

Three-phase AC Power Routing and Its Field Demonstration

Ryo Takahashi*, Daichi Nishihara[†] and Takashi Hikihara[†]

*Department of Mechanical and Electrical Systems Engineering, Kyoto University of Advanced Science, Kyoto, Japan,

[†]Graduate School of Engineering, Kyoto University, Kyoto, Japan

Email: *takahashi.ryo@kuas.ac.jp

Abstract—In this paper, the feasibility of three-phase AC power routing is shown with a power router designed for three-phase AC system. The feasibility of three-phase power routing is clarified based on not only the laboratory experiments but also field demonstration using the prototype of the SiC three-phase power router and self-owned power line along railway's track. The demonstration shows that the circuit switching for the power routing causes no impact to the communication for railway's control.

Index Terms—Power routing, Power router, Three-phase system, Field demonstration

I. INTRODUCTION

In recent years, the introduction of decentralized power sources such as solar power and wind power has been promoted to secure the necessary supply to meet the expanding energy demand. Unlike power generation from fossil fuels, power generation using renewable energy sources such as solar power has the advantage of not having a limit on the energy supply. With the expansion of introducing decentralized power sources, various research and development is progressing for the efficient operation of various power sources and energy storage devices using advanced information and communication technologies. One such technology proposed is power routing technology. The concept of power routing was already proposed in the 1990s [1], and recently, research and development of systems to realize power routing have been progressing by multiple groups [1]–[9].

One of the apparatuses that realize power routing technology is the power router. The AC power router our group proposed is a switch matrix circuit of the circuit switching method that achieves the active power distribution management [2]–[4]. This technology is expected to enable the selection of transmission path and the selection of power sources according to the quality and quantity of power required by the load.

Our group has developed an AC power router for single-phase AC [2] and has studied its introduction to three-phase AC. In the case of three-phase AC, it is possible to realize power routing in three-phase AC by connecting a single-phase AC power router to each phase. Based on these results, we designed an AC power router for three-phase AC. In this paper, the basic configuration of the three-phase AC power router is shown, and the feasibility of three-phase power routing

is investigated based on the field demonstration using the prototype router.

II. POWER ROUTER FOR THREE-PHASE AC

Fig. 1 shows a configuration of the three-phase AC power router which has two input ports and two output ports. The three-phase AC power router has two inputs and two outputs, allowing the connection of two sets of three-phase power sources and two sets of three-phase loads. The three-phase AC power router is based on the structure of the single-phase AC power router in [2], combining six of the switching circuits shown in Fig. 2. The lines that can be switched are limited to those of the same color. This is to prevent the occurrence of phase reversal switching at the output destination of the input power source voltage due to line switching. The switching circuits in the AC power router are controlled by an embedded FPGA. The switching in the AC power router can be individually set for each phase. Therefore, it is possible to examine multiple line switching methods, such as individual operations or simultaneous operations of line switching for each phase. In this paper, two switching methods are examined, *i.e.*, equipotential circuit switching (ECS) and simultaneous circuit switching (SCS). Here, the ECS is the method where circuit switching is executed at the moment when the two types of power supply voltages connected to the AC power router become equipotential. This method was already implemented and examined in the single-phase AC power router [3]. In the three-phase AC power router, each voltage of the input phase that can be switched are compared, and the ECS is executed individually. This method can suppress the surge voltages and reduce the stress on the power devices during switching. On the other hand, the SCS is a method where the lines of each of three phases existing are switched simultaneously. With this method, there is no need to wait until the circuit is equipotential to switch circuits. The power supply destination can be switched instantaneously.

The prototype three-phase AC power router is intended for use in the 140 V voltage system, and the switch for line switching adopts the SiC power MOSFET whose rating is 1200 V/40 A/262 W. To operate the switching remotely, Power Line Communication (PLC) function (120 – 400 kHz, spread spectrum method) is implemented in the prototype.

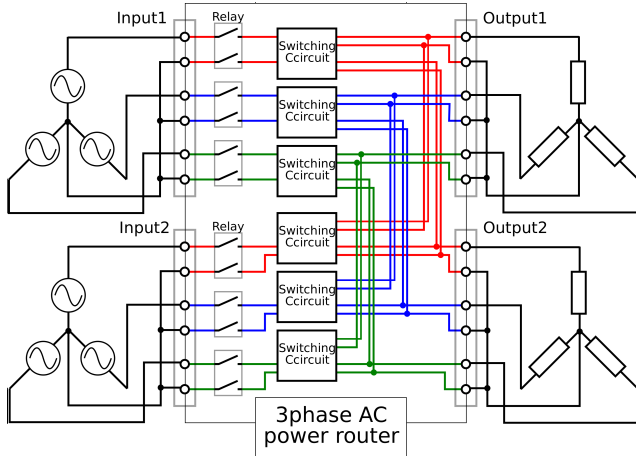


Fig. 1. Configuration of three-phase AC power router.

