

Development of ACG Using Regulator Rectifier with Phase Control

Yutaka SONODA*

Kazuhiko ONO*

Miku OTSUJI*

Katsuhiro OUCHI*

ABSTRACT

To get free from the risks that arise from price variations of rare-earth metals, an alternative current generator for motorcycles was developed using conventional ferrite magnet while keeping the same amount of electricity generation as that of using rare-earth metal. For the application of ferrite magnet to a motorcycle, the way of having a larger size cannot be allowed because of the increases of the mass and moment of inertia associated with that. Accordingly, in our development, the increase of electricity generation was realized by changing the current control from regulated short-circuit rectifier method to phase shifting method with a precise control of the effective range of phase shifting. For that purpose, newly developed configuration was implemented to the sensor for phase control to have it under permissible temperature range against resulting high installation temperature. Through those measures, it was achieved by using ferrite magnet to generate a compatible amount of electricity generation to that of using rare-earth metals without changing the dimensions of the generator.

1. Introduction

The price of rare earth metals started to go up since 2010 and it is still under the risk of price fluctuations. With these circumstances, it has become an urgent request for currently used materials in alternating current generators (ACGs) in motorcycles to replace them with materials free from rare earth metals. One of the practical methods to substitute them is an adoption of ACG using ferrite magnets. However, compared to ACGs using magnets with rare earth metals, the electric power generation is small. Consequently, with conventional control method, the amount of power generation cannot meet the requirement, especially, when the rotation speed is slow. To increase the electric power generation, making ACG in larger dimensions is a commonly applied method. However, that increases the mass and the moment of inertia. However, it is difficult to apply that method to motorcycles that severely require light weight and small size. Accordingly, in our development, the control method for electrical power generation was changed from a regulator rectifier method, using short-circuiting control, to a phase control method. By changing the control method, the power generation at low rotation speed was ensured and the dimensions of the ACG were kept almost the same as those of ACG using magnets containing rare earth metals. In this paper, the technologies that enabled this

development will be described. One of those is the phase control method to increase the power generation, which has been applied to a system in a motorcycle for the first time. Another is the sensing method to detect the positions of magnetic poles that endure the increased heat generation associated with the increase of the power generation.

2. Regulated Rectifier with Phase Control

In motorcycles, a regulated rectifier with short-circuiting control method had been commonly used. In that system, the charging voltage was regulated by the charging current while varying the proportion of time between a full wave rectification period and a short-circuiting period (Fig. 1). On the other hand, in the system with a regulated rectifier by phase control, the voltage delivered from the battery is applied to create the induced voltage in ACG. In addition, the phase of applied voltage is varied to control the generated voltage making the output current to be regulated in an almost flat direct current. By using this method, a larger amount of power generation is attainable compared with the system applying a short-circuiting control (Figs. 2 and 3).

The diagram of the equivalent circuit of a single-phase ACG is shown in Fig. 4. In the diagram, the left side illustrates a circuit of an alternating current generator with

* Motorcycle R&D Center

the induced voltage of E and the inductance of L . The right side of it illustrates an alternating voltage power source, with the output voltage of V , which is composed of a battery and an inverter. As a control method, phase control is applied. The target current level I can be obtained by changing the phase of the output voltage V in reference to the phase of the induced voltage E .

Next, the behavior of the current I will be explained when the phase of the voltage V is varied on condition that the frequency of E is the same as that of V . Based on the voltage equation of the equivalent circuit, the current is derived as down below. Where the angular frequency is defined as ω .

$$\dot{E} = j\omega L \dot{I} + \dot{V} \quad (1)$$

$$\dot{I} = \frac{\dot{E} - \dot{V}}{j\omega L} \quad (2)$$

In the Eq. (2), the current I can be varied by changing the phase of V while ω , L and E are maintained to the same values. When it is illustrated by vector diagram, it is shown as in Fig. 5. As you see in the diagram, the amplitude and the phase of the current I changes according to the variations of the phase of V which is defined in reference to

