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Extreme Solar: Towards 24-7 Renewable Energy

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***Abstract*—This paper describes a method of connection and control algorithm for photovoltaic panel-integrated storage that can be interfaced to a grid using commercial dc-ac microinverters. Emulation of an appropriate i-v characteristic allows the integrated panel to operate with any inverter, e.g., peak-power tracking inverter, droop mode or stand-alone. or a battery inverter in droop mode. Rechargeable zinc-manganese dioxide ($ZnMnO_2$) battery cells developed by Urban Electric Power (UEP) are used as a source of energy storage. The batteries are charged with excess solar and discharged in the evening or when additional power is required. A battery management algorithm is developed, charge/discharge data is collected from each cell, and a proof of concept is demonstrated.**

Keywords*—*dc-dc bidirectional converter, Rechargeable $ZnMnO_2$ battery cells, battery, solar-PV, microinverter, bidirectional power flow, dc coupling, energy storage.

I. INTRODUCTION

Microinverters represent a mature technology and the high efficiency and reliability of microinverter enhances the power generation from individual PV panel and improve the system performance, thus, providing economic benefits [1, 2, 3]. Energy storage systems are crucial while considering standalone or grid-connected solar-PV systems. The most feasible and common configurations to couple the energy storage devices with PV systems are; (a) ac coupled PV energy storage systems (b) dc coupled PV energy storage systems, and (c) reverse dc coupled PV energy storage systems [5]. Reference [4] discusses a few other connection methods to integrate the energy storage system with PV. In dc coupling, popular method is the direct series connection of the battery in which, a diode is used to isolate the PV panel and the battery.

Most of the string inverters available in the market can work either in maximum power point tracking (MPPT) mode or the grid storage mode, and the control algorithm controls the transition between the two modes. But, the microinverters available in the market are always operating on MPPT mode to maximize power generation. Therefore, most of the microinverter-based solar-PV systems follow the ac coupled connection method as shown in Fig. 1. The main disadvantage of this connection is the poor efficiency due to multiple power electronic conversions for charge-discharge cycles [5]. To overcome this and improve the system reliability, this paper proposes a dc-coupled energy storage system for microinverter-based solar-PV power generation. The proposed method of connection and battery charge-discharge control algorithm is used to manage the PV and battery power effectively.

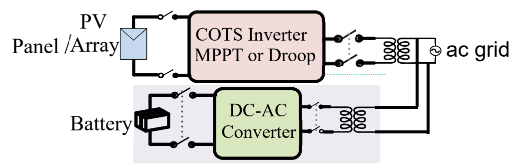

Fig. 1. Existing ac coupled system for energy management.

II. SYSTEM CONFIGURATION AND CONTROL ALGORITHM

The proposed dc coupled configuration is shown in Fig. 2. It consists of a PV panel connected to a grid-tied microinverter, and a bidirectional dc-dc converter with energy storage. A bidirectional converter based on buck and boost topologies is shown for illustration, but other topologies can be used. The dc-dc converter output is connected in parallel with the PV panel. The proposed control algorithm controls the dc-dc converter output voltage-current characteristic in a manner that allows the battery to directly charge from the PV panel and discharge through the microinverter. For example, if the microinverter operates in a MPPT mode, the controller synthesizes a peak power point corresponding to the desired battery discharge current.

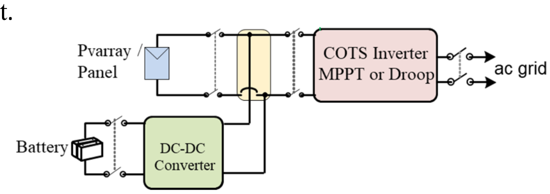

Fig. 2. Proposed dc coupled energy storage configuration with microinverter.

A. Battery Cells

The rechargeable $ZnMnO_2$ battery cells developed by UEP are used as energy storage. Fig. 3(a) shows a schematic diagram of the battery in a large cylindrical form factor. The battery cells are manufactured in fully charged state which eliminates the need of initial charge. The battery cell's open circuit voltage (OCV) is around 1.55V and the self-discharge rate is very slow at about 0.2% per month. The nominal discharge voltage is about 1.3 V. The $ZnMnO_2$ battery cell can be charged in 4 hours or less in a wide range of power levels, temperatures (between -10 to 50 ºC) and applications. Fig. 3(b) is a plot demonstrating the performance of a $ZnMnO_2$ cell tested under the IEC 61427-1 protocol for secondary cells for photovoltaic off-grid application. This solar cycling protocol has been developed so that 45 days of testing at 40°C is equivalent to 1 year of daily solar cycles at the specified nameplate capacity. In 45 days of testing, periods of low solar insolation are captured by cycling at low SoC (state of charge). Periods with excess insolation are captured by cycling at high SoC. These conditions on the average try to capture a realistic range of scenarios to which the battery systems are exposed. The UEP $ZnMnO_2$ battery cell demonstrated a cycle life equivalent to 7 years under this extremely demanding protocol.

