CFMs - A New Family of Electrical Machines

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Abstract: Traditional design of electrical machines is based the premise that the excitation of the machine is provided by a sinusoidal voltage source resulting in ac machine which produce a sinusoidal emf. 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 revolution that is taking place and points to recent key developments.

1. Introduction

Electric machine design is one of the classical studies in electrical engineering that is commonly thought to have reached its zenith as a research topic in its "golden era" of the 1920's and early 1930's. 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. The evolution of power electronic converters over the past thirty years has clearly stretched the limits of this simplifying assumption. However, for the first several decades of the power electronic era, machines continued to be designed from this perspective 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, led to the development of the so-called switched reluctance machine in the 1980's [1]-[4]. A simple 6 pole stator/4 poles rotor version is shown in Fig. 1. The switched reluctance machine is, in reality, identical to the variable reluctance motor or stepper motor which was traditionally used for incremental motion type applications. These traditional applications concerned machine with very small ratings, however, in which the windings were sequentially supplied by a voltage source. The current in the windings were essentially limited by the resistance of the winding itself or by an external resistor.

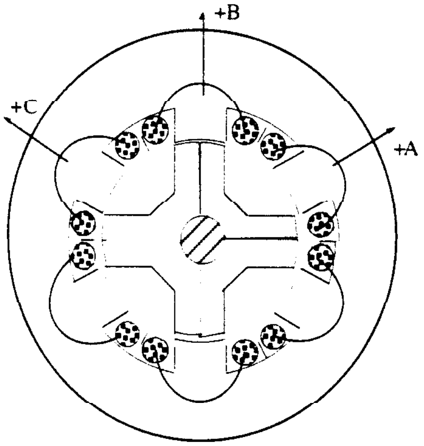


Fig. 1 Variable reluctance motor having 6 stator poles and 4 rotor poles.

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. Clearly, it was current control of the converter which led to the new concept and not any aspect related to the design of the motor. However, the motor was christened as a new type of motor, a "switched reluctance" motor, an unfortunate but pervasive new terminology. (Use of the equivalent CRPWM converter concept in conjunction with an induction machine did not lead to a rechristening of it as a "switched induction motor".)

Regardless of the terminology, [1] represented a turning point in the design of electrical machines. This new machine was incapable of operating satisfactorily unless supplied by a switching power converter. For the first time, it was recognized 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 [5].

The emergence of the variable reluctance motor has prompted researchers in the 1980's to rethink the assumptions embedded in classical machine design and to rethink many of the issues seemingly resolved during the "golden era", 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). This paper calls attention to this fact and summarizes the progress made in the development of CFMs.

2. Historical Perspective

As is the case for nearly all aspects of electrical machinery, the converter fed principle can be traced back to the golden era of electrical machines. In 1924 Maxstadt illustrated how the rectification of three triangular emf waves results in a DC output voltage having essentially no ripple [6]. A three phase, 5 kW synchronous having both field and compensating windings was built and tested using 100 kV, 0.2 A "Kenotron" tubes. The project apparently met with problems because of the impedance of the step up transformer needed to develop transmission line level voltage which caused undesirable harmonics on the dc side of the rectifier.

In 1938 Stohr wrote two classic papers devoted to the calculation of the output rating of commutatorless "inverter" motors having various connections [7],[8]. In today's nomenclature these machines could be termed multiphase synchronous machine with emf commutation. Winding utilization factors of roughly 50% were obtained when compared with conventional sinusoidal wound and excited synchronous machines. However, the now-classical three phase bridge circuit had not been invented (or appreciated) at that point in time. In 1975 Leitgeb brought the work of Stohr up to date by considering other winding configurations made possible by thyristor technology, particularly the bridge configurations [9]. Winding utilization factors approximately equal to about 0.95 were obtained for the three phase bridge. However, one of the major weaknesses of Leitgeb's as well as Stohr's work was that they assumed very strong amortisseur winding and neglect all spatial harmonics beyond the fundamental component. Hence, the added benefits of an machine designed with an intentional non-sinusoidal winding distribution was apparently not recognized.

