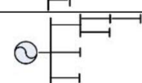
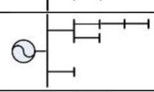
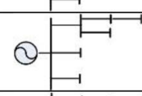
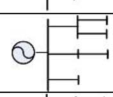
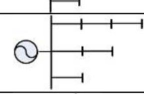
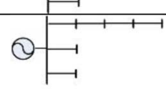
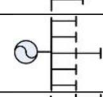
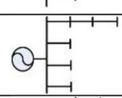
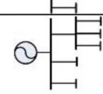
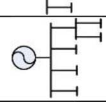
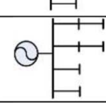
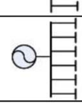
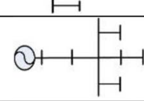
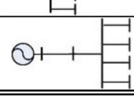
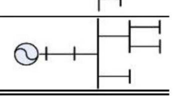
Types	Topologies	Types	Topologies
1		2	
3		4	
5		6	
7		8	
9		10	
11		12	
13		14	
15		16	
17		18	

TABLE II
DGS AND ESSS IN THE TUMT

Type	Component	Specification
DGs	Polycrystalline Si PV	10 kW
	Monocrystalline Si PV	10 kW
	Thin film PV	10 kW
	Dual-axis solar tracking PV	10 kW
	wind turbines with PMSGs	8 × 1 kW
	wind power simulation system for DFIG	30 kVA
	CCHP	30 kW
	PEMFC	5 kW
ESSs	Flywheel	250 kVA × 90 s
	Ultracapacitor	30 kW × 60 s
	Lithium-ion battery	2 × 30 kW × 4 hr
	Lead-Acid battery	2 × 10 kW × 2 hr
	VRB	5 kW × 4 hr
	CAES	85 kW × 15 min

speed can be adjusted by the control system to simulate output characteristics of the wind turbines in different wind speeds.

The CCHP system in the TUMT is constituted by a micro-turbine, a lithium bromide-water absorption chiller and water circulation system. By consuming natural gas, the micro-turbine generates electricity and by-product of high temperature exhaust fumes, then the lithium bromide-water absorption chiller transfers thermal energy from the exhaust fumes to rooms. In this process, water is used as the refrigerant and lithium bromide as the absorbent. When thermal requirement of the room was satisfied, thermal energy would be stored in two underground pools for later use. The controller of CCHP connects directly with the management system of the testbed to decide the system operation whether in grid-connected modes or in islanded modes.

Hydrogen storage system is another form of energy storage. It is comprised of a hydrogen production unit, a PEMFC generation unit, and a hydrogen tank. The electrolyzer of the hydrogen production unit absorbs electricity from ac bus to produce H_2, and transfers electricity to chemistry energy. The fuel cell generation unit could generate electricity for loads in the same ac bus.

According to the time duration of charging and discharging, ESSs in the TUMT could be divided into two classes.

1) The long-term ESSs, comprised of the VRB, Lithium-ion (Li-ion) battery, and the CAES, are applied to maintain long-lasting energy supply in testbed.
2) The short-term ESSs, including ultracapacitor and flywheel with extremely high energy densities and fast

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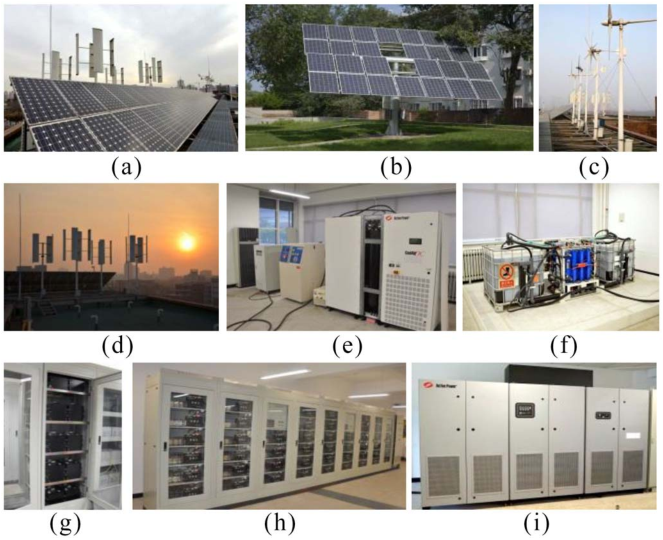

