http://dx.doi.org/10.11142/jicems.2014.3.4.451

Journal of International Conference on Electrical Machines and Systems Vol. 3, No. 4, pp. 451~457, 2014

System Construction Method of Parallel Operation System constructed with Three Electric Power Converters

Keisuke Ishikura [*], Hiromi Inaba [*], Keiji Kishine [*], Mitsuki Nakai [**], and Takuma Ito [*]

Abstract – **Parallel operation systems have an advantage in that they can be constructed quickly and inexpensively by combining existing electric power converters. However, in this case, there is a peculiar problem in that a cross current flows between the electric power converters. To design a control system more simply and commonalize the core of combination reactors, we reviewed a system construction method for parallel operation systems constructed with three electric power converters.**

Keywords: **Power converter, Cross current, Combination reactor, Current control**

1. Introduction

When increasing the motor capacity used in elevators installed in skyscrapers, the capacity of the electric power converter for the motor drive also needs to be increased. Although a parallel operation system can be adopted to increase capacity, cross current that circulates between electric power converters occurs. Suppressing this circulating current is important from the viewpoint of efficiency. Conventionally, cross current suppression has been performed by synthesizing output currents through a combination reactor, which has a passive suppression effect. However, fabricating a system mounted with equipment that has high density in a limited space is important to miniaturize the reactor. Therefore, a summation and difference control method that suppresses the cross current with the aim of miniaturizing the reactor was proposed [1]. Moreover, from the viewpoint of standardization and improving the flexibility of system construction, a combination of electric power converters with different proportions of output current has also been considered [2]-[4]. In addition, a structure that extends the combinations of parallel connections to three has been considered [5]-[6]. However, the design of a current control system has been complicated in the case of the previous structure. Further, due to synthesizing every two electric power converters, the large amount of occupied space of the combination reactors has been a problem.

In this paper, we focus on how to structure the parallel operation system with three electric power converters. In particular, a current control method and method for synthesizing output currents were reexamined. On that basis, we propose a structure for a current control system with the aim of simplifying the design. In addition, a method for commonalizing the combination reactor cores is proposed. We evaluated them in a circuit simulation and experiment.

2. Previous Construction of Parallel Operation System

Fig. 1 shows a parallel operation system constructed with three electric power converters that have been considered before. The outputs of each electric power converter are supplied to the motor M through combination reactors. Motor speed is measured with a pulse generator PG. Output currents i_1, i_2, and i_3 are measured with current detectors CT_1, CT_2, and CT_3. The information obtained from them is processed in a controller that performs speed control (ASR), current control (ACR), and PWM control. PWM commands provided from the controller control the output voltage of electric power converters.

Fig. 2 shows a control block diagram of the system in Fig. 1. The previous method was used to commonalize two or more summation current controls. The aim was to reduce the cross current by decoupling each summation current control. However, since the sharing ratio of output is different for each inverter, it had become difficult to derive the control model. Cross current suppression controls are also the same. Further, it became difficult for output

---

[*] Dept. of Electronic Systems Engineering, the University of Shiga Prefecture, Japan. (zn23kishikura@ec.usp.ac.jp, inaba.h@usp.ac.jp, kishine.k@usp.ac.jp, zn23titou@ec.usp.ac.jp)
[**] Ishida Co., Ltd., Japan. (mimimi.mitsuki@gmail.com)

Received 23 October 2014; Accepted 18 November 2014

currents to flow to the motor when the impedance of the combination reactor was much smaller than that of the motor. The sharing rate of the outputs necessary to take full advantage of the effect of the combination reactor is 1:1:2. However, even in this case, there was a problem in that output currents can be influenced by the difference of impedances of the inverter side.

