Core Loss Analysis of Linear Switched Reluctance Motor

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Abstract : The paper calculates the loss of a switched reluctance motor (SRM) with non-oriented electrical steel cores through the use of analytical equations. The core loss forges to be one of the key factors in deciding the performance of an electric machine and requires extensive considerations to minimize it. The non-oriented electrical steel sheets belong to the category of soft ferromagnetic materials and constitute the electromagnetic core of rotating electrical machines. The materials on being exposed to time-varying magnetic fields bring in the occurrence of the core losses. The losses represent the power dissipated in the ferromagnetic material and owe their dependence to the frequency and magnetic flux density level of the applied time-varying magnetic field. The effort suggests alternatives to the variety of electrical steel sheets and consequently the material of iron core (for both stator and rotor) used in the SRM. The experimental core loss measurements made on the 12/8 SRM using M19G29 over M15G29 serve to validate the results obtained from the numerical computations. The analysis depicts the fact that the core loss dominates around the corner of the rotor and stator cores of the motor and illustrates the choice of M15G29 to be the best core material from the viewpoint of the core loss of the SRM.

***IndexTerms* - Core loss, FEM, non-oriented steels, SRM, time stepped 2D analysis.**

I. INTRODUCTION

The electric motor systems appear to use around 70% of the power demand from the industries [1] to support the emerging automated environment. However the energy scarce scenario and clean energy enforcements augur an efficient use of electric energy in the motor systems. The improvements in the power electronics technology enable the affordable nature of the variable-speed drives and offer resurgence to the use of hybrid vehicles.

Among a host of drive motors the switched reluctance motor (SRM), owing to its exclusive features such as lack of any coil or permanent magnet on the rotor continue to occupy a pre-eminent place. The use of silicon steel in the stator winding allows recycling and ensures a higher reliability for the operation of SRM in hard or sensitive conditions [2]-[4]. Besides the salient rotor structure produces a high torque/inertia ratio to guarantee a fast acceleration and deceleration with low load inertia. Despite the recent developments in the design and application of the SRM [5]–[9], the cost and supply of rare-earth permanent magnets poses a problem for future mass production.

The reports reveal that the SRM can be designed to be competitive with permanent magnet brushless dc motors from the standpoint of efficiency [10]. The use of 6.5% Si steel with 0.10 mm thickness for the core material appears to be the primary reason for enabling the loss reduction and achieving a higher efficiency. It thus becomes important to use proper electrical steel sheets as material for the core [11] and gathers merit to predict the motor iron loss reliably. It turns out to be imperative for estimating the dependence of the motor core loss on the typical magnetic properties in terms of the choice of the core material.

The magnetic cores for the low-voltage ac electric motors, drawn from cold rolled non-oriented (CRNO) electrical steel sheets [12]-[13] classify themselves as soft ferromagnetic materials produced from Fe-Si-C alloys. The cold rolled non oriented electrical steel sheets with nearly isotropic magnetic properties enjoy restricted silicon levels to about 3–3.5% due to rolling behaviour [12]. The issue of the iron losses prediction in CRNO steel sheets invites attention for the designers of magnetic cores [14].

The influence of lamination material on the performance of a single-phase induction motor under sinusoidal waveform excitation [15] and an inverter-driven three-phase induction motor [16] have been investigated by Honda et al. and found that optimum Si content and the other associated material conditions change in accordance with the design considerations such as the stator flux density and the rotating speed. The new magnetic parameters, closely correlated with the 1.5 T core loss and 1.0 T permeability have been reported by Blazek et al. to be effective for predicting the motor efficiency of single-phase and three-phase induction motors [17].

The design of a SRM with a rotor consisting of two hollow iron cylinders and a stator excited in a way that allows a one directional current flow to minimize the iron losses has been discussed in [18]. The core losses and efficiency of the SRM in continuous current mode of operation has been predicted using analytical technique by Amir Parsapour et al. [19]. The core losses have been computed in different parts of the SRM using FEM (Finite Element Method) and Transient-FEM in [20] and [21] respectively. The effect of dynamic eccentricity (DE) and static eccentricity (SE) on the power losses of the induction machines has been examined using PWM voltage control by 2D-FEM [22].

