Research Report

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Advanced Motor Technologies: Converter Fed Machines (CFMs)

T.A. Lipo

Wisconsin Power Electronics Research Center
University of Wisconsin-Madison
Madison WI 53706-1691

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

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T.A. Lipo
University of Wisconsin
1415 Johnson Drive
Madison WI 53706, U.S.A.

1. Introduction

Until recently, all electrical machines have been designed on the basis of having available a utility supply. That is, it has been assumed that the machine is excited with a sinusoidal voltage supply. This assumption inevitably leads to design of conventional induction, wound field synchronous and permanent magnet machines in which the stator windings are distributed sinusoidally around the air gap so as to couple optimally with the sinusoidally supply. However, the emergence of power electronic converters has removed the need for such a concept as the basis for machine design. Beginning with the switched reluctance machine a new era 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). This paper documents the new perspective in machine design that is taking place and points to recent developments.

2. Evolution of Converter Fed Machines

For the first several decades of the power electronic era beginning effectively in 1960, machines continued to be designed from a classical perspective which assumes a sinusoidal source voltage even though the inverter waveform can only be considered as a very rough approximation of a sinusoid. As power electronic control of induction motors evolved in the 1970's it gradually became apparent of the need for the implementation of a current regulated type of power electronic converter. That is, while the converter itself represents a voltage source, feedback of the instantaneous motor phase currents in its tight regulation in a current feedback loop converts the converter into a controllable current source. The term current regulated pulse width modulation (CRPWM) has been used to describe this type of current source. The use of CRPWM has subsequently become an essential part of nearly all high performance vector controlled drives on the market today.

The evolution of the regulated current source principle, in turn, has led to the development of the so-called "switched" reluctance machine in the 1980's [1]. A simple 6 pole stator/4 poles rotor version of such a machine is shown in Fig. 1. The switched reluctance machine is, in reality, identical to the variable

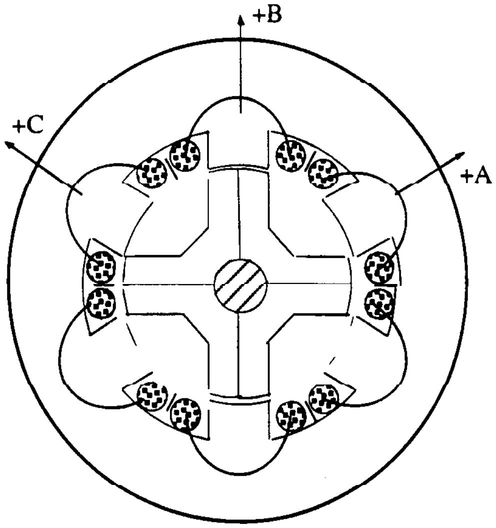


Fig. 1 Variable ("Switched") Reluctance Machine.

reluctance motor or stepper motor which was traditionally used for incremental motion type applications. It was recognized in [1] that when the current is carefully controlled by means of a switching power converter, this type of machine is capable of competing with more conventional squirrel cage induction machines. This paper recognized, for the first time, that with proper control of the motor phase current by means of the switching power converter, classical performance criteria such as torque/rms ampere, torque/volume, and torque/weight could be matched by an unconventional non-sinusoidally wound machine. This new concept was not without its own set of new problems as would be expected from new development, namely audible noise and torque pulsation issues. However, these problems have been generally overcome and the machine is finding application in small consumer applications where the induction machine competes unfavorably due its relatively large magnetizing current. Other applications are in very rugged environments where rotor heating limits the power density of an induction machine such as mine drilling and high speed generators embedded in gas turbines.

The emergence of the variable reluctance motor prompted some researchers to rethink many of the issues seemingly resolved, that is such as whether three phase is still the optimum number of phases, whether sinusoidal voltage is the best motor waveform and even whether radial air gap machines are most appropriate for converter fed machines. This, in turn, has led to a quest for new electrical machines which reject the premise of sinusoidal air gap flux density, (sinusoidal emf) but, rather, incorporate winding distributions, saliencies, and/or permanent magnets in manner more amenable for use with a switching power converter source (or sink). This effort over the last decade has led, furthermore, to remarkable progress in the design of special machines designed to be operated only power converters: *converter-fed machines* (CFMs) [2].