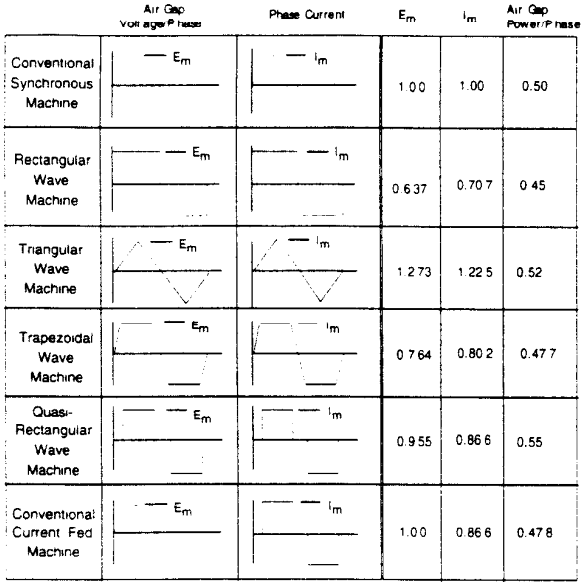
In 1971 Boenig reported work which to some extent duplicated that of Leitgeb [10]. A motor was constructed with tapped mesh stator and rotor windings in which the stator and/or rotor could be connected as a three, six or nine phase winding. Although the utilization factor for the winding was high, the utilization of the switches was poor since, for the nine phase motor, 18 switches were needed and each device carried current only 1/9 of a complete cycle (1/6 for six phase, 1/3 for three phase). Another interesting paper is that of C. St. J. Lamb in 1970 [11]. Lamb also employed a gramme ring type winding but in this case the stator was slotless making the commutating inductance very small improving the utilization factors. The slotless construction however, made the machine relatively bulky.

Although many of the findings were presaged by many authors including J. Byrne, M. Harris, H. Bausch, J. Stephenson, W. Ray and R. Davis, L. Unnewehr and others it was Ref. [1] and its extensive discussion that prompted a serious investigation into the possibility of developing machine with greater output and/or efficiency than conventional ac machine designs. This paper cited experimental results that indicated this machine had the same 86% efficiency at the same torque and speed as an induction motor when installed in the same frame size. In general, much of the wildly enthusiastic comments of the discussers of this paper have proven, in time, to be overblown and even completely in error. However, it was these discusser's comments together with the claims of the paper that created excitement about the possibilities of this somewhat ancient machine when operating from a modern current regulated converter supply. The fallout from this paper prompted an intense investigation of "switched" reluctance motors which continues to this day.

3. Emergence of Converter Fed Machines

The success of the variable reluctance machine has prompted investigators to ponder whether similar benefits can be obtained from other motor or generator topologies. In 1982 Ref. [12] examined the issue and concluded that greater output than even a conventional synchronous machine operating at unity power factor at the air gap could be obtained if the emf were designed to be non-sinusoidal. A figure from this paper is shown as Fig. 2. It is assumed that the voltage at the air gap corresponds to the emf of energy conversion. Flux due to armature reaction is assumed cancelled by air gap adjustment or a compensating winding.

It is useful to consider in more detail the manner in which this table was determined. When the peak emf voltage and phase current are defined as one per unit the contribution of the phase to energy conversion is clearly 0.5 per unit. In the case of each machine it is assumed that the core flux is the same (or else the OD's of the machine would not be the same thereby unfairly favoring the rectangular wave machine. Designating the conventional machine as machine "1", the gap flux contribution of one phase of the conventional machine is related to the emf by



