Modified Bi-Directional Cuk Converter For Cell Balancing Using PI And Fuzzy Logic Control Method

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Keywords

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Abstract

In this study, a modular and converter-based active balancing topology is presented. In the design, there are insulated cuk converter modules that perform bidirectional energy transfer corresponding to each battery cell connected in series. By designing an isolated bi-directional cuk converter circuit and equalization controller, five battery cells connected in series were tested separately in charging, discharging, and idle states. The PI control and fuzzy logic control (FLC) methods have been applied to the proposed topology and verified with the Matlab/Simulink program.

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1. INTRODUCTION

One of the most important functions of the battery management system is cell balancing. Balancing is the term used for the process of equalizing the SOC levels of each cell in series-connected battery cells to maximize battery capacity (Andrea, 2010). In the literature, there are various cell-balancing topologies under the main headings of passive and active balancing. Both passive and active balancing methods have their advantages and disadvantages. Passive balancing is simple and inexpensive in design but has low efficiency as energy is wasted. Excess energy is dissipated as heat through a resistor, so low balancing currents are used. Active balancing is complex and costly to design but highly efficient as excess energy is transferred to other cells. In active balancing, balancing can be done at very high currents compared to passive balancing. Active balancing topologies are very important in terms of energy efficiency. In active balancing, there are capacitive, inductive, and converter-based topologies. Converter-based topologies stand out due to their energy efficiency and balancing speed. In general, converter-based topologies are designed as cell-to-cell, string, and bus topologies. In cell-to-cell topology, energy is transferred between adjacent cells. In the string topology, energy is transferred from the cell to the battery pack and vice versa. In the bus topology, energy is transferred between a bus isolated from the battery pack and a cell (Andrea, 2020). In the bus topology, the bus voltage is low because it does not depend on the number of cells connected in series. The lower bus voltage allows cheaper DC-DC converters to be used. The same DC-DC converters can be used regardless of the number of battery cells connected in series. In other words, battery cells can be easily added to or removed from the designed system afterwards. Isolated DC-

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DC converters are bidirectional, and only DC-DC converters are connected to the bus (Andrea, 2020). Because of these advantages, a bus-based topology is investigated in this study. When the literature is examined, in reference (Ling, Dan, Wang, & Li, 2015), a modified cuk equalizer for the energy bus-based distributed equalization network is proposed, and a synchronous control strategy is used to improve the equalization efficiency. In reference (Wu, Ling, & Tang, 2017), the dynamic equalization of an electric vehicle's battery during charging, discharging, and driving moments was examined, and a model-predictive control strategy was proposed to deal with changes in operating state. In reference (Zhong, Li, & Wang, 2019), the analysis and modeling of the modified isolated Cuk-based equalizer are presented, and an adaptive sliding-mode control (SMC) is proposed. In reference (Ling, Dan, Zhang, & Chen, 2014), a bidirectional flyback converter-based equalization circuit was designed, and the output power of the converter was regulated by a PI controller.

2. ANALYSIS AND DESIGN OF MODIFIED ISOLATED BIDIRECTIONAL CUK CONVERTER

A cuk converter is a DC-DC converter that can increase or decrease the voltage applied to its input and has reverse polarity at its output relative to the input (Bildirici & Karaarslan, 2017). The modified isolated bidirectional cuk converter circuit is shown in Figure 1 (Zhong, Li, & Wang, 2019). In order to realize the power transfer between the battery cells and the energy bus bidirectionally, the cuk converter circuit is modified to have a symmetrical structure. When we replace the diode in the cuk converter with a mosfet, the circuit simply becomes symmetrical. There are two MOSFETs with body diodes in the circuit that determine the direction of energy transfer. Four inductors are used to reduce di/dt when switches for different equalizers are turned on at the same time (Ling, Dan, Wang, & Li, 2015). The isolation between the battery string and the energy bus is provided by the C1a and C1b capacitors in the middle (Wu, Ling, & Tang, 2017).