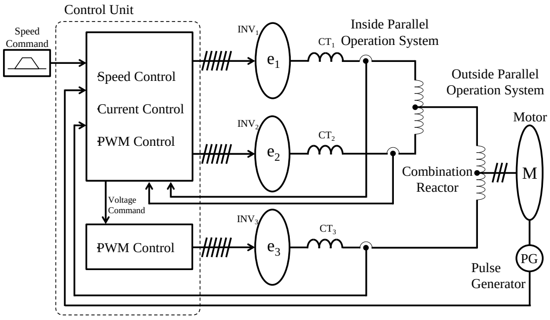


Fig. 1. Conventional overall configuration schematic

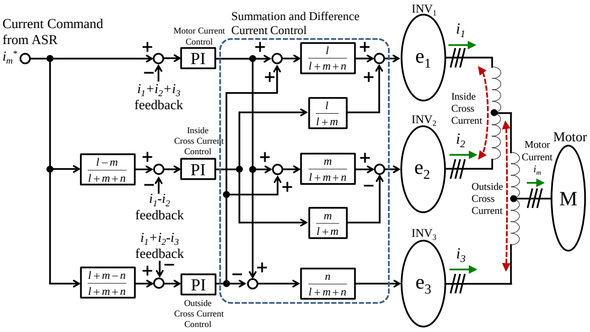


Fig. 2. Block diagram of previous current control system

3. Proposed Construction of Parallel Operation System

3.1 Whole System Construction

Fig. 3 shows the parallel operation system constructed with the three electric power converters that were proposed in order to solve the problems of the previous structure. Compared with the previous system, the only difference was that the method for synthesizing output currents uses a combination reactor. Output synthesizing uses a three-input combination reactor. The sharing ratio of output currents is 1:1:1.

3.2 Proposed Current Control Method and Circuit Structure

Fig. 4 shows the proposed extended summation and difference current control method used to solve the complexity of the control model, and Fig. 5 shows an equivalent circuit model obtained by using the summation. From Fig. 5 (a), the following equation was obtained:

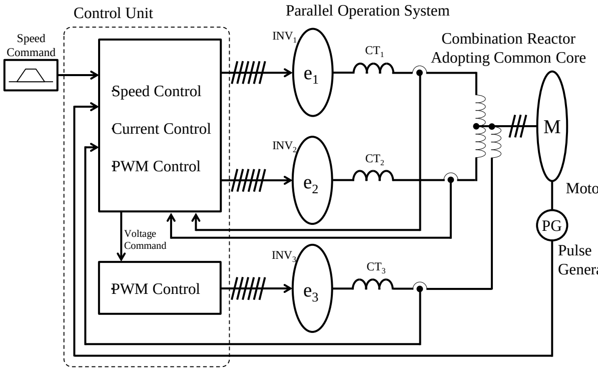


Fig. 3. Reviewed overall configuration schematic

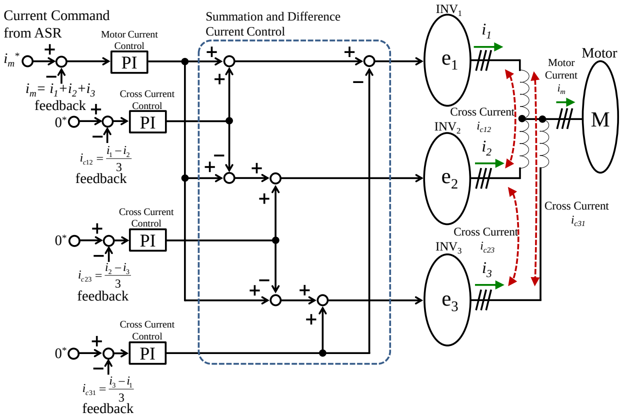
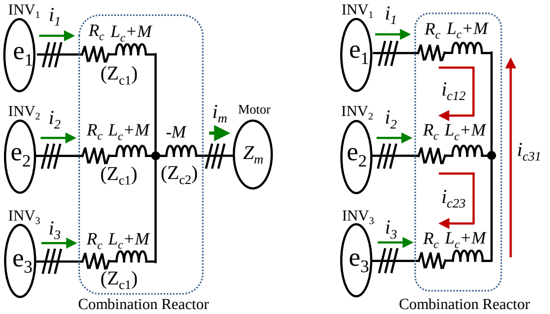