	Air Gap Voltage/Phase	Phase Current	E_m	I_m	Air Gap Power/Phase
Conventional Synchronous Machine	E_m	I_m	1.00	1.00	0.50
Rectangular Wave Machine	E_m	I_m	0.637	0.707	0.45
Triangular Wave Machine	E_m	I_m	1.273	1.225	0.52
Trapezoidal Wave Machine	E_m	I_m	0.764	0.802	0.477
Quasi-Rectangular Wave Machine	E_m	I_m	0.955	0.866	0.55
Conventional Current Fed Machine	E_m	I_m	1.00	0.866	0.478

Fig. 2 Comparison of phase voltage, current and power of six prototype machines with non-sinusoidal winding distributions.

$$E_1 = \frac{d\Phi_{1(g)}}{dt} = \frac{d\Phi_{1(g)}}{d\theta}\frac{d\theta}{dt} \tag{1}$$

The core flux is the integral of the gap flux so that, From Eq. (1),

$$\Phi_{1(core)} = \int_0^{\pi/2} \frac{d\Phi_{1(g)}}{d\theta}\, d\theta = \int_0^{T/4} E_1.dt \tag{2}$$

whereupon,

$$\Phi_{1(core)} = \frac{T}{2\pi}E_{m1} \tag{3}$$

The rms value of the phase current of conventional machine "1" is obviously

$$I_{1(rms)} = \frac{I_{m1}}{\sqrt{2}} \tag{4}$$

where "$m1$" denotes the maximum value of the current and voltage sine waves. Also in Eq. 3, "T" is the period of one cycle of the emf and θ is the angular rotation of the rotor in electrical degrees.

If "2" is used to denote the machine of the second row of Fig. 1 (i.e. the rectangular wave machine), then the flux in the core is given by

$$\Phi_{2(core)} = \int_0^{T/4} E_1.dt = \frac{T}{4}E_{m2} \tag{5}$$

The rms phase current is clearly

$$I_{2(rms)} = I_{m2} \tag{6}$$

If the core flux and rms current of the two machines are to remain constant for the purpose of comparison then from Eqs. (3) and (5),

$$E_{m2} = \frac{2}{\pi}E_{m1} \tag{7}$$

and

$$I_{m2} = \frac{I_{m1}}{\sqrt{2}} \tag{8}$$

In the case of the rectangular wave the air gap power is clearly

$$P_2 = E_{m2}I_{m2} = \frac{\sqrt{2}}{\pi}E_{m1}I_{m1} \tag{9}$$

or in per unit,

$$P_2 = \frac{\sqrt{2}}{\pi} = 0.45 \tag{10}$$

which is only 90% of the power capability of an equivalent conventionally wound synchronous machine operating with unity air gap power factor.

The process can be continued for the remaining machines of Fig. 2 and for other possible winding distributions. It can be noted that the triangular wave machine and especially the quasi-rectangular machine actually exceed the capability of the conventional machine. In particular, the quasi-rectangular machine is capable of 10% more torque than a sine wave fed machine and as much as 15% if compared with a sine wave machine fed with the same rectangular currents. Since such currents normally flow when a synchronous generator is connected to a thyristor bridge, the comparison is particularly meaningful. It is important to note again that the reference machine for this comparison is a conventional synchronous machine operating with unity internal power factor, i.e. a machine operating at its maximum torque/ampere point. Since the power factor at the air gap of an induction machine is roughly 0.9, a further 10% increase could be expected when compared to an induction machine. Recent improvements in the basic design of variable reluctance machine include the use of commutating windings [13],[14], and full pitch rather than short pitch coils [15].

The promising results suggested by Fig. 2, led to an investigation of generators with a quasi-rectangular emf waveform [12]-[18]. It was determined that six concentrated winding phases provided a good utilization of the stator surface while the armature reaction could be overcome with the design of an asymmetric air gap over the pole face [12]. Motoring operation was also studied [17]. A pole are of 115° rather then the 120° could further increase the per unit output [18]. A machine was built and tested which demonstrated 2% gain in efficiency compared to a conventionally wound machine [18].

