DC Arc-Free Circuit Breaker for Utility-Grid Battery Storage System

Public Project Report
Project RENE-005

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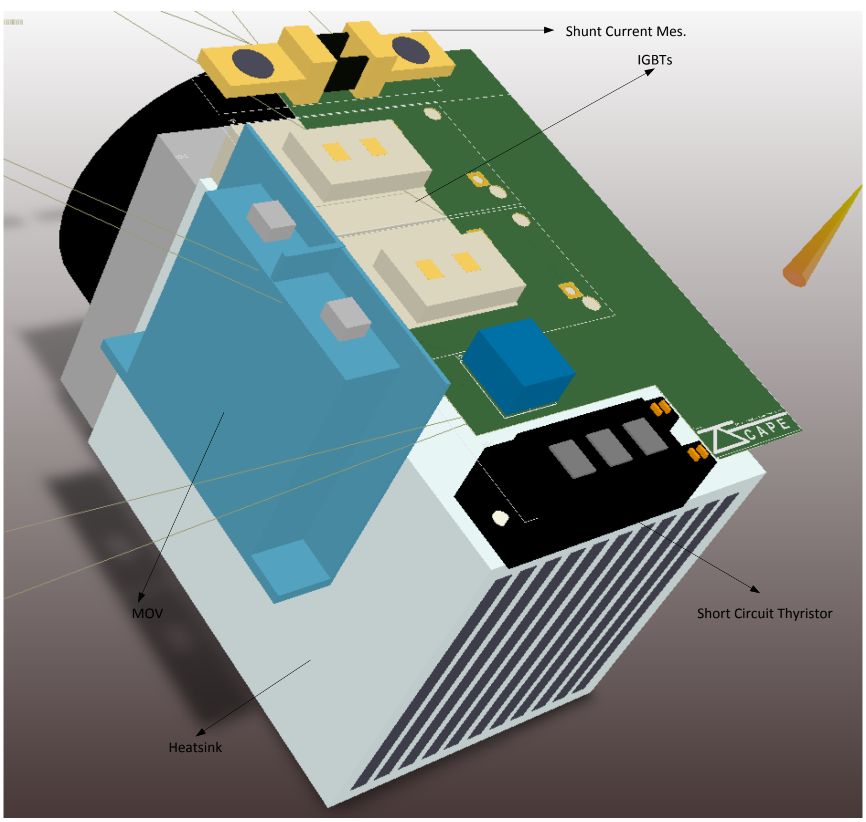

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Executive Summary

This report highlights the concept, activities, conclusions and long term outcomes activities of the project ecoENERGY R&D # RENE-005 for the period of October 17, 2012 to March 31, 2016. This project is led by the University of Toronto. In addition to the project leader, three researchers, two graduate students and two Postdoctoral Fellow were the members of the project team.

The main objective of this Project was to research and develop a novel Direct-Current (DC) Circuit Breaker (DC-CB) technology for fast protection and/or isolation of utility-grade battery storage systems.

DC breakers protect and isolate a battery module, in response to internal failure modes and/or EMS (Energy Management System) commands, to guarantee reliable and safe operation of the battery storage system. There is neither a technically feasible nor a commercially viable DC-CB product in the market for battery system applications. In this regard, the developed DC-CB of this R&D project is new and the concept is novel and innovative. The main novelty of this product is the Auxiliary Suppression Circuit (ASC), which actively prevents stresses across electronic switches and prevents arcing of mechanical switches. Another novel aspect of the proposed DC-CB is its modularity, which provides (i) scalability and thus enables applications of different voltage levels based on an optimally designed building block; (ii) ease of maintenance and reduction in down time; and (iii) reduction in space, cost and management of spare parts. It should be noted that the application of DC-CB is not limited to storage and can be directly extended to low- and medium-voltage DC-microgrid systems.

The development of DC-CB eliminates one of the main technical challenges/barriers to the market-acceptance and integration of battery storage as an enabling technology to accommodate high depth of penetration of distributed generation and EV/PHEV in the context of smart distribution systems. This technology will be a key Canadian advantage, providing environmental and economic benefits to Canada. In addition, the University of Toronto will be offering graduate student training, at the Master's and doctoral levels in research topics related to clean and renewable electricity and the integration of renewable resources and EV/PHEV based on utilization of battery storage systems, thus further developing competitive Canadian expertise in this area.

Introduction

The integration of renewable energy sources onto the grid has many important economic and environmental benefits for Canadians, and therefore, the increase in electricity generation from these sources has grown dramatically with the support of federal and provincial policies, and public and industrial interest. However, many renewable energy sources are distributed and variable, putting significant pressure on an electrical grid designed decades ago to handle large, dispatchable generators. In addition, the modern electrical grid will face challenges from electric vehicle charging.

