The Method of Equalizing the Inter-Terminal Voltage of the Capacitors Connected in Series

Yoshifumi Takeda*, Takashi Kawaguchi** and Harumi Takeda**

Abstract

In this paper, the method to equalize the inter-terminal voltage of each capacitor connected in series using a transformer is proposed. That is, it is realizable in the simple circuit with a single transformer and multiple switches, and the method can carry out equalizing of the inter-terminal voltage of each capacitor, and it can charge it efficiently by varying the voltage rise ratio of the transformer.

And, by carrying out charging experiments, and comparing the method where the voltage rise ratio is fixed with the method where it is variable, it became clear that in which a suitable value is selected for the voltage rise ratio of the transformer, regeneration is done more efficiently than when the ratio is fixed, and the inter-terminal voltage of each capacitor is equalized. It confirmed that the suggested method is effective.

1. Introduction

Capacitors for storing electric power such as electric double layer capacitors or lithium ion capacitors are not accompanied by chemical reactions such as those seen in secondary batteries, and since they physically store the electrical charge, they have advantages such as low internal resistance, high Power density and a long cycle life. But, one defect is that there is a large dispersion in their capacitance.

Also, normally, a power storage device is made up of multiple capacitors connected in series or in parallel. But, when connect multiple capacitors in series and start charging them, as the charging progresses, the dispersion in capacitance causes a dispersion of inter-terminal voltage of each of the capacitors, and the capacitor with the smallest capacitance reaches full charge first, followed by the others, and this eventually results in overcharging, which causes degradation, and in the worst case, could lead to failure.

In order to control the dispersion of inter-terminal voltage of multiple capacitors which have been connected in series, Okamura and others have suggested a method in which a circuit known as a Parallel Monitor, basically consisting of a resistor R and a switch S, is attached to each capacitor , so that if the inter-terminal voltage of each of the capacitor exceeds the upper limit of the rated voltage, the switch S is turned ON to forcibly bypass the charging current and prevent overcharging [1]~[3].

As shown in **Fig. 1**, the Parallel Monitor is basically made up of a resistor R and a switch S, and it is a circuit which works by turning the switch S ON if the inter-terminal voltage of each of the capacitors exceeds the upper limit of the rated voltage in order to forcibly bypass the charging current.

But, when the Parallel Monitor works to prevent overcharging, there is increased loss of heat due to resistance, and this brings down the charging efficiency, added to which there is also the extremely serious practical problem that it cannot be put into the sealed case which houses the power storage unit, as a result

---

* Communication Systems Center, Mitsubishi Electric Corp., 8-1-1 Tsukaguchi-hommachi, Amagasaki

**Graduate School of Engineering, Osaka Electro-Communication University, 18-8, Hatsu-cho, Neyagawa

which it has not been implemented.

The problem of making the inter-terminal voltage of each of the capacitors connected in series uniform is an extremely serious problem not just in order to prevent overcharging, but also in order to improve the charging efficiency of the capacitor power storage device. Hereafter, Making the inter-terminal voltage of all the capacitors in the power storage unit uniform is referred to as voltage equalization. Various methods have been suggested in order to equalize the voltage of capacitors connected in series. But, in many of these methods, the charging is slow, or the configuration of the circuit is complicated.

Fig. 1 Principle of the Parallel Monitor

For example, although the method indicated to Reference [4] is well-known as a circuit to equalize the inter-terminal voltage of capacitors connected in series, since each capacitor is charged by constant voltage power supply, the charging speed is not high.

Therefore, the authors suggest a method which uses a transformer to carry out power regeneration in order to equalize the voltage of the capacitors connected in series.

2. The method of using a transformer to equalize the inter-terminal voltage of the capacitors connected in series

Even before this, methods have been suggested to equalize the inter-terminal voltage of each of the capacitors connected in series by using a transformer for each capacitor which makes up the power storage unit [5]-[7], but this paper suggests a method which can be implemented as a simple circuit using a single transformer and multiple switches.

The power storage unit made up of 6 capacitors which carry out charging while using a transformer for power regeneration in order to equalize the voltage, as shown in **Fig. 2**, and the principle is shown below.

In the same figure, switches Sw1-Sw6 are all (bipolar single-throw switches). By doing high-speed switching of any one of the switches Sw1-Sw6, it is possible to transfer the power which flows to the capacitors connected to the switch, or the power stored in the capacitors, from the primary coil L1 to the secondary coil L2 of the transformer.

For example, if the inter-terminal voltage of capacitor C1 is the highest among all the capacitors making up the power storage unit, then, as shown in **Fig. 3**(a), by doing high speed switching of the switch Sw1, the inter-terminal voltage of the capacitor C1 is switched, and the voltage V_1 of the primary coil L1 becomes as it is shown in Fig. 3(b), and as shown in Fig. 3(c), the voltage of the voltage V_2 of the secondary coil L2 is raised.

In addition, about the current I_1 and I_2, like voltage, although it becomes current on a pulse, since it is $V_2 > V_1$ as shown in the below-mentioned equation (4.3), I_2 becomes smaller than I_1. So, each switch should just have current several times the amperage rating characteristic of I_1.