The good results obtained from the synchronous machine study prompted the investigators to consider similar designs for an induction motor [19]-[21]. Again a non-sinusoidal MMF can be impressed on the air gap by the stator windings. However, in this case the machine does not respond with a predictable emf since the emf of energy conversion is, in this case the voltage induced in the stator windings by the currents in the squirrel cage. While the rotor bar currents respond to sinusoidal excitation with sinusoidal current flow, the same can not necessarily be expected when the rotor bars are excited with an MMF which is rectangularly distributed in space and which suddenly steps ahead in the air gap rather than rotating smoothly. Although the stepping process can be eliminated with a sufficient number of phases [22], the rotor MMF responds only with an approximation of the impressed stator MMF which, in turn, acts to reduce the additional energy conversion contribution of the space harmonics. In this case an improvement of only 5% was realized when compared to an induction machine with conventionally wound stator [21].

The promising results obtained for the variable reluctance motor has also prompted researchers to examine more closely its close cousin, the synchronous reluctance motor. The synchronous reluctance differs from the variable reluctance type in that only the rotor is salient as compared to the double saliency of the variable reluctance type. It has been shown that when the saliency ratio X_d/X_q reaches 7.0 this machine begins to compete favorably with the induction motor in a motor drive environment [23]. Five phase concentrated full pitch winding distributions having been examined [24], [25] and it has been shown that a 14% increase in torque output is possible for the same rms current compared to a sine wave wound machine. This increase is effectively due to the presence of a third harmonic component in the emf and current waveform. A simple two phase synchronous reluctance motor again having concentrated full pitch windings with non-sinusoidal induced emf has also been built and tested [26]. It has been shown that with unipolar rectangular currents impressed on the windings, the torque capability of this machine can exceed that of a variable reluctance of the same size.

Efforts to optimally interface an electrical machine with a switching power converter is also actively being explored by Weh and his associates [27], [28]. 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. [29]-[31] since the exciting field and torque producing field can be regulated independently. Fig. 3 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. 4. 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.

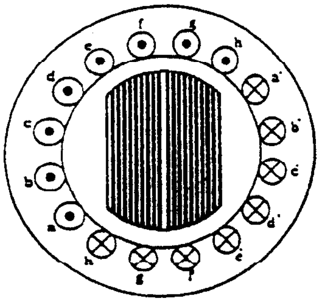


Fig. 3 Two pole field regulated reluctance machine.

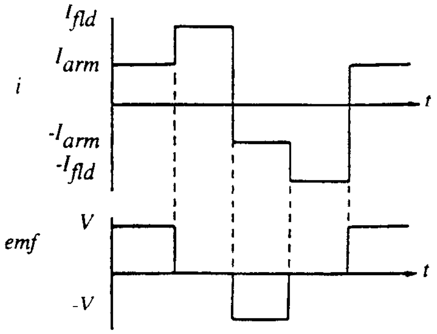


Fig. 4 Optimum phase current and emf waveforms for field regulated reluctance machine.

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 [32],[33]. Fig. 5 shows a simplified version of 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.

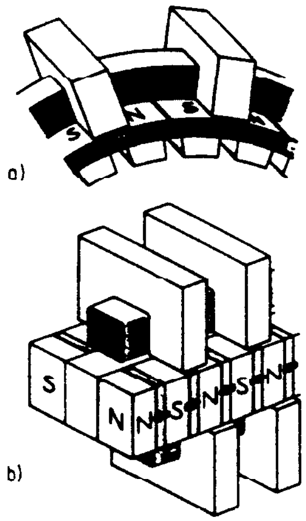


Fig. 5 Transverse flux (TF) machine of Weh.

