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RESEARCH ON THE USEFULNESS OF WINDING SWITCHING DURING DRIVING OF A BRUSHLESS DC MOTOR

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Abstract. *In recent years, a high efficiency brushless DC motor is often used for a drive unit of an electric vehicle. However, depending on how the coil of the brushless DC motor is wound, a back electromotive force is generated due to the inductance, and there is a problem that the maximum value of the current that can be supplied to the motor is smaller than the standard. Therefore, in order to solve the problem in the current adjustment by the winding method of the coil, the research purpose is to change the winding method of the winding by the motor itself and to adjust the current.*
Keywords: Brushless DC motor, Winding switching

1. Introduction.

In recent years, electric vehicles and hybrid electric vehicles, which are expected to save energy, have become widespread due to the seriousness of environmental problems on the earth. The performance required for the drive motor of such vehicles is to be high efficiency, high torque, and constant output. It is necessary to adjust the torque value and the traveling speed depending on the road on which the vehicle travels. Depending on the performance of the motor, only a fixed value can be output. However, there are papers that consider changing the motor parameter by switching the motor winding and expanding the speed range [1-5]. In [1], two inverters are used to control the current of the winding, resulting in a large system and complicated circuit. [2] proposes a dual inverter feed drive system, which makes the system large and complex. [3] proposes a new current controlled voltage source inverter in this paper. [4] proposes a feed motor drive using a new low voltage inverter with variable parameters achieved through independent armature windings for automotive traction motors. Katayama and Haga [5] propose a configuration that applies a 9-switch inverter as a configuration of a motor drive system that uses winding switching. Many of the circuit configurations in these papers use a plurality of inverters, leading to an increase in system size and cost. Therefore, this section describes a method of expanding the motor speed range with a simple structure using one inverter and a plurality of electromagnetic relays for switching the winding. To explain further, it is a method of sandwiching an electromagnetic relay between the coils and directly changing the current flow to adjust the speed.

2. Equipment Used.

2.1. Circuit configuration.

This motor drive circuit configuration is shown in Figure 1.

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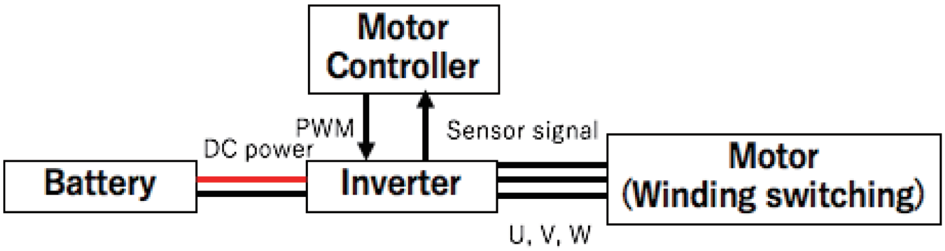

Figure 1. Motor drive circuit

The control method of the motor is a PWM method. Power is supplied to the inverter from the DC stabilized power supply. Based on the value of the sensor signal, the motor controller controls the position and timing of the current flow. This time, an electromagnetic relay is attached to the coil used for the motor, winding switching is performed, and the values of speed and torque are changed.

2.2. **Main parts.** The parts used this time are shown in Table 1. Figures of the parts are shown in Figures 2-4.

The parts used this time are easy to obtain, and are considered to be easy to create by not using too many parts.

3. **Coil Winding Pattern.** The brushless motor can freely change the characteristics of the motor by changing the winding method. This chapter shows the difference in characteristics due to the change in winding method. Here, we will describe the three

Table 1. Parts used

Parts used	
Brushless DC motor	Outer rotor type 12 poles 18 slots
32-bit microcontroller V850	The V850 has a built-in flash memory and the program is downloaded to the microcomputer.
Inverter board	It is driven by the H-bridge method using two MOSFETs per phase. What kind of output waveform is output from the driver board to the motor is determined by the command from the control board.
Electromagnetic relay × 12	It is sandwiched between coils and used to change the flow of current.