Fig. 2. Parts of DGs and ESSs in the TUMT. (a) Fixed PV. (b) Dual-axis solar tracking PV. (c) Horizontal-axis PMSG wind turbines. (d) Vertical-axis PMSG wind turbines. (e) CAES. (f) VRB. (g) Ultracapacitors. (h) Li-ion battery. (i) Flywheel.

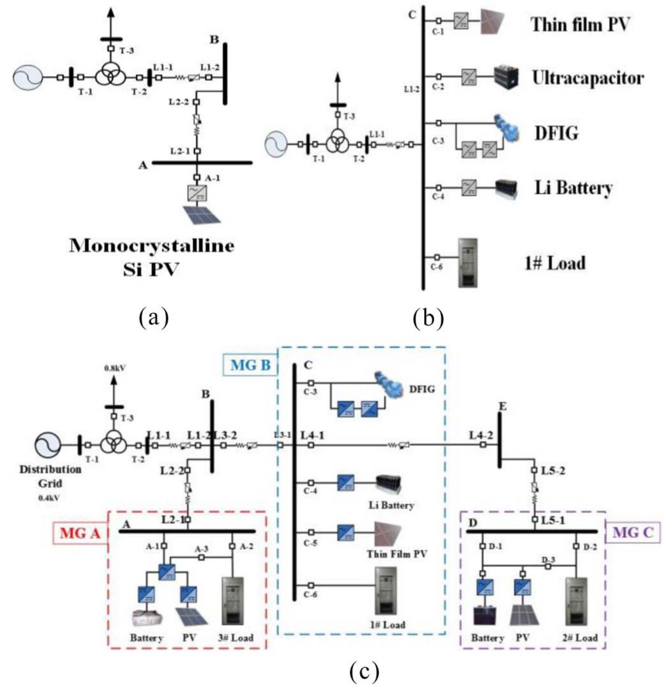

Fig. 3. Categories of tests. (a) Mode 1, single source in single bus. (b) Mode 2, multiple sources in single bus. (c) Mode 3, multiple sources in multiple buses.

response time, are often used for minimizing power spikes or power fluctuations.

The VRB system generates power by the redox reaction of vanadium, which consists of reservoirs and ion exchange membranes. The data of stack voltage and state of charge can be delivered via RS485 communication interface.

Li-ion battery ESS has functions of data collecting, temperature detecting, SoC calculating, current balancing, etc. The battery management system (BMS) integrated in the Li-ion battery ESS includes battery management units (BMU) in the bottom layer, battery cluster management systems (BCMS) in the middle layer and battery arrays management system (BAMS) in the top layer. For the sake of the CMS dispatching, BMU in the bottom layer collects and delivers data of each battery to the BCMS and BAMS successively in real time. Furthermore, the BMS is able to turn off the dc switch in time for safety whenever temperatures or voltages of battery cells are beyond protection setting value continuously.

Unlike battery-based ESS which combines a large number of battery cells in series and parallels, the CAES is comprised of an air compressor, air tanks, a thermal storage unit (TSU), turbine, a small flywheel, and converters. Conventionally, air tanks, in which compressed air is stored, are maintained at full capacity by online compressor. When the CAES discharges, the high-pressure compressed air is constantly released from the air tanks, and drives the turbine after heated in TSU. Meanwhile, the flywheel in parallel connection uninterruptedly provides electrical power until the turbine spins up.

Flywheel is a short-term ESS in which energy can be transformed between machinery and electricity rapidly. Once power is demanded, the flywheel converts mechanical energy to electricity with continuous declination of flywheel speed. Parts of DGs and ESSs in the TUMT are shown in Fig. 2.

