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Iron Loss Trends in BLDC Motors

Electric machines account for nearly two third of electricity consumption in the US, most of which can be accounted for by electric motor driven appliances. Energy efficient designs of electric machines could therefore translate into significant savings both financially and in terms of energy resources. Even fractional improvements in the efficiency of electric machines would translate into significant savings. Efficiency of electric machines depend on four main sources of loss; ohmic, magnetic, mechanical and stray losses. Depending on the type of application, magnetic losses (iron losses) could be a significant fraction of the total loss in such machines. This article considers computing iron loss trends in interior permanent magnet (IPM) and surface mounted magnet rotor (SMMR) BLDC motors and some of the lessons that can be learned from them.

Recent advances in computational capabilities and new algorithms as well as the development of new machine design software have significantly enhanced the possibility of accurately predicting iron loss values in electric machines. The results and discussions presented here will show that computing loss trends can be a useful tool for understanding the behavior of electric machines. These lessons can be used to set and/or fine tune the machine parameters.

Iron Loss Theory, Challenges and New Tools

Iron losses are generally divided into three components; hysteresis, eddy current and anomalous losses. Hysteresis loss is the energy cost associated with the forced alignment of electric dipoles and domain-wall movements due to a time varying external magnetic field. Eddy current loss is due to induced currents in laminated steel and anomalous losses due to "other" unknown sources of loss in electric machines. Theory and classification of iron losses are an area of research spanning various fields of engineering and physics and their review is beyond the scope of this article. Instead, the most general computational aspects of iron losses are reviewed here.

The Steinmetz equation, presented nearly a century ago, quantifies iron losses as a function of frequency and magnetic field strength and is given by,

$$Loss = C_m f^{\alpha} B^{\beta} + C_e f^2 B^2 \quad . \qquad (1)$$

Here, the first term represents the combined hysteresis and anomalous loss components and the second term represents eddy current losses. Over the years, many variants of Equation 1 have been used to compute iron losses but their success in accurately predicting the losses have been limited and the form shown above is still the foundation of most approaches in use. The unknowns, a, ß, C_m , C_e , in Equation 1 are usually determined from experimental data (provided as W/kg) by fitting loss curves generated from so-called Epstein frame tests (ring tests, single sheet tests and/or other test methods) of iron loss versus peak magnetic field strength (B_{peak}) at various frequency and temperature, as a function of lamination thickness. The main challenges of this approach and its application to BLDC, switched reluctance and other electric machines are summarized below.

One of main drawbacks of the curve fitting approach is the difficulty associated with implementing the data for practical electric machines that are driven by various types of inverters and are subjected to non-sinusoidal, orientation dependent flux density waveforms. The second problem, which is essentially a computational problem, is that different parts of the machine are subjected to different waveforms so the computations must be carried out at all regions of the machine. The first problem is an area of significant theoretical and experimental research. Experimental efforts have revolved around designing test benches that are subjected to sinusoidal and non-sinusoidal (PWM) waveforms, flux density orientations and with various sample geometries. Attempts have been made to apply the results "universally" or to a large variety of problems. Theoretical efforts have revolved around trying to understand the sources and mechanisms of iron losses and accurately predicting the loss values. Physical phenomenon such as the application of skin depth analysis to iron loss calculations is a simple example of this. Semi-analytic modeling of eddy current loss is another example of the type of theoretical effort that has been made to predict iron losses. It suffices to say that iron loss related theoretical, experimental, modeling related research is quite extensive and much remains to be done.

The second problem is essentially a computational problem. It implies that accurate accounting of iron loss calculations can only be done using models in which the loss calculations must be applied to different parts of a device. This renders an FEA based approach almost mandatory for accurate computation of machine efficiency.

The calculations presented in this article were done using MotorSolve, a 2D FEA based motor design software. The algorithm in MotorSolve for iron loss calculations is summarized next. The loss calculations are based on Equation 1 in which the unknowns, i.e., the exponents and loss coefficients, are determined using curve fitting of experimental data. Once these coefficients have been determined, transient analysis is performed of a machine model that is allowed to reach steady state. The flux data in each element of the FEA model of the device is then used to compute the hysteresis and eddy current loss components. For the eddy current loss values, harmonic decomposition of the flux profile in each element implies very accurate estimation. Hysteresis loss is estimated by extrapolating the loss data from that due to sinusoidal waveforms. The

	IPM and SMMR
Number of Poles	6
Number of Slots	9
Rotor speed (rpm)	10,000
Voltage (V)	15
Outer dia (mm)	21.7
Bore dia (mm)	11.81
Stack (mm)	5.95
Lamination material	M16 - 29 G

Table 1. Summary of SMMR and IPM BLDC parameters

method used for hysteresis loss computations are superior to those based on other methods such as loop counting. Also, the method is orientation independent, which is advantageous over similar approaches.

