Various Discussions and Improvements of Voltage Equalizer for EDLCs Including Secondary Batteries

Keiju Matsui, Kouhei Yamakita, Masaru Hasegawa
Chubu University
Kasugai, Japan
keiju@isc.chubu.ac.jp, mhasega@isc.chubu.ac.jp

Abstract-**Among various storage devices, EDLCs offer high energy density and long life span, so a lot of applications may be anticipated in the realm of energy storage devices, such as those used in electric vehicles or electric power stabilization in power systems, etc. However, since the voltage limit of the devices is low, it is necessary to connect them in series in 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, a novel voltage equalizer and modified versions are presented, employing a CW (Cockcroft-Walton) circuit. Characteristics of the proposed circuit are analyzed and improved, especially about charging response and charging capability.**

Keywords-EDLC; Voltage Equalizer; Voltage Balancer; EDLC; Cockcroft-Walton circuit; Buck-boost chopper.

I. INTRODUCTION

Various energy storage devices, including general secondary batteries, have been reported and examined. Among them, EDLCs (Electric Double Layer Capacitors), which are usually called super capacitors, 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 be used efficiently, these devices must be used in a well-balanced manner. Amongst various voltage equalizing techniques, an equalizing 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 discussed, which use inverter circuits and transformers. By utilizing the charge and discharge of EDLCs, their voltages can be held effectively in equilibrium between device 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 [6-10]. In a similar 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 [14].

Considering the various types of EDLC voltage equalizers, perfect or even adequate solutions have not been obtained. Although, in the future, various other methods will be studied and proposed. In the light of the above research into voltage equalizers for EDLCs, we had initially studied reference [6-9], and derived novel methods which was examined and discussed in [10]. An alternative approach to voltage balancing was presented, employing a Cockcroft-Walton circuit (CW circuit), which was invented long ago [13] for high 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 equalizing is achieved with an ac power supply or buck-boost chopper. [14] Their analyzed results and the mechanism are presented and discussed. In this paper, these results are applied to equalize the small voltages of EDLC cells. Another splendid equalizer was also proposed [11, 12], in which the cells are controlled by means of a string of reference capacitors and double groups of switches. The equalizing operation is a little analogous to the CW circuit, so its principle is interesting. The circuit and its operation, however, is a little complicated, and yet the operational principle is entirely different. Under such background, analytical and experimental results will be presented and discussed.

 ISBN: 978-1-61208-213-4

II. CIRCUIT CONFIGURATION AND OPERATION

Figure 1 shows the proposed fundamental circuit for the equalized charging of EDLCs, using CW (Cockcroft-Walton) circuit. C_1^* to C_5^*, on the left-hand side, indicate, for example, electrolytic capacitors, which have relatively uniform values and can be obtained at low cost. e is ac power supply, which often uses commercial frequency. The purpose is not to supply the output power to these, but to supply relatively reduced power in order to compensate the EDLC of voltage unbalanced.