Fig. 4. Block diagram of proposed current control system



(a) Motor current component (b) Cross current component

Fig. 5. Equivalent circuit models

$$\begin{cases} e_1 = Z_{c1} i_1 + (Z_{c2} + Z_m)(i_1 + i_2 + i_3) \\ e_2 = Z_{c2} i_2 + (Z_{c2} + Z_m)(i_1 + i_2 + i_3) \\ e_3 = Z_{c3} i_3 + (Z_{c2} + Z_m)(i_1 + i_2 + i_3) \end{cases} \quad (1)$$

$$e_1 + e_2 + e_3 = Z_{c1}(i_1 + i_2 + i_3) + 3(Z_{c2} + Z_m)(i_1 + i_2 + i_3) \quad (2)$$

where $Z_m(= R_m + j\omega L_m)$ is the impedance of the motor. R_m is the winding resistance, and L_m is the inductance. In addition,

$Z_{c1}(= R_c + j\omega(L_c + M))$, $Z_{c2}(= -j\omega M)$ are the impedances of the combination reactor. R_c is the winding resistance, L_c is the self-inductance, and M is the mutual inductance.

Moreover, for $e_1 = e_2 = e_3 = e$ and $i_m = i_1 + i_2 + i_3$, for the summation current control system, the following equation was obtained:

$$e = (\frac{Z_{c1}}{3} + Z_{c2} + Z_m)i_m \tag{3}$$

From Fig. 5 (b), the following equation was obtained:

$$\begin{cases} e_1 - e_2 = Z_{c1}(i_1 - i_2) \\ e_2 - e_3 = Z_{c1}(i_2 - i_3) \\ e_3 - e_1 = Z_{c1}(i_3 - i_1) \end{cases} \tag{4}$$

Considering $e_1 - e_2 = e_{c12}$, $e_2 - e_3 = e_{c23}$, $e_3 - e_1 = e_{c31}$, $(i_1 - i_2)/3 = i_{c12}$, $(i_2 - i_3)/3 = i_{c23}$, $(i_3 - i_1)/3 = i_{c31}$, (4) becomes

$$\begin{cases} e_{c12} = 3Z_{c1}i_{c12} \\ e_{c23} = 3Z_{c1}i_{c23} \\ e_{c31} = 3Z_{c1}i_{c31} \end{cases} \tag{5}$$

3.3 Three Input Combination Reactor

The three input combination reactor is used for synthesizing the output currents of inverters. In (3), considering $M = kL_c$ (k: coupling coefficient), the following equation is obtained:

$$e = (\frac{R_c}{3} + R_m)i_m + j\omega(\frac{1-2k}{3}L_c + L_m)i_m \tag{6}$$

The magnetic flux caused by the summation current components of each reactor is cancelled inside the reactor. Further, the impedance looks small for not occurring a voltage drop in the reactor. Therefore, when the voltage drop caused by the combination reactor equals zero, the following equation is obtained:

$$L_c(1-2k) = 0 \tag{7}$$

From (7), the coupling coefficient is $k = 0.5$.