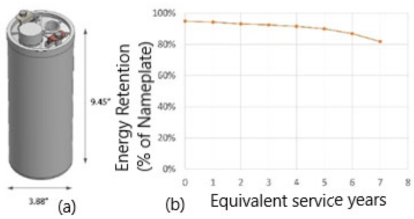

Fig. 3(a) Schematic diagram of the a UEP $ZnMnO_2$ battery cell. (b) Energy retention of a UEP $ZnMnO_2$ cell.

B. Control Algorithm

The proposed battery charge-discharge control algorithm combines a bi-directional converter current control and a

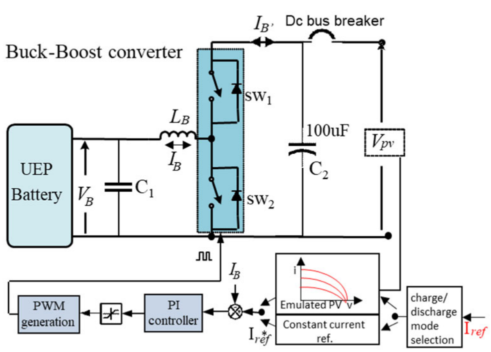

Fig. 4. Proposed algorithm for battery management.

current reference generation method for emulating the PV curve as shown in Fig. 4. The algorithm handles charging mode and discharging mode separately based on the operating conditions. The battery charges directly from PV through the dc-dc bidirectional converter with a constant current reference. In this mode, the charging current is, of course, less than the PV current at the peak-power point, thus allowing the microinverter to peak power track. But during the discharging mode, the converter emulates a PV characteristic to accommodate the microinverter MPPT Mode. The discharging mode has two different operating scenarios; (a) with PV power, and (b) without PV power. In case (a), the microinverter extracts power from both the PV panel and from the battery. In case (b), PV power is zero and battery is the only power source to the microinverter.

III. EXPERIMENTAL ANALYSIS

A proof-of-concept has been developed and consists of rooftop PV panels (Fig. 5(a)), 16 battery cells in series (Fig. 5(b)), an Enphase IQ 7A microinverter, and a dc-dc bidirectional converter (Fig. 5(c)). Texas Instruments LAUNCHXL-F28379D development kit is used as the controller, and Orion Jr. Battery Management System (BMS) is used to record the individual cell voltage, total current, and battery pack temperature. The BMS logs the data at a sampling rate of 5 samples/sec. Additionally, a novel data acquisition system is developed to collect data from the PV panel and microinverter at a sampling rate of 12 samples/min. The system parameters are given in Table I.

The proposed system is tested under different weather conditions to validate the performance. Fig. 6 shows the experimental result on a sunny day. The microinverter turns on automatically when the solar irradiation is enough to produce PV power. The red color curve indicates the PV panel output current, and blue curve represents the microinverter DC side current. When the battery discharges, then the DC side current of the inverter will be more than the PV current (blue curve above the red curve). When the battery charges from the PV current, then the inverter DC side current will be less than the PV current (blue curve below the red curve).

TABLE I. NOMINAL SYSTEM PARAMETERS

Parameters	Value
PV panel power	345W
PV panel V_{MPP}	27-35V
DC-DC bidirectional converter power	200W
DC-DC bidirectional converter inductor	270µH
DC-DC bidirectional converter capacitor	100µF
Nominal cell voltage	1-2V
Battery pack voltage	16-30V
Nominal switching frequency	15kHz

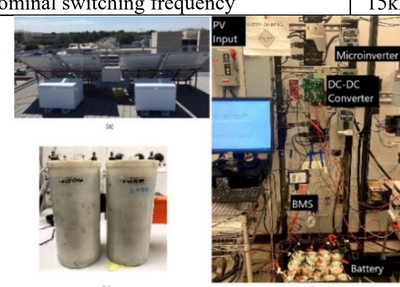

Fig. 5. Experimental setup in NMSU.

As demonstrated in Fig. 6, around 10:30 AM, the battery pack begins charging with 5A current. The PV panel current (red curve) remains same and there is change in the microinverter current (blue curve). After half an hour, the battery charging current reference is reduced to 4A and after one hour the reference changed to 3A. During the transition from 4A to 3A the converter went to unstable mode due to the microinverter ac voltage variation. After charging the battery with 3A, the converter is kept idle for few hours. During battery discharge, the PV panel breaker is turned off to test the dc-dc converter performance. A 6A discharging current reference is activated for a duration of two hours. From Fig. 6, it is clear that, both charging and discharging is seamless and the proposed method of connection and control algorithm is effective.