Iron Loss Separation and Trends

Iron loss separation and trend results are reported here for some representative examples of BLDC motors. Two practical high-speed motors, one with surface mounted magnet rotor (SMMR) and another with IPM have been used. In order to facilitate meaningful comparisons, the characteristics of the IPM and the surface mounted motor parameters have been selected such that their cogging torque, back emf and output torque are very close. A summary of their properties is shown in Table 1.

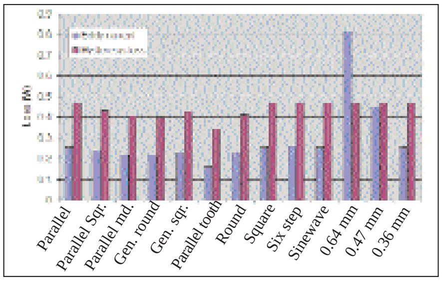

Figure 1. SMMR loss vs. lam. Thickness, drive-type and stator geometry

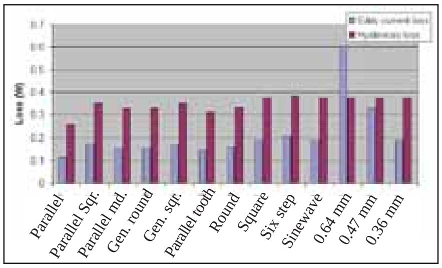

Figure 2. IPM loss vs. lam. Thickness, drive-type and stator geometry

It was found that the average cogging torque, rms back emf and output torques for IPM and SMMR respectively are; 0.0025 Nm (peak), 4.25 V peak and 0.024 Nm for the IPM and 0.0030 Nm (peak), 5.05 V peak and 0.026 Nm for the SMMR.

Iron loss trends as a function of lamination thickness, drive type, stator geometry and operating speed have been studied for each motor type. The software used in this study reports losses at the model component level and some of the significant results are presented next. Figures 1 and 2 show the variations of the stator hysteresis and eddy current loss components as a function of lamination thickness, drive type (sine-wave and six-step) and stator geometry for the SMMR and IPM, respectively. The corresponding efficiency plot is shown in Figure 3.

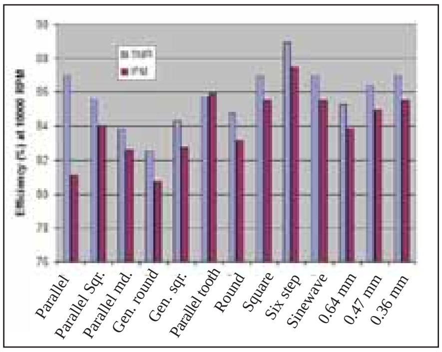

Figure 3. IPM and SMMR efficiency vs. lam. Thickness, drive-type and stator geometry

article continued on page 24

article continued from page 23

A number of interesting observations can be made from these charts. First consider the BLDC loss trends in Figures 1 and 2. As a function of lamination thickness, the eddy current losses are clearly seen to increase (parabolically) for both SMMR and IPM, as expected. The corresponding increase in efficiency is approximately 2 percent, for both SMMR and IPM rotor geometry. Hysteresis losses are unaffected by lamination thickness, also as expected. Consider now the loss values as a function of drive types. The results show that six-step drives generate more losses (both hysteresis and eddy current losses) than sine-wave drives. Comparison of the efficiency versus stator tooth geometry show that for IPM, square tooth geometry gives the best results whereas for the SMMR, parallel tooth is the most efficient design. These are some simple examples of the computation and analysis that can be done using a tool such as MotorSolve. In general, during any stage of the design process, such computations can be invaluable for determining machine parameters.

In light of the simple examples, the main point of this article can be summarized as follows. Rapid progress in computational power and development of tools such as MotorSolve are likely to revolutionize CAD of electric machines. It is usually expected that a great deal of experience and knowledge are required to design electric machines. However, considering the fact that machine design is ultimately an exercise in iteration and optimization (at least up to, but not including, the control system design), generating machine characteristics as a function of design parameters will become common place in future as new design tools become available and existing ones evolve. Also, the problem of generating machine design parameters based on required characteristics may very well have exact solutions based on databases and surface plots of efficiency and other characteristics coupled with the implementation of efficient search algorithms. This will likely reduce the need for vast and diverse knowledge for designing efficient electric machines in the not too distant future.

Dr. Rahman joined Infolytica Corp. in 2006 where he is presently involved in a number of development, consultancy and support related projects. He is part of a team that is developing algorithms for the design of Switched Reluctance Motors (SRMs). He is also involved with exploring applications of FEA based multi-physics engineering applications for a variety of problems related to motors, actuators and design optimization. He can be reached at tanvir@infolytica.com.

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