

Field loss calculation of a wind-powered axial flux alternator by analytical equations

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Abstract

Various techniques have been investigated and proposed for core loss minimization in electrical machines. Nevertheless, many of such methods are mostly complicated and not suitable for consideration at a preliminary design stage. In this work, a simplified procedure which uses an analytical approach to minimizing the field's losses of an Axial Flux Permanent Magnet Alternator (AFPMA), is presented. First, the output equation of an AFPMA is referred, and then the minimization of the losses is investigated by analytical differential equations. The result of the derived-specific magnetic loading is investigated using three different core materials, namely 35RM300, 50JN350, and 65JN800, and is found to reduce with increased frequencies. The 35RM300 core material gives the maximum specific magnetic loading and minimum power loss at investigated frequencies of 50 to 500 Hz. Although the 35RM300 core material gives the best performance, the optimal values are only determined as suitable by the manufacturer's design criteria. This study is a key indicator for a simple and efficient core material selection in the design of a Wind-Powered AFPMA without the need for complicated analyses at the preliminary design stage.

KEYWORDS

axial flux, core materials, field losses, permanent magnet alternator

1 | INTRODUCTION

Axial flux permanent magnet machines (AFPMM) have been largely investigated in the past four decades for their variety of applications and performances with growing interests in key aspects of the analysis.¹ Generally, the direction of flow of flux, determine whether a permanent magnet (PMs) machine is axial-flux or radial-flux.^{2,3} In axial flux PM machines, the flux is linked with the stator conductors in axial direction. AFPMM have compact and simple construction, short frame, high power density, high efficiency, no rotor power loss due to the PM excitation and of low-speed configurations, hence, are preferred alternative to the radial flux permanent magnet machines.⁴⁻¹⁰ AFPMM are configured as either single or double-sided, slotted or slot-less, surface-mounted, or interior permanent magnet, single or multi-stage external

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stator or rotor.^{4,8,11,12} Advantages of the slotless configurations include high flux density at the airgap, no cogging torques, lower stator inductance, elimination of iron saturation in the stator teeth, and so forth. Although with a major setback of an increased number of PMs for equal magnetic field density compared with the slotted configuration, the advantages outweigh the drawback since the slotless structure potentially offers simplicity in construction, lesser cost, and higher efficiency.^{8,13,14} Some areas of applications of AFPMM include electric vehicles, fans, pumps, and wind generators,^{9,15} and so forth.

AFPMM utilize neodymium iron boron magnets (NdFeB) which are increasingly being deployed due to its high energy production, high coercive force, and relatively low cost.¹⁶⁻²⁰ They are the strongest PM available with their improved saturation magnetization and its demand continuously on the increase.²¹⁻²⁵ PMs have gained increased attention due to their high torque-inertia ratio, high efficiency, high power density, and robustness.^{11,26,27} The adoption of these high energy density NdFeB type permanent magnets for PM machine designs allow for complete ironless stator configurations and hence, are suitable for direct drive applications.^{13,28-30} These machines possess high torque or power density, high efficiency, and low maintenance,³¹ hence, making them the greatest choice for various direct drive applications like electric vehicles, wind turbines, and marine energy converters,^{32,33} and so forth. Furthermore, PM machines have become more popular given its possibility of reduced motor size with increased qualitative parameters.³¹

AFPMM are grouped and analyzed depending on the configurations of the PMs and the windings on the stator and the rotor. These include stator-rotor arrangement as single-stator single-rotor (single-sided); Double stator single rotor (The Kaman type); Single stator double rotor (Torus type); or multi-disk structure (The Kaman, Torus or multi stator-multi rotor). The winding can be drum wound or ring wound depending on the configuration, existence of armature slots as slotted stators or toroidally wound slot-less stators (which can be of iron or ironless core). Also, the classification can be based on the technique of integrating the PMs to the rotor as either surface-mounted PMs type or internal/buried PMs type.^{1,4,5,7,8,34} The external-stator configurations utilize fewer PMs but require more windings whereas the external rotor configuration presents limited space, mechanically robust, and improved torque-to-volume ratio.¹¹ The minimum configuration of the multi-disk structure is either comprised of two external stators and an internally placed rotor or one internally positioned stator and two externally placed rotors. This configuration is generally comprised of some number of stator and rotor arrangements that are one less than the other. Figure 1³⁵ shows a typical AFPMM with two external rotors and one internal stator.

