Power Loss Testing System for Complex Electromagnetic Core Designs Used in New Direct Drive DC Brushless Motors

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Abstract

In direct drive DC brushless motor applications, the main incentive is to improve the form factor of the active magnetic design to increase the torque and power densities of the motor.

Significant performance improvements in motor characteristics are seldom achieved with the use of conventional topologies based on laminated electrical steels. This is because there are classical limitations as to how much the form factor can be varied to minimize the bulk of the magnetic mass required to generate the required torque and power output. Also there are the classical issues concerning the eddy, hysterisis and excess eddy current losses, which stem from alternating inter-lamina flux distributions and rotational flux patterns in complex electromagnetic designs. Unless significant changes are made to the adopted design topologies very limited torque and power densities improvements can be achieved.

The most important factors in applications such as in-wheel direct drive DC brushless motors are cost, form factor and weight, as well as simplification of the design for cost-effective manufacturing and reproducibility of the dynamic characteristics of the motor.

To address these challenges, a new range of permanent magnet DC brushless motor has been developed, with an improved torque density, typically up to 20Nm/kg. This has been achieved by careful weight reduction in the active mass of the motor with the use of Soft Magnetic Composite (SMC) materials. Due to the changes introduced in the design of the magnetic circuit of the motor, unique electromagnetic cores have been developed, which minimize the active mass and the core losses of the motor while maintaining the desired motor performance characteristics at the operating frequencies and inductions.

To test and evaluate the intrinsic magnetic properties of these machine cores, a new magnetic loss testing system has been developed. This system allows various core designs with complex geometries to be fully characterized prior to assembly. This paper discusses the loss testing system and highlights the results found under different test frequencies and inductions for different electromagnets used in a new range of brushless motors.

Introduction

A new range of DC (synchronous) brushless permanent magnet motor has been developed based on the patented Multiple Magnetic Path electric motor concept [1]. This inverted motor topology is intended for near-wheel or in-wheel gearless propulsion applications, where it can deliver a variety of speed-torque-efficiency profiles on selectable dynamic basis [2].

Depending on the maximum deliverable torque and permissible maximum angular velocity of the application along with the available DC supply bus voltage, the electromagnetic designs of these new motors can be reconfigured to increase the peak and continuous power outputs, as well as the intrinsic no-load speed of the machine for a given compact design. Such design considerations tend to have an effect on the internal and external infrastructure of the stator as careful design synthesis have to be carried out to find out the most optimum synergy between the Machine, Torque and Back emf constants, otherwise referred to as K_t, K_m and K_e, respectively.

In contrast with the continual emergence of low loss non-oriented electrical steels, greater emphasis are directed toward the modularization of the design and an increase in the power and torque density of the motor. With these requirements the need for an improved form factor in the design of the electromagnetic constituent of the motor becomes more critical. These requirements dictate the engineering envelopes set for the desired torque and power densities level, precluding the use of classical machine geometries with poor form factors.

The designs considered for this paper were predominantly based on 24V and 48V DC bus supply voltage with a peak current ranging from 100 to 750 Amps. These motors are currently being developed for different transportation, medical and electric propulsion applications, most of which require different electro-mechanical considerations for their dynamic operational characteristics. Depending on the design topology and application requirements, the motoring and regenerative braking of these motors are being assessed to establish the magnitude of the electrical power, which could be recaptured in regeneration mode from the machine. The motoring and regenerative braking of these propulsion systems, combined with the implemented driving hardware and specific excitation control algorithms, will prolong the longevity of the on-board rechargeable batteries and thus extend the range of intended propulsion application in a given application.

To ensure that the desired motor characteristics were realized, a greater emphasis was put on the design and AC measurements of the electromagnets used in the motor. This paper describes the design and development of a new magnetic loss tester used for evaluating the characteristics of the electromagnet core designs used in a new range of inverted DC brushless motors.

The Design Considerations for the New Motors

For the purpose of this paper two machine topologies were developed and simulated to assess their unique electromagnetic characteristics. They are listed Table:1.