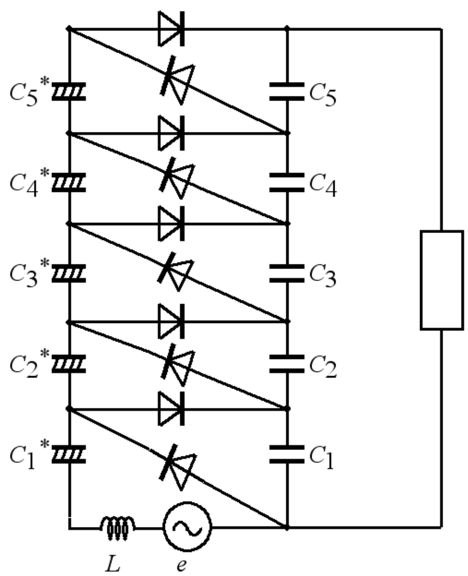

Figure 1. Basic novel voltage equalizer

Let us discuss about charging the C_1 on the first stage. First, C_1^* is charged in the first half cycle to $V_{c1}^* = E$, where E is average value over half cycle. After that, in the second half cycle, C_1 is charged by the sum of power supply e and C_1^* voltage. As a result, C_1 is charged toward $V_{C1} = 2E$. The mechanism of the proposed circuit using CW circuit is analogous to SC (switched capacitor) method [7]. By means of switching between two groups of capacitors, each different value of voltage can be averaged between each device. In SC method, the voltage can be transferred towards the both direction, upper and lower sides, however, in the proposed CW circuit the voltage is transferred only in one direction. However, alternative circuits are attached to the lower terminal of the power supply *e*, the corresponding voltage can be transferred towards such lower side, In conclusions of this chapter, in the proposed circuit, as shown below the number of switches can be reduced to single from many ones in the conventional voltage equalizer systems. The ac supply voltage shown as ***e***, sometimes called as ac voltage exciter, might have not strict value. Even if the supply voltage is given by rough value, the corresponding capacitor voltages can become a desired value. The reason can be explained as follows; if the voltage is large than we thought, the total piled up terminal voltage is increased. As a result, the discharged current or ac supply current is also increased, so the voltage drop across inductor L is increased, leading to the reduced ac voltage exciter.

Ⅲ. BUCK-BOOST CHOPPER METHOD

For another example of circuit configuration, we have proposed a modified circuit, which is constructed using buck-boost chopper. Their chopping frequency is high, and by turning-on and turning-off with suitable duty cycle, a certain ac voltage is generated across the inductance L1, which plays the role of ac voltage power supply, as above mentioned ac power supply. In an analogous manner, each voltage on the EDLCs can be controlled uniformly. At the bottom side of the circuit, chopper exciter is constructed by familiar Zeta converter. As such converter, the circuit can play a role of buck-boost chopper, which is employed as chopper exciter without switching surge.

