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Magnetic Materials for Rotating Electrical Machines: A Selection Perspective

J.Kartigeyan[1] and M.Ramaswamy[2]

[2]Member IEEE
[1,2] Department of Electrical Engineering, Annamalai University, Tamil Nadu - 608002, India.
e-mail[1]: j.kartigeyan@gmail.com, e-mail[2]: prof.m.ramaswamy@gmail.com

Abstract

Electrical steel appears to be a key material in the manufacture of power apparatus in electric home appliances, industrial and transport machinery. Specifically they form the cores in motors and serve to efficiently convert the magnetic energy into electricity. The magnetic properties of the steel laminations play a significant role in enabling the choice of the material for a particular application. The paper attempts to investigate the properties and characteristics of typical magnetic materials used as the core for rotating electrical machines. The analysis forges to examine the suitability of the use of the material at the chosen operating frequencies and develop measures for arriving at precise estimates for designing the electrical machine. The study revolves around the influence of the magnetic parameters that include the flux density and permeability of the material on its core loss. The exercise owes to throw light on the cost of the material and pave the way for the designers to select the most appropriate material for a machine application.

Keywords: Rotating Electrical Machines, Soft Magnetic Materials, Magnetic Properties, Relative Cost.

INTRODUCTION

The enormous attempts to reduce nefarious emissions of toxic gases from fossil fuel sources together with a persistent drive to increase the renewable energy production augur the compliance of the energy act. However the theory of global warming invites consistent effort for reducing the world-wide energy consumption and ushering in changes in the general framework of the future energy policies.

Owing to the fact that the total energy consumption world-wide continues to increase drastically [1] especially in Asian and third world countries, there arises a need to enhance the energy infrastructure. The energy framework evinces the electrical energy to encompass a central role and foster as the most valuable form of energy with its outstanding properties in flexible generation, transmission and possible storage forms.

The present status exhibits that the electrical machines consume around three quarters of the electrical energy produced from the different sources [2]. It further reveals that there exists a possibility of saving around 15% to 30% of the consumed energy if the fixed-speed machines can be replaced using variable-speed drives. Though this solution does not allow increasing the power density of the system, it can actually decrease the efficiency of the electrical machine itself. The optimization of the objective function formulated towards higher efficiency and/or higher power density closely relies on improving the current knowledge about the losses and their impacts on the whole machine. The advent of the efficiency classes in global standards [3] forays to be a direct incentive for carrying out further investigations on the losses in electrical machines and drives [4], [5].

The iron losses occur mainly in the various parts of the stator and the rotor of any rotating electrical power apparatus. It turns out to be the major component of the loss particularly for high-speed electrical machines and imposes challenges in predicting the iron loss in light of the view that they depend heavily on the material characteristics as well as the machine geometry. The emphasis incites to improve the efficiency of electrical motors through possible loss reduction mechanisms [1].

The focus endeavors to myriad of choices that emerge in determining the best material for use in the cores of electrical machines. It bestows to reflect from the characteristics of the type and thickness of the lamination, saturation flux density, permeability and cost of the material under study. The investigations involve a detailed insight to the losses that account at the operating frequencies to contemplate on the performance of the machine.

MAGNETIC MATERIALS IN ELECTRICAL MACHINES

The ferromagnetic materials such as iron (Fe), nickel (Ni), and cobalt (Co) constitute the basic varieties used in the manufacture of cores for the electrical machines. Their magnetic properties mainly depend on the atomic structure and the electron configuration on the outer atomic shell and its distance to the atomic nucleus [6]. The physical properties can be improved by alloying them with other metals and the typical magnetic material alloys include

1. Cold- Rolled Motor Lamination Steel
2. Thin-Gauge Silicon steel
3. Non-Oriented Electrical steel
4. 48% and 80 % Nickel-Iron alloy

1. Cold- Rolled Motor Lamination Steel (CRML)

The cold-rolled motor lamination steel belong to the class of very low carbon content steels with approximately 0.06 % of carbon , 0.5% silicon and 0.6% manganese and laminations of 0.46 mm - 0.79 mm thickness [7]. They find their use when the cost drives the design and requires higher values of saturation flux density or permeability [7], [8]. They correlate to the poor core loss properties in-spite of the fact that the contemporary grades of CRML steels [8] now exhibit loss characteristics competitive with certain grades of non-oriented silicon steels. The lack of substantial alloying elements and abrasive insulation coatings helps extend tooling life, resulting in additional savings in manufacturing costs. The applications include high-volume production of appliance motors, automotive motors and alternators, and industrial motors and generators [8].