	Machine 1	Machine 2
Output Power (kW)	0.7	17
DC Supply (V)	36	48
Max Torque (Nm)	75	450
No load speed (RPM)	260	450
Rotor stator air gap (mm)	1.5	2.0
Torque / weight (Nm/kg)	7.5	14
Back emf constant (V/RAD)	.75	1.1
Torque constant (Nm / mp)	0.75	0.6 to 0.75
Machine constant (Nm/watts$^{1/2}$)	1.91	3.35

Table: 1
The main machine parameters of the motors developed

The stator sub-system consisted of the plurality of independent electromagnet constituents, which omits the mutual inductances normally seen in a multi-phase machine design. Due to the complexity of the three-dimensional (3d) topologies of the electromagnetic cores used in these machines, the required electromagnetic cores were manufactured from two commercial Soft Magnetic Composite (SMC) powder alloys as appose to laminated electrical steels. The unique core design on Machines 1 and 2 is shown in Figures 1A and 1B.

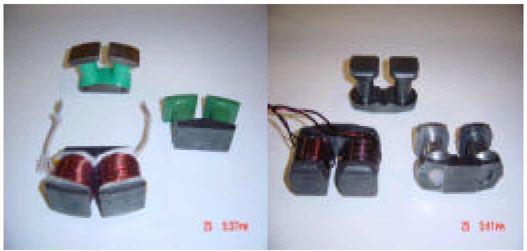

1A 1B

Figure: 1 The SMC core designs for Machinea 1 and 2

This approach allowed all the stringent geometrical constrains and the required electromagnetic characteristics to be met for the designated electrical power requirements. Moreover, SMC alloys promoted the realization of a specific acceptable power loss (W/kg) and relative permeability at the application flux density levels and excitation frequencies, allowing the desired peak torque output to be achieved with a significant reduction in material weight and manufacturing overheads. Due to the isotropic nature of the SMC materials, the construction magnetic paths were fully optimized in 3d with respect to the volumetric and physical constants of each machine specification.

With the ability to define the magnetic field in 3d, the flexibility of the powder metallurgy allows efficient production of complex-shaped parts and a significant streamlining of the electromagnetic design assembly with an increase in effective power output and weight reduction. [3]

To achieve the required loss and mechanical characteristics in the electromagnetic parts, several wet and dry compaction methods were considered. These selections, along with the compaction, and heat treatment techniques and tool design considerations for a given powder mix, allowed the desired density levels to be achieved for each SMC core design.

Due to the compaction and heat treatment of the SMC materials, the electrical resistivities achieved were found to be as high as 1,000 S/m, with adequate levels of relative permeability at critical induction levels. Such intrinsic characteristics play an important role in the reduction of alternating and rotational eddy current, as well as excess eddy current losses under high operating flux densities and excitation frequencies. [4]

The SMC materials, however, do exhibit higher hysteresis loss due to their non-ideal grain structure formation, compounded by large non-uniform strains induced onto the powder lattice during compaction.[5]

Considerations for such loss constituents were of paramount importance in machine efficiency calculation and core losses minimization in the magnetic assembly of the machine. This, in turn, influenced the provisions put in place for adequate thermal management and cooling of the motor.

Soft Magnetic Composites also exhibit good dimensional accuracy and stability with smooth surface finishes, which is an important factor in improving the form factor of the design of the magnetic circuit, as well as the configuration of the excitation coils. The improvements achieved in the form factor also have a signification influence on the packing factor and the considerations made for the thermal management of the integral electromagnetic embodiments. With the use of alternative coil and winding techniques, specifically for high current excitations at moderate Pulsed Width Modulation (PWM) and commutation frequencies, additional performance improvements are conceivable.

For the designs disclosed, the required core geometries and core dimension, along with their relevant tolerances, were optimized to maximize the magnetic potential gradient developed between coupled pole-pairs of rotor permanent magnet and stator electromagnet segments. The changes in the magnetic potential-difference between the rotor and stator tend to create very large tangential and radial forces generated between the partially aligned electromagnet and permanent magnet poles. The moments of these forces acting around the pivoting shaft of the system generated resultant torque of the propulsion system under a given excitation current density.