Therefore transferring the power flowing to C1 and the power stored in C1 from the primary coil L1 to the secondary coil L2 of the transformer, and using it to regenerate all the capacitors in the power storage unit via the diode D, it is possible to actively equalize the inter-terminal voltage for each of the capacitors .
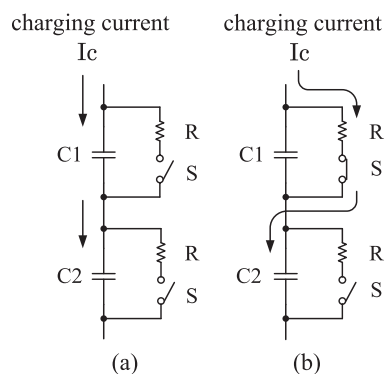
Using such a function, all the capacitors can be charged while they are connected in series, and if there is a variance in the voltage, it can be equalized by carrying out a regeneration operation.

In addition, input impedance Zi of the primary side coil L1, the voltage V_1 of the primary side coil L1, and the relation of the current I_1 become like the following equation (since the impedance of switch Sw1 is small, it is disregarded). Therefore, the amperage rating of switch Sw1 must be, more than current I_1 shown by equation (4.1).

$$I_1 > V_1 / Z_i \tag{4.1}$$

In order to use the power transferred from the primary coil L1 to the secondary coil L2 to regenerate the power storage unit, the output voltage V_2 of L2 must not be higher than the voltage required for regeneration (Power storage unit voltage Vt ＋ voltage drop of diode V_d connected to the secondary side of the transformer).
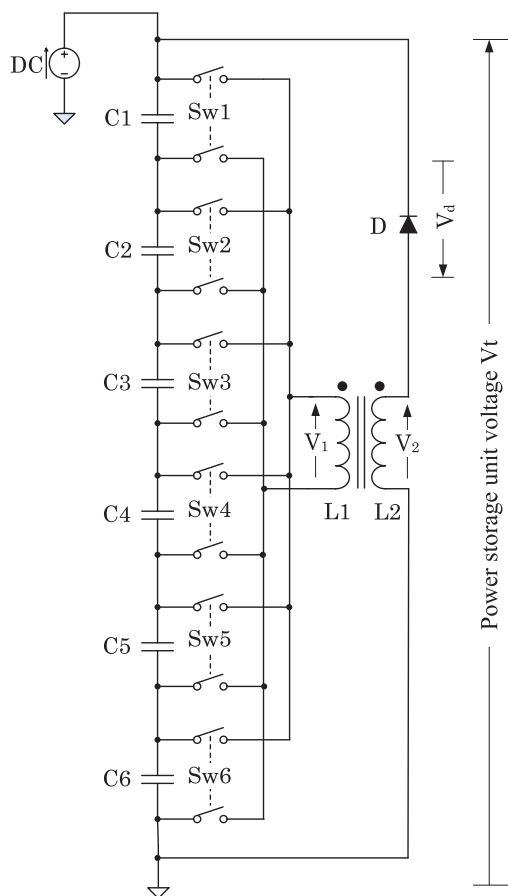
Fig. 2 The principle behind the method of voltage equalization by power regeneration using a transformer
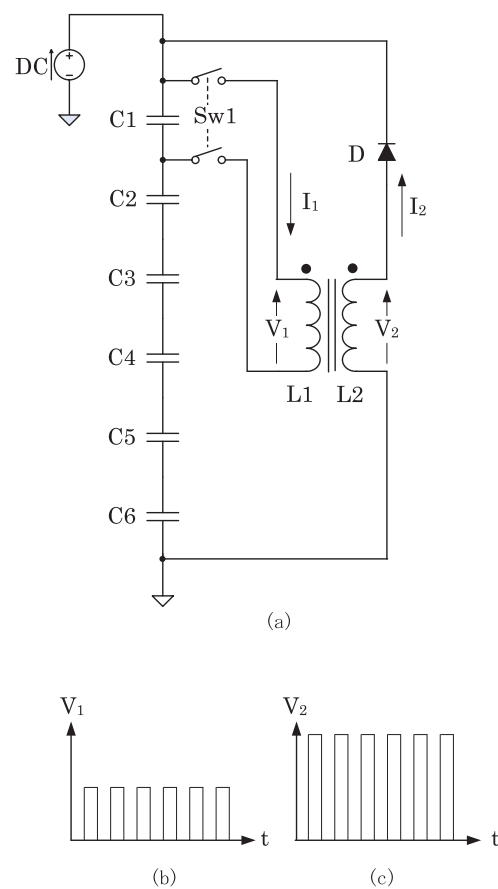
Fig. 3 The principle of voltage equalization by regeneration

In other words, the following equation must be true.

$$V_2 > V_t + V_d \tag{4.2}$$

But, if the power conversion efficiency of the transformer is not considered when carrying out regeneration, the loss of power will increase. Here, the relation between the current I_1 and voltage V_1 at the

<center>— 3 —</center>

primary end of the transformer and the current I_2 and voltage V_2 at the secondary end of the transformer is as shown in the equation (4.3).

$$\frac{I_1}{I_2} = \frac{V_2}{V_1} \tag{4.3}$$

Therefore, if a value for the voltage rise ratio of the transformer set too high, the current regenerated will be lower and the regeneration efficiency will drop. In other words, the voltage rise ratio of the transformer must be set to a suitable value which is neither too high nor too low. But, since the voltage of the power storage unit fluctuates according to the quantity of stored charge in each capacitor, the suitable value of voltage rise ratio also changes.

It is for this reason that the authors have suggested a method as shown in **Fig. 4** to make the secondary coil of the transformer into a multi tap coil so that the voltage rise ratio of the transformer can be varied. In the same figure, the switches S_T1-S_T4 which are in the secondary coil unit of the transformer are switches to make the voltage rise ratio of the transformer variable.