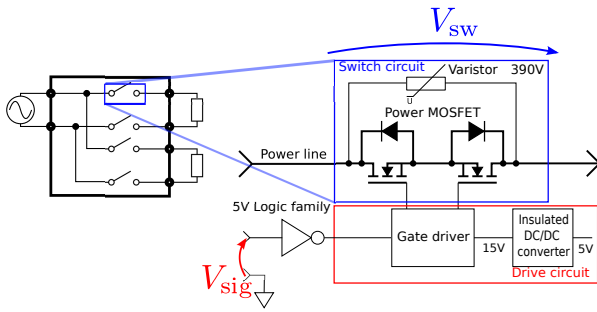


Fig. 2. Configuration of switching circuit.

III. EXPERIMENTAL VERIFICATION OF THREE-PHASE AC CIRCUIT SWITCHING

Here, we examine the case where a balanced load is connected to the three-phase AC power router. Circuit switching is executed while the power supply is on. The circuit switching was performed using both the SCS and ECS methods explained above.

The schematic diagram for the circuit switching experiment when a balanced load is connected to the three-phase AC power router is shown in Fig. 3. Input 1 of the three-phase AC power router is a symmetric three-phase four-wire AC power supply with an amplitude of 200 V and a frequency of 60 Hz. Additionally, a 200 V/100 V transformer with the power supply is attached to Input 1 as shown in the figure. A symmetric three-phase AC with an amplitude of 100 V and a frequency of 60 Hz is configured using a 200 V/100 V transformer with the common power supply and connected to Input 2. Outputs 1 and 2 distribute power to a 1 k Ω Y-connected resistive load as a three-phase load independently.

A. Simultaneous Circuit Switching (SCS)

The results of SCS are shown in Fig. 4. Each figure shows the voltage waveforms for each phase. These waveforms are obtained simultaneously. In this figure, the circuit switching results in the 200 V power supply connected to Input 1 being

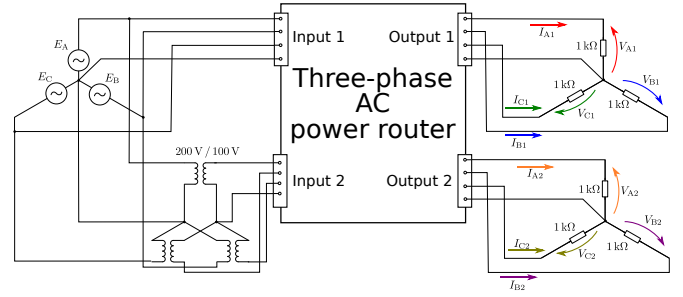


Fig. 3. Schematic diagram of the experiment

switched from Output 1 to Output 2. Conversely, the 100 V power supply connected to Input 2 is switched from Output 2 to Output 1. These results show that the SCS of all phase in three-phase AC was successfully achieved. The SCS enables suppression of instantaneous current imbalance that would occur if each phase was switched individually.

B. Equipotential Circuit Switching (ECS)

Fig. 5 shows measured voltage waveforms of the equipotential line switching. These results show that the ECS of all phases in three-phase AC was successfully achieved. These results demonstrate that the ECS, when a balanced load is connected, can suppress voltage fluctuations associated with circuit switching compared to SCS.

IV. FIELD DEMONSTRATION OF THE THREE-PHASE AC POWER ROUTER OPERATION

A field experiment of the operation of a three-phase AC power router was conducted using the Osaka Metro environment in the Sakishima district of Osaka city, Japan. Fig. 6 shows the overview of the field setting. In the experiment, a pressure fan is connected as a three-phase AC motor load to the router outputs 1 and 2, respectively. The router selects either of the pressure fans by its circuit switching function as the target of power supply. A distributed power source (3 ϕ 220 V, 20 kVA) was adopted. The output from this distributed power source was stepped up to 6.6 kV using a transformer and transmitted through a privately-owned line laid along a railway track. It was stepped down from 6.6 kV to 210 V using the other transformer before the connection to Input 1 of the three-phase AC power router. The connection from the transformer to the three-phase AC power router consisted of a three-phase three-wire configuration. Additionally, a pressure fan (3 ϕ 200 V, 0.4 kW) was connected to each of Output 1 and Output 2 as a load.

