Evaluation of the Transverse Flux Circumferential Current Machine by the Use of Sizing Equations

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Abstract — **With the evolution of numerous high power density machines, it becomes important to compare the power potential of machines with vastly different topologies having a variety of different waveforms of back emf and current. The approach of this paper is based on general purpose sizing and power density equations which will permit comparison of the main dimensions and power of such machines previously reported. In this paper, the comparison method of machine power densities is extended to include the transverse flux circumferential current type permanent magnet (TFCCPM) machine, and furthermore to compare the power production capability between the TFCCPM machine and the well-known squirrel cage induction machine.**

I. INTRODUCTION

Traditional design of AC electrical machines is based on the premise that the machine has a longitudinal radially directed air-gap flux and a single stator and rotor supplied by a sinusoidal source which assumes a sinusoidal emf at the air-gap of the machine. It was recognized in [1] and [2], however that the emergence of power electronics has removed the need for such a concept as the basis for machine design. Beginning with the switched reluctance machine, a new phase of electrical machine technology has been evolving based on the principle that the best machine design is the one that simply produces the optimum match between the machine and the power electronic converter; the converter fed machine (CFM) [1].

The logical structure of a CFM system is idealized in Fig. 1. In order to study or compare among such systems, three types of analysis tools need be implemented; (1) a sizing analysis and optimization method for such electrical machines; (2) a convenient interface definition between the two objects of Fig. 1; (3) sizing and cost analysis of the associated converter. Although a practical optimized synthesis of a CFM can be designed only after the three tools above are available, the sizing analysis, optimization and comparison of electrical machines, as well as the definition of interface are the first main effort of such an approach and is the topic of this paper. As long as the models of electrical machines and the interface are clearly defined and studied, a design of a CFM can be easily predicted based on the balanced selection between the converter rating (cost) and machine performance.

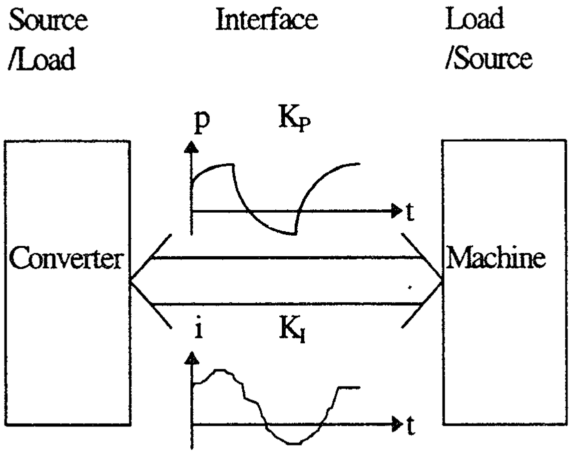

Fig. 1 A CFM system

In general, comparison of different machine types is a very formidable task. In 1996, S. Huang et. al. [4] developed general purpose sizing and power density equations and established a systematic method to compare the capabilities of machines with different topologies. The procedure includes (1) a concept for comparing the power density on the basis of total occupied volume instead of air-gap volume; (2) special factors were introduced to account for the effects of current and back emf waveforms, which also served as a convenient interface definition between the converter and electrical machine; (3) comparison methods were focused on radial flux and axial flux type machines respectively in [4] and [5]. As developments have occurred in the field of transverse flux PM machines issues have been raised concerning the power density of such machines when compared with more conventional topologies [3]. As a further contribution to this study, a detailed approach will be presented in this paper for the application of the general purpose sizing and power density equations to the TFCCPM machine, followed by a comparison of the TFCCPM machine with traditional induction machines.

II. SIZING EQUATIONS AND POWER DENSITIES

Derived from the general purpose sizing equations [4], the sizing equations for transverse flux machine takes either form,

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$$P_R = \frac{m}{2}\frac{1}{1+K_\phi} K_e K_i K_p K_L \eta B_g A \frac{f}{p} \lambda_o^2 D_o^2 L_e \qquad (1)$$

or

$$P_R = \frac{m}{2}\frac{1}{1+K_\phi} K_e K_i K_p K_L^2 \eta B_g A \frac{f}{p} D_g^3 \qquad (2)$$

where

P_R	rated output power of the machine.
K_ϕ	ratio of electrical loading on rotor and stator. (In a machine without a rotor winding, K_ϕ=0.)
m	number of phases of the machine.
K_e	emf factor which incorporates the winding distribution factor K_w and the per unit portion of the total air gap area spanned by the salient poles of the machine (if any).
K_i	current waveform factor.
K_p	electrical power waveform factor.
η	machine efficiency.
B_g	flux density in the air gap.
A	total electrical loading includes both the stator electrical loading A_s and rotor electrical loading A_r.
f	converter frequency.
p	machine pole pairs.
D_o	diameter of the outer surface of the machine.
D_g	equivalent diameter of the air-gap surface of the machine.
L_e	effective stack length of the machine.
K_L	aspect ratio coefficient of the effective stack length vs. the diameter of the air-gap surface in radial air gap flux machines.
λ_o	ratio of the diameter of the air-gap surface vs. the diameter of the outer surface of the machine.