Efforts to optimally interface an electrical machine with a switching power converter is actively being explored by Weh and his associates [3]. In particular, a multiphase, full pitch winding synchronous reluctance motor was proposed in which several of the armature windings are excited to produce the excitation flux while the remainder of the armature windings are used to produce torque (and armature reaction flux). This type of machine as been termed as a field regulated reluctance machine (FRRM) by Law et. al. [4] since the exciting field and torque producing field can be regulated independently.

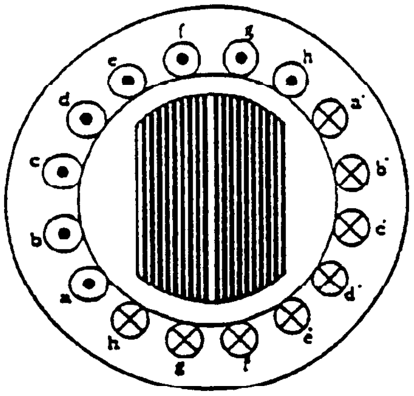


Fig. 2 Field regulated reluctance machine

Fig. 2 shows a sketch of a six phase two pole version of the FRRM. Note that at any instant three stator windings (located in the interpolar space) form the equivalent of a field winding which magnetizes the direct axis rotor member as well as the stator iron. The remaining three windings (located under the rotor pole) form the equivalent of a torque producing armature winding which produces flux in the quadrature axis interpolar space located at right angles to the direct axis. The emf of one phase and the resulting current that must be applied to the winding to optimally couple the converter with the machine is shown in Fig. 3. Since a given phase winding is continuously active producing either torque or field flux, more effective use of the stator copper is possible. Also, field weakening can be achieved with lower losses.

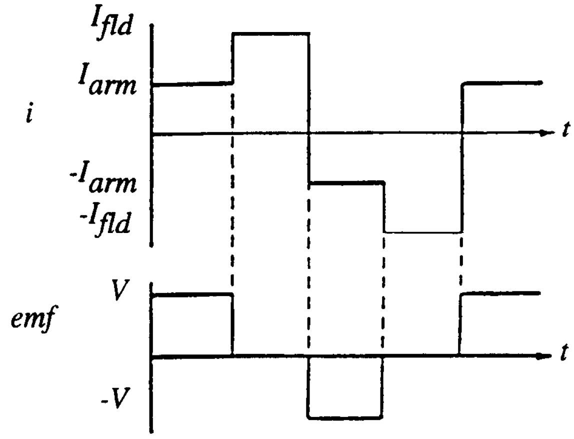
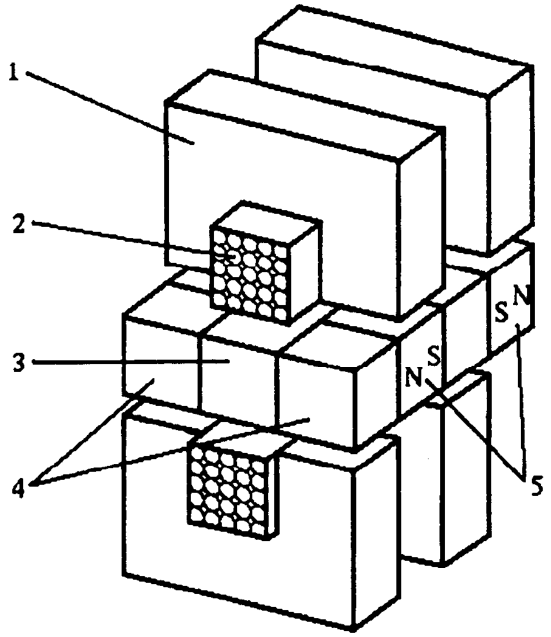


Fig. 3 Armature current and emf of one stator phase of field regulated reluctance machine

The field of permanent magnet machines is also being actively explored from the perspective of having a "converter fed" supply rather than being "utility fed". Of particular interest is the so-called transverse flux machines in which the magnetic field plane is perpendicular to the direction of motion rather than in the plane of motion as in a conventional machine [5].