As shown in Fig. 6, the modem of PLC and the three-phase AC power router were connected to the same line. The circuit switching command from the modem was sent via the power line. In this experiment, the ECS method was used for the circuit switching of the three-phase AC power router. In the connection states shown in Fig. 6, there was railway communication equipment near the 6.6 kV private line, and the impact to this communication equipment from the private line was investigated. The circuit switching was performed while

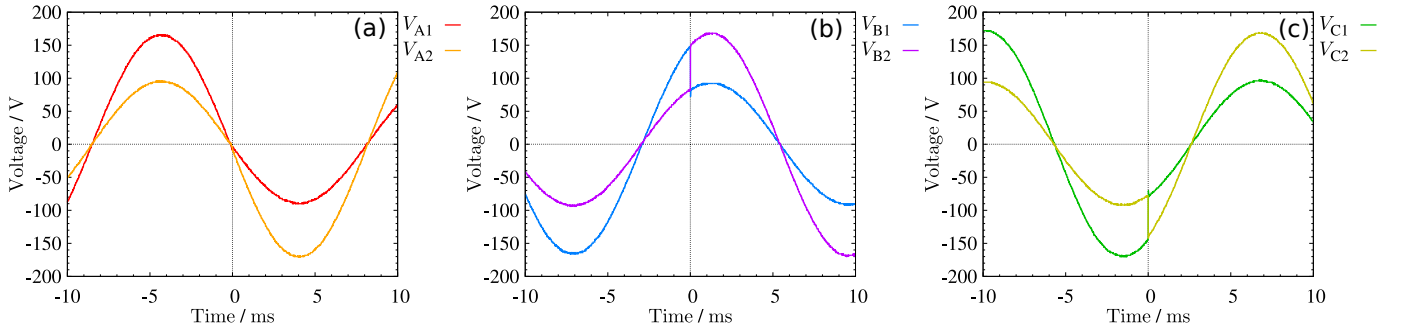


Fig. 4. Measured voltage waveforms during SCS. (a) Phase-A, (b) Phase-B, (c) Phase-C.

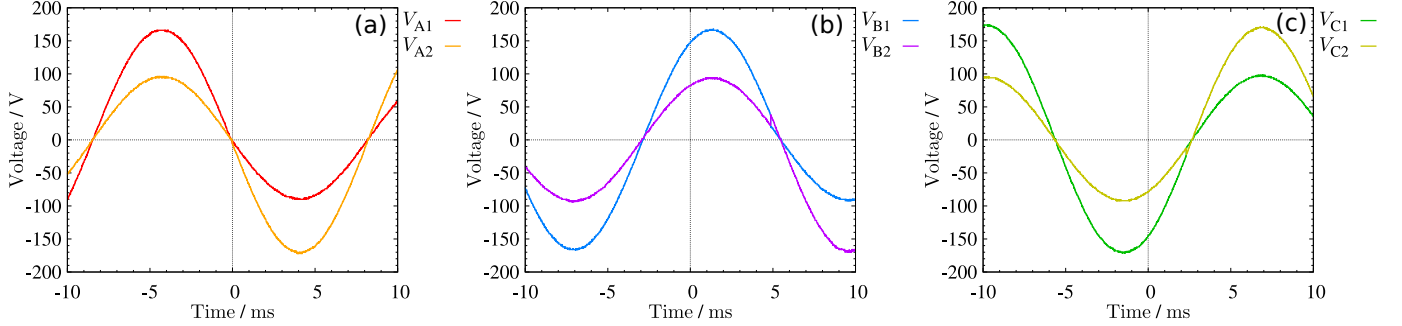


Fig. 5. Measured voltage waveforms during ECS. (a) Phase-A, (b) Phase-B, (c) Phase-C.

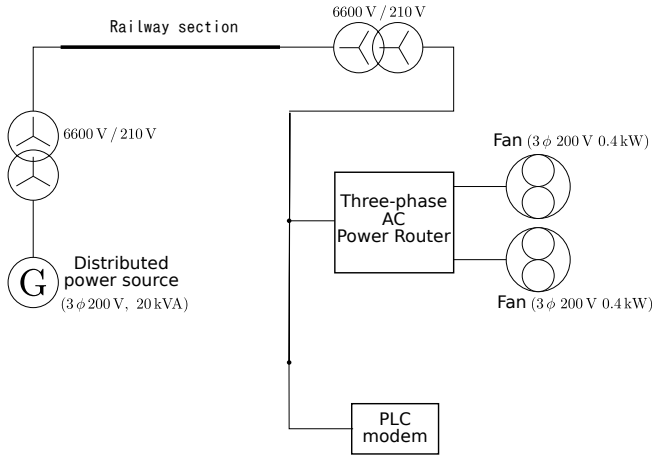


Fig. 6. Schematic diagram of the field experiment

the railway was in operation. As a result, it was confirmed that the switching did not affect the communication for controlling railway.