A topological variation on the transverse flux machine is the machine shown in Fig. 6 [34]. In this case the flux confined to

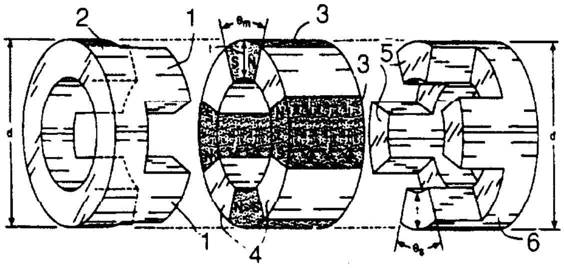


Fig. 6 Axial flux PM machine. 1,2 stator poles, 3, rotor pole pieces, 4, ferrite magnets, 5,6 stator poles.

flow in identical slotted stators which are located on either side of the rotor. More effective use of the available space is therefore possible compared to the transverse flux machine of Weh. In this machine, the permanent magnet flux is alternately shunted from one stator to the other by means of saliencies on the stator. Because the magnet flux is accumulated in rotor pole pieces before crossing the gap, air gap flux densities of nearly any desirable value can be achieved with only the use of ferrite magnets. Large axial forces are obviously set up in this machine which would cause abnormally large forces on the bearings. However, by use of multiple numbers of rotors, these forces can be effectively cancelled.

Another interesting permanent magnet machine which inherently develops trapezoidal rather than sinusoidal emf is the so-called Torus machine shown in Fig. 7 [35]-[36]. 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. 8. The corresponding optimum waveform for this machine is again a trapezoid [37],[38]. The Torus machine has been proposed for use as an automotive generator, propulsion motor, and electric vehicle wheel motor.

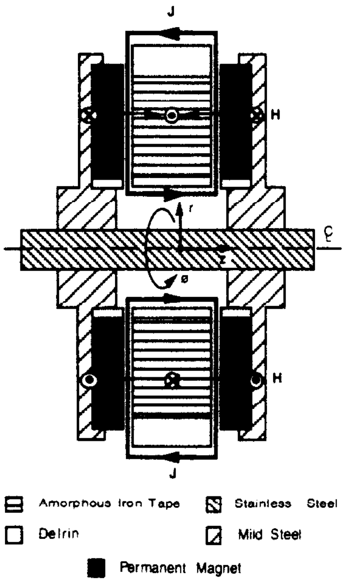


Fig. 7Axial flux toroidal PM machine.

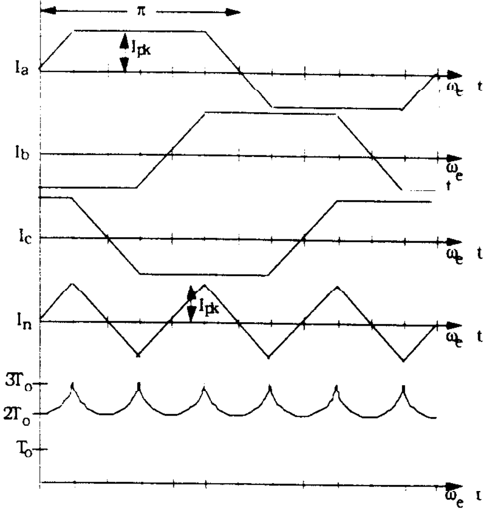


Fig. 8 Optimum current and resulting torque waveform for toroidal machine. I_a.I_b.I_c– phase currents, I_n– motor neutral current, T_0 –torque

In the search for new topologies, combinations of reluctance permanent magnet machines have been proposed [39],[40]. One of these machines, the doubly salient pm machine, is shown in Fig. 9. 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. 10 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 and, perhaps, a derivative of the

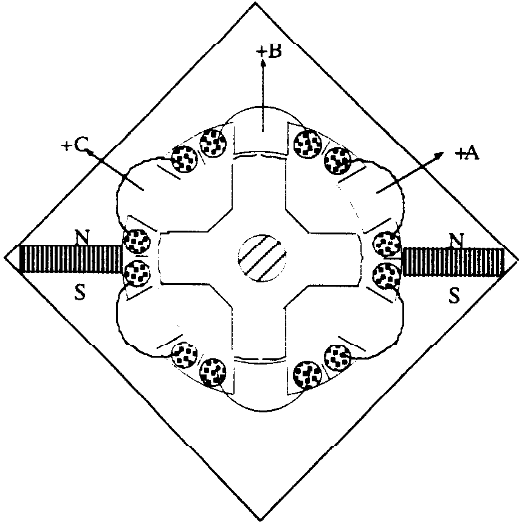


Fig. 9 Doubly salient permanent magnet machine.

