A study on the selection of the optimal number of poles for maximizing the magnetic flux of spoke type permanent magnet motor

Sung Gu Lee[1], *Jaenam Bae*[2] *and Won-ho Kim*[3]

1. Busan University of Foreign Studies, Busan, Korea , 2. Dongyang mirae University, Seoul, Korea 3. Gachon University, Gyeonggi-do, Korea

Tue-Af-Po2.06-32 [94]

MT25

Background

Recently, spoke type permanent magnet (PM) motor capable of maximizing the surface area of a PM at a limited rotor size has been actively studied. Since the magnetic flux amount generated from PMs of the same volume increases as the surface area of the PM increases, the Spoke type PM motor is more advantageous in terms of output density than any other PM type motors. The spoke PM motor shows a large change in the total magnetic flux amount that determines the torque constant depending on the number of poles. Especially, in the spoke PM motor, there is a pole number in which the maximum magnetic flux amount is generated when only the number of poles of the motor is changed under the condition that the PM usage amount is the same. This is a phenomenon that did not occur in conventional surface mount permanent magnet (SPM) motors.

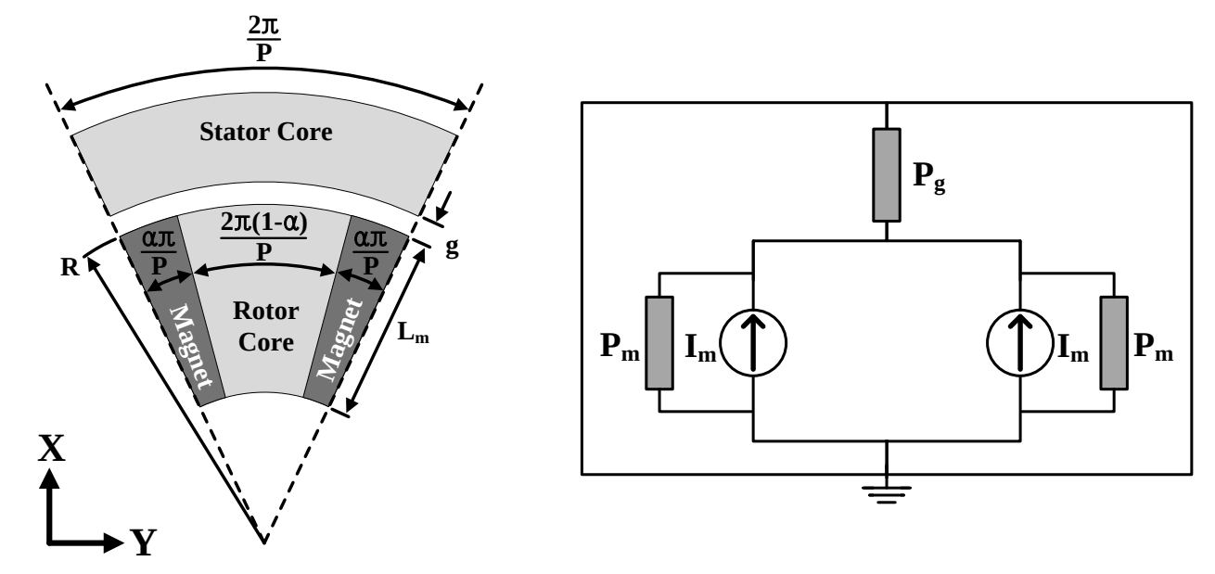
Objectives

- Total magnetic flux representation of spoke PM motor as a function of geometric parameters such as number of poles, rotor radius, and length of air-gap
- Expression of factor that can show how the total magnetic flux of SPOKE motor increases compared with SPM motor of equivalent condition

Conclusion

- In SPM motors, the number of poles are increased under the same amount of PMs, but the total flux and torque constant do not increase. Rather, the torque constant decreases as the number of poles increases as the leakage magnetic flux increases.
- However, in the spoke motors, unlike SPM, it is possible to increase the total flux and torque constant by changing only the number of poles in a state where other variables are fixed. As a result, there is a pole number that can maximize the torque constant of the spoke in a state where the PM usage amount is constant.
- In this paper, we have defined an factor that can show how efficiently a spoke PM motor generates magnetic flux using equivalent magnetic circuit. This factor is the total flux of the spoke divided by the total flux of the same SPM such as rotor diameter, length of air gap, stack length, number of poles, PM usage, and number of turns.

