

Approaches to Suppressing Shaft Voltage in Non-Insulated Rotor Brushless DC Motor driven by PWM Inverter

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Abstract – The voltage source PWM inverter generally used to drive the air conditioning (A/C) fans has been posing a large issue that the bearings in air conditioning fan motors are highly possible to be corroded electrically. Potential difference called shaft voltage is generated between inner and outer rings of the bearings due to inverter switching. The shaft voltage causes bearing lubricant breakdown dielectrically. As a result, bearing current is caused. This current causes the bearing corrosion. In previous work, we demonstrated that the shaft voltage can be reduced by using an insulator inserted between the outer and inner cores of the rotor in an air conditioning fan motor without grounding. This paper proposes the other countermeasure for reducing the shaft voltage in fan motors. The countermeasure which adds a capacitor between the brackets and the stator core is effective even for fan motors with non-insulated rotor. The effectiveness is confirmed by both simulated and experimental results.

Keywords: Shaft Voltage, Bearing, Common-mode Voltage

1. Introduction

As the need for energy-saving measures increases, the number of brushless DC motors used to drive air-conditioning fans have been rapidly increasing. And voltage-source pulse-width modulation (PWM) inverters generally used to drive the fan motors have been posing a major problem. The problem is a high probability of the electrical erosion of bearing in the motors. A potential difference, called the shaft voltage, is generated between the outer and inner races by inverter switching, and this voltage causes the dielectric breakdown of the bearing lubricant. The current produced by the dielectric breakdown, also called “electric discharge machining (EDM) current”, results in a current passing through the bearing and causes electrical erosion in the bearing [1]-[14].

The shaft voltage can be suppressed by suppressing either the common-mode voltage causing shaft voltage or

the shaft voltage itself. Previously, we proposed an insulated rotor which can suppress the shaft voltage in brushless DC motors for air conditioning [6],[13],[14].

However, the subject that new equipment was required for an insulated rotor occurred.

In this paper, we report on suppressing shaft voltage by addition of a capacitor to the non-insulated rotor brushless DC motor driven by PWM inverter. First, shaft voltage is simulated from the equivalent circuit and it is confirmed that the simulated shaft voltage has good agreement with a measurement result. Next, the structure, which is added a capacitor between the brackets and the stator core, is presented. And also the optimal placement of the capacitor is investigated by simulation of shaft voltage.

2. Shaft Voltage Reduction with the Non-Insulated Rotor

2.1 Common-mode Equivalent Circuit of Ungrounded Motor

Fig. 1 shows the external view of a concentrated winding brushless DC motor used to drive an air conditioning fan. This motor is a surface permanent magnet synchronous motor in which the stator core and stator windings are molded with resin and a ferrite plastic magnet is also

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molded on the rotor core surface. Metal brackets are mounted on the top and bottom of the stator to hold the earing. Both metal brackets are connected each other inside the motor. The inverter circuit to drive the motor is mounted on the stator of the motor. The rated output power of the motor is 60 W, and the inverter operates under two-phase modulation. Two 608 type bearings are used and each are lubricated by a ureabased lubricant with a base-oil viscosity of 53 mm²/s.

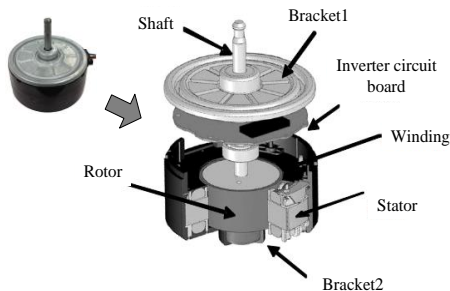


Fig. 1. Brushless DC motor

Fig. 2 shows the capacitive coupling in the brushless DC motor. The shaft voltage of the motor v_{sh} is the voltage between shaft and brackets and is also the voltage across bearing capacitances C_{b1} and C_{b2} . And the electric potential of the shaft is decided by voltage division of shaft side capacitances C_s , C_g , C_{mg} , C_m and C_{sn} , and the potential of the bracket is decided by voltage division of bracket side C_{sb} and C_n . Based on the bridge equivalent circuit in Fig. 3, the motor was disassembled into each component such as stator and rotor, and capacitances were measured for each respective part exclusively or in combination.