2. Thin-Gauge Silicon Steel

The thin gauge silicon steels, generally 0.25 mm and thinner [9] reduce the thickness of the lamination material and its resistivity to lower the eddy current losses [10] and thus the overall core losses in a given lamination. The thin-gauge silicon steels fall into two categories, those with a standard silicon content of slightly less than 3% and those with a silicon content of about 6.5 %.Their characteristics make them attractive for special motor and power generation applications [10], especially those operating at high rotational speeds [10]. The standard chemistry steels find a place where lower losses become imminent while incurring the least cost impact [9]. The 6.5 % silicon steels though being expensive [9] offer lower losses and extremely low magnetostriction characteristics due to their higher silicon content.

3. Non-Oriented Electrical Steel

The Non-oriented silicon steel epitomizes to be a special steel with low carbon content and up to 2.7 % of silicon [11] and processed to provide for uniform magnetic properties both longitudinally and transversely [12]. It inherits higher permeability [13], low average core loss [14] and good gauge uniformity together with cold finishing [15] plus strip annealing enabling a smooth surface and reduces buckles and waves to result in excellent flatness and a high stacking factor. Of moderate silicon content, they allow for reasonably long tool life to enjoy a wide variety of motor [16] and generator applications, including servo motors for motion control systems, aerospace accessories, hybrid and other electric vehicle traction motors [17] and industrial and public service motors and generators.

Though there remain fewer grades to choose from, their magnetic properties can be slightly manipulated during the post-stamping annealing cycle to provide for a range of characteristics. The fully-processed materials generally see use in lower volume production and the semi-processed steels in higher production scenarios where the final annealing cycles can be automated to reduce the processing times and costs.

4. Nickel-Iron Alloy

Alloying iron with nickel significantly reduces the core losses in the steel, and markedly improves permeability [18] of the material. The nickel-irons as a class of materials provide the lowest losses [18] of any steel commonly used in the rotating machinery. The two primary types of nickel-iron steel used in rotating machinery are those with 48% nickel [18] and those with about 80% nickel [18]. The forty-eight percent nickel-iron often used in motors with low loss requirements, such as dental and surgical instruments operate in closely regulated thermal ranges, and in non-motive devices such as resolvers. Due to its fairly low saturation flux density [18], 80% nickel-iron finds a place in resolvers, tachometers and other feedback devices. The nickel-iron steels require a very high-temperature annealing accompanied by the introduction of a surface oxide layer to develop their optimal magnetic properties.

TEST BENCH DESCRIPTION

The Fig. 1 shows the test bench used to measure the magnetic properties of sample materials in Figs. 2-23 using Epstein frame. The excitation and measurement system involves a crystal accurate 16 bit sine wave generator, which provides 25 Hz to 450 Hz and equipped with an amplifier rated at peak values of 40 A and 110 V. The instrument manufacturer certifies the repeatability of the measurement system at 0.5% for magnetic field measurements and 0.2% for power loss measurements [19]-[21].

