The Influence of Magnet Number and Dimension on Torque Characteristics in the Interior Permanent Magnet Synchronous Motor (PMSM)

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Abstract. Permanent magnet synchronous motors (PMSMs) are commonly used in electric vehicles because they have specific advantages such as high power density, high torque, and high efficiency. This paper presents the design of an interior permanent magnet (IPM) rotor motor with 5kw capacity as an electric motorcycle propulsion machine. Principal design calculations obtain initial design parameters. The choice of using a magnet dimension has a significant impact on performance. Optimization is applied to achieve the required torque characteristics by varying the permanent magnet size with fixed volume and length. The simulation is performed using finite element analysis software to obtain the speed and torque characteristics. The results showed that the motor torque was higher with a wider magnet scale and fewer magnets per pole. Furthermore, using thicker magnets obtained better motor efficiency. Hence, this needs to be taken into consideration when designing the motor according to torque specifications.

1. Introduction
The development of transport technology attempts to minimize the consumption of fossil fuels, one of which is electric vehicles. One of the main components used as propulsion in the electric vehicle is an electric motor. Permanent magnet synchronous motors (PMSMs) are currently widely used in electric vehicles because they have several advantages: high power density, reduced weight and volumetric dimensions, high torque, and high efficiency [1]. Several parameters may have an impact on performance in the design of PMSMs, one of which is the use of permanent magnets. PMSMs characteristics are strongly influenced by the characteristics and size of the permanent magnets. It is important to know the application of the motor [2].

The selection of the dimensions of permanent magnets in the brushless motor will significantly affect motor performances. Several findings on the effect of magnetic size changes have been obtained from previous research. Maximum output torque will be achieved when both the length and width of the magnet are maximized. The increment of torque will not determine the increases in motor efficiency as well [3]. According to magnet size, air gap clearance changes and torque of motor changes. Air gap clearance is proportional to permanent magnet width. If air gap clearance is long, the flux line and torque are reduced even though the permanent magnet usage increases [4]. Modifying the width of the stator teeth, geometry, and the width of the permanent magnets on the rotor is the most efficient way to reduce the cogging torque [5,6]. The effect of the number of pole pairs and the width of the magnet on the mechanical torque of magnetic coupling is obtained. As wider are the permanent magnets, higher is the mechanical torque of the magnetic coupling [7]. Based on the findings of previous research, this paper
presents the PMSM design process by varying the size and the number of magnets per pole in the rotor’s interior permanent magnet.

The purpose of this research is to design a PMSM 5 kW capacity as an electric motorcycle propulsion machine. The design target is torque close to 40 Nm at rated speed. The design considers the availability of permanent magnet sizes in the laboratory. Principal design calculations obtain initial design parameters. The design was simulated using finite element analysis software to achieve performance. The choice of using a magnet dimension has a significant impact on the performances. Optimization was applied to achieve the required torque characteristics by varying the number of permanent magnets per pole and magnet size with fixed volume and length. Therefore, the efficient design of the number and dimensions of magnets is expected to minimize costs.

2. Method

2.1. Process design

Several processes are performed to design a PMSM. The stages of the process design flow diagram can be seen in Figure 1.

![Figure 1. Process design flow diagram](image)

The design begins with the specification of the design. Design considerations are interior permanent magnet type rotor and M250-35A used for stator and rotor laminations material, power output (Pout) 5 kW, 1200 rpm synchronous speed, 100 Hz frequency, 3-phase star supply voltage, and 72 V DC-link voltage on inverter side. The inverter voltage drop is assumed at 5% [8]. The NdFeB N48 permanent magnets should be distributed at the interior permanent magnet rotor. The length of the permanent magnet is 40 mm. The product $\eta \cos \phi$ the rated load is assumed at 0.9.

2.2. Principle of Calculation

There are several calculation procedures, and the following are the motor calculation steps [9-11].

The rated armature current is calculated by following equation (1).

$$I_a = \frac{P_{out}}{3V_1 \eta \cos \phi}$$ (1)
$V_i$ is the inverter’s output voltage. Its value takes into account the voltage-drop.