The acting forces calculated were used in conjunction with other structural and mechanical forces to simulate the dynamic and static characteristics of the motor and stator housings during different application conditions.

The main parameters of interest in the design of the stator were:

- Design of the electromagnets circuit for reduced active mass
- Pole to pole separation of the electromagnet cores
- Magnet/electromagnet permissible air gap
- Power loss of the core material (hysteresis/eddy current/anomalous loss)
- Saturation flux density and permeability of the material
- Thermal management temperature and physical stability of the permanent magnets
- Mechanical rigidity and environmental stability
- Excitation current, phase angle, duty cycle
- Overall sequencing and the control strategy of the stator system in a given application
- Optimum angular positioning with respect to the chosen excitation scheme

The angular positioning of the electromagnet core was critical in assessing the optimum position and the highest partial repulsion and attraction forces of the active phase over the effective arc of the motor. Extensive complex 3D Finite Element analysis was carried out to optimize the electromagnetic path of the machine and that of the complimenting control system. The resultant motor achieved high stall-torque and high-continuous torque across a wide range of angular speeds. It also exhibited good average efficiency at different torque/speed ranges.

For the required 3D Finite Element analysis, a target energy conversion of 2.0% was set in the Ansoft Maxwell 3d Optometrics-Parametrics Finite Element Analysis (FEA) software. In reaching this energy level, the meshing of various critical embodiments within the model was optimized and refined manually or automatically to achieve a better resolution for the FEA synthesis. For the required calculations, Direct and Incomplete Conjugate Gradient Solvers were used. The finite element meshing was performed according to Delaunay tetrahedrization algorithm. For this study the actual 3D model was imported from a Computed Aided Design (CAD) model with few simplifications to capture all the electromagnetic parasitic effects of the model geometry.

Most of the torque and force calculations were carried out using the Electromagnetic Coenergy equations and the results were exported to other structural FEA platforms for mechanical and thermal design iterations.

Incentives for Designing an Application Specific Loss Tester

Components and sub-assemblies made of magnetic materials are in common use in the manufacturing of electromechanical devices. In many cases, the overall performance of a given device is strongly influenced by the magnetic properties of components or sub-assemblies. Since the successful operation of a given device may depend on the specific magnetic properties of a magnetic component or sub-assembly, the ability to guarantee these properties is crucial.

Historically, conventional testing equipment and techniques have been used to determine certain gross magnetic characteristics. These include off-line systems such as Epstein Test Frames, Single Sheet Testers and Torodial Loss Testing systems, which predominately would measure the magnetic characteristics of the material in a specific test fixture. Other systems such as on-line loss testing systems have also been developed, which tend to have comparable results with the standardized off-line test systems named above.

However, as more sophisticated magnetic materials and manufacturing techniques have evolved, the need for application-specific testing systems with traceable accuracies has also increased. More sophisticated instrumentation systems, such as automatic magnetic loss testers and Hysteresisgraphs, have become more prevalent in both magnetic component manufacturing and incoming inspection and testing.

However, the conventional automatic magnetic loss testers are only designed as general-purpose instruments. To design an accurate testing system, the complexities of the test component should also be taken into account, prompt the need for a unique test fixture design. The design of the test fixtures, along with techniques used for capturing the flux density and the magnetic field intensity variations on the component, is the key challenge involved in acquiring meaningful and traceable results.

The main purpose of this new loss testing system was to create a universal testing system to conduct accurate characterization of hysteresis properties of magnetic materials with unique geometries. The purpose of the system was to perform an absolute closed-circuit AC tests with traceable results, which could be correlated and compared with results captured on internationally accepted testing systems [6].

The system discussed in this paper is capable of being utilized as a Quality Assessment tool for scrutinizing the magnetic properties of the components, thus reducing the number of magnetic component failures due to non-characterized or unmatched abnormalities in their hysteresis properties. Such variations may be induced into the material during the compaction, pressing or heat treatment stages of the components prior to their integration into a motor.