In spite of the study, still it calls for efforts to reduce the iron losses of the core of the electric motors in a perspective to improve its magnetic circuit performance and assuage a higher operational efficiency.

The primary effort extends to examine the choice of proper electrical steel sheets as core material [22] and facilitate to predict the motor iron loss reliably at the design stage. The key feature corners to reduce the core loss of the motor and allow it perform to the best of its capability. The procedure involves stages of simulation and experimental validation to foresee a path for enhancing the performance of the motor. The theory relates to the study of the influence of material magnetic properties on the motor core loss of a 12/8 (12 teeth on stator and 8 teeth on rotor) SRM using various non-oriented steels for the core material.

II. Specification and Iron Material

2.1 Specification

The exercise relies on building the core loss model based on the SRM lamination shapes and dimensional parameters in Table 1 to investigate the influence of electrical steel sheets on the magnetic characteristics and the core loss. It involves varying the material of iron core (both stator core and rotor core) with the other specifications kept consistent. The motor models tested by experiment as seen from Fig. 5 depend on using the progressive die to manufacture the iron cores by the automatic lamination process.

Table 1 Specification of SRM

Sl. No.	Item	Specification
1	No. of phases	3
2	No. of stator/rotor poles	12/8
3	Stator outer diameter	120 mm
4	Stator yoke thickness	11 mm
5	Stator-rotor gap	0.3 mm
6	Rotor outer diameter	70 mm
7	Rotor yoke thickness	7 mm
8	Shaft diameter	30 m

2.2 The Laminated Silicon Steel

The core losses measured according to various acceptable standards [23] [24] [25] remain the same irrespective of their manufacturer, even though different steel manufacturers follow different standards and different nomenclatures for their steel. However the material inherits the same properties like the permeability, resistivity and thickness and thus the core losses. Increasing the electrical resistance of the steel by alloying it with silicon and aluminium reduces the losses of the material while increasing its permeability. The non-oriented steel with 0.5-3.25% silicon up to 0.5% aluminium and 0.005% carbon provide the higher silicon percentages to lower the magnetostriction and together with other alloys decrease the curie temperature of the material for defining a specific material grade.

The Table 2 shows the electrical and physical properties [26] of the non- oriented fully processed (FP) steel with data for the materials M15G29 and M19G24 [27].

Table 2 Magnetic and Material Properties of Used Core Material

Material	Thickness (mm)	Core Loss at 1.5T/100Hz(W/kg)	Density (kg/m^3)	Resistivity ($\mu\Omega-cm$)	Relative Permeability
M19G29	0.3556	5.92	7650	50	6500
M15G29	0.3556	5.65	7650	50	7200