[Example] This is a description of the parts C1 - C6 in the power storage unit in Figure 11 which are made up of lithium ion capacitors for which the upper limit of the rated voltage is 3.8 [V] and the lower limit is 2.2 [V].
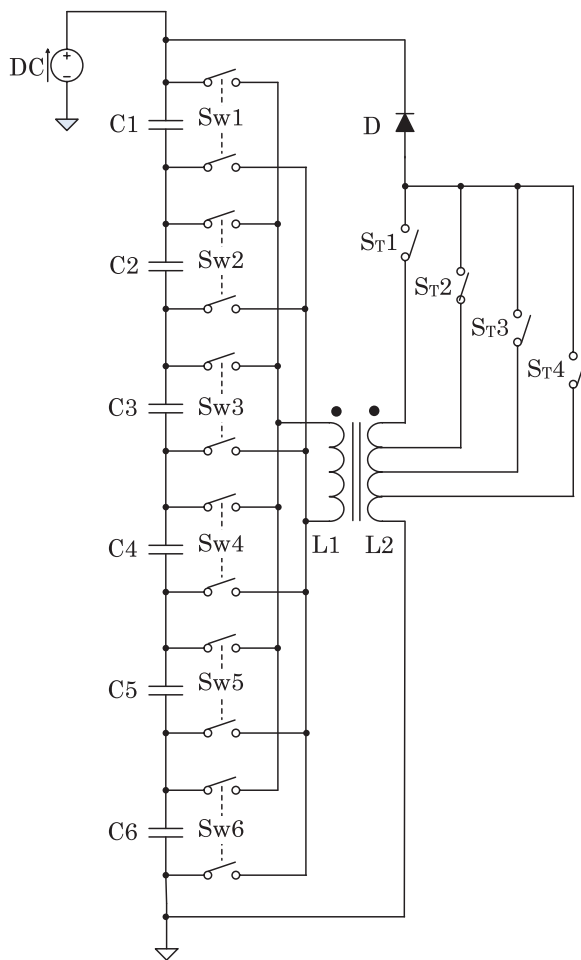

If the voltage rise ratio of the transformer is set up too high a value, this will cause the generated current to drop, which in turn will reduce the effectiveness of the regeneration process. Therefore, in order to set a suitable value for the voltage rise ratio of the transformer, set the value depending on the inter-terminal voltage of the capacitors.

Hence, since the upper limit of the rated voltage for capacitors C1 - C6 is 3.8 [V] and the lower limit is 2.2 [V], as shown in **Fig. 5**, the voltage rise ratio of the transformer is set as follows when the inter-terminal voltage of each of the capacitors is 3.8 [V], 3.4 [V], 3.0 [V] and 2.6 [V] respectively.

Fig. 4 The principle of the method of voltage equalization by power regeneration using a transformer which can vary the ratio of rise in voltage
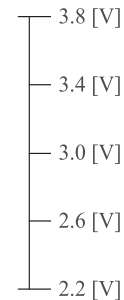
Fig. 5 The voltage between the terminals of the capacitors used to set the ratio of rise in voltage of the transformer

(1) If there is no measurement error in the capacitance of the capacitors, and all of C1 - C6 are fully charged (the inter-terminal voltage is 3.8 [V]), the voltage of the power storage unit Vt＝3.8×6＝22.8 [V]. And, since the power storage unit has 6 capacitors connected in series, the ratio of the inter-terminal voltage of a single capacitor used for regeneration to the voltage of the power storage unit is approximately 1:6.

Therefore, in order to carry out regeneration, the ratio of the primary winding to the secondary winding should be atleast 1:6. But, since the secondary side voltage V_2 of the transformer should satisfy the equation (4.1), if the voltage drop by a diode is taken into consideration, the ratio of the windings should preferably be 1:6.5.

(2) Next, when the inter-terminal voltage of each of the capacitors is 3.4 [V], in other words, if the voltage of the power storage unit Vt＝3.4×6＝20.4 [V], since it is 11% less than 22.8 [V] which is the voltage of the power storage unit when each capacitor is fully charged, the ratio becomes 1：(1×6×0.89)=1：5.4, and therefore the ratio of the primary winding to the secondary winding needs to be atleast 1:5.4, and if the voltage drop by a diode is taken into consideration, the ratio of the windings should preferably be 1:6.

(3) And, when the inter-terminal voltage of each of the capacitors is 3.0 [V], It is the same as that of the above, the ratio of the primary winding to the secondary winding needs to be atleast 1:4.7, and if the voltage drop by a diode is taken into consideration, the ratio of the windings should preferably be 1:5.5.

(4) Further, when the inter-terminal voltage of each of the capacitors is 2.6 [V], the ratio of the primary winding to the secondary winding needs to be atleast 1:4.1, and if the voltage drop by a diode is taken into consideration, the ratio of the windings should preferably be 1:5.

The above points have been summarized in **Table 1**.

Table 1　The voltage of the power storage unit and the ratio of rise in voltage

Voltage of the power storage unit	Ratio of rise in voltage
22.8 [V]	1：6.5
20.4 [V]	1：6.0
18.0 [V]	1：5.5
15.6 [V]	1：5.0

3. Experiment

First, in order to check the effectiveness of the regeneration operation with regard to measurement errors in the capacitance, in the Exp.1and Exp.2 described below, an electric capacity error is enlarged purposely, C1 is formed by connecting a capacitor with a nominal capacitance of 180[F] in parallel to a capacitor with a nominal capacitance of 1000[F] to create a capacitance of 1180[F], while a lithium ion capacitor (LIC) with a nominal capacitance of 1000[F] is used for each of C2 - C6 to make up the power storage unit. Moreover, in the Exp.3, the LIC of the nominal capacitance 1000 [F] was used for C1 - C6.