Description of the System

In a given operation, magnetic loss testers are precision, computer-controlled systems for testing and analyzing the hysteresis properties of magnetic materials. Figure 2 illustrates a magnetic measurement system and two specialized test fixtures.

Figure: 2 A view of the loss testing system and the test fixtures

The Magnetic Loss Tester includes a central processing unit (CPU), a data acquisition system (DAQ), two digital Wattmeter/Flux meters and a linear class A-B power amplifier. There are two different test fixtures to accommodate the two electromagnet core designs used for the motors discussed in this paper. Each test fixture includes an H sense shut resistor, a B sense coil, a closed circuit yoke and main magnetization coil windings.

The embedded CPU is a conventional central processing unit used in conventional magnetic hysteresis systems, and is physically attached to DAQ, a conventional data acquisition system. DAQ is physically attached to the two flux meters. One flux meter is connected to H shunt resistor, and the other is connected to B sens coil. The B sense coil is a conventional sense coils used in magnetic field measurements. The design has the potential of using a Rogowski-Chattock Magnetic Potentiometer (RCMP) method for detecting the uniformity of the magnetic field intensity along the longest path of the component. At the initial stages of the development the RCMP approach was not employed, because it required additional software calibration and synchronization with the excitation circuit.

Figure 3 illustrates the output screen of the Loss Testing System with the conventional hysteresis curve including an applied magnetic field H and a magnetic field B intrinsic to the material. Fields H and B form the two axes for graphing the magnetic hysteresis. Also illustrated is a typical initial charging curve showing the magnetic path for the particular material after an initial external magnetic field has been applied and the saturation point at which the material is fully magnetized. Point Br is a remnant field, where the H value is zero, and $_{B}$Hc is the point at which the magnetic flux density to the material also reaches zero.

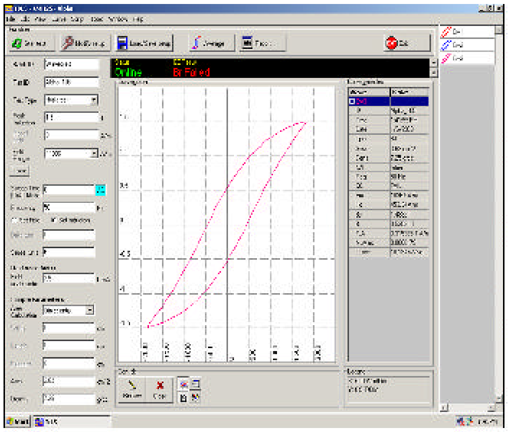


Figure 3: The output of the Loss Testing System

The software uses CPU and associated hardware to control DAQ in such a way that DAQ drives the linear amplifier with a pre-determined waveform. The main software is script-based QBASIC, which allows different non-sinusoidal waveforms to be generated and applied to excitation coil windings. The changing magnetic fields through H shunt resistor and B sense coil produce current and voltage signals, which are then integrated by the H and B flux meters, respectively.