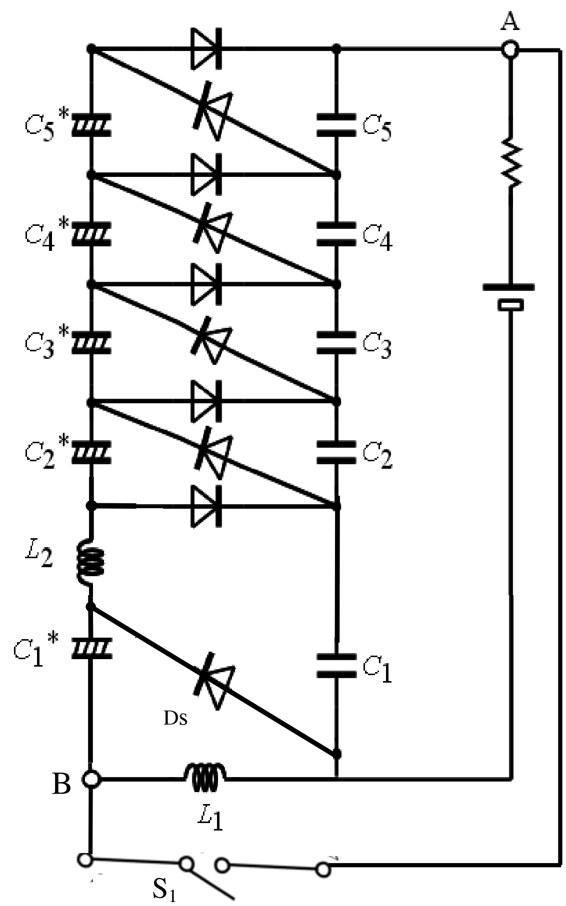

Figure 2. Voltage equalizer using chopper

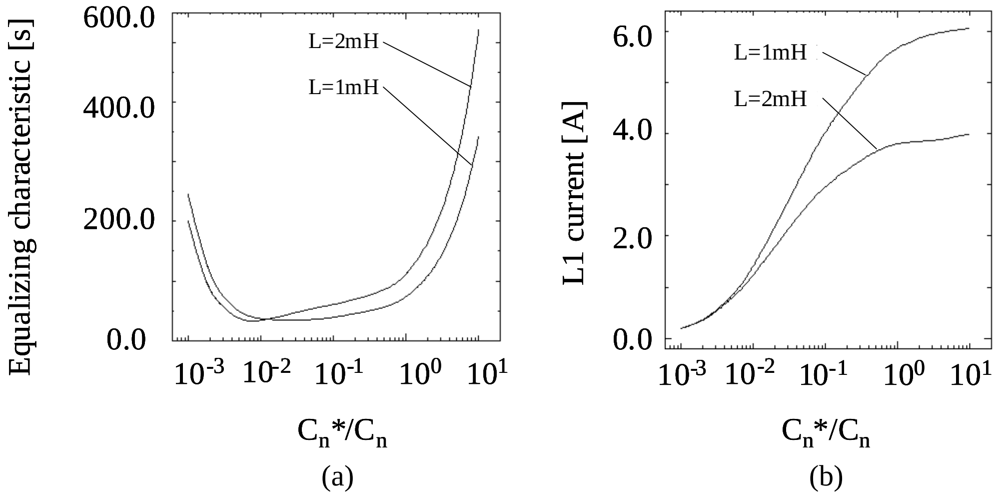

Figure 3. Convergent characteristics

IV. Improvements of Fundamental CW Circuit

A. Improvement of Dynamic Response

In the fundamental CW circuit as voltage equalizer in Figure 1, the boost circuit on the left-hand side is constructed by electrolytic capacitors shown by C_1^* to C_5^*. Even though by increased such capacitance, however, the long charging time is required, leading to long equalization compensating time. In terms of dynamic response, it is disadvantageous as practical applications. From such reasons, such dynamic response characteristic is examined and resolved as follows; The EDLCs, C_n on the right-hand side are kept constant, while electrolytic capacitors, C_n^* on the left-hand side are made gradually increased, by which convergent characteristics can be obtained as shown in Figure 3(a), For reduced value of C_n^* , as the charging and discharging current are much smaller, so convergent time is limited by such reduced capacitance, leading to deteriorated dynamic response. For such case of significantly reduced C_n^* compared to C_n, the dynamic response is poor. An adequate selection for C_n^* could be much important. In the figure, when C_n^* is gradually increasing and C_n^* /C_n reaches beyond 1/100, then the convergent characteristics are much improved as shown.

After keeping straight line curves with nearly constant, the characteristics is becoming deteriorated again from about C_n^* /C_n= 1. The reason can be explained that the charging current is gradually saturated about from that C_n^* /C_n =1 due to rush current suppression inductor L in Figure 1. From such saturated point, the increasing rate of current is suppressed. Figure 3(b) shows the variation of current due to C_n^* / C_n. From about C_n^* /C_n =1, the current is saturated by suppresion inductor L. By means of such reasons, we can obtain a conclusion that the optimum convergent characteristic can be obtained between C_n^* /C_n = 1/100 and 1.0. The convergence deterioration by further increasing C_n^* is due to above mentioned additional inductor to suppress the excessive rush current. In such way, as C_n^* is increasing, the required electric charge is also increased. It can be seen that the optimum region of C_n^* /C_n exists.

B. Improvement of Dynamic Response by Devising the Circuit Arrangement

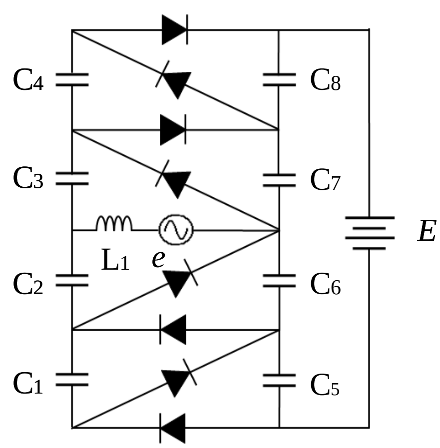

Figure 4. Modified equalizer in the CW circuit

In this section, to improve the dynamic response, the CW circuit is a little modified, where another circuit is added at the lower side as well as the upper one in the fundamental circuit. That circuit is shown in Figure 4. In this figure, the voltage of C_2 and C_3 are charged in half compared to the other capacitor one. Though the circuit operation has two equalizing directions, the principle of the voltage equalization is the same as the fundamental

