Microgrid System and Component Evaluation: Mobile Test Platform with Battery Storage

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***Abstract*— This paper describes a mobile test unit designed to address challenges in deploying smart microgrid systems with battery energy storage. Despite the large body of knowledge around microgrid design and control, there is a limited understanding in the practical deployment and real-world operation of microgrids. The mobile and flexible test system has been built to better understand the operation and performance of microgrid systems and energy storage systems, and to provide a platform for advanced testing, training and research. The system is housed in a custom-built shelter containing a 273kWh Li-ion battery, 270kW bi-directional inverter, 350kVA isolating transformer, switchgear and protection systems required for grid connection. An advanced internet of things control system is used, and connects to the distribution network's control system. A flexible high-speed data acquisition and long-term data logging system captures power flow, power quality values, high resolution event waveforms, and environmental measurements.**

***Index Terms*—Battery energy storage, nanogrid, microgrid, smart grid.**

I. INTRODUCTION

The primary requirements in a power grid are to deliver power safely with high quality, high reliability and at low cost. The recent increase of intermittent renewable energy generation, particularly PV generation, has changed the load profile [1] and the balance between load and generator. This not only impacts the reliability of the grid, but also affects the power quality [2] and the stability of the power system [3].

Energy storage systems (ESS), particularly battery storage, can improve reliability, and are a key technology for integrating intermittent renewable energy sources [4]. Energy storage can improve power quality [5][6]. however, smart grid technologies may also have adverse consequences on power quality [7], hence a better understanding of these technologies is required.

Demand side management aims to improve the balance between generator and load by controlling the load shape [8]. Energy storage in a smart grid can perform load shaping [9]. There is also a recent focus on energy sharing, supported by underlying energy storage devices [10], and there has been an increased focus on community energy storage (CES) [11].

Battery energy storage can improve reliability and help mitigate the issues caused by renewable generation, when used with the right control methods [1]. Decentralised control may be fully distributed [12], but may also exist as a part of a hierarchical control structure [4], where the distribution network service provider (DNSP) dispatches commands to a microgrid or nanogrid system, allowing for aggregated energy sources to appear as a virtual power plant [13].

The *Internet of Things* (IoT) can provide a platform for the control of smart grids, and integrate into smart home systems and domestic appliances [14]. IoT based approaches are also considering contingency management and the handling of faults [15]. Building on the IoT platform, *fog computing* for microgrids extends the concept of cloud computing to the edge of the network [16], enabling lower latency communication.

Many of the methods and techniques in literature have not been tested in microgrid systems [4]. This paper describes a mobile and flexible smart microgrid test system, with IoT based control system, that has been developed to better understand the component level interactions, power quality, and real-world power system interactions of a microgrid system.

II. REVIEW OF TEST SYSTEMS

There have been efforts to better understand the operation of smart grids and energy storage systems through experimental testing and verification.

A PV measurement campaign is described in [2] for a 20kW PV system, with a focus on the power quality of both AC and DC sides of the system. Power measurements were made using a LabVIEW based data acquisition system, and a pyranometer was used for measuring solar irradiance.

Xtreme Power developed a hardware in the loop (HIL) battery energy storage test system for the evaluation of control system components [17]. The fixed location system is operated by a LabVIEW and MATLAB/Simulink based control system, and has been used to test a 1MW/1MWh battery energy storage system.

DC interconnected nanogrids are studied in [18], including control and communication strategies. A full-scale experiment was conducted on the author's university campus, that involved distributed PV panels and battery storage.

The transient performance of hybrid AC/DC microgrids is studied in [19], with tests involving 15.5kW of PV panels, micro-turbine, and a lithium-ion battery energy storage system.

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Battery storage mitigating the effects of high PV generation was investigated in [20]. Lab based tests used a power system simulator, 1.7kW PV inverter, 5kW/13kWh lead acid battery, and LabVIEW based control system.

III. MICROGRID AND ENERGY STORAGE TEST SYSTEM

The Australian Energy Storage Knowledge Bank (AESKB) mobile test system is designed to address the challenges of deploying smart microgrid systems with battery energy storage. The aim is to better understand the performance and operation of smart microgrids, and to provide a platform for advanced testing, training, research and knowledge sharing. The test system is portable, allowing it to be used in the field anywhere in Australia. The system can be operated in various on-grid and off-grid applications, as part of a microgrid, and operated with multiple distributed generation sources that include diesel, PV, and wind generators.