3.4 The Current Control Model

Therefore, by applying $k = 0.5$ and (3), (8) was obtained. The summation current control calculation model R, L became (9).

$$e = (\frac{R_c}{3} + R_m + j\omega L_m)i_m \tag{8}$$

$$\begin{cases} R = \dfrac{R_c}{3} + R_m \\ L = L_m \end{cases} \tag{9}$$

Further, by applying $k = 0.5$ and (5), (10) was obtained. The difference current control calculation model R, L became the following (11).

$$e = 3(R_c + j\omega(1+k)L_c)i_c \tag{10}$$

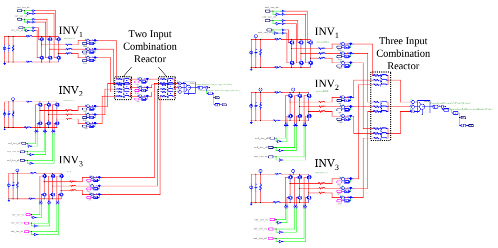
$$\begin{cases} R = 3R_c \\ L = \dfrac{9}{2}L_c \end{cases} \tag{11}$$

Thus, the number of control models was only two. In the simulation, we proceeded with this configuration.

4. Simulation Comparison

The cross current suppression performance of the proposed system was compared with that of the previous system in a circuit simulation. Each control system was constructed on the circuit simulation software PSIM. The speed pattern of a trapezoid was given as the speed command. Fig. 6 shows the main circuit structured with a motor, inverters, and combination reactor. Fig. 7 shows the control unit of the previous system. Fig. 8 shows the control unit for the proposed method. Both systems used ASR and ACR. Originally, the electric power converter was constructed with an inverter and a converter. However, since this paper is focused on the current control method of the inverter side, the converter was replaced with a DC power supply. Simulation results showed the U-phase components of each inverter output current.

First, the simulation was carried out in an ideal condition. Fig. 9 shows results with the previous method, and Fig. 10 shows the results with the proposed method. The motor current is i_u, inside cross current is i_{ic}, outside cross current is i_{oc}, the cross current between INV$_1$ and INV$_2$ is i_{c12}, and