And, a microprocessor having an A/D conversion function (PIC : PIC16F887) has been used as a controller for the circuit shown in Figure 3.

In order to measure the inter-terminal voltage of each of the capacitors, and the voltage of the power storage unit (referred to as the power storage unit voltage below), OP-Amp was connected between the terminals of each capacitor, and the output was inputted into PIC. And depending on the results obtained,

high speed switching of each the switches Sw1 - Sw6 is carried out, and this is how the regeneration operation is controlled.

Further, during regeneration, based on the signals from PIC, high speed switching of each the switches Sw1 - Sw6 is carried out at a frequency of 100 [kHz] which is the most efficient frequency of the manufactured transformer.

In addition, the input impedance of the primary coil L1 of the manufactured transformer is Z_i=0.2[Ω], and the voltage of the capacitor at the time of full charge is 3.8 [V], I_1 must fill the following equation. So, FET of the amperage rating 60 [A] was used for switch Sw1 - Sw6, and S_T1 - S_T4.

$$I_1 > 3.8/0.2 = 19 \text{ [A]}$$

And, after charging starts, when the voltage difference between the capacitor with the highest inter-terminal voltage, and the capacitor with the lowest inter-terminal voltage exceeds the set voltage, start the regeneration operation and when the voltage difference of the inter-terminal voltage for all the capacitors is less than or equal to the set voltage, regenerate the power storage unit from the capacitor with the highest voltage between its terminals onwards. And, stop charging when any 1 capacitor reaches full charge.

Hereafter, the voltage at which the regeneration operation starts is referred to as the difference in voltage at the start of regeneration, and the voltage when regeneration is stopped is referred to as the difference in voltage when regeneration is stopped.

Using the above system, charging experiments were conducted under the following experimental conditions.

[Exp. 1]

With the voltage in all the capacitors making up the power storage unit at 2.20[V] when charging is started, the charging current at 1[A], the difference in voltage at the start of regeneration at 0.10[V] or more, and the difference in voltage when regeneration is stopped at less than 0.05[V], charge until any 1 capacitor reaches the full charge of 3.8[V]. Hence, even if the regeneration operation works, inter-terminal voltage of each of the capacitors do not match exactly, and even after they are fully charged, a difference of voltage of 0.05 [V] remains between the terminals.

[Exp. 2]

With the voltage in all the capacitors making up the power storage unit at 2.20[V] when charging is started, the charging current at1[A], the difference in voltage at the start of regeneration at 0.05[V] or more, and the difference in voltage when regeneration is stopped at less than 0.02[V] (which is the boundary value of the comparison of the difference of the inter-terminal voltage of each of the capacitors due to the PIC AD convertor), charge until any 1 capacitor reaches the full charge of 3.8[V]..

[Exp. 3]

With the voltage in capacitor C1= 2.20[V], C2-C6 = 2.25 [V]   when charging is started, the charging current at 1[A], the difference in voltage at the start of regeneration at 0.05[V] or more, and the difference in voltage when regeneration is stopped at less than 0.02[V] (which is the boundary value of the comparison of the difference in inter-terminal voltage of each of the capacitors due to the PIC AD convertor), charge until any 1 capacitor reaches the full charge of 3.8[V].

For each of the experimental conditions of the experiment 1 -3 (Exp.1-3), the charging experiments

shown in (a), (b) and (c) below was conducted in order to check the usefulness of regeneration and the effectiveness of varying the voltage rise ratio of the transformer.

(a) Without carrying out regeneration

(b) Charging by carrying out regeneration with the voltage rise ratio of the transformer fixed to a maximum of (1:6.5).

(This is referred to below as the method of fixing the ratio of rise in voltage.)

(c) Charging by carrying out regeneration while varying the voltage rise ratio of the transformer.

(This is referred to below as the method of varying the voltage rise ratio.)

As shown in **Table 2**, the abovementioned charging experiments (a), (b) and (c) for Exp. 1, and the abovementioned charging experiments (b) and (c) for Exp. 2, and the abovementioned charging experiments (b) and (c) for Exp. 3 was conducted. Hereafter, these experiments are referred to as Exp. 1-(a), Exp. 1-(b), Exp. 1-(c), Exp. 2-(b), Exp. 2-(c), Exp. 3-(b) and Exp. 3-(c) respectively.

Table 2 Experimental conditions

	Control method	Voltage when charging starts	Voltage difference when regeneration starts	Voltage difference when regeneration stops
Exp.1	(a) No regeneration	C1～C6 : 2.20 [V]	---	---
	(b) Fixed voltage rise ratio		0.10 [V]	0.05 [V]
	(c) Variable voltage rise ratio			
Exp.2	(b) Fixed voltage rise ratio	C1～C6 : 2.20 [V]	0.05 [V]	0.02 [V]
	(c) Variable voltage rise ratio			
Exp.3	(b) Fixed voltage rise ratio	C1 : 2.20 [V] C2～C6: 2.25 [V]	0.05 [V]	0.02 [V]
	(c) Variable voltage rise ratio			

Nominal capacitance
[Exp.1] [Exp.2]   C1 : 1180 [F]   C2～C6 : 1000 [F]
[Exp3]   C1～C6 : 1000 [F]

4. Experimental results
4.1 Results of Exp. 1

The results of Exp. 1-(a), i.e. the voltage of the power storage unit and the voltage of each LIC when regeneration is not carried out are shown in **Fig. 6**. The results of Exp. 1-(b), i.e. the voltage of the power storage unit and the inter-terminal voltage of each capacitor when the regeneration is carried out by fixing the voltage rise ratio, are shown in **Fig. 7**. The results of Exp. 1-(c), i.e. the voltage of the power storage unit and the inter-terminal voltage of each capacitor when the regeneration is carried out in a circuit while varying the voltage rise ratio, are shown in **Fig. 8**.

