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Electromechanical Power Generation for Interplanetary Space Travel Beyond Low Earth Orbit

Sushant Barave¹, and Badrul H. Chowdhury, *Senior Member, IEEE*

Abstract-- Preliminary results of investigating high frequency power generation using a permanent magnet synchronous machine is presented. The specific application is crew exploration vehicles for space travel beyond low earth orbit.

Keywords—Crew exploration vehicle, high frequency power generation, permanent magnet synchronous machine.

I. INTRODUCTION

As NASA readies itself for new space exploration initiatives starting with a human return to the Moon by the year 2020 eventually leading to human exploration of Mars, the requirements for a safe, efficient and comprehensive power system to support the exploration missions will become important issues to consider.

NASA's shuttle orbiters as well as the International Space Station (ISS) are both examples of modern engineering marvels. Power generation on the ISS is based on solar photovoltaics (PV) wherein large solar arrays can be made to follow the sun so as to produce maximum power. Batteries are in place to produce power during dark stages in the orbit. The power generation and distribution on the ISS are strictly dc. The Shuttle Orbiter has a fuel cell based power generation with a combined dc/ac distribution. The dc power system consists of 3 similar strings, each powered by one H₂/O₂ fuel cell rated at 7 KW nominal, 12 KW peak. The ac side has 3 similar strings at 117/203 volts, 3 phase, 400 Hz, 4 wire Y configuration with the neutral grounded to structure.

Mars-bound crew exploration vehicles present extraordinary challenges mainly because of the never-before-attempted human interplanetary travel involved as well as the need to transport some payload for creating a habitat on Mars. Two complex issues need to be considered with regard to power generation and distribution:

- Type of prime mover – Because solar power may not be readily available on parts of the Lunar/Mars surface and also during the long duration flight to Mars, the primary source of power will most likely be nuclear power (Uranium fuel rods) with a secondary source of fuel cell (Hydrogen supply).

- Electric power generator – With nuclear power being the most likely prime mover, the electric power generation source will most likely be an ac generator at a yet to be determined frequency. Thus, a critical issue is whether the generator should generate at constant or variable frequency. This will decide what type of generator to use – whether it is a synchronous machine, an asynchronous induction machine or a switched reluctance machine.

Because of the need for light weight on crew exploration vehicles, higher frequency ac generation at frequencies 400 ~ 1200 Hz as the fundamental frequency is a good option to explore. There is a wealth of literature on application of 400 Hz systems in naval ships and the aerospace industry. Some of US Navy's newest ships use 400 Hz, 3-phase nuclear power generation. The current state-of-the-art in aerospace power is 400 Hz, 115 V (line-neutral), at either variable frequency or constant frequency. Current aircraft electric power generation technology uses both the constant speed drive (CSD) and the variable speed constant frequency (VSCF) technology. The CSD is an engine mounted generator system complete with an electrical generator and a variable displacement pump that constantly adjusts the output shaft rotation to maintain 24,000 RPM regardless of the throttle setting of the engine.

The VSCF system is becoming the technology of choice lately mainly because of the advantages that power electronics provides from the perspective of weight and reliability. Fig. 23 shows a block diagram of such a system.

Unfortunately, some of the conditions for future explorations beyond LEO will be quite different. The fuel source will be different and the system will be required to operate at higher voltage and power levels and for much longer durations without maintenance.

This paper presents preliminary results of a study meant to investigate the use of a permanent magnet synchronous machine as a possible source of electromechanical power generation:

II. THE PERMANENT MAGNET GENERATOR

A permanent magnet machine topology is selected for final design and performance analysis. The requirements of the generator are listed below:

- High power density and energy density - this will ensure that the machine is compact, which is a major

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consideration, as the machine needs to be transported along with the vehicle.

- Relatively high electrical frequency resulting in reduced machine size.
- Low rotor loss causing less heating and in turn enhancing machine life.
- Low torque ripple (low cogging) and lower THD of flux results in a safer, interference-free operation.
- High thermal endurance and ability to operate in vacuum without extensive cooling requirement.

A conceptual block diagram of the overall generating system is depicted in the block diagram of Fig. 1. It gives a fair idea about the involvement of power electronic circuitry in the system.