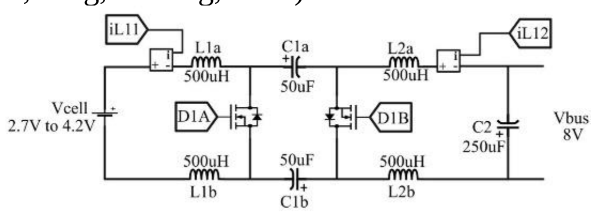

Figure 1. Modified isolated bidirectional cuk converter.

The modified cuk converter operates in Continuous Conduction Mode (CCM) in two different transfer modes: from battery side to bus side and from bus side to battery side. In the designed balancing system, the minimum and maximum voltages of the battery cells are determined between 2.7V and 4.2V in order to operate in the safe zone. In addition, the charge and discharge currents of the batteries are limited to 3A. Within these limits, the components in the circuit designed for efficient and stable operation of the converter in the CCM region (Karaarslan, 2018).

2.1 Fuzzy Logic Controller for Modified Isolated Bidirectional Cuk Converter

Due to its straightforward architecture, fuzzy logic control is frequently utilized in DC-DC converters. Fuzzy control rules are developed within the scope of certain criteria based on the system's behavior. If the converter's output is distant from the reference point, the duty cycle change must be big for the output to rapidly return to the reference point. If the converter's output approaches the reference point, a slight modification in the duty cycle will be sufficient. The duty cycle should stay constant if the output is steady and has reached the reference point. The duty cycle change should be negative if the output exceeds the reference point. If the converter's output greatly exceeds the reference point, the duty cycle change must be negative and big to swiftly return the output to the reference point. Five fuzzy levels (NB) negative large, (NS) negative small, (Z) zero, (PS) positive small, and (PB) positive large are selected as fuzzy set values. Table 1 shows the rule base.

Table 1. The rules

		Change of error				
		NB	**NS**	**Z**	**PS**	**PB**
Error	**NB**	NB	NB	NB	NS	Z
	NS	NB	NB	NS	Z	PS
	Z	NB	NS	Z	PS	PB
	PS	NS	Z	PS	PB	PB
	PB	Z	PS	PB	PB	PB

The converter and fuzzy logic controller block diagram designed in Matlab/Simulink program is shown in figure 2 for mode-1(discharging) and mode-2(charging). In mode-1 energy transfers from cell to bus and in mode-2 energy transfers from bus to cell.

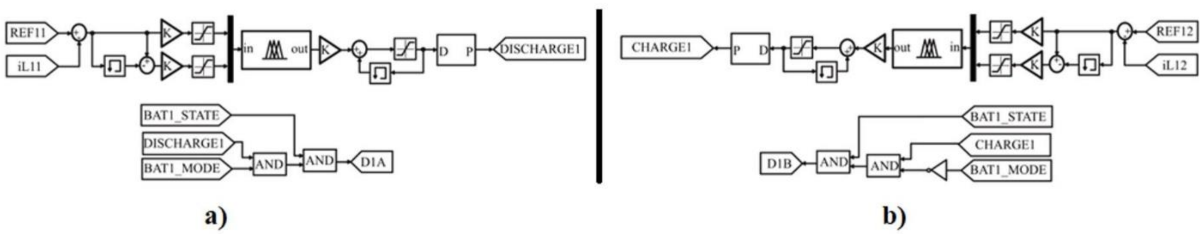

Figure 2. The cuk converter with FLC Matlab/Simulink block diagram; a) mode-1, b) mode-2

2.2 PI Controller for Modified Isolated Bidirectional Cuk Converter

Because of its simple implementation, the PI controller is one of the most popular controllers used to control DC-DC converters. The small signal model of the cuk converter is given in Equations 1.1, 1.2, 1.3, and 1.4. Using these equations, transfer functions for PI control design are easily obtained.

