

Derivation of Novel Equivalent Circuit Considering Parasitic Capacitance of AFPM Motor

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Space Vector Pulse Width Modulation (SVPWM), known for its superior voltage utilization, is widely utilized in motor control systems. However, the high-speed switching of inverters generates harmonics, which subsequently lead to the occurrence of Common Mode Voltage (CMV). CMV induces shaft voltage, resulting in phenomena such as pitting and fluting that can damage the bearings. As a result, the motor shaft is not securely fixed, which can lead to mechanical and electrical failures. Therefore, analyzing the characteristics of shaft voltage is crucial for ensuring high reliability in motors. In the case of Interior Permanent Magnet Synchronous Motor (IPMSM), Surface Permanent Magnet Synchronous Motor (SPMSM), induction motor extensive research has been conducted on the shaft voltage characteristics. However, studies on Axial Flux Permanent Magnet (AFPM) motors remain relatively insufficient. In this paper derives the internal parasitic capacitance and a new equivalent circuit for AFPM motors, considering their structural and electromagnetic characteristics, and validates them through comparison using FEM.

Index Terms— Axial Flux Permanent Magnet motor, Novel equivalent circuit, Parasitic Capacitance, Shaft voltage

I. INTRODUCTION

Due to the advancements of the electrification era, the demand for electric motors in various industries is rapidly increasing. Accordingly, research on achieving high output, high reliability, and high efficiency in electric motors is actively being conducted. In particular, high reliability is essential in fields such as industrial equipment, railways, and electric vehicles. For high reliability, research on fault analysis and diagnosis of electric motors is very important. Among electric motor faults, the most frequently occurring fault is bearing fault, and one of the main causes is shaft voltage. Shaft voltage is caused by common mode voltage (CMV) generated by high-speed switching of the inverter. In particular, the input voltage is becoming higher to improve the efficiency of the system recently, and this increases the magnitude of CMV, further increasing the frequency of bearing faults [1]. Meanwhile, extensive research has been conducted on the shaft voltage of IPMSM, SPMSM, and induction motors, but research on the AFPM motor is relatively insufficient.

Therefore, this paper derives the internal parasitic capacitance to analyze the shaft voltage characteristics of the AFPM motor and proposes an equivalent circuit for the shaft voltage. In addition, FEM simulation and MATLAB Simulink were performed to verify the equation of the proposed parasitic capacitance.

II. PROPOSAL OF EQUIVALENT CIRCUIT OF AFPM MOTOR

As shown in Fig. 1, the CMV applied to the winding interacts with the parasitic capacitance inside the motor to form three circulating current paths. The parasitic capacitance inside the AFPM motor consists of C_{ws} , C_{wf} , C_{rf} , C_{wr} , C_{sr} , and C_b . At this time, since the circulating current flows to the ground through the bearing, it generates a shaft voltage in the bearing.

Fig. 2 shows shaft voltage equivalent circuit of AFPM motor. Through this equivalent circuit, the shaft voltage is defined as the ratio of the input voltage and the bearing voltage, as in (1), and is determined by the motor's internal parasitic capacitance.

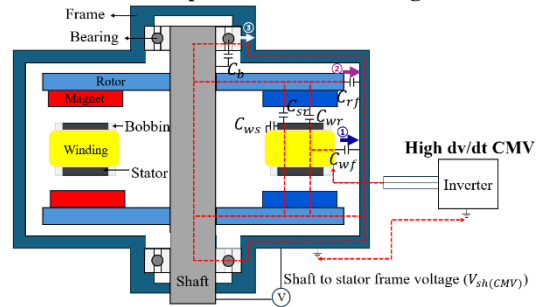


Fig. 1. Parasitic capacitance configuration and circulating current of AFPM motor.