A. Power System Overview

The test system is built in a custom insulated shelter that houses a 273kWh Lithium-ion battery, a 270kW bi-directional inverter operated as a voltage source with virtual synchronous machine functionality, a 350kVA isolation transformer, and an 800A AC switchboard that contains all the switchgear and protection systems required for safe automatic and manual operation, LV grid connection as well as smooth separation and re-integration of the microgrid from/to the main grid.

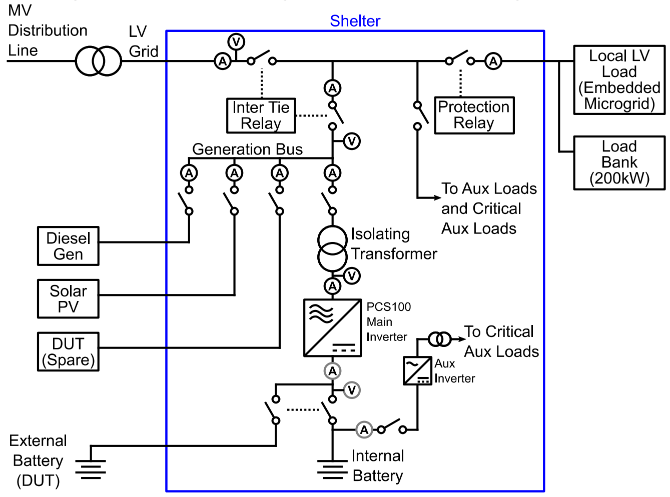

Fig. 1. Mobile test system single line diagram.

The system includes several external connections to provide flexibility in test and operating modes, and to allow for future expansion. The system can be inserted between the grid and an LV load or microgrid, and can also directly connect to several AC generation sources. The DC bus is also externally accessible, allowing for the connection of external batteries.

B. Operating Modes and Control Modes

The flexibility of the switchgear and control systems allows for a range of operating modes. The system may operate parallel to the mains with or without islanding, parallel to the mains with an embedded autonomous LV microgrid and/or PV and diesel generator, and parallel to isolated microgrid [21]. These operating modes allow for testing and investigation of desirable smart grid features including feeder peak load lopping, energy arbitrage, intentional islanding or islanding on loss of supply, grid voltage support or island voltage control, grid frequency support or island frequency control, PV ramp rate control and curtailment. Moreover, the individual performance of microgrid and energy storage components during these operations can be examined, with light being shed on interactions between components, the grid, and external loads/embedded microgrids. Because testing and evaluation in the field is possible, components can be evaluated in terms of the reaction to network faults, poor power quality, and extreme weather events.

C. Control System

The control system is built on the Parallel Distributed Energy Resources Control System (PaDECS®) developed by Power Technology Engineered Solutions Pty. Ltd.. The PaDECS system is an IoT based distributed control system for smart grid applications, including nanogrid/microgrid and community energy storage (CES) applications [22].

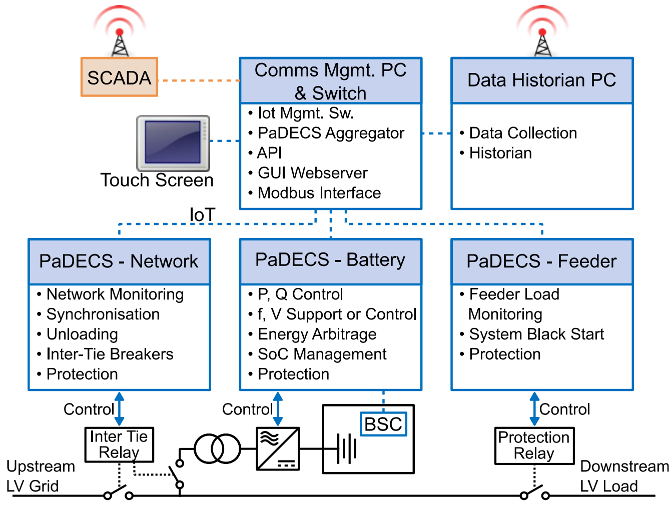

Fig. 2. IoT control system architecture.

The control system offers flexible wired and wireless communication methods and offers a so-called fog computing platform, i.e. it uses IoT communication technologies in combination with a local server for fast, real-time responsive control. This approach allows for fast aggregation of power, energy and status data of the distributed energy sources and loads, where the aggregated data is used in each parallel controller to locally determine the optimal control action. The local server ("Aggregator") also allows for local operation via a GUI on a touch screen, as well as for remote operation via a Modbus/TCP API. The system can also be directly dispatched by the grid DNSP via the Modbus interface to the utility SCADA system. Components can also be controlled via SCADA/DNP3.