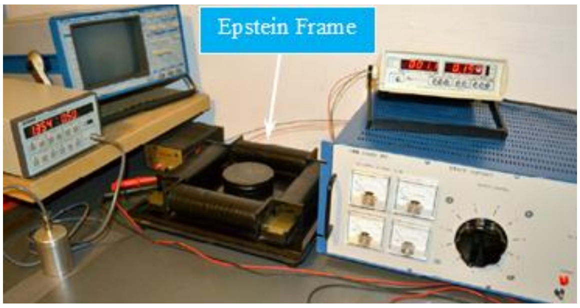

Figure 1: Epstein Frame Test Bench

RESULTS AND DISCUSSION

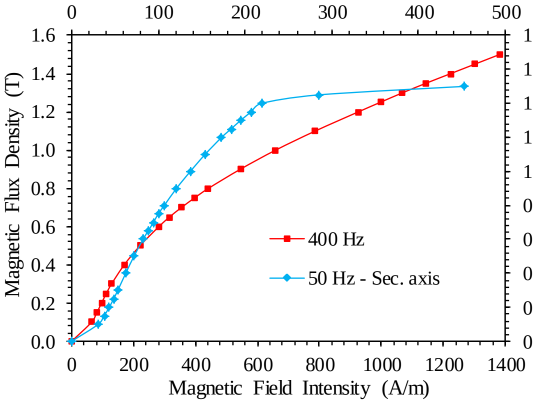

Figure 2: B-H Curve of CRML Steel-Grade Q-Core II-0.79 mm

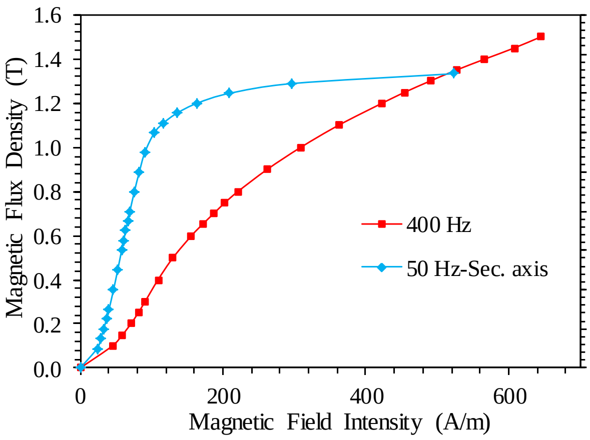

Figure 3: B-H Curve of CRML Steel-Grade Q-Core-0.47 mm

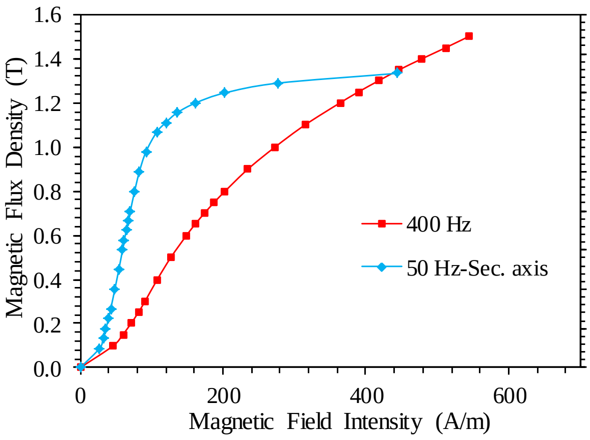

Figure 4: B-H Curve of CRML Steel-Grade Q-Core II-0.46 mm

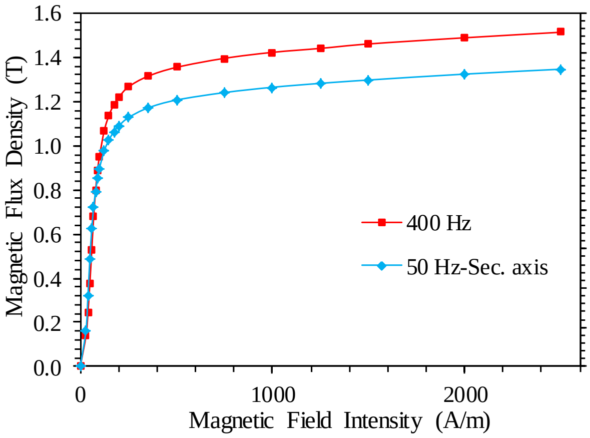

Figure 5: B-H Curve of Thin-Gauge Silicon Steel-Arcelor NO-20 -0.20 mm

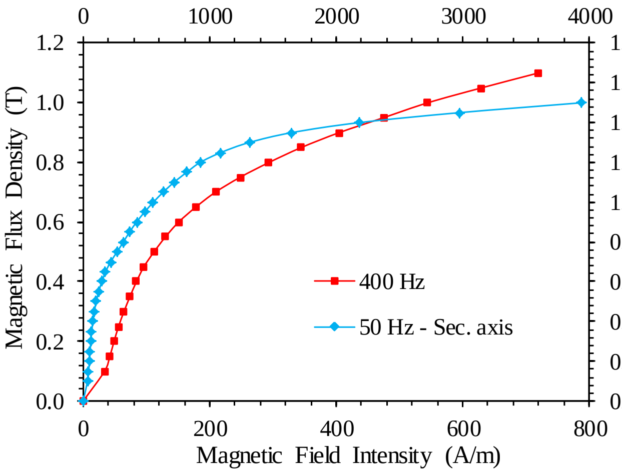

Figure 6: B-H Curve of Thin-Gauge Silicon Steel-10JNHF600-0.10 mm

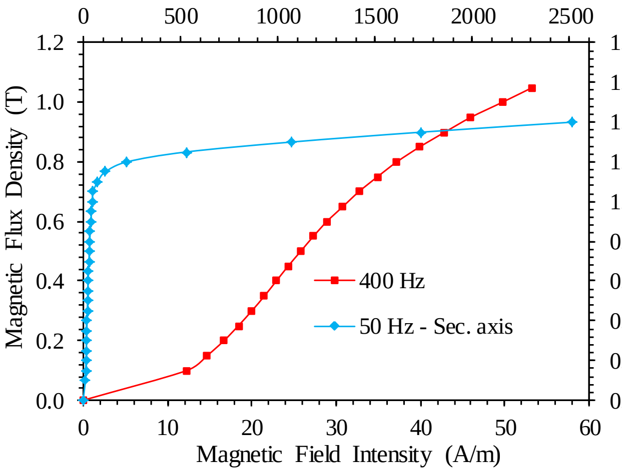

Figure 7: B-H Curve of Thin-Gauge Silicon Steel-10JNEX900-0.10 mm

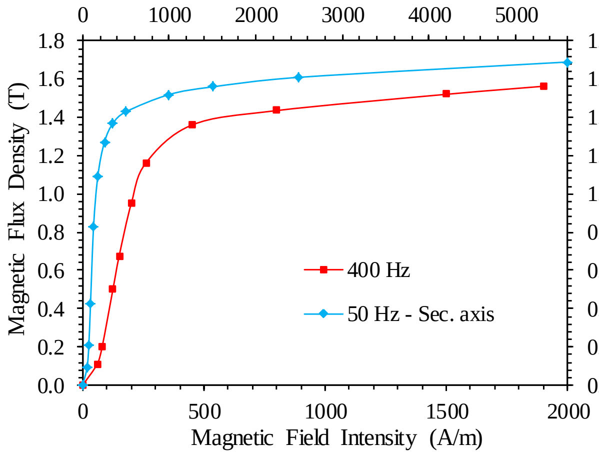

Figure 8: B-H Curve of Non-Oriented Electrical Steel- M400-50A-0.50 mm

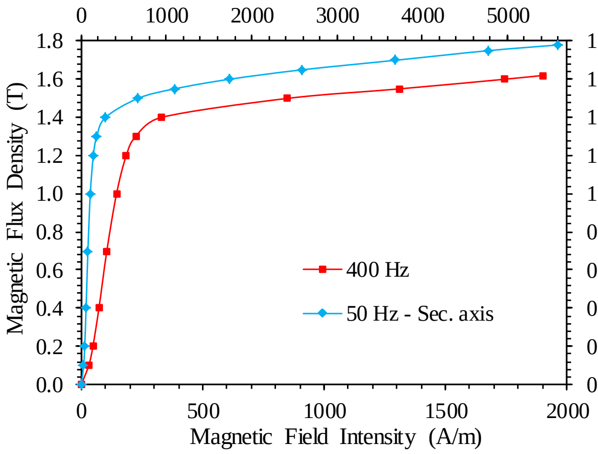

Figure 9: B-H Curve of Non-Oriented Electrical Steel- DI MAX-M19-0.35 mm1

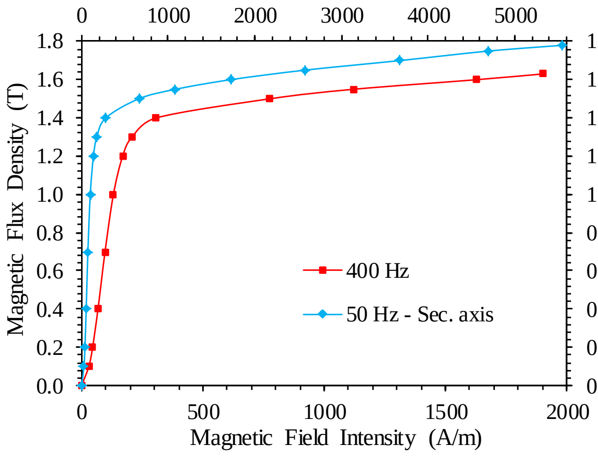

Figure 10: B-H Curve of Non-Oriented Electrical Steel- DI MAX-M15-0.35 mm

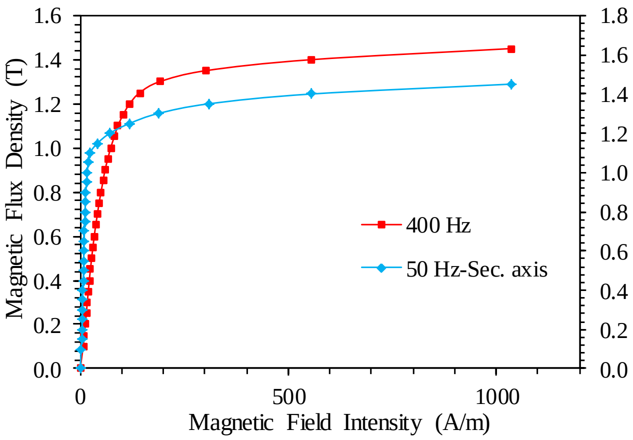

Figure 11: B-H Curve of Nickel-Iron Alloy- Alloy 49 Rotor Grade-0.36 mm