Additionally, there are some auxiliary devices available for wide range applications, such as active power filter, simulated loads, fault simulator, battery testing equipment, transformer, and induction voltage regulator, etc. Specifically, active power filter is utilized to suppress microgrid testbed harmonics. Fault simulator generates a variety of precisely controllable faults (i.e., fault duration, types, and location are controllable). Battery testing equipment enables programmable test schemes for most of battery based ESS (e.g., life cycle, quality control test). Transformer and induction voltage regulator plays an important role in testbed voltage adjustment under normal working condition, and limits fault circuit current injected from the grid when faults occur in the testbed.

C. Categories of Microgrid Tests

In the TUMT, characteristics and status of practical microgrids can be simulated by the microgrid testbed in laboratory environment. Numerous tests can be carried out with different combination and location of DGs and ESSs for specific research objectives, but they can be divided into three categories considering some structural similarities among connection modes. To be specific, these categories are (ranging from simple to complex): 1) Mode 1, single source in single bus mode; 2) Mode 2, multiple sources in single bus mode; and 3) Mode 3, multiple sources in multiple buses. Taking example for the topology of the TUMT in Fig. 1, the typical test categories are shown in Fig. 3.

In Mode 1, only one DG or ESS is connected, and probably a set of simulated load is matched for it. This category of tests mainly focus on performance analysis and modeling of DGs or ESSs, which are basic researches of microgrid. Fig. 3(a) is an example of Mode 1, in which monocrystalline Si PV system is connected to bus A. Based on the experiment results, PV models can be evaluated for microgrid transient analysis or power dispatch.

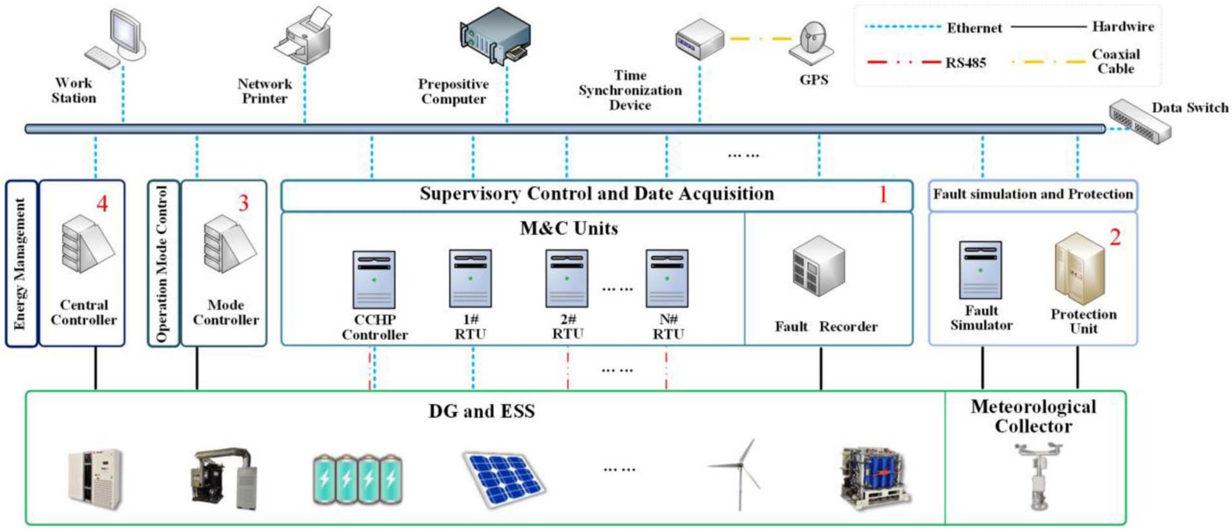

Fig. 4. Architecture of the CMS in the TUMT.