The number pole pairs,

$$ p = \frac{f}{n_s} \quad (2) $$

Where $f$ is frequency and $n_s$ is rotating speed in rotating per second (rps). The number of poles is eight for rated speed 1200 rpm.

Output coefficient,

$$ \sigma p = \frac{P_{\text{out}} \epsilon}{D_{\text{lin}} L_{s} n_s} = 0.5 \pi^2 k_{w1} A_m B_g \eta \cos \phi \quad (3) $$

Here, $k_{w1}$ is stator winding factor. The value is between 0.8 - 0.99. $A_m$ is stator line current density. $A_m$ ranges from 10000A/m for small motors to 55000A/m for medium power motors. This design has been assumed to be 45000A/m. $\epsilon$ is no load EMF to phase voltage ratio (0.60 – 0.95).

From equation (3), we get ratio stacking length $L_i$ and stator inner diameter $D_{\text{lin}}$. The design is defined using a laminate length of 40 mm. It is due to the availability of magnets in our laboratory. The ratio of the stator’s inner diameter to the length of the stacking is obtained.

Outer stator slot diameter,

$$ D = \frac{D_0 - 0.647}{1.175 + \frac{1.5}{p}} \quad (4) $$

Width teeth body,

$$ w_{tb} = \frac{2 \pi R_{ro} B_g}{N_s K_{st} B_t} \quad (5) $$

Width stator yoke,

$$ w_{sy} = \frac{\pi R_{ro} B_g}{N_m K_{st} B_{sy}} \quad (6) $$

Where $R_{ro}$ is outer rotor diameter, $N_s$ is number slot stator, $K_{st}$ is lamination stacking factor (0.8-0.99), $B_g$ is air gap flux density, for NdFeB N48 = 1.38 T. $B_t$ is stator teeth density and $B_{sy}$ is stator yoke flux density.

Diameter frame,

$$ D_f = D_o + 2 w_{sy} \quad (7) $$

The cross-section area of the armature conductors is

$$ s_a = 2 \pi d_{a}^2 \quad (8) $$

Three parallel conductors AWG 12 with 3.31mm$^2$ have been chosen. The cross-section area of the armature conductor is 9.93mm$^2$.

The current density in the armature winding,

$$ J_a = \frac{I_a}{s_a} \quad (9) $$

The current density is 7.0 A/mm$^2$. This value can be accepted for continuous operation of small PMSM motors.

Pole pitch,

$$ \tau = \frac{\pi D_{\text{lin}}}{2p} \quad (10) $$

Coefficient volume,

$$ c_v = \frac{2 k_{ocf} k_f k_{ad}(1+\epsilon)}{\pi^2 \xi} \quad (11) $$

The overload capacity factor has been assumed $k_{ocf}$= 1.5, the coefficient utilization of the permanent magnet can be estimated as $\xi = 0.5$. $k_f$ is the form factor of the excitation field, $k_{ad}$ is the armature reaction factor in the d axis.
The volume of all PMs used in motor, 

$$V_m = \frac{c_v P_{out}}{f_B H_c}$$

(12)

Br is remanent magnetic flux density, the value for NdFeb is between 0.6 – 0.8.

$$Vm = 2ph_Mw_Ml_M$$

(13)

2p is the number of poles, h_M, w_M, l_M are the height, width and length of the permanent magnet.

2.3. Variation

The parameters obtained from the calculation will be optimized with variation of number magnet per pole, width and thickness. A variation is performed with fixed volume and length. Variation design is shown in Table 1.

| Table 1. Magnet dimension of variation (w_m x t_m) in mm |
|--------------------------------------------------------|
| Design 1                                               |
| 30 x 4                                                 |
| 15 x 4                                                 |
| 10 x 4                                                 |
| Design 2                                               |
| 26 x 4.5                                               |
| 13 x 4.5                                               |
| 9 x 4.5                                                |
| Design 3                                               |
| 24 x 5                                                 |
| 12 x 5                                                 |
| 8 x 5                                                  |

Determination of the magnetic variation based on the volume resulting from the calculation. The total volume of the magnet can be obtained from equation 12. The total volume of magnet used is approximately 4811.15 mm³ per pole. With a fixed magnetic volume and a lamination stacking length, we can determine the magnets’ variations.