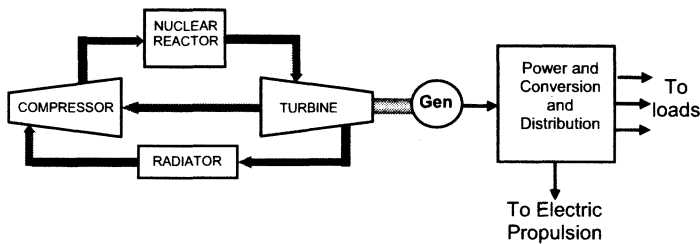


Fig. 1. Conceptual block diagram of the generating system

III. DESIGNING A HIGH FREQUENCY PERMANENT MAGNET MACHINE

The permanent magnet generator is a synchronous machine where the rotor windings have been replaced with permanent magnets. This in turn reduces the copper losses in the machine. Iron losses form a larger portion of total losses in PM machines [3]. The permanent magnet generator is popular in automotive applications because of its efficiency, reliability, high power density, and possibilities for high speed operating points. These qualities make it a very promising candidate for space application. These machines are becoming popular in view of their higher potential efficiencies, high power densities and the availability of high-energy permanent magnet materials [9], [10], [12]. The axial flux PM machine is one variation of the traditional PM machine. This type of machine is discussed in [13] [14] and [6]. This study will only concentrate on the radial flux type PM machines.

Advantages

- Permanent magnet topology can impart savings in machine weight and size
- Permanent magnets enhance manual voltage control regulation as the PMG provides a more stable power source to the manual control.
- A certain types of permanent magnet generators [2] can result into an improvement of power densities by almost a factor of 2, over induction machines.
- With proper design PM machine generally results in higher energy efficiency than any other type of rotating machine an equivalent power output. PM machines have between 90 and 95% efficiency

compared to a starter generator that provides up to 80% efficiency.

- Absence of brushes, slip-rings, excitation windings result in an impressive decrease in losses.

Disadvantages

- The problem with permanent magnet generators is that if they are overloaded, their maximum torque is lost until the magnet is re-magnetized.
- They have a high manufacturing cost due to permanent magnets in rotor.
- While improving power and torque density, the efficiency of machine might suffer.

Many parameters are involved in the design of any electrical machine. There are no definite guidelines for the procedure. Hence one has to rely heavily on some assumptions as a starting point in the design. It is absolutely necessary to assign constant values to some of the parameters and then determine the remaining part of the design [5]. Again these fixed parameters may vary as per the design purpose. Common fixed parameters will be rated speed, torque, power output, permitted volume and related geometrical as well as electrical properties of materials. The magnetic properties desired and the electrical quantities dictate the geometrical parameters which are assumed. The axial length, rotor outer radius, stator outer radius are assumed to be fixed. By specifying these, the design equations follow in a straightforward fashion and no iteration is required to find the solution to the design problem. Design process for a radial flux PM machine is written in MATLAB due to its flexibility and ability to give results in various formats. Various assumptions in the code are supported by the references there itself in the commented parts. The design is started from the basic geometrical constraints and the magnetic circuit describing the flux flow. The design equations relating fixed parameters and the desired characteristics are used in the code. Loss calculation is one aspect which has numerous approaches [3] [7] [8]. These loss computations lead to defining efficiency of the machine. Permanent magnet does not have rotor windings, hence lower copper losses. Also the machine will most probably be operated in vacuum, which is a reason fair enough to assume very low windage losses. The design procedure followed here is just one of the many processes. The designing of machine emerges out as basically a game of studied trade-offs. The material we choose for every component of the machine has a very high impact on the performance characteristics. Permanent magnet materials have come a long way [9], [10]. The MATLAB code attached herewith needs modifications with regards to the loss calculations and dependence of a certain quantities on frequency. Some variations of PM machines such as switched reluctance generators, axial-flux PM machines are also attractive candidates for this application. Keeping that in mind an attempt is made to create a basic structure of the design so that it can be adapted for designing of these machines as well.