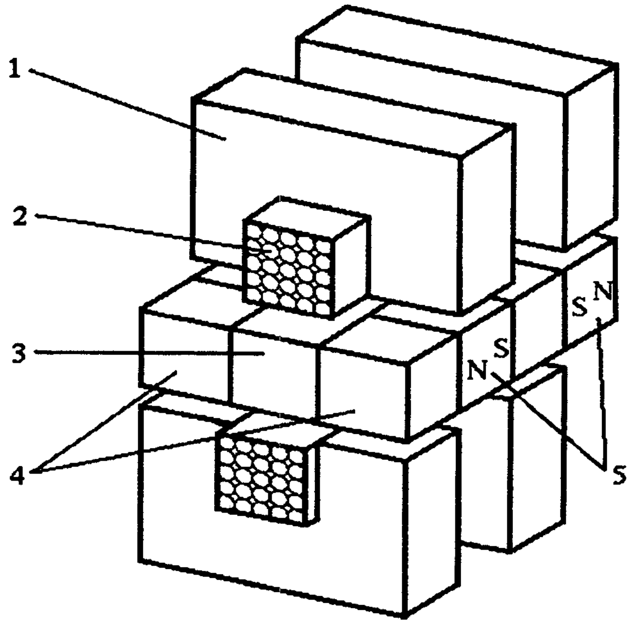
The machine power density for the total volume can be defined as

$$\xi = \frac{P_R}{\frac{\pi}{4} D_o^2 L_e} \qquad (3)$$

For the TFCCPM topology (Fig. 2), it can be determined that $K_e = p\pi(1-K_s)/2$, the number of phases of the machine m=2. Because there is no rotor winding K_ϕ= 0. Considering the trapezoidal waveforms in Ref. [4] Table I (row 4), it can be determined that $K_i K_p$ = 0.881. From Eq. (1), the following TFCCPM machine sizing equation is then obtained

$$P_{R(TFCCPM)} = 0.441\,\pi(1-K_s)\, K_L\, \eta\, B_g A f \lambda_o D_o^2 L_e \qquad (4)$$

and the power density of the TFCCPM machine is



1. Stator core 2. Ring winding 3. Fiber ring
4. Rotor soft iron 5. Permanent magnet

Fig. 2 Transverse Flux Circumferential Current PM (TFCCPM) Machine

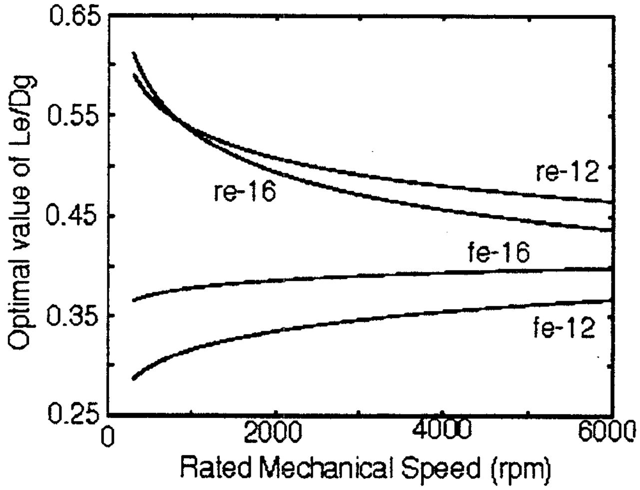


Fig. 3 Optimal value of K_L of the TFCCPM machine vs. rated mechanical speed n_s with different pole pairs p for maximum power density. A=60 kA/m, J_s=6.2x10^6 A/m^2, P_R=75kw, p=6 (fe-12) and p=8 (fe-16) using ferrite PM, p=6 (re-12) and p=8 (re-16) using rare earth PM.

$$\xi_{(TFCCPM)} = 1.762\,(1-K_s)\, K_L\, \eta\, B_g A f \lambda_o \qquad (5)$$

In Eqs. (4) and (5), the only independent terms existing are K_L and K_s while the other terms either depend on K_L, or K_s, or have certain physical limitations. The optimal values of the ratio K_L and K_s were given considering power density and efficiency. A deeper investigation indicates that the optimal value of K_s is about 1/6 for a practical design, while the optimal value of K_L has a close connection with the rated mechanical speed n_s. Under a given electrical loading A, current density J_s, and the rated output power P_R, a group of curves can be generated which indicate the relationships between the optimal value of K_L and the rated mechanical speed n_s for different pole pairs p (Fig. 3). From this data, through power regression, it is possible to obtain the following equation

$$K_L=\frac{L_e}{D_g}=\begin{cases}0.1770n_s^{0.0838} & p=6 \\ 0.3087n_s^{0.0295} & p=8\end{cases}\ \text{Ferrite Magnets} \quad \begin{cases}0.9276n_s^{-0.0792} & p=6 \\ 1.1545n_s^{-0.1116} & p=8\end{cases}\ \text{Rare-earth Magnets} \tag{6}$$