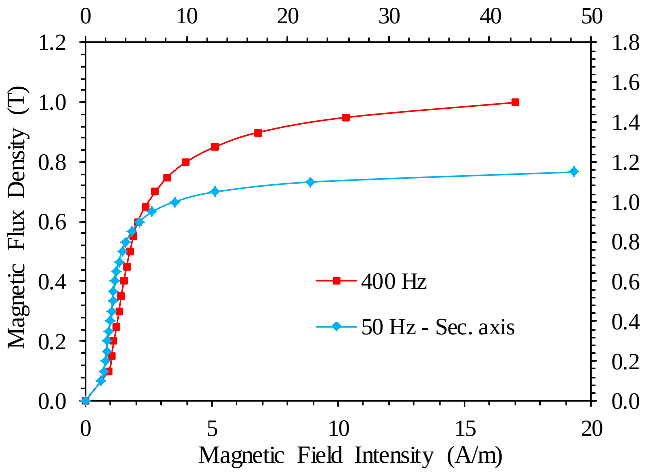

Figure 12: B-H Curve of Nickel-Iron Alloy- Supra 50-0.35 mm

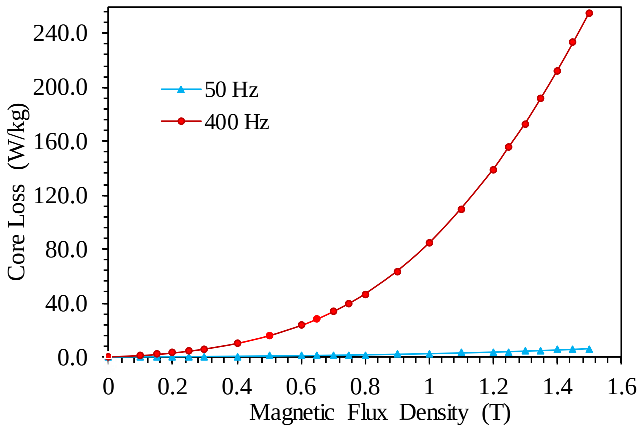

Figure 13: Iron loss Curve of CRML Steel-Grade Q-Core II-0.79 mm

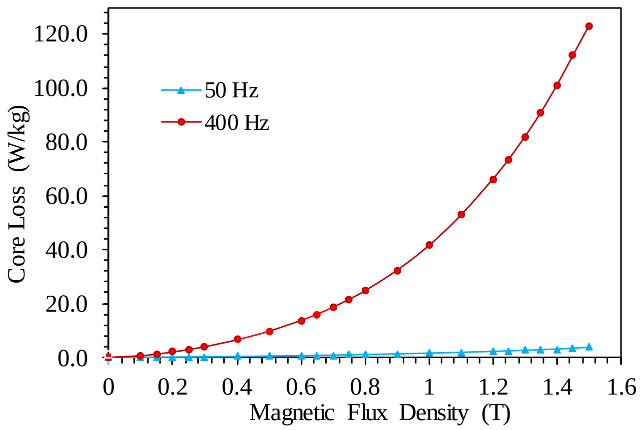

Figure 14: Iron loss Curve of CRML Steel-Grade Q-Core-0.47 mm

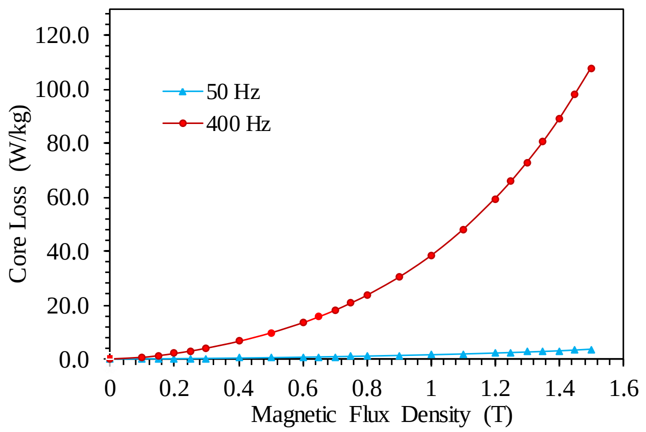

Figure 15: Iron loss Curve of CRML Steel-Grade Q-Core II-0.46 mm

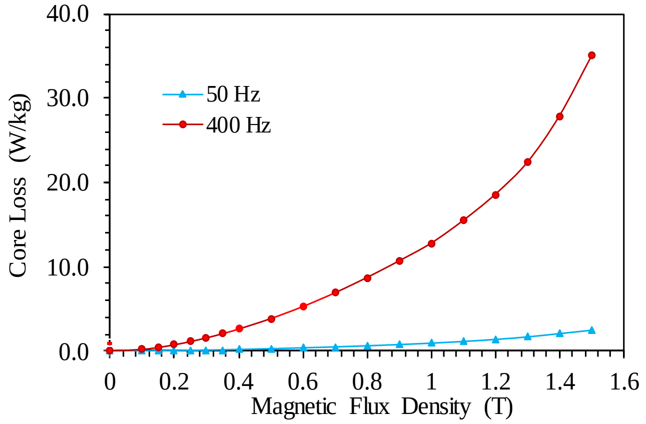

Figure 16: Iron loss Curve of Thin-Gauge Silicon Steel-Arcelor NO-20 -0.20 mm

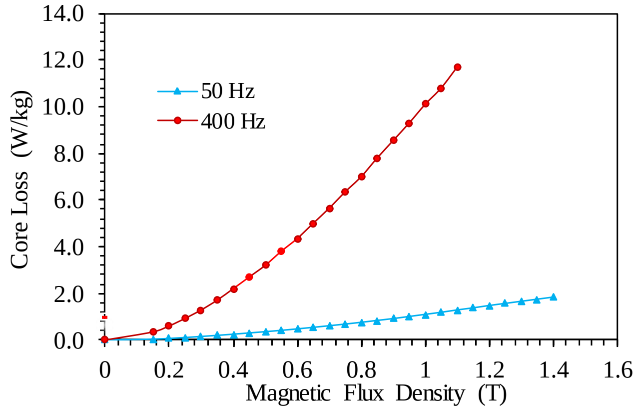

Figure 17: Iron loss Curve of Thin-Gauge Silicon Steel-10JNHF600-0.10 mm

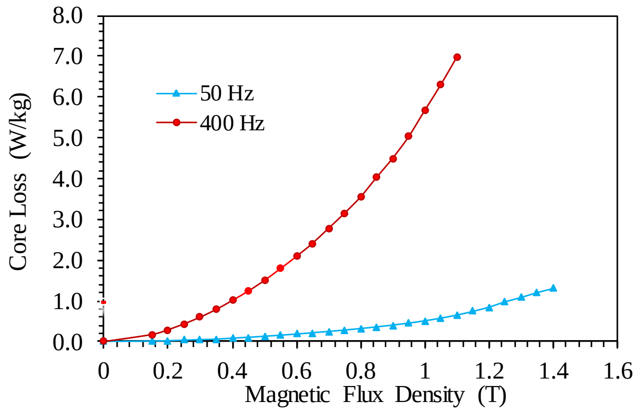

Figure 18: Iron loss Curve of Thin-Gauge Silicon Steel-10JNEX900-0.10 mm

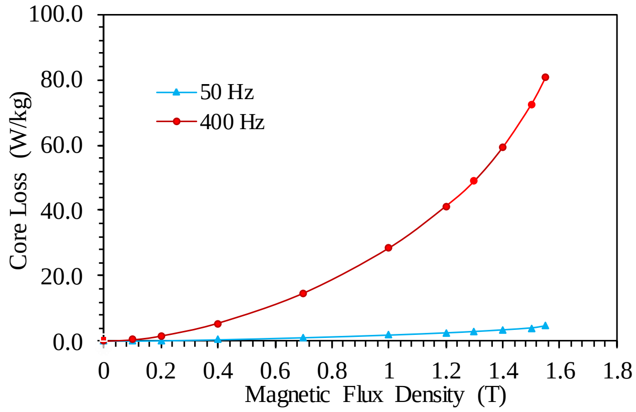

Figure 19: Iron loss Curve of Non-Oriented Electrical Steel-M400-50A-0.50 mm

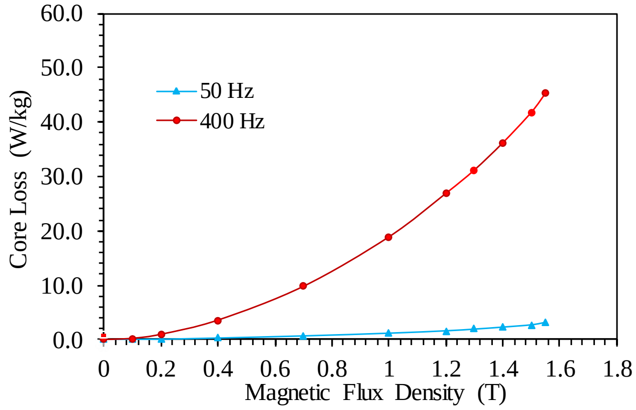

Figure 20: Iron loss Curve of Non-Oriented Electrical Steel-DI MAX-M19-0.35 mm

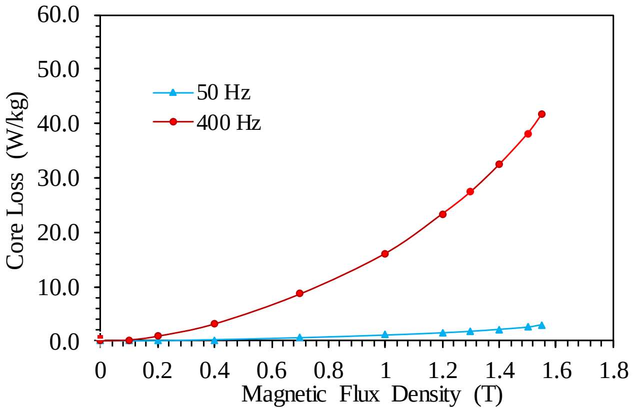

Figure 21: Iron loss Curve of Non-Oriented Electrical Steel-DI MAX-M15-0.35 mm

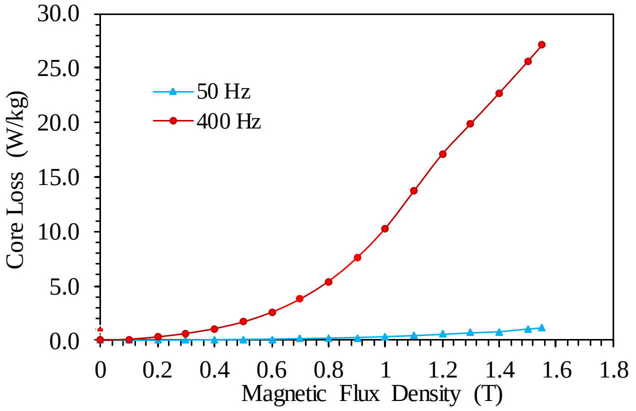

