

Lamination Core Loss Measurements in Machines Operating with PWM or Non-sinusoidal Excitation

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Abstract—Variable Speed Drives (VSDs) are becoming standard supplies for motors in industries because of their benefits in increased process control and energy savings. The benefits of employing a VSD are derived at a cost of increased core losses and motor temperature rise. Core loss measurements with sinusoidal supplies are guided by international standards. However, there are currently no international standards for the fast growing variable frequency supplies and the associated core losses. In this paper, a test bench for core loss measurements under variable frequency supplies proposed by [1] is adopted. Work reported in this paper serves to validate the proposal and extends the test bench proposal to switched reluctance motor (SRM) lamination core loss measurements. An Epstein frame was used for direct core loss measurements. The methods and test bench used are detailed in the paper, along with test results.

I. INTRODUCTION

Magnetic material properties reported by the manufactures are considered a measure of its quality or suitability for a particular application. Although the ultimate measure of a material's characteristics may be its final application, suppliers and users of the material must have common, objective methods for specifying and confirming its magnetic properties. Core loss data is one of the major characteristics used to grade electrical steel. In electrical machines, core losses amount to 20 – 25 % of the losses [4]; this estimation is only valid under sinusoidal supplies, usually 50 Hz or 60 Hz. Under an inverter, such as a PWM inverter, a motor sees various frequencies higher than 50/60 Hz and the 50/60 Hz core loss data from steel manufacturers is not appropriate. References [1] - [3] and [7] have reported an increase in electrical core losses when excited with non-sinusoidal supplies. Since inverters are becoming standard in industry, the standardizing bodies such as the American Society of Testing and Materials (ASTM) will have to consider developing standards to characterize electrical steel under non-sinusoidal excitations, for common inverters such as PWM inverters. In [1], a test bench has been proposed for measuring core losses on magnetic samples under variable frequency supplies. That is verified here and extended to SRM core loss testing, which represents an extreme form of non-sinusoidal excitation.

SRMs are becoming popular as part of a drive system and represent a real alternative to conventional drives in many applications. This is mainly because of their rotor construction with no windings. In high-speed applications of

SRMs, core losses become a dominant component of the total losses. In order to develop an optimized SRM drive, a model for calculation of the losses is important, the complexity of which is attributed to the nature of the flux waveforms, i.e., non-sinusoidal and fundamentally different in different parts of the motor. The waveforms change with the motor design: number of stator and rotor poles, number of phases etc, and operating conditions: conduction angle and mechanical speed. The saturation of the magnetic core, which is an important feature of this type of motor, has different levels in various sections of the magnetic circuit [6]. Since the core saturates, superposition cannot be applied to estimate core losses.

The publication [1] on the development of the test bench is adopted and forms the core of the work reported in this paper. Section II presents results and analysis of findings on PWM losses. Section III presents the flux model development and core loss results when the magnetic samples were fed from non-sinusoidal waveforms similar to those of the SRM stator and rotor parts. Finally, Section IV presents conclusions drawn from this work.

II. PWM LOSS MEASUREMENT RESULTS AND ANALYSIS

The following PWM inverter parameters were varied to observe their influence on core losses:

- Modulation index (m_a , amplitude ratios of the control to the switching waveform)
- Switching frequency (f_s)

Using a sinusoidal PWM and unipolar switching, core losses were measured. A peak fundamental flux was used as a reference. Using the separation of loss principle, total core losses can be expressed as:

$$P_{core} = P_h + P_c + P_e \quad (1)$$

$$\text{Where } P_h = K_1 \int H dB, \text{ (W/kg)} \quad (2)$$

$$P_c = K_2 \int \left| \frac{dB}{dt} \right|^2 dt, \text{ (W/kg)} \quad (3)$$

$$P_e = K_3 \int \left| \frac{dB}{dt} \right|^{3/2} dt, \text{ (W/kg)} \quad (4)$$

Where P_h , P_c and P_e is the hysteresis, classical and excess loss components, respectively and K_i ($i = 1, 2, 3$) are constants

determined from the physical properties of the steel. Bertotti [10] showed the origin of the excess loss component, P_e . Each of the PWM inverter characteristics are considered below and their contribution to equation (1) is shown.

i. Modulation Index

With switching frequency fixed ($f_s = 1$ kHz), core losses were measured for different m_a values and plotted as a function of the fundamental peak flux as shown in Fig. 1 below.