In Mode 2, coordinated operation methods and energy management strategies are the major focuses for both grid-connected [20], [21] and islanded operation modes [22]. Fig. 3(b) is an example of Mode 2. Thin film PV system, DFIG, ultracapacitors, batteries, and loads are integrated into bus C to form a hybrid microgrid. DGs and ESSs often have different dynamic behaviors, and the interaction among them have great impacts on stability of microgrid. With respect to such influences, control schemes should be designed to ensure the stability of microgrid and the optimal operation of DG and ESS at the same time.

In Mode 3, this category of tests mainly concentrates on microgrid comprehensive control. Under normal condition, energy management strategies should be implemented to improve microgrid performance, such as operation cost minimization [23]. Further, transient dynamic behavior, such as fault analysis [24], should also be investigated to enhance the stability of microgrid. Fig. 3(c) is an example of Mode 3. DGs and ESSs are located in three buses to simulate three microgrids (i.e., MG A, MG B, and MG C) controlled by their respective microgrid operation strategies.

D. CMS

For an integrated microgrid testbed, a comprehensive real-time management platform is necessary for testbed monitoring, test implementation, and control strategies deployment and verification.

The modular CMS is such a management system that has a flexible architecture as shown in Fig. 4. It can be categorized into four groups based on its functions: 1) the supervisory control and data acquisition (SCADA) unit; 2) the fault simulation and protection unit; 3) the operation modes control unit; and 4) the microgrid energy management unit.

In the CMS, the supervisory control and date acquisition unit is designed to collect data of the whole testbed. It consists of two parts, the measuring and control (M and C) units and the fault recorder, and has different data sampling frequency. The sampling frequency of M and C units is 2 Hz via the interface of RS-485 or Ethernet, while the frequency of the fault recorder is 5000 Hz via cable connection. The data collected by M and C units in low frequency can successfully be provided to hourly-based energy management of microgrid. The frequency of the data sampled by fault recorder is relatively high, which can be used for transient analysis and DG control both in grid-connected and islanded modes.

Fault simulation and protection unit is employed in the CMS to simulate faults and deploy protection schemes, in order to investigate fault transient and guarantee the correct removal of system faults.

The mode controller in the operation mode control unit is responsible for microgrid mode transition between islanded mode and grid-connected mode. Control strategies of distributed energy sources can adjusted online for new operation condition. On the other hand, the mode controller can regulate operation states of DGs and ESSs in order to reduce the difference (e.g., voltage magnitude, frequency, and phase angle) and exchange power between the microgrid and the local grid to meet the requirements of mode transition.

The central controller in microgrid energy management unit can not only execute present energy management strategies for the microgrid energy optimization, but also use the data collected by SCADA unit to figure out the new commands for the next control period.

The other parts of the CMS include time synchronization device for data time tagging, work stations for history events recording, etc.

The modularization design of the CMS makes easy access for each unit, and it is conducive to function extension in future development.

III. Experimental Study

The TUMT is a testbed designed for physical simulation and experimental research on microgrid. It is able to assist topologies planning, control strategies validation, and optimization of microgrid in projects. It has been used for the early stage studies of many practical projects. Take an example for

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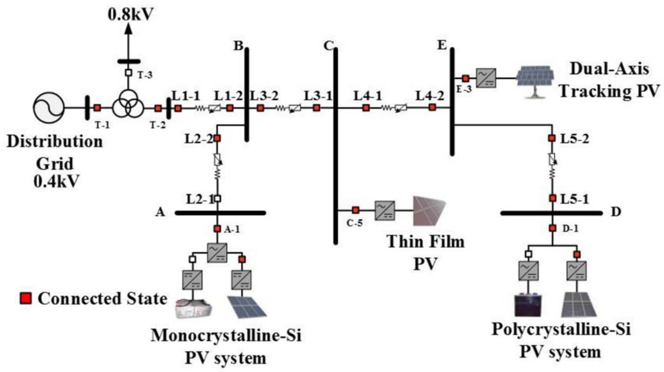

Fig. 5. Schematic of the PV comparison test.