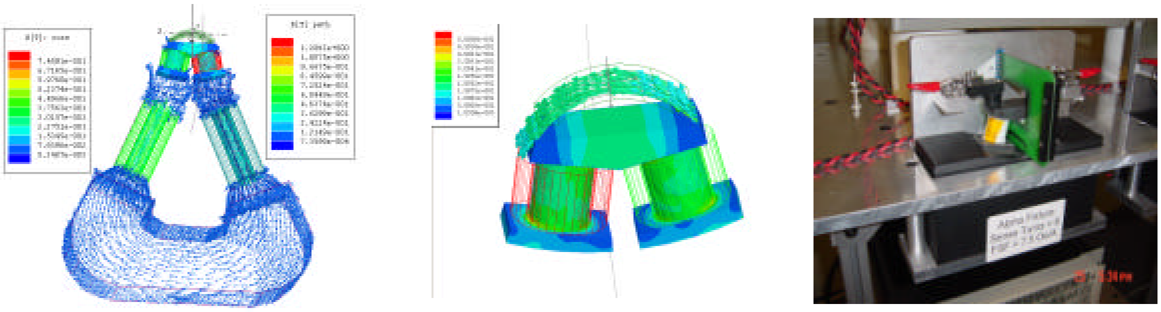
The analog of the magnetic field strength produced by the flux meters is sent to DAQ and is converted into the digital domain. An on-board CPU is programmed to digitize the flux density and field intensity waveforms thus reconstructing the digitized B-H loop of the material at a given test induction and frequency, with respect to which total specific loss, relative permeability, coercive field strength and remnant flux density values are captured and logged. Prior to the actual test, a low frequency demagnetization field is applied to completely de-magnetize the test part. The demagnetization cycle, as well as the intensity of the demagnetization field, can be changed for different test cores.

For the two specific core design, two specific test fixtures were designed and analyzed using Ansoft Maxwell 3d Optometrics-Parametrics FEA software.

Figures 3A and 4A show the FEA output of the magnetizing test circuit for electromagnets used in Machines 1 and 2, respectively.

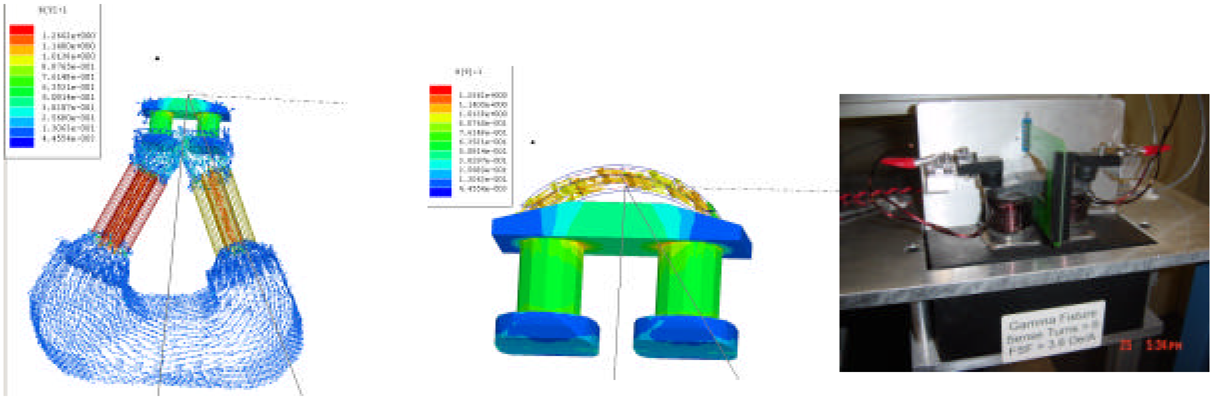
Figures 3B and 4B show component and possible variation in incorporating a Rogowski-Chattock Magnetic Potentiometer (RCMP) method for measuring the magnetic field potential sample for designs 1 and 2, respectively. Figures 3C and 4C show the actual the test fixtures used for electromagnet designs of the Machines 1 & 2, respectively.

Each test fixture consisted of an electromagnetic yoke made from laminated M19 non-oriented electrical steels. The mating surfaces of the yokes were machined and tapered to account for all surface contours of the test cores. On each test frame, there are two excitation coil windings that can provide the required magnetizing field for the loss tester. These coils were designed according to electromagnetic FEA models of the magnetizing circuit to produce the



3A 3B 3C

Figure 3: The test fixture for the SMC core used in Machine 1. (A) The FEA analysis of the test fixture, (B) The FEA analysis of the part under the test with the RCMP path modeled, (C) The actual test fixture used with the Loss Testing System



4A 4B 4C

Figure 4: The test fixture for the SMC core design used in Machine 2. (A) The FEA analysis of the test fixture, (B) The FEA analysis of the part under the test with the RCMP path modeled, (C) The actual test fixture used with the Loss Testing System

required field intensity in the test parts. Both coil windings are connected in assisted-series configuration and energized from the main linear power amplifier. To maintain a safe operating level, the peak excitation current was limited to 25 Amps in the main excitation coils. This limited the flux density level of the yoke to 1.8 T thus preventing any saturation from occurring in the effective magnetic path of the yoke under high induction test conditions.