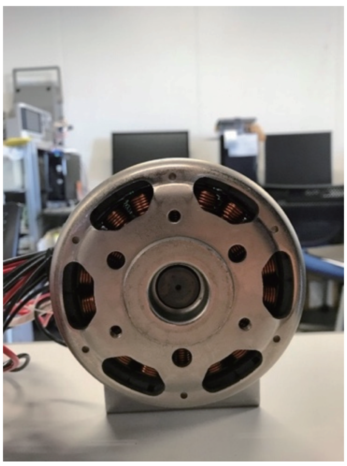

Figure 2. Brushless DC motor

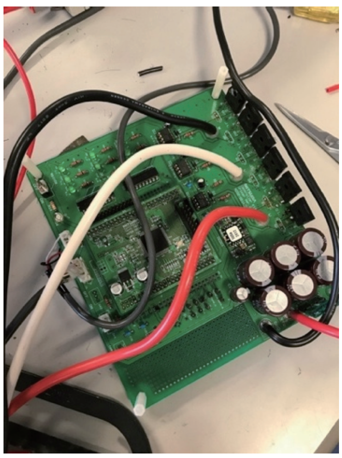

Figure 3. 32-bit microcontroller V850 and inverter

Figure 4. Electromagnetic relay

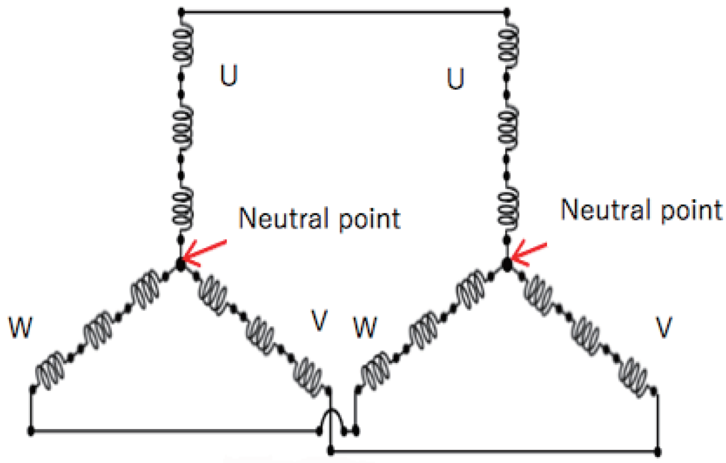

Figure 5. Circuit diagram of 3 series 2 parallel

straight two and two straight three used in this experiment. Also, since the motor used this time is 18 teeth, a total of 18 coils are required.

3.1. **3 series 2 parallel circuit and 2 series 3 parallel circuit.** Three-series two-parallel is a circuit in which three coils are connected in series and two series circuits are connected in parallel. Figure 5 shows the circuit diagram.

Two-series three-parallel is a circuit in which two coils are connected in series and three series circuits are connected in parallel. Figure 6 shows the circuit.

3.2. **Comparison of 2 series 3 parallel and 3 series 2 parallel.** Paralleling is equivalent to doubling the cross-sectional area of the coil wire. Because this motor is 18 turns each

- **3 series 2 parallel:** 54 turns → 1 time cross section of coil
- **2 series 3 parallel:** 36 turns → 1.5 times the cross sectional area of the coil

As the cross-sectional area becomes 1.5 times and the resistance value decreases, a larger current flows, and the maximum value of the flowing current increases. That is, the maximum value of input power is increased. Then, even if the maximum value of the current is raised by the inverter, the maximum value of the current becomes low if the coil parallel is small. However, when the cross-sectional area of the line is large because there are many parallel lines and the cross-sectional area of the line is small, horsepower does not appear, and there is a disadvantage that the speed reduction becomes severe when slope resistance on an uphill or the like increases. That is, by increasing the number of