Fig. 3 shows an ungrounded 3-phase common-mode equivalent circuit. Table I lists measured capacitances from parts of the motor for the equivalent circuit [6]. In previous paper [6], we proposed an equivalent circuit for the insulated rotor brushless DC motor. The equivalent circuit has a bridge-type structure, and was developed with consideration of the following fact:

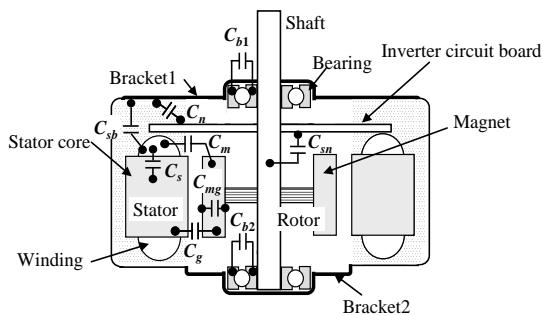


Fig. 2. Motor capacitive coupling

- The shaft voltage varies depending on the capacitance value of the insulated rotor, and
- The polarities of both common-mode and shaft voltages become reverse when the capacitance of the insulated rotor diminishes.

In Fig. 3, we use the equivalent circuit for the ungrounded motor by removing a capacitor for the insulated rotor.

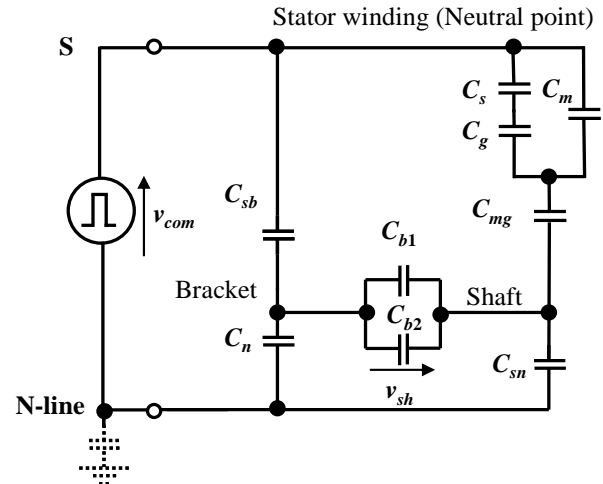


Fig. 3. Bridge-type equivalent circuit of the motor common-mode (ungrounded and non-insulated motor)

Table 1. Measured Capacitance in Each Part of Motor

Symbol	Parameter	Measured value
C_s	Stray capacitance; winding to stator core	400 pF
C_g	Stray capacitance; stator core to magnet	70 pF
C_{mg}	Magnet capacitance	69 pF
C_m	Stray capacitance; winding to magnet	8 pF
C_b	Bearing capacitance ($C_{b1}+C_{b2}$)	100 pF
C_{sb}	Stray capacitance; winding to bracket	19 pF
C_{sn}	Stray capacitance; shaft to N-line	7.7 pF
C_n	Stray capacitance; bracket to N-line	20 pF

The shaft voltage v_{sh} is generated between the outer and inner races by inverter switching, because common-mode voltage v_{com} , which is the voltage between a neutral point S of the inverter output voltage and negative potential N of the DC link, is divided by capacitances inside the motor.

The measurement results are shown in Table 1 [6]. LCR meter ZM2353 manufactured by NF Corporation was used for the measurements and the measurement frequency was 20 kHz (carrier frequency of the inverter).

- Combined capacitance between the winding and the stator core, C_s : Electrostatic capacity between the neutral

point of the stator windings and the stator core was measured.

- Electrostatic capacity between the stator core and the magnet, C_g : The rotor was inserted in the un-wound stator, electrostatic capacity of the stator core and the magnet surface were measured.

- Magnet capacitance, C_{mg} : The electrostatic capacity between the rotor surface and the shaft was measured.

- Combined capacitance between the N electric potential and the bracket, C_n : The bracket and the inverter circuit were inserted in the molded stator only, and the electrostatic capacity between the bracket and inverter was measured.

- Bearing capacitance, C_{b1} , C_{b2} : Electrostatic capacities of bearings 608ZZ at 1000min-1.

- Combined capacitance between the winding and the magnet, C_m : The rotor was inserted in the stator, and electrostatic capacity between the neutral point and the shaft was measured as the combined capacitance of C_m , C_g and C_{mg} , and C_m was calculated.