The magnetic field intensity can either be measured using a reference precision shunt resistor or an H sense search coil placed above the surface boundary of the test piece. An additional H sense coil could also physically installed on an electromagnetic frame to test the applied field. The B sense coil was physically installed over the magnetic component perpendicular to the main path of the effective flux. Adequate air flux compensation was used in the software to account for the loss in flux linkage in the B search coil.

On each fixture the, test component was clamped down to ensure that there was a complete surface-to-surface contact between the magnetizing yokes. This clamping mechanism also ensured that the part would not vibrate during high induction and high frequency magnetization.

Core Loss Measurements

Loss testers are normally calibrated according to the National Institute of Standards and Technology (NIST). Core loss is a crucial parameter used to determine the performance of a material in an electromagnetic device. In fact, it is often the most critical material parameter specified. To measure core loss, the magnetizing fixture will require primary and secondary winding around a test sample. An alternating current is generated in the primary winding, and the resultant secondary voltage is analyzed. In non-standardized core pieces, such as the ones used in the current machine designs, the induction of the required magnetic field and the capture of the induced flux density are of critical importance. The magnetizing test fixture for this exercise was carefully simulated and designed to meet the testing conditions to which the test parts would be subjected.

On this testing systems, a Hysterisis measurement technique was used which has been proven to be comparable with the classical Wattmeter method. A Wattmeter determines core loss by multiplying the instantaneous voltage and current, and then averaging this product over time. This calculation is expressed as:

$$P = \frac{1}{T}\int_{0}^{T} v(t).i(t)dt$$

Eq: 1

where P is the power in Watts, $i(t)$ is the primary current, $v(t)$ is the secondary voltage and T is the period in seconds, or the reciprocal of the excitation frequency.

Core loss in Watts per kilogram can therefore be expressed as:

$$W = \frac{f}{m}\int_{0}^{T} v(t).i(t)dt$$

Eq: 2

where W is the core loss in watts per kilogram, f is the frequency in hertz, and m is the effective mass of the sample in kilograms.

Now in a conventional loss tester, the voltage induced in the secondary windings is proportional to the rate of change of flux, which is given by:

$$v(t) = N_S \frac{d\Phi(t)}{dt}$$

Eq: 3

where N_s is the number of turns in the secondary windings and $F(t)$ is the magnetic flux in units of Webers. The magnetic flux F is equal to the magnetic induction in units of Tesla multiplied by the cross sectional area in units of square meters of the sample, expressed as:

$$\Phi(t) = \int B(t).A.dA$$

Eq: 4

which leads to the following expression for voltage:

$$v(t) = N_S.A.\frac{dB(t)}{dt}$$

Eq: 5

The primary current of the magnetizing circuit, the magnetic field applied to the test sample, is proportional to the primary current, given by:

$$H(t) = \frac{N_p}{l}.i(t)$$

Eq: 6

where $H(t)$ is the magnetizing field in amperes per meter, N_p is the number of primary turns, and l is the magnetic path length in units of meters. The applied magnetizing current from Equation 6 results in:

$$i(t) = \frac{H(t).l}{N_p}$$

Eq: 7

Note that this excitation current in most test conditions can to be distorted to induce a sinusoidal flux density in the B coils. On this test system the exaction current waveform can be carefully altered to create different harmonic components in the flux density.

Substituting Equations 5 and 7 into Equation 2 results in the following equation for the core loss:

$$W = \frac{N_s}{N_p}.\frac{Alf}{m}\int_0^T B(t)dt.H(t) \qquad \text{Eq: 8}$$

Since the area times the path length is the volume of the specimen, and the volume divided by the mass is equal to the density, Equation 8 can be rewritten as:

$$W = \frac{N_s}{N_p}.\frac{f}{r}\int_0^T B(t)dt.H(t) \qquad \text{Eq: 9}$$

where ρ is the density (kg/m^3) of the electromagnetic core under the test.