The PaDECS platform and its modular application software provide a flexible, modern control system suitable for the operation and testing of microgrids. The control system is expandable, enabling further integration of energy sources, loads and other smart grid systems.

A data historian for long-term storage of the control system data is part of PaDECS. In addition, the Battery Section Controller, that forms part of the battery component, provides long-term records of battery data down to the cell level.

D. Data Acquisition System

To enable comprehensive data collection and analysis, a state of the art data acquisition system has been embedded throughout the test platform. The system is based on National Instruments Compact DAQ hardware that provides a modular, expandable and reconfigurable data acquisition platform. Voltage and current measurements are made in 36 locations using LEM CV 3-1000, DVL 500, and LF x10-S series transducers, and interfaced via custom signal conditioning. All measurements are sampled simultaneously with multiple sample rates between 100kHz to 500kHz. A Trimble Thunderbolt GPS disciplined frequency source drives all sample clocks, ensuring accurate sample rates and UTC aligned samples.

Environmental and weather data is also collected via ten resistance temperature detectors (RTDs) embedded in the shelter, and via an external weather station with pyranometer. This data provides a context for the behaviour of the microgrid system components, and their response to weather events.

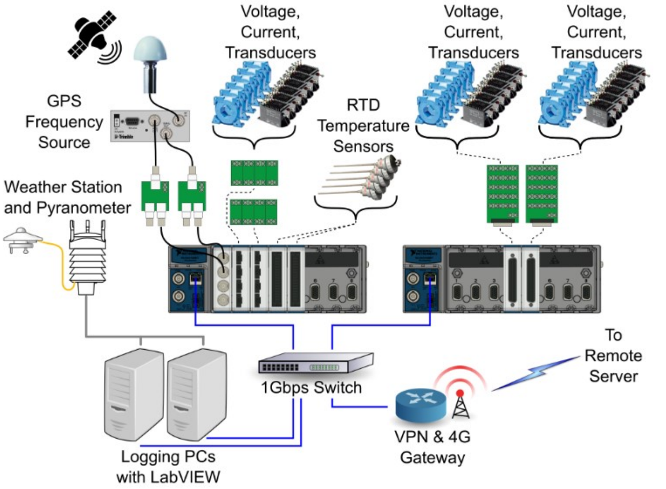

Fig. 3. Data acquisition system.

The acquired waveforms are processed by a LabVIEW based datalogging application. The application uses a modular, plug-in based analyser architecture that supports different methods and algorithms for processing the incoming data. Data may be split between multiple analyser modules at different sample rates, and modules may be rearranged or reconfigured before each test, allowing for future expansion of measurement channels. The core of the analysis is performed by an IEC 61000-4-30 based analyser module that measures the DC, RMS, power, energy, and frequency of each data channel. IEC harmonics, THD, symmetrical components, unbalance, and flicker power quality values are also measured. The methods used have been extended to 1PH AC, 3PH AC, and DC voltage and currents, where applicable. The DC power quality values (inrush, harmonics, distortion) are also of interest considering the recent attention given to DC nanogrids.

In addition to the long-term (months to years) testing and data recording offered, the acquisition system can also take high resolution waveform snapshots of critical events. Such events can be triggered by dip/swell/interruptions on any channel, with recorded waveforms spanning several seconds. Because these waveforms are taken before analysis, more advanced offline analysis can be used to evaluate the power system events that caused them.

To further enhance the reliability of the long-term data logging, the system has been deployed in a hot-standby redundant configuration. Two instances of the application run on separate computers, and monitor each other via a complex state machine. Should the primary machine become unresponsive or fail, the redundant machine will automatically take over, ensuring data acquisition and measurement continues.

IV. PRELIMINARY TEST RESULTS

Preliminary test data was collected during factory tests and commissioning in Melbourne, Australia. Fig. 4 shows a battery charging test: at t_1 the start charge command was issued for 0kW, gradually increasing the AC power to 20kW at t_4. Charging was stopped at t_5, and then the inverter was disconnected from the grid at t_6. Fig. 4 (d) shows that only reactive power is present until the inverter is enabled at t_1, resulting in significant current at the inverter terminals. Fig. 4 (f) show the total harmonic distortion (THD) in both the AC and DC currents. DC THD is measured using a modified version of the standard THD formula to produce Equation 1:

$$THD_{DC} = \sqrt{\frac{1}{I_0} \sum_{h=1}^{H} {I_h}^2}. \tag{1}$$

This measurement reflects the presence of AC grid frequency harmonics in the DC current, and can expresses how 'non-DC' the waveform has become with respect to an ideal DC current.