III. COMPARISON BETWEEN INDUCTION AND TFCCPM MACHINES

It is now possible to compare the power densities of TFCCPM machines through the use of the sizing and power density equations that have been derived. Because the squirrel cage induction machine is regarded as the "workhorse" of the ac machine community, it can be considered as a "point of reference" for the other machines. Fig. 4 shows the comparison of power densities among the 4-pole induction machines (IM-4) (Ref.[4]), the 16-pole TFCCPM machines with ferrite magnet (fe-16) and the 16-pole TFCCPM machines with rare earth magnet (re-16). Note that a power density improvement of nearly a factor of three can be achieved for low speed machines. Although machines with rare earth magnets can achieve higher power density, further study has verified that the application of ferrite magnets to this structure is much more economical as expected. Thus, the proper material should, as expected, be chosen according to the purpose intended.

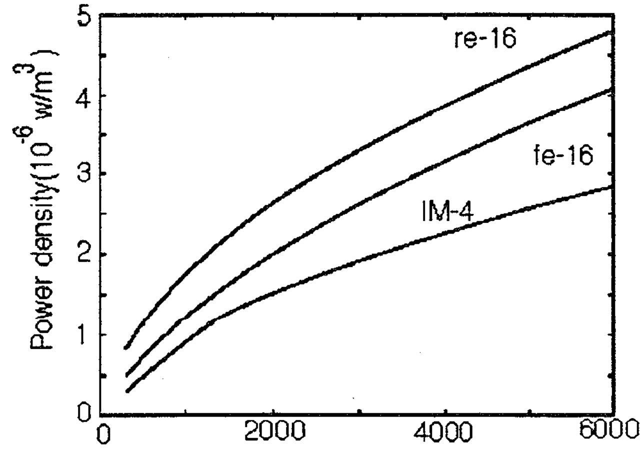


Fig. 4 Power densities of four pole induction machine and TFCCPM machines (A = 60kA/m, J_s = 6.2 x 10^6 A/m^2 ,P_R = 75 kw).

IV. CONCLUSION

In this paper, the following results have been obtained:

1. A detailed approach is outlined to realize specific sizing and power density equations for the transverse flux machine, by means of the application of the general purpose sizing and power density equations previously developed [5]. By defining suitable ratios and considering the duality between transverse and radial flux machines, the sizing equations for the transverse flux machine take a similar form to the general purpose sizing equations of radial flux machines. These equations permit a direct comparison of the capability of two basically different machine topologies based upon overall occupied volume.

2. It is shown that optimization of the factor K_L will achieve the maximum power density and also nearly the highest efficiency. In comparison with traditional optimization methods, optimization based on the sizing equation using the outer diameter has more benefit, especially for the transverse flux machines.

3. The optimal value of K_L depends upon electrical loading, flux density, frequency, permanent magnet materials, and machine topology etc.. However, further study shows it is more dependent on machine permanent magnet materials more than other factors. Hence, for a given machine and choice of PM, the optimal value of K_L varies over a relatively small range. For example, in fe-16 machine, the optimal K_L is between 0.365 to 0.40. On the other hand, different permanent magnet materials will result largely different range of the optimal K_L For example, in re-16 machine, the range is 0.435 to 0.61.

4. It is shown in the paper that the Weh transverse flux machines have higher power density than the traditional induction machine over a wide range of rated speeds. In particular, when the rare earth magnet is applied the improvement can reach a factor of two to three. Even when the ferrite magnet is used for low cost, the power density still increases by roughly a factor of two at low speed.

REFERENCES

[1] T. A. Lipo and Yue Li, "CFMs - A New Family of Electrical Machines", JESC'95, Japan, 1995, pp. 1-6.

[2] T. A. Lipo and F. X. Wang, "Design and Performance of Converter Optimized AC Machines", IEEE Trans. on Industry Applications, vol. IA-rr20, No. 4 July/August 1984, pp. 834-844.

[3] H. Weh, "On the Development of Inverter Fed Reluctance Machines for High Power Densities and High Outputs", etz Archiv, Bd. 6, 1984, pp. 135-144 (In German).

[4] S. Huang, J. Luo, F. Leonardi, and T. A. Lipo, "A General Approach to Sizing and Power Density Equations for Comparison of Electrical Machines", IEEE -IAS Annual Meeting, Oct. 1996.

[5] S. Huang, J. Luo, F. Leonardi, and T. A. Lipo, "A Comparison of Power Density for Axial Flux Machines Based on General Purpose Sizing Equations", IEEE Power Engineering Society, 1997 Winter General Meeting. (pending)

[6] E. Levi, "Polyphase Motors -- A Direct Approach to Their Design", John Wiley and Sons, Inc., New York, 1984.