A. Design Approach

The design equations are based on an approach which starts with basic motor geometrical constraints and a magnetic

circuit model. The electrical model is usually a consequence of the magnetic model in machine design. This is so because of the need to create and maintain a certain amount of flux. After surveying a number of permanent magnet machines of a wide range of ratings for high frequency operation [11], [3], [8], [1], a certain constraint for the size of the machine is assumed as a starting point. Thus assumption of a compact machine dimensions for a certain power output at a specific frequency is the initiation of the design process. Apart from the loss component calculations, the design equations used are based on the processes and analysis in [6] and [15]. Radial flux topology is considered at the beginning, as it is the most widely available for future testing purpose.

B. Fixed Parameters of the Machine

Machine design is a process which cannot be defined in terms of a specific sequence and set of equations. As a result of a lot of unknown parameters, it is necessary to fix some of them and then determine the remaining as a part of the design [6]. The choice of fixed parameters is totally dependent on the designer. As we know that the machine required for this particular application has to be compact, with a high power density, the assumptions are in line with these requirements. Parameters like rated power, operating frequency, EMF, maximum conductor current density are measures of the output and input of the machine. Geometrical and constructional details such as number of phases, magnet poles, slots per phase, etc. are also classified as fixed parameters. By making a certain assumptions about the properties of the materials, we can proceed to a design procedure. Use of other materials will affect the entire machine performance, but going through the design procedure once, gives an idea of impact of the material properties on the entire design. The fixed parameters are listed in Table 1.

The design equations which are used for the design are included in a MATLAB routine for finding out operating parameters as the size of the machine varies. A similar routine to examine the effect of varying the designed frequency was also developed.

Geometric parameters

Using the fixed parameters, the various radii associated with the machine are identified as follows –

The stator outer radius is calculated from the inner radius and the back iron width. This further leads to the rotor outer radius. From the angular pole pitch one can find out the pole pitch at inner stator surface as,

$$\tau_p = R_{si} \theta_p \quad (1)$$

Where the angular pole pitch is, $\theta_p = \frac{2\pi}{N_m}$

Coil Pitch at Stator Inner Radius is given by,

$$\tau_c = \alpha_p \tau_p \quad (2)$$

[NOTE: Here $\alpha_p = \frac{\tau_c}{\tau_p} = \text{int} \frac{(N_{spp})}{N_{spp}}$]

Table 1. The fixed parameters of the PMSM

Parameter	Description
P	Power (Hp)
f	Operating frequency (Hz)
E_{\max}	Maximum EMF (V)
J_{\max}	Maximum slot current density (A/m ³)
N_{ph}	Number of phases
N_m	Number of magnet poles
N_{sp}	Number of slots per pole phase $N_{sp} \geq N_m$
g	Air gap length (m)
l_m	Magnet length (m)
R_{so}	Stator outside radius (m)
R_{ro}	Rotor outside radius (m)
L	Motor axial length (m)
k_{st}	Lamination stacking factor
ρ_{bi}	Steel mass density
ρ	Conductor resistivity
k_{cp}	Conductor packing factor
α_m	Magnet fraction
B_r	Magnet remanence (T)
μ_R	Magnet recoil permeability
B_{\max}	Maximum steel flux density (T)
w_s	Slot opening (m)
α_{sd}	Shoe depth fraction

This is the expression for the pitch factor. When N_{spp} is an integer, then pitch factor is 1. But sometimes N_{spp} comes out to be a fraction. In that case coil pitch is less than the pole pitch and the winding is said to be short-pitched. This design does not consider short pitched coils.]

Along similar lines, the slot Pitch at Stator Inner Radius is found out to be,

$$\tau_s = R_{si} \theta_s \quad (3)$$

Where Angular Slot-Pitch in mechanical radians is $\theta_s = \frac{2\pi}{N_s}$

From this data, the slot and teeth dimensions can be determined as follows –

Tooth Width is,

$$w_t = \tau_s - w_s \quad (4)$$

And Slot Bottom Width is given by,

$$w_{sb} = R_{sb} \theta_s - w_{tb} \quad (5)$$

[NOTE: The dimensions of tooth are given by

$d_s = d_1 + d_2 + d_3$, where d_s is the tooth projection from the back iron core. The shoe of the tooth has height given by, $d_1 + d_2 = \alpha_{sd} w_{tb}$. The portion of the slot which houses a conductor is having a height $d_3 = d_s - \alpha_{sd} - w_{tb}$.

