Active voltage balancing circuit using single switched-capacitor and series LC resonant energy carrier

A.K.M. Ahasan Habib, S.M.A. Motakabber, M.I. Ibrahimy and M.K. Hasan✉

Single switched-capacitor and series LC resonant converter-based active voltage balancing circuit are presented in this Letter. This converter is proposed to balance the cell voltage in series-connected electrochemical energy storage devices namely battery or super-capacitor. This balancing circuit directly transfers the energy from higher capacitive energy storage cells to lower energy storage cells in the string. It realises the maximum energy recovery and zero voltage gap between the cells and overcomes the drawback of switching loss, conduction loss, balancing time duration, and the voltage difference between the cells of conventional switched-capacitor as well as single LC converter. The details of the balancing circuit operation, theoretical, and mathematical analysis are presented. The experimental result demonstrated that the balancing circuit result where the voltage difference is 451–0 mV in 124 min for two 12 V, 4.5 Ah lead-acid batteries.

Introduction: The demand for an electrochemical energy storage system (EESS) is prominently increased in the field of electric vehicle, renewable energy storage system, and portable electronic devices in consumer and industrial applications. EESS is mainly battery and super/ultra-capacitor. Owing to the limitation of device and manufacturing, the voltage of the individual battery cell and super/ultra-capacitor is varied and imbalanced on the charging or discharging time in the string. For this, during the charging time, higher capacitive EESS is not fully charged and lower capacitive EESS is fully charged. If the charging process is continued for fully charged the higher capacitive EESS then lower capacitive EESS are damaged or explosion for overcharge [1, 2]. To increase the EESS lifetime and save from damage or explosion, many researchers are working on voltage balancing circuits. There are two types of charge balancing circuits one of energy dissipative or passive balancing, another is energy non-dissipative or active balancing. In a passive balancing system, the resistor uses heat (cell to heat) to balance the energy. Inactive balancing system, energy balanced by the inductor, capacitor, and transformer through transfer from higher to lower energy capacitive cell in cell-to-cell (C2C), cell-to-pack (C2P), pack-to-cell (P2C), pack to pack (P2P) or C2P-to-cell [3–7]. Among all the active balancing circuits, C2C balancing circuits are most preferable for balancing time, control complexity, circuit size, and cost [3]. There are several C2C balancing circuits developed. These balancing circuits are divided into two groups. One is adjacent C2C balancing and another is direct C2C balancing. The adjacent C2C balancing circuits are switched-capacitor [5], inductor [7], or combination of both capacitor and inductor namely resonant converter [8] based balancing circuit. Direct C2C balancing circuits are single switched-capacitor [9], inductor-based [6], single resonant converter [1, 2, 4], and push–pull converter [6] based balancing circuit. Using the direct C2C balancing circuit, energy can transfer directly from a higher capacitive to a lower capacitive energy storage cell in the series EESS string.

The objective of this Letter is to present an active voltage balancing circuit for a series-connected battery or super-capacitor using a single switched-capacitor and series LC resonant converter. The concept of this balancing circuit is to modify the single energy carrier in a direct C2C balancing circuit to reduce the balancing time between two cells. When the cell voltage variance occurred, then the balancing circuit executes its balancing process and it can be scaled up and used in a P2P balancing system.

Proposed balancing circuit and working process: The proposed balancing circuit schematic diagram is shown in Fig. 1. This balancing circuit consists of battery cells, MOSFET switches, single switches-capacitor, series resonant energy carrier, cell monitoring integrated circuit (IC), and master controller. In the proposed balancing circuits, cell_1 and cell_n are connected to two MOSFET switches and cell_2 to cell_{n-1} are connected to anti-series bidirectional MOSFET switches.

The anti-series bidirectional MOSFET switches are used to protect the negative voltage in the MOSFET intrinsic body diode because the low-voltage MOSFET cannot protect the body diode conduction. All associate switches of each cell are operated at the same gate pulse and turned on or off by near-zero current switches for minimising the switching loss. In the proposed balancing circuit, the switching gate pulse is 50% of the duty cycle and the switching frequency is equal to the resonant frequency so that all MOSFETs switched are achieved soft switching. Also, this soft-switching minimised the impedance and allow flowing the maximum current and reduced the voltage balancing time. When the cell voltage variation occurred in the EESS string between two cells then associate switches of the highest energy capacitive cell are turn on in the fast phase MOSFET gate pulse and energy temporally store in single switches-capacitor and series LC tank. In the second phase MOSFET gate pulse, all associate switches of the lowest energy capacitive cell are turned on and the stored energy is transferred. This process is repeated until the voltage balancing achieves between two cells.

