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# Innovative Electrical Machines for Traction Applications

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# Innovative Electrical Machines for Traction Applications

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***Abstract*** — In recent years new developments in the electrical machine technology have demonstrated the possibility to make great improvements in traction applications. Ansaldo Trasporti, as a major competitor in the electrical railway vehicles market, has investigated the performances of different emerging machines to understand the benefits and the costs of such technology. Special attention has been paid to the following criteria: high power density (small size), high efficiency, low weight, long life, maintenance free (brush less) and low cost. The results are very encouraging and suggest that the technology can bring in the long term benefits over the induction machine. The analysis has taken into consideration the following machines that are of novel construction. All machines are inverter driven. The results are very encouraging. The power densities of some machines are on the average more than two and a half times than that of the induction machine. The weight is greatly reduced, reaching values as little as 15 percent of the induction machine weight. The efficiencies values are predicted as between 92 and 96 percent. These results can easily suggest many benefits that the introduction of such machines in railway electric vehicles can bring: reduction of total vehicle weight, reduction of axle load, bogie simplification, power distribution along the train in the case of EMU's, high speed trains and trams and consequently increased adhesion.

## I. INTRODUCTION

With the application of power electronic semiconductors, such as the GTOs and IGBTs, and availabilty of advanced controls, such as the field orientation, the well known induction machine has reached a high level of maturity and reliability and it has become a point of reference for railway applications: locomotives, Electrical Multiple Units, Metros and Trams.

In recent years new developments in the electrical machine technology have demonstrated the possibility to make great improvements in traction applications. The decreasing cost of permanent magnets has been probably the main factor hat has permitted a better utilization of magnet in such machines. Ansaldo Trasporti as a major competitor in the electrical railway vehicles market has investigated the performances of different emerging machines to understand the benefits and the costs of such technology. Special attention has been paid to the following criteria: high power density (small size), high efficiency, low weight, long life, maintenance free (brush less) and low cost. The results are very encouraging and suggest that the technology can bring in the long term benefits over the induction machine. Ansaldo Trasporti has conducted 2 investigations: the first for a 50 kW motor, applicable in a tram as a wheel motor, the second for a 300 kW motor, that can be used in distributed power trains, such as EMU's and high speed trains. The analysis has taken into consideration the following machines that are of novel construction under development at the University of Wisconsin: Doubly Salient Permanent Magnet machine (DSPM), Axial Flux Toroidal Permanent Magnet machine (AFTPM), Homopolar Axial flux Permanent Magnet motor (HAFTPM), Radial Flux 2 Stator Permanent Magnet machine (RF2SPM). All machines are inverter driven. The Doubly Salient Permanent Magnet machine has been considered in 2 different structures: inner and outer rotor. The Surface Mounted Permanent Magnet Synchronous Machine (SMPM) has been introduced as it is one of the best performing of the conventional machines. The squirrel cage induction machine, being the state of the art for traction applications, has been kept under consideration as a "point of reference" for the other machines. The result are very interesting. The power densities of some machines are on the average more than two and a half times than that of the induction machine. The power density is greatly increased, reaching values as great as four times that of the induction machine. Corresponding improvements in size and weight can be realized. The efficiencies values are between 92 and 96 percent. These results can easily suggest many benefits that the introduction of such machines in railway electric vehicles can bring: reduction of total vehicle weight, reduction of axle load, bogie simplification, power distribution along the train in the case of EMU's, high speed trains and trams and consequently increased adhesion. In this paper the investigation conducted by Ansaldo Trasporti and the University of Wisconsin will be described showing the characteristics of the innovative machines and the performance results obtained in the analysis.

## II. THE SIZING EQUATION

In general, comparison of different machine types is a very formidable task since many variables exist for each machine and it is difficult to select those variable which should be held constant for purposes of comparison. One traditional method of comparison is to use the $D_g^2L_e$ sizing equation, which compares the machine power on the basis of air gap surface diameter $D_g$ and effective stack length $L_e$.