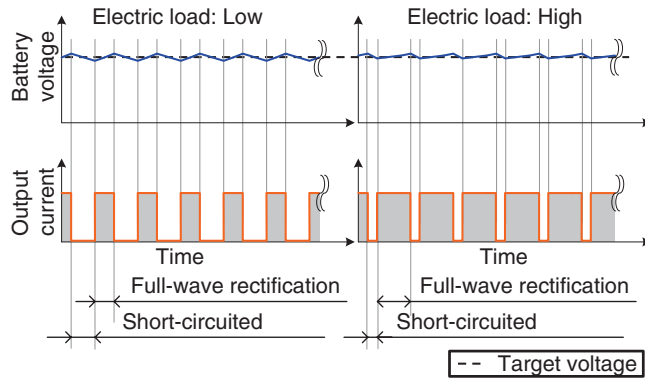


Fig. 1 Schematic illustrations of charging currents under short-circuit type control in different load conditions

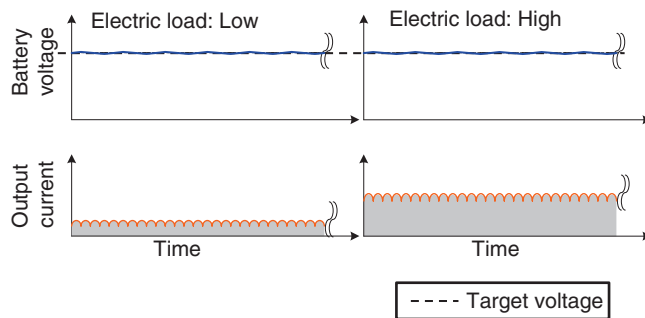


Fig. 2 Schematic illustrations of charging currents under phase control in different load conditions