Spoke without leakage



(a) Geometric shape (b) Equivalent magnetic circuit

Fig. 1 Birdgeless type spoke PM motor

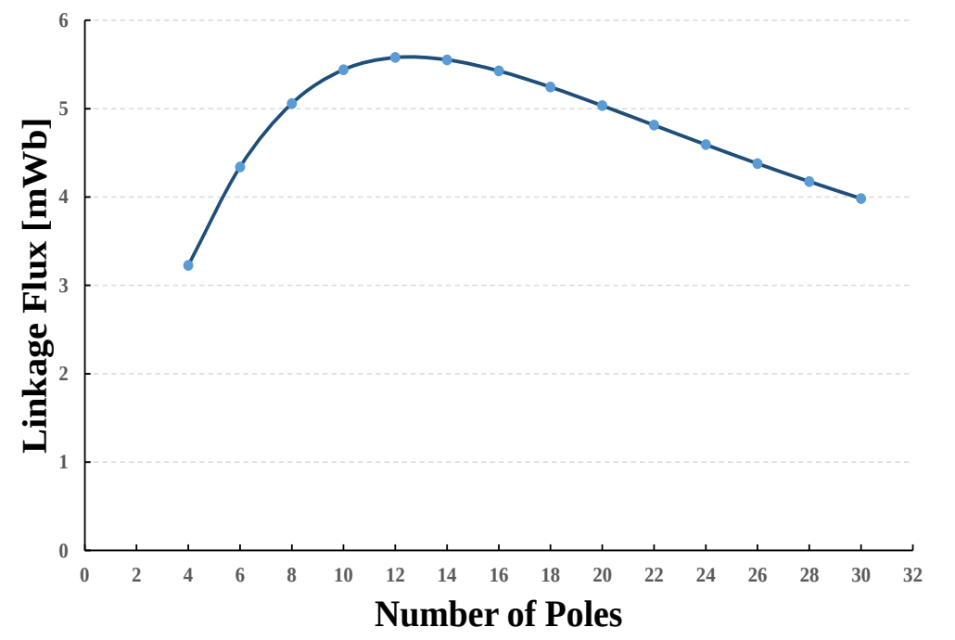


Fig. 2 Total magnetic flux calculation according to the number of poles

$$P_g = \frac{1}{\Re_g} = 1\Big/\int_R^{R+g} \frac{1}{\mu_0 \frac{2\alpha\pi}{P} r L_s} dr = \frac{2\mu_0 \alpha\pi L_s}{P \ln\left(1+\frac{g}{R}\right)} \quad \cdots\cdots(1)$$

$$P_m = \int_{R-L_m}^{R} \frac{\mu_0 \mu_r L_s}{\frac{\pi}{P}(1-\alpha) r} dr = \frac{P\mu_0\mu_r L_s}{\pi(1-\alpha)} \ln\left(\frac{R}{R-L_m}\right) \quad \cdots\cdots(2)$$

$$I_m = B_r L_m L_s \quad \cdots\cdots(3)$$

$$\lambda_{spoke,pole} = \frac{2P_g I_m}{2P_m + P_g} = \frac{2\alpha(1-\alpha)\pi^2 B_r L_m L_s}{P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2} \quad \cdots\cdots(4)$$

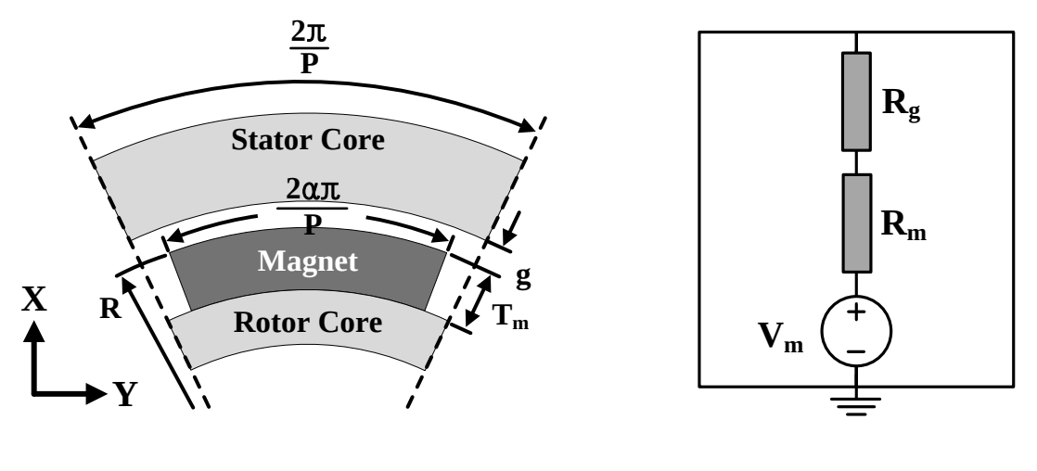
$$\lambda_{spoke} = P\lambda_{spoke,pole} = \frac{P 2\alpha(1-\alpha)\pi^2 B_r L_m L_s}{P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2} \quad \cdots\cdots(5)$$

$$Vol_m = 2\pi(1-\alpha)(2R-L_m)L_m L_s \quad \cdots\cdots(6)$$

$$\boxed{\eta_{spoke} = \frac{\lambda_{spoke}}{Vol_m} = \frac{P\alpha\pi B_r}{(2R-L_m)\left(P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2\right)} \quad \cdots\cdots(7)}$$

η_{spoke} is an indicator of the magnetic flux generated per PM volume in the spoke motor. As shown in Fig. 2, the value of η_{spoke} varies depending on the number of permanent magnet poles in spoke motors. As a result, η_{spoke} of a spoke motor at a certain pole number has a maximum value.

