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RESEARCH ARTICLE

Fault-tolerant reconfigurable second-life battery system using cascaded DC- DC converter

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Abstract

Objectives: To control the power flow resulting in improved utilization of the available cells, increased lifetime, and higher reliability. Reduce the gross energy demand and global warming potential and to promote Zero Waste.

Methods: A reconfigurable battery system using second-life batteries based on cascaded DC-DC converters is presented. When compared to conventional boost converters, it can be demonstrated that each submodule's power can be controlled separately, improving the battery system's available capacity. Faulty battery modules can be bypassed, increasing the system's reliability and fault tolerance capability. The chosen approach is shown with cascaded system using proportional integral derivative (PID) controller and the Single-phase inverter with SPWM technique for the Stationary load application

Findings: The proposed cascaded system act as a fault tolerant system since the source is the second-life battery even though there is fault has occurred in the system meets the load demand. These simulations are done in MATLAB and the results are discussed. The DC link voltage of the cascaded system has more ripple based on the tuning of the PID controller with the values of Kp,Ki, Kd the ripple can be decreased.

Novelty: Cascaded system with a fault-tolerant system using the second life battery will promote the zero-carbon waste of the batter and it is the new approach.

Keywords: Cascaded DC-DC, Reconfigurable battery, Second life battery, Fault tolerance.

Introduction

The transportation industry has experienced remarkable expansion and is now the world's second largest energy consumer. As a result, the automobile industry is one of the leading sources of air pollution and carbon dioxide emissions. Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs), and Plug-in Hybrid Electric Vehicles (PHEVs) are the four primary types of Electric Vehicles (EVs) available worldwide (PHEV) (Lee, Noh and Ha, 2021).

The use of electric vehicles is increasing, as per the International Energy Agency (IEA) data. Because the battery, which is one of the most important components in an electric vehicle, would be discarded and recycled once, reducing its specific performance, the concept of repurposing EV batteries for different uses has become a popular alternative (Ota, Sato and Akagi, (2015).

Energy storage systems (ESSs) are being considered as a use for used EV batteries due to growing environmental concerns about discarded EV batteries. Second Life Battery (SLB) addresses EVs' environmental concern while creating a new revenue stream. Based on the manufacturer's description and published literature, SLB potential forecasts that EV batteries will achieve 70 to 80 percent of the nominal capacity. At this point, EV primary batteries will be termed dead. Because of the lesser mileage and pace, this form of end is the most common. The battery's State of Charge is represented by the percentage of capacity (SOH). Battery will degrade after 5 to 8 years or 170000 Kms of travel, whichever comes first. Even though the retired first-life EV battery will have a lower SoH (Figure 1), it can still be used in other residential household applications (Bischof, Blank and Weber (2020).

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Figure.1: Comparison of application requirements for first- and second-life batteries.

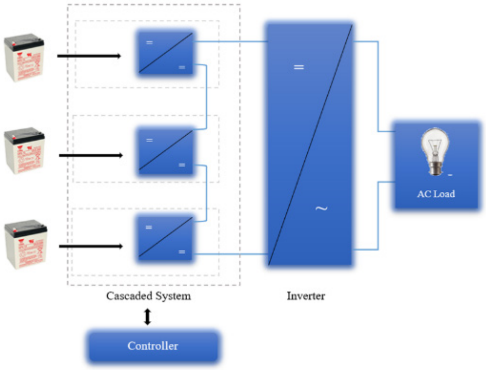


Figure 2: Block Diagram

In an electric vehicle system, the battery is a crucial component. Because it indirectly measures the battery properties, metrics like status of charge and state of health are required to determine the battery capacity. Because the battery can only store a limited amount of energy, it is vital to use it efficiently. Battery modelling aids in predicting the battery's performance in the future (Boujelben et al., 2017).

It's important to remember that even if the battery's performance is between 70 to 80% of its initial capacity, not all EV owners will replace their batteries because they may not need the whole capacity to get to their destination. The second-life battery has been put to the test by industry and researchers (SLB). In comparison to natural gas, especially during peak demand, recycling EV batteries for secondary usage might reduce CO_2 emissions by 56%. Reusing EV batteries has advantages for the environment but may also generate income for things that would otherwise be discarded.

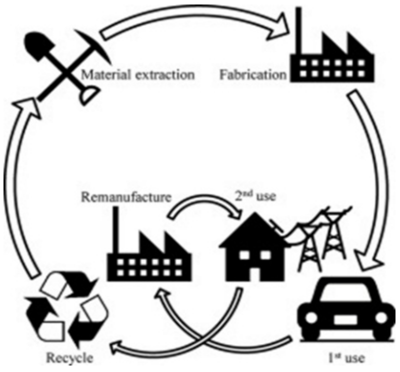


Figure 3: Second Life battery Cycle

Table 1: Design specification for the proposed converter

Parameters	*Ratings*
Input Voltage	12V
Output Voltage	90V
Output Current	2A
Switching Frequency	100kHz
Output Power	180W
Output Resistance	50Ω

It is generally accepted that the transportation industry contributes significantly to both global greenhouse gas emissions and other dangerous pollutants. The idea of electrifying transportation was first sparked by the pollution problems generated by non-EV vehicles. The primary factor is that EVs do not produce any emissions when being used.