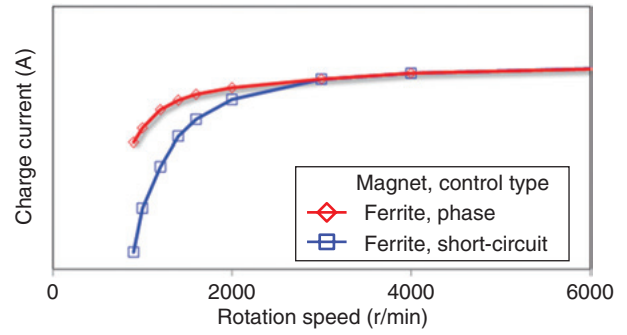


Fig. 3 Characteristics of charge currents under different types of control

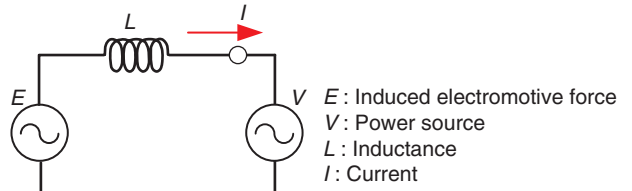


Fig. 4 Circuit composed of two AC power sources and inductance

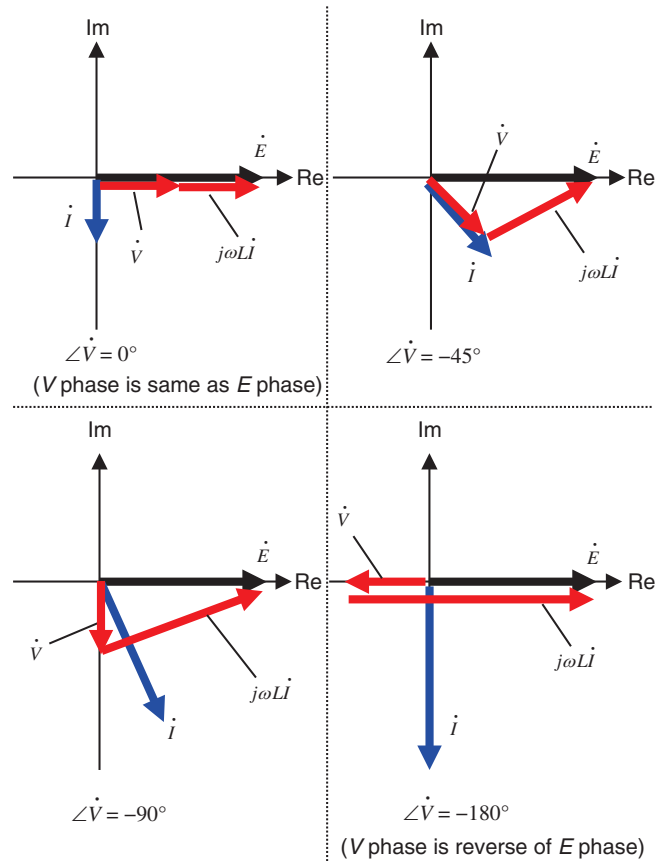


Fig. 5 Vector diagrams with varied phases of supply voltage of V

the phase of E (Fig. 5)⁽¹⁾⁻⁽³⁾.

Accordingly, it is possible to control the current by phase control method by changing the phase of the supplied voltage V . In the actual circuitry to be implemented, a measure to detect the phase of induced voltage E or the angular position of a magnet pole is necessary to determine the phase of the supplied voltage V . Moreover, the resistance of generator coils and the power factor in association with V and I should be taken into consideration as well. Therefore, descriptions that appear in the actual equation are more complicated than the ones described here.

3. Phase Control to Increase Power Generation

It is generally understood, when a phase control is applied, that the selection of the phase range to be controlled has a significant impact on the characteristics of the output power. In our development, it was made possible to yield a larger amount of power generation compared to the short-circuiting method by expanding the range of phase control toward the phase-delaying direction. In Fig. 6, the characteristics of the output current are shown when the phase of the voltage applied from the battery is varied in reference to that of the induced voltage. As the figure shows, around the phase difference of 0° , it has such characteristics that the output current decreases when the phase is shifted toward phase-advancing direction (to the right in the figure), and it increases when the phase is shifted toward phase-delaying direction (to the left in the figure). Utilizing these characteristics, a feedback control is implemented to regulate the output voltage at the predetermined level. The output current is 22.5 A at the phase difference of -68 degrees. From that point, when the phase difference is shifted toward more delayed phase values, the line current of the ACG still increases accordingly. However, the output current begins to decline from that point and keeps decreasing after that. In this

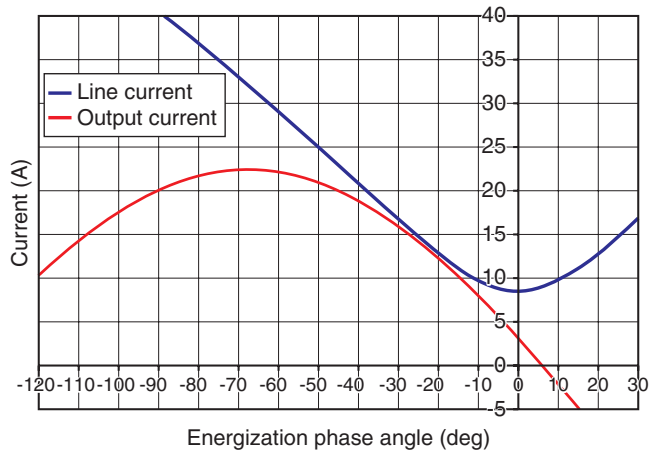


Fig. 6 Characteristics of charging currents to the phase of line current

region, the control status falls into positive feedback. Accordingly, in this region, the generated power declines, and the fluctuation of heat generation by the ACG and/or an unstable status of the control system are likely to happen. To avoid these situations, the phase region in which the shifted phase points to be designated for the control should be restricted within an appropriate range. Furthermore, to enable that control, the information of angular positions that can be used as reference points of the control, which is either of the phase of the induced voltage or the angular positions of magnet poles, is inevitably needed.

4. Developed Method to Detect Rotational Position of Magnet Poles to Cope with Increased Heat Generation

There are several methods to detect a reference position for the system control with high accuracy. One of the most common methods is to install a Hall Effect sensor between coils of the stator and detect the rotational positions of the magnetic poles. When the power generation is increased at a low revolution speed, the temperature of the coils may exceed 200°C , where the heat resistant temperature of Hall Effect sensor is 150°C . Accordingly, if a Hall Effect sensor is applied, it cannot meet the temperature requirement (Figs. 7 and 8).