$$\dot{\hat{x}} = A\hat{x} + B\hat{u} \qquad 1.1$$

$$\begin{pmatrix} \dot{\hat{i}}_{L_1} \\ \dot{\hat{i}}_{L_2} \\ \dot{\hat{v}}_{C_1} \\ \dot{\hat{v}}_{C_2} \end{pmatrix} = \begin{pmatrix} 0 & 0 & \frac{D-1}{L_1} & 0 \\ 0 & 0 & \frac{D}{L_2} & -\frac{1}{L_2} \\ \frac{(1-D)}{C_1} & -\frac{D}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{pmatrix} \begin{pmatrix} \hat{i}_{L_1} \\ \hat{i}_{L_2} \\ \hat{v}_{C_1} \\ \hat{v}_{C_2} \end{pmatrix} + \begin{pmatrix} \frac{1}{L_1} & 0 & \frac{V_{C_1}}{L_1} \\ 0 & 0 & \frac{V_{C_1}}{L_2} \\ 0 & 0 & \frac{-I_{L_2}-I_{L_1}}{C_1} \\ 0 & -\frac{1}{C_2} & 0 \end{pmatrix} \begin{pmatrix} \hat{v}_g \\ \hat{i}_z \\ \hat{d} \end{pmatrix} \qquad 1.2$$

$$\hat{y} = C\hat{x} + E\hat{u} \qquad 1.3$$

$$\begin{pmatrix} \hat{v}_o \\ \hat{i}_i \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \hat{i}_{L_1} \\ \hat{i}_{L_2} \\ \hat{v}_{C_1} \\ \hat{v}_{C_2} \end{pmatrix} + \begin{pmatrix} 0 & 0 \end{pmatrix} \qquad 1.4$$

Equations 1.5, 1.6 and 1.7 are transfer functions for mode-1(charging). Figure 3 shows the Matlab/Simulink program block diagram of PI control.

$$Gvd = \frac{\widehat{v_o}}{\hat{d}} = \frac{2.46e08s^2 - 2.4e12s + 3.395e15}{s^4 + 3937s^3 + 4.192e07s^2 + 8.631e10s + 9.522e13} \quad 1.5$$

$$Gid = \frac{\hat{i}_i}{\hat{d}} = \frac{1.23e04s^3 + 1.116e08s^2 + 8.171e11s + 2.533e15}{s^4 + 3937s^3 + 4.192e07s^2 + 8.631e10s + 9.522e13} \quad 1.6$$

$$Gvi = \frac{\widehat{v_o}}{\hat{i}_i} = \frac{2.46e08s^6 + 2.691e11s^5 + 1.081e16s^4 + 5.298e18s^3 + 1.045e23s^2 + 2.319e26s + 3.375e29}{1.23e04s^7 + 1.187e08s^7 + 1.437e12s^5 + 8.244e15s^4 + 4.098e19s^3 + 1.336e23s^2 + 2.107e26s + 1.645e29} \quad 1.7$$

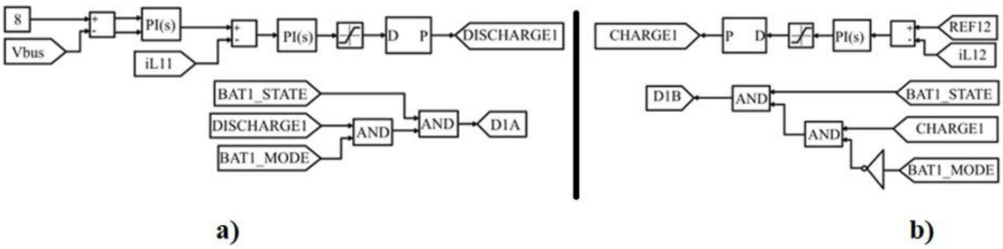

Figure 3. The cuk converter with PI control Matlab/Simulink block diagram; a) mode-1, b) mode-2

Kp and Ki values are determined by the PID tuner in the Matlab/Simulink program. The inner loop PI control parameters that control the reference current are $K_p = 2$ and $K_i = 950$. For the bus voltage to remain constant at 8 volts, the outer loop PI control parameters are $K_p = 0$ and $K_i = 166.6$. Equation 1.8 is transfer function for mode-2(charging). In mode-2, energy is transferred from the bus to the cell. The PI control parameters that control the reference current for this mode are $K_p = 0.31$ and $K_i = 9.71$.

$$Giz = \frac{\hat{i}_i}{\hat{i}_z} = \frac{1.805e14}{s^4 + 1.405e06s^3 + 4.195e07s^2 + 3.084e13s + 3.443e14} \quad 1.8$$

3. SIMULATION RESULTS

The initial SOC (%) of each battery cell is 74, 74.1, 74.2, 74.5, and 74.6, respectively. Also, each battery cell has a nominal capacity of 2.6Ah and a nominal voltage of 3.7V. Figure 2 shows the SOC changes of battery cells in idle state, discharging state and charging state.