(a) Previous main circuit (b) Proposal main circuit

Fig. 6. Main circuit

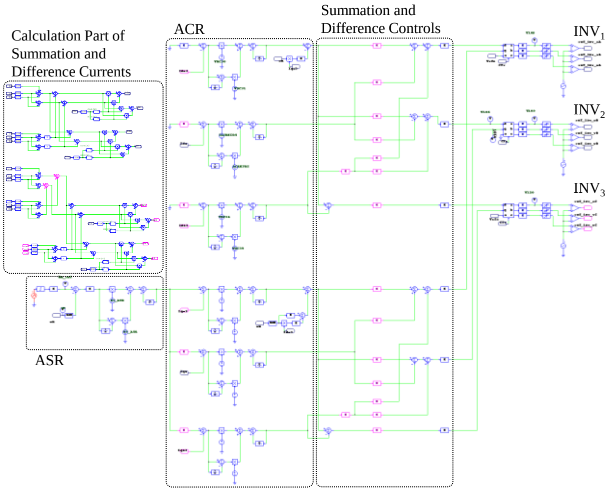


Fig. 7. Previous control circuit

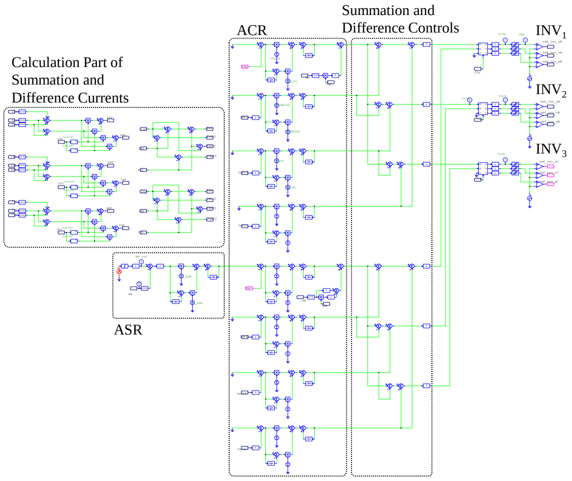


Fig. 8. Proposed control circuit

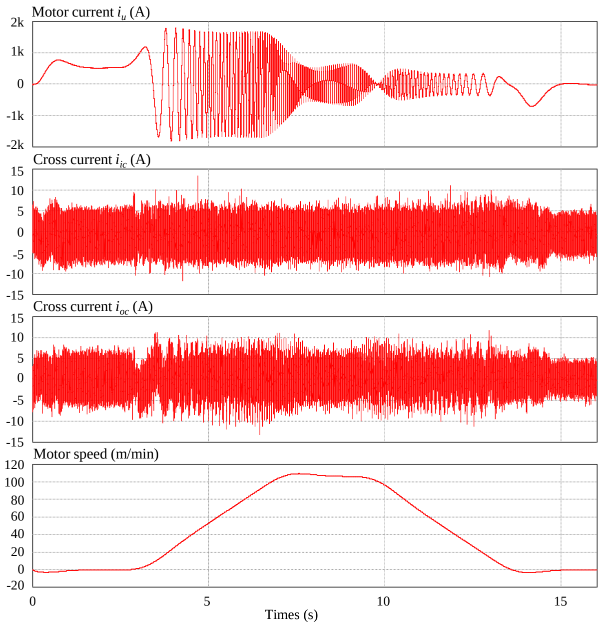


Fig. 9. Cross current waveform of previous method

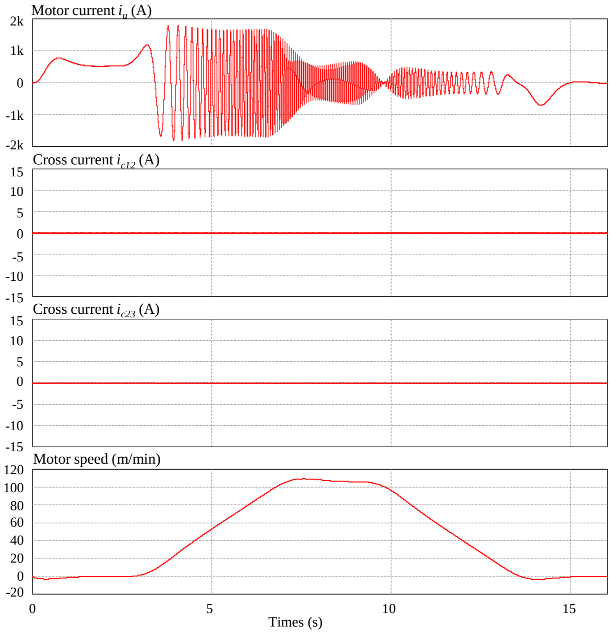


Fig. 10. Cross current waveform of proposed method

the cross current between INV_2 and INV_3 is i_{c23}. For the previous method, the output current sharing ratio of INV_1, INV_2, and INV_3 was 1:1:2. This created a balance that had the effect of suppressing the cross current of the combination reactor. Here, each summation current control system was compared. The effective value of the previous system was 688.30 A, and that of the proposed system was 688.32A. There was no significant difference between both summation current control methods. Moreover, each difference current control system was compared. The proposed method sufficiently suppressed cross currents in the ideal condition. In comparison, in the case of the previous method, cross current on both side was generated even in the ideal condition. The currents were not caused by the main circuit structure being symmetric, as viewed from the motor side in the case of proposed system.

Next, in the actual parallel operation system, a potential difference occurred between the DC voltage sources that were rectified by converters supplied to the inverters. This problem influences the cross current suppression that brings about a potential difference between the output voltages of each inverter. Therefore, we compared the influence that the error of the DC voltage source gives to difference current control. This influence was simulated by giving error intentionally to the DC power source supplied to INV_2. As other disturbances, the phase delay of the carrier used in the PWM control can be considered. However, because it cannot be suppressed in the control, we do not mention it in this paper [7]. Fig.11 shows the variation of the inside cross current in the case of altering the voltage of the DC power supply of INV_2 to INV_1. There was no significant difference in the cross current suppression effect between both methods. Fig. 12 shows the change of the outside cross current in the case of altering the voltage of the DC power supply of INV$_2$ to INV$_1$. The proposed method was slightly inferior as compared with the previous method. However, the increasing value was slight when compared with the value of the motor current.