When the teeth are parallel-sided a trapezoidal shaped slot area is achieved. It maximizes the winding area available and is used when the windings are to be wound turn-by-turn. On the other hand a parallel-sides slot design is used when the windings are formed prior to insertion into the slot. We have considered a trapezoidal slot here.]

Once we achieve the dimensional details of slots and various radii, we can find out the slot cross sectional area available for conductors as,

$$A_s = d_3 \left[\theta_s \left(R_{sb} - \frac{d_3}{2} \right) - w_{tb} \right] \quad (6)$$

[NOTE: Stator windings occupy this cross-sectional area, but due to insulations, slot-liners, etc. this entire area is not filled with conducting material. Hence a conductor packing factor needs to be defined as $k_{cp} = \text{Area occupied by conductors} / \text{Total area}$]

Slot width just after the shoe portion of tooth is,

$$w_{si} = (R_{si} + \alpha_{sd} w_{tb}) \theta_s - w_{tb} \quad (7)$$

Where slot fraction is $\alpha_s = \frac{w_{si}}{(w_{si} + w_{tb})}$

Total Slot Depth is given by,

$$d_s = R_{sb} - R_{ro} - g \quad (8)$$

Magnetic parameters

The flux path from rotor magnets-to-air gap-to-stator and back to rotor magnets shows that the machine can be modeled as one closed loop flux that repeats itself indefinitely. Flux from each magnet on rotor splits equally on both sides and couples to the two adjacent magnets. Thus we have a complete magnetic circuit with flux flowing through a number of reluctances such as rotor back iron, stator back iron, and air gap reluctance. The reluctances can be represented as permeances and parallel permeances are added. Expressions for the permeances in terms of geometric parameters are used to simplify the magnetic circuit. To find out the air gap flux density we need a magnet leakage factor, flux concentration factor, permeance coefficient and carter coefficient. These quantities are defined in terms of geometric as well fixed parameters as follows –

First of all we have to take into account the irregularities introduced by the slotted design. This calls for a correction in air gap dimension. This correction is given by Carter Coefficient. For Carter Coefficient, the effective airgap is

$$\text{given by } g_c = g + \frac{l_m}{\mu_r}$$

Air-gap area is now given by

$$A_g = \frac{(\tau_p)(L)(1+\alpha_m)}{2} \quad \text{Where } \alpha_m \text{ is the Magnet Fraction} \quad (9)$$

[NOTE: In all the above expressions, α_m is the Magnet Fraction defined as follows –

$$\alpha_m = (\text{Periphery covered by Magnets} / \text{Total Periphery})]$$

Using the above data, we can arrive at the air gap flux density and hence the air gap flux,

$$B_g = \left[\frac{C_\phi}{\left(1 + \frac{(\mu_R)(k_c)(k_{ml})}{P_c}\right)} \right] B_r \quad \text{And } \phi_g = B_g A_g \quad (10)$$

Where $k_c = \text{Carter Coefficient}$

$k_{ml} = \text{Magnet Leakage Factor}$

$\mu_R = \text{Magnet Recoil Permeability}$

$P_c = \text{Permeance coefficient}$

$B_r = \text{Magnet Remnance}$

This flux splits equally into both stator and rotor back irons and gets coupled to the adjacent magnets. Thus the back iron flux is given as,

$$\phi_{bi} = \frac{\phi_g}{2} \quad (11)$$

We know the maximum flux density B_{\max} allowed in the back iron from the fixed parameters. Using that, back iron width can be found out,

$$w_{bi} = \frac{\phi_g}{2(B_{\max})(k_{st})(L)} \quad (12)$$

Now the air gap flux can also be used to determine the tooth width as we already know the maximum flux density allowed in the teeth. The air gap flux travels through the same number of teeth as the number of slots per pole. Using this we get the tooth width as,

$$w_{tb} = \frac{\phi_g}{(N_{sm})(B_{\max})(k_{st})(L)} = \frac{2w_{bi}}{N_{sm}} \quad (13)$$

Thus from the magnetic model, we have achieved the knowledge of actually construction details of the machine stator.