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

Fig. 4 Transverse flux permanent magnet machine

Fig. 4 shows a simplified version of the concept. Note that the flux produced by the magnet is forced to close its path first in the upper iron poles and then alternately in the lower pole pieces producing large radial forces. Drives having 10 Nm/kg capability has been reported. However, this machine is penalized by having a large amount of inactive material (air space) so that while the machine is not necessarily heavy it is bulky.

Another interesting permanent magnet machine which inherently develops trapezoidal rather than sinusoidal emf is the so-called "Torus" machine shown in Fig. 6 [6]-[8]. In this machine the air gap flux is axially directed. The stator is a “square” donut (Torus) shape and is wound in much the same manner as a toroid but with a three phase winding. The stator is “sandwiched” between two rotor discs upon which are embedded magnets. The flux path of the magnet is, for a four pole machine for example, across the air gap, down the stator toroid for 90 degrees, back across the air gap and then closing in the rotor over a 90 degree arc. The fact that the windings are typically placed in the air gap of this machine result in a very low leakage inductance making the machine ideal for a current source type of power supply. The placement of the stator windings is uniform over a 60 degree pole arc making the emf induced in the winding a trapezoid as shown in Fig. 6. The corresponding optimum waveform for this machine is again a trapezoid [7],[8]. The Torus machine has been proposed for use as an automotive generator, propulsion motor, and electric vehicle wheel motor.

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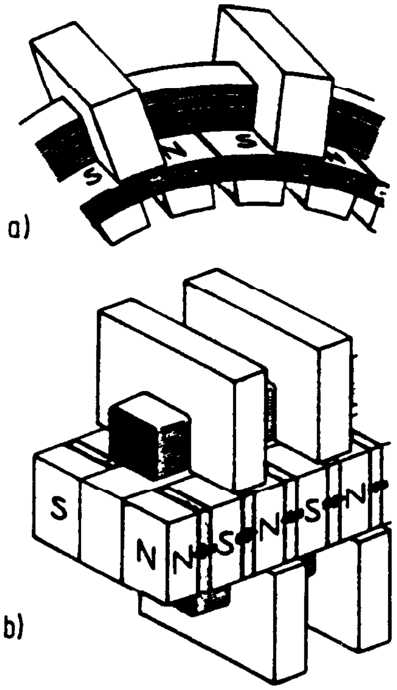

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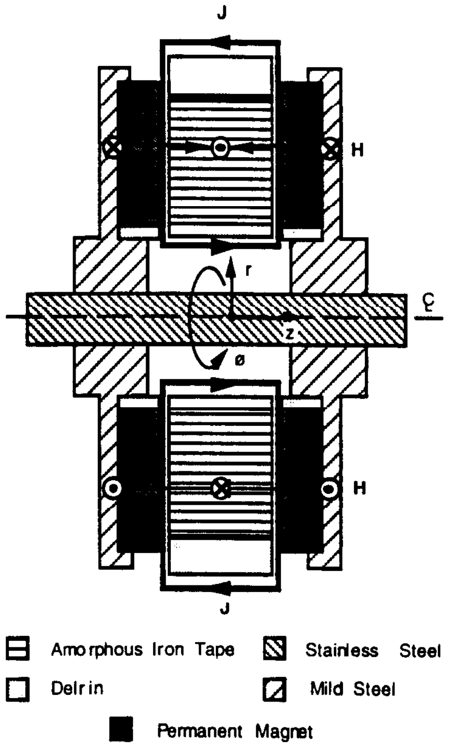

Fig. 5 Axial flux toroidal PM machine (AFT PM or "Torus" machine)

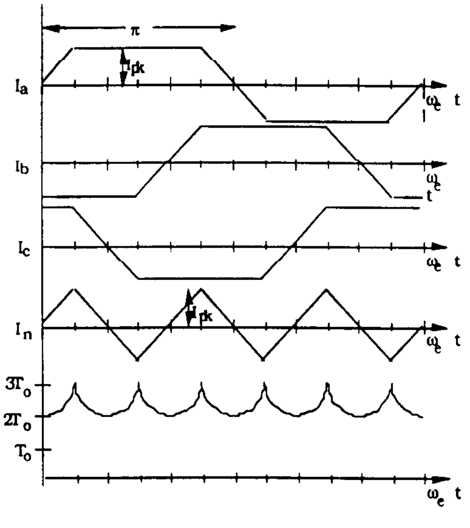

Fig. 6 Optimum current waveforms for AFT PM machine.