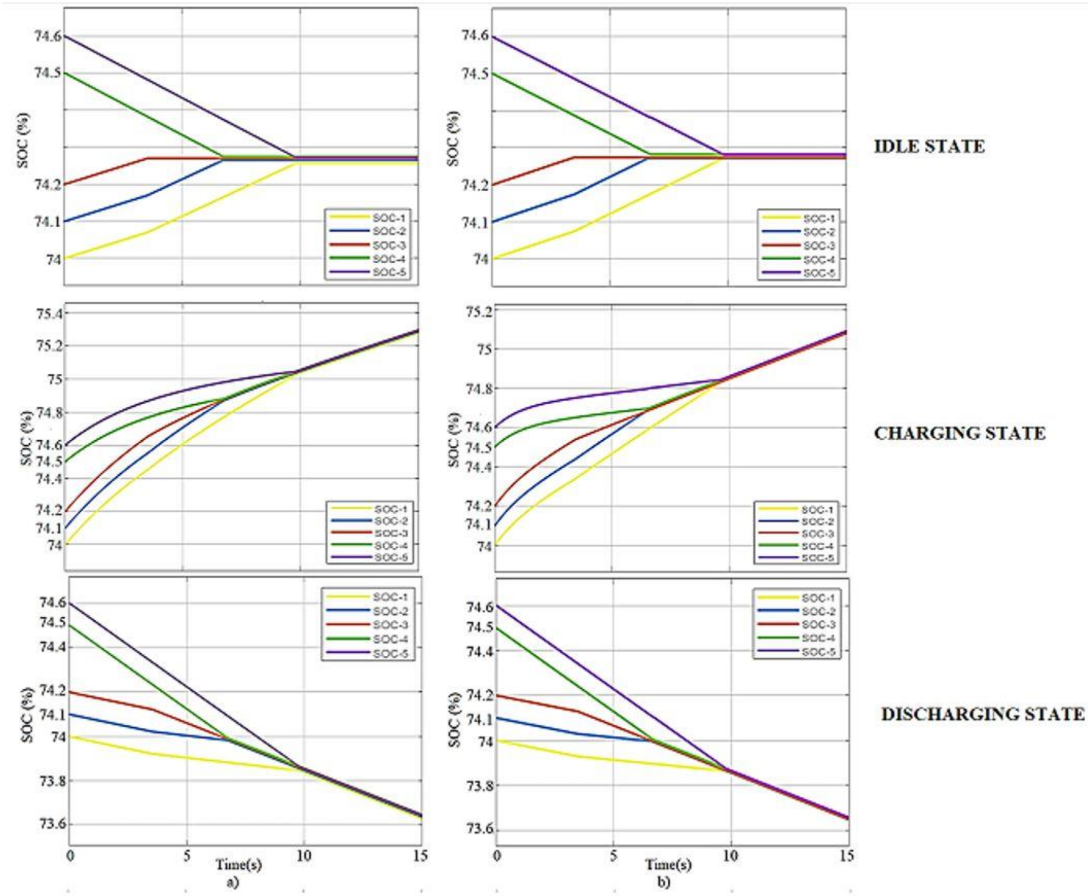

Figure 4. SOC changes at idle, charging and discharging state: a) PI control, b) FLC.

In Table 2, the balancing times of the systems designed with FLC and PI control methods are given comparatively in the three states of the battery pack.

Table 2. Balancing time comparison.