Figure 22: Iron loss Curve of Nickel-Iron Alloy- Alloy 49 Rotor Grade-0.36 mm

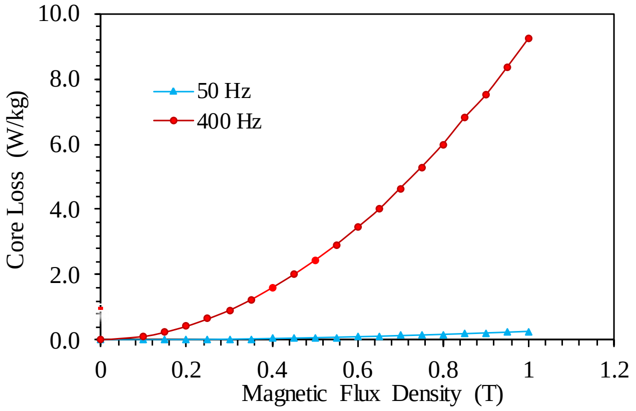

Figure 23: Iron loss Curve of Nickel-Iron Alloy- Supra 50-0.35 mm

Table 1: Relative Properties of Soft Magnetic Materials

Material Type	Core Loss	Sat. Flux Density	Permeability	Ease of Processing	Raw Material Relative Cost
CRML Steel	Poor	Good	Good	Best	0.5
Thin-Gauge Silicon Steel	Better	Good	Good	Fair	10
Non-Oriented Electrical Steel	Good	Good	Good	Good	1.0
Nickal-Iron Alloy	Better	Fair	High	Care Required	15

Costs are indexed in arbitrary units to non-oriented steel=1

The graphical summary of the magnetization and core loss properties of the common types of lamination materials seen in Figs. 2 – 23 perpetuate interesting information on the choice of the material. The chart provides a closer look at the core loss properties of each class of material at 50 and 400 Hz and at lower and higher values of 0.1 and 1.5 T respectively. It follows that an increase in the operating frequency increases the core losses.

The overlap in the core loss performance among many of the material grades as the frequency and magnetising force rise pulls out further interesting facets to govern the choice of the material. A similar judgment can be made when assessing changes in the magnetization characteristics or the permeability as a result of the increasing frequency.

