BATTERY MODULE BALANCING WITH A CASCADED H-BRIDGE MULTILEVEL INVERTER

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ABSTRACT

Electrochemical advances in lithium-ion batteries are now being complemented by advances in battery management systems (BMSs). The larger-format lithium-ion storage systems can require significant control of module balance levels, as well as temperatures and other safety parameters. Most BMSs use passive balancing, where modest amounts of energy are allowed to bleed from stronger cells to adjust average per-cell charge over a long time period. The balancing of such systems is slow and reduces battery system efficiency. In addition, virtually all BMS solutions suffer from a high degree of vulnerability to a single component fault. This paper describes an active battery module balancing system based on a cascaded H-bridge multilevel inverter that improves the speed and efficiency of balancing, while providing fault tolerance in some situations.

Keywords: battery management system, multilevel inverter, lithium titanate

INTRODUCTION

Grid Storage

As significant penetration of renewable energy sources becomes a reality, and increasing load from plug-in electric vehicles appears on the horizon, renewed attention has been directed to well-known grid challenges ranging from frequency regulation at the Independent System Operator (ISO) level down to time-of-use charge management for individual residences. It is evident that energy storage will play a critical role in addressing these challenges. Recent publications [1,2] have quantified the economic benefits of various storage applications, as well as the costs associated with storage technologies. Battery-based storage is a viable contender for a subset of these applications. The following work presents a battery storage system appropriate for the modest energy and power demands of residential, commercial, and community storage systems.

Battery Management

Large battery systems present challenges in performance, safety, and reliability. Cell chemistry and manufacturing place an upper bound on these metrics. However, the operational features of a battery management system (BMS) to a large extent determine whether the overall system meets its anticipated goals in practice. A BMS typically consists of cell voltage and temperature monitoring to prevent failures, and balancing circuits that compensate for capacity mismatch among cells and modules configured in series.

Modular Systems

Systems with more than about 10 cells are often subdivided into modules. This approach has advantages for both manufacturing and system design. A battery module typically has a cell-level BMS to address monitoring and balancing of cells within the module. However, module-to-module balance still must be managed.

MULTILEVEL INVERTERS

Multilevel inverter topologies were first described 20 to 25 years ago for high-voltage grid interface and motor drive applications [3-5]. The three basic topologies all share the useful features of having reduced semiconductor voltage ratings, and AC waveforms with low total harmonic distortion (THD).

Of the various multilevel topologies, the cascaded H-bridge inverter shown in Figure 1 is perhaps best suited to battery-based applications. The inverter can accommodate multiple DC sources, and has a highly modular structure. Using this configuration, a different level of power can be drawn

from each DC source independently. In this manner, battery modules can be balanced while charging or discharging.
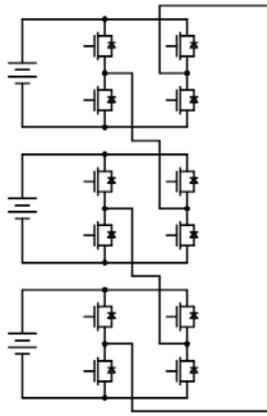

Fig. 1. A seven-level cascaded H-bridge inverter.

SYSTEM DESIGN

Battery Pack

An energy storage system has been designed in which three Altairnano [6] 23-volt (V) 50-Ah 1-p10s modules of lithium titanate (LiTO) chemistry are used. The Altairnano batteries are distinguished from other lithium chemistries by having nano LiTO spinel making up the anode instead of the conventional carbon. Their safety, very long life (16,000 cycles – full depth of discharge), high efficiency (>94% round trip 20 ºC), very wide operating temperature range (-40 ºC to +55 ºC) and quick charge capability (6 C rate – 10 minutes) make these batteries ideal for a number of applications, including renewable energy, transportation vehicles, and grid storage systems.

Power Semiconductors

The power switches in the multilevel inverter need to carry current in both directions to realize bidirectional power flow. A typical implementation uses Metal-Oxide-Semiconductor-Field-Effect-Transistors (MOSFETs) or Insulated-Gate Bipolar-Transistors (IGBTs) with anti-parallel diodes. Power MOSFETs can operate at a higher switching frequency than the IGBTs, resulting in a smaller filter size. In addition, new power MOSFETs are designed with exceptionally low on-state drain-to-source resistance (RDSon), resulting in reduced conduction loss. Therefore, the power MOSFETs were used in the inverter described here.

System Communication and Control

The control system consists of a master controller and a slave controller for each battery module. The master controller implements closed-loop control of the AC current to produce the desired power at unity power factor. If balancing of the modules' voltages or state of charge (SoC) is desired, the duty cycle to each module can be adjusted based on measurements from the slave controllers. Note that since the modules are cascaded, the communication channel to each module must be galvanically isolated from the others.

EXPERIMENTAL RESULTS

Operation

The prototype modular energy storage system is connected to a single-phase 120-V, 60-Hertz line through a 1:4 transformer to achieve proper voltage. The system can charge from or discharge to the line with power up to 3 kilowatts. Figure 2 shows typical waveforms measured at the inverter terminals: the characteristic stepped voltage waveform and a clean sinusoidal current waveform.
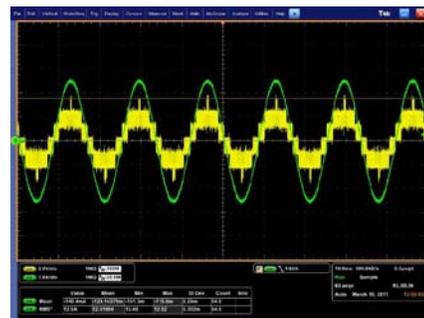

Fig. 2. Inverter voltage (stepped) and current (sinusoidal).