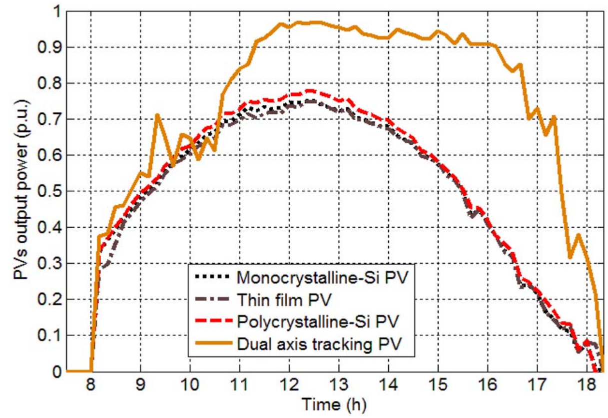

Fig. 6. Output power of PV systems.

Dongfushan microgrid projects, which is a stand-alone microgrid constructed in Dongfushan island of China. The microgrid is a hybrid ac/dc microgrid, incorporated with PV system, wind turbines, batteries, and loads. Based on TUMT, the structure design, control strategy, energy management method, etc. have been studied before it was constructed. Now, the Dongfushan microgrid has been in operation for more than two years. It is verified that such a testbed is very powerful and many key issues can be solved before the construction of a practical project.

Extensive research works on microgrid have also been carried out. It covers various aspects of microgrid application, such as performance evaluation of DGs and ESSs, coordinated control of the hybrid microgrid system, fault transient of microgrid, and cluster management of multimicrogrids. In this paper, some experimental case studies are shown: 1) DG and ESS performance evaluation study, which focuses on transient and steady-state performances of DGs and ESSs under normal operation condition; 2) coordinated control of hybrid microgrid system, which is designed to verify the effectiveness of control strategies in a hybrid ac/dc microgrid; and 3) fault transient and protection scheme, which is conducted with the aim of microgrid performance analysis under fault conditions and the effectiveness of protection scheme demonstration.

A. Performance Evaluation of DG and ESS

Performance evaluation of DGs and ESSs are to evaluate the operation behavior of renewable energy units within the limits of the nominal range, including MPPT analysis, comparison tests, load tracking capacity under different conditions, etc.

To take an instance of the comparison test of PV systems, this test focuses on performance comparison between different types of PVs. Four PV systems are integrated in Mode 3 (multiple sources in multiple buses). Fig. 5 shows the schematic of this test. As mentioned before, thin-film PV, monocrystalline-Si PV, and polycrystalline-Si PV are three fixed PV systems, which PV panels are mounted on fixed frame facing south with the tilt angel of 35°. The dual-axis tracking PV system can track the altitude and azimuth angular of the sun. The peak power of each PV system is 10 kW.

The data were measured from 8:00 until 18:10 on a clear sunny day, and collected at intervals of 10 min by the CMS. As it can be seen in the Fig. 6, because of the same tilt angle and rated capacity, the output power of the three fixed PV system have little difference from each other, and only maintain the maximum for a few hours in the middle of the day. The output power of the dual axis tracking PV system is higher than the three fixed PV systems at most of time. From 11:00 to 18:10, the dual-axis tracking PV system provides better performance as compared to the fixed PV systems due to its tracking capability. The energy output of the tracking PV is nearly 50% higher than the fixed PV systems.

Nevertheless, it can be observed that from 8:00 to 11:00 the output power of the dual axis tracking PV system is similar to the fixed PV systems. This is because that the dual axis tracking PV system is in the shadow of nearby trees and buildings during this time. After 11:00, the output power of dual axis tracking PV system shapely increases because it goes out of the shadow.

B. DC Bus Voltage Control in Hybrid AC/DC Microgrid

This test is designed to verify the effectiveness of control scheme of dc bus voltage control in a hybrid ac/dc microgrid. In a hybrid ac/dc microgrid, it is a critical problem that the dynamics of dc bus voltage exert a strong influence on the microgrid operation. Voltage fluctuations of dc bus could incorrectly trigger dc protection so that power supply will be disrupted in dc microgrid or even in the whole microgrid. To improve the dynamic regulation of dc bus voltage, practical dc bus voltage control schemes should be verified by experimental case studies. In the TUMT, several experimental studies have been conducted to verify the effects of different dc bus voltage control schemes [25].