3. Results and Discussion

Parameters PMSM have been found after performing calculations. The motor parameters were shown in Table 2.

| Table 2. Parameters of PMSM |
|-----------------------------|
| Item                        | Value          |
| Stator                      |                |
| Outer Diameter              | 182 mm         |
| Inner diameter              | 130 mm         |
| Number slot                 | 24             |
| Height slot                 | 16.95 mm       |
| Width teeth body            | 6.22 mm        |
| Width stator yoke           | 9.12 mm        |
| Rotor                       |                |
| Outer diameter              | 128 mm         |
| Inner diameter              | 35 mm          |
| Number of pole              | 8              |
| Winding                     |                |
| Number of turn              | 4              |
| AWG size                    | 12             |
| Strand                      | 3              |

The magnetic flux distribution of the PMSM was designed to be shown in figure 2.
Figure 2. Magnetic flux distribution

The maximum saturation value of the lamination material used is above 1.8 T. The distribution area of the magnetic field that exceeds more than 1.8 T moves from yellow to orange. Between the corner magnet rotor and the stator slot shoe, an orange colour appears, but it's not dominant. Magnetic flux leakage causes this. By using more magnets per pole, the more likely the magnetic flux leakage will be to occur. It can be avoided by creating a flux barrier.

The PMSMs can work in the overspeed range. This means that the real speed of the motor can exceed the nominal rated speed. The torque is inversely proportional to the rpm so that the output power remains constant for the range where the nominal rpm is exceeded [12]. The ideal characteristic torque curves are shown in Figure 3.

Figure 3. The ideal characteristic torque curves of PMSM

Curves of the relation between a characteristic torque and motor speed in rotations per minute are shown in Figure 4. All of which are the result of changes in the dimensions and number of magnets.
Based on the simulation results shown in figure 4, the highest torque was obtained by using a magnet dimension of 30x4 mm, with the number of magnets per pole being a magnet. The output torque is 38.52 Nm when the speed is 1200 rpm, but the efficiency is lower when the speed is higher. At a speed of 1680 rpm (140%), the torque becomes zero. The lowest torque was obtained using a magnet dimension of 8×5 mm with the number of magnets per pole being three magnets. The output torque is 25.1 Nm when the speed is 1200 rpm, but the efficiency is higher when the speed is higher. At a speed of 2520 rpm (210%), the torque becomes zero.

In reference [3], the output cogging torque is increased due to expansion on both parameters for height of the magnet and width of the magnet. The cogging torque of the design variation is shown in Figure 5.

The cogging torque increases when the thickness and width of the magnets increase and the designs have the same number of magnets per pole. In design 1, the cogging torque is larger than design 2 because the width of the magnet is larger. The cogging torque in design 3 is higher than design 2 because the size of the magnet is thicker. When comparing the torque results between the number of magnets per pole, the results show that design 2, which uses two magnets per pole, has a smallest cogging torque (0.68Nm). Design 3, which uses three magnets per pole, has the largest cogging torque (2.73 Nm).
4. Conclusion
This paper provides the concept design of PMSM, Interior Permanent magnet (IPM) type rotor, with 5 kW capacity as an electric motorcycle propulsion machine. The specifications and considerations of the design are predefined. The results of the calculations and simulations were obtained in accordance with the specification requirements. The effect of the number and size of magnets per pole on motor torque and speed was discussed and analyzed. Using fewer magnets per pole and a wider scale would provide higher torque. Furthermore, using thicker magnets increases efficiency. The torque becomes zero at higher speeds. The cogging torque increases with an increase in the thickness or width of the permanent magnet.

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