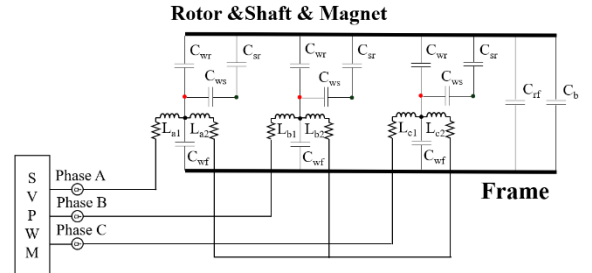


Fig. 2. Shaft voltage equivalent circuit of AFPM motor

$$BVR = \frac{\frac{C_{ws}C_{sr}}{(C_{sr}+C_{ws})} + C_{wr}}{\frac{C_{ws}C_{sr}}{(C_{sr}+C_{ws})} + C_{wr} + C_b + C_{rf}} CMV \quad (1)$$

III. DERIVATION OF INTERNAL PARASITIC CAPACITANCE

A. Rotor to frame parasitic capacitance (C_{rf})

C_{rf} is calculated as (2) assuming the parallel plate capacitance. Also, since the distance between the two parallel plates is very small, the fringing effect does not need to be considered.

$$C_{rf} = 2 \frac{\epsilon_0 \pi (R_{or}^2 - R_{if}^2)}{d_{rf1}} + 2 \frac{\epsilon_0 2\pi \left(\frac{R_{of} + R_{or}}{2} \right) h_{rf2}}{R_{of} - R_{or}} + 2 \frac{\epsilon_0 \theta_m N_m \left(\frac{R_{of} + R_{om}}{2} \right) h_{rf3}}{R_{of} - R_{om}} \quad (2)$$

where R_{of} is frame outer radius, R_{or} is rotor outer radius, R_{om} is magnet outer radius, R_{if} is frame inner radius, θ_m is magnet arc, N_m is number of magnets, h_{rf2} is rotor height, h_{rf3} is magnet height, d_{rf1} is axial distance between rotor and frame.

B. Winding to rotor parasitic capacitance (C_{wr})

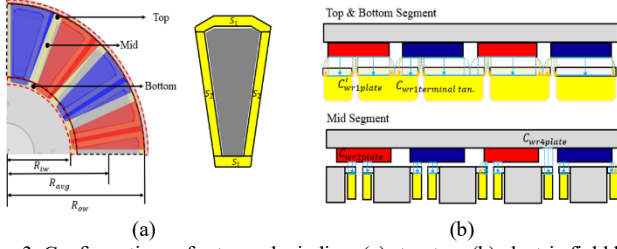


Fig. 3. Configurations of rotor and winding. (a) structure (b) electric field lines

As shown in the Fig. 3 (b), since the capacitance of the two parallel plates is much larger than the capacitance considering the fringing effect in the tangential direction, it is ignored and only the fringing effect in the radial direction is considered. It can be expressed as equation (7) as follows.

$$C_{wr1plate} = C_{wr1air} || C_{wr1bo} = \frac{2}{\frac{1}{N_c \frac{\epsilon_0 S_{w1}}{g}} + \frac{1}{N_c \frac{\epsilon_{bo} S_{w1}}{d_{bo}}}} \quad (3)$$

$$C_{wr1terminal rad.} = \frac{N_s 2(l_{wo} + l_{wi})}{2} \frac{4}{\pi} \ln 2 \quad (4)$$

$$C_{wr2plate} = C_{wr2air} || C_{wr2bo} = \frac{2}{\frac{1}{N_{cm} \frac{\epsilon_0 S_{w2}}{g}} + \frac{1}{N_{cm} \frac{\epsilon_{bo} S_{w2}}{d_{bo}}}} \quad (5)$$

$$C_{wr4plate} = C_{wr4air} + C_{wr4bo} = 2N_{cr} \frac{\epsilon_0 S_{w2}}{g + h_m} + 2N_{cr} \frac{\epsilon_{bo} S_{w2}}{d_{bo}} \quad (6)$$

$$C_{wr} = C_{wr1plate} + C_{wr1terminal rad.} + C_{wr2plate} + C_{wr4plate} \quad (7)$$

where N_s is number of slots, ϵ_{bo} is permittivity of the bobbin, d_{bo} is thickness of bobbin.