- Combined capacitance between the N electric potential and the bracket, C_n : The bracket and the inverter circuit were inserted in the molded stator only, and the electrostatic capacity between the bracket and the inverter was measured.

Fig. 4 shows the simulation results of common-mode voltage v_{com} and shaft voltage v_{sh} of the motor. The DC link voltage was 280 V, the motor rotating speed was 1000 min-1, and the motor was operated with no-load.

From the figure, the peak to peak value of the shaft voltage v_{sh} is 10 V.

Specifications of air-conditioning motor are listed in Table 2.

Table 2. Specification of air-conditioning motor

Components	Item (Unit)	Value
Motor	Input voltage (V_{dc})	200-391
	Maximum out put power (W)	60
	Rated rotation speed (min^{-1})	1,000
	Rated torque (N-m)	0.3
	No. of pole	8
	No. of slot	12
	Rotor diameter (mm)	50.3
	Magnet length (mm)	24
	Stator outer diameter (mm)	87
	Stator inner diameter (mm)	50.9
	Stack length (mm)	13
	Inverter	Switching frequency (kHz)
modulation method		two-phase
Grease (Type 608)	Base grease	Urea-based
	Kinematic viscosity [m^2/s](at 40°C)	53
	Outer diameter	22
	Inner diameter	8

2.2 Shaft Voltage Measurement of ungrounded Motor

Fig. 5 shows the measurement results of common-mode voltage v_{com} and shaft voltage v_{sh} of the motor. The conditions of the measurement were made into the same conditions as the simulation.

From the figure, the bearing lubricant is dielectrically broken down at the peak to peak value of the shaft voltage v_{sh} is 10 V. The results of the simulated value and the measured value were mostly in agreement.

3. New Further Reduction Method of the Shaft Voltage

3.1 Common-mode Equivalent Circuit of New Method

We examined places to add a capacitor C_{adj} (adjusting capacitor) by the equivalent circuit. The places that can be added the capacitor is N-line of the inverter, the brackets and the stator core, there are three ways to connect the capacitor and they are as follows:

- Between the brackets and the stator core
- Between the N-line of the inverter and the brackets
- Between the N-line of the inverter and the stator core

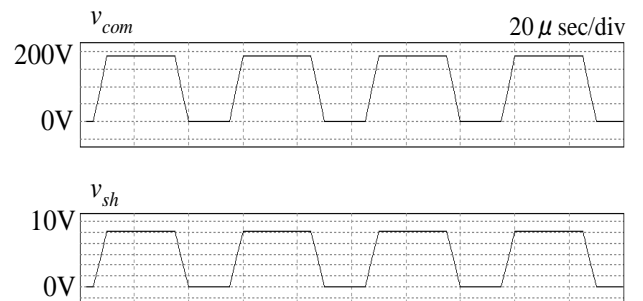


Fig. 4. Simulated common-mode voltage v_{com} and shaft Voltage v_{sh}

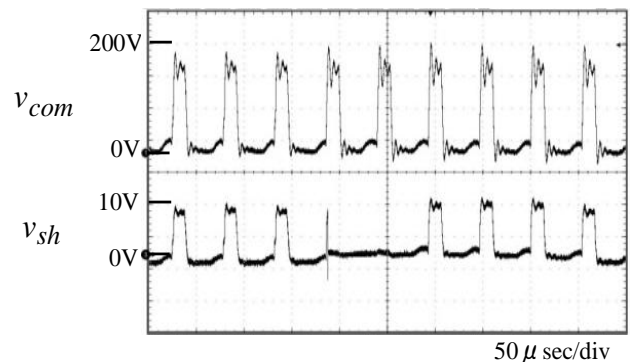


Fig. 5. Measured common-mode voltage v_{com} and shaft voltage v_{sh} (ungrounded and non-insulated motor)

Fig. 6 shows an equivalent circuit with the adjusting capacitor C_{adj} between the brackets and the stator core. Fig. 7 shows a simulation result of the shaft voltage when the value of C_{adj} is changed. Fig. 8 shows the simulation result of the shaft voltage when the value of C_{adj} is 75 pF. From the figure, we can find that the value of v_{sh} is 0.1 V, the polarity of v_{sh} is opposite to that of v_{com} .