Electrical storage using utility-scale batteries is an important emerging opportunity for managing the increased challenges imposed on modern distribution grids from variable supply and demands.

Given the significant potential benefits of electrical storage technologies in supporting the integration of renewable energy in Canada, the ecoENERGY Innovation Initiative call for research and development proposals identified this as part of the scope of the call for proposals, and the University of Toronto proposal to develop a Direct-Current (DC) Circuit Breaker (CB) was selected for funding. The DC-CB is an electrical apparatus to protect the battery system subjected to abnormal currents, e.g., due to sudden overload scenarios such as internal component failures, and internal short-circuits of the battery system. Its basic function is to rapidly interrupt electrical current flow after the detection of abnormal conditions.

The development of the DC-CB eliminates one of the main technical challenges/barriers to the market-acceptance and large-scale applications of battery storage as an enabling technology to (i) accommodate high-depth of penetration of distributed generation and Electric Vehicle (EV)/Plug-In Hybrid Electric Vehicle (PHEV) in the context of smart distribution systems and (ii) facilitate integration of solar and wind energy resources in remote communities to reduce diesel fuel consumption. Currently there is no proven and accepted technology which is economically attractive as a DC-CB for such applications.

The University of Toronto developed two new DC-CB concepts in this Project based on newly developed circuitry that shows promise of providing a commercially viable option.

Background

The DC-CB is an electrical apparatus used to protect a DC (Direct Current) system subjected to abnormal currents, e.g., due to sudden overload scenarios such as internal component failures, and internal short-circuits of the DC system. Its basic function is to rapidly interrupt electrical current flow after the detection of abnormal conditions.

Current interruption in DC systems are more problematic than in AC systems since there is no natural current-zero available and the magnetic energy stored in the circuit inductance must be dissipated. Breakers must not only be able to interrupt, but also reduce the current to zero within a certain time frame. During the interruption process, an excessively high voltage should not be created in the system.

A current-zero can be created in two ways. The first method is the traditional method used in DC circuits: a switching device develops arc voltages significantly in excess of the system voltage. The second method creates a virtual current-zero by producing a counter-current from auxiliary commutation circuits. This counter-current is usually provided by a capacitor bank through a resonant circuit.

A great amount of research and development has been completed on DC breakers up to the 1980s. After 1985, the interest in DC breakers dropped significantly and only in recent years, with the interests in HVDC[1] networks and DER[2], has it sparked interest again.

Some proposals for high-voltage systems have been made, but none of them have a proven efficiency or been successful in real applications.

Pure semiconductor switches have also been discussed, not only for HVDC, but also for low- and medium-voltage DC and AC systems. The clear advantage is switching time can be very short compared to a few (ten) ms[3] of a mechanical switch with separating metal contacts. The main drawbacks are costs and the fact that the resistance in conducting mode is in the order of a few mΩ and thus considerably higher than a few μΩ for a mechanical switch. The full forward conduction losses of the solid state devices are about 0.1–0.4% of the transmitted power.

The University of Toronto developed two new DC-CB concepts in this Project based on newly developed circuitry that shows the promise of providing a commercially viable option.

[1] High-Voltage Direct Current
[2] Distributed Energy Resource
[3] millisecond

Objectives

The main objective of this Project is to research and develop a novel Direct-Current (DC) Circuit Breaker (CB) technology for fast protection and/or isolation of utility-grade battery storage systems. The Project targeted a battery system that is composed of multiple lithium-ion battery modules. Two concepts are developed 1) DC-CB-1: a bidirectional power electronic switch and 2) DC-CB-2: a fast mechanical switch. The objectives for this Project are:

(i) proof of concept for the DC-CB-1 concept;

(ii) development and laboratory tests of a full-size DC-CB-1 prototype ready for beta site installation and tests; and

(iii) feasibility studies and proof of concept of DC-CB-2 based on simulation studies and test cases of a laboratory-scale prototype unit.

Objective (i)

DC-CB-1 is a bidirectional power electronic switch, i.e., two insulated-gate bipolar transistors and their anti-parallel diodes, that can be turned on and off by the IGBT gating signals. To meet the objective, comprehensive simulation analysis has been carried out to identify the key performance characteristics of DC-CB1.