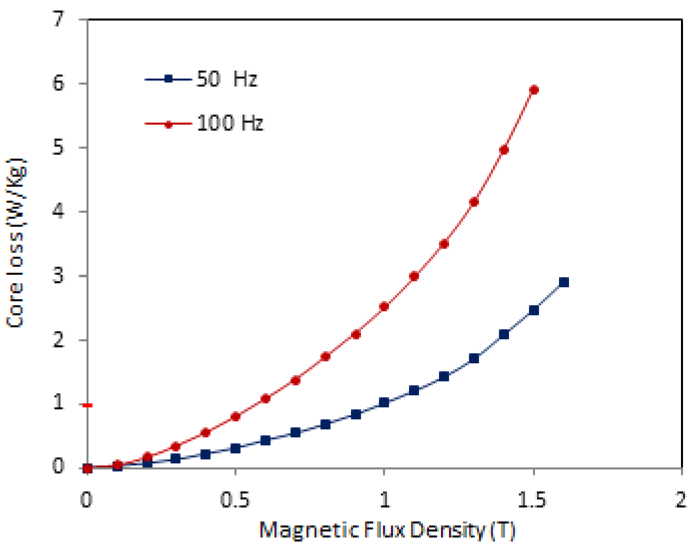

Fig.1 Core loss curve of M19G29 steel at 50 Hz and 100 Hz

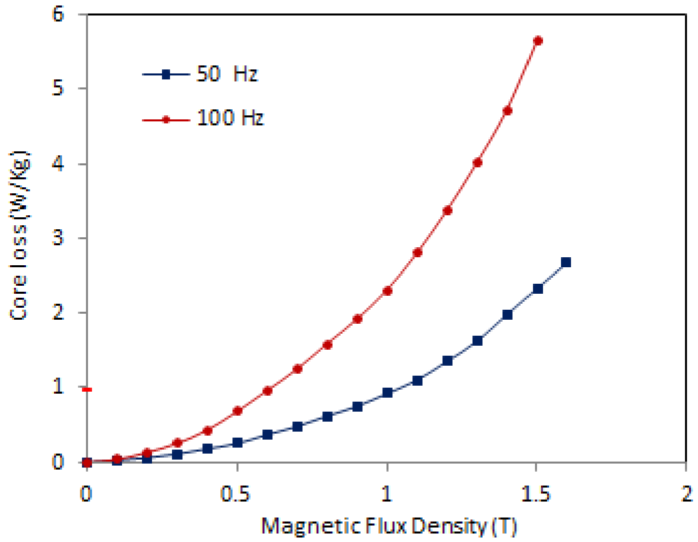

Fig.2 Core loss curve of M15G29 steel at 50 Hz and 100 Hz

III. CORE LOSS EXPRESSION

The modeling of the iron losses in ferromagnetic materials appears to be an enviable task and based on empirical equations obtained from the measurement data. Though a host of methods for determining iron losses remain in vogue [28], still the models based on the Steinmetz equation and the loss separation models invite attention and seem to be best suited for fast iron losses estimation. The commonly used models to estimate the iron losses of ferromagnetic materials [28]-[29] is

$$W_c = K \cdot f^{\alpha} \cdot B_m^{\beta} \tag{1}$$

Where W_c is the core loss, f the field excitation frequency and B_m the magnitude of magnetic flux density and k, α, β refers to the material parameters. However these material parameters range their validity for a limited frequency and the magnetic flux density [28]-[29]. The modifications to Eq. (1) form part of the contributions in [28] and [30]. The second method of estimating the iron losses traces back to the work of Jordan [31] where the iron losses separate into static hysteresis losses (W_h) and dynamic eddy current losses (W_e):

$$W_c = W_h + W_e \tag{2}$$

The hysteresis losses from Eq. (2) can be calculated from Eq. (1) with α = 1. The eddy current losses from Eq. (2) can be calculated with the help of Maxwell's equations [28],

$$W_e = \frac{\sigma \cdot \pi^2 \cdot d^2}{6 \cdot \rho} \cdot B_m^2 \cdot f^2 \tag{3}$$

where σ is the conductivity of the iron material, d is the steel sheet thickness and ρ is the mass density of the ferromagnetic material. The Eq. (3) derived on the homogenous condition of the magnetic material both under consideration of electrical and magnetic conditions [32] follows the assumption of negligible skin effect and the hysteresis losses from Eq. (2) therefore cannot be calculated but requires to be determined by fitting the model to the measurement data.

The third method to improve Eq. (2) is to introduce the excess losses (W_{ex}) [33]:

$$W_c = W_h + W_e + W_{ex} = K_h f (B_m)^2 + K_e (fB_m)^2 + K_{ex} (fB_m)^{1.5} \tag{4}$$

where, the coefficients K_h for hysteresis loss, K_e for eddy current loss and K_{ex} for excess loss. The core loss coefficients such as K_e and K_{ex} are defined by electrical properties of steel material and can be found by curve fitting of the core loss data as shown in Fig. 1 and Fig.2.