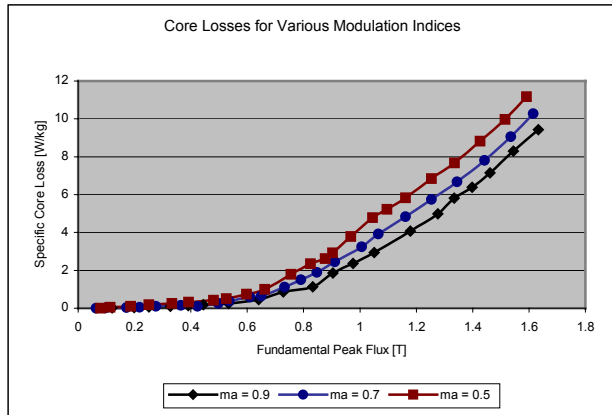


Fig 1: Specific loss vs. flux density for various modulation indices

Fig.1 shows the measured specific losses as a function of the peak fundamental flux density. The results show that the iron losses decrease with increasing modulation index. In fact, if $m_a \geq 1$, the PWM output voltage tends to be the same as the full square wave inverter output; which have been found [1] to yield core losses less than the PWM waveforms. Reducing m_a increases hysteresis losses due to the creation of minor loops. From equation (1), it is seen that for non-sinusoidal supplies, the eddy current loss component depend more on the rate of change of flux (slope, dB/dt), as observed by [7]. The current ripple has been found to increase with the decreasing modulation index. Hence the loss increase under PWM supplies is attributed mainly to the increase in eddy current losses, [2] also confirmed in this finding.

ii. Switching Frequency

To investigate the dependence of core losses on the inverter switching frequency, core loss were measured at different peak fundamental flux densities while keeping the fundamental output frequency at 50 Hz, $m_a = 0.9$ and varying f_s from 500 Hz to 20 kHz. The specific iron losses (in W/kg) are plotted as a function of switching frequency as shown in Fig 2. The plots show that for $f_s \geq 5$ kHz the specific losses remain almost constant while f_s is increased at constant flux density. Core losses are seen to increase slightly at low frequencies (less than 5 kHz) –effectively what [1] observed. Increasing f_s smooths out the flux steps (dB/dt) and current ripples, resulting in reduced core losses. However the drive switching losses will increase; hence it is not necessary to increase the switching frequency beyond 5 kHz. In other

words the diminishing returns effect becomes effective, as drive losses will increase.

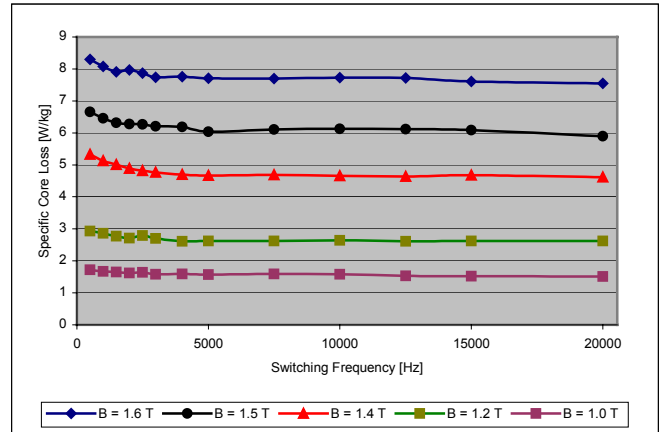


Fig 2: Specific Core Losses vs. Flux Density for Different Switching Frequencies

III. MEASUREMENT OF CORE LOSSES IN THE SRM

The test bench used is described below. The non-sinusoidal signals are generated by DSP based dSPACE software with a real-time interface with SIMULINK. A high bandwidth linear amplifier (AMP 100 kHz) is used to boost the signals and used as a power source for core loss measurement on the Epstein frame. A single-phase transformer (TX) was connected between the amplifier and the Epstein frame. A current probe (CP) and an isolated differential voltage probe were used to measure the exciting current and secondary voltage, respectively. A digital storage oscilloscope (DSO), Nicolet Integra 40 model was used to monitor and store exciting current, secondary voltage and their instantaneous product (power) for offline analysis. The non-oriented magnetic strips tested in our laboratory are from AK Steel, product code DI-MAX, M-45FP 29 gauge.