SPM



(a) Geometric shape (b) Equivalent magnetic circuit

Fig. 3 SPM motor

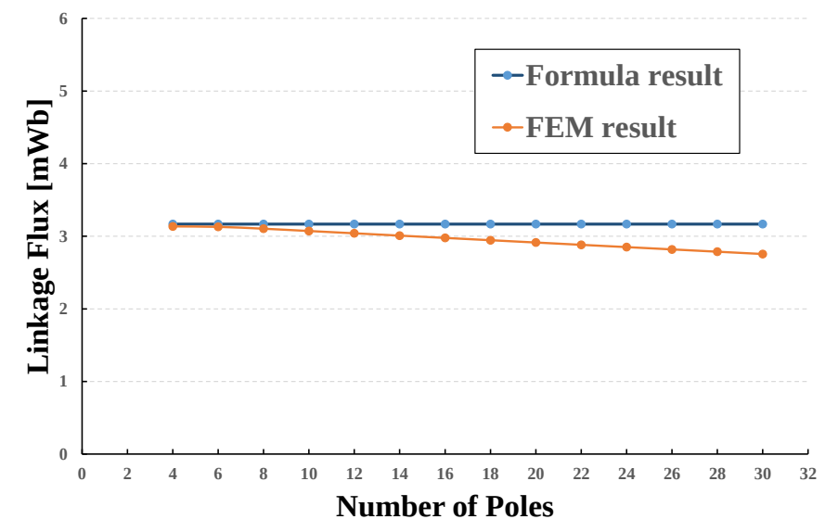


Fig. 4 Total magnetic flux calculation according to the number of poles

$$R_g = \int_R^{R+g} \frac{1}{\mu_0 \frac{2\alpha\pi}{P} r L_s} dr = \frac{P \ln\left(1+\frac{g}{R}\right)}{2\mu_0 \alpha\pi L_s} \quad \cdots\cdots(8)$$

$$R_m = \int_{R-T_m}^{R} \frac{1}{\mu_0 \mu_r \frac{2\alpha\pi}{P} r L_s} dr = \frac{P \ln\left(\frac{R}{R-T_m}\right)}{2\mu_0 \mu_r \alpha\pi L_s} \quad \cdots\cdots(9)$$

$$V_m = \frac{B_r T_m}{\mu_0 \mu_r} \quad \cdots\cdots(10)$$

$$\lambda_{SPM,pole} = \frac{V_m}{R_g + R_m} = \frac{2\alpha\pi B_r L_m L_s}{P\mu_r \ln\left(1+\frac{g}{R}\right) + P\ln\left(\frac{R}{R-T_m}\right)} \quad \cdots\cdots(11)$$

$$\lambda_{SPM} = P\lambda_{SPM,pole} = \frac{2\alpha\pi B_r L_m L_s}{\mu_r \ln\left(1+\frac{g}{R}\right) + \ln\left(\frac{R}{R-T_m}\right)} \quad \cdots\cdots(12)$$

$$\boxed{\eta_{SPM} = \frac{\lambda_{SPM}}{Vol_{magnet}} = \frac{B_r}{(2R-T_m)\left(\mu_r \ln\left(1+\frac{g}{R}\right) + \ln\left(\frac{R}{R-T_m}\right)\right)} \quad \cdots\cdots(13)}$$

η_{SPM} is an indicator of the magnetic flux generated per PM volume in the SPM motor. As shown in Fig. 4, unlike spoke, η_{SPM} in SPM is constant regardless of the number of poles. Actually, as the number of poles increases, the value of η_{SPM} decreases as the leakage flux between poles.

Flux improvement factor

T_m = Magnet thickness of SPM motor with the same volume as Spoke

Spoke PM volume = SPM PM volume

$$2\pi(1-\alpha)(2R-L_m)L_m L_s = 2\pi\alpha(2R-T_m)T_m L_s \quad \cdots\cdots(14)$$

$$T_m = \frac{\alpha R - \sqrt{(\alpha R)^2 - \alpha(1-\alpha)(2R-L_m)L_m}}{\alpha} \quad \cdots\cdots(15)$$

$$F_i = \frac{\eta_{spoke}}{\eta_{SPM}} = \frac{P\alpha\pi(2R-T_m)\left(\mu_r \ln\left(1+\frac{g}{R}\right) + \ln\left(\frac{R}{R-T_m}\right)\right)}{(2R-L_m)\left(P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2\right)} \quad \cdots\cdots(16)$$

