Novel Voltage Equalizers for Secondary Batteries including EDLCs using CW circuit

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Abstract

Various secondary batteries including EDLCs are widely used in various electric vehicles, etc. Among them, EDLCs offer high energy density and long life span, so various applications may be anticipated in the realm of those energy storage devices. However, since the voltage limit is low of the devices, it is necessary to connect them in series or parallel. In addition, it is required that they be used in the region of their critical voltage limit or capacity limit. In order to apply them efficiently, the devices should be used with balanced voltage. In this paper, some novel voltage balancers are presented, employing a CW (Cockcroft-Walton) circuit as a basic construction. Characteristics of proposed circuits are analyzed and improved especially about circuit construction strategies.

Keywords: Secondary battery¹, EDLC²; voltage equalizer³, Cockcroft-Walton circuit⁴, buck-boost chopper⁵

1. Introduction

Secondary Batteries as energy storage devices have been examined and reported. Among them, EDLCs (Electric Double Layer Capacitors), which are often called supercapacitors, can offer high energy storage performance in terms of surge power, efficiency, cold temperature operation and large number of energy cycles⁽¹⁾.

For these reasons, in power compensating equipments for voltage fluctuations or instantaneous voltage drop in the power systems, EDLCs are expected to be applied as energy storage equipments. Additionally, in various vehicles, such as electric cars and trains, these applications have just been introduced. In such EDLCs, however, as voltage limit of devices is low, it is necessary to connect

them in series or parallel configurations, and to use them in the vicinity of their voltage limit. Consequently, in order to use efficiently, these devices must be used in well balanced manner. Amongst various voltage balancing techniques, a balancing method using resistors can be applied as the most fundamental, simple and effective solution⁽²⁾. When considering the power losses, however, such methods have restricted application in practice. Another method, using Zener diodes, has been discussed and evaluated^(1,3). In considering the energy consumption of such Zener diodes, the power capacity of the system may be limited. Methods employing chopper circuits have also been proposed^(3,4), but the number of switching devices and their accompanied control circuitry is increased, leading to the high cost of such systems. Other original strategies have been presented and components⁽⁵⁾. Though the inverter circuit is complicated and charging operations are needed, such methods are suited to the required increased capacities. The most orthodox method is thought to be the forward converter method, using transformers, which accompany each EDLC, and charge and discharge through their primary and secondary windings^(6,7). Similarly to solution⁽³⁾, their controls may be complicated by many devices like transformers. Although such devices are necessary, however, their size is very small. Thus, this technique is expected to be widely used in extensive applications like the electric vehicles^(8,9).

Considering the various types of EDLCs voltage balancers, perfect or even adequate solutions have not obtained. However, in the future, various other methods will be studied and proposed. In the light of the above research into voltage balancers for EDLCs, we had initially studied reference^(10,11), and derived novel methods which was examined and discussed⁽¹⁰⁻¹²⁾. An alternative approach to

voltage balancing was presented, employing a Cockcroft-Walton circuit (CW circuit), which was invented long ago ⁽¹³⁾ for high dc voltage generation and employs numbers of capacitors and diodes. By means of this CW circuit, EDLCs having different capacitances were made to provide identical voltage. Voltage balancing is achieved with a high frequency power supply or buck-boost chopper. Their analyzed results and the mechanism are presented and discussed. In this paper, these results are applied to balance the small voltages of EDLCs. Another splendid equalizer is also proposed ^(15,16), in which the cells are controlled by means of a string of reference capacitors and double groups of many switches. The balancing operation is a little analogous to the CW circuit, so its principle is interesting. The circuit and its operation, however, is a little complicated, many switches should be provided and yet the operational principle is entirely different. Under such background, in March, 2008, a novel voltage equalizer using CW circuit had been proposed ⁽¹⁴⁾ firstly in the world by one of the authors. Various further versions and their results are to be presented and discussed including experiments.

2. Fundamental Circuit Configuration

2.1 Operation Analysis in AC Power supply

Fig.1 shows the proposed circuit for the balanced charging of EDLCs, using CW (Cockcroft-Walton) circuit. $C1^*$ to $C5^*$, on the left hand side, indicate, for example, electrolytic capacitors, which have relatively uniform values and can be obtained at low cost. e is the ac power supply. The purpose is not to supply the output power to these, but to supply

relatively reduced power in order to balance the EDLC voltage on the right hand side. These EDLCs can be replaced by usual secondary batteries if it is necessary. In this paper, the subject of study is EDLCs. By means of adjusting the voltage or frequency, voltage equalizing conditions can be obtained. By an operation of e , EDLCs. can be held effectively in voltage equalization.

3. Double Switches Method

Fig.2 shows another version of voltage equalizer using modified CW circuit having double switches. As comparison to already reported buck-boost chopper [16], their main switches are removed, the inductors of chopper is replaced by diodes and double switches S_1 , S_2 are equipped, which are turned on and off periodically. By means of this construction, simple equalizer can be obtained.

Fig.1. Basic equalizer with CW circuit.

Fig.2. Double switches equalizer.

3.1 Equalizing operation

a) circuit operation at turned-off. The charging current is flowing through double paths root 1 and root 2 in Fig.3. C_1 or C_8 shares each current in parallel path whose voltage becomes about double compared to others.

Fig.3. The circuit operation at switch turned-off.

b) Circuit operation at turned-on. Due to turned-off operation, for example, as C_8 voltage is higher than C_4 voltage, excess charge is delivered from C_8 to C_4 through root 3 as shown in Fig.4. Also in the bottom stage, the excess charge is delivered from C_1 to C_5 through root 4 in the similar reason.