 ISBN: 978-1-61208-213-4

one in Figure 1. The convergent characteristic for the conventional one is shown as case A and the proposed modified one is shown as case B in Figure 5. With compared between both cases, the convergence time is improved at twice over the whole region, where the horizontal axis shows the ac supply voltage. As it can be seen, as the voltage is increasing, the convergent time is becoming gradually improved. For modified one as case B, dynamic response can be much reduced to half as mentioned.

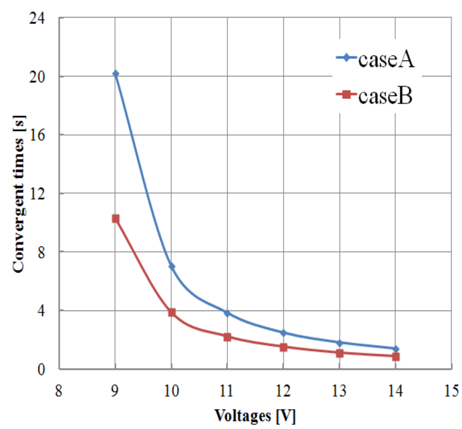

Figure 5. Convergent characteristics for driving voltage

V. IMPROVEMENT OF DEVICE UTILIZATION FACTOR

In previous publications, the authors have discussed a novel voltage equalizer under various view points. Using the CW circuit, the circuit is constructed by a chopper or an ac power supply, and the boost circuit of electrolytic capacitors on the left-hand side. If the boost circuit on the left-hand side is replaced by EDLCs, such capacitors could be sufficiently utilized by energy storage devices that device utilization factor for energy storage capability could be much increased.

A. Ac Power Supply Method

Figure 6(a) is a fundamental voltage equalizer using ac power supply, e as an exciter. Both C_1 to C_3 on the left-hand side and C_4 to C_6 on the right-hand side are entirely EDLCs to charge and discharge with voltage equalization function. L_1 to L_3 are for rush current suppression, where L_2 is for charging and L_3 is for discharging C_1 to C_3 with respect to external power supply. After C_1 is charged by ac power supply e, the following discharge current due to reversed voltage of e is prevented by diode D_1. At this time, the electric charge of C_1 is transmitted to C_4 through L_3-C_1-C_4 , and can be obtained an equality, $V_{C1}= V_{C4}$

At the second stage, as each capacitor can be operated like the first stage operation. In such way, subsequent operation at the upper side, an analog operation can be repeated like one of fundamental circuit in Figure 1. Thus, C_1 to C_6 can be charged in equalization. This circuit merit is that as the whole capacitors are employed as storage devices, the device utilization factor can be much improved. As the whole capacitors can play the role of storage devices having identical voltage, there is no need to make a particular specification as compared to the basic CW equalizer having different value of electrolytic capacitors and voltage.

B. Chopper Circuit Method

Figure 6(b) shows another proposed method using chopper circuit instead of ac power supply in Figure 6(a). By means of switching operation of S_1 , the voltage is applied across the L_1, by which the similar operation is performed compared to that of Figure 6(a). Thus, C_1 to C_6 can be made equal voltages.