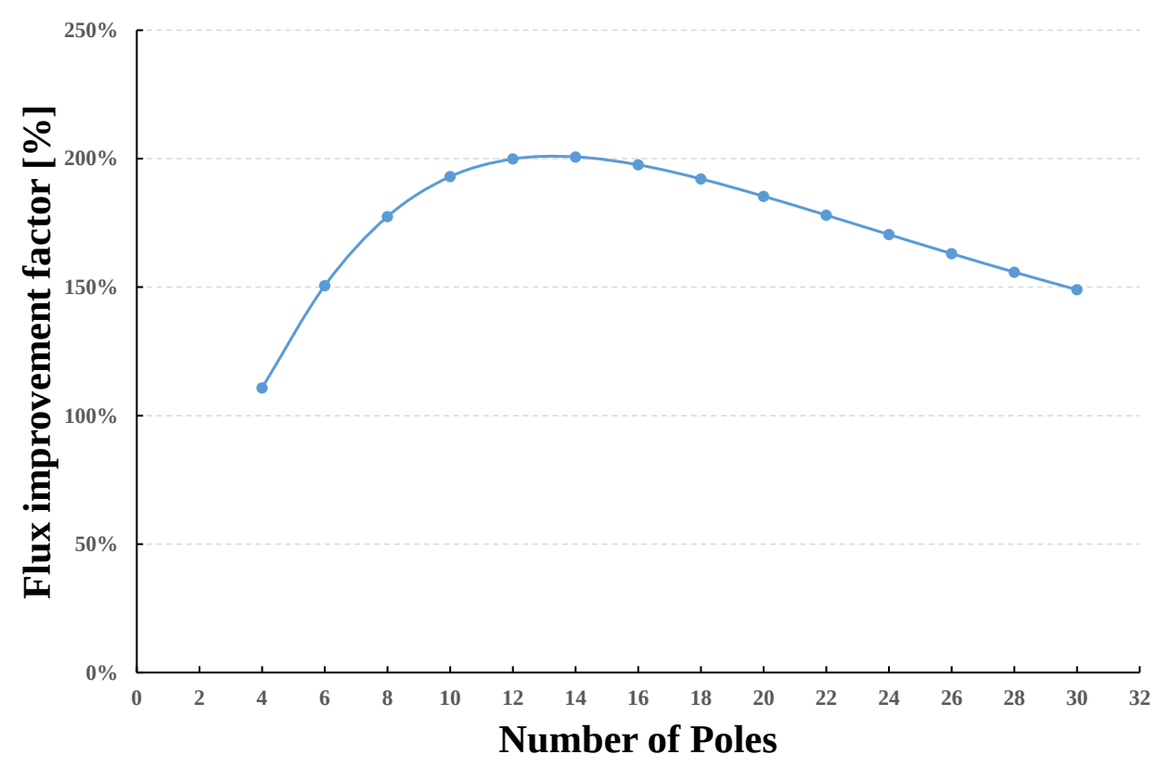


Fig. 5 F_i (Flux improvement factor) of Eq. (16) according to the number of poles calculated by the specifications in Table 2

Table 1. Meaning of the variables used in the preceding formula

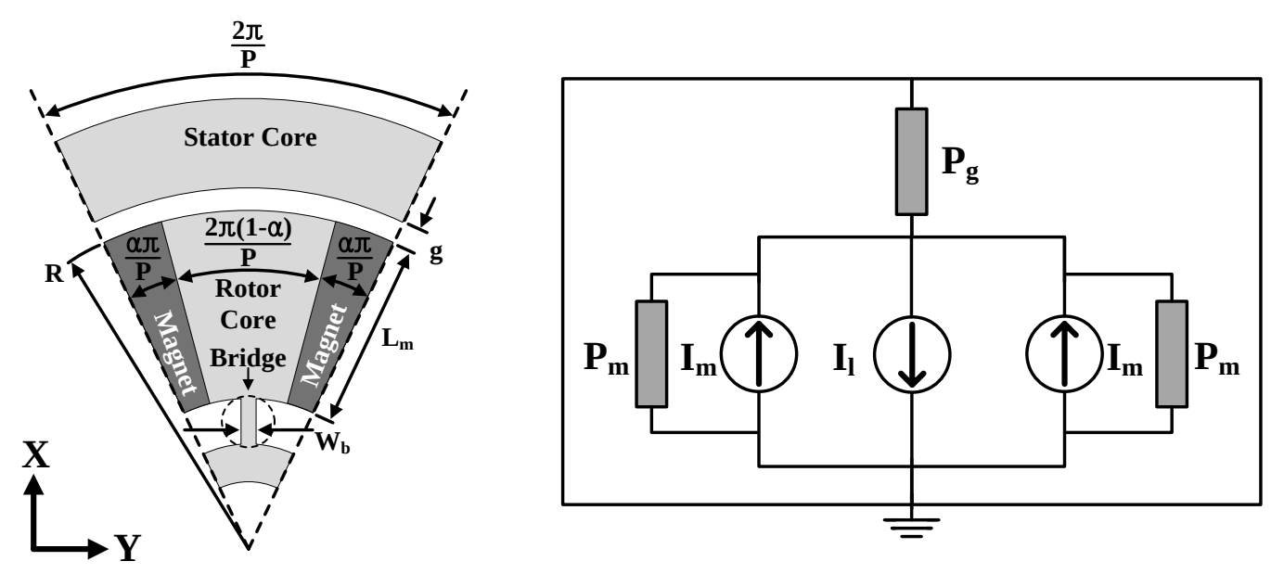
Symbol	Description
P	Number of poles
R	Radius of rotor
g	Length of air gap
α	The ratio of the flux generation area based of pole pitch
μ_0	Permeability of vacuum
μ_r	Relative permeability of permanent magnet
L_m	Length of PM in spoke
T_m	Thickness of PM in SPM
L_s	Stack length
B_r	Residual magnetic flux density of PM
W_b	Width of rotor core bridge

Table 2. The motor specifications used in the calculation of Eq. (16)

Symbol	Value
P	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30
R	33 mm
g	0.45 mm
α	0.7
L_m	18.5
μ_r	1.05

Influence of leakage flux in spoke

① Leakage flux through the rotor core (Bridge leakage)



(a) Geometric shape (b) Equivalent magnetic circuit

Fig. 6 Bridge leakage flux in the spoke PM motor

$$I_l = B_s W_b L_s \quad \cdots\cdots(17)$$

$$\lambda'_{spoke} = P\frac{P_g(2I_m - I_l)}{2P_m + P_g} = \frac{P\alpha(1-\alpha)\pi^2(2B_r L_m - B_s W_b)L_s}{P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2} \quad \cdots\cdots(18)$$

