Fundamental Modeling for Optimal Design of Transverse Flux Motors

Genevieve Patterson*, Takafumi Koseki (University of Tokyo)

1. Introduction

Direct drive motors and generators have recently become popular in applications such as ship propulsion and wind turbines. This drive configuration has gained popularity due to the possibilities for high torque, low speeds, and high power density. Because these applications require motors with high input frequency, short pole pitch, and strong excitation, motor designers are increasingly making transverse flux type permanent magnet motors (TFM).

While this kind of motor is capable of high output and power density at low speeds, the literature shows that these motors have complicated electromechanical configurations, thick permanent magnets, and resultant low magnet permeability. At high frequencies these disadvantages contribute to a significantly low power factor. Ultimately the low power factor characteristic of transverse flux machines becomes an obstacle against this type of machine attaining a high real power to volume ratio. For example Rolls-Royce Ltd. manufactured a TFM for marine propulsion that was capable of large thrust but had power factor ratings of less than 0.7 [1].

The aim of this paper is to illustrate a theoretical model for calculating the power factor and thrust values of TFMs. Using this mathematical model, a designer's recourse for improving power factor will be explored. This model will show that despite decreasing the magnetic reluctance of the motor's flux path, decreasing the permanent magnet thickness by itself will only reduce power factor. The authors propose that by maintaining a constant magnet volume and excitation strength, the power factor can be maintained at a constant value while the thrust is increased by increasing the input frequency, which has no effect on power factor. The authors also suggest that motor designers can create high output thrust by using high volume field magnets. By manipulating the magnet depth to thickness ratio designers may be able to decrease adverse affects like leakage flux, which are detrimental to high power factor, while still producing a large thrust.

2. Magnetic Circuit Analysis

The model consists of one pole of a machine. The sections 2.1-2.3 will outline the model and show how thrust and power factor calculations are made using this model.

< 2.1 >> One-Pole Magnetic Circuit Model

The basic unit of a transverse flux machine is a C-shaped core with an air gap through which the rotor/mover permanent magnets can pass. The armature winding is wound around the yoke of the C-core. There are examples of TFMs with slightly different stator configurations, but the flux path is essentially the same.

Fig. 1 illustrates the unit C-core. The input to the model is the armature current I_a. B_a is the armature flux, and B_f is the flux contributed by the field magnets.

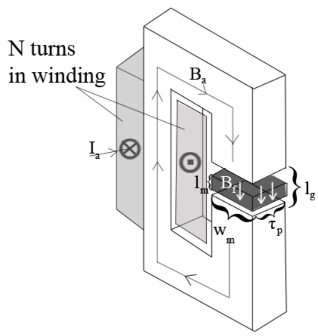

Fig. 1. One-Pole Model Diagram

As I_a changes, the polarity of B_a also fluctuates, which pulls the alternating polarity magnets through the air gap, creating thrust. The movement of the magnets through the armature flux field also induces an internal EMF.

< 2.2 > Single Phase Quasi-Stationary Equivalent Circuit Model

Fig. 2 shows the equivalent circuit for a 3-phase machine composed of n connected C-cores. L_s and R_s are the synchronous armature inductance and resistance, respectively, but for the sake of simplicity R_s is ignored in the following calculations. V_0 is the induced EMF, and V_a the armature voltage.

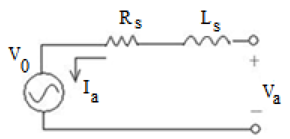

Fig. 2. Per Phase Equivalent Circuit Model

Assuming that the motor has a n number of poles per phase and a three-phase star connection, Eqns. 1-5 show how the synchronous armature voltage drop V_s and the induced voltage are calculated. The per phase armature self-inductance L_a and 3-phase synchronous inductance L_s, are inversely proportional to the air gap length l_g as shown in Eqns. 2-4.

$$V_s = L_s \omega_e I_a \quad (1)$$

$$L_s = \frac{3}{2} L_a \quad (2)$$

$$L_a = N^2/R \quad (3)$$

$$R = \frac{l_g}{\mu_0 S} \quad (4)$$

$$V_0 = 3/2\, \beta S N B_f \omega_e \quad (5)$$

In Eqns. 4-5 S is the surface area of the PM and ω_e the synchronous angular speed. β is a form factor for matching the realistically jagged V_0 signal to a fundamental frequency. Eqn. 6 determines the PM flux density, which depends inversely on the air gap reluctance R. Eqn. 7 determines that the armature flux density, and B_a has the same inverse proportionality to R.

