Assessing the Core Losses in Switched Reluctance Machines

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***Abstract*—This paper looks briefly at aspects of iron loss assessment in switched reluctance machines and addresses issues that can arise when attempting to measure the flux linkage/current loops and the magnetizing curves experimentally.**

***Index Terms*—Switched reluctance motors, iron loss, current flux linkage loops**

I. Introduction

Core losses are usually calculated using the Steinmetz equation, however in switched reluctance machines (SRMs) the flux waveforms are non-sinusoidal and different parts of the magnetic circuit have different flux waveforms. Several methods to evaluate the core losses in SRM have been previously described by several authors including Hayashi [1], Materu [2] and Liou [3]. This paper will look at typical predicted losses in an SRM using the *SPEED* software, which uses a modified Steinmetz equation. Then it will then address the problems by looking at measured current/flux linkage curves and also the magnetizing curves.

II. Predicted Losses in an SRM Using *SPEED* Software

An 8/6 SRM (Fig. 1 and Table I) was used to assess the core losses and the package PC-SRD from the *SPEED* Laboratory, University of Glasgow, was used to calculate the core losses (from analytic magnetic circuits) under similar performance parameters for different core materials (6 different steels were simulated). The machine had an original winding which was damaged; it was rewound by hand with a winding with fewer turns but slightly thicker wire. This brought down the voltage rating. The main control parameters for the simulations are presented in Table II. In addition to the voltage de-rating, the speed was reduced because of the speed rating of the load. From the results obtained (Table III), it can be clearly observed that the core losses vary considerably depending on the core material of the motor, and this is an important area for the study since it affects the efficiency (varying from 41.3 % to 73.2 %). The experimental machine has an M19 29 gage material and the machine is operating with a current density of 4 A/mm^2 which suggests that it is not at maximum current and far from fully loaded. However the torque was measured as 0.54 Nm compared to 0.7 Nm simulated. The difference will be addressed in the following sections.

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TABLE I
Motor Specification

No. of phases	4
No. of stator/rotor poles	8/6
Stator outer diameter [mm]	120.7
Stator slot-bottom diameter [mm]	96.8
Rotor outer diameter [mm]	60.0
Rotor slot-bottom diameter [mm]	43.2
Air gap [mm]	0.3
Shaft diameter [mm]	25.4
Stack length [mm]	75
Stator pole arc	22.6°
Rotor pole arc	23°
Turns per coil	38
Resistance @ 20°C	0.3 Ω
Minimum inductance [mH]	1.45
Maximum inductance [mH]	9.15
Rated voltage of original machine [V]	270
Rated speed of original machine [rpm]	5000

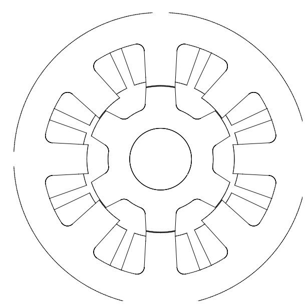

Fig. 1. Cross section of 8/6 Pole Switched Reluctance motor

TABLE II
Motor Control Parameters

Speed	1500 rpm
DC Voltage	80 V
Current limit	7 A
Current Hysterisis band	0.2 A
Turn-on angle Th0	35°
Turn-off angle ThC	55°

III. Aligned Magnetizing Curves

Fig. 2 shows the magnetizing curves for the experimental machine when the rotor is aligned. It might be expected that the high voltage loop would enclose the larger area (due to eddy current loss) but this was found not to be the case.

However, the flux density is slightly higher in the low voltage case. The period for the loop in the high voltage case was 2 ms and for the low voltage case it was 15 ms. The aligned magnetizing curve calculated from *SPEED* is also included and it can be observed that the agreement is good for the high voltage case and reasonable for the low voltage case.