Consequently, an investigation on the possibility to

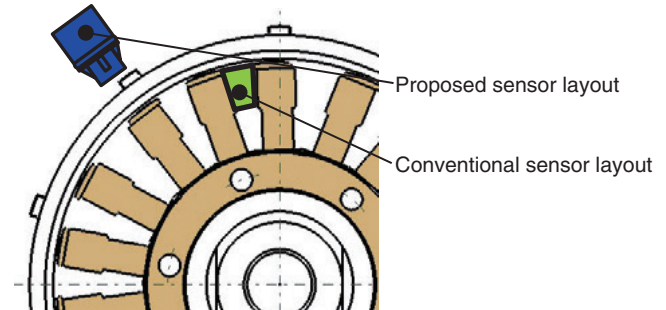


Fig. 7 Comparison of sensor configurations between in-stator location and out-of-flywheel location

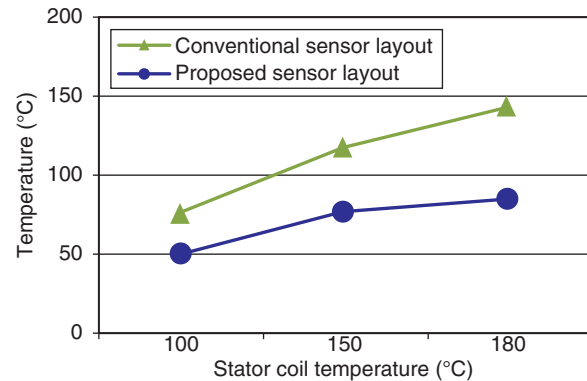


Fig. 8 Comparison of sensor temperatures

Table 1 Comparison of accuracies of detection angles

Sensor layout	Proposed layout		Conventional layout
	Before correction	After correction	
Detection error angle (°)	±43.5°	±4°	±3°

develop a new sensing method to detect magnetic poles had been conducted.

For conducting the investigation, four requirements had been set as follows:

- (1) The design change associated with the engine shape should be minimal.
- (2) The sensor currently mass produced should be commonly applicable.
- (3) The sensor should be located where it has the least chance to be damaged by a vehicle tip over.
- (4) Angular position sensing accuracy should be within ±10°.

After thorough investigations on various methods, it was decided to attempt a method, in which a protrusion was provided on the perimeter of the flywheel with the same angular position of a magnet pole and a phase of the induced voltage was detected by a single Hall Effect sensor (Fig. 7). The advantage of this method is that only one sensor is needed and can be selectively located where the temperature is low (Fig. 8). However, if no extra measures are implemented, the angular position error of a magnetic pole is as large as ±43° or more, and the accuracy requirement cannot be met (Table 1). This is primarily because the mechanical errors of several parts, such as ACG and engine coverings, are accumulated. Accordingly, some error compensation technique is necessary to adopt this sensing method (Fig. 9).

When a full wave rectification is applied, there is a predetermined relationship among the phases of each line currents in ACG and the phase of the induced voltage, and

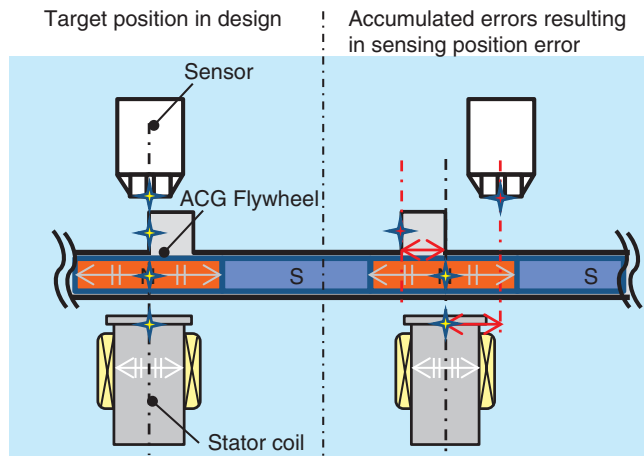


Fig. 9 Source of errors affecting detection angle accuracy of out-of-flywheel type sensor configuration

that relationship varies depending on the frequency. To cope with aforementioned accuracy issue, this relationship had been noticed. The line currents passing through the coils are generated by the induced voltage caused in the stator coils while the flywheel is rotating. Therefore, predetermined phase differences are occurred among the line currents and the induced voltage depending on the frequency of the inducing voltage and the total resistance in the line the charging current goes through. In the equivalent circuit shown in Fig. 10, the induced voltage E of ACG is described as:

Where:

$$\dot{E} = (j\omega L + R)\dot{I}$$

L : Inductance of the stator coil

R : Load resistance of the circuit

$$\dot{I} = \frac{\dot{E}}{j\omega L + R}$$

The phase difference θ in this condition is given as:

$$\theta = \tan^{-1} \frac{\omega L}{R}$$

Next, the wave forms appear in the circuit and their phase differences (Fig. 11). In the figure, (α) the output of the Hall effect sensor (the output of magnetic pole sensing), (β) the induced voltage and (γ) the line current are shown respectively. Under those wave forms, phase differences are

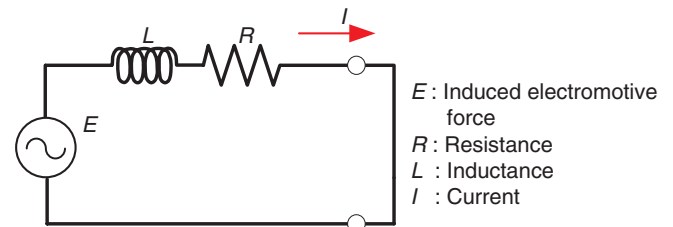


Fig. 10 Equivalent circuit of ACG (single-phase)

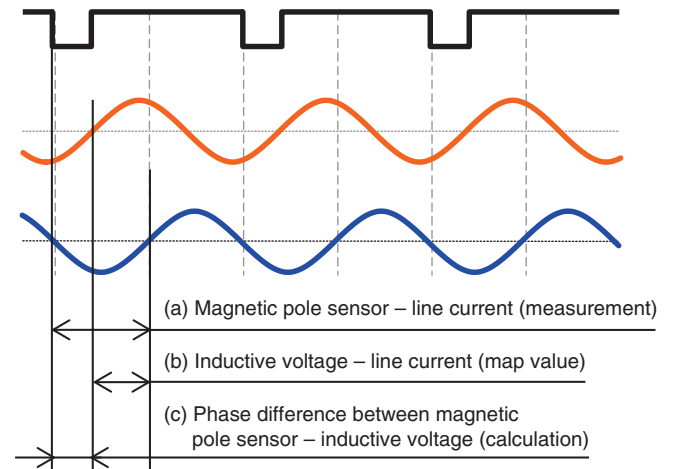


Fig. 11 Timing chart illustrating error compensation

shown, i.e. (a): between (α) and (γ), (b): between (β) and (γ), (c): between (α) and (β), respectively. The phase difference (c) is calculated using (a) and (b). This phase difference (c) is used as an argument in the function to yield the output current control.

Meanwhile, as shown in Fig. 12, in the equivalent circuit that is representing the system to be applied to an actual vehicle, the load resistance R_2 varies depending on the changes of the total electrical load of the devices in a vehicle. Consequently, compensation of the amount of the phase shift was carried out based on the measured value of the output voltage between the terminals of the regulated rectifier. The result after compensation is shown in Table 1. The error after compensation was reduced to $\pm 4^\circ$ for the intended phase variation range towards phase-delaying direction. Thus, the accuracy was enhanced to meet the requirement.

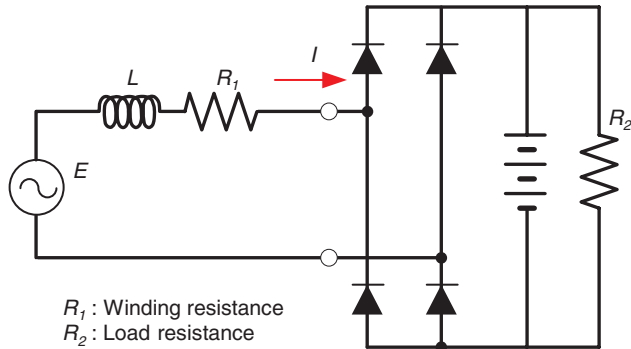


Fig. 12 Equivalent circuit of total charging system applied to the production design (single-phase)

5. Validation of Power Enhancement by Phase Control System

The enhancement of the output current by the regulated rectifier controlled by phase control method was verified. ACGs used in the tests were the one made of magnets containing rare-earth metals and the one made of ferrite magnets. The control methods were regulated rectifier with short-circuiting method and that with phase controlling method. The combinations of those ACGs and control methods are shown in Table 2. According to these combinations, measurements of the output current characteristics were conducted and the results were compared to each other. Table 3 shows the measurement conditions and Fig. 13 shows the measurement results.