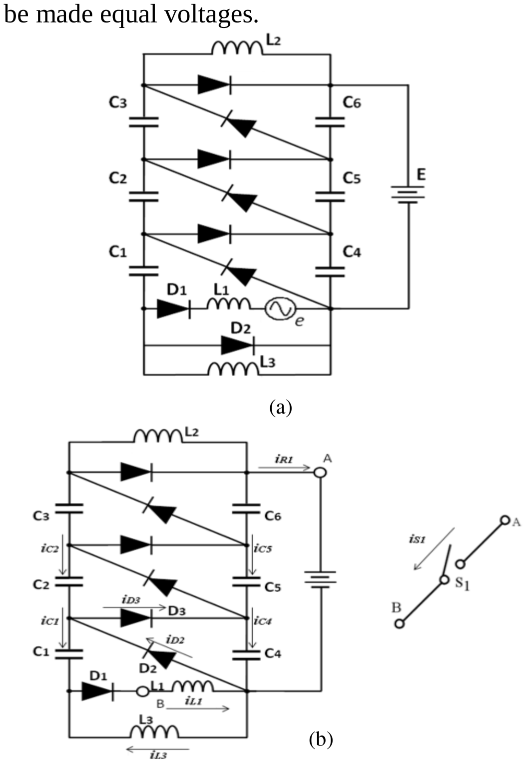

Figure 6. Novel equalizers. ac voltage exciter (a) and chopper exciter (b)

The operation mechanism can be described as follows. By means of S_1 turning-on, magnetic energy is stored in L_1, whose energy is discharged by the subsequent turning-off and stored in C_1. As far as L_1 energy is concerned, there is no surge generation through closed loop during turning-off. In the ac voltage exciter method in Figure 6(a), there is unnecessary current loop like L_1 - e - L_3, during positive polarity ac voltage, where L_1, energy is lost towards L_3. For a case of chopper excitation in Figure 6(b), however, such unsatisfactory current could be much reduced, leading to make circuit specification simpler.

VI. Operation Characteristics

A. Ac Power Supply Method

Figure 7 shows the voltage equalizing characteristics for ac voltage excitation in Figure 6(a), where as voltage is 35 V, frequency is 1 kHz, external dc voltage is 45 V, capacitance of C_1 to C_6 is 0.2F, where C_2 and C_4 is 0.1F, which are assumed to be deteriorated by aging. The initial voltage is given by $C_1 = C_3 = C_5 = C_6$ =11.25V, $C_2 = C_4$ = 22.5V, respectively. It can be seen that after the excitation starts, each EDLC, C_1 to C_6 is converging towards desired voltage 15 V in about 9 sec. Even though different value of capacitance, each voltage is converging toward such desired voltage.

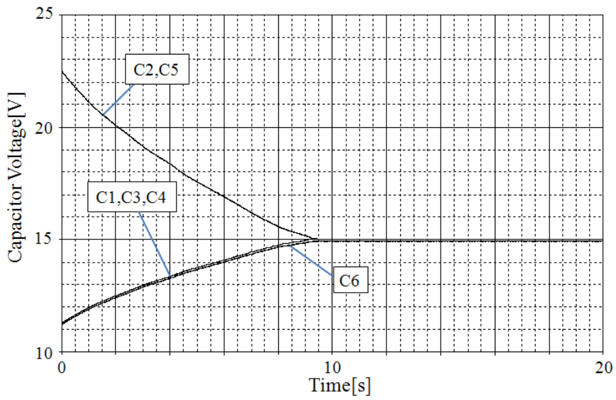

Figure 7. Voltage converging characteristics by ac supply exciter

B. Chopper Circuit Method

Figure 8 shows the convergent characteristic for Figure 6(b). The duty cycle of chopper, d = 0.02, dc power supply E = 45V, C_1 to C_6 = 0.2F, where C_2 and C_4 are assumed to be deteriorated by aging. That is, 0.1F. The initial voltages are $C_1 = C_3 = C_4 = C_6$ = 11.25 and $C_2 = C_4$ =22.5V. EDLCs of C_1 to C_6 can be converged to the desired value of 15V in about t = 47s. As it can be seen, it is required to take a long converging time. The reasons could be described as follows; because of unstable specification due to reduced duty cycle and of the significant influence of the external dc power supply having constant voltage source, it would require to take a long time to reach in a stable state.