IV. Results and Discussion

4.1 Simulation

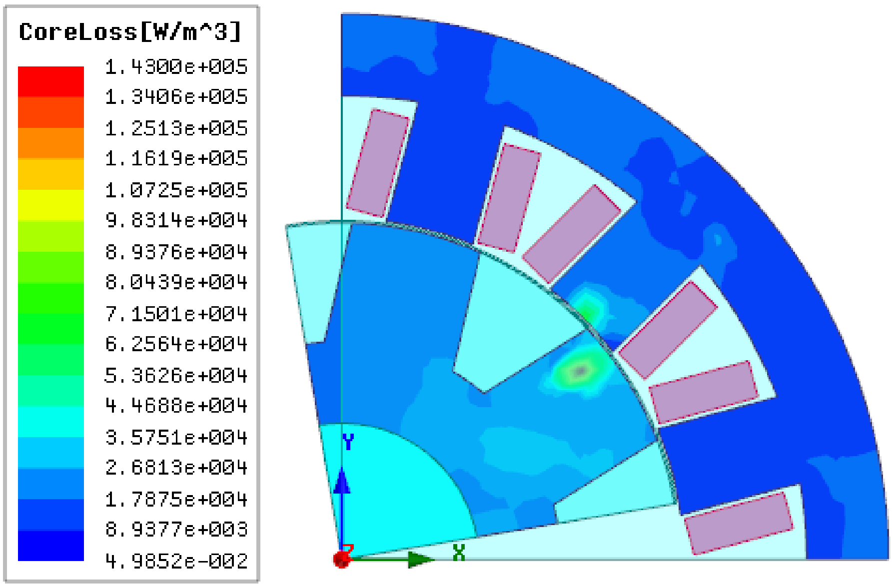

Fig.3 Core loss of switched reluctance motor using M19G29

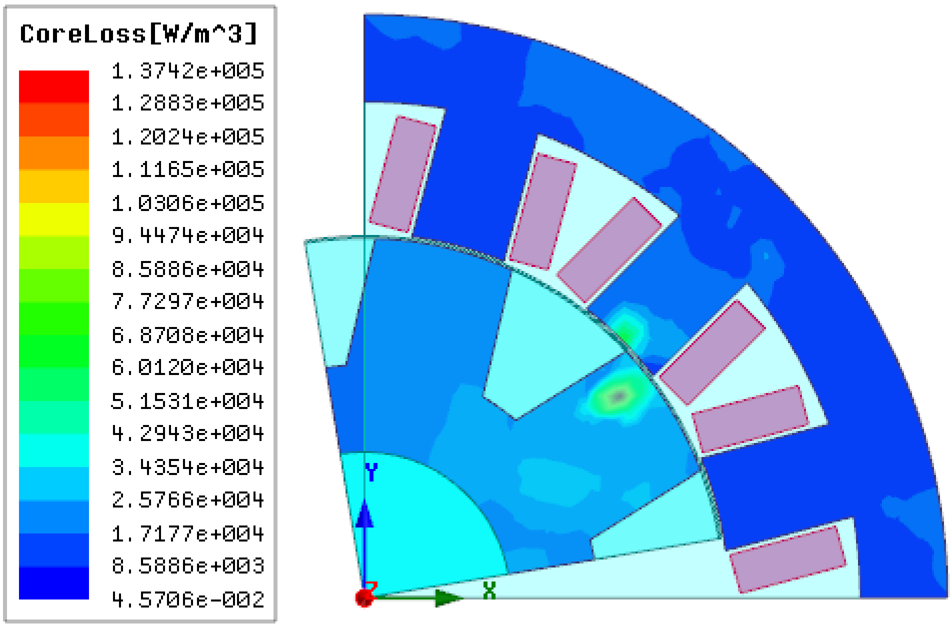

Fig.4 Core Loss of Switched Reluctance Motor Using M15G29

The SRM constructed as the 2-D FEM model for transient simulation includes two different materials in the study. The procedure evaluates the core losses in the SRM fed by an asymmetric H-bridge converter from the core loss curves displayed in Fig.1 and Fig.2. The Fig.3 and Fig.4 show the core loss in the stator to be higher than that in the rotor core. It further establishes that the core loss dominates around the corner of the mover and stator cores and brings out that M15G29 possesses the best property of electrical steel to be used as the core material from the core loss point of view for the SRM.