Further, the portion on the graph enclosed by dotted lines which represents the changes in the inter-terminal voltage of each capacitor in Fig. 7(b) and Fig. 8(b) is the period when regeneration is being carried out.
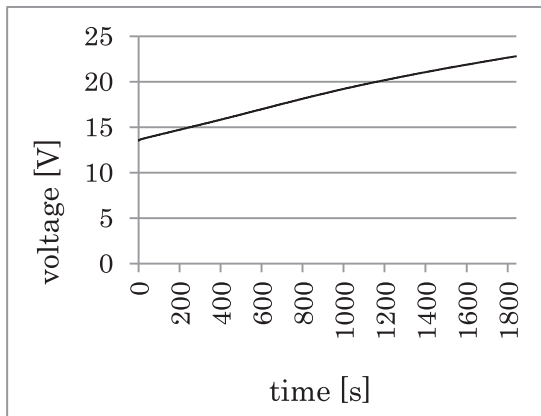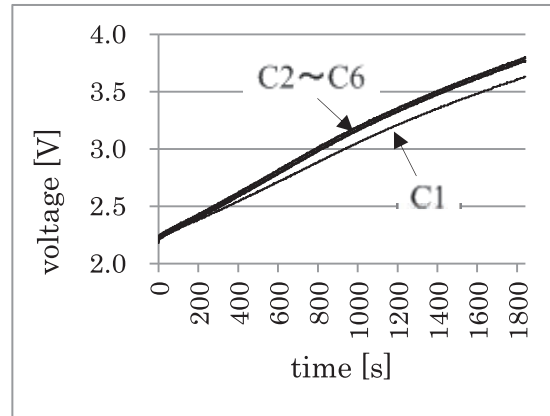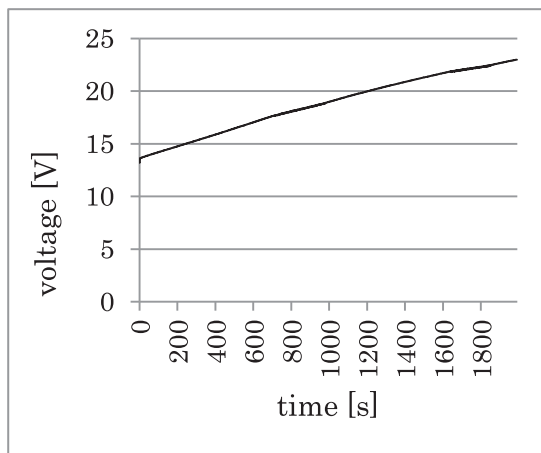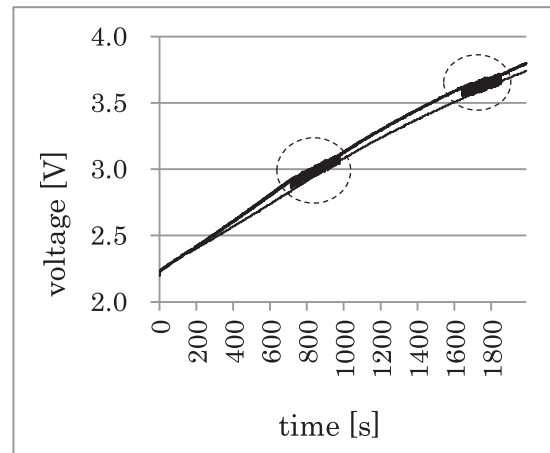
(a)　　　　　　　　　　　　　　　　　(b)

Fig. 6 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each capacitor (b) during the charging experiment when regeneration is not carried out.
(Voltage in C1-C6 when charging starts＝2.20 [V])

(a)　　　　　　　　　　　　　　　　　(b)

Fig. 7 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each capacitor (b) when carrying out regeneration using the method of fixing the ratio of rise in voltage.
(Voltage in C1-C6 when charging starts＝2.20 [V], difference in voltage when regeneration starts= 0.10 [V] and difference in voltage when regeneration is stopped = 0.05 [V])

(a)   (b)