In the search for new topologies, combinations of reluctance permanent magnet machines have been proposed [9],[10]. One of these machines, the doubly salient PM machine, is shown in Fig. 7. In this case the flux linking one phase by the magnet takes on a quasi-triangular shape leading to an induced emf of the form shown in Fig. 8 requiring that the current supplied to the motor be a similar waveform. Since the magnets of this machine are based on the stator, this machine qualifies as a type of homopolar type machine. It is evident that since the rotor is simple and robust, very high rotational speeds can be reached with this machine. High energy magnets are however, required since the two halves of the stator are at different magnetic potentials, resulting in leakage flux outside the outer circumference of the machine. Finally, similar machines with the permanent magnet based on the rotor have been investigated. These machines have similar desirable characteristics as the stator based *PM* machine but with a less robust rotor assembly [11].

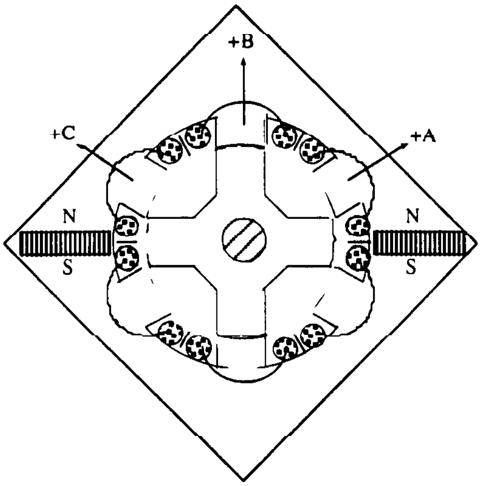

Fig. 8 Doubly salient PM (DSPM) machine

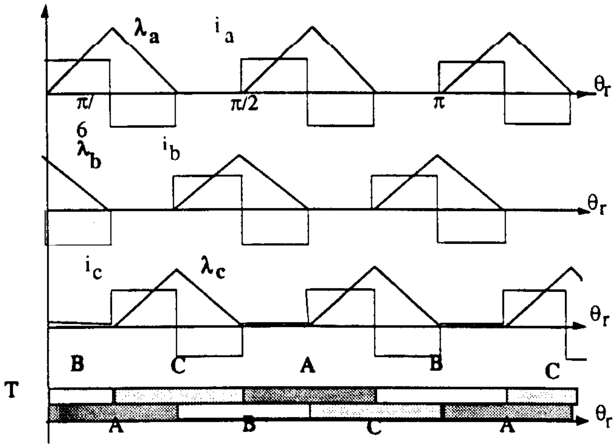

Fig. 9 Optimum current waveforms for DSPM machine

The issue of field weakening of permanent magnet machines is a perplexing issue that is inhibiting the widespread application of machines in motor drives. In most machines field weakening is a very difficult task since the magnets rotates so that they cannot be easily accessed. However, the doubly salient PM topology of Fig. 10 is amenable to field weakening since the magnets on this machine are stator based. Hence, the magnets can be easily "shorted" by means of a sleeve having magnetic and non-magnetic portions which fits over the stator outer periphery as shown in Fig. 10.