TABLE III
SPEED CALCULATED LOSSES WITH DIFFERENT MATERIALS AT 1500 RPM

MATERIAL	CORE LOSSES (W)	TOTAL LOSSES (Inc mech loss) (W)	IRON LOSS AS PROPORTION OF TOTAL LOSS (%)	TRQUE (Nm)	EFFNCY (%)
M19 29 gage (actual)	11.0	40.1	27.4	0.70	73.2
M19 24 gage	21.9	51.0	42.9	0.63	65.9
M19 3% Si	14.0	43.0	32.5	0.67	71.0
Losil 800 / 65	56.0	85.1	65.8	0.38	41.3
Losil 500 / 65	28.3	57.2	49.5	0.57	60.8
Transil Bs 35	13.5	42.4	31.8	0.66	71.1

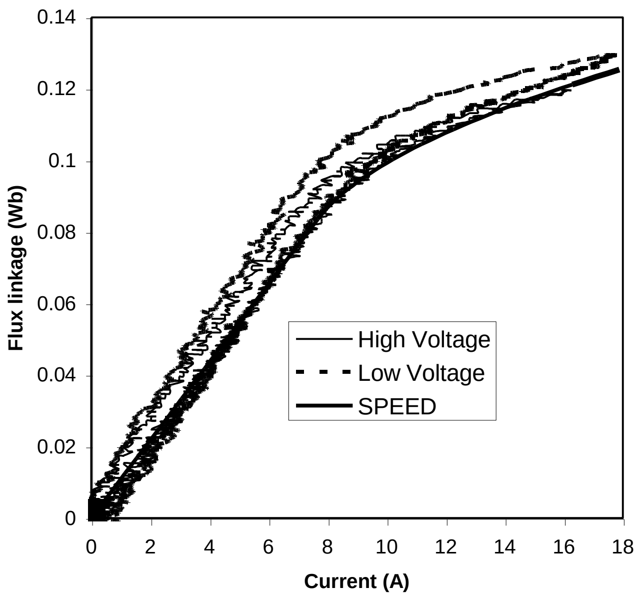

Fig. 2. Magnetizing curves at high voltage (120 V) and low voltage (20 V).

IV. MEASURED FLUX LINKAGE/CURRENT LOOP

The current/flux linkage curves cannot be obtained directly and it requires the integration of the voltage signal to derive them. The flux linkage can be obtained by integration of a search coil voltage but to get the actual flux linkage curve, the voltage across the actual coils should be measured and the voltage drop across the coil resistance subtracted. This requires accurate resistance measurement and any thermal change in resistance to be incorporated. The incremental change in flux linkage is given by

$$\Delta\Phi_n(t) = \left(v_n(t) - i_n(t)R\right)\Delta t \tag{1}$$

where Δt is the step period. As well as careful measurement of phase resistance care should be taken to ensure that there is no voltage or current offset. The flux is then given by

$$\Phi_n(t) = \sum_1^n \Delta\Phi_n(t) \tag{2}$$

Fig. 3 gives the flux linkage loops for one phase over a period of 50 ms. Since for a speed of 1500 rpm this represents a period of 1.25 revolutions, i.e, 7.5 strokes per phase (7 complete strokes). The voltage and current waveforms from the digital storage scope are unprocessed and unfiltered. There are 2000 samples, thus the sample time is 0.025 ms.

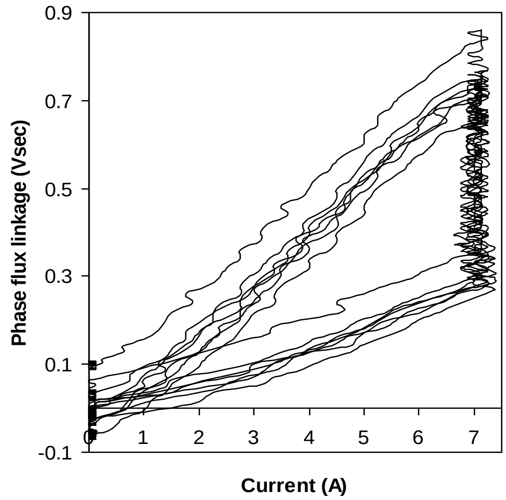

Fig. 3. Flux linkage/current loops when the firing angles are Th0 = 35° and ThC = 55°

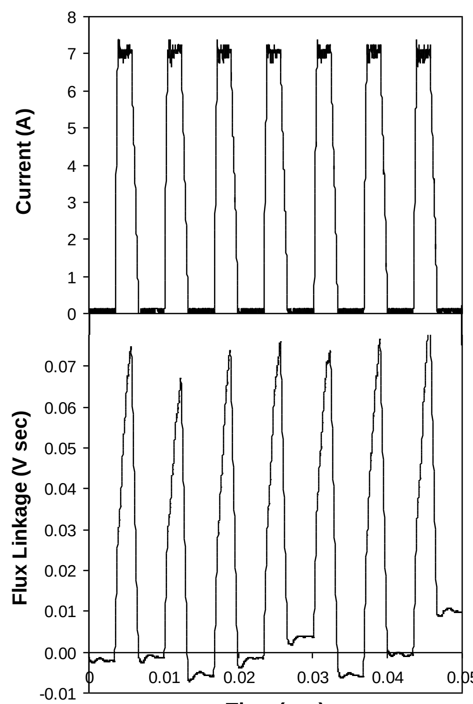

Fig. 4. Phase current (top) and flux linkage (bottom) when the firing angles are Th0 = 35° and ThC = 55°