Fig. 8 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each capacitor (b) when carrying out regeneration using the method of varying the ratio of rise in voltage.
(Voltage in C1-C6 when charging starts＝2.20 [V], difference in voltage when regeneration starts= 0.10 [V] and difference in voltage when regeneration is stopped = 0.05 [V])
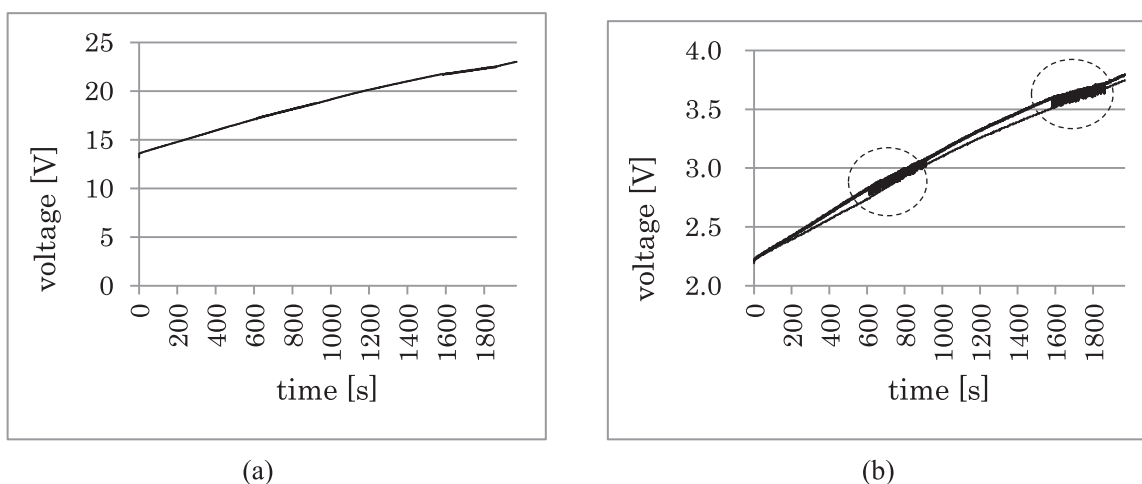
From Fig. 6, it turns out that if the capacitance measurement error is large, and if regeneration is not carried out, there is an increase in the inter-terminal voltage of each capacitor, but if regeneration is carried out, the maximum difference in inter-terminal voltage of each capacitor is kept at 0.10 [V] or less.

Table 3 is a summary of the results of Exp. 1 pertaining to the charging time and the maximum difference in inter-terminal voltage of each capacitor when charging is complete. As shown in this table, when regeneration is carried out, the charging time is longer than when it is not carried out, but the maximum difference in inter-terminal voltage of each capacitor when charging is complete is reduced and this shows that the regeneration operation is working.

Table 3   Results of Exp. 1

Control method	Time [mm:ss]	Maximum voltage difference in the voltage between terminals of C1-C6 when charging is complete
No regeneration	30:41	0.17 [V]
Fixed voltage rise ratio	33:11	0.06 [V]
Variable voltage rise ratio	32:50	0.05 [V]

And, even when regeneration is carried out, the charging time taken in the method with a fixed voltage rise ratio is 21 seconds more than in the method with a variable ratio. Moreover, it turns out that the maximum difference in voltage of each capacitor when charging is complete is 0.01 [V] lower in the method where the voltage rise ratio is variable than in the method where it is fixed, and that the regeneration efficiency goes up by changing the voltage rise ratio.

— 9 —

4.2 Results of Exp. 2

The results of Exp. 2-(b), i.e. the voltage of the power storage unit and the voltage of each LIC when regeneration is carried out by fixing the voltage rise ratio, are shown in **Fig. 9**. The results of Exp. 2-(c), i.e. the voltage of the power storage unit and the inter-terminal voltage of each capacitor when the regeneration is carried out in a circuit with a variable voltage rise ratio, are shown in **Fig. 10.**

And, the portion on the graph enclosed by dotted lines which represents the changes in the inter-terminal voltage of each capacitor in Fig. 9(b) and Fig. 10(b) is the period when regeneration is being carried out.
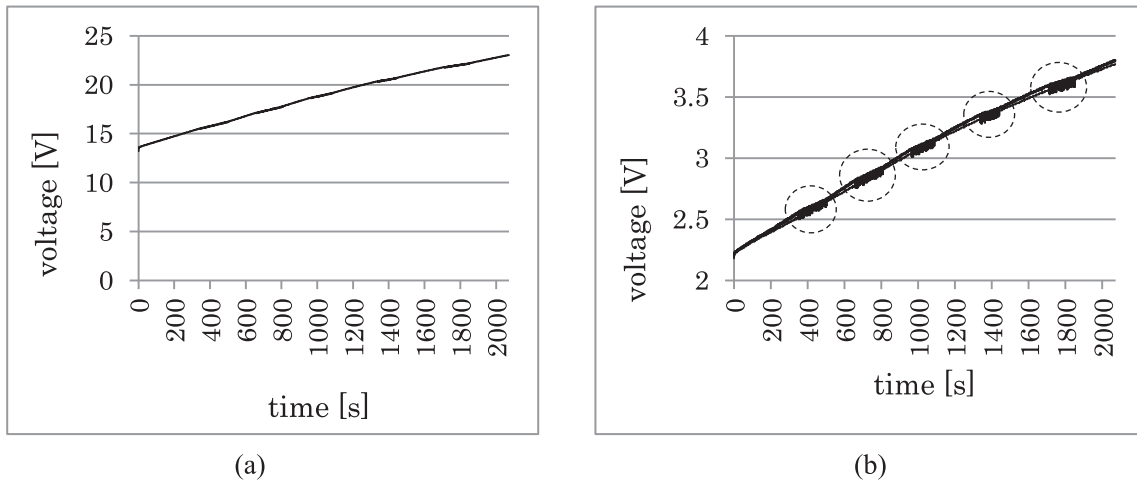

(a)   (b)

Fig. 9 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each
capacitor (b) when carrying out regeneration using the method of fixing the ratio of rise in
voltage.
(Voltage in C1-C6 when charging starts＝2.20 [V], difference in voltage when regeneration
starts= 0.05 [V] and difference in voltage when regeneration is stopped = 0.02 [V])