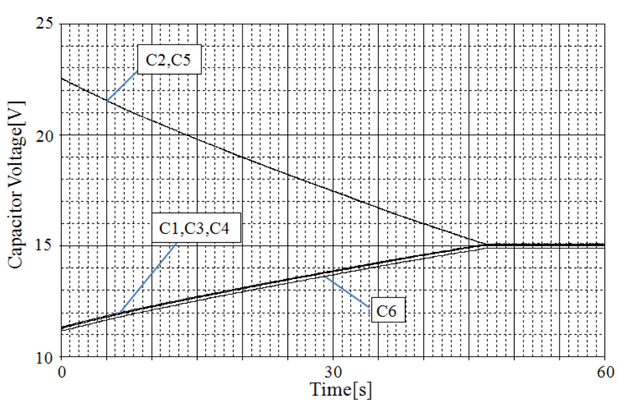

Figure 8. Voltage balance characteristics by chopper exciter

Figure 9 shows various operational waveforms when the convergent characteristics can be obtained by chopper excitation method in Figure 6(b). Because of stable state after reaching to convergent, each current is fairly reduced. By means of switch S_1 turning-on, the current i_{S1} is increased linearly. As a result, the direct connected next inductor L_1 is also increasing in a similar as i_{L1}.

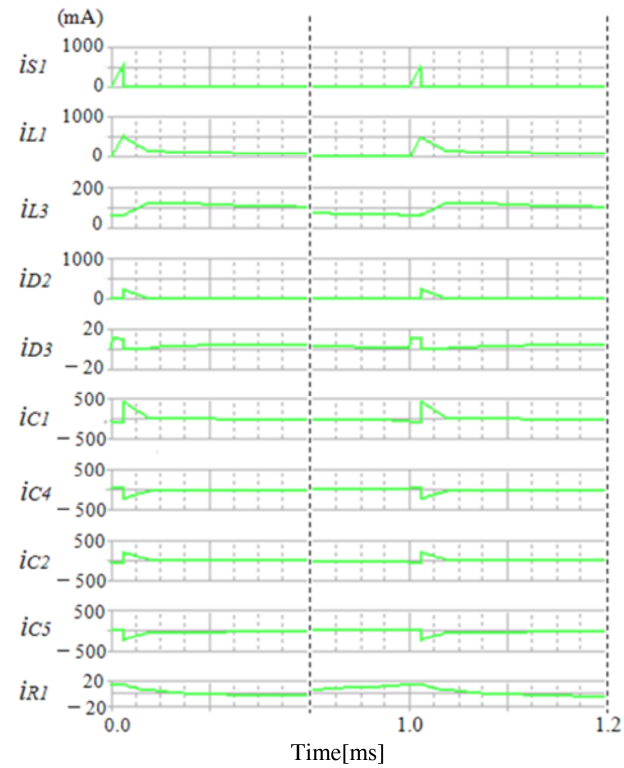

Figure 9. Current waveforms for chopper exciter

VII. Conclusion

A novel voltage equalization using a CW circuit with ac supply or chopper has been proposed and discussed. Various modified version have been also considered. 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 correct unbalanced voltage. Since such compensating power is not large, the ac power supply or chopper is small in size.

On the first stage in this paper, Zeta converter as buck-boost chopper is presented as a novel version, where the circuit operation is analyzed and specified. The proposed method needs a corresponding number of electrolytic capacitors. However, it may be possible that such capacitors can be replaced by EDLCs, in which case, the system capability in capacity could be somewhat increased. In such purpose, a novel voltage equalizer is newly proposed. Since every device is constructed by EDLCs, the circuit specification could be simple and the dynamic response could be expected to be much improved because of transmittal current can be more increased.

The proposed method has a slight disadvantage, in terms of circuit response, because the command is gradually delivered from the bottom to the top side. As far as the circuit construction is concerned, however, the proposed configuration piles up multiple devices in succession, so the extension of a circuit is very easy.

In this paper, voltage equalizer for EDLC is discussed. For various secondary batteries like lithium-ion battery, however, the proposed system could be applied in a similar manner. Especially, in an electric vehicle, such batteries are much expected to be practically employed at low cost. If the proposed system could be applied to such ones, simple voltage equalizer might be realized in the near future.