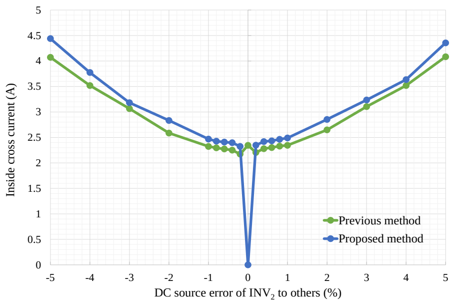


Fig. 11. The influence on inside cross current

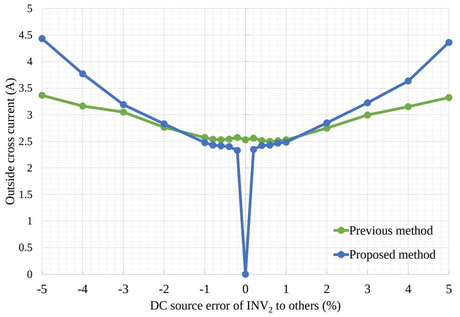


Fig. 12. The influence on outside cross current

5. Experimental Result

The cross current is generated by factors such as the output voltage error between inverters and the variability of the device characteristic in an actual circuit. We simulated these factors, to confirm whether the cross current suppression effect of the proposed method was sufficiently obtained relative to the previous method. Next, a simple laboratory equipment was built in order to verify the proposed system. We examined the cross current suppression effect by using this. Fig. 13 shows the equipment used for measurement. Table 1 shows the parameters of the circuit elements used. First, we constructed a simulation model of an actual mini model, shown in Fig. 14. In addition, we simulated it in the ideal condition. The magnitude of the cross current changes depending on the amount of change in the output current. Therefore, the motor was driven at a constant velocity so that cross current was at a certain magnitude. Fig. 15 shows the U-phase output results of the cross currents i_{c12}, i_{c23}, i_{c31}, and motor current i_m and motor speed for the proposed method. It was possible to achieve an output sharing ratio of 1:1:1 even in the experiment. Moreover, the cross current was sufficiently suppressed with respect to the motor current.