Under the measurement conditions applied in the tests conducted this time, the output current yielded by phase control method was larger, across the entire range of rotational speed, than that yielded by short-circuiting control method (1).

Table 2 Combinations of ACG and regulated rectifier

Combination		Short-circuit (1)	Short-circuit (2)	Phase control
ACG	Outer diameter	$\phi 132.5$	$\phi 132.5$	
	Magnet type	Rare-earth magnet	Ferrite magnet	
Regulated rectifier	Control method	Short-circuit control		Phase control

Table 3 Test conditions

ACG temperature	Stator coil temperature 120°C
Ambient atmosphere temperature	Room temperature
Test equipment	Motor bench
Test circuit	

In the low rotational speed range of 3000 r/min or less, the output current was larger in the one with phase control method than the one with short-circuiting method (2). In particular, at the rotational speed of 1000 r/min, which is the speed when idling, the output current was 2.3 times larger than the case controlled by short-circuiting method (2). In the high speed range of 3000 r/min or above, as the graph shows, no significant difference in the output currents was noticed between short-circuiting method using rare-earth contained magnets and phase control method using ferrite magnets. Based on these results, it was made possible to substitute ferrite for rare-earth contained material as ACG magnet material. Thus, the system applicable to motorcycles was successfully realized.

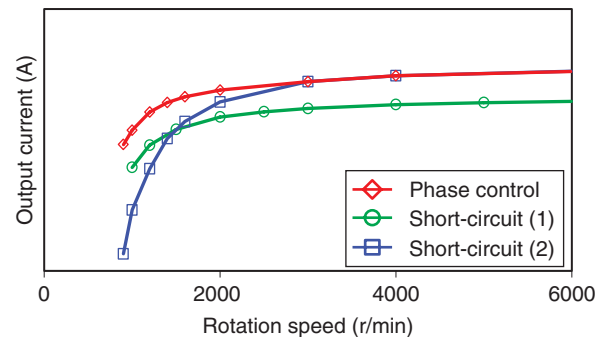


Fig. 13 Characteristics of output current to rotation speed

6. Conclusions

To realize an ACG system using ferrite magnets that is applicable to motorcycles, phase control method was applied.

In the development, the following technologies were established:

- 1) Phase range restriction method for phase shift control to effectively increase the output power while avoiding instability.
- 2) Sensing method to detect angular positions of the magnet poles that is durable under a large heat condition caused by increased power generation.

Through this development, it was made possible to fulfill the requirements for ACGs used in motorcycles by using ferrite magnets without applying rare-earth containing materials to the magnets. As a consequence, it was made possible to get away from the risks caused by price variations of rare-earth metal containing magnets and that brought about a stable cost for ACG manufacturing. The ACGs that employ aforementioned phase-controlled regulated rectifier are already applied to motorcycles on the market. It is highly expected for this ACG to be applied to much more motorcycle models in the future.

References

- (1) Miyairi, S.: Denkishi Hansayou, Daigakukougi Saishindenkikigaku Kaiteizouho, MARUZEN PUBLISHING CO., LTD., p. 199-201 (1979) (in Japanese)
- (2) Uno, S., Isobe, N.: Hakeibunseki, Kaitei Kouryukairo, Tokyo Denki University Press, p. 128-131 (1991) (in Japanese)
- (3) Nishikata, S.: Doukiki, Yokuwaku Power Electronics to Denikiki, Ohmsha Ltd., p.105-110 (1995) (in Japanese)

■ Author ■



Yutaka SONODA



Kazuhiko ONO



Miku OTSUJI



Katsuhiro OUCHI