An active field of research in AFPMM is the loss analysis which has resulted in various analytical and systematic approaches.^{1,4,10,34} The major losses accounted for in this type of machine are hysteresis losses, eddy current losses, and stator copper losses.³⁶ PMs are recommended for a direct drive or high-powered wind turbine configuration due to their high torque/volume ratio, longer operating life, and increased efficiency.^{5,7,10,29,37} However, they are characterized by a potentially unacceptable level of core losses especially in multi-disks configurations of the rotor equipped with PMs. The stator copper loss depends directly on the current induced which depends on the field density at the airgap. Moreover, the use of PM excitation means the possibility of surface mounting with the advantage of low or no field losses.^{38,39} Therefore, the main losses of AFPMM are due to the core losses.⁴⁰

Several approaches exist for achieving general designs, optimization, and performance evaluation of AFPMM and these include analytical approaches, shape modifications, deterministic methods, geometrical analysis, or simulation

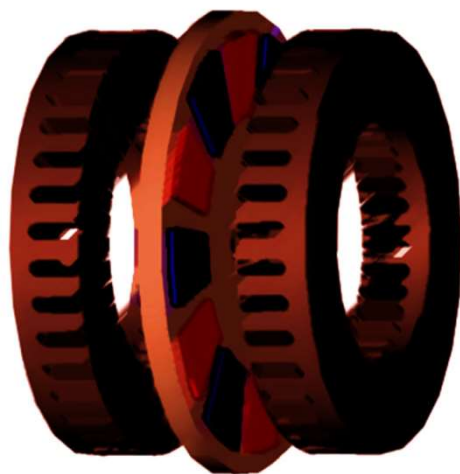


FIGURE 1 A typical AFPMM structure

techniques.^{4,7-11,31} However, close emphasis on iron loss reduction for increased efficiency must be ensured. Another key issue in the design of Axial Flux Permanent Magnet Alternator (AFPMA), is the magnetic saturation which must also be considered as it is capable of increasing the losses and degrading the machine performance.³² Several techniques including substitution techniques of reducing the use of PMs, steady state thermal modeling, Finite Element Analysis, and some optimization techniques based on machine sizing equations have been presented in the modeling and various performance analysis of various aspects of AFPMM.^{11,32,41-45} Nonetheless, they are mostly computationally expensive and generally found unfavorable for consideration at the preliminary design stage.

In this work, an analytical approach for minimizing the field losses of an AFPMA which is suitable for consideration at the preliminary design stage is presented. This machine is a multi-disk structure of two external rotors and one internal stator with a slot-less stator type of concentrated air-cored winding while the rotor is of the surface-mounted PMs type with the magnets axially distributed. Each rotor face carries 8-pole PMs. The minimized core loss of the machine structure is derived. This work is a continuation of an aspect of the work presented in Reference 10 which gave detailed analytical steps to the design of the machine's parameters. The specific magnetic loading equation is derived from the output equation of the AFPMA. Minimization of the specific magnetic loading is analytically carried out using differential equations. The result of the derived specific magnetic loading is investigated using three different core materials namely 35RM300, 50JN350, and 65JN800 on different range of frequencies to observe the specific magnetic loadings and power loss characteristics. The obtained results are then discussed and its implication on the selection of core materials by manufacturers is also stated. The next section, Section 2 gives the step-by-step analytical equations and the general methodology. The results and discussion are given in Section 3 while conclusion and recommendation are drawn in Section 4.

2 | METHODOLOGY

This work adopts analytical equations to examine the field loss of an AFPMA. First, the total loss of the referred AFPMA is expressed. Each component of the loss equation is then replaced based on its output equation. To examine the field component, the equations are then analyzed to consider the specific magnetic and electrical loadings. The differential of the resulting loss equation derived in terms of the specific magnetic loading is then investigated for minimum power loss. Three core materials, 35RM300, 50JN350, and 65JN800 are examined to determine the change in specific magnetic loadings and power losses with respect to frequency change.