Fig. 7 is the schematic of dc bus voltage control test. The dc microgrid, is considered to be a miniature power generation and ESS, which is able to track the dispatched power in combination with DGs deployed in ac bus. It is connected to ac bus via an ac/dc converter with bidirectional power flow capability. In dc microgrid, three dc/dc converters are employed to integrate units of ultracapacitor, Li-ion battery, and thin film PV panels with the common dc bus. For its fast-respond dynamic, the ultracapacitor unit is applied to stabilize dc bus voltage in this test. Additionally, the utilization of the bidirectional ac/dc converter and the other two dc units (Li-ion battery unit and thin film PV unit) are used, on the one hand, to control the

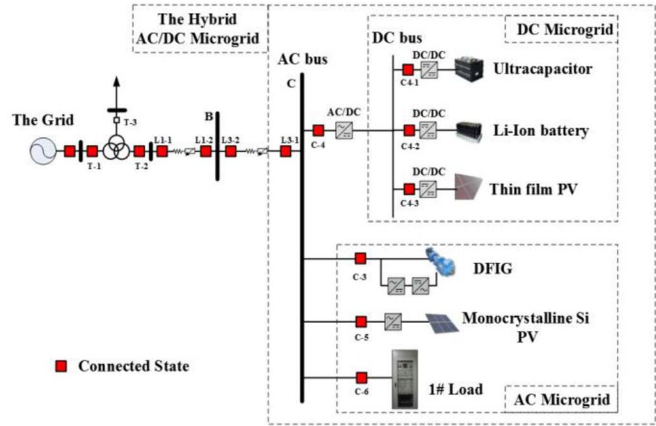

Fig. 7. Schematic of dc bus voltage control test.

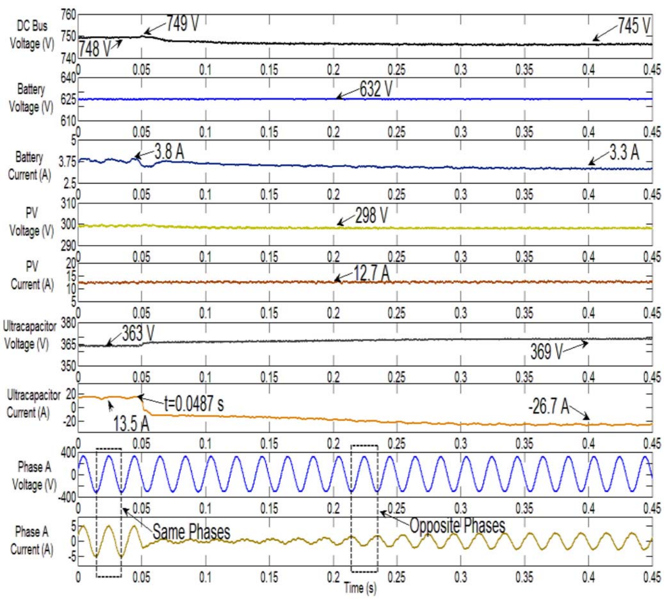

Fig. 8. Experiment results in dc bus voltage control test.

power flow between dc microgrid and ac microgrid, on the other hand, to ensure energy balance within dc microgrid.

In the test, the initial power, fed into the ac microgrid from dc microgrid, is about 10 kW, which is controlled by the ac/dc converter. Meanwhile, power output of PV unit and battery unit are about 3.8 and 2.4 kW, respectively. To maintain the dc voltage around 748 V, the ultracapacitor current (13.5 A on average) varies according to energy balance needs of dc microgrid in the range of 12.3 to 14.7 A (the ultracapacitor voltage is around 363 V), as shown in Fig. 8.