This test bench is an extension of what [1] proposed, as shown in Fig 3. This is the same instrumentation which was employed for PWM testing.

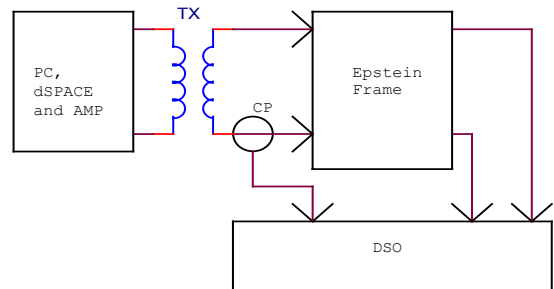


Fig 3: Test bench used to measure core loss under non-sinusoidal excitations

To measure the iron losses in the SRM, the flux pattern in various segments of the machine should be known in order to

derive the waveforms of the voltage source to be applied to the Epstein laminations core.

i. Flux Model

In the SRM, each stator pole has one coil, and each phase consists of m coils connected in series ($m = 2, 4, 6, \dots$) and there is no mutual coupling among the different phases. The number of rotor poles (N_r) determines the phase switching frequency.

$$f_{ph} = \frac{N_r \omega}{2\pi}, T_{ph} = \frac{1}{f_{ph}} = T_{rp} \quad (5)$$

Where ω is the rotor mechanical speed [rpm], and f_{ps} is the phase switching frequency. For a q phase machine, the phases are excited successively with switching frequency,

$$f_s = qf_{ph} \quad (6)$$

The stator flux pulse that is created through phase excitation is represented as a piecewise linear function:

$$\Phi(t) = \begin{cases} \frac{\Phi_m}{T_c} * t & \dots\dots\dots 0 \leq t \leq T_c \\ \frac{\Phi_m}{T_c} * (2T_c - t) & \dots\dots\dots T_c \leq t \leq 2T_c \\ 0 & \dots\dots\dots 2T_c \leq t \leq T_{rp} \end{cases} \quad (7)$$

Where Φ_m is the peak flux, in an SR motor, this peak flux is scaled by $1/N_{ph}$, where N_{ph} is the number of turns per phase. The maximum conduction interval is $T_{rp}/2$ and $T_c = \gamma * T_{rp}/2$ with γ being a controllable parameter. A detailed mathematical development of the flux waveforms has been presented by [5] and [6]. Using the above flux derivations and considering a 4 phase 8/6 machine: Suppose U, V, W and R represent the four phases of the 8/6 pole machine and the associated generated fluxes are $\Phi_U(t), \Phi_V(t), \Phi_W(t)$ and $\Phi_R(t)$ as shown in Fig 4 below:

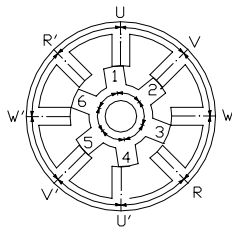


Fig 4: The segments of a 4-phase 8/6 SRM

The flux model described above was implemented in MATLAB SIMULINK and the patterns for the above 4 phase 8/6 SR machine are shown Figs 5 to 7 for speed of 500 rpm (50 Hz) with $T_c = T_{rp}/2$. Starting from the normalized stator

pole flux waveforms, the rest of the motor flux patterns are derived.