For many years, researchers have been interested in considering instead the machine outer surface diameter $D_o$ because it is more directly related with the volume and thus the cost and size of the machine. In 1986 V.B. Honsinger developed a $D_o^3L_e$ sizing equation for induction machines [1] which served to fix the outer surface diameter and stack length. This method paid attention to the optimal electrical loading $A$ and the machine internal geometry for a given power level. Unfortunately, the approach can be shown give reasonable designs only for small pole number since optimizing $D_o^3L_e$ is clearly not the same as optimizing $D_o^2L_e$.

The traditional sizing equation is based on the premise that the excitation of the machine is provided by a sinusoidal voltage source resulting in ac machines which produce a sinusoidal emf. It was recognized in [2] and [3] that the emergence of power electronic converters has removed the need for such a concept as the basis for machine design. Beginning with the reluctance and permanent magnet 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 produce the optimum match between the machine and the power electronic converter.

With the evolution of converter fed machines (CFMs), it becomes important to compare power potential of machines with vastly different topologies, having a variety of different waveforms of back emf and current. A systematic and easy-to-use method based on sizing equations and the power density concept is needed for comparing the capability of machines with different structure.

In order to eliminate the deficiencies of traditional sizing equation, this paper introduces special factors to account for the effect of non-sinusoidal current and back emf waveforms. A particular effort is made to express the sizing equation which characterizes the output power $P_R$ as a function of overall volume of the machine. Thus, machines can be compared based upon the total occupied volume, instead of the air gap volume. The application of this general purpose sizing equation should provide machine designers with an important tool in their quest for new high power density machines and structures.

In 1996, S. Huang et al. [4],[5] developed general purpose sizing and power density equations and introduced a systematic method to compare the capabilities of machines with different topologies. The power density was compared on the basis of total occupied volume instead of air gap volume. Special factors were introduced to account for the effects of non-sinusoidal current and back emf waveforms. As a further study, several type of machine topologies have been investigated as wheel motors. They are the Doubly Salient Permanent Magnet machine (DSPM), including inner and outer rotor structures, the Axial Flux Toroidal Permanent Magnet machine (AFTPM), the Homopolar Axial flux Permanent Magnet motor (HAFTPM), the Radial Flux 2 Stator Permanent Magnet machine (RF2SPM). All machines are inverter driven. The Surface Mounted Permanent Magnet Synchronous machine (SMPM) has been introduced as it is one of the best performing of the conventional machines. The squirrel cage induction machine, being the state of the art for traction applications, has been kept under consideration as a "point of reference" for the other machines

## III. GENERAL PURPOSE SIZING EQUATIONS

The general purpose sizing equations for radial gap machines take the form, [4]

$$P_R = \frac{1}{1+K_\phi}\,\frac{m}{m_1}\,\frac{\pi}{2}K_eK_iK_p\,\eta B_g A\,\frac{f}{p}\,\lambda_o^2 D_o^2 L_e \qquad (1)$$

and

$$P_R = \frac{1}{1+K_\phi}\,\frac{m}{m_1}\,\frac{\pi}{2}K_eK_iK_p\,k_l\,\eta B_g A\,\frac{f}{p}\,\lambda_o^3 D_o^3 \qquad (2)$$

The general purpose sizing equations for axial gap machines take the form, [5]

$$P_R = \frac{1}{1+K_\phi}\,\frac{m}{m_1}\,\frac{\pi}{2}K_eK_iK_p\eta\,B_g A\,\frac{f}{p}\,(1-\lambda^2)\frac{1+\lambda}{2}D_o^3 \quad (3)$$

and

$$P_R = \frac{1}{1+K_\phi}\,\frac{m}{m_1}\,\frac{\pi}{2}K_eK_iK_p\,K_L\,\eta B_g A\,\frac{f}{p}\,(1-\lambda^2)\frac{1+\lambda}{2}D_o^2 L_e \qquad (4)$$

where

| | |
|---|---|
| $K_\phi$ | ratio of electrical loading on rotor and stator. (In a machine without a rotor winding, $K_\phi$=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 incorporating the winding distribution factor $K_w$ and the ratio between the area spanned by the salient poles and the total airgap area |
| $K_i$ | current waveform factor. (TAB I). |
| $K_p$ | electrical power waveform factor. (TAB I) |
| $\eta$ | machine efficiency. |
| $B_g$ | flux density in the air gap. |
| $A$ | total electrical loading including both the stator electrical loading $A_s$ and rotor electrical loading $A_r$. |
| $f$ | converter frequency. |

$D_o$ diameter of the outer surface of the machine.
$L_e$ effective stack length of the machine.
$k_l$ aspect ratio coefficient $L_e/D_g$ of the effective stack length over the gap diameter in radial air-gap machines.
$\lambda_o$ ratio of the diameter of the air-gap surface vs. the diameter of the outer surface of the machine.