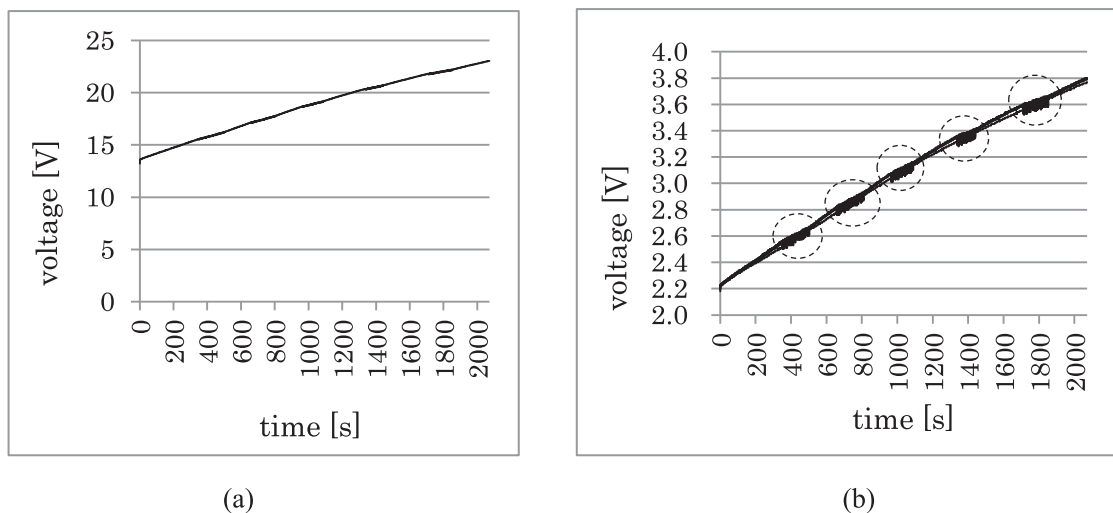(a)   (b)

Fig. 10 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each
capacitor (b) when carrying out regeneration using the method of fixing the ratio of rise in
voltage.
(Voltage in C1-C6 when charging starts＝2.20 [V], difference in voltage when regeneration
starts= 0.05 [V] and difference in voltage when regeneration is stopped = 0.02 [V])

Since the electric capacity of C1 is larger than other capacitors, even if it is once equalized by regeneration, with advance of charge, voltage shows variation again and it is revived 5 times in Fig.9 and Fig.10.

Table 4 is a comparison of the results of Exp. 1 and 2 which are the charging time and the maximum difference in voltage between the terminals of each capacitor when charging is complete in the method when the voltage rise ratio is fixed, and the method when it is variable.

Table 4 Comparison of the results of Exp.1 and 2

	Control method	Time mm:ss	Maximum voltage difference in the voltage between terminals of C1-C6 when charging is complete	Voltage difference when regeneration starts	Voltage difference when regeneration stops
Exp.1	Fixed voltage rise ratio	33:11	0.06 [V]	0.10 [V]	0.05 [V]
	Variable voltage rise ratio	32:50	0.05 [V]	0.10 [V]	0.05 [V]
Exp.2	Fixed voltage rise ratio	34:32	0.03 [V]	0.05 [V]	0.02 [V]
	Variable voltage rise ratio	34:15	0.02 [V]	0.05 [V]	0.02 [V]

From Table 4, it turns out that if the difference in voltage when regeneration is stopped is set as a small value, it reduces the maximum difference of the inter-terminal voltage of each capacitor when charging is completed, but the charging time is longer.

And in the method with a variable voltage rise ratio, the inter-terminal voltage is the same for all the capacitors, and the charging time is also shorter than in the method with a fixed voltage rise ratio. In other words, charging takes place more efficiently in the method with a variable voltage rise ratio, in which the voltage rise ratio of the transformer is suitably selected, than in the method with a fixed voltage rise ratio, and that the inter-terminal voltage is being equalized for all the capacitors is confirmed.

4.3 Results of Exp. 3

The results of Exp. 3-(b), i.e. the voltage of the power storage unit and the inter-terminal voltage of each capacitor when the regeneration is carried out by fixing the voltage rise ratio are shown in **Fig. 11**. The results of Exp. 3-(c), i.e. the voltage of the power storage unit and the inter-terminal voltage of each capacitor when the regeneration is carried out in a circuit with a variable voltage rise ratio, are shown in **Fig. 12**.

Further, the portion on the graph enclosed by dotted lines which represents the changes in the inter-terminal voltage of each capacitor in Fig. 11(b) and Fig. 12(b) is the period when regeneration is being carried out.
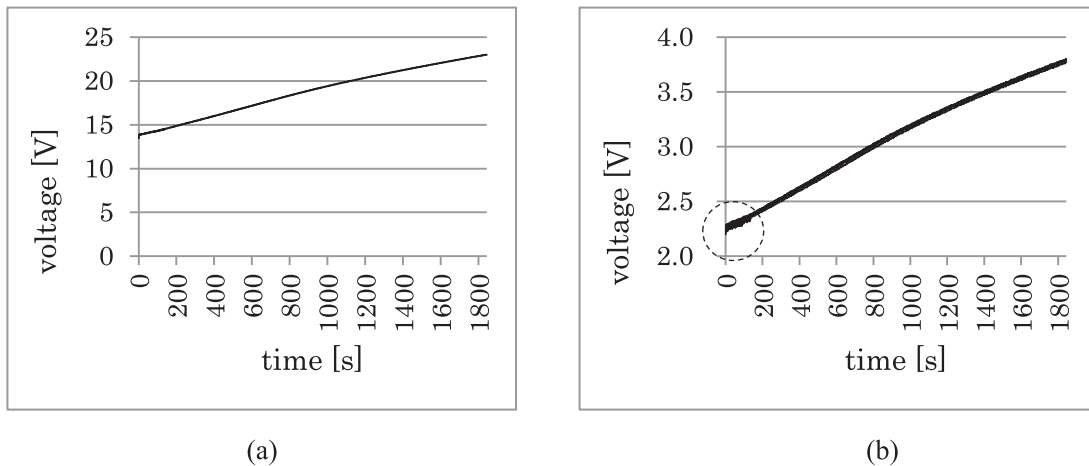
(a)   (b)