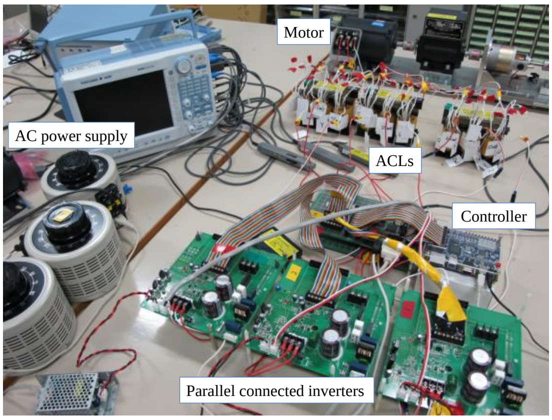


Fig. 13. Simple laboratory equipment

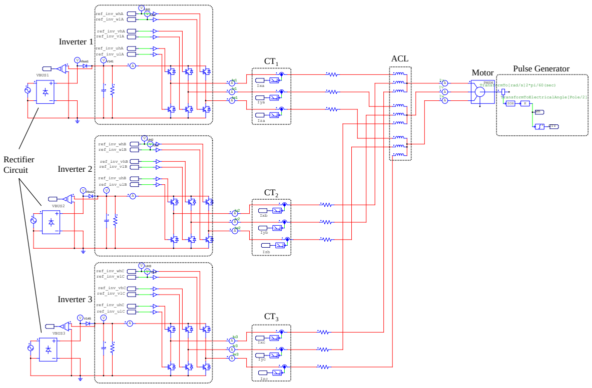


Fig. 14. Experimental main circuit

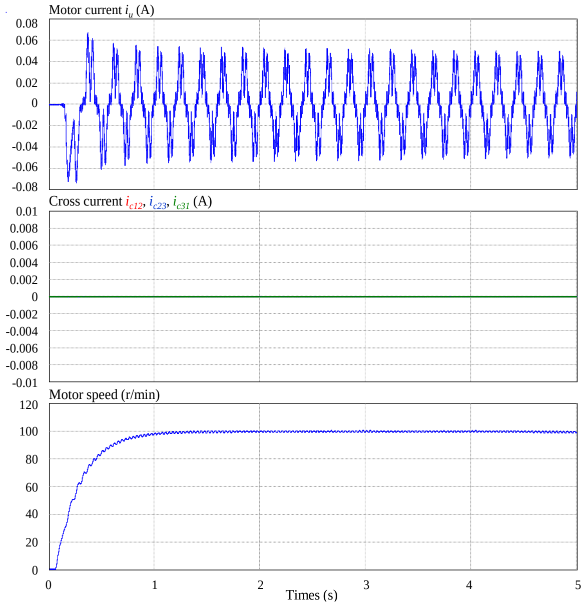


Fig. 15. Simulation result of laboratory equipment model

Table 1. System parameters

Switching frequency	5kHz	Stator resistance	2.74
Dead time	4s	d-axis inductance	0.02H
Sampling cycle of current detection	5kHz	q-axis inductance	0.03H
Calculating frequency of ACR	0.0002s	Number of poles	6
Sampling cycle of speed detection	5kHz	Shaft time constant	0.4085s
Calculating frequency of ASR	0.002s	Inductive voltage	91.8V/krpm
Rotation speed	100r/min	Winding resistance of ACL	0.0675
Input voltage (AC)	25V	Winding inductance of ACL	0.025H

Finally, measurement was actually performed. Fig. 16 shows U-phase results of the motor current i_{um}, the output currents i_{u1}, i_{u2}, and i_{u3} of the inverters and the cross currents i_{c12}, i_{c23} and i_{c31} between the inverters. The motor current for the proposed method was 78.17 mA. The cross current i_{c12} was 2.38 mA, i_{c23} was 3.31 mA, and i_{c31} was 2.5mA. We found that a sufficient suppression effect was obtained relative to the motor current. Operation with the proposed method was confirmed with actual equipment.

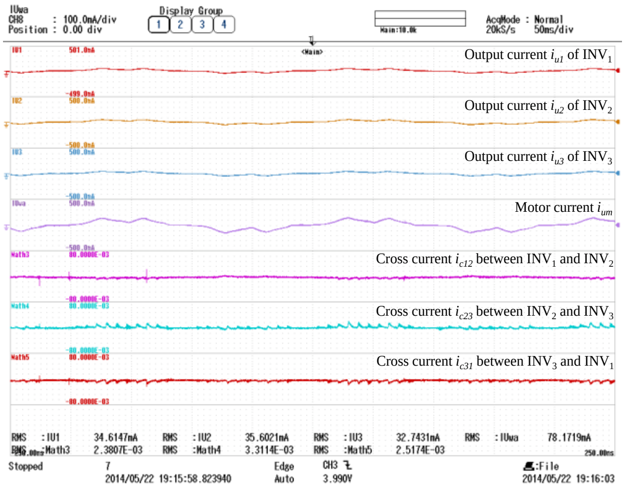


Fig. 16. Experimental results

4. Conclusion

The structures of main and control circuits were reexamined in a parallel operation system constructed with three electric power converters. Both the simulation and the experimental results verified the validity of the proposed system. In conclusion, the present study elucidated a structure that simplifies the design of a control system with a cross current suppression effect almost equal to that of the previous structure.