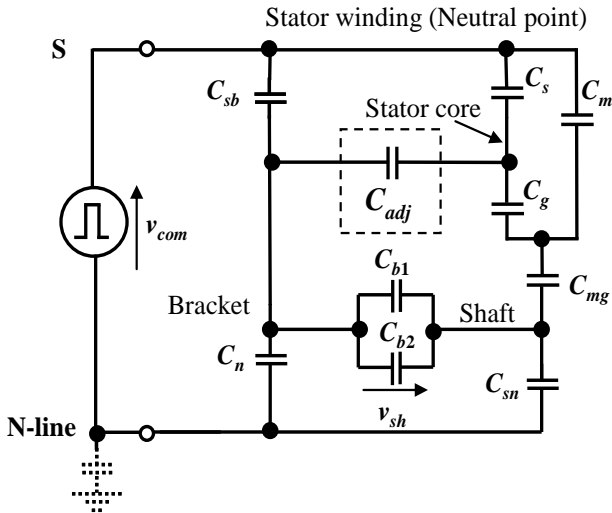


Fig. 6. Equivalent circuit with adjusting capacitor C_{adj} between the brackets and the stator core

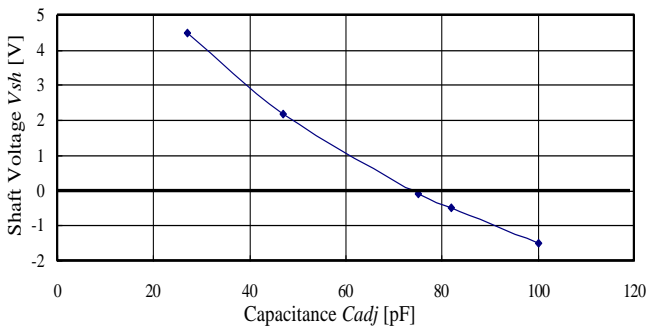


Fig. 7. Simulated shaft voltage v_{sh} when C_{adj} is changed (C_{adj} is between the brackets and the stator core)

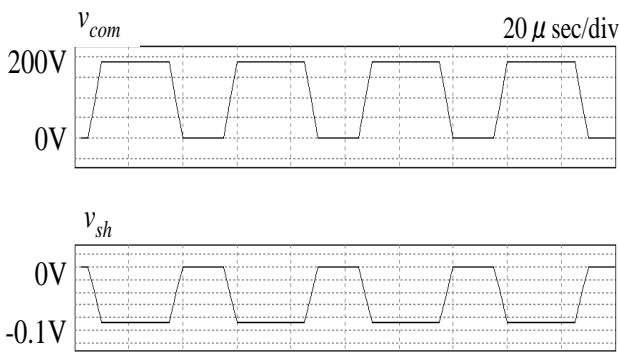


Fig. 8. Simulated shaft voltage v_{sh} ($C_{adj} = 75\text{pF}$)

Fig. 9 shows an equivalent circuit with an adjusting capacitor between the N-line and the brackets. Fig. 10 shows a simulation result of the shaft voltage when the value of C_{adj} is changed. Fig. 11 shows a simulation result of the shaft voltage v_{sh} when the value of C_{adj} is 10 pF and the peak to peak value of v_{sh} is 10 V, the polarity of v_{sh} is same to that of v_{com} .

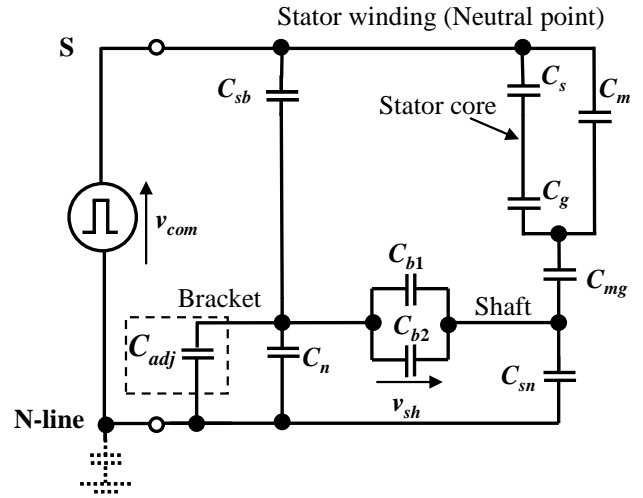


Fig. 9. Equivalent circuit with adjusting capacitor C_{adj} between the N-line and the brackets