The integral is equal to the area inside the AC BH-curve and has units of Tesla- Amperes per meter. A Tesla-Ampere per meter is identical to a joule per cubic meter. So the core loss can be expressed as:

$$W = \frac{N_s}{N_p}.\frac{f}{r}.\Gamma \qquad \text{Eq: 10}$$

where Γ is the area inside the BH-curve in Tesla-Ampere/m.

Having captured the digitized B-H loop of the sample, the software detects the magnitude of the discrete *H(t)* and *dB(t)/dt* signals at corresponding zero crossing points to evaluate the remaining key magnetic parameters of interest. All the corresponding data were collated for Quality Assessment purposes and validation of the desired magnetic properties in the cores.

Application of the System

After calibrating of the testing parameter using reference test samples, the uncertainty and the resolution of the systems were carried out. The test results were then compared with the results captured on a standardized loss testing system as described in IEC 606-4. The accuracy of the system was also a function of the average density of the test cores used. Since the cores were made from compacted SMC powder materials, due to the complexity of the geometries, the density of the powder varied along the effective path of the flux. This caused some uncertainty in loss calculations. To address this uncertainty, an average density value was calculated and used through out the test of each core design.

Having incorporated the relevant correction factors for the density and air flux compensation of the captured B signal, the test systems allowed the following closed-circuit magnetic evaluation to be carried out for:

1. The measurement of the total specific loss, relative and maximum permeability, remnant flux density and saturation flux density, the maximum and typical coercive field strength
2. The back emf stability of the core
3. Thermal behaviors of the cores under different excitation and induction levels
4. Different demagnetization and re-magnetization cycles

The system has been put into commission and is being used as a validation means for electromagnets core designs currently being used in a new range of DC brush less motors.

Figures 5, 6 and 7 summarize the core loss results captured on the two core designs currently being used for Machine 1 and 2.