Method	Idle state	Charging state	Discharging state
PI Control	9.811s	9.828s	9.805s
FLC	9.808s	9.636s	9.775s

The waveform of the current change in the cells during the balancing process is shown in Figure 3. The charge-discharge currents of the cells are limited to a maximum of 3A. Initially, 3 cells with SOC values lower than the reference receive energy from the bus, while 2 cells with SOC values higher than the reference transfer energy to the bus. Battery cells that reach the limits of the calculated average SOC reference value are excluded from the energy transfer process as they have reached equilibrium. As the number of cells participating in the balancing process changes, the reference current values of the battery cells in the energy transfer process also change. The balancing module of the battery cell that reaches the reference SOC value is disabled, and the current in the transfer process becomes zero. When the balancing process is complete, the current values of all battery cells become zero since no energy is transferred.

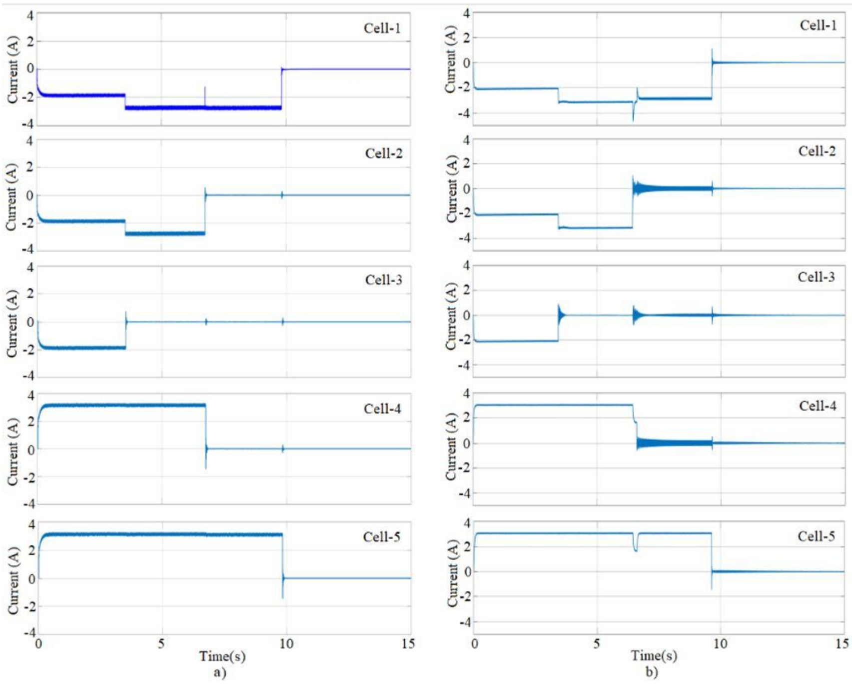

Figure 5. Cells' current variations in the balancing process; a) PI control, b) FLC.

Figure 3 shows the responses of the systems designed with PI control and FLC method to reference current changes. When compared to FLC, PI control has faster transient response and less maximum deviation from steady state. On the other hand, the FLC method has a faster rise and settling time.

Table 3. Simulation results of rise time and settling time

Parameters	Description	PI control rise time(s)	FLC rise time(s)	PI control settling time(s)	FLC settling time(s)
Cell-1	Cell Current 1	0.147	0.043	0.333	0.15
Cell-2	Cell Current 2	0.147	0.043	0.333	0.15
Cell-3	Cell Current 3	0.147	0.043	0.333	0.15
Cell-4	Cell Current 4	0.147	0.052	0.333	0.15
Cell-5	Cell Current 5	0.147	0.052	0.333	0.15

4. CONCLUSION

In this study, an active balancing topology is presented for balancing battery cells. Bus-based topology is created with modified isolated bidirectional cuk converter modules. Excess energy is transferred bidirectionally via a bus where the balancing modules are connected in parallel. In the balancing process, the energy that the converter modules will transfer is calculated and regulated by the balancing algorithm. The equalization system designed with five series-connected battery cells with different SOC values has been verified in the Matlab/Simulink program. As a result, the balancing process is carried out successfully with both control methods, and a comparative analysis is made.

Conflict of Interest

Author declare that there is no conflict of interest.

Contribution of Authors

This study is based on the Eyup KOSEOGLU's master's thesis. Prof. Dr. Ahmet KARAARSLAN is the thesis supervisor.

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