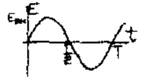
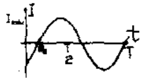
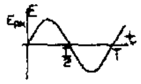
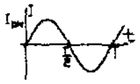
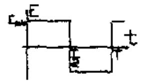
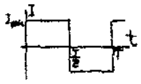
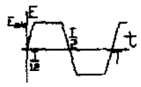
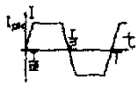
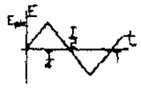
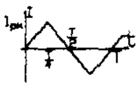
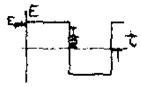
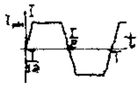
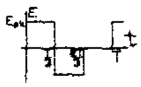
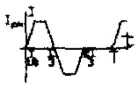
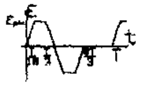
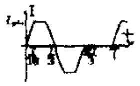
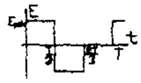
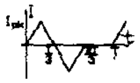
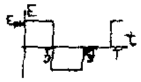
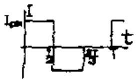
The definition of the factors $K_i$ and $K_p$ are [4]

$$K_p = \frac{1}{T}\int_0^T \frac{e(t)\times i(t)}{E_{pk}\times I_{pk}}\,dt = \frac{1}{T}\int_0^T f_e(t) f_i(t)dt$$

and

$$K_i = \frac{I_{pk}}{I_{rms}} = \left(\frac{1}{T}\int_0^T \left(\frac{i(t)}{I_{pk}}\right)^2 dt\right)^{-1/2}$$

TABLE I
TYPICAL PROTOTYPE WAVEFORMS

| Model | e(t) | i(t) | $K_i$ | $K_p$ |
|---|---|---|---|---|
| Sinusoidal waveform |  |  | $\sqrt{2}$ | $\frac{1}{2}\cos\phi$ |
| Sinusoidal waveform |  |  | $\sqrt{2}$ | 0.5 |
| Rectangular waveform |  |  | 1 | 1 |
| Trapezoidal waveform |  |  | 1.134 | 0.777 |
| Triangular waveform |  |  | $\sqrt{3}$ | 0.333 |
| Rectangular & Trapezoidal waveform |  |  | 1.134 | 0.8 |
| Rectangular & Trapezoidal waveform |  |  | 1.389 | 0.556 |
| Trapezoidal waveform |  |  | 1.389 | 0.519 |
| Rectangular & Trapezoidal waveform |  |  | 1.5 | 0.333 |
| Rectangular waveform |  |  | 1.225 | 0.667 |

In order to compare, the machine power density for the total volume can be defined as

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

Also, a parameter *Heat-diss* is defined to the temperature rise, which is called the "heat dissipation" factor,

$$Heat-diss. = \frac{Copper\_loss + Iron\_loss}{\pi \bullet D_o \bullet Total\_length}$$

## IV. MACHINE TOPOLOGIES CONSIDERED

Several machine topologies will be introduced in this section and the corresponding factor in the general purpose sizing equations will be provided based on the analysis of the principle of the machines.

1. The Induction Machine

The induction machine for this application is based a squirrel cage rotor structure. The design factors are estimated from recursion formulas using actual designs as:

| $K_\phi$ | $K_e$ | $K_i$ | $K_p$ |
|---|---|---|---|
| $1.06P_R^{0.0116}\,p^{-0.062}\,f^{-0.054}$ | $2\pi K_w$ | $\sqrt{2}$ | $0.5\cos\phi$ |

where $P_R$ is the rate power output, $p$ is the pole pairs, $f$ is the frequency of converter, $K_w$ is the stator winding factor including distribution and pitch effects.