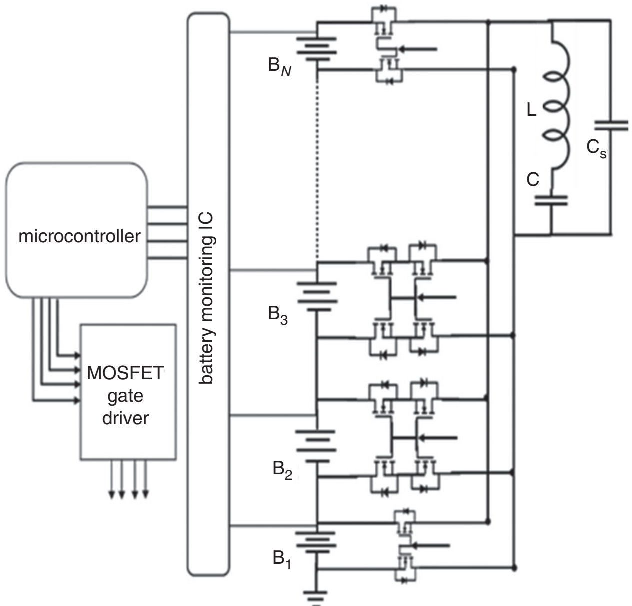

Fig. 1 *Proposed balancing circuit schematic diagram*

Two-cell voltage balancing process analysis: Based on the circuit analysis proposed in [4], the resonant analysis is obtained below. All associate MOSFET switches in a cell are considered a loop and the loop resistance is R_{loop} and voltage drop in the MOSFET switch is $V_{\text{MS\_D}}$. The capacitor voltage across in the energy carrier ($C + C_S$) is $V_{\text{Capacitor}}$. When the highest capacitive cell (cell voltage is $V_{\text{C\_highest}}$) associate switch is turn on the energy starts to transfer and the voltage across the L will be equal

$$L\frac{\mathrm{d}i}{\mathrm{d}t} = V_{\text{C\_highest}} - \text{V}_{\text{Capacitor}} \tag{1}$$

$V_{\text{Capacitor}}$ starts to charge and store the energy and the amplitude of the resonant current is

$$I_{\text{m}} = \frac{V_{C\_\text{highest}} - V_{\text{Capacitor}}}{\omega L} = V_{\text{C\_highest}} - V_{\text{Capacitor}}\sqrt{\frac{C + C_{\text{S}}}{L}} \tag{2}$$

After the fast phase gate pulse, $V_{\text{Capacitor}}$ reaches the maximum voltage

$$V_{\text{Capacitor\_Max}} = V_{\text{C\_highest}} - V_{\text{Capacitor}} \tag{3}$$

In the discharging time, when the lowest capacitive cell (cell voltage is $V_{\text{C\_lowest}}$) associate switch is turn on the amplitude of the resonant current is

$$I_{\text{m}} = \frac{V_{\text{Capacitor}} - V_{\text{C\_lowest}}}{\omega L} = V_{\text{Capacitor\_Max}} - V_{\text{C\_lowest}}\sqrt{\frac{C + C_{\text{S}}}{L}} \tag{4}$$

In the second phase-gate pulse, $V_{\text{Capacitor}}$ reaches the minimum voltage

$$V_{\text{Capacitor\_Min}} = V_{\text{Capacitor\_Max}} - V_{\text{C\_lowest}} \tag{5}$$

During the balancing time, energy carrier charging and discharging current is

$$i_{\text{charge}} = \frac{V_{\text{C\_highest}} - \left(V_{\text{MS\_D}} + V_{\text{Capacitor}}\right)}{\omega L} \mathrm{e}^{-\sigma t} \sin \omega t \quad (6)$$

$$i_{\text{discharge}} = \frac{V_{\text{Capacitor}} - \left(V_{\text{MS\_D}} + V_{\text{C\_lowest}}\right)}{\omega L} \mathrm{e}^{-\sigma t} \sin \omega t \quad (7)$$