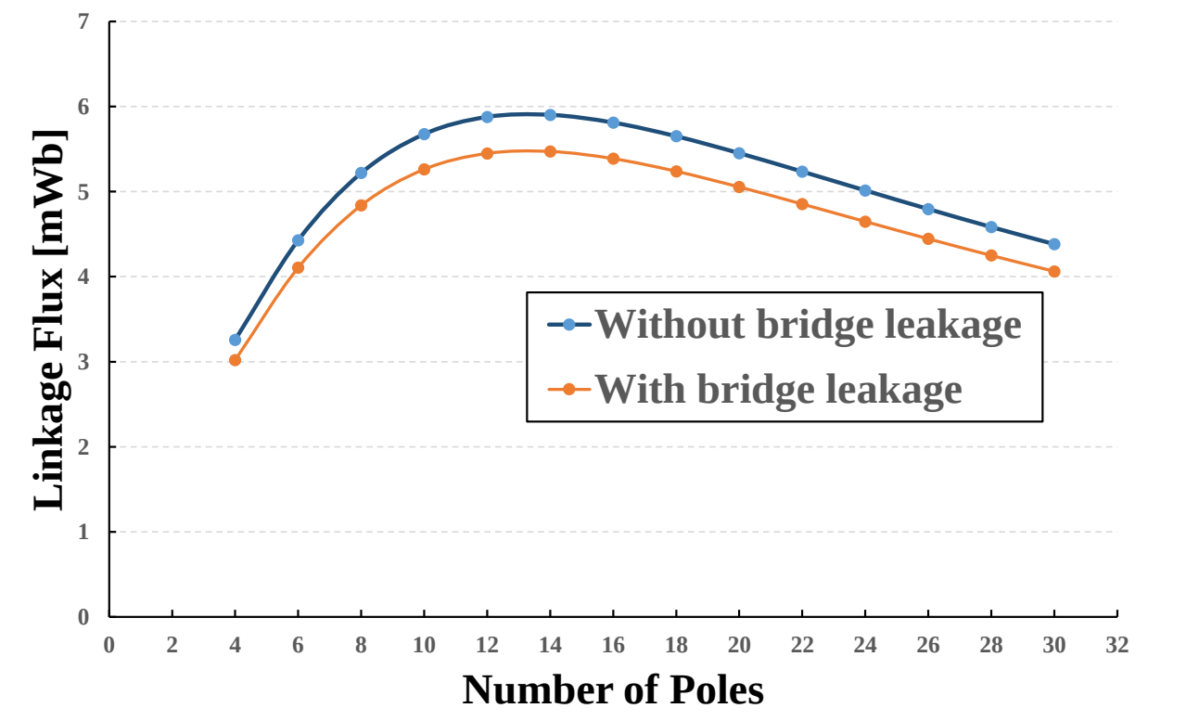
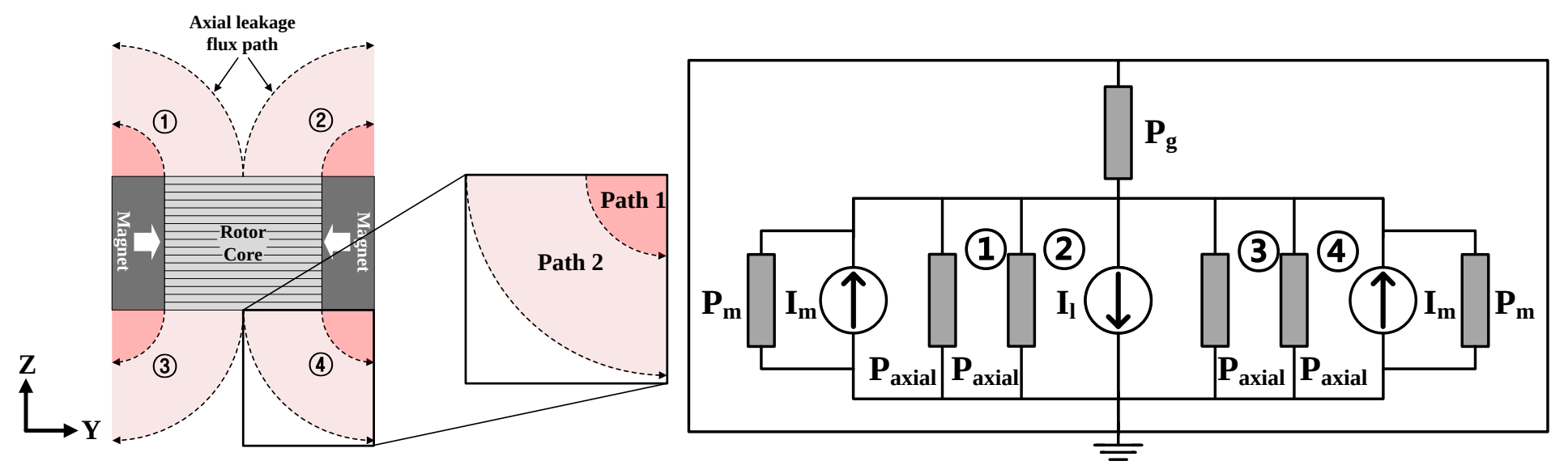


Fig. 7 Total magnetic flux calculation according to the number of poles with considering the bridge leakage

② Leakage flux through the axial air (Axial lekage)

$$P_{axial} = \int_{R-L_m}^{R} \int_{\frac{\alpha\pi}{P}}^{\frac{\pi}{P}} \frac{\mu_0}{\frac{\pi}{2} r\sin\theta} r\,dr\,d\theta + \int_{R-L_m}^{R} 0.264\,\mu_0 dr = \frac{2\mu_0}{\pi} \ln\left(\frac{\tan\left(\frac{\pi}{2P}\right)}{\tan\left(\frac{\alpha\pi}{2P}\right)}\right) L_m + 0.264\,\mu_0 L_m \quad \cdots\cdots(19)$$