2. DSPM : Doubly Salient Permanent Magnet Machine:

The DSPM family is based on a doubly salient magnetic structure, with salient poles on both rotor and stator. This particular feature allows to concentrate the flux produced by a large ferrite magnet into the small pole area, achieving a high airgap flux density.

Fig. 1 show the inner rotor structure and Fig. 2 shows the outer rotor structure. Concentrated coils are wound on each stator pole. They are connected in series or parallel with other coils to create a three phase or a two phase winding, depending on the machine pole number.

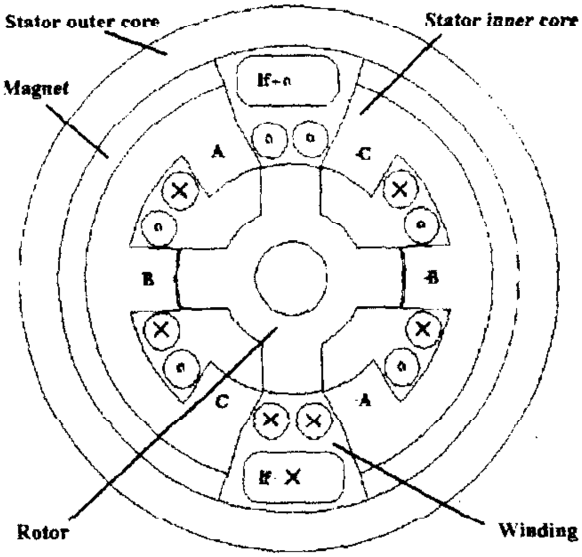


Fig. 1 DSPM Motor (inner rotor) with field coil

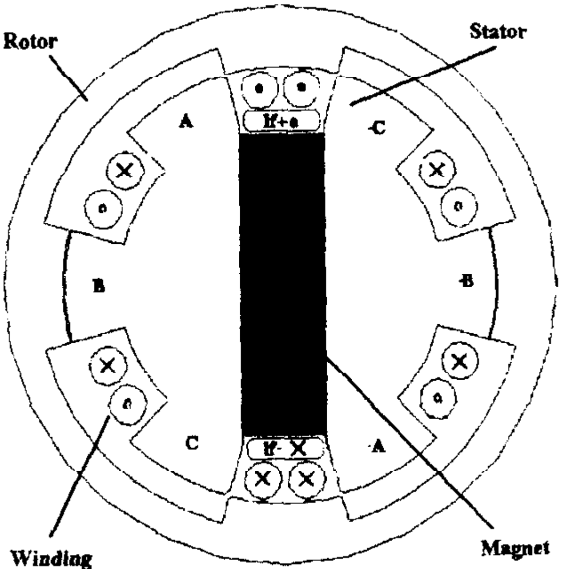


Fig. 2 DSPM Motor (outer rotor) with field coil

In this machine the rotor and stator have a different pole number, as for Variable Reluctance Machines, so that only some of the poles are aligned while other are not, for any rotor position. When a pole is aligned, the corresponding coil is linking its maximum flux, while the pole is unaligned the coil is linking the minimum flux. Due to this property an alternated emf is induced in the coils when the rotor rotates. If a current matching the back emf is forced into the coils by means of a suitable power converter, a net power is generated by the machine.

The sizing equation for the DSPM machines gives the machine volume as a function of the machine ratings and of the main design parameters. The coefficients that appear in the sizing equation(1) that are peculiar to this machine are:

| $K_\phi$ | $K_e$ | $K_I$ | $K_p$ |
|---|---|---|---|
| 0 | $\pi$ | 1.39 | 0.52 |

### *3. AFTPM: Axial Flux Toroidal PM Machine*

As shown on Fig. 3 and 4, the Axial Flux Toroidal PM machines are characterized by a slotless stator and a three phase winding wound on a toroidal stator core. The stator is double sided and is sandwiched between two rotors, with surface mounted permanent magnets that provide the field excitation. This mounting configuration naturally favors high residual field strength magnets (rare earth magnets), but very interesting designs can be done also with ferrite magnets if sufficient space is allowed. In fact the optimal aspect ratio for ferrite based toroidal PM machine is very unusual, with a short axial length and a large diameter. The optimal diameter for ferrite magnets, 50 kW rating, is considerably above the allowed 45 cm, and therefore the choice is here restricted to models equipped with rare earth magnets.