REFERENCES

[1] Michio Okamura: “Electric Double Layer Capacitors and its Energy Storage Systems”, 3rd Edition, Nikkan Kogyo Shinbun-sha, 2005

[2] Akitoshi Minemura, Masahiro Yashiro, Yasuyoshi Kaneko, and Shigeru Abe: “Equalization of the Voltages Using Passive Resistors for Electric Double Layer Capacitors”, The 2007 National Convention Record of IEE Japan, no. 4-018, 2007

[3] Philippe Barrade, Serge Pittet, and Alfer Rufer, “Energy storage system using a series connection of EDLCs, with an active device for equalizing the voltages” IPEC-Tokyo-2000, pp. 1555-1560, 2000

[4] Alfer Rufer and Pilippe Barrade, “A EDLC-Based Energy-Storage System for Elevators with Soft Commutated Interface”, IEEE Transaction on Industry Applications, vol. 38, no. 5, Sept/Oct 2002

[5] Takatsugu Kishi and Toshihisa Shimizu, “A Study of Voltage Balancer for Electric Double Layer Capacitors”, Technical Meeting on Semicondector Power Converter SPC-04-37, 2004

[6] Kazuya Mori, Akio Hasebe, Kiko Tsuruga, Takahiko Itoh, and Sumiko Seki, “Voltage Balancer for Electric Double Layer Capacitors”, The 2001 National Convention Record of IEE Japan, no. 4-207, 2001

[7] Eiji Sakai, Koosuke Harada, S. Muta, and Kiyomi Yamasaki, “Swiching Converters using Double-Layer Capacitors as Power Backup”, The 19th International Telecommunication Energy Conference, Proceedings of IEEE-Intelec 1997, pp. 611-616, Oct 1997

[8] Nasser H. Kutkur, Deepak M. Divan and Donald W. Novotny, “Charge Equalization for Series Connected Battery Strings”, IEEE Transaction on Industry Applications, vol. 31, no. 3, pp. 562-568, May/June, 1995

[9] H. Sakamoto, K. Murata, E. Sakai, K. Nishijima, K. Harada, S. Taniguchi, K. Yamasaki, and G. Akiyoshi, “Voltage Balanced Charging of Series Connected Battery Cells”, The 20th International Telecommunication Energy Conference, Proceedings of IEEE-Intelec 1998, pp. 311-315, Oct 1998

[10] Keiju Matsui, Hiroto Shimada, and Masaru Hasegawa, "Novel Voltage Balancer for an Electric Double Layer Capacitor by using Forward Converter”, The 4th International Telecommunication Energy Special Conference, Vienna Austria, Proceedings of IEEE-telescon 2009, II.3-1, pp. 1-6, May, 2009

[11] Kimihiro Nishijima, Hiroshi Sakamoto, and Koosuke Harada, “Voltage Equalizing System for Series Connected Battery Cells”, IEICE Trans. On B, vol. J84-B, no. 9, pp. 1701-1708, Sep 2001

[12] Jonathan W. Kimball, B. T. Kuhn, and P. T. Krein, “Increased Performance of Battery Packs by Active Equalization,” IEEE Vehicle Power and Propulsion Conference, pp. 323–327, Sep 2007.

[13] J. D. Cockcroft and E. T. S. Walton: "Further development on the method of obtaining high velocity positive ions", Proc. Royal Society London, UK, 1932.

[14] Keiju Matsui, Isamu Yamamoto, Masaru Hasegawa, and Hiroto Shimada, ”A Novel Voltage Balancer for EDLCs Using Cockcroft-Walton Circuit”, 2008 National Convention Record IEE Japan, vol. 4, 4-138, pp. 230-231, March 2008

[15] Nasser H. Kutkur, Herman L.N.Wiegman, Deepak M. Divan, and Donald W. Novotny, “Design Considerations for Charge Equalization of an Electric Vehicle Battery System”, IEEE Transaction on Industry Applications, vol. 38, no. 5, pp. 28-35, Sep/Oct 1999

[16] Keiju Matsui, T. Suzuki, H. Shimada, M. Hasegawa, and K. Ando, “Further Development on Voltage Balancer for EDLCs Employing Cockcroft-Walton Circuit”, Proceedings of IEEE –Intelec - 2009, p. PES-4.1-6