2.1 | Analytical formulation of the total losses

The main losses in an AFPMM with respect to the performance are the iron or core (Fe) losses, copper (Cu) losses, rotational losses (mechanical losses) and some untraceable losses which are often classified as stray losses. Figure 2 shows the simplified representation of the analyzed AFPMA and their associated losses. D_o is the outer diameter with radius r_o and D_i is the internal diameter with radius r_i . D_{av} is the average diameter given by Equation (1).

$$D_{av} = \frac{D_o + D_i}{2} \quad (1)$$

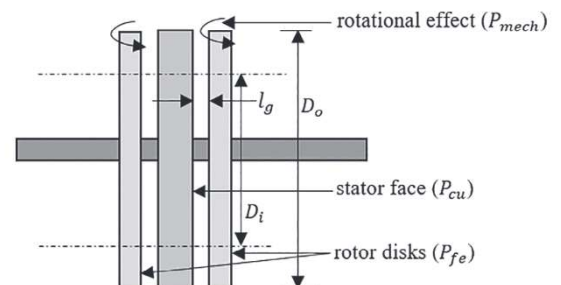


FIGURE 2 A cross section of an AFPMA

Mathematically, the total losses, P_{Tloss} , in an axial flux machine can be deduced as given in Equation (2).

$$P_{Tloss} = P_{fe} + P_{cu} + P_{mech} + P_{stray} \quad (2)$$

where P_{fe} represents the component of the core losses, P_{cu} , the stator copper losses, P_{mech} , the mechanical (i.e., the rotational or friction and windage) losses and P_{stray} , represents the component of the extra losses unaccounted for. The core losses can be expressed as given in Equation (3).

$$P_{fe} = P_{hyst} + P_{eddy} \quad (3)$$

where P_{hyst} is the hysteresis loss and P_{eddy} , the eddy current loss.

Substituting $P_{hyst} = k_h f B_g^2$, $P_{eddy} = K_e f^2 B_g^2$, and $P_{cu} = m R_s I_{ph}^2$ in Equation (2) with k_h and K_e being the hysteresis and eddy current loss constants while B_g is the specific magnetic loading, Equation (4) is obtained.

$$P_{Tloss} = k_h f B_g^2 + K_e f^2 B_g^2 + m R_s I_{ph}^2 + P_{mech} + P_{stray} \quad (4)$$

2.2 | The specific loadings

The specific loadings (electric and magnetic) directly determine the output and they express the relations between the dimensions of the machine and its rating. These parameters allow for the proper selection and sizing of the materials. Since the specific magnetic loading, B_g is of interest in this design, the electric loading, k_1 , is substituted for, to allow for the investigations of change in B_g . Using the relation for the electrical loading, k_1 (Equation [5], as derived in the earlier work),¹⁰ where I_{ph} is the stator phase current, N_{ph} , the number of turns per stator coil, and D_{av} the average diameter of the stator. I_{ph} and P_{cu} can be obtained as expressed in Equations (6) and (7), respectively with R_s being the stator resistance per phase. Efficiency is a direct function of the losses and can be expressed as Equation (8).

$$k_1 = \frac{2\sqrt{2} I_{ph} N_{ph}}{\pi D_{av}} \quad (5)$$

$$I_{ph}^2 = \frac{\pi^2 D_{av}^2 k_1^2}{8 N_{ph}} \quad (6)$$

$$P_{cu} = m R_s I_{ph}^2 = m R_s \frac{\pi^2 D_{av}^2 k_1^2}{8 N_{ph}} \quad (7)$$

$$\eta = (P_{in} - P_{Tloss}) / P_o \quad (8)$$

where P_{in} and P_o are the input and output powers, respectively. To determine the electric loading, k_1 of the machine, the inside apparent power of the machine, P_a , is first determined based on the output equation (Equation (9)).¹⁰

$$P_a = \left(\frac{1}{2} h B_g k_w k_1 \times 10^{-3} \right) D_{av}^2 L_i w_m \quad (9)$$

where k_w is the winding factor (taken as 1), L_i is the effective length of the stator core, w_m is the mechanical speed of the rotor in rps, and h is the number of stator faces. From Equation (9), k_1 is derived (Equation (10)). Squaring both sides of Equation (10) gives Equation (11). A constant C_1 of Equation (12) is established to give a simplified version of Equation (11) to clearly establish the relationship between k_1 and B_g (Equation (13)). Substituting Equation (13) in (7), Equations (14) and (15) are derived with the introduction of another constant, C_2 (Equation (16)) to show the dependence of P_{cu} on B_g .