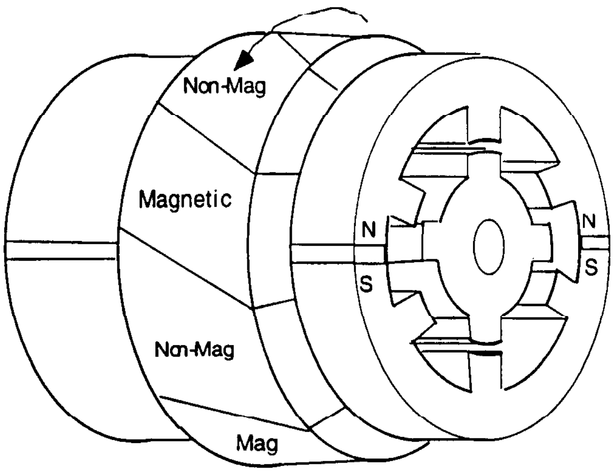

Fig. 10 Mechanical field weakening scheme for DSPM machine

The magnetic field in the air gap can be adjusted by simply moving the magnetic portion of the sleeve over the magnets. A field weakening capability of 5 to 1 has been experimentally recorded [12].

Field weakening of the permanent magnets in such a machine can also be attacked by rearranging the magnets to the position shown in [13]. In this case, the magnet has been designed o be intentionally thin with a wide cross sectional area. In this case, the ampere turns of a separate field winding, also located on the stator, is readily able to aid or oppose the magnet flux thereby accomplishing field weakening in a field weakening capability by passive electrical means. The wide cross section allows a flux focusing ability of 3 to 1 or more, again permitting the use of ferrite magnets as was the case for the machine of Fig. 5. Again a generating, rather than a motoring capability can be engineered.

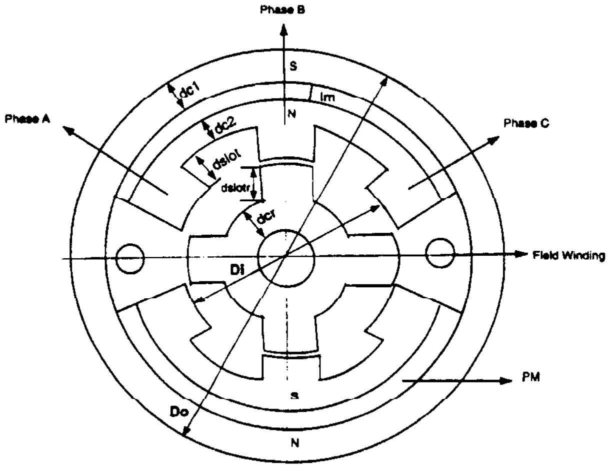

Fig. 11 DSPM machine with field weakening winding

3. Comparison of Motor Types

3.1 Sizing and Power Density Equations

While the capability of conventional ac machines are well understood, even when supplied from a switching power converter, many of the recently developed machines that have described are too new to have undergone careful scrutiny. In general, comparison of different machine types is a very formidable task. However, S. Huang et. al. [15] have developed general purpose sizing and power density equations and have established a systematic method to compare the capabilities of machines with different topologies. Reference 49 includes, in particular, (1) a new concept for comparing power density on the basis of total occupied volume instead of air-gap volume, (2) introduction of special factors to account for the effects of current and back emf waveforms, (3) methods for comparison of radial flux, axial flux and transverse flux machines to induction machines. These machines were examined in detail respectively in [15], [16] and [17].

For radial flux machines the general purpose sizing equations takes the form [15]:

$$P = \frac{1}{1+K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} \lambda_o^2 D_o^2 L_e \tag{1}$$

For the axial flux machine [16]:

$$P = \frac{1}{1+K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p K_L \eta B_g A \frac{f}{p} (1-\lambda^2) \frac{1+\lambda}{2} D_o^2 L_e \tag{2}$$

For the transverse flux machine [17]:

$$P = \frac{m}{2} \frac{1}{1+K_\phi} K_e K_i K_p K_L \eta B_g A \frac{f}{p} \lambda_o^2 D_o^2 L_e \tag{3}$$

where

K_ϕ	ratio of electrical loading of rotor to stator. (In a machine without a rotor winding, K_ϕ=0.)
m	number of phases of the machine.
m_1	number of phases of each stator (if there is more than one stator, each stator has the same m_1).
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	peak flux density in the air gap (T).
A	total electrical loading which includes both the stator electrical loading A_s and rotor electrical loading A_r (A/m).
f	converter frequency (Hz).
p	machine pole pairs.
D_o	diameter of the outer surface of the machine (m).
L_e	effective stack length of the machine (m).