Fig. 5 shows raw, high speed waveforms captured in response to a DC bus voltage swell when the battery was disconnected from the inverter at t=37.494s, and the inverter automatically disabling at t=37.524s. Fig. 5 (b) highlights the presence of AC harmonics in the DC current. The inverter voltage waveforms in Fig. 5 (c) show a large amount of noise produced by the inverter switching, however the grid waveform in Fig. 5 (e), measured after the transformer, shows a clean waveform when the inverter is active or idle. Fig. 5 (d) and (f) show the distorted shape of the AC current, which is present on both sides of the transformer. Note that after the inverter stops (t=37.524s), distorted current and reactive power are still present. This is understood to be caused by the interaction of the transformer and the inactive inverter terminals with the grid. These undesirable interactions highlight the importance of a deeper understanding of power quality in smart grids.

Fig. 6 shows the inverter efficiency as a function of DC output power. This data represents intermittent operation over a single day, with each point representing a 3 second period of operation at that power level. All data points shown are for battery charging, AC to DC power flow.

The system will shortly begin a yearlong field trial in regional South Australia. The large volume of data will allow for a better understanding of long term grid performance, including seasonal variations, and the impact of an energy storage system on that location.

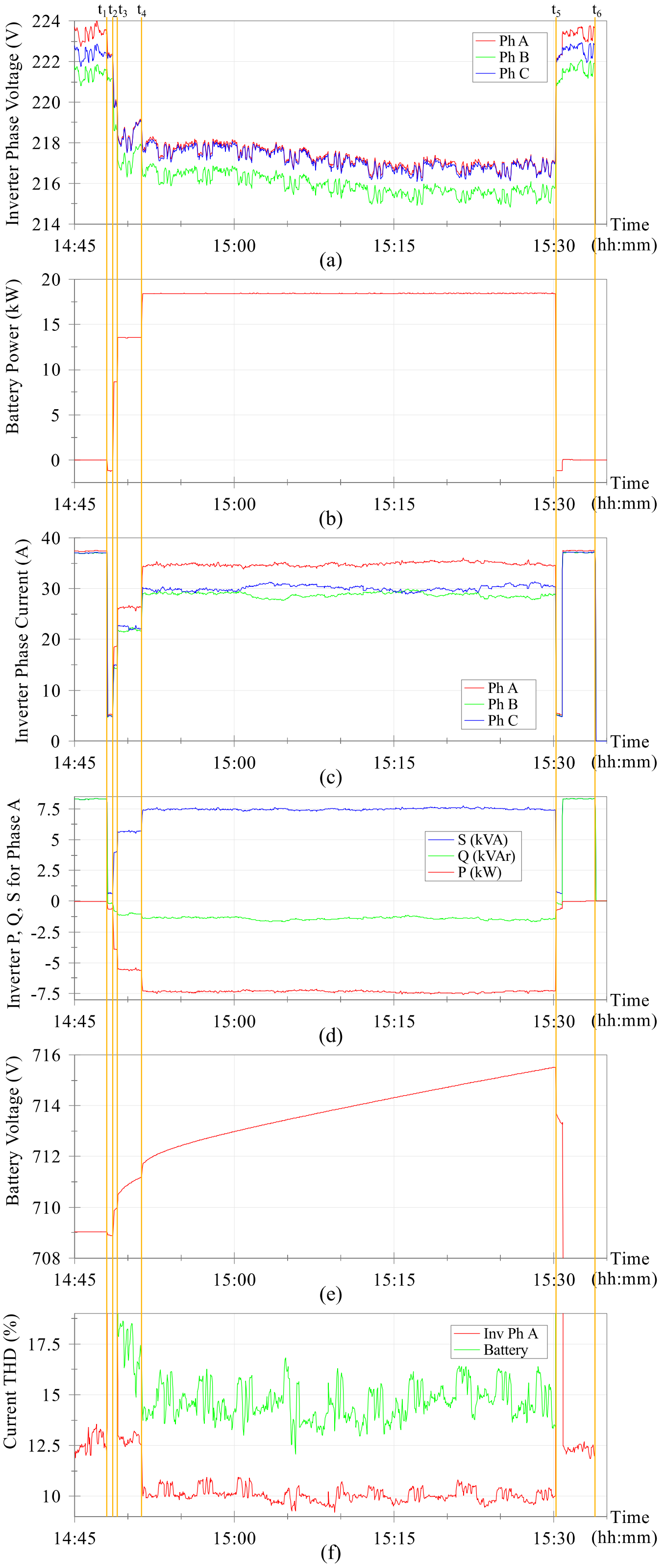

Fig. 4. 20kW charge Test.