Electrical Parameters

Electrical parameters are a consequence of the geometric and magnetic design of the machine. The parameters resistances, inductances, current, EMF are all dependent on how the windings are. Machine ratings like the rated power, torque, speed, etc. dictate these parameters. The relationships which lead to acquiring the electrical parameters are as follows:

The rated angular speed is determined from the desired frequency at which we want the machine to operate.

The force produced by interaction of N_m magnet poles providing an air gap flux density of B_g with each pole interacting with n_s conductors, each carrying i current exposed over length L is given by,

$$F = (N_m)(B_g)(L)(N_{spp})(n_s)(i) \quad (14)$$

Now this force can be used to express machine torque in terms of the machine parameters already derived and assumed as fixed parameters as,

$$T = (N_m)(B_g)(L)(N_{spp})(n_s)(i)(R_{ro}) \quad (15)$$

When the number of slots per pole per phase is greater than one then a distribution factor comes into picture, which accounts for the reduction in the peak flux. A pitch factor also needs to be applied to the flux in that case. Also if the magnets are skewed, a skew factor is included as well. The final expression for torque becomes,

$$T = (N_m)(k_p)(k_d)(k_s)(B_g)(L)(N_{spp})(n_s)(i)(R_{ro}) \quad (16)$$

From the torque expression, the back emf is gives as

$$e_{\max} = \frac{T(w_m)}{i} = (N_m)(k_p)(k_d)(k_s)(B_g)(L)(N_{spp})(n_s)(R_{ro})(w_m) \quad (17)$$

This is the peak back emf at rated speed. This emf multiplied by the number of turns per slot gives the total emf. E_{\max} . This can lead us to find out the number turns per slot to be used to find out e_{\max} .

$$n_s = \text{int}\left[\frac{E_{\max}}{(N_m)(k_p)(k_d)(k_s)(B_g)(L)(N_{spp})(R_{ro})(w_m)}\right] \quad (18)$$

This truncated value of number of turns per slot is used to find out the actual emf resulting from the design.

The number of turns per slot also gives the total slot current,

$$I_s = \frac{T}{(N_m)(k_p)(k_d)(k_s)(B_g)(L)(N_{spp})(R_{ro})} \quad (19)$$

This slot current gives us the knowledge of the slot current density, as we already know the slot area. If this value exceeds the maximum permissible current density J_{\max} then, the slot area has to be increased by changing the stator outer radius and rotor outer radius.

Once we have the slot current, we can deduce the expression from phase current as we know the total number of slots and the number of phases.

$$I_{ph} = \frac{I_s}{(N_{ph})(n_s)} \quad (20)$$

Now that we have established the expression for current, we proceed to model the resistances and inductances in the machine. These components will prove to be useful while calculating the losses for the purpose of testing the efficiency of the machine.

TOTAL RESISTANCE

The total resistance of the winding is composed of two significant components, the slot resistance and end turn resistance. Using the value of resistivity and geometric orientation of the conductors in the slot, the two components are found out as,

$$R_s = \frac{(\rho)(n_s^2)(L)}{(k_{cp})(A_s)} \quad \text{and} \quad R_e = \frac{(\rho)(n_s^2)(\pi)(\tau_c)}{2(k_{cp})(A_s)} \quad (21)$$

Here slot cross-sectional area and conductor packing factor (defined earlier) are used to find out the resistance for a single slot. It is further multiplied by the number of slots per phase to get the total resistance.