K_L aspect ratio coefficient, for the radial flux and the transverse flux machines $K_L=L_e/D_g$ and for axial flux machines $K_L=D_o/L_e$.

λ_o ratio of the diameter of the air-gap surface D_g vs. the diameter of the outer surface of the machine D_o.

λ ratio of the diameter of the inner surface D_i vs. the diameter of the outer surface of the machine D_o.

For the radial flux machine the machine power density per total external volume can be defined as [15]:

$$\xi = \frac{P_R}{\frac{\pi}{4} D_o^2 L_t} \tag{4}$$

where L_t is the total length of the machine including the stack length and the protrusion of the end winding from the iron stack in the axial direction.

For the axial flux machine [16]:

$$\xi = \frac{P_R}{\frac{\pi}{4} D_t^2 L_e} \tag{5}$$

where D_t is the total outer diameter of the machine including the stack outer diameter and the protrusion of the end winding from the iron stack in the radial direction.

Finally for the transverse flux machine [17]:

$$\xi = \frac{P_R}{\frac{\pi}{4} D_o^2 L_e} \tag{6}$$

3.2 Sizing and Power density Equations for Induction Machine

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. The sizing equation for induction machine utilizing the outer diameter is [15]

$$P_{IM} = \frac{\sqrt{2}\pi^2}{2(1+K_\phi)} K_w \eta \cos\phi_r B_g A \frac{f}{p} \lambda_o^2 D_o^2 L_e \tag{7}$$

and corresponding power density equation is

$$\xi_{IM} = \frac{2\sqrt{2}\pi^2}{(1+K_\phi)} K_w \eta \cos\phi_r B_g A \frac{f}{p} \lambda_o^2 \frac{L_e}{L_t} \tag{8}$$

where $\cos\phi_r$ is the power factor which is related to the rated power P_{IM}, the pole pairs p of the machine and the converter frequency f. Using regression analysis, an estimate of $\cos\phi_r$ for the squirrel-cage motor obtained from NEMA designs is [15]

$$\cos\phi_r = 1.07\, P^{0.015} p^{-0.08} f^{-0.07} \tag{9}$$

and the electrical loading K_ϕ can be established as [15]

$$K_\phi = 1.06\, P^{0.0116} p^{-0.062} f^{-0.054} \tag{10}$$

3.2 Sizing and Power Density Equations for Three Phase Variable Reluctance Machine

For the variable reluctance machine, Fig. 1, the sizing and power density equations can be shown to be [18]

$$P_{VR} = \frac{\pi^2}{2} K_i K_p \eta B_g A \frac{f}{p} \lambda_o^2 D_o^2 L_e \tag{11}$$

where the power density of the variable reluctance machine is

$$\xi_{VR} = 2\pi K_i K_p \eta B_s A \frac{f}{p} \lambda_o^2 \frac{L_e}{L_t} \tag{12}$$

The factors K_i and K_p as shown to depend upon the back emf and current waveforms respectively. The variable reluctance machine is unlike most other machines in that the back emf and current waveforms may vary and are determined by the rated speed n_s, the turn-on and turn-off angles, the applied voltage, and the rate of change of inductance. Hence, to determine both K_i and K_p factors at rated speed n_s for this machine it is necessary to actually simulate the operation of the machine and converter [18].

The following comparisons are based on the same rated power P_R, the same rated speed n_s. The total electrical loading A and the current density J_s of the compared machines are assumed the same so as to result in the same heat dissipation. Moreover, since the comparison has to be on the optimized designs, it is very important to choose an optimal value for the diameter ratio λ_o and also reasonable values of flux density. Iron losses have been incorporated but in an approximate manner. Work on this aspect is continuing before reporting final results. Fig. 12 shows a comparison of the power density for designs of the 4-rotor-pole/6-stator pole (VR4/6) variable reluctance machine to that of a four pole induction machine. From this curve, comparisons between designs of a 4-pole induction machines and designs of the 4-rotor-pole / 6-stator-pole variable reluctance machines can, for example, be determined for two specific speeds as