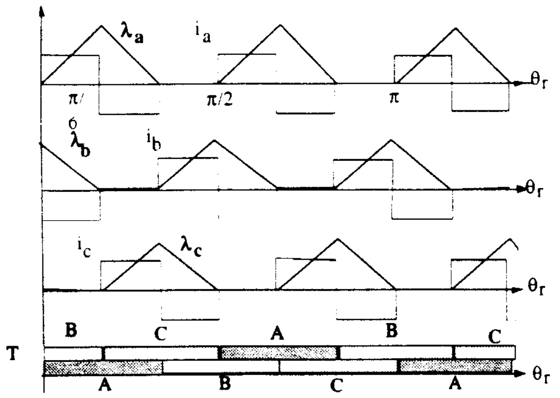


Fig. 10 Flux variation and phase currents and resulting torque for doubly salient pm machine of Fig. 9.

"flux switch" machine [41]. 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.

A four pole rotor/six pole stator type machine suitable for generator operation has also been examined [42]. In this case it has been shown that this new machine is capable of 40% more torque for the same *rms* current than for an equivalent variable reluctance machine [43]. 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 [44].

The issue of field weakening of permanent magnet machines is a perplexing issue that is inhibiting the widespread application of *pm* 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. 9 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. 11. 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 [45].

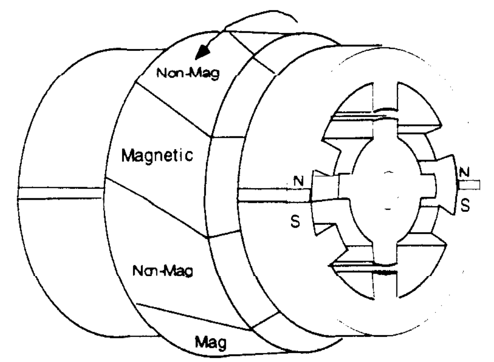


Fig. 11 Field weakening arrangement using movable sleeve.

Field weakening of the permanent magnets in such a machine can also be attacked by rearranging the magnets to the position shown in [46]. In this case, the magnet has been designed to 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. 6. Again a generating, rather than a motoring capability can be engineered [47].

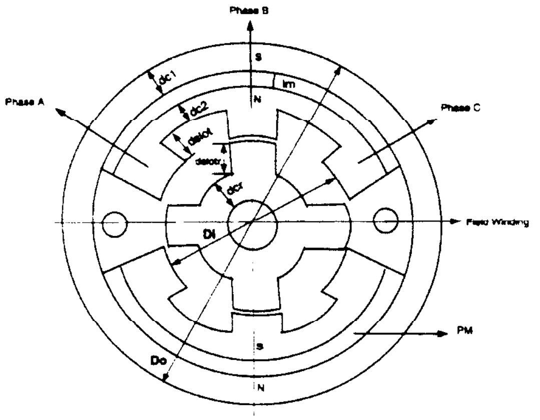


Fig. 12 Doubly salient PM machine capable of field weakening.