Where damped oscillation, $\sigma = R_{\text{loop}}/l$ and angular frequency, $\omega = \sqrt{1/(L(C + C_s))}$

The flowing current of the balancing circuit is estimated by the equation

$$i = \frac{V_{\text{C\_highest}} - 2V_{\text{MS}_\text{D}} - V_{\text{C\_lowest}}}{\omega L} \mathrm{e}^{-\sigma t} \sin \omega t \quad (8)$$

Energy transfer efficiency can be calculated by this equation

$$\eta = \frac{V_{\text{C\_lowest}} \times i}{V_{C_{\text{highest}}} \times i} \times 100\% \quad (9)$$

This circuit worked like a damped oscillation circuit and energy transfer depends on the amplitude oscillation time. As the parasitic resistance remains low then maximum efficiency is possible.

Result and discussion: A prototype was implemented in the lab for four lead-acid batteries to experiment with the validity of the proposed circuit shown in Fig. 2. For monitoring the battery voltage status, LM301 Op-amp based on a different amplifier circuit is used. All of the resistance remains the same on the different amplifier and a complementary pulse-width modulation signal is generated from the microcontroller operated the MOSFET switches through a photo-coupler gate driver. The proposed balancing circuit components list is shown in Table 1.

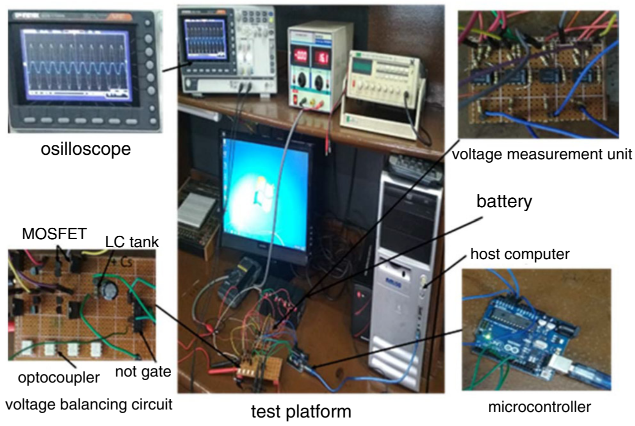

Fig. 2 *Proposed balancing circuit experimental setup*

Table 1: List of the components

Parts		Value
switches	single MOSFET	IRF450A nMOSFET
	bidirectional MOSFET	2N7000 nMOSFET
resonant tank	inductor	100 µH
	capacitor	220 µH
	single capacitor (C_S)	2200 µH
gate driver	optocoupler	817c
	logic gate	SN7404
monitoring IC	different amplifier	LM 350 Opamp
	resistance	100 Ω
microcontroller	Arduino Uno	atmega328p
battery	lead-acid	12 V 4.5 Ah

Fig. 3 shows the voltage balancing result for two lead-acid batteries during the relaxation mode. In the beginning, the highest energy capacitive battery voltage was 11.61 V and the lowest energy capacitive battery voltage was 11.15 V, where the initial difference between the two batteries was 451 mV. The balancing process executes until the lower capacitive battery reached the same voltage theoretically it will be 11.375 V but after 124 min the voltage difference is 0 mV and the battery voltage is equal to 11.35 V. This balancing circuit reached the zero voltage gap and balancing efficiency near about 97% that calculated from 9 no. equation.