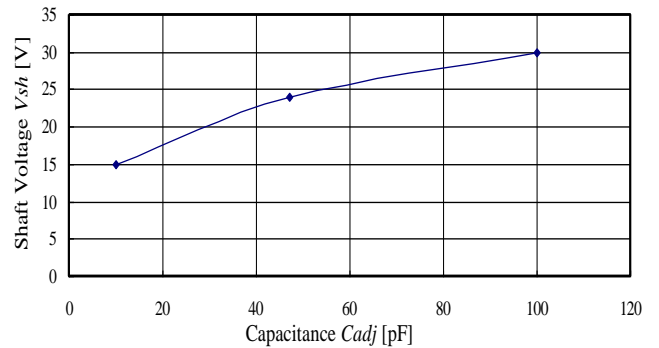


Fig. 10. Simulated shaft voltage v_{sh} when C_{adj} is changed (C_{adj} is between the N-line and the brackets)

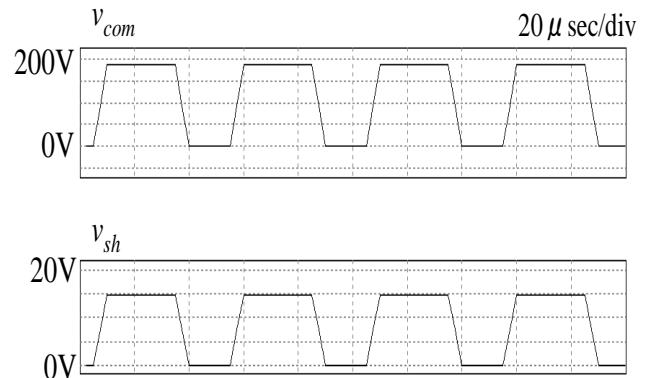


Fig. 11. Simulated shaft voltage v_{sh} ($C_{adj} = 10\text{pF}$)

Fig. 12 shows an equivalent circuit with an additional capacitor between the N-line and the stator core. Fig. 13 shows a simulation result of the shaft voltage when the value of C_{adj} is changed. Fig. 14 shows a simulation result of the shaft voltage when the value of C_{adj} is 330 pF and the peak to peak value of v_{sh} is 0.1 V, the polarity of v_{sh} is same to that of v_{com} .

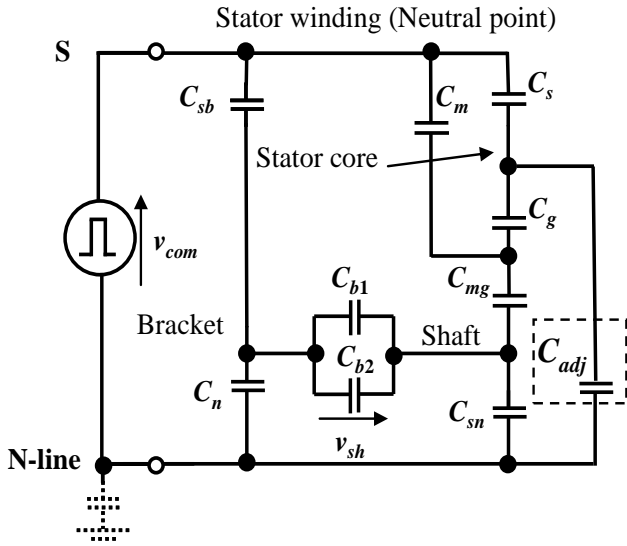


Fig. 12. Equivalent circuit with adjusting capacitor C_{adj} between the N-line and the stator core

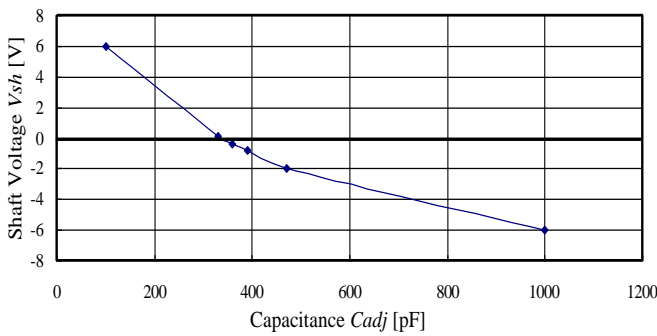


Fig. 13. Simulated shaft voltage v_{sh} when C_{adj} is changed (C_{adj} is between the N-line and the stator core)