At $t = 0.0487$ s, a power disturbance is introduced into dc microgrid to emulate power exchange fluctuations between the dc and ac bus. The power flow reference of dc microgrid is abruptly changed from 10 to -5 kW, with the result that the ac current (shown as phase A current) and ultracapacitor current are sharply decreased. However, under the dc voltage control scheme embedded in dc/dc controller, the dc bus voltage fluctuation goes below 749 V. It takes about 0.35 s that dc voltage reaches the steady state of 745 V. During the transient, the battery unit has a smooth transition from 3.8 to 3.3 A. The decrease of ultracapacitor discharge current from 13.5 to -26.7 A leads to a slight rise in ultracapacitor voltage from 363 to 369 V shown in the sixth plot of Fig. 8. The change of power flow can be figured out by comparing the current and voltage of phase A in terms of magnitude and phase.

During this test, dc bus voltage of dc microgrid is hardly affected by the large power disturbance under dc bus voltage control scheme. The voltage fluctuation is less than 4 V, which indicates that the dc voltage control scheme is effective.

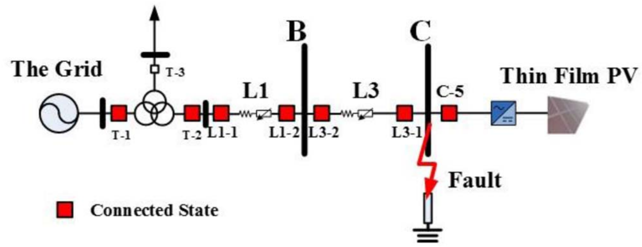

Fig. 9. Schematic of fault transient and protection test.

C. Fault Transients and Protection Schemes

With the growing deployment of RESs in microgrid, DGs and ESSs exert considerable influence on microgrid control schemes when faults occur. There is an urgent need for practical microgrid protection schemes, since it enables the correct removal of power system faults under various faulty conditions. In the TUMT, different faults are simulated, in terms of fault types, locations, and duration, to exploit fault transients and protection coordination of renewable energy facilities and microgrids.

This test is aimed to verify protection schemes of renewable energy facilities. Taking example for thin film PV system, Fig. 9 is the schematic of the fault transients and protection tests of PV system. Before fault occurrence, thin film PV system operates in grid-connected mode and delivers power to the grid with the initial RMS current value of 8.1 A. To evaluate facility protection schemes employed by inverter-based PV system (over-current protection is primary protection, and the preset value is 25A; under voltage protection is set to be back-up protection with 0.15 s delay, and the preset value is 85% of nominal value) and fault transients, protections of the transformer and feeders are set to be inactive during this test.

At $t = 0.135$ s, a two phase to ground fault of 0.5 s duration is simulated on bus C. It results in unbalance voltage sag in phase B and C, and the voltages of phase B and C drop to 80% nominal value shown in Fig.10. During the voltage sag, the distorted fault currents of phase B and C largely injects into the testbed from the distributed network through feeder L1 and L3. The maximum value of fault current is 105 A. At the same time, the fault currents of PV system, slightly increase from 14 to 16 A. Because the fault current of the thin film PV system is far less than 25 A, the over-current protection is inactive. After 0.19 s, the PV system is disconnected by the under-voltage protection fitted in inverter when fault occurred. Totally, the actual action time is 0.19 s, including under-voltage delay set of 0.15 s and respond time of 0.04 s.

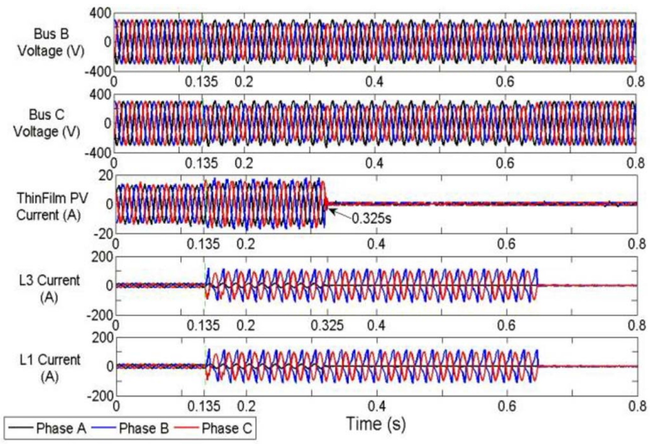

Fig. 10. Microgrid protection test in the TUMT. Two phase to ground fault on bus C, 0.5 s duration, and voltage dip of 80% rate value.