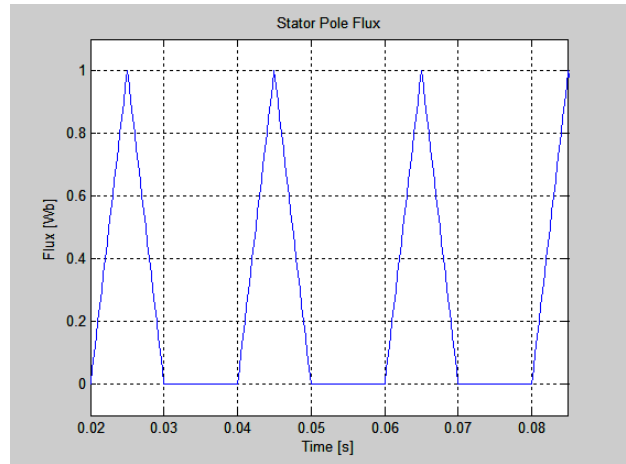


Fig 5: Typical SRM stator pole flux waveforms from simulations

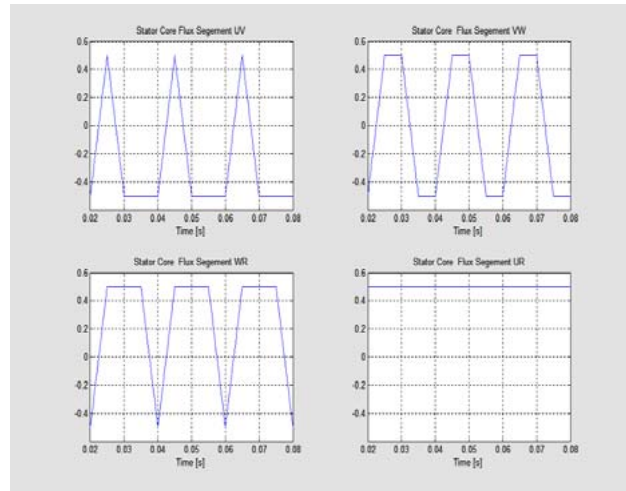


Fig 6: Typical SRM stator yoke flux waveforms from simulations

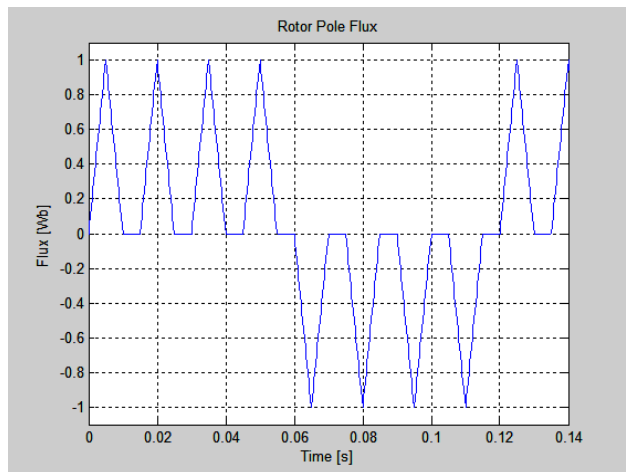


Fig 7: Typical SRM rotor tooth flux waveforms from simulations

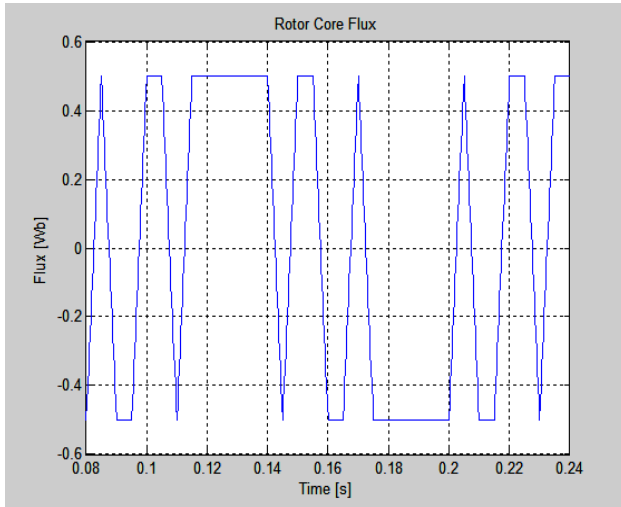


Fig 8: Typical SRM rotor yoke flux waveforms from simulations

ii. Measurement Results

Using the above flux patterns, the excitation voltage signals are derived by differentiating the respective flux waveforms. This assumes that the winding voltage drop (ir) is negligible. The Epstein frame was excited with these different voltages and the specific iron losses in different segments of the SRM measured. The measured specific core losses with respect to stator pole fundamental peak flux value are plotted and compared as shown in Fig 9. Also plotted on Fig 9 are the loss results at 50 Hz (sinusoidal) to emphasize the loss increase in moving from sinusoidal to SRM equivalent waveforms.