(a) Axial leakage flux path (YZ-plane) (b) Equivalent magnetic circuit

Fig. 8 Axial leakage flux in the spoke PM motor

$$\lambda''_{spoke} = P\frac{P_g(2I_m - I_l)}{2P_m + P_g + 4P_{axial}} = \frac{P\alpha(1-\alpha)\pi^2(2B_r L_m - B_s W_b)L_s^2}{\left(P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2\right)L_s + 2P\pi(1-\alpha)\ln\left(1+\frac{g}{R}\right)\left(\frac{2}{\pi}\ln\left(\frac{\tan\left(\frac{\pi}{2P}\right)}{\tan\left(\frac{\alpha\pi}{2P}\right)}\right) + 0.264\right)L_m} \quad \cdots\cdots(20)$$

$$k_{leakage} = \frac{\lambda''_{spoke}}{\lambda_{spoke}} \quad \cdots\cdots(21)$$

$$F_i' = k_{leak}F_i = k_{leak}\frac{P\alpha\pi(2R-T_m)\left(\mu_r \ln\left(1+\frac{g}{R}\right) + \ln\left(\frac{R}{R-T_m}\right)\right)}{(2R-L_m)\left(P^2 \mu_r \ln\left(1+\frac{g}{R}\right) \ln\left(\frac{R}{R-L_m}\right) + \alpha(1-\alpha)\pi^2\right)} \quad \cdots\cdots(22)$$

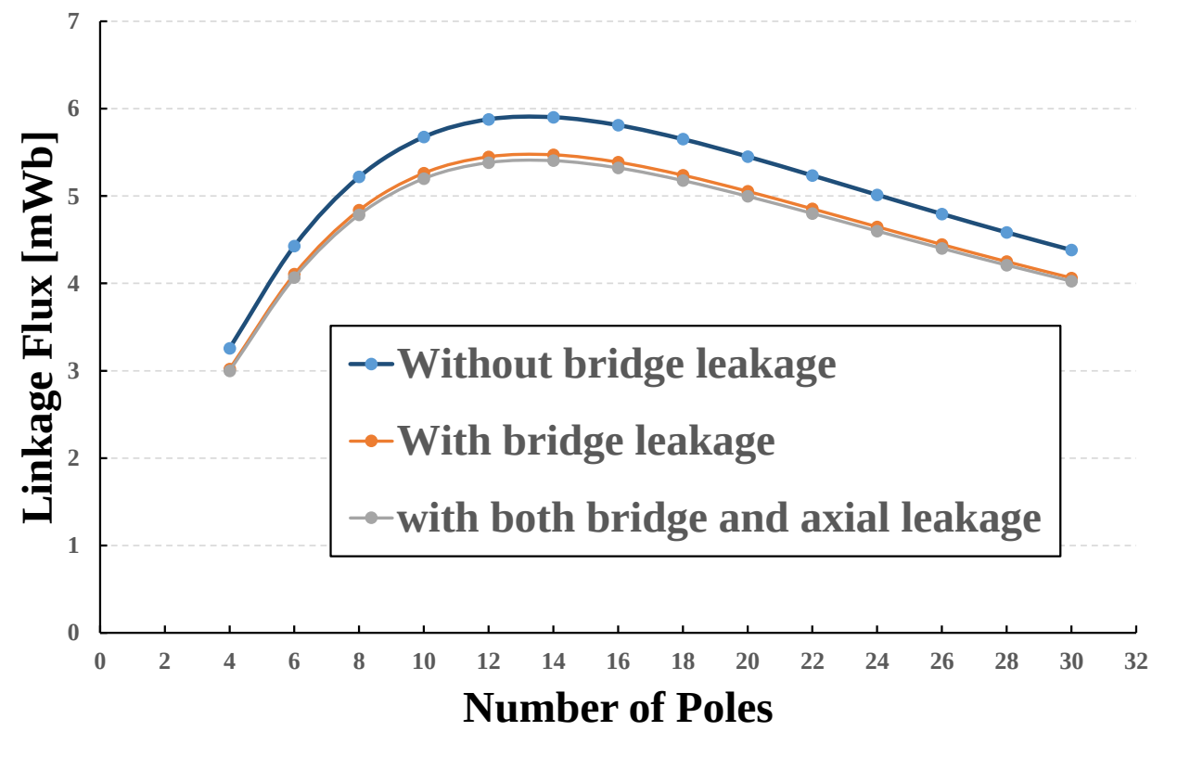
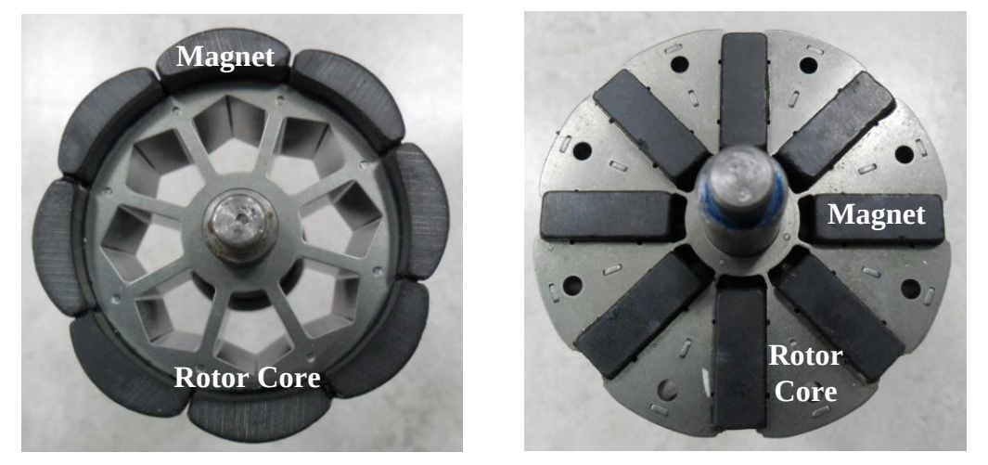