at n_s =1500 rpm

$$\xi_{VR} / \xi_{IM} = 1.21 \tag{13}$$

at n_s =6000 rpm

$$\xi_{VR} / \xi_{IM} = 1.39 \tag{14}$$

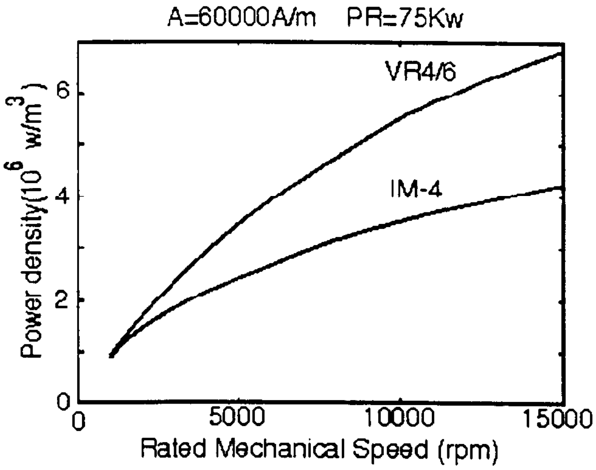

Figure 12 Comparison of 4 rotor/6 stator pole variable reluctance motor designs with that of conventional 4 pole induction motor designs

3.3 Sizing and Power Density Equations for Transverse Flux Machine

Comparisons for the transverse flux machine of Fig. 4 can be determined in a similar manner and similar power density equations derived [17]. Figure 13 shows comparison of the power density of a 16 pole designs of this machine as compared with designs of a standard 4 pole induction machine. Comparisons for the same two sample speed points are [17]

at n_s =1500 rpm

$$\xi_{AFPM} / \xi_{IM} = 1.74 \qquad (15)$$

at n_s =6000 rpm

$$\xi_{AFPM} / \xi_{IM} = 1.69 \qquad (16)$$

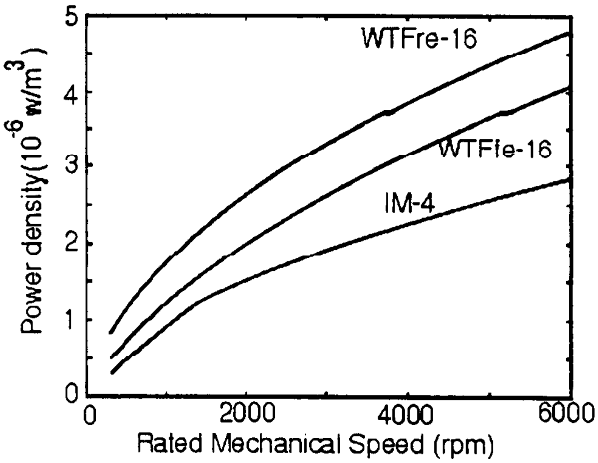

Figure 13 Comparison of designs for 16 and 18 pole transverse flux circumferential current machines with four pole induction motor designs

3.4 Sizing and Power Density Equations for the Axial Flux Toroidal Machine

Comparisons between 4-pole induction machines and 8-pole axial flux toroidal PM machines, Fig. 5, is presented in Fig. 14. These curves indicates the following ratios for design of axial flux PM machines to squirrel cage induction machines [16]