From Fig 9, the rotor teeth are seen to experience higher losses. The loss variations in the motor can be attributed to three factors: 1) different flux peaks reached, 2) rate of change of flux (dB/dt) and 3) the different flux frequencies. The first one affects mostly the hysteresis losses, known to depend on the peak flux reached. In a typical SRM, the rotor tooth reaches the same maximum flux as the stator poles. The second factor, dB/dt , affects mainly the eddy current losses; which are dependent on the rate of change of flux. From Fig 6, for one rotor revolution the rotor pole flux slope changes signs sixteen times, whereas the stator poles flux changes signs twelve times. The third factor, frequency dependence, has been widely published: linear for hysteresis loss component and quadratic with eddy current losses. The waveform of f_{ph}/N_r (8.33 Hz) and a carrier at $N_s/N_r * f_{ph}$ (66.66 Hz), this carrier frequency is higher than the fundamental stator pole voltage. Therefore rotor poles incur higher losses than the stator poles--particularly the eddy current losses. This is somehow contrary to what [6] reported for a 12/10 machine. However, [5] reported similar results as reported in this paper, for a 6/4 SRM.

The rotor and stator cores fluxes reach half the respective poles' peak fluxes. Stator core VW was found to experience

relatively lower losses, compared to segments UV and WR. The loss differences can be justified by noting that although the fluxes patterns of these segments have similar slopes and magnitudes, their frequency distributions are different. Fluxes in cores WR and UV have a higher frequency content than core VW. The frequency content of the stator poles is similar to that of core UV and WR. The rotor core losses were found to be similar to the stator core segment VW. The stator RU' segment flux pattern is almost dc, with some ripple whose magnitude depends on the conduction time. This segment does not experience as much core losses as the other stator segments because flux does not alternate, resulting in reduced hysteresis loss [8].

It has been observed that at higher speeds the stator losses tend to dominate and the rotor core losses remained almost unchanged; and the rotor pole losses increased slightly. Minor loops present a challenge to estimating losses under non-sinusoidal supplies. This warrants attention for future work. Using superposition with the Fourier coefficients is controversial since the SRM core easily saturates. The authors are still working on loss estimation methods that will use the original steel manufacturer's loss data to estimate losses under distorted waveforms.

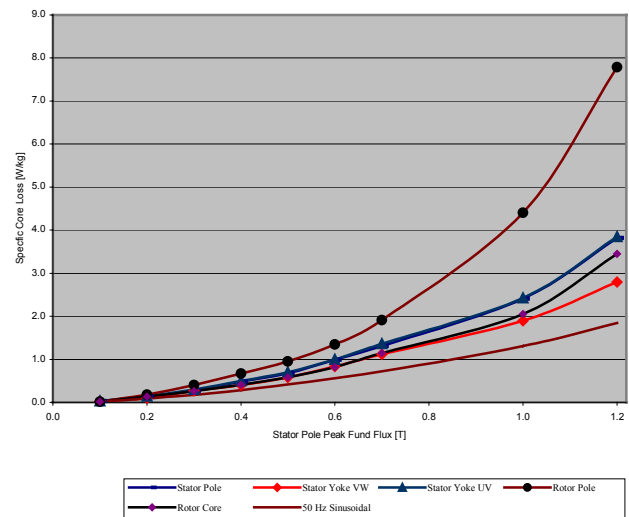


Fig 9: Specific core losses vs. flux density for various SRM segments

IV. CONCLUSIONS

This paper has successfully applied the test bench and methodologies proposed by [1] and verified the effects of varying the modulation index and the switching frequency on PWM core losses, by measurements. The paper confirms that PWM core losses are highly dependent on the modulation index, and for high switching frequency (≥ 5 kHz) core losses are relatively independent to changes in the switching frequency. This paper has shown the possibility of estimating loss trends in SR motors using a simple Epstein frame, without having to build a prototype and run measurements. At lower speeds, the rotor teeth are found to contribute more

core losses to the overall motor core losses, whereas at high speeds, the stator losses increase and dominate. The loss trend in the stator yoke segments is different for each segment; this may result in non-uniform heating around the stator yoke. The loss trend presented in this paper gives motor designers a feel of the loss distribution inside the machine and thus present opportunities for design optimization. This paper also showed the need for measurement standards to characterize electrical steel under non-sinusoidal excitations. Future work will include loss estimations methods under distorted supplies, using the loss data that motor designers get from steel manufacturers.

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