The line-to-neutral voltage and current waveforms for each phase on the input side were measured when the circuit switching was performed as shown in Fig. 7. In addition, Fig. 8 shows the voltage waveforms on the output side measured at the same time with the inputs. Here, the zero-phase voltage is subtracted from each voltage waveform. The output voltages were used to detect the equipotential moment to perform the ECS. In the figures, the waveforms are when the power output destination is switched from Output 2 to Output 1. In Fig. 8,

about 13 A current starts to flow to the fan immediately after switching. After passing this transient state, it was confirmed that the current becomes approximately 3 A in a steady state.

In Fig. 7, although the ECS of the three-phase AC power router started at 0 ms, the change in current began at 3 ms. This is because, in a three-phase three-wire AC system, the circuit is formed and current flows after a two-wire switching between phases A and B is performed. In this experiment, the power was supplied by a three-phase three-wire AC system, which differs from the three-phase four-wire AC system discussed in previous section. Therefore, it was shown that realizing the ECS in a three-phase three-wire AC system is difficult compared to the three-phase four-wire AC system. From the relationship between the voltage and current waveforms after switching shown in Fig. 7, the inductance value of the fan can be estimated. The inductance calculation results for phases A, B, and C were 20.3 mH, 20.0 mH, and 19.9 mH, respectively, and the fan's inductance was approximately 20.2 mH.

This experiment clarifies the feasibility of the three-phase AC power routing with the inductive loads, and its circuit switching causes no disruption to the communication for railway's control.

V. CONCLUSION

In this paper, the feasibility of three-phase AC power routing was experimentally clarified using the prototype power router for three-phase. The power routing of three-phase was demonstrated using distributed power supplies, three-phase inductive loads, and self-owned power lines along railway's tracks. This demonstration clarifies the power routing with the

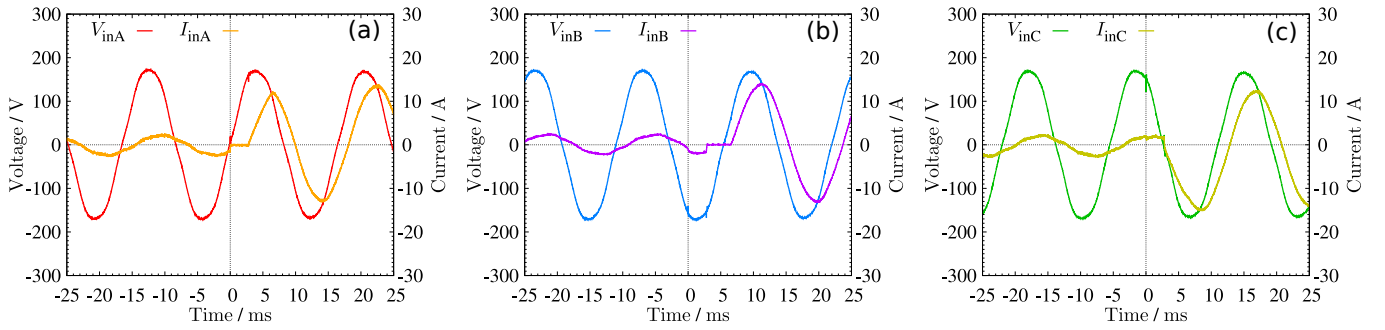


Fig. 7. Measured input voltage and current waveforms during ECS. (a) Phase-A, (b) Phase-B, (c) Phase-C.