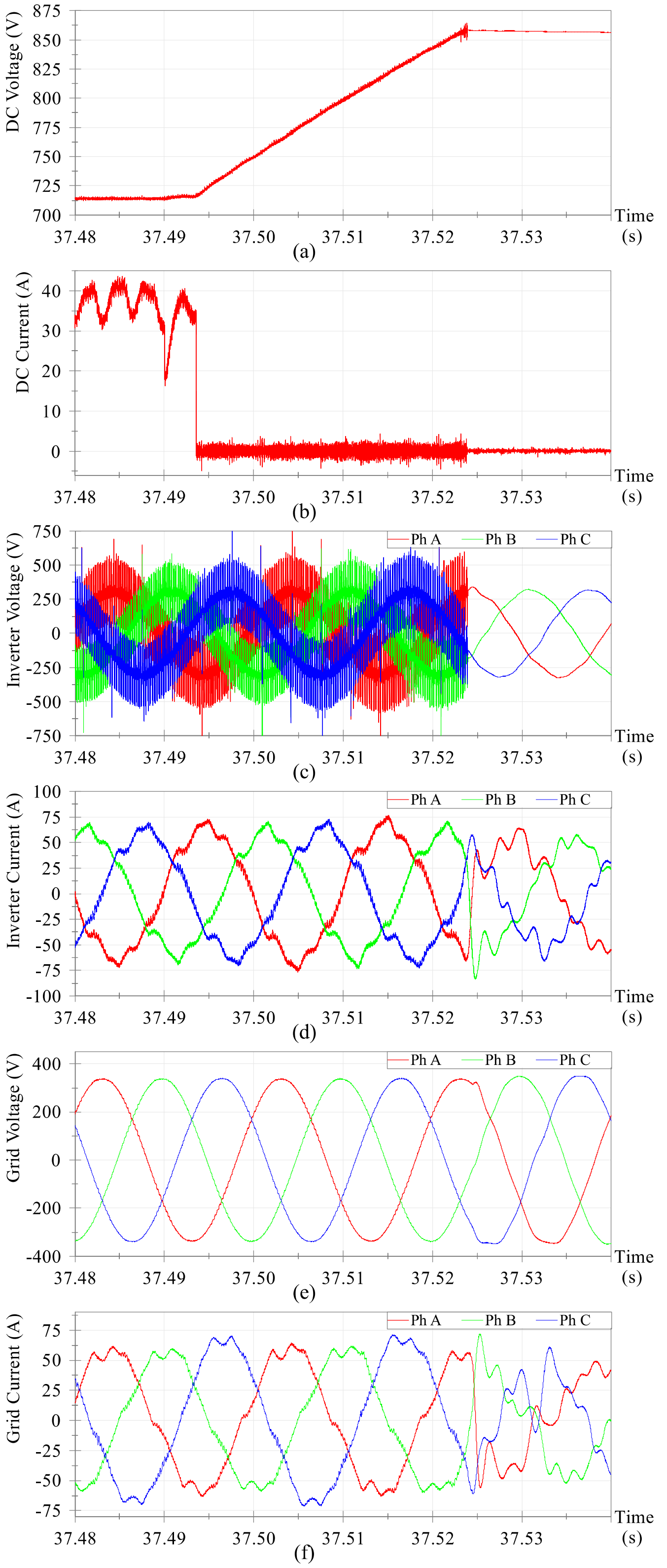

Fig. 5. Raw waveforms for a battery disconnect event.

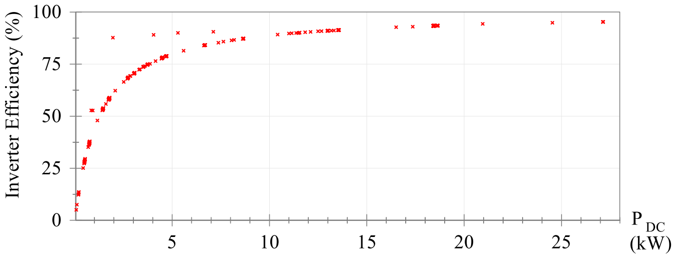

Fig. 6. Inverter efficiency vs DC output power (charging).

V. CONCLUSION

Smart microgrids and battery energy storage will play a central role in the future transformation of the electricity network. To realise the advantages of this technology without compromising the security of the power system, a deeper understanding of these emerging technologies is required. The test system described here allows for the development and real world, in-field testing needed to better understand the performance of microgrids with energy storage, and the power quality and component level interactions of these systems.

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