The entries in Table 1 eclipse the way of reducing energy loss in an electromagnetic core for a given material grade by using thinner lamination steel but must be weighed against other factors especially cost in choosing the best steel for a particular machine. Within the standard range of lamination thicknesses 0.36mm to1.0 mm lamination, the costs siege to a large measure on the weight of the part and thus the individual laminations made from a lighter gauge boil down to cost less than their thicker companions.

However thinner laminations especially if less than 0.25 mm may succumb to be costly due to additional rolling and processing cycles. In any case manufacturing laminations from lighter gauge steel can cost substantially more. If the overall core dimensions remain the same the use of thinner material requires more laminations, and result in a lowering of the core's lamination factor or iron density. The thinner laminations tend to experience slightly lower saturation flux density and may also limit motor output.

The cost of steel is one of the key variables to be considered when selecting a lamination material and obeys limiting factors similar to the other material attributes in the sense the changing steel ventures to achieve a lower raw material cost and bring with it a reduction in the other properties. Conversely a steel with one or more enhanced magnetic properties can most likely be obtained only at a higher price as observed from the Table 1. With ever-increasing demands for lower priced machines, including those with advanced performance, the engineer must constantly juggle performance issues against the cost of the finished machine.

The price of lamination steel can be influenced not only by the cost and availability of raw materials and efficiencies in steel production, but also by such market forces as competition among producers, international trade agreements among countries and other geopolitical concerns, and the contractual agreements between the mill and the user.

A close reading of the magnetic characteristics of lamination materials provide the best information on their individual properties and an understanding of the general properties of different types of lamination steels. Despite the allegiance that each class of material does have strengths and weaknesses that need be addressed, a detailed consideration of all the issues outlined above strives to help the engineer arrive at the lamination steel that best supports both the performance and marketability requirements of the machine.

CONCLUSION

The study has been enticed to enable the choice of the suitable type of magnetic material for use in the electrical machines. The exhaustive analysis has been dealt with to bring out the influence of the magnetic parameters on the occurrence of loss in the material. The investigations have been explained to foresee the possibility of the different operating frequency in the search for the appropriate thickness of the lamination for use in the core. The efforts have been strengthened through an amalgamation of the issues under consideration and the cohesive picture relating to the choice brought out. The elucidations have been presented to arrive at the appropriate material for a chosen application and add to subscribe for opening up fresh dimensions of the use of rotating electrical machines in the utility world.

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