4. Comparison of Motor Types

While the capability of conventional ac machine are well understood, even when supplied from a switching power converter, many of the machines that have been described are too new to have undergone scrutiny. In general, comparison of machine types is a very formidable task since many variables exist for each machine and it is difficult to select those variables to hold constant for purposes of comparison. One traditional method of comparison is by the use of the *D^2L Sizing Equation* which expresses the power as the product of the peak gap flux density B_g *(tesla)*, the rms surface current density A_{rms} *(A/m)*, the speed n_s *(rpm)*, the volume of the machine *(meters ^{3})* at the air gap, efficiency η and power factor $\cos\phi$. For purposes of comparison it is well known that the sizing equation of a squirrel cage induction machine is [48]

$$P_{im} = \frac{\sqrt{2}\pi^2}{120}\eta \cdot \cos(\phi)\, n_s \cdot B_g \cdot A_{rms} \cdot D_i^2 L \qquad (11)$$

It can be shown that a similar equation can be derived for all of the machines presented in Section 3. Space does not permit a complete derivation of all equations. The results shown below are taken from a more detailed paper on this aspect which is in preparation [49].

4.1 Sizing Equation for Three Phase Variable Reluctance Motor

For the variable reluctance motor, Fig. 1, the sizing equation can be shown to be, [49]

$$P_{vrm} = \frac{7\sqrt{3}\pi^2}{2160}\eta B_g A_{rms} n_s (D_i^2 L) \tag{12}$$

If the speed of the induction and variable reluctance are assumed equal, then the ratio of Eq. (12) divided by (11) yields an equation expressing the *power density* of the variable reluctance motor as a per unit of the induction motor. Expressing this ratio as ζ, then it is clear that

$$\begin{aligned}\zeta_{vrm} &= \left(\frac{P_{vrm}}{(D_i^2 L)_{vrm}}\right) \div \left(\frac{P_{im}}{(D_i^2 L)_{im}}\right) \\ &= \frac{7\sqrt{3}}{18\sqrt{2}}\left(\frac{B_{g(vrm)}}{B_{g(im)}}\right)\left(\frac{A_{rms(vrm)}}{A_{rms(im)}}\right)\left(\frac{\eta_{vrm}}{\eta_{im}}\right)\frac{1}{\cos\phi}\end{aligned} \tag{13}$$

For purposes of comparison it can be assumed that the efficiencies of the two machines are roughly the same. Also, if the heat rejection of the two machines is limited by the stator loss then the surface current densities of the two machine can be equated. However, since the flux in the gap of the variable reluctance is close to the saturation flux density of the iron pole, the ratio of the flux densities of the two machines can be assumed to be a factor of two ($B_{g(vrm)} = 0.7$ T, $B_{g(vrm)}$=1.4), Finally, if it is assumed that the power factor of the induction motor is 0.85 then

$$\zeta_{vrm} = 1.12 \tag{14}$$

4.2 Sizing Equation of Field Regulated Reluctance Machine

The sizing equation for the Field Regulated Reluctance machine of Fig. 3 is,

$$P_{frrm} = K_I \frac{\pi^2}{72}\eta B_g A_{rms} n_s D_i^2 L \tag{15}$$

The factor K_I is an armature winding "utilization factor" which accounts for the fact that some of the armature windings are being used as equivalent field current windings at any instant and varies from 0.8 to 0.9. The resultant sizing factor is

$$\zeta_{frrm} = 1.18 \tag{16}$$

4.3 Sizing Equation for Transverse Flux Machine

The sizing equation for the Weh Transverse Flux machine of Fig. 5 is, [49]

$$P_{tfm} = \frac{\sqrt{2}\pi^2}{360} K_\lambda K_1 K_k K_{w1} \eta B_g A_{rms} n_s \cos\phi P \tag{17}$$

where:

- K_1 = current waveform factor,
- K_d = PM leakage flux factor,
- K_{w1} = rotor slot pitch factor,
- $K_\lambda = 1/\lambda - 1$
- $\lambda = D_i / D_o$, D_i and D_o are stator (and rotor) inner and outer diameters,
- P = number of poles.