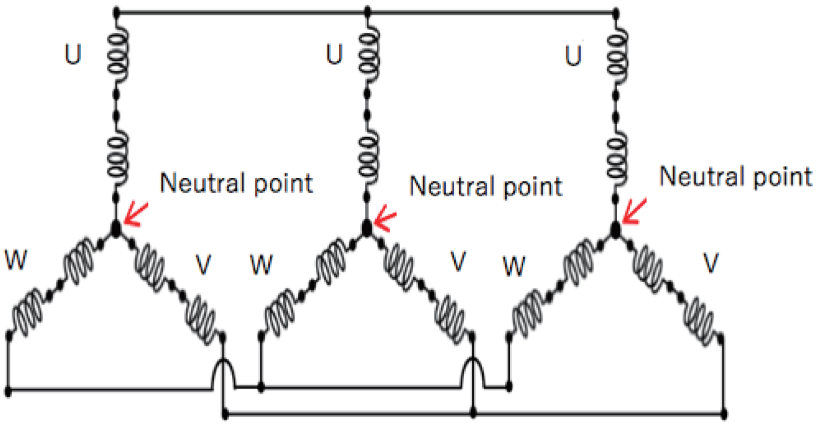

FIGURE 6. Circuit diagram of 2 series 3 parallel

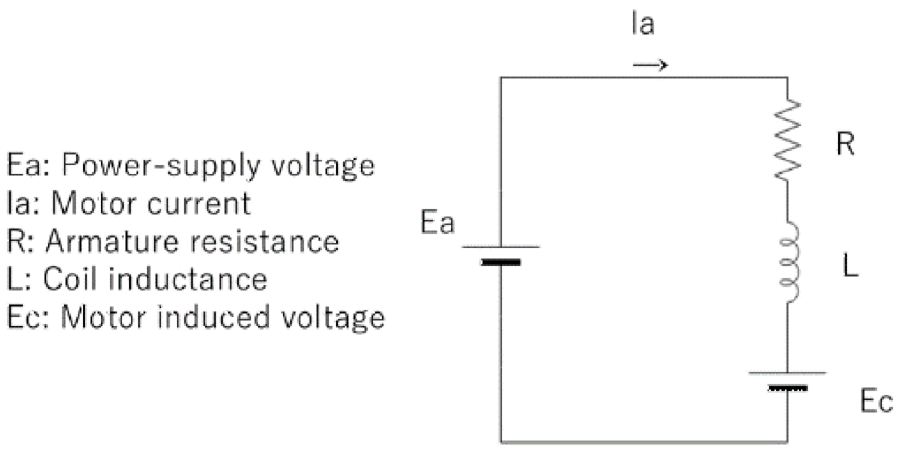

FIGURE 7. Equivalent circuit of brushless DC motor

parallel connections, the maximum power can be increased and the rotational speed can be increased. However, the torque becomes weak and is used in a drive motor, etc. There is also a drawback that it is greatly affected by the slope resistance. Figure 7 shows an equivalent circuit of a brushless DC motor. From this equivalent circuit, the DC relational expression of the closed circuit is as shown in (1).

$$Ea = E \times Ia + Ec \tag{1}$$

The power-supply voltage Ea is a value obtained by adding the induced voltage Ec to a value obtained by multiplying the armature resistance R and the motor current Ia. The armature resistance is a resistance component of a winding or an iron core. It is Ohm's law itself that resistance × current becomes voltage. The induced voltage is a voltage generated by the rotation of the motor (power generation), which is an additional voltage. Furthermore, the motor induced voltage is (2).

$$Ec = Ke \times N \tag{2}$$

The induced voltage Ec of the motor is a value obtained by multiplying the rotation number N by the power generation constant Ke. Therefore, the induced voltage of the motor is proportional to the number of revolutions. The motor torque can be obtained by Equation (3).

$$T = Kt \times Ia \tag{3}$$

The torque T of the motor is a value obtained by multiplying the torque constant Kt by the motor current Ia. Thus, the motor torque is proportional to the current. From that point on, the relationship between rotational speed and torque can be expressed by (4).

$$N = \frac{Ea}{Ke} - \frac{R}{Ke \times Kt} \times T \tag{4}$$

Figure 8 shows the rotational speed and torque values determined using the simulation software "JMAG-Express Online" [5].