C. Winding to stator parasitic capacitance (C_{ws}), Stator to rotor parasitic capacitance (C_{sr})

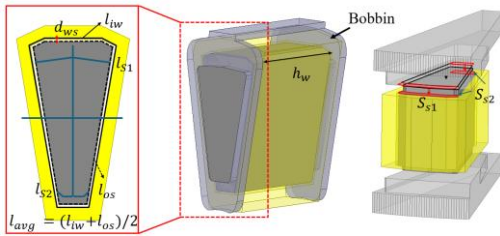


Fig. 4. Configurations of stator, rotor and winding.

C_{ws} is calculated assuming that the winding and stator are parallel plates as shown in (8). In addition, the fringing effect in which a potential is formed from the end of the winding to the stator was considered, and the dielectric medium in this case is a plastic bobbin as shown in Fig. 4.

$$C_{ws} = \frac{\epsilon_0 l_{avg} h_w}{d_{ws}} + l_{avg} \left(\frac{\epsilon_{bo}}{\pi} + \frac{\epsilon_{bo}}{\pi} \ln \left(\frac{2\pi h_w}{d_{ws}} \right) \right) \quad (8)$$

In the case of C_{sr} , it is calculated as (9) considering the terminal capacitance and fringing capacitance. In this case, in the case of $C_{sr2plate}$, since there are two dielectric media, bobbin and air, it is calculated in parallel [2].

$$C_{sr} = C_{sr1plate} + C_{sr1terminal rad.} + C_{sr1fringe} + C_{sr2plate} = 2 \left(N_s - N_s \frac{\text{pole open width}}{\text{pole pitch}} \right) \left(\frac{\epsilon_0 S_{s1}}{g} + \frac{\epsilon_0 (l_{s1} + l_{s2})}{2} \frac{4}{\pi} \ln 2 \right) + \frac{\epsilon_0 (l_{s1} + l_{s2})}{2} \frac{2}{\pi} \ln \left(1 + \frac{d_{bo}}{g} \right) + \frac{\epsilon_0 S_{s2}}{g} || \frac{\epsilon_{bo} S_{s2}}{d_{bo}} \quad (9)$$

IV. COMPARATIVE VERIFICATION OF FEM SIMULATIONS AND PROPOSED METHOD

The parasitic capacitance derived through the proposed method and FEM simulation (Q3D) was compared and verified. Additionally, BVR was performed using Matlab Simulink. The results for this are summarized in Table 1 and Fig. 5.

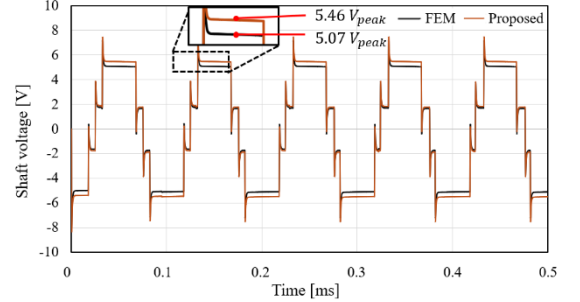


Fig. 5. Simulink shaft voltage waveform of the proposed equivalent circuit.

TABLE 1 RESULTS OF PARASITIC CAPACITANCE AND SHAFT VOLTAGE CALCULATION				
Items	FEM	Proposed	Unit	Error [%]
C_{wr}	34.07	33.95	pF	0.35
C_{ws}	856.53	829.56	pF	3.15
C_{sr}	69.22	64.06	pF	7.45
C_{rf}	214.2	221.6	pF	3.45
V_{sh}	5.46	5.07	V_{pk}	7.14

V. CONCLUSION

In this paper, a new shaft voltage equivalent circuit of the AFPM motor and parasitic capacitance according to the motor structure were derived. Through this research, it is possible to derive shaft voltage according to the input voltage, through which bearing failure can be predicted, and parasitic capacitance according to the motor structure can be analyzed and designed to reduce it.

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