The total phase resistance is the simple addition of these two components.

$$R_{ph} = N_{sp}(R_s + R_e) \quad (22)$$

TOTAL INDUCTANCE –

The phase inductance has three main components that are dictated by the machine geometry and the magnetic design. The air gap inductance, slot inductance and end turn inductance are as follows,

Air gap inductance is,

$$L_g = \frac{(n_s^2)(\mu_R)(\mu_o)(L)(\tau_c)(k_d)}{4[l_m + (\mu_R)(k_c)(g)]} \quad (23)$$

(Here k_d is used to compensate the air gap inductance roughly for distributed windings)

Slot leakage inductance per slot is,

$$L_s = n_s^2 \left[\frac{\mu_o d_3 L}{3w_{sb}} + \frac{\mu_o d_2 L}{(w_s + w_b)} + \frac{\mu_o d_1 L}{w_s} \right] \quad (24)$$

(In this expression the first term accounts for inductance of the straight part of the slot, the second term is the inductance of sloping portion of the shoe part of the slot and the third term accounts for the inductance of the shoe tip of the slot). When width of the slot bottom is expressed in terms of the slot cross-sectional area, we get,

$$L_s = n_s^2 \left[\frac{\mu_o d_3 L}{3A_s} + \frac{\mu_o d_2 L}{(w_s + w_b)} + \frac{\mu_o d_1 L}{w_s} \right] \quad (25)$$

End turn inductance is given by

$$L_e = \frac{n_s^2 \mu_o \tau_c}{8} \ln \left(\frac{\tau_c^2 \pi}{4A_s} \right) \quad (26)$$

The total phase inductance per phase is the combination of these three inductances multiplied by the number of slots per phase.

$$L_{ph} = N_{sp} (L_g + L_s + L_e) \quad (27)$$

Operating Parameters

These are the quantities which are in some way result of the design process carried out so far. The fixed parameters and all other design and performance parameters derived from them; are used in the following expressions to see whether the machine designed to give a specific output; performs as desired. Main concern in designing any machine is to have minimum losses. For this particular application, where efficiency is of utmost importance, it becomes mandatory to pay much attention to the efficiency of the designed machine. For finding out the efficiency, there are well established set of procedures. First of all various loss components are modeled from the available machine parameters and then these loss components are added up to give the total losses. Performance measures also include material cost, tooling and fabrication cost, power density and efficiency. Out of which the power density aspect is discussed in detailed in [2], which shows an improvement of nearly a factor of two for high-speed Doubly Salient Permanent Magnet (DSPM) machine over the induction machine. A slight efficiency penalty is expected at high speeds. SRMs which are very much like the DSPM machines are a good candidate for improving power density. The Radial Flux Permanent Magnet machine is from the same family and hence an acceptable magnitude of power density is a fair approximation at this stage.

Loss Components:

As specified earlier, to compute efficiency, it is necessary to compute

- Ohmic winding losses
- Core losses
- Other losses like Friction and Windage losses, Bearing losses etc.

Ohmic Losses -

In most of the machines these losses cover a great deal of the total loss. In PM machine there are no rotor windings. Hence one major source of ohmic losses is eliminated. The loss mainly takes place in stator winding. This loss is the sum of $I^2 R$ loss from all the phases and it is given as,

$$P_r = N_{ph} (I_{ph}^2) R_{ph} \quad (28)$$

As a square wave EMF distribution is assumed, this loss can actually be higher than that given in this equation.

Core Losses -

Core losses are mainly comprised of Hysteresis loss and Eddy current loss. Of all the loss components, the core loss is the most difficult to compute accurately. The magnets and the rotor back iron experience little variation in magnetic flux and hence do not generate significant core loss. On the other hand the stator back iron and stator teeth experience a variation of the magnitude B_{max} at the fundamental electrical frequency.

Using this knowledge the stator core loss can be roughly approximated. In reality, various areas of stator experience different flux density magnitudes and different flux wave shapes as well. This makes it difficult to use the traditional core loss curves which are based on the traditional sinusoidal flux density assumption. There are various methods for computing the core loss. Some of them are discussed in [3], [6], [7], and [14]. All the methods revolve around the same principle. We have used the classical expressions [6] which make use of Hysteresis constant and Eddy constant. Hysteresis loss is directly proportional to the size of hysteresis loop for the specific material. It is proportional to magnitude of excitation.

$$P_h = (k_h)(f)(B_m^n) \quad (29)$$

Where, k_h is the hysteresis constant which depends upon the material type and dimensions. f , is the frequency and B_m is the maximum flux density within the material and the index n depends on the material used. (Usually ranges between 1.5 to 2.5)