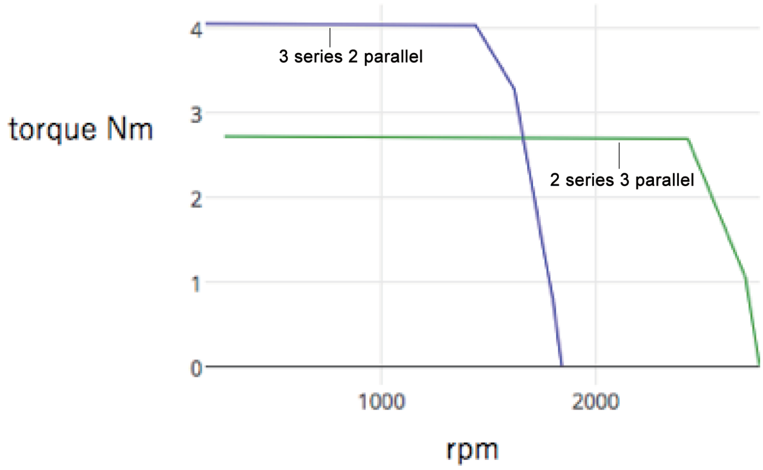

Figure 8. Two series three parallel and three series two parallel torque and rpm

It can be understood from the figure that the values of the rotational speed and the torque change depending on how the inductance is connected.

4. **Experimental Method.** In this chapter, we will describe the circuit diagram of switching between 2 series 3 parallel and 3 series 2 parallel created at the time of experiment.

This time, we created a circuit that switches from 2 series 3 parallel to 3 series 2 parallel. However, the winding method is a circuit that switches in two series by three series using three in series for the electromagnetic relay, but when the electromagnetic relay is off, it switches in two series and three series, and when it is on, it has become switches in three series and two parallel. The electromagnetic relay was used for the role of the switch for switching two straight and three straight. The circuit is switched by applying a voltage of 15.6 V to the electromagnetic relay as described in the specification. For the environment around the motor drive, voltage and current were from a stabilized power supply without changing from the environment before switching, and an inverter board was used for motor control. Figure 9 shows one of the three phases U, V and W. Moreover, the voltage of 24 V is sent to the inverter board using the stabilized power supply. The inverter board and the microcomputer board convert the voltage into 5 V and flow it to the motor.

5. **Experimental Result.** It shows in Figure 10 of the relationship between the number of rotations and the current at the time of switching in two series and three series and two series using the electromagnetic relay.

As a measurement method, the value of rpm was raised from 0, and the value of the current value was measured every 100 rpm.