Acknowledgements

The authors thank everyone in the Electronics Circuit Laboratory, Department of Electronic Systems Engineering, School of Engineering, the University of Shiga Prefecture.

References

[1] H. H. Anayo, et al., “Electrical driving techniques for large-scale and ultra-high speed elevators,” *Journal of the AEM(Japan)*, vol.16, no.1, pp.1-6, 2008.

[2] H. Inaba, et al., “A study on construction and control method of parallel connected power converter,” in *IEEJ Annual. Meeting Rec.*, 4-069, pp128, 2011.

[3] H. Inaba, et al., “Simulation analysis of construction and control method of parallel connected power converter,” in *Japan Ind. Appl. Conf. Rec.*, 1-2, pp.I-103-106, 2011.

[4] H.Inaba, et al, “An electric power conversion system composed of two parallel-connected converters providing different output currents,” ICEMS, DS4G4-2, 2012.

[5] M. Nakai, et al., “Parallel connected power converter constructed with odd number converters,” in *Japan Ind. Appl. Society Conf. Rec.*, 2012, in press.

[6] M.Nakai, et al, “Parallel multiple electric power conversion system constructed by connecting three power converters,” ICEMS, PCI-0970, 2013.

[7] K.Ishikura, et al, “Simulation analysis of control methods for parallel multi-operating system constructed by the same output power converters,” ICEMS, PCI-0971, 2013.

Keisuke Ishikura received the B.S. degree of electronic systems engineering from The University of Shiga Prefecture in 2013. Since the same year, he has enrolled a master’s course Graduate school of Engineering in The University of Shiga Prefecture. His research interests are a parallel connected power converter and motor drive.

Hiromi Inaba was born in Tokyo, Japan, on September 1, 1950. He received the B.S. and Dr. Eng. degrees from Hokkaido University, Hokkaido, Japan, in 1974 and 1997, respectively. In 1974 he joined Hitachi Research Laboratory, Hitachi, Ltd., Ibaraki, Japan. He has been engaged in research and development on an elevator and steel control system. In 2008, he became a Professor with the school of engineering, The University of Shiga prefecture, Shiga, Japan. Dr. Inaba is a member of the IEEE Industry Applications Society (IAS) and the Institute of Electrical Engineers (IEE) of Japan.

Keiji Kishine was born in Kyoto, Japan, on October 26, 1964. He received the B.S., and M.S. degrees in engineering science from Kyoto University, Kyoto, Japan, and Ph.D. degree from in informatics from Kyoto University, Kyoto, Japan, in 1990, 1992, and 2006, respectively. In 1992, he joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan. He has been engaged in research and design of high-speed, low-power circuits for Gbit/s LSIs using Si-bipolar transistors, with application to optical communication systems in NTT System Electronics Laboratories, Kanagawa, Japan. From 1997, he has been worked on research and development of over Gbit/s Clock and Data Recovery IC at Network Service Innovation Laboratory in NTT Network Innovation Laboratories, Kanagawa, Japan. Now, He is working at Ubiquitous Interface Laboratory in NTT Microsystems Integration Laboratories, Kanagawa, Japan. In 2008, he became an Associate Professor with the school of engineering, The University of Shiga prefecture, Shiga, Japan. Dr. Kishine is a member of the IEEE Solid-State Circuits Society (SSCS) and Circuits and Systems (CAS), the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, the Institute of Electrical Engineers (IEE) of Japan.

Mitsuki Nakai received the B.S. and M.S. degrees of electronic systems engineering from The University of Shiga Prefecture in 2012 and 2014. In 2014, he joined Ishida Co., Ltd., Shiga, Japan. His research interests are a parallel connected power converter and motor drive.

Takuma Ito received the B.S. degree of electronic systems engineering from The University of Shiga Prefecture in 2013. Since the same year, he has enrolled a master’s course Graduate school of Engineering in The University of Shiga Prefecture. His research interests are an inverter and a multi motors drive.