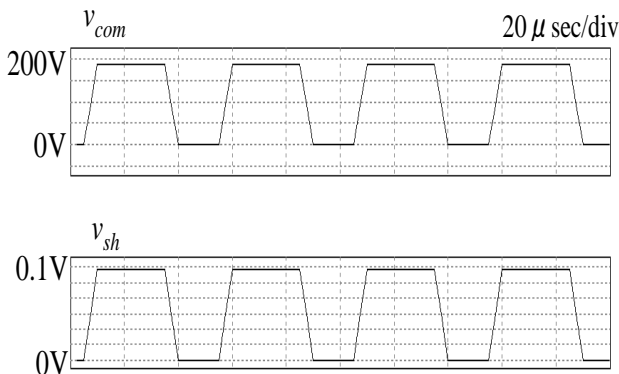


Fig. 14. Simulated shaft voltage v_{sh} ($C_{adj} = 330\text{pF}$)

From Figs. 6-14, it is found that putting the adjusting capacitor both between the N-line and the stator core or between the brackets and the stator core are effective to reduce the shaft voltage.

Fig. 15 shows the capacitive coupling in the brushless DC motor which was added an adjusting capacitor C_{adj} between the brackets and the stator core. To confirm the simulated results, an experiment for the structure in Fig. 15 was done and it is described in the next section.

3.2 Shaft Voltage Measurement of New Method

We propose adding the adjusting capacitor C_{adj} which is a commercial part. The capacitor C_{adj} is placed between the brackets and the stator core to enlarge the margin by bringing the shaft voltage close to 0 V from over 10 V.

Fig. 16 shows the measured waveform of shaft voltage with a capacitance $C_{adj} (= 75 \text{ pF})$, at the peak to peak value of the shaft voltage v_{sh} , 0.2 V.

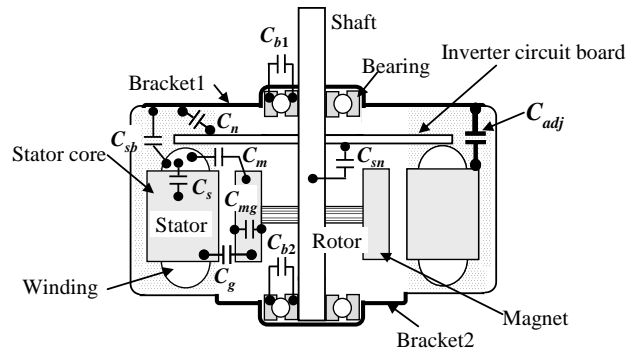


Fig. 15. Motor capacitive coupling for proposed new method

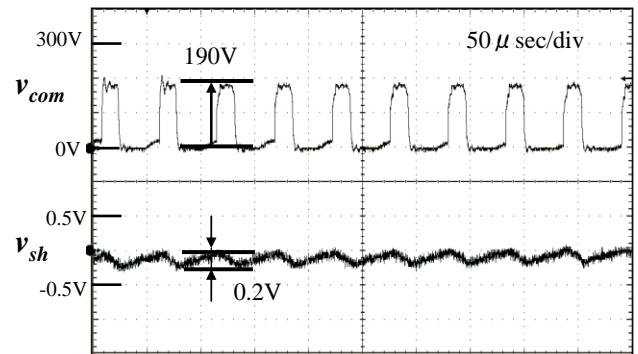


Fig. 16. Measured common-mode voltage v_{com} and shaft voltage

4. Conclusion

For non-insulated rotor brushless DC motor driven by

PWM inverter, placements of an adjusting capacitor were investigated to reduce the shaft voltage by simulation using simple common-mode equivalent circuit. Three kinds of placements (between the brackets and the stator core, between the N-line of the inverter and the brackets and between the N-line of the inverter and the stator core) were investigated and it was clarified that the placements both between the brackets and the stator core and between the N-line and the stator core are effective for reduction of the shaft voltage.

Based on the simulated results, the new method putting an adjusting capacitor C_{adj} between the brackets and the stator core was proposed to reduce the shaft voltage in the molded brushless DC motor, and its effectiveness was verified by calculation of simplified equivalent circuit.

Additionally, the other new method putting an adjusting capacitor C_{adj} between the stator core and the N-line was proposed, and its effectiveness was also verified by calculation of simplified equivalent circuit.

For the former method, the effectiveness was checked by the experimental results which show the reduction of peak to peak value of shaft voltage v_{sh} .

We would like to apply this examination result to other types of brushless motors.

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