3.2 Voltage equalizing operation by simulation

Also in the other stages, the excess charge of left hand

side capacitor is delivered toward that opposite side capacitor at the right hand side. As such operation at turned-off, the excess charge of capacitor at the right hand side is delivered toward just upper side capacitor of the opposite side. From such operations, we might consider whether above switch S_1 is necessary or not. For turned-off period, however, the excess charge of C_8 due to root 1 and root 2 in Fig.3 must be delivered to C_4 . And also, the excess charge of C_4 should be delivered toward C_8 . In such way, double switches are necessary for the transmittal operation of excess charge from the right hand side capacitor to just lower side capacitor in the opposite side of the left hand side. For above description, simultaneous operation of both switches was verified and discussed. The simultaneous operation of both ones is not always necessary. Even though with alternating switching, operation can be performed successfully, where one switch is open and other is closed, or vice versa. Even though the frequency is different each other, the voltage equalization can be obtained.

In Fig.5, region A is called constant current charging operation and B is constant voltage one. This figure shows equalization characteristic, where C_1 to $C_8 = 1\text{mF}$ except $C_5 = 0.6\text{mF}$ reduced by deterioration, and duty ratio = 20%, $I_{DC} = 0.1\text{A}$, $E = 100\text{V}$. For the first rising region shown by A, the equalizing characteristic can be kept satisfactorily as shown, but for the region B shows little discrepancies in the curves,

Fig.4. The circuit operation at switch turned-on.

which becomes slightly out of desired value of 25V. The reason can be explained as follows; in the region A, compensating effect due to switching is more significant. Meanwhile, in the region B, such effect due to switching is a little worse. In order to improve the equalization characteristic, the duty factor is increased to 30%, where such result is shown in Fig.6. In the figure, by means of merely turned-on and off, satisfactory characteristic can be obtained, where every EDLC voltage is completely converging toward the desired value of 25V.

Fig.5. Equalizing characteristic with double switches.

Fig.6. Satisfactory equalizing characteristic.

On the other hand, when one switch S_1 is removed from the equalizer, equalizing characteristic is lost, whose characteristic is shown in Fig.7. C_8 voltage is increased about double, because current is flowing in parallel path through C_8 . For C_1 voltage, however, by attached switch voltage is somewhat compensated.

4. Single Switch Method

Instead of double switches method, single switch method is proposed in this chapter. Double switches in Fig.2 are taken the place by double inductors and added another switch as shown in Fig.8. By means of switching of S , the voltage is applied across the terminal of equalizer. As a result, in the equalizer,

Fig.7. Unsuccessful equalizing characteristic without S1

5. Single Switch Method

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Fig.8. Single switch equalizer.

Fig.9. Operation circuit at turned-on.

current flow can be altered according to the switching state.

In Fig.9, when the switch is turned-on, the supply voltage is applied thr equalizer terminal. However, the current flows through inductor as I_L in addition to I_D , as shown. At the beginning, this current I_L is fairly reduced value because of adequate large inductance of L_2 . However, this current

flows through C_1 as I_D . Because of this function, the current source type is preferable as the power supply. If the voltage of C_5 is larger than C_2 one, the current though root 5 as shown.

Fig.10. Operation circuit at turned-off.

In Fig. 10, the switch is turned-off, when the current flows through L_2 . As a result, The excess charge of C_1 can be transmitted toward C_5 side. By means of repetition of switching, both column voltages can be kept an identical value.

6. Experiment and its Discussions

Fig.11. Equalizing characteristic at experiment.

Fig.11 shows voltage equalizing characteristic at trial experiment. The term “trial” means that instead of EDLC, electrolytic capacitors are used because sometimes unexpected excess charge was generated in a process of various experiments. Because of application of higher voltage against EDLC having lower voltage limit, electrolytic capacitor was chosen as experimental capacitor. External power supply is 12V dc supply having series resistance of 100 ohm which behaves like a current source. Each capacitance is 6.8 mF except assumed deteriorated C_5 of 3.4mF. Switching frequency is 60Hz in which both switch operate simultaneously. Every curve lies on single line. It can be seen that equalization characteristic is performed successfully.

Fig.12. Single switch equalizer for experiment.

In the experiment of single switch equalizer, experimental circuit can be modified into simple configuration, whose circuit construction is shown in Fig.12. The half wave rectifier can be substituted for switching device.

7. Conclusions

A novel voltage equalizer using a CW circuit with switching has been proposed and discussed.

It is easy to apply, because of its simple and concise construction. The purpose of this system is not to obtain boosted power, but to obtain balanced voltages. Since such delivered power is not large, the ac power supply or switches are small in size.

The proposed circuit using a CW approach is compared with the forward converter method [9-10], which is called the conventional method in this paper and that application might be most orthodox way at this time.

i) The conventional method needs a transformer, even though the size is small because of high frequency used. Transformer and its design are complicated to every EDLC installation. The proposed method does not need particular design, and can be used as general-purpose.

ii) The proposed method needs a corresponding number of auxiliary capacitors. However, it may be possible that such capacitors can be replaced by EDLC, in which case, the system storage capacity could be significantly increased.

iii) The proposed method has a little deteriorated characteristic, in terms of circuit response, because the command is gradually delivered from the bottom to the top side. The conventional method is advantageous in relation to response. However, the aging time lapse is long, so quick response may be unnecessary for voltage balancer of EDLCs.

iv) For a case of using EDLC only having double switches or single one, circuit becomes in much simple construction, but equalizing operation can be obtained only at charging period. During discharging period such equalizing characteristic could not be obtained unfortunately.

In this period, however, such feature could be accepted because a fatal over voltage would not be generated

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