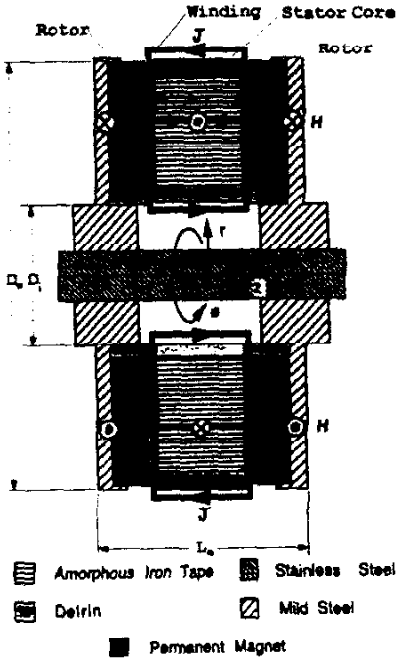


Fig. 3 AFTPM Machine

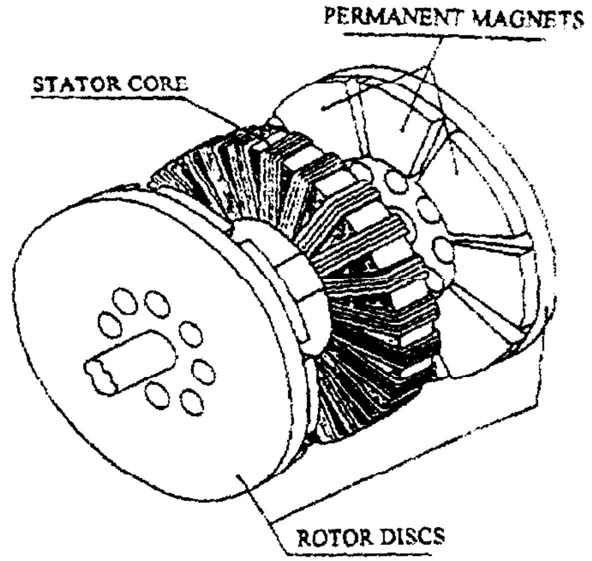


Fig. 4 AFTPM Machine

The high field strength of the magnets is at the basis of the high power density of the AFTPM. The major limitation is in the magnet thickness, which is driven by the airgap thickness. In spite of a mechanical clearance comparable with those of all the other machines that are considered in this study, the magnetic gap between the magnets and the stator core is very wide. In fact the slotless nature of the stator enlarges the effective gap by the coils height. This results in an optimal airgap flux density of only 0.4T and a magnet thickness of approximately 2.6 cm. The associated magnet cost exceed that of any other machine.

The coefficients in general sizing equation (10) are

| $K_\phi$ | $K_e$ | $K_l$ | $K_p$ |
|---|---|---|---|
| 0 | $\pi K_w$ | 1.134 | 0.777 |

*4. HAFPM: Homopolar Axial Flux Permanent Magnet Motor*

This unusual doubly salient axial flux PM machine is a mix of the DSPM and the AFTPM families. It is characterized by a double sided rotor with salient poles, and a flat magnet ring with unidirectional magnetization (Fig. 5).