Eddy current loss expression is also based on a similar expression mentioned in [6] and [15]. These losses are caused due to induced electric currents within the ferromagnetic material under time-varying excitation. The power loss takes place due to resistivity of the core material. Eddy current loss expression is,

$$P_e = (k_e)(f^2)(B_m) \quad (30)$$

Where, k_e is the Eddy constant. From the expressions it is evident that the Hysteresis loss component is dominant at low frequencies and Eddy loss component is dominant at high frequencies. As per [8], a stacking factor can be used in the expressions for these losses. This factor accounts for the reduction in the magnetic material available to carry the flux, due to lamination. Typical stacking factors are 0.5 to 0.95.

Finally total core loss will be given by the addition of these two components,

$$P_{cl} = P_h + P_e \quad (31)$$

Friction and Windage Loss -

Air Friction Losses -

These losses can be calculated using Axial Reynolds's Number, when forced air-cooling is used [13]. For this purpose we need to make use of a friction coefficient which depends on Reynolds's number, density of fluid angular velocity and dimensional details. As far as this particular application is considered, the machine will in all probabilities, be operating in vacuum or a controlled environment. The assumption of very low friction losses sounds to be fair under these conditions. Other source for friction loss is the bearings. This loss would depend on the material used, lubrication, speed of operation, etc. Usually the manufacturers provide the data for friction losses in bearings (viz. 1 kW at 7000 rpm). Overall the friction and windage losses will contribute very little to the total loss as compared to the core loss.

The whole purpose of investigating the losses in detail is to get a fair idea about the efficiency of the machine. Once we know the losses the efficiency can be calculated as,

$$\eta = \text{Output Power} / (\text{Output power} + \text{Losses}) \quad (32)$$

Now that we have an insight into the efficiency of the machine, we can say that an important parameter of the machine is in our control. The equations and the assumptions presented represent just one of the many approaches towards the machine design. There can be as many approaches as the number of designers. Though all the approaches lead to different designs; the trade-offs will remain more or less the same. The performance of the machine will certainly deviate from these design equations. And this deviation will depend on how the assumptions are met. For instance, we have assumed a certain values for conductivities, or permeabilities for the materials used. Now, if the actual materials used do not adhere to these assumptions then we can surely expect some unexpected results.

IV. RESULTS

The results obtained from this design procedure are presented along with this report. The machine performance is observed in terms of the efficiency, torque, losses, and phase currents against the variation in the operating frequency. Keeping in mind that the frequency of the machine will dictate the size, we have obtained the results at 60Hz, 400Hz, 800Hz and 1200Hz. The results show a similar trend in the variation. But one important thing to note here is again the effect of some of the assumptions made. A few assumptions are very critical to the overall performance of the machine. One set of assumptions which was visibly very dominant in dictating the performance was K_e (Eddy current constant for the core material) and K_h (Hysteresis constant for the core material). A small change in the values of these constants imparts a huge change in the efficiency of the machine. This is because these constants are responsible for determining the losses in the machine. The variation in efficiency of machine as against the change in these constants is shown in Figs. 2 and 3.

There can be a number of design philosophies, but it is very difficult to get rid of the variations and unexpected results obtained due to a few assumptions. The previous case is just one of the examples of the magnitude in which these assumptions can affect the performance of the machine.

V. COMPUTER-AIDED DESIGN AND STUDY

A computer aided design was also carried out using Ansoft's RMXprt tool. For this purpose we use the parametric data obtained so far and follow a set of design steps:

- General data such as rated power output, rated voltage and number of poles is determined.
- From the previous computational analysis we have a fair idea about the dimensions of the machine. This data is used to define some stator parameters such as slot type and dimensions, stator diameter, winding orientation, etc.
- Rotor data like permanent magnet material, rotor shape, pole embrace, etc. are defined as visible from the following screen captures.

The detailed design process with ANSOFT is based on the steps mentioned above. The outcome worth looking at was the size of the machine. Using a fixed set of inputs, RMXprt comes up with a design which facilitates the comparison between the machine performance at various frequencies. The comparison is presented in Table 2.