The usage of electric vehicle batteries as ESSs contributes to two major ideas in waste management: emissions reduction, preservation of natural resources and minimization of climate change. To begin with, the idea of waste management is used to extend a product's life cycle. This idea is used to offer EV batteries a "second life" or a specialized second use as an ESS. The advantages of reusing EV batteries for further 5–7 years provide a more environmentally friendly approach. SLB, for example, can cut gross energy demand and global warming potential by 15–70%.

By forgoing the construction of further warehouses (Figure 3), we can avoid initially creating the garbage i.e., the storage facilities thereby implementing the second notion of waste management, Waste Reduction. Waste from additional construction by-products is also prevented. Building warehouses may result in the extinction of animals and plants which should be preserved because they serve as natural carbon dioxide absorbers (Bischof, Blank and Weber (2020).

Methodology

Second Life Battery

With increasing renewable-energy technologies, there is a need for energy storage to store excess energy during periods of overproduction and provide energy during

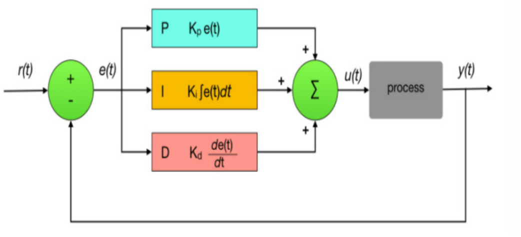


Figure 4: Proportional Integral Derivative Controller Block Diagram

periods of under generation efficiently. Because of consumer electronics, batteries have been used almost constantly for a very long time. When cell phone and laptop batteries were thrown away, there was a worry that they would be used again because recycling facilities were limited. While lead-acid (Pb-acid) able to recycle is relatively developed, the dominant lithium-ion (Li-ion) technology does not have the same privilege. However, the use of Li-ion batteries is increasing and is showing no signs of stopping, particularly in high-capacity applications like electric vehicles. This is clearly evident from the rise in EV sales over the past several years. Second-life EV batteries can be divided into two main categories: type 1 batteries approach the end of their first life through the typical process of capacity reduction, and type 2 batteries have a lower service life than their first-life counterparts. After its propulsion use (PHEV), it will still have 19.2 kWh, or 80% of its beginning energy. Considering 80% of depth of discharge (DOD), it will generate nearly 15 kWh. Future applications demanding less power can make use of this (Bischof, Blank and Weber (2020).

System Design

The proposed cascaded converter (Figure 2) consists of the cascaded system, lead acid battery, DC-DC boost converter, inverter and PID controller. Cascaded system comprises of three level interleaved boost converter cascaded to

give the required output. (Hassanifar et al, 2021). The cascaded system is connected to the single-phase inverter. Each single leg boost converter is connected to the 12V Lead acid battery of 20 Ah capacity. The proportional integral derivative (PID) control algorithm is the most often employed in industry and is well recognized in industrial control. PID controllers appeal systems in part from its resiliency under a wide range of operating situations, as well as their functional

simplicity, which allows engineers to operate them in a simple and uncomplicated manner. Here based on the transfer function obtained for the boost converter, step response is

obtained based on the transfer function and using the step response the value of the Kp, Ki and Kd are designed and further the values are tuned for the accurate results (Figure 4).

Calculation Of Inductor

$$L = \frac{V_{in}(V_{out} - V_{in})}{f_{sw}\, K_{ind} V_o} = 70\mu H$$

Calculation Of Output Capacitor

$$C_o = \frac{I_o\, D}{f_{sw}\, \Delta V_o} = 880\ \mu F$$

PID Controller

The proportional integral derivative (PID) control algorithm is the most often employed in industry and is well recognized in industrial management (Makarim et al, 2019). The attractiveness of PID controllers is partly due to their adaptability to various operating conditions and their functional simplicity, which enables engineers to use them conveniently. The design values of the proposed converter is given in Table 1.

Results And Discussion

DC- DC Cascaded Boost Converter

Figure 5a shows the proposed system's circuit schematic with the cascaded DC-DC Converter and the Single-phase Inverter**.** Three Lead acid battery of 12V is connected to the boost converter, where the switches used in the boost converter is MOSFET, Figure 5b shows the sub block of the Cascaded converter has the conventional type boost converter controller is used for the closed loop control (Kiguchi and Nishida, 2018).