The density of steel laminations used in the motor is 7650 kg/m^3 as seen from Table 2. Besides the maximum core loss employing M19G29 and M15G29 are found to be (5.83 W/kg) and (5.60 W/kg) respectively.

4.2 Prototype Switched Reluctance Motor

The Fig. 5 depicts the test machines manufactured with M15G29 for driving a battery-operated electrical vehicle. The motor orients to offer higher efficiency when compared to ac and dc motors of the same size and rating currently used in this application. The significant reduction in losses, the absence of rotor windings and implementation of M15G29 non-oriented electrical steel as core material project a longer battery lifespan and extended operating cycles.

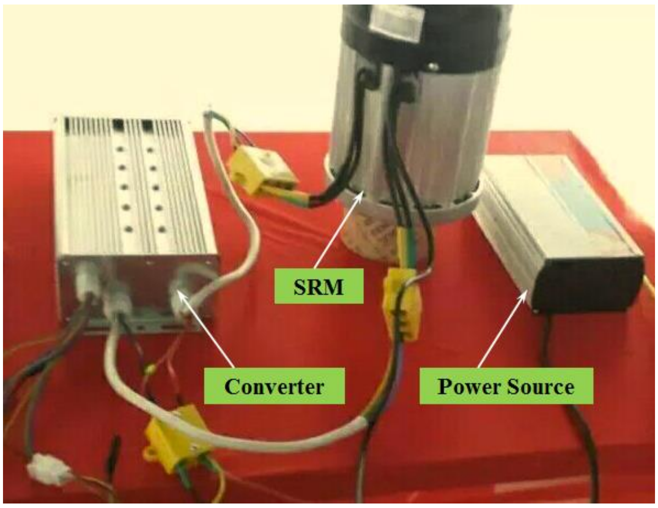

Fig. 5 Switched reluctance motor prototype

The core loss W_c in switched reluctance motor is calculated from the shaft output P_{out}, the copper loss W_{cu}, the mechanical loss W_{mech}, and the input electric power P_{in} as

$$W_c = P_{input} - P_{out} - W_{cu\_stator} - W_{cu\_rotor} - W_{mech} \quad (5)$$

The three-phase winding resistances and rms currents are assumed as R_A, R_B, R_C, I_A, I_B, and I_C, respectively and the copper loss W_{cu_Stator} is calculated as

$$W_{cu\_stator} = R_A I_A^2 + R_B I_B^2 + R_C I_C^2 \quad (6)$$

Table 3 Measured Core Loss of Switched Reluctance Motor

SRM	Measured Core Loss (W/kg)	Simulated Core Loss (W/kg)
M19G29	5.83	5.75
M15G29	5.60	5.49

The readings in Table 3 showcase the lower core loss at no load for the SRM with M15G29 than M19G29 in accordance with superior magnetic property of M15G29 than M19G29.

V. CONCLUSION

The effect of non-oriented electric steel for the stator and rotor core of the SRM has been examined through both 2-D FEM simulation and using related experimental study. A loss model has been developed from the manufacturer's data and the coefficients for the various terms predicted. The analytical expressions have been used to compute the losses and the results verified by experiments. The material M15G29 has been borne to offer a lower core loss for the SRM and seen to adapt well with the change of motor core losses. The investigations have been portrayed to bring out the suitability of M15G29 as the core material and claim a better performance for the SRM. The results have been belied to explore fresh dimensions for the use of SRM in the utility world.

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