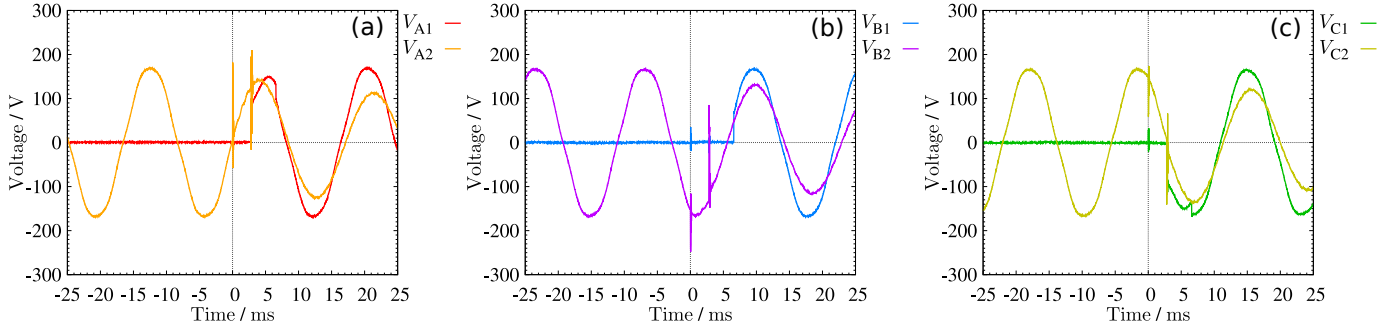


Fig. 8. Measured output voltage waveforms of during ECS. (a) Phase-A, (b) Phase-B, (c) Phase-C.

circuit switching cause no impact to the communication for railway's control.

As shown in this paper, various circuit switching methods can be considered in the three-phase AC power router. The switching operation such as the SCS and ECS in the power router can be selected according to the characteristics of the load, such as the magnitude of surge voltage and the tolerance of current imbalance. Therefore, a study the circuit switching method according to the load and clarification of appropriate switching method will be conducted in near future.

In the management of electricity, the frequency of switching depends on the power rating of the system. Therefore, it is considered to use different routing systems depending on the rating. For example, a DC power packet dispatching system can be introduced for small rated systems where high frequent switching is employed to manage multiple loads and power sources of various ratings and to regulate power [2], [8], [9]. The AC power routing system can be installed for lower ratings that do not require such frequent switching. In medium and large rated system, switching for power routing is expected to be even less frequent. The design of power routing system suitable for medium and large ratings is one of the research topics to be discussed in the future.

ACKNOWLEDGMENT

This work was partially supported by the Global Warming Mitigation Measure Technology and Demonstration Research Project from the Japanese Ministry of Environment, and the Super Cluster Program from the Japan Science and Technology Agency. The authors highly appreciate Dr. Shinya

Nawata, Dr. Shiu Mochiyama, the member of Sakishima Smart Community Demonstration Project Plan, Osaka city, and Osaka Metro.

REFERENCES

- [1] J. Toyoda and H. Saitoh, "Proposal of an open-electric-energy-network (OEEEN) to realize cooperative operations of IOU and IPP," in *Proc. 1998 Int. Conf. Energy Manage. Power Del. (EMPD)*, vol. 1. Singapore, pp. 218–222.
- [2] T. Takuno, M. Koyama and T. Hikiyara, "In-home power distribution systems by circuit switching and power packet dispatching," in *Proc. 1st IEEE Int. Conf. SmartGridComm*, Gaithersburg, MD, USA, 2010, pp. 427–430.
- [3] T. Takuno, Y. Kitamori, R. Takahashi, and T. Hikiyara, "AC power routing system in home based on demand and supply utilizing distributed power sources," *Energies*, vol. 4, no. 5, pp. 717–726, 2011.
- [4] R. Takahashi, Y. Kitamori, and T. Hikiyara, "AC power local network with multiple power routers," *Energies*, vol. 6, no. 12, pp. 6293–6303, 2013.
- [5] M.M. He, E.M. Reutzel, X. Jiang, R.H. Katz, S.R. Sanders, D.E. Culler, and K. Lutz, "An architecture for local energy generation, distribution, and sharing," in *Proc. 2008 IEEE energy 2030 conference*, Atlanta, GA, USA, 2008, pp. 1–6.
- [6] B.P. Stalling, T. Clemmer, H.A. Mantooth, R. Motte, H. Xu, T. Price, and R. Dougal, "Design and evaluation of a universal power router for residential applications," in *Proc. 2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, USA, 2012, pp. 587–594.
- [7] F. Girbau-Llistuella, J. M. Rodriguez-Bernuz, E. Prieto-Araujo and A. Sumper, "Experimental validation of a single phase intelligent power router," in *Proc. IEEE PES Innovative Smart Grid Technologies, Europe*, Istanbul, Turkey, 2014, pp. 1–6.
- [8] R. Takahashi, S. Azuma, M. Hasegawa, H. Ando, and T. Hikiyara, "Power processing for advanced power distribution and control," *IEICE Trans. Commun.*, vol. E100-B, no. 6, pp. 941–947, 2017.
- [9] R. Takahashi, S. Azuma, and T. Hikiyara, "Power regulation with predictive dynamic quantizer in power packet dispatching system," *IEEE Trans. Ind. Electron.*, vol. 63, no. 12, pp. 7653–7661, Dec. 2016.