Upon choosing the following: $P = 8$, $\lambda = 0.6$, $K_I = 5/6$, K_{w1} - 1/2, $B_g = 1.4$ T, $K_d = 0.9$.$D_i = L$, the sizing factor ζ becomes

$$\zeta_{tfm} = 1.33 \tag{18}$$

4.4 Sizing Equation for Axial Flux PM Machine

The sizing equation for the Axial Flux PM machine of Fig. 6 is,

$$P_{afpm} = \frac{\pi^2}{240}\left(\frac{1}{\lambda^2} - 1\right) K_d \eta B_g A_{rms} n_s D_i^3 \tag{19}$$

where, again $\lambda = D_i / D_o$, D_i and D_o are stator (and rotor) inner and outer diameters and the constant $K_d$is the PM leakage flux factor. If $D_i = L$, $\lambda = 0.5$, $K_d = 0.9$, $B_g$the

$$\zeta_{afpm} = 1.91 \tag{20}$$

4.5 Sizing Equation for Axial Flux Toroidal PM Machine

The sizing equation for the Axial Flux Toroidal PM machine of Fig. 7 is,

$$P_{aftpm} = \frac{5\pi^2}{720}\eta B_g A_{rms} n_s D_i^3 \left(\frac{1}{\lambda^2} - 1\right) \tag{21}$$

where $\lambda = D_i / D_o$ and where D_i and D_o are the inner and outer diameters of the toroid shaped stator respectively. It is assumed that $D_i = L$, and $\lambda = 0.5$ If a rare earth magnet is used for this machine with residual flux density of 1.2 tesla then a reasonable gap flux density is $B_g = 0.85$. The sizing factor ζ becomes,

$$\zeta_{aftpm} = 1.22 \tag{22}$$

4.6 Sizing Equation of Three Phase Doubly Salient PM Motor

The sizing equation for the Three Phase Doubly Salient PM machine of Fig. 9 is, [50]

$$P_{dspm} = \frac{\sqrt{2}\pi^2}{120\sqrt{3}} K_d \eta B_g A_{rms} n_s (D_i^2 L) \tag{23}$$

where K_d is a leakage factor to account for permanent magnet leakage flux. In general this leakage factor varies from 0.8 to 0.9 so that it can be assumed for simplicity that the ratio $K_d / (\cos\phi) = 1.0$ where $\cos\phi$ is the induction motor power factor. Again the gap flux density of this machine can be assumed as twice the gap flux density of the induction motor whereupon

$$\zeta_{dspm} = 1.154 \tag{24}$$

4.7 Sizing Equation for Three Phase Doubly Salient PM Motor with Field Weakening Capability

The sizing equation for the Three Phase Doubly Salient PM machine of Fig. 12 is the same as the previous machine.

$$P_{dspmfw} = \frac{\sqrt{2}\pi^2}{120\sqrt{3}} K_d \eta B_g A_{rms} n_s (D_i^2 L) \qquad (25)$$

so that

$$\zeta_{dspmfw} = 1.154 \qquad (26)$$

5. Discussion

The results obtained clearly suggest that this new family of machine can be a serious competitor with squirrel cage induction machine used for drive applications with improvements in power density ranging from 12 to 90%. While admittedly a rough calculation it should be mentioned that this analysis was, in fact, tilted in favor of the induction motor when it was simultaneously assumed that the stator surface current density all machines as well as their efficiencies were equal. In effect, the rotor losses of the induction machine were neglected. Clearly, if the total copper losses of all machines were held constant, the stator currents of all 7 converter fed machines could be increased by somewhere between 120 and 150% (or else the efficiency increased by several percent) since no rotor current flows on any of these machines. Hence, in reality, these numbers are conservative and applying a multiplying factor of 1.2-1.4 to the sizing factors to compensate for this effect would be reasonable.

It should also be pointed out that based on this study, among all of the converter machines listed, the variable or "switched" reluctance machine surprisingly appears to be the poorest option.

6. Conclusions

This paper has demonstrated that the opportunity for innovation in electrical machines is clearly on the uprise. 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 the emf of energy conversion within the machine. The next decade could, in fact, produce the second "golden era" of electrical machine design.

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