Figure 6 Shows the DC link voltage of the Cascaded converter where the ripple voltage of the converter is 40V and the Voltage required for this is 270V where the required voltage is obtained.

Figure 7 shows the output voltage waveform of the single-phase inverter where the required voltage of 230V is obtained at the converter. The Sinusoidal pulse width modulation (SPWM) Technique is employed to generate pulses for the inverter. Figure 8 shows the output current of 8A, is observed at the inverter output. The inverter's output voltage will be utilized for the stationary household applications.

Faulted Battery DC-DC Boost Converter

Figure 9 demonstrates the circuit diagram of the proposed system for faulty batteries that uses cascaded DC-DC converters. The third leg battery is considered a faulted battery condition.

Figure 10 shows the DC link capacitor voltage of the Cascaded converter where because of the faulted condition of the batter the dc link required voltage is not met by the converter where the voltage obtained is 220V.But in Figure 10 the required output voltage of the converter is 230V where the converter meets that and the output current is 5A. Figures 11 and 12 display the output voltage and current during fault condition.

Tuning Of Pid Controller

Design of Transfer Function:

Output to input transfer function of the boost converter is given by (Choi, 2021).

$$\frac{V_o}{V_{in}} = \frac{V_{in}}{(1-D)^2} \frac{\left(1 + \frac{s}{\omega_{esr}}\right)(1 - \frac{s}{\omega_{rhp}})}{1 + \frac{s}{Q\omega_o} + \frac{s^2}{\omega_o^2}}$$