$$k_1 = \frac{2P_a \times 10^3}{h B_g k_w D_{av}^2 L_i w_m} \quad (10)$$

$$k_1^2 = \left(\frac{2P_a \times 10^3}{hk_w D_{av}^2 L_i W_m} \right)^2 \times \frac{1}{B_g^2} \quad (11)$$

$$C_1 = \left(\frac{2P_a \times 10^3}{hk_w D_{av}^2 L_i W_m} \right)^2 \quad (12)$$

$$k_1^2 = \frac{C_1}{B_g^2} \quad (13)$$

$$P_{cu} = mR_s I_{ph}^2 = mR_s \frac{\pi^2 D_{av}^2}{8N_{ph}} \times \frac{C_1}{B_g^2} \quad (14)$$

$$P_{cu} = \frac{C_1 C_2}{B_g^2} \quad (15)$$

$$C_2 = mR_s \frac{\pi^2 D_{av}^2}{8N_{ph}} \quad (16)$$

The total losses can now be re-written as Equation (17) by substituting Equation (15) in Equation (4). To minimize the total losses with respect to the specific magnetic loading, B_g , Equation (17) is differentiated with respect to B_g to give Equation (18). The minimum loss is obtained at $dP_{Tloss}/dB_g = 0$ and Equation (19) is the obtained expression for B_g at the minimum power loss.

$$P_{Tloss} = k_h f B_g^2 + K_e f^2 B_g^2 + \frac{C_1 C_2}{B_g^2} + P_{mech} + P_{stray} \quad (17)$$

$$\frac{dP_{Tloss}}{dB_g} = 2k_h f B_g + 2K_e f^2 B_g - \frac{2C_1 C_2}{B_g^3} \quad (18)$$

$$B_g = \sqrt[4]{\frac{C_1 C_2}{k_h f + K_e f^2}} \quad (19)$$

3 | RESULTS AND DISCUSSION

The analytical results of Equation (17) show the total losses for an axial flux alternator while Equation (19) gives a critical expression that signifies the minimum specific magnetic loading for the machine at minimum core loss. This value is very useful for manufacturers in carrying out preliminary analysis for material selection before embarking on production. Final decisions are reached based on the nature of the core material of interest. Referring to the key features of the core materials selected for this study and as described in Reference 36, Table 1 gives the minimum loss based on Equation (19) using the machine parameters given in an earlier work¹⁰ with the calculated values of B_g estimated at frequency of 60 Hz. At higher frequencies indicative of higher field weakening region, the losses are higher and so, the values of the specific magnetic loading at these values decrease. Figure 3 shows the variations of these values for each of the studied materials in the frequency range of 50 to 500 Hz in steps of 50 Hz while the corresponding minimum power losses for each of the materials are as presented in Figure 4. Note that the mechanical and stray losses are of less significance since they exhibit no dependence with B_g as shown in Equation (18).

TABLE 1 Field loss values at 60 Hz for the selected materials

Core Material Type	35RM300	50JN350	65JN800
k_h	151	263	495
K_e	0.29	0.39	0.89
Total core loss (at 60 Hz/) in W/kg	3.25	4.45	10.15
B_g (at minimum loss) in mT	5.27	4.62	3.93