Objective (ii)

To meet the objective (ii), a scaled unit of DC-CB1 (20-Adc/200-Vdc) was designed, developed and tested. The developed prototype is used for the proof of concept and verification of the analytical and simulation results. Component procurement, development of experimental test cases and set-up, design verification and modifications based on steps, beta site selection and development of test cases/procedures, and beta site tests are some key steps of developing the full-scale prototype DC-CB1. Based on the results achieved in Simulation and scaled unit of DC-CB1, a full-scale prototype was developed which is ready for actual field conditions in a beta-site

Objective (iii)

DC-CB-2 utilizes a fast mechanical switch, e.g., a high-speed contactor, instead of the electronic switch of DC-CB-1. To meet objective (iii), a comprehensive simulation analysis has been carried out to identify the key performance characteristics of DC-CB2 and a scaled unit of DC-CB2 was designed, developed and tested.

Benefits

The outcome of the project is a DC-CB technology that enables cost-effective and versatile applications of a utility-grade battery storage system.

The results of the project are a major step to (i) enable proliferation of electricity storage as a viable and economical mean to increase the share of renewables-based electricity generation and (ii) facilitate EV/PHEV integration to reduce greenhouse gases and other emissions associated with the conventional thermal power plants and (iii) to offset transportation emission. Availability of reliable and economic battery storage provides cost reduction of electric power generation in Canada's remote communities by lowering consumption of diesel fuel through the integration of wind and solar power. Thus will allow the government to reduce its share of fuel costs associated with remote communities.

This technology will be a key Canadian advantage, providing environmental and economic benefits to Canada. In addition, the University of Toronto will offer graduate student training at the Master's and doctoral levels in research topics related to clean electricity and the integration of renewable resources and EV/PHEV based on the utilization of battery storage systems, further developing competitive Canadian expertise in this area.

The project developed a field-trial ready technology of a DC-CB that enhances the market acceptability of this battery system that could create new jobs and provide high-quality personnel training in clean energy and renewable resources.

Technology/Knowledge Development Objectives

This main contributions of the project are (i) development of a novel technology, the DC-CB for the Lithium-ion battery system, and (ii) new knowledge related to the control, protection and operation of the grid-integrated battery equipped with the developed DC-CB.

There is neither a technically feasible nor a commercially viable DC-CB product in the market for this type of battery system applications. In this regard, the DC-CB developed from this R&D project is new and the concept is novel and innovative. The main novelty of this product is the Auxiliary Suppression Circuit (ASC), which actively prevents stresses across electronic switches (DC-CB-1) and prevents arcing of mechanical switch (DC-CB-2). Another novel aspect of the proposed DC-CB is its modularity, which provides (i) scalability, thus enabling applications to different voltage levels based on an optimally design building block; (ii) ease of maintenance and reduction in down time; and (iii) reduction in space, cost and management of spare parts.

The IP associated with the DC-CB technology is disclosed to UofT. We expect two or three patents based on the R&D results and tentatively plan to complete the patent applications. Subsequent to securing the intellectual property rights, the R&D results will be published in journal papers, and presented at conferences and technical panel sessions. Workshops at UofT or technical exhibitions will be organized to introduce the technology to the broader industry.

Challenges and Barriers

There is neither a technically feasible nor a commercially viable DC-CB product on the market for battery system applications at this time. One of the main technical challenges and an outstanding knowledge gap in reliable and cost efficient integration of battery technologies at large, and lithium-ion battery technology specifically, is the development of a mechanism for protection of the battery and its rapid isolation from the rest of the system under emergency conditions, based on either battery EMS or net controller commands of the battery-converter unit. This project offers a novel technology to enable a cost-effective solution to the problem for battery storage systems within the range of a few hundred kW to multi-MW range for LV- and MV-voltage applications

Conclusion and Follow-up

The outcomes of the project include

(i) proof of concept for DC-CB-1,
(ii) development and laboratory tests of a full-size DC-CB-1 prototype which is ready for beta site installation and tests,
(iii) feasibility studies and proof of concept of DC-CB-2 based on simulation studies and test cases of a laboratory-scale prototype unit.

Next Steps

The project target for the next steps include

(i) beta site tests and commercialization of DC-CB-1,
(ii) full-scale prototype development and beta site test of DC-CB-2,
(iii) proof of concept and laboratory scale development and testing of multi-module DC-CB, and
(iv) evaluation of multi-module configurations of DC-CB-1 and DC-CB-2.

Our long-term objectives include

(i) commercialization of DC-CB-2 configuration;
(ii) commercialization of multi-module DC-CB (DC-DB-3) for medium DC voltage applications in DC collector for wind power plants, DC collector system for solar power plants, and DC microgrids; and
(iii) proof-of-concept of DC-DB-3