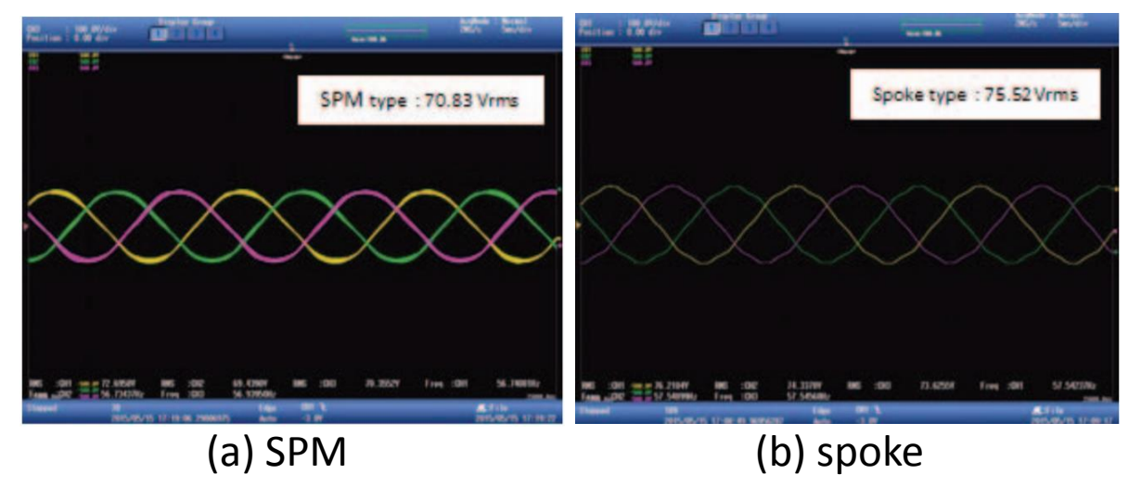
Fig. 9 Total magnetic flux calculation according to the number of poles with considering both the bridge leakage and the axial leakage

Verification through experiments



(a) Manufactured SPM rotor (b) Manufactured spoke rotor

Fig. 10 The rotor of the manufactured motor



(a) SPM (b) spoke

Fig. 11 No-load back electromotive force measurement result of manufactured motors @ 900rpm

Table 3. Comparison of main specifications of manufactured SPM and spoke PM motor

Item	SPM	Spoke	
		Manufactured	Conversion
Number of poles	8	8	8
Number of slot	12	12	12
Diameter of stator [mm]	104	104	104
Diameter of rotor [mm]	67.2	66.8	66.8
Length of air gap [mm]	0.4	0.4	0.4
Core material	50PN1300	50PN1300	50PN1300
Br of PM [T]	0.41	0.41	0.41
Length of PM [mm]	-	18.5	18.5
Thickness of PM [mm]	6	-	-
Total weight of PMs [g]	177	177	177
Stack length [mm]	30	25	**30**
Coil turns per slot	390	330	**390**
No-load back-EMF [Vrms]	70.83	75.52	**107.1**