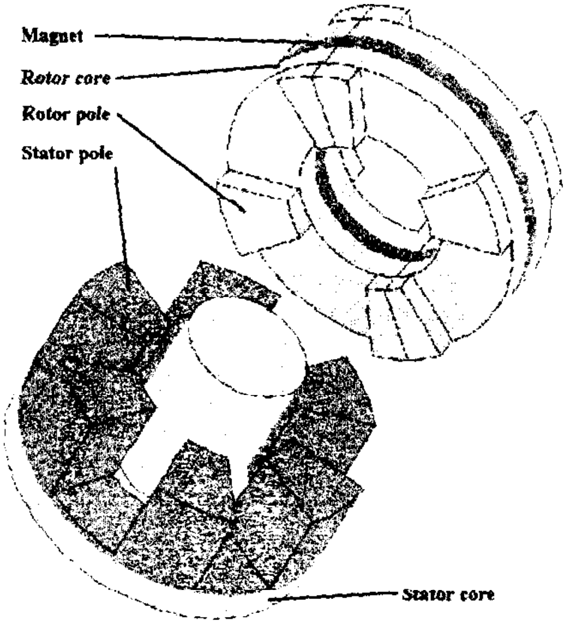


Fig.5 Homopolar Axial Flux Permanent Magnet Motor

The coefficients in the general sizing equation (10) are, for this machine,

| $K_\phi$ | $K_e$ | $K_l$ | $K_p$ |
|---|---|---|---|
| 0 | $\pi/4$ | 1.389 | 0.519 |

*5. RF2SPM: - Radial Flux Double Stators Permanent Magnet Motor*

The RF2SPM motor is shown on Fig. 5. The rotor carries the magnets, mounted between the rotor teeth. The structure is not mechanically salient but has a magnetic saliency due to the different permeability of steel and permanent magnets. The magnetization othe magnet is oriented tangent to the airgap circumference, alternately clockwise and counter-clockwise. The stator is split in two sections (Stator 1 and Stator 2), carrying one phase winding each. Concentrated coils are wound on the stator teeth. The two cores are mounted on the same shaft, and some space should be left between them, to allow the placement of the coil end turns. The core alignment is displaced by 90 electrical degrees so that the induced back emfs are in quadrature.

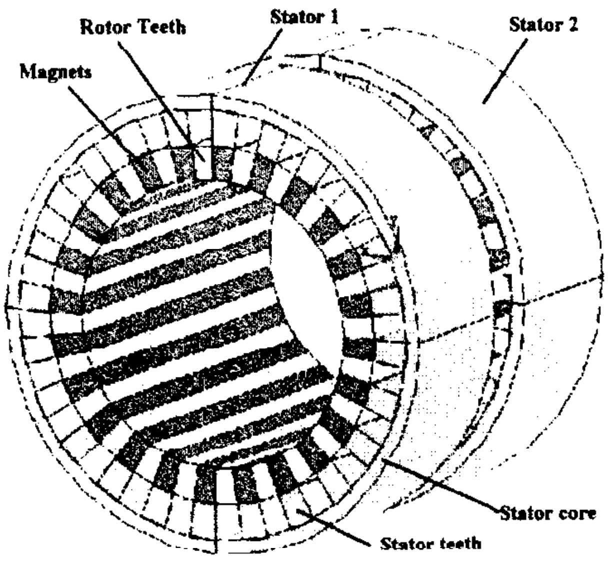


Fig. 5 RF2SPM Motor: PM in a darker color

The machine has a very high inner/outer diameter ratio and a 360 elec. degrees current conducting period. This result in a very good power density and the possibility of a very interesting design. Even better results are obtained if instead of the power per unit of volume, the power per pound is selected as comparison criteria

The coefficients in general sizing equation (2) are

| $K_\phi$ | $K_e$ | $K_I$ | $K_p$ |
|---|---|---|---|
| 0 | $\pi/4$ | 1.389 | 0.519 |

*6. SMPM - Surface Mount Permanent Magnet Motor*

The Surface Mount Permanent Magnet Motor for this application is based inner rotor structure. Considering the leakage flux, the waveform will be sinusoidal and the factors are

| $K_\phi$ | $K_e$ | $K_I$ | $K_p$ |
|---|---|---|---|
| 0 | $2\pi K_w$ | $\sqrt{2}$ | $0.5\cos\phi$ |

## V. COMPARISON

In order to compare those machines on a fair basis, each machine design was optimized under a specific operating condition. TABLE II shows the comparison for 50 KW wheel motor application. Because the machine is mounted to the wheel directly, the rated speed is only 380*rpm*. All the machines will have the same electrical loading *A* (600 A/cm) and current density *J* (6.2 A/mm). A similar research has been done for 300 KW application, which is under a higher speed (1900 rpm) and is shown on TABLE III. Clear benefits in adopting several of these alternative machine design are clearly apparent

TABLE II. Comparison of 50KW wheel motors.