$$B_f = \frac{H_c l_m}{RS} \quad (6)$$

$$B_a = \frac{I_a N}{RS} \quad (7)$$

$$F = 3/2\, \beta B_a H_c l_m w_m \quad (8)$$

Eqns. 8 shows the thrust force produced by the whole three-phase machine. If the mechanical clearance, the space in the air gap not occupied by the magnet, is a value significantly smaller than l_m, then l_m and l_g are approximately the same. Thus, increasing l_m while keeping all other factors constant will not significantly increase thrust. The whole volume of the magnet is effectively controlled by $l_m w_m$ because the pole pitch must remain a constant value for a given input frequency. Magnet volume or its excitation strength, indicated by H_c, must increase in order to raise F. Eqns. 6 and 7 indicate that if a larger mechanical clearance is necessary then the designer must accept lower flux density.

< 2.3 > Phasor Diagram and Power Factor Calculation

In order to determine the power factor for the basic unit model, Fig. 3 shows the phasor diagram for the 3-phase configuration's synthesized voltage vectors. In Fig. 3 the angles φ_{Ra} and φ are the power factor angles considering armature resistance and disregarding it, respectively. The value of φ_{Ra} would always be smaller than φ regardless of the value of the armature resistance, thus real-world PF values may be slightly better than those estimated by the model in this paper. Future research will likely include consideration of R_a.

Eqns. 9 and 10 show how the power factor and power factor angle are calculated. It is important to note that φ is not dependent on the input frequency, as shown in Eqn. 10. This indicates that ω_e can be increased, which increases the output thrust, but the power factor will remain the same. The absolute values of the internal voltages will however increase.

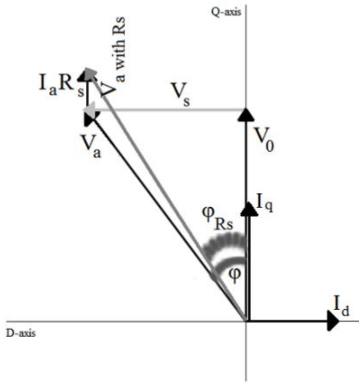

Fig. 3. Phasor Diagram for Symmetrical 3-phase Machine

$$p.f. = \cos\varphi \quad (9)$$

$$\tan\varphi = \frac{V_s}{V_0} = \frac{3\,\mu_0 N I_a}{2\,\beta H_c l_m} = \frac{l_g F}{\beta H_c^2 l_m^2 w_m} \quad (10)$$

$$I_a = \frac{2\, l_g F}{3\, N \mu_0 H_c l_m w_m} \quad (11)$$

Assuming $l_g \cong l_m$

$$\text{Then, } \tan\varphi = \frac{F}{\beta H_c^2 l_m w_m} \quad (12)$$

Using the expression for I_a in Eqn. 11, the formula in Eqn. 12 illustrates the relationship between the power factor angle and thrust. If the volume and strength of the magnet are constant, when thrust F raises the power factor lessens. The model verifies that there is an unavoidable tradeoff between power factor and thrust when the permanent magnet excitation is constant.

3. Conclusion

In this article, the authors have introduced a new mathematical model for estimating the internal voltages and output parameters of transverse flux machines. This model will help to optimize future designs, as the tradeoffs between thrust and power factor can be easily calculated and graphed. Volumetric distribution of the field magnets can also be optimized using this model. Ultimately, this model verified that there is no way to avoid sacrificing power factor for thrust except for using larger and/or more powerful permanent magnets.

Future work on this topic would include considering the effect of parasitic impedances on the magnetic circuit, creating a fundamental design for a new machine based on the simulation results from this model, and testing the prototype of such a motor.

References

(1) Husband, S.M., Hodge, C.G., "The Rolls-Royce Transverse Flux Motor Development," *Electric Machines and Drives Conference*, Vol. 3, pp. 1435-1440, IEEE, 2003.

Acknowledgements

The authors would like to thank Mr. Yasuaki Aoyama and his associates at the Hitachi Research Laboratory for their technical advice in support of this research.