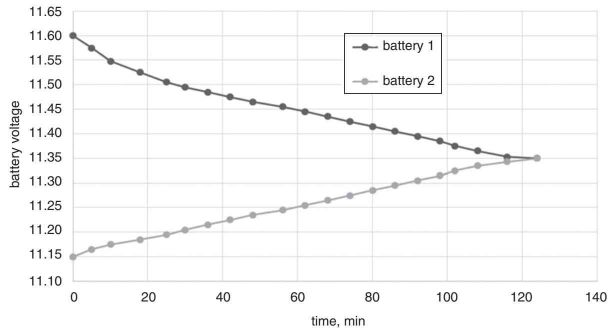

Fig. 3 *Proposed balancing circuit prototype for four cells in the laboratory*

The proposed balancing circuit is a bidirectional and work on charging or discharging mode. Fig. 4 illustrates the cyclic test of the proposed circuit where 1 A current was applied for charge and used no load ET-PGM22A-24500, Eton DC motor for discharge. Using the balancing circuit, in discharging mode, the voltage difference was 77 mV after 144 min voltage difference of two cells was 0 mV and equally discharged next 65 min. Subsequently, after 150 min the balancing cells were charged and reached near high-voltage limit.

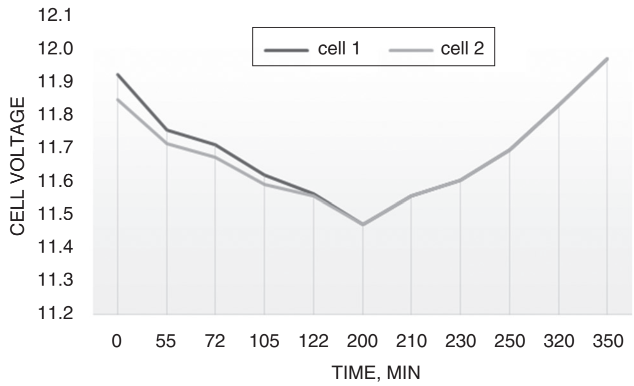

Fig. 4 *Measured result from proposed circuit for two lead-acid batteries*

Fig. 5 shows the voltage balancing result for series-connected four lead-acid batteries during the relaxation mode. Initially, battery voltage was, respectively, 11.568, 11.452, 11.262, and 11.151 V, where the initial difference between the batteries was 417 mV. The balancing process executes until the lower capacitive battery reached the same voltage theoretically it will be 11.358 V but after 185 min the voltage difference is 0 mV and the battery voltage is equal to 11.351 V. This balancing circuit reached the zero voltage gap and reached near 96.4% of balancing efficiency.

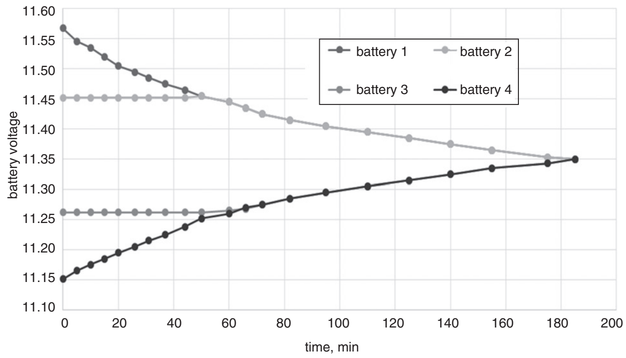

Fig. 5 *Balancing operation during charging and discharging mode*

The proposed voltage balancing circuit has achieved some advantage over the conventional C2C voltage balancing circuits. This balancing circuit is to reduce the direct C2C balancing time and voltage gap in the string, highly efficient, circuit cost, and implement complexity. In the proposed balancing circuit, the number of passive components is reduced; hence, a single switched-capacitor and series LC tank are used for this it is reasonable cost and miniature size. A comparison between the C2C voltage balancing circuit is shown in Table 2. The circuit proposed in [8] is the conventional adjacent C2C balancing circuit, where a resonant circuit and a transformer are used. In the circuit proposed in [1] is presented a single resonant converter-based voltage balancing circuit which reduced the number of associate components compared with the circuit proposed in [2]. Table 2 presents a comparison between the proposed and conventional C2C balancing circuits based on different parameters.