| | η | Bg | Power Den. | | Heat Dis. |
|---|---|---|---|---|---|
| **Machine Type** | **%** | **(T)** | **Ratio** | **[w/cm3]** | **[w/cm2]** |
| Induction Machine | 89.1 | 0.8 | 1.00 | 0.53 | 0.55 |
| SMPM (rare earth) | 89.6 | 0.6 | 1.41 | 0.75 | 0.70 |
| **DSPM Inner Rotor** | | | | | |
| DSPM6/8(inner rotor) | 90.8 | 1.4 | 1.08 | 0.57 | 0.44 |
| DSPM8/12(inner rotor) | 90.6 | 1.3 | 1.21 | 0.64 | 0.50 |
| DSPM12/16(inner rotor) | 90.3 | 1 | 1.26 | 0.67 | 0.53 |
| **DSPM Outer Rotor** | | | | | |
| DSPMO4/6(rare earth) | 90.9 | 1.6 | 1.66 | 0.88 | 0.59 |
| DSPMO6/8(rare earth) | 91.2 | 1.4 | 1.56 | 0.83 | 0.53 |
| DSPMO8/12(ferrite) | 92.2 | 1.6 | 2.28 | 1.21 | 0.61 |
| DSPMO8/12(rare earth) | 92.2 | 1.6 | 2.28 | 1.21 | 0.61 |
| DSPMO12/16(ferrite) | 92.0 | 1.3 | 2.06 | 1.09 | 0.58 |
| DSPMO12/16(rare earth) | 92.4 | 1.4 | 2.18 | 1.16 | 0.56 |
| **AFTPM** | | | | | |
| AFTPM-12(rare earth) | 94.2 | 0.6 | 3.97 | 2.11 | 0.64 |
| **HAFPM (ferrite)** | | | | | |
| HAFPM8/12 | 87.0 | 1.4 | 1.44 | 0.76 | 1.10 |
| **RF2SPM (ferrite)** | | | | | |
| RF2SPM Inner Rotor | 86.5 | 1.4 | 2.37 | 1.26 | 1.06 |

TABLE III Comparison of 300KW application.

| | η | Bg | Power Den. | | Heat Dis. |
|---|---|---|---|---|---|
| ***Machine Type*** | ***%*** | ***(T)*** | ***Ratio*** | ***[w/cm3]*** | ***[w/cm2]*** |
| Induction Machine | 95.8 | 0.8 | 1.00 | 1.66 | 0.64 |
| SMPM (rare earth) | 96.0 | 0.5 | 2.09 | 3.47 | 1.10 |
| **DSPM Inner Rotor** | | | | | |
| DSPM4/6(inner rotor) | 96.1 | 1.3 | 1.48 | 2.45 | 0.59 |
| DSPM6/8(inner rotor) | 96.1 | 1.2 | 1.77 | 2.95 | 0.65 |
| DSPM8/12(inner rotor) | 96.0 | 1.1 | 2.00 | 3.34 | 0.76 |
| DSPM12/16(inner rotor) | 96.0 | 1 | 2.22 | 3.69 | 0.86 |
| **DSPM Outer Rotor** | | | | | |
| *DSPMO4/6(ferrite)* | 95.0 | 0.7 | 1.31 | 2.17 | 0.69 |
| DSPMO6/8(ferrite) | 95.0 | 0.6 | 1.29 | 2.15 | 0.61 |
| DSPMO8/12(ferrite) | 96.0 | 1.1 | 2.28 | 3.78 | 0.65 |
| DSPMO12/16(ferrite) | 96.0 | 1 | 2.36 | 3.92 | 0.70 |
| **AFTPM** | | | | | |
| AFTPM-12(rare earth) | 94.4 | 0.4 | 3.45 | 5.74 | 1.35 |
| **RF2SPM (ferrite)** | | | | | |
| RF2SPM Inner Rotor | 95.0 | 1.2 | 2.12 | 3.52 | 1.11 |

## VI. CONCLUSIONS

This paper has presented a brief treatment of ongoing research on innovative permanent magnet machine topologies. These topologies make optimum use of the fact that they are operated from a power electronic converter which is inherently capable of providing the machine with an optimum current waveform. Calculations based on newly developed sizing equations for these machines indicate substantial improvements in size and weight over the conventional squirrel cage induction machine.

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