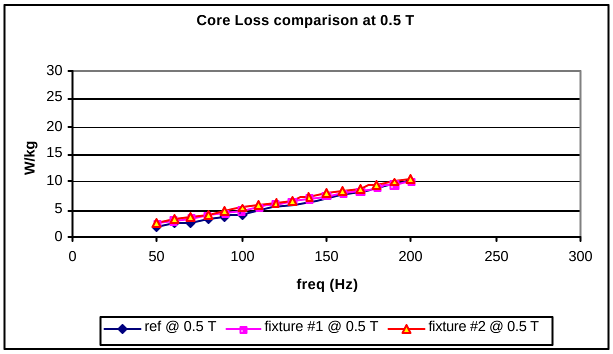


Figure: 5 Core Loss Comparison on the Core design for Machine 1 and 2 at 0.5T

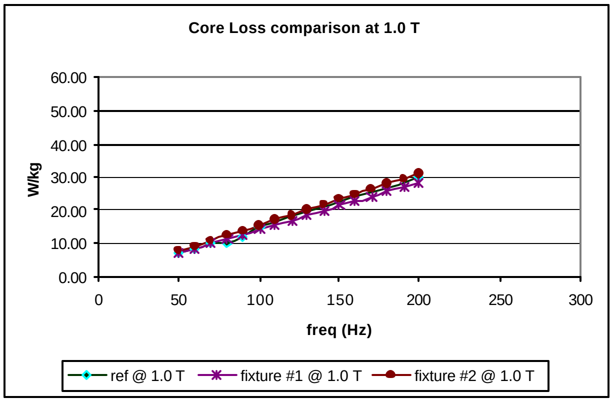


Figure: 6 Core Loss Comparison on the Core design for Machine 1 and 2 at 1.0T

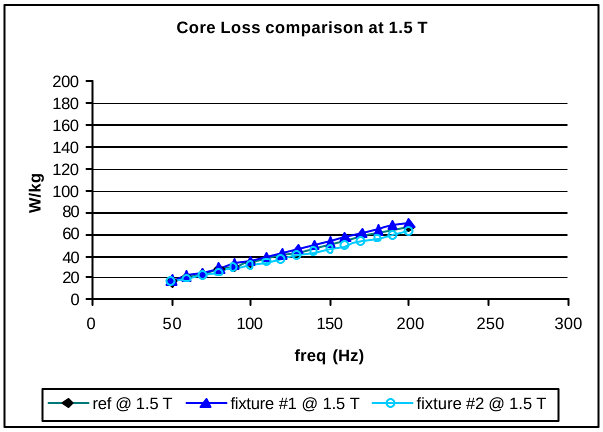


Figure: 7 Core Loss Comparison on the Core design for Machine 1 and 2 at 1.5T

These core losses were compared with the manufacturer's reference data and measured according to the current testing standard. The results show the core losses at three set indications, namely, 0.5 T, 1.0 T and 1.5 T at different frequencies. The uncertainty of the measurement was calculated to be within +/- 2%. This was based on no modification to the software, or the magnetizing or the signal acquisition hardware. Further work will allow this uncertainty to be reduced even further.

The purpose of the system was not only to perform an absolute test according to an internationally accepted standard, but also to perform reference and cooperative testing on large quantities of samples and to trace the results to the manufacturer's data sheets of SMC powder materials. This was found to be very critical as various compaction and heat treatment process parameters had to be controlled to develop the required magnetic and physical properties in the core material for the designed geometries. These process-related parameters were found to have significant influences on the final desired magnetic properties of the electromagnetic cores.

To assess the thermal characteristics of the cores at high induction levels corresponding with low exaction frequencies (i.e., high torque in the motor) and low induction levels corresponding with rapid excitation (i.e., high speed and moderate torque levels), different extended excitation cycles were carried out.

The thermal behavior of the cores were studied and subsequently used in thermal management and cooling design provisions employed for the stator housing.

Further enhancement work on the systems is being carried out to allow the system to be used for characterizing other complex electromagnet core designs for a variety of motor design architectures.

Scope for Future Activities

Recent experiments on 2d and 3d alternating and circular rotational loss measurements have been carried out on Somaloy 500 grade (Hoganas AB, Sweden). [6], [7]. This study has shown that the classical hysterisis, eddy current and anomalous (excess eddy) loss coefficients can be approximated for SMC materials as it is done for electrical steels. This was based on the classical equation expressed as:

$$W = \sum \left\{ k_{hys} f B^{h}, k_{eddy} (fB)^{2}, k_{ex} (fB)^{1/2} \right\} \qquad \text{Eq: 11}$$

where B (T) is the peak value of the flux density in the material, f is the excitation frequency, and h, k_{hys}, k_{eddy}, k_{ex} are the loss coefficients. The corresponding coefficients for alternating and rotational losses were approximated to be:

	Alternating	Rotational
h	1.58	1
k_{hys}	0.142	1
k_{eddy}	0.00000123	0.00023
k_{ex}	0.0003645	0

Table: 2
Core loss Coefficients of Somaloy 500 grade (Hoganas AB, Sweden).

Further work will have to be carried out to verify the measured total loss using the developed magnetizing fixture to ascertain the validity of the calculation methods used in the testing software and that of the extrapolations method used for the coefficients. This exercise will be carried out not only on the two electromagnetic core designs, but also on other new complex 3d core design intended for future motors. Additional improvements will have to be made to extend the frequency response of the system to allow loss measurements to be carried out reliably at higher induction and excitation frequencies. These will include non-sinusoidal or distorted excitation waveforms with the omission and/or the inclusion of odd harmonic frequency components. Using this approach, it would be possible to assess what would be the most optimized excitation profile for a given core design intended for a given application. The results will help to reach a compromise between an improved torque, speed and overall efficiency in the electromagnetic constituents of these new motors. [8]

Acknowledgement

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