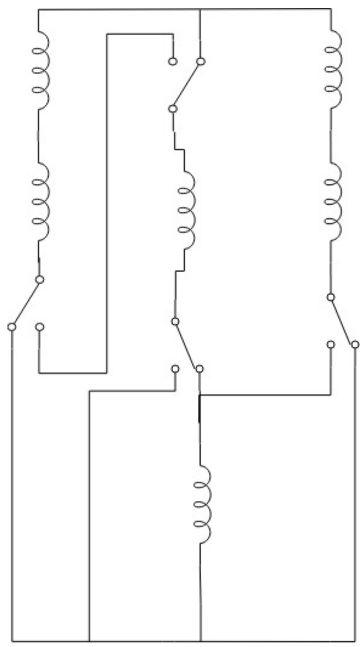

Figure 9. Design drawing of switching circuit using electromagnetic relay

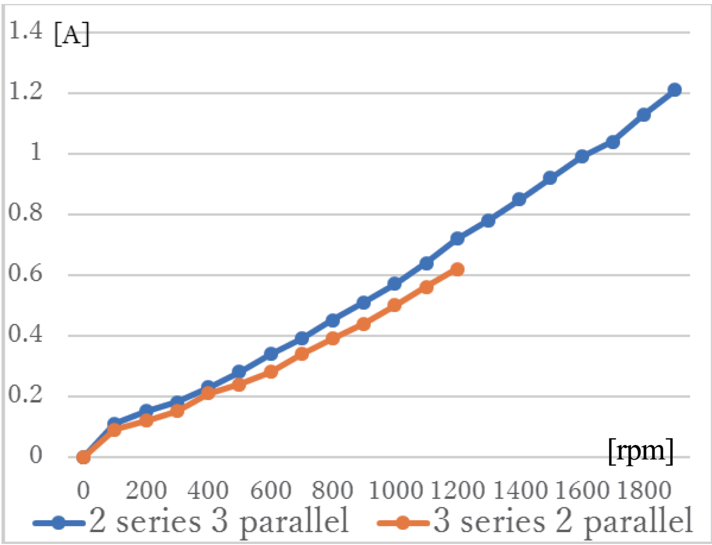

Figure 10. Relationship between rotational speed and current

6. Consideration.

6.1. **About experimental results.** As shown in Figure 10 of Chapter 5, it can be seen that more current flows in the same resistance in the case of 2 series 3 parallel with a large number of parallels as compared with 3 series 2 parallel. Also, as can be seen from the values of the maximum currents of the 2 series 3 parallel and 3 series 2 parallel, in the 3 series 2 parallel with a small number of parallels, the maximum current was knocked off at 0.62 A, and the rotation speed also stopped changing from about 1200 rpm. However, in the 2 series 3 parallel, the maximum current increased to 1.21 A, and the rotational speed increased to about 1900 rpm. As described in the comparison of 2 series 3 parallel and 3 series 2 parallel in Chapter 2, it is understood that the maximum power can be increased and the number of rotations can be increased by increasing the number of parallel in Figure 10. It also turned out that 2 series 3 parallel and 3 series 2 parallel can be switched by it. Furthermore, while 3 series 2 parallel with a small number of parallels does not rise from a certain current value due to back electromotive current, 2 series 3 parallel with a large number of parallels usually has current and maximum current of approximately 3 series 2 parallel. It was measured that twice the current was flowing. Also, it was found from these experiments that "the upper limit of the maximum current increases and the number of revolutions increases as the number of parallel increases, but the torque decreases".

6.2. **Difference between simulation and actual measurement.** The relationship between motor duty ratio and rotational speed is shown in Figure 11. The theoretical values are 2 series (sim) and 3 series (sim). Actual values are 2 series and 3 series. Comparing these, it can be seen that both theoretical values are higher in terms of rotational speed values than measured values. It is considered that this is affected by losses in the FET used as the switching element, the electromagnetic relay used this time, and the wiring. The main consideration is copper loss. Because 12 electromagnetic relays were used, the wiring for that amount was increased. Therefore, in addition to resistances such as windings, the influence of wiring also appeared in the form of rotation speed. As the maximum current increases to increase the rotational speed, it is a future task to reduce the decrease in rotational speed due to the loss.