Table 2: Comparison between conventional and proposed balancing circuit for *N*-cells in the string

Parameter	Resonant converter [8]	Single resonant converter [1]	Proposed circuit
no. of components	4*N* switches	4*N* switches	$4N-4$ switches
	1 LC tank	1 LC tank	
	1 transformer	3 diodes	1 LC tank
	1 capacitor		1 capacitor
balancing time	good	good	very good
voltage and current stress	medium	low	low
control complexity	more complex	complex	simple
Implementation complexity	complex	average	simple
power loss	medium	low	low
balancing types	neighbour cell	any C2C	any C2C
measuring cells	lead-acid battery	super-capacitor	lead-acid battery
	12 V, 7 Ah	300 F, 2.7 V	12 V, 4.5 Ah
voltage gap	yes	yes	no
efficiency	high	very high	very high
size	large	small	small
cost	high	medium	medium

Conclusion: In this Letter, a single switched-capacitor and series LC tank-based active balancing circuit are proposed. This circuit worked on bidirectional and three operation modes. For validation, an experimental prototype was built in the lab. The experiment was conducted for lead-acid battery in charging, discharging, and relaxation mode. The proposed circuit easily scaled up the number of cells/batteries in a string and transferred the energy from higher capacitive storage to lower capacitive storage cells/batteries. In addition, this balancing circuit can be applied in the P2P balancing system due to its fast balancing mechanism, miniature size, minimum cost, and high efficiency.

Acknowledgments: This research was supported by the North Garth Institute of Technology Fundamental Research grant and National University of Malaysia (UKM) under research grant GGP P72086.

© The Institution of Engineering and Technology 2020
Submitted: *14 May 2020*
doi: 10.1049/el.2020.1417
One or more of the Figures in this Letter are available in colour online.

A.K.M. Ahasan Habib, S.M.A. Motakabber and M.I. Ibrahimy (*Department of Electrical and Computer Engineering, Faculty of Engineering, International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia*)

M.K. Hasan (*Faculty of Information Science & Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*)

✉ E-mail: mkhasan@ukm.edu.my

References

1 Yu, Y., Saasaa, R., Khan, A.A., *et al*.: 'A series resonant energy storage cell voltage balancing circuit', *IEEE J. Emerging Sel. Top. Power Electron.*, 2019, to appear, p. 1, doi: 10.1109/JESTPE.2019.2914706

2 Lee, K.M., Chung, Y.C., Sung, C.H., *et al*.: 'Active cell balancing of li-ion batteries using LC series resonant circuit', *IEEE Trans. Ind. Electron.*, 2015, **62**, (9), pp. 5491–5501, doi: 10.1109/TIE.2015.2408573

3 Lee, S.W., Choi, Y.G., and Kang, B.: 'Active charge equalizer of Li-ion battery cells using double energy carriers', *Energies*, 2019, **12**, (12), p. 2290, doi:10.3390/en12122290

4 Habib, A.A., Motakabber, S.M.A., and Ibrahimy, M.I.: 'A series regeneration converter technique for voltage balancing of energy storage devices', *Indonesian J. Electr. Eng. Comput. Sci.*, 2017, **8**, (2), pp. 475–481, doi: 10.11591/ijeecs

5 Yuanmao, Y., Cheng, K.W.E., and Yeung, Y.P.B.: 'Zero-current switching switched-capacitor zero-voltage-gap automatic equalization system for series battery string', *IEEE Trans. Power Electron.*, 2011, **27**, (7), pp. 3234–3242, doi: 10.1109/TPEL.2011.2181868

6 Pham, V. L., Duong, V. T., and Choi, W.: 'A low cost and fast cell-to-cell balancing circuit for lithium-Ion battery strings', *Electronics*, 2020, **9**, (2), p. 248, doi: 10.3390/electronics9020248

7 Yang, Y., Zhu, W., Xie, C., *et al*.: 'A layered bidirectional active equalization method for retired power lithium-ion batteries for energy storage applications', *Energies*, 2020, **13**, (4), p. 832, doi: 10.3390/en13040832

8 Zeltser, I., Evzelman, M., Kuperman, A., *et al*.: 'Zero current switching resonant converter based parallel balancing of serially connected batteries string', *IEEE Trans. Ind. Appl.*, 2019, **55**, (6), pp. 7452–7460, doi: 10.1109/TIA.2019.2920227

9 Benny, L.P., Maneesha, K.M., Unnikrishnan, R., *et al*.: 'Microcontroller based Li-ion cell balancing using single switched capacitor for spacecraft application', *Indian J. Emerg. Electron. Comput. Commun.*, 2017, **4**, (2), pp. 702–710