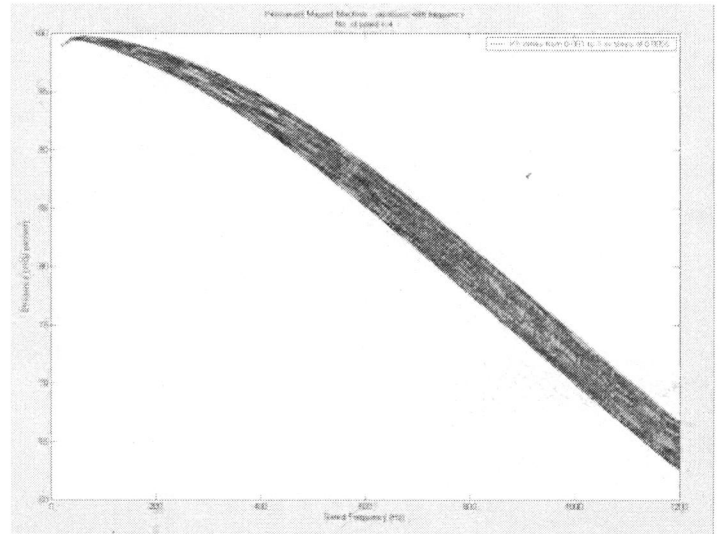


Fig. 2. Variation in efficiency as a function of frequency as well as K_h

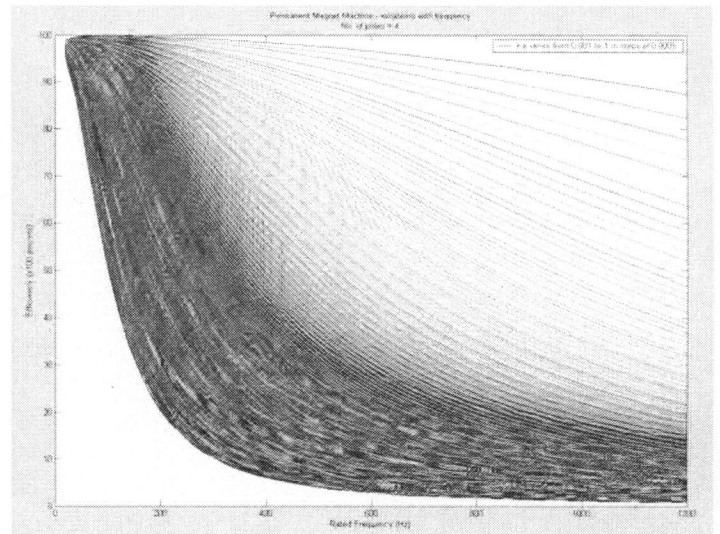


Fig. 3. Variation in efficiency as a function of frequency as well as K_e

VI. CONCLUSION

This study clearly points out the fact that as we go on opting for higher operating frequencies, the machine can deliver more power for the same dimensions. But there is not a large variation in frequency beyond a certain point, which means that for a high frequency operation the input power has to be more. This will dictate the choice of a prime mover. Considering this particular application the prime mover has to be capable of providing that much of input power continuously for a long time. The variation in the size of the machine will directly affect the magnetic flux density and the magnetic flux existing in the machine, as discussed in

equations (9), (10), and (11). The Carter Coefficient will change due to change in the dimensions of the machine. This will affect the operating characteristics.

Table 2. Machine comparisons at different frequencies

Operating Frequency (Hz)	60	400	600	800	1000
Power Output (W)	458	19206	41687	71508	107590
Input Power Required (W)	538.2	19940	44828	77730	115904
Total Losses (W)	80.14	733.43	3140.9	6222.2	8314.0
Core Losses (W)	59.97	706.34	3105.5	6175.8	8254.3
Copper Losses (W)	0.169	7.0877	15.384	26.389	39.704
Efficiency (%)	85.1	96.321	92.993	91.995	92.827
RMS Phase Current (A)	9.09	63.897	94.137	123.29	151.23
Armature Current Density (A/mm ²)	0.058	0.3761	0.5541	0.7257	0.8901
Stator Teeth Flux Density (T)	0.83	0.8305	1.3380	1.5649	1.5650

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