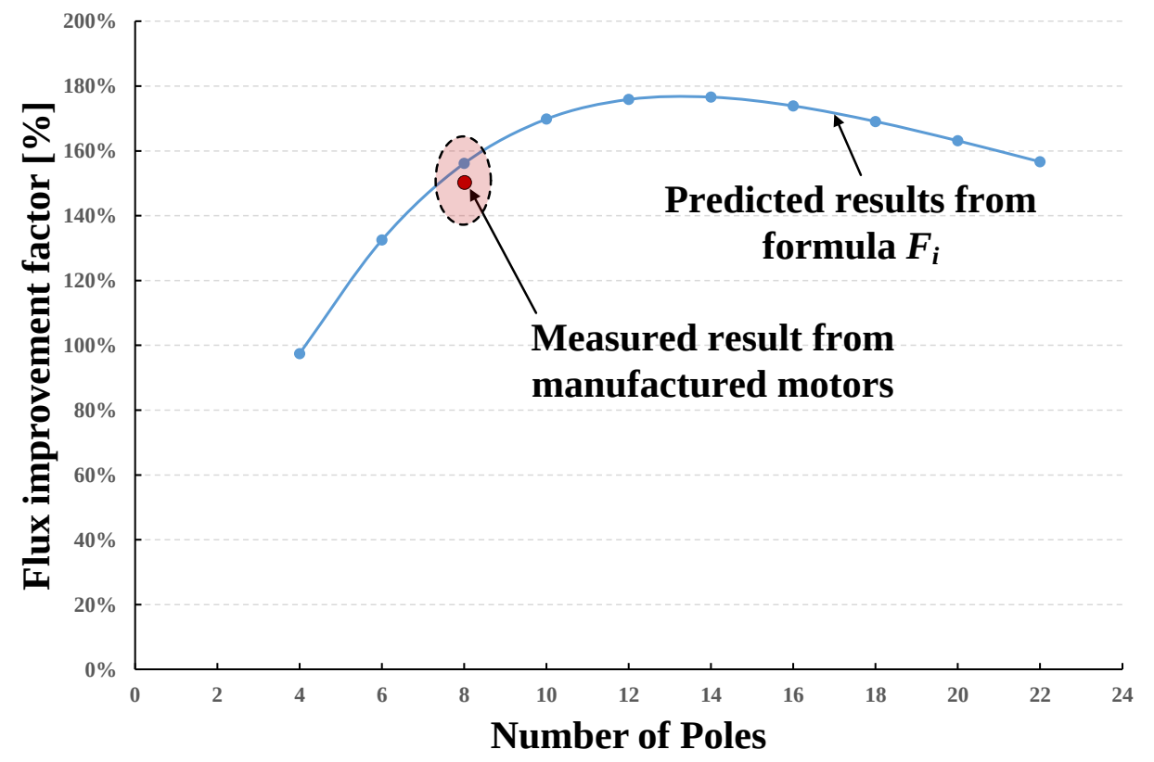
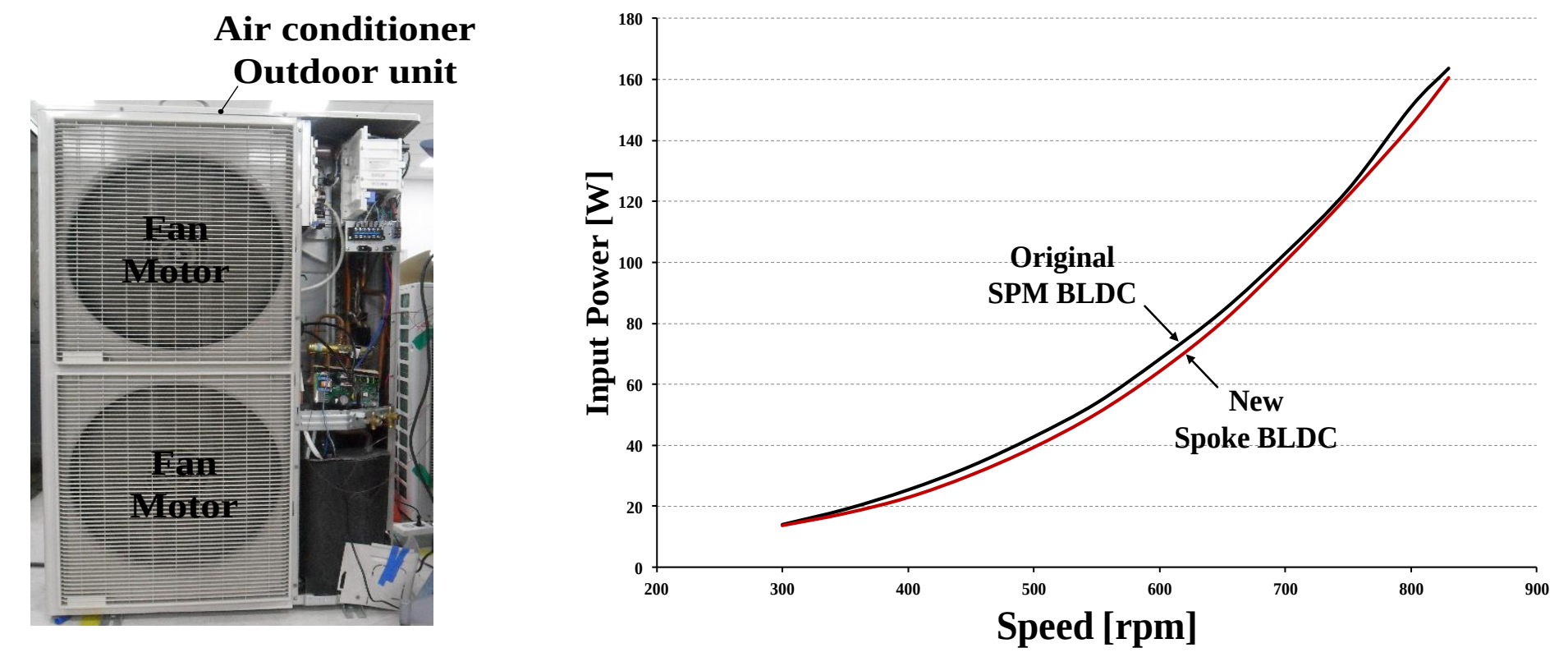


Fig. 12 Comparison of the magnetic flux improvement amount of the spoke to the SPM predicted by the proposed Eq. (22) (from 4 pole to 22 pole) and the measured value of the actually manufactured motors (only 8 pole)



(a) Motor mounting for load test (b) Comparison of input power by load speed

Fig. 13 Load test results of spoke and SPM motor (for Air conditioner outdoor fan motor)

※If the spoke is made of the same stack length and number of turns as SPM, excessive efficiency increase occurs. So the spoke stack length and number of turns should be designed to be less than SPM so that the efficiency is only about 2% p higher than SPM. If the stack length and number of turns of spoke are made to the same level as SPM, the total flux of spoke is 151% of SPM.

Presented at the 25th International Conference on Magnet Technology, Aug. 27 – Sep. 1, 2017, Amsterdam Netherlands; Poster Session: Motors-II; Program I.D. number: Tue-Af-Po2.06-32 [94]