Fig. 11 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each capacitor (b) when carrying out regeneration using the method of fixing the ratio of rise in voltage.
(Voltage when charging starts in C1＝2.20 [V] and in C2-C6＝2.25 [V], difference in voltage when regeneration starts= 0.05 [V] and difference in voltage when regeneration is stopped =

(a)   (b)
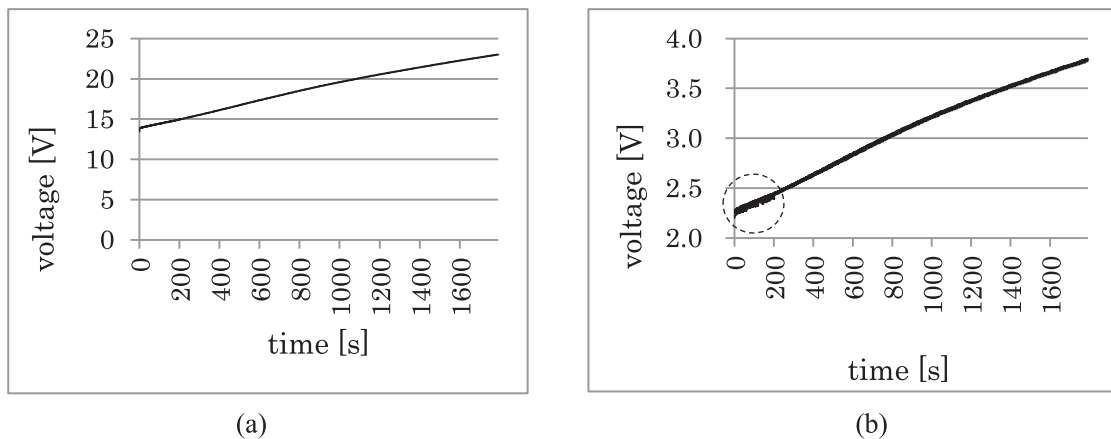
Fig. 12 Time transitions of the power storage unit voltage (a) and inter-terminal voltage of each capacitor (b) when carrying out regeneration using the method of varying the ratio of rise in voltage.
(Voltage when charging starts in C1＝2.20 [V] and in C2-C6＝2.25 [V], difference in voltage when regeneration starts= 0.05 [V] and difference in voltage when regeneration is stopped = 0.02 [V])

In Exp.3, there is no nominal capacitance variation of all the capacitors, and first, beforehand, it distinguished between the initial voltage of one LIC, and has started charge.

If Fig.11 and Fig.12 is performed and equalized immediately after a charge start, in order that the variation in the voltage between terminals may seldom arise henceforth but it may be less than regeneration start conditions, having ended regeneration operation at once is shown.

Table 5 is a comparison of the results of Exp. 3 pertaining to the charging time and the maximum difference in voltage between the terminals of each capacitor when charging is complete.

Table 5 Results of Exp. 3

	Control method	Time mm:ss	Maximum voltage difference in the voltage between terminals of C1-C6 when charging is complete	Voltage difference when regeneration starts	Voltage difference when regeneration stops
Exp.3	Fixed voltage rise ratio	30:44	0.03 [V]	0.05 [V]	0.02 [V]
	Variable voltage rise ratio	29:51	0.02 [V]	0.05 [V]	0.02 [V]

From Table 5, It turns out that regeneration works adequately even when the voltage of the capacitors when charging starts is different, and the time for charging is shorter in the method where the voltage rise ratio is variable than in the method where the voltage rise ratio is fixed.

5. Conclusion

In this paper, the method of using a transformer to equalize the inter-terminal voltage of each capacitor connected in series is described. That is, it is realizable in the simple circuit with a single transformer and multiple switches, and the method can carry out equalizing of the inter-terminal voltage of each capacitor, and it can charge it efficiently by varying the voltage rise ratio of the transformer.

And, by carrying out charging experiments, and comparing the method where the voltage rise ratio is fixed with the method where it is variable, it turned out that in the method where the voltage rise ratio is variable, in which a suitable value is selected for the voltage rise ratio of the transformer, regeneration is done more efficiently than when the ratio is fixed, and the inter-terminal voltage of each capacitor is equalized. It confirmed that the suggested method is effective.

And, it has also become clear that if the voltage difference when regeneration is stopped is set up small, then the maximum difference in inter-terminal voltage of each capacitor when charging is complete is also reduced.

References

[1] M. Okamura: Fundamental research on electrical power storage devices, J. IEEJ, **B-5**, 504/510 (1995)

[2] M. Okamura, T. Morimoto and K. Hiratsuka: How to control the voltage in a capacitor, JP3309259 (2002)

[3] M. Okamura：Storage Capacitor Power Supply, EP0564149 (1993)

[4] M. Uno and A. Kukita: Monolithic voltage equalization circuit for power storage cells connected in series, Patent publication No.2012-186881

[5] M. Yamagishi, M. Shimizu and M. Okamura: Method of charging capacitor batteries, and charging devices , JP3238841(2001)

[6] K. Mori and A. Hasebe: Storage devices for electrical energy －Devices for regulation of the cell energy level and method for regulation of the cell energy level－, JP3764633 (2006)

[7] K. Yamashita: Charging device for capacitors, JP3854592 (2006)