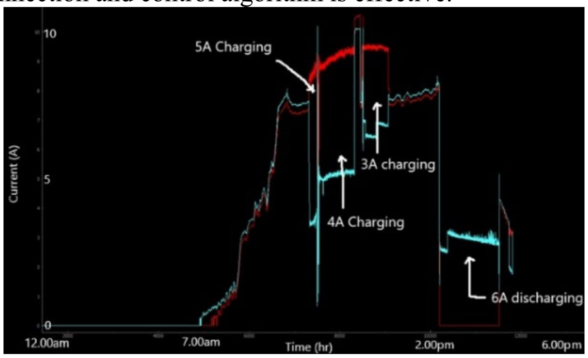

Fig. 6. Battery charge-discharge sequence on a sunny day.

The individual cell voltages from the BMS are shown in Fig. 7. As mentioned earlier, there are 16 cells in series with an upper voltage limit of 2V (each cell) and lower limit of 1V. From time 10:30am -12.30pm, the cells are in charging mode until the cell reaches a voltage of 1.8V. From 12.30pm to 2.30pm, the cells kept idle. After 2.30pm, the cells started discharging at a rate of 6A. The corresponding battery pack current is shown in Fig. 8.

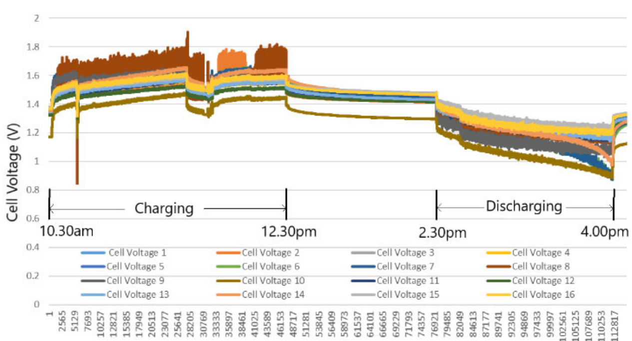

Fig. 7. Individual cell voltages.

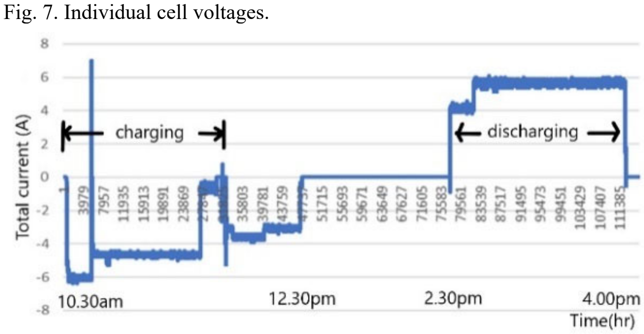

Fig. 8. Total battery pack current.

Fig. 9 shows system performance on a cloudy day. Around noon, a 2A charging current reference is given to the dc-dc converter. It can be observed that, the converter is operates in a stable during sudden change in the solar radiance due to clouds. After few hours, the PV panel circuit breaker is turned off and the battery started discharging at 5A. The above experimental results show the proof concept system is stable during the charging/discharging process.

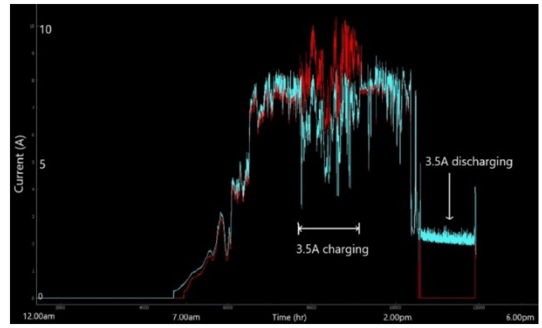

Fig. 9. Battery charge/discharge sequence on a cloudy day.

IV. CONCLUSION

A dc coupled Panel-Converter-Battery system with a novel connection method and control algorithm is proposed to achieve the seamless charging-discharging of energy storage. The dc-dc converter acts as a 'PV emulator' so that, the combination can be operated with any inverter that has a peak power tracker. As a unit, the battery and dc-dc converter can be simply connected in parallel with an existing PV system at the panel or array level. The unit can also be used for grid connection of battery energy storage using off-the-shelf PV inverters. Future work includes converter optimization and further testing including battery management and efficiency measurement. This kind of fully integrated, low-cost solar-storage system holds significant commercial potential in markets across the globe.

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