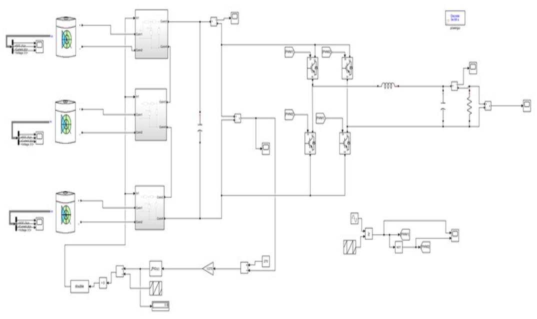


Figure 5a: Circuit Diagram

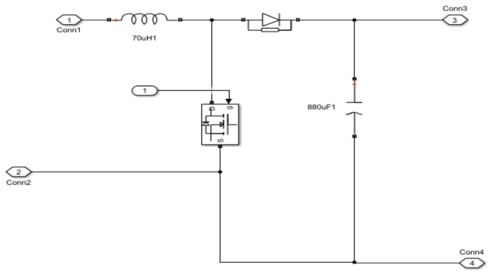


Figure 5b: Sub Block Circuit

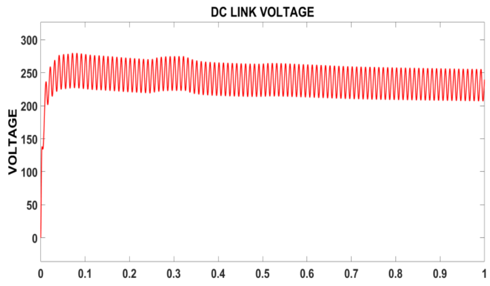


Figure 6: DC Link Voltage Waveform

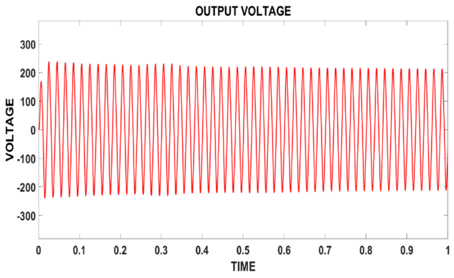


Figure 7: Output Voltage Waveform of Proposed System

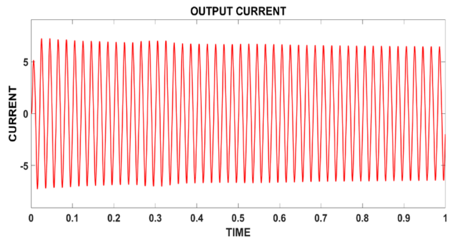


Figure 8: Output Current Waveform of Proposed System

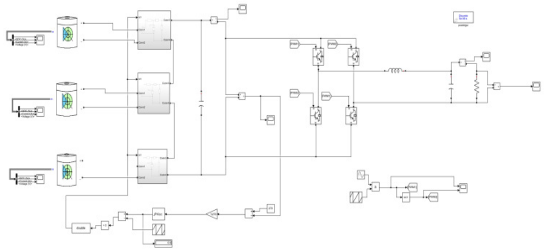


Figure 9: Faulted Battery Circuit Diagram

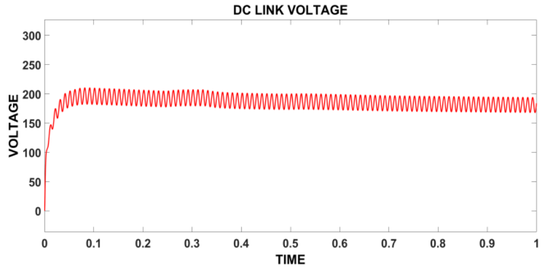


Figure 10: Faulted Battery DC Link Voltage

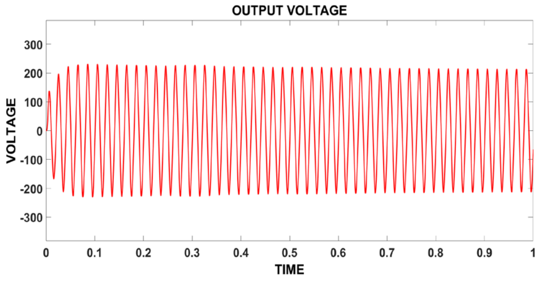


Figure 11: Faulted battery Output Voltage

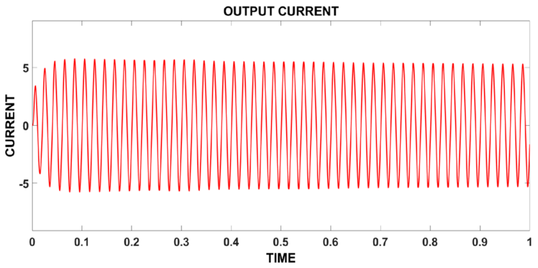


Figure 12: Faulted battery Output Current

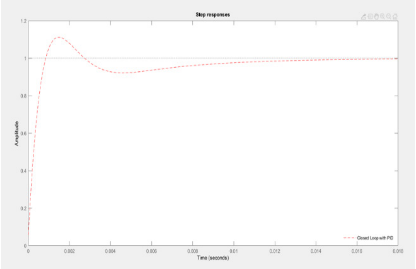


Figure.13: Step Response for the desired Transfer Function

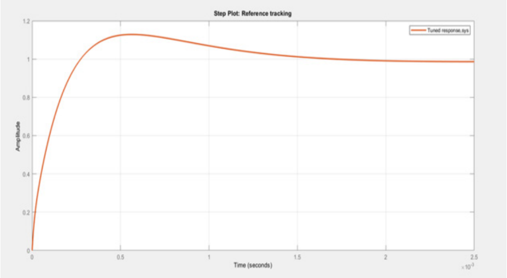
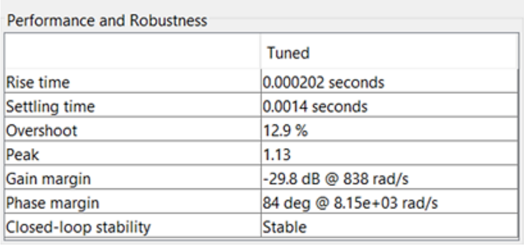


Figure.14: Tuning of Step Plot


Performance and Robustness

	Tuned
Rise time	0.000202 seconds
Settling time	0.0014 seconds
Overshoot	12.9 %
Peak	1.13
Gain margin	-29.8 dB @ 838 rad/s
Phase margin	84 deg @ 8.15e+03 rad/s
Closed-loop stability	Stable

Figure 15: Controller Parameters

The transfer function for the desired converter topology is given by

$$\frac{\mathrm{V_o}}{\mathrm{V_{in}}} = \frac{618\mathrm{s} + 23.42\mathrm{e}6}{\mathrm{s}^2 + 37\mathrm{s} + 23.42\mathrm{e}4}$$

Figure 13 shows the Step response for the desired transfer function and with respective to the step response the Kp, Ki, Kd values are determined and the values are used for the PID Controller.

Tuning of Step Response:

Figure 14 shows the Tuning way for the step response and the tuner based on the Response time and the transient Behaviour, by varying the response time faster we can able to tune the values. Based on the tunning, the Kp, Ki, Kd can be obtained and the value can be updated in the PID Controller block (Rabiaa et al., 2018).

Figure 15 shows the performance and robustness of the PID controller where the designed control system is stable and the overshoot is 13% the peak is 1.13. The values are based on making the response faster and reducing the transient of the step response is being altered to obtain the values of Kp,Ki, Kd values for the PID controller.

Conclusion

A closed-loop cascaded boost converter is designed to realize a fault-tolerant second-life battery system based on the battery voltage and required output load. The cascaded system of the converter produces the required DC output voltage to the load. The closed loop system is also analyzed during the occurrence of a fault in a battery. The system is found to satisfy the load demand though fault is occurring in the battery system. THD of Faulted and Un faulted batteries is Reduced with usage of the Filter.

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