Balancing

Because the inverter stages are connected in series and hence have the same current, the AC voltage of each stage determines the power drawn (neglecting losses) from the corresponding battery module. Thus module balancing is accomplished by a feedback loop from module voltage to inverter duty cycle. If an accurate SoC estimate is available, this can be substituted for module voltage.

The result of an experiment applying balancing control to three modules with mismatched SoC is shown in Figure 3. The initial mismatch of 422 millivolts (mV) corresponds to a 10% SoC mismatch. After one charge-discharge cycle at a 0.5 C rate, mismatch is reduced to 45 mV.
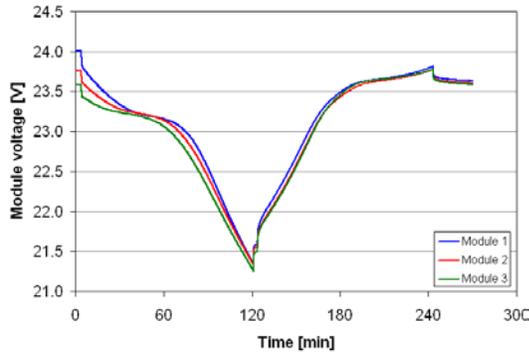
Fig. 3. Battery module voltage balancing.

Efficiency

Figure 4 shows the experimental efficiencies of the multilevel inverter when power is transferred from the battery to the grid. The upper curve shows the efficiency without the AC filter, which peaks at 99.2% at 200 watts (W) output power. The bottom curve shows the efficiency with the AC filter, which is about 94% at 950 W output power.
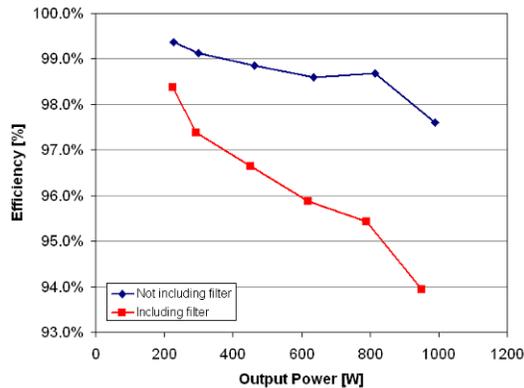

Fig. 4. Measured inverter efficiency.

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BIOGRAPHICAL NOTES

Conference presenter: Matthew Senesky received A.B. and B.E. degrees from Dartmouth College, and M.S. and Ph.D. degrees in electrical engineering from the University of California at Berkeley. His academic research included topics in flywheel energy storage and micro-scale power generation. Since graduating in 2005, he has held positions at Artificial Muscle and Tesla Motors. In his current position at National Semiconductor, he performs research and development in power electronics for renewable energy, energy storage, and electric vehicle applications.

Chet Sandberg received a B.S. degree from the Massachusetts Institute of Technology and an MS from Stanford. He then joined the Chemelex Division of Raychem Corporation, where he managed technology projects for 30 years. In October 2002, he retired from Raychem/Tyco. He currently consults for Altairnano, a lithium-ion battery manufacturer. He also consults with Athabasca Oil Sands Corporation, Trendpoint, and Energy Recovery Inc. on various electrical and mechanical engineering projects. He is also involved with Silicon Valley startups and is an angel investor in some. He is a member of the National Electrical Code Panel 17. In December 1999, Mr. Sandberg was honored by the Institute of Electrical and Electronics (IEEE) by being elevated to their highest member level of IEEE Fellow. He is also a Senior Member of the International Society of Automation (ISA), a member of the American Society of Mechanical Engineers (ASME), the National Fire Protection Association (NFPA), and the Society of Petroleum Engineers (SPE).

Kosha Mahmodieh graduated with a B.Sc. from the Electrical Engineering and Computer Science (EECS) Department of University of California, Berkeley, with an emphasis on Digital and Analog Design in 2008. He joined National Semiconductor in 2007 and has been working on various "power"-related projects, such as photovoltaic and grid storage. He is currently studying part-time towards an M.S. in Analog/System Design.

Hao Qian received the B.S. and M.S. degrees in electrical engineering from Zhejiang University, China, in 2003 and 2006, respectively. He is currently working toward the Ph.D. degree at Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg. Since 2006, he has been a Research Assistant at the Future Energy Electronics Center (FEEC), Virginia Tech. His current research interests include soft-switching converters, grid-tie inverters, and high-efficiency power conditioning systems for renewable energy and energy storage applications.

Dr. Shahrdad Tabib holds BEE and BME degrees from the University of Minnesota, Minneapolis, MSME from the University of California, Berkeley, and Ph.D. in Mechanical and Aeronautical Engineering from the University of California, Davis. He has been with National Semiconductor Corporation since 2009 working in the area of green and renewable energy systems.