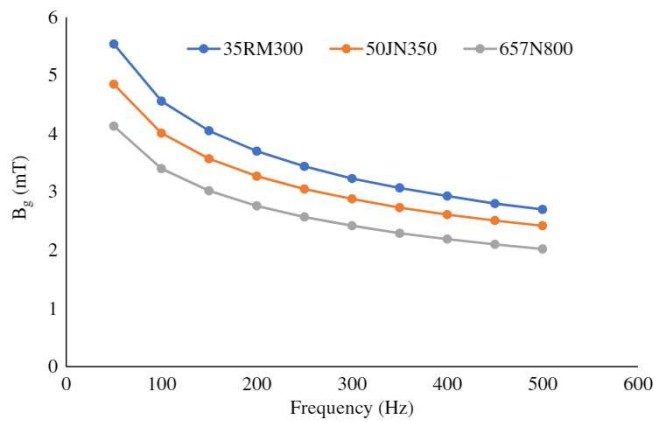


FIGURE 3 Field loss curve at minimum power loss for the selected core materials

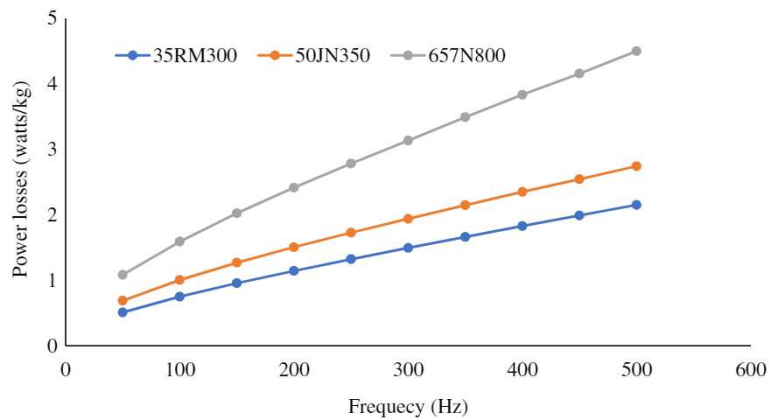


FIGURE 4 The minimum power losses between the frequency range of 50 to 500 Hz

Figures 3 and 4 give the trend indicative of typical core material behavior. Note that k_h and k_e are extrapolated using the loss curve for the selected material. The core material, 35RM300, gives the best performance since it indicates maximum magnetic loading (or minimum core loss) and minimum power loss at all operating frequencies. Although, the optimal values depend on manufacturers' preference and other performance parameters, core material 65JN800 is not suitable for AFPMA as it depicts a sharp increase in the power loss with an increase in the operating frequency. The core loss from 50 to 500 Hz varies at about 76% compared with the work presented by Dutta et al³⁶ and with about 82% variation, for all the three selected core materials. Also, 35RM300 and 65JN800 give the lowest and highest losses, respectively. Equation (19) is derived based on AFPMA, nonetheless, it is a generic model that is amenable to other AFPMM with constants C_1 and C_2 describing the nature of the core materials used. The manufacturer chooses the most suitable material depending on the application, desired operating frequency, temperature, and most importantly, the structure of the machines. No previous work on AFPMA has discussed the preliminary material selection based on core losses as presented in this work. This work has advanced existing research works on the need to further provide a guide for material selections for AFPMA designs.

4 | CONCLUSION AND RECOMMENDATION

This work has presented an analytical formulation and estimation of core losses of an AFPMA at minimum power loss. First, the analytical equations were derived from the output equation which formed the basis for the derivation of the loss model at the minimum power loss. Three core materials, namely, 35RM300, 50JN350, and 65JN800, were investigated using the proposed analytical model. The core material 35RM300 gives maximum magnetic loading (or minimum core loss) and minimum power loss at all operating frequencies, while 65JN800 is found not suitable for AFPMA due to the recorded sharp increase in the power loss with an increase in the operating frequency. The obtained values may be useful to manufacturers in making decisions on the type of core materials suitable for the design of AFPMA at the

preliminary design stage. The machine data used is for those of surface-mounted machine and may not fairly be representative for other structures of the alternator type. However, the model formulation is generic but amenable to other AFPMM with the constants adjusted accordingly depending on the nature of the core materials. For further verification and improvement, these procedures may be formulated and simulated for other structures of the AFPMM for further investigations.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Abdulrahaman Otuoze: Conceptualization; formal analysis; investigation; methodology; resources; validation; visualization; writing-original draft; writing-review and editing. **Olatunji Mohammed:** Conceptualization; formal analysis; investigation; methodology; resources; validation; writing-original draft; writing-review and editing. **Oladimeji Ibrahim:** Conceptualization; formal analysis; investigation; methodology; resources; supervision; validation; visualization; writing-original draft; writing-review and editing. **Sani Salisu:** Conceptualization; formal analysis; investigation; methodology; resources; supervision; validation; writing-original draft; writing-review and editing. **Abioye Emmanuel:** Conceptualization; formal analysis; investigation; methodology; resources; validation; writing-original draft; writing-review and editing. **Ayinde Usman:** Conceptualization; formal analysis; investigation; methodology; resources; validation; writing-original draft; writing-review and editing. **Abdulhakeem Dobi:** Conceptualization; formal analysis; investigation; methodology; resources; validation; writing-original draft; writing-review and editing.

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