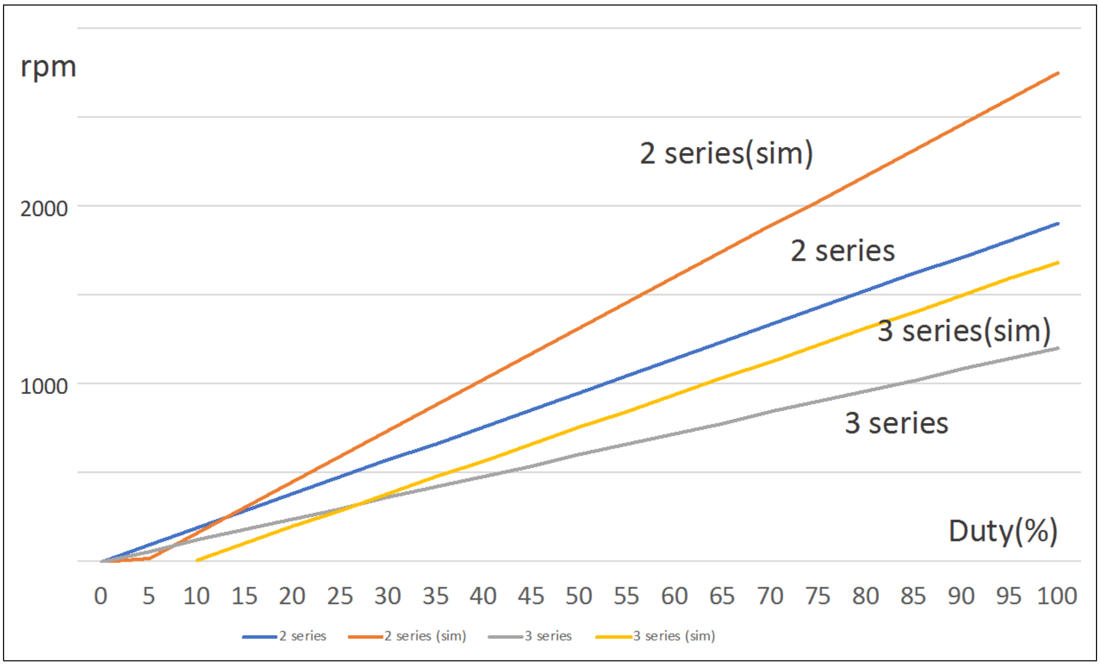

Figure 11. Comparison of motor simulation results and measurement results

7. **Conclusion.** In this research, we designed switching circuits of 2 series 3 parallel and 3 series 2 parallel of brushless motor, and experimented motor driving using that circuit. As a result, data of rotational speed and current were acquired. In addition, reducing the delay of the electromagnetic relay, reducing the size and power consumption, and converting the electromagnetic relay into a transistor, and reducing the loss from the wiring and the like are future issues.

REFERENCES

[1] S. Atiq, T. A. Lipo and B.-I. Kwon, Wide speed range operation of non-salient PM machines, *IEEE Trans. Energy Conversion*, vol.31, no.3, pp.1179-1191, 2016.

[2] B. Tian, Z. Zhang, J. Wei and T. A. Lipo, Investigation of dual-inverter-fed drives for per-manent magnet synchronous motor with winding switching, *The 40th Annual Conference of the IEEE Industrial Electronics Society*, pp.709-714, 2014.

[3] S. Atiq, T. A. Lipo and B.-I. Kwon, Novel field weakening technique for surface mounted permanent magnet machine using current ragulated voltage source inverters, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, pp.836-841, 2014.
[4] H. Jijikata, Y. Sakai, K. Akatsu, Y. Miyama, H. Arita and A. Daikoku, Wide speed range operation by low-voltage inverter-fed MATRIX motor for automobile traction motor, *IEEE Trans. Power Electronics*, vol.33, no.8, pp.6887-6896, 2018.
[5] S. Katayama and H. Haga, Wide range speed operation of dual core surface permanent magnet synchronous motor using nine-switch-inverter with winding switching method, *The Papers of Technical Meeting on Semiconductor Power Converter*, IEE Japan, pp.37-42, 2019.
[6] *JMAG-EXPRESS ONLINE*, https://www.jmag-international.com/jp/express/, Accessed on 20 Aug. 2019.