at n_s =1500 rpm

$$\xi_{AFTPM} / \xi_{IM} = 2.64 \qquad (17)$$

at n_s =6000 rpm

$$\xi_{AFTPM} / \xi_{IM} = 3.27 \qquad (18)$$

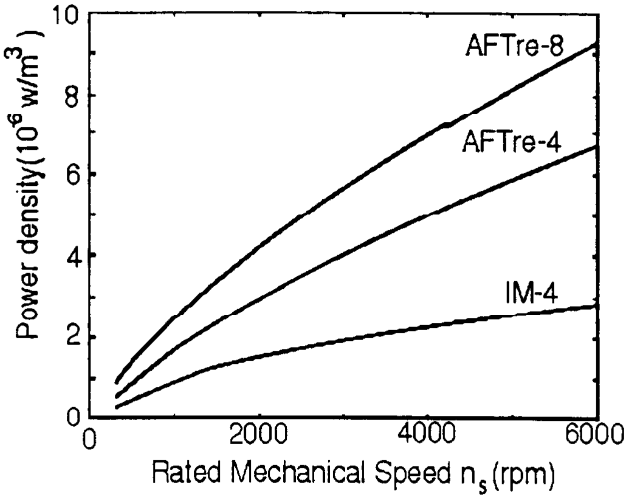

Figure 14 Comparison of power densities between induction machines and AFTPM machines.

3.6 Sizing and Power Density Equations for Three Phase Double Salient PM Machine

Comparisons obtained between 4-pole induction machines and a 4-rotor-pole/6-stator-pole double salient PM machine of the type shown in Fig. 9 were carried out in Ref. 15. The results are shown in Fig. 16. The results for designs at the two sample speed points are as follows

at n_s =1500 rpm

$$\xi_{DSPM} / \xi_{IM} = 1.46 \qquad (19)$$

at n_s =6000 rpm

$$\xi_{DSPM} / \xi_{IM} = 1.84 \tag{20}$$

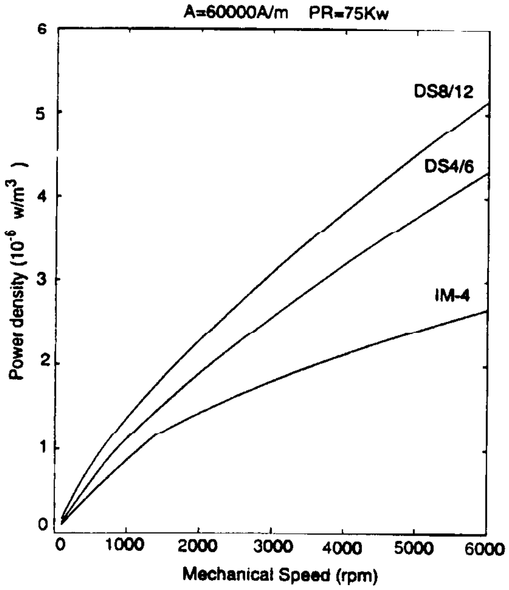

Fig. 16 Power densities of four pole induction machine and DSPM machines

The comparisons between the 4-pole induction machines and the 4-rotor-pole / 6-stator-pole double salient PM machine with field weakening capability, typified by Fig 11, can be computed in the same manner. At the two sample speed points, [15]

at n_s =1500 rpm

$$\xi_{DSPMFW} / \xi_{IM} = 1.36 \tag{21}$$

at n_s =6000 rpm

$$\xi_{DSPM\,FW} / \xi_{IM} = 1.74 \tag{22}$$

4. Discussion

It is clear from the results presented in the previous section that this new family of converter fed machines can be a serious competitor with squirrel cage induction machine used for drive applications with a predicted increase in power density ranging from 140 to 327% when compared with typical induction machines. It is important to mention that improvements of this order do not violate any laws of physics and can potentially also be reached with more conventional PM structures. However, such machines require substantial use of rare earth magnets fastened to an expensive rotor structure whereas these machine are potentially mechanically more robust and can use inexpensive ferrite magnets.

It should also be pointed out that based on this study, among all of the converter fed machines listed, the variable or "switched" reluctance machine surprisingly appears to be the poorest option of all of the machines studied. This, perhaps, is to be expected since the variable reluctance machine produces its torque by means of the reluctance mechanism rather than the reaction mechanism utilizing permanent magnets as is the case of all of the other machines.

5. Conclusions

This paper has demonstrated that the opportunity for innovation in electrical machines is clearly increasing. A promising new generation of "converter fed" machines is evolving based on the principle of using a switching power converter to deliver currents of optimum waveform to match that of emf of energy conversion within the machine. As a result of the power electronics revolution the future for innovation in electrical machine design continues to remain bright.

6. Acknowledgment

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