The experimental results show transients behaviors of inverter-based PV under a two-phase-fault to ground condition. With cooperation of current and voltage protection, PV system can be quickly isolated from the grid when the fault occurs.

IV. Conclusion

The TUMT is presented in this paper incorporating with DGs and ESSs of multiple energy carriers. With different combinations of buses and feeders, there are various topologies available to meet different research requirements. Three categories are used for classification of microgrid tests on the basis of the connection modes ranging from simple to complex. To manage this complex microgrid testbed effectively, the modular CMS with four functional groups has been built to control the TUMT remotely.

The TUMT is designed for physical simulation and experimental research on microgrid. Extensive project simulations and experiments involving different research fields have been carried out. Dongfushan project and some experimental tests are shown in this paper. The continuous operation of the project and results of the tests indicate that such a testbed is very powerful to conduct researches on major issues of microgrid.

At present, the TUMT is well designed for accessing new units and controllers readily. In order to improve the interoperability and versatility for microgrid controllers, further researches are being conducted such as the application of IEC61850.

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Chengshan Wang (SM’11) received the Ph.D. degree in electrical engineering from Tianjin University, Tianjin, China, in 1991.

He is currently a Professor with the School of Electrical Engineering and Automation, Tianjin University. His current research interests include distribution system analysis and planning, distributed generation system and microgrid, and power system security analysis.

Xianshen Yang was born in Hebei, China, in 1982. He received the B.S. degree in electrical engineering from North China Electric Power University, Baoding, China, in 2008. He is currently pursuing the Ph.D. degree from the School of Electrical Engineering and Automation, Tianjin University, Tianjin, China.

His current research interests include modeling and optimization of hybrid energy system.

Zhen Wu received the B.S. and Ph.D. degrees in electric engineering from Tianjin University, Tianjin, China, in 2009 and 2014, respectively.

His current research interests include modeling and simulation of microgrids and energy storage system.

Yanbo Che received the B.S. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1993, and the M.S. and Ph.D. degrees in electrical engineering from Tianjin University, Tianjin, China, in 1996 and 2002, respectively.

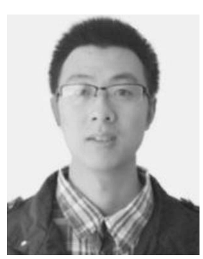
He has been engaged in teaching and scientific research of power electronic technology and power systems since 1996. He is currently an Associate Professor with the School of Electrical Engineering and Automation, Tianjin University.

Li Guo (M’11) received the B.S. and Ph.D. degrees in electrical engineering from the South China University of Technology, Guangzhou, China, in 2002 and 2007, respectively.

He was with Tianjin University, Tianjin, China, as a Post-Doctoral Fellow from 2007 to 2009. He has been an Associate Professor with Tianjin University since 2009. His current research interests include optimal planning and design of microgrid, the coordinated operating strategy of microgrid, and the advanced energy management system.

Shuhuai Zhang received the B.S. degree in electrical engineering from Tianjin University, Tianjin, China, in 2012, where he is currently pursuing the Ph.D. degree.

His current research interests include microgrid control, dc–dc converters, and soft switching.



Yixin Liu was born in Fujian, China, in 1989. He received the B.S. degree from the School of Electric Engineering and Automation, Tianjin University, Tianjin, China, in 2009, where he is currently pursuing the Ph.D. degree with the Department of Electrical Engineering and Automation.

His current research interests include the energy management system of microgrid, and control of the distributed generations and microgrid.