The flux linkage and current waveforms are shown in Fig. 4. It can be seen that there is a variation of flux linkage over the seven cycles; this can also be observed in Fig. 3. It is difficult to assess whether this is numerical error or switching error without comparison to a search coil voltage, however it is anticipated that the total energy conversion can be obtained by calculating the total area enclosed in all the loops across all four phases; this gives the total energy conversion and iron loss over the 50 ms period. An average can also be taken to obtain an average loop. The actual voltage across the phase is shown in Fig. 5; obviously this is supplied by a PWM bridge converter and since the voltage is being sampled then a variance (aliasing) between successive voltage cycles due to the phasing between the PWM switching and the sampling frequency is possible.

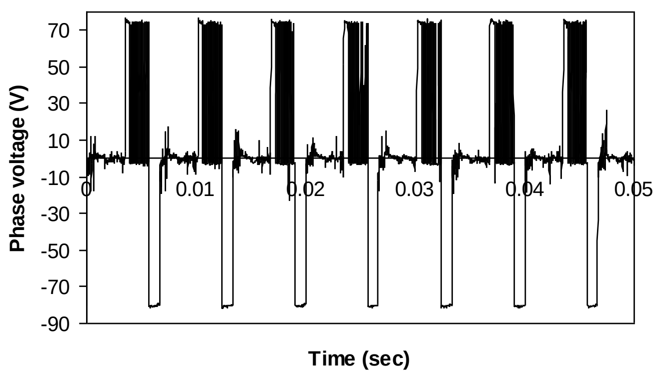

Fig. 5. Phase voltage when the firing angles are Th0 = 35° and ThC = 55°

V. Assessment of Iron Loss From Experimental Results

The iron loss can be assessed by consideration of the area of the flux linkage loops. This represents the electromechanical energy conversion and the iron loss. The electromechanical energy conversion is split between the shaft torque and the friction and windage loss. The latter can be determined by measuring the torque when the motor is turned unexcited at 1500 rpm. This gave a torque of 0.068 Nm which is a 10.5 W loss. The area enclosed by all flux linkage loops for all four phases can be obtained from the equation:

$$E_{Loop} = \sum_{Ph=1}^{4}\sum_{n=2}^{N}\left\{\frac{\left(\Phi_n^{Ph}(t)+\Phi_{n-1}^{Ph}(t)\right)}{2}\left(i_{n-1}^{Ph}(t)-i_n^{Ph}(t)\right)\right\} \quad (3)$$

so that the iron loss is

$$P_{\mathrm{Fe}} = \frac{E_{Loop}}{\text{Measured period}} - T_{\text{measured}}\omega_r - P_{\text{Friction+Windage}} \quad (4)$$

The input power could be obtained using a power analyzer, however, to check for consistency, the power can also be obtained from the voltage and current by multiplying them together to get the instantaneous power, then averaging over the measured period. Similarly the copper loss can be obtained from the measured current and resistance. Table IV shows power and loss components from the measurements for each phase and compares the results obtained from the measured values to the results from the *SPEED* simulation. The predicted iron loss from the modified Steinmetz equation seems reasonable (given the experimental error observed in the measurements) however there appears to be an overestimate of the torque due to a large flux linkage loop. Therefore Fig. 6 compares the average measured flux linkage loop to the simulation. Clearly the divergence appears to be during turn-on where the simulation predicts a faster response.

TABLE IV
Power and Loss Components per Phase (Measured)

PHASE	1	2	3	4	Total	*SPEED*
P_{in}	30.1	31.9	34.1	31.5	127.6	149.7
P_{cu}	4.7	4.3	4.3	3.8	17.1	18.6
P_{in} - P_{cu}	25.4	27.6	29.8	27.7	110.5	131.1
P_{Loop}	25.5	27.5	28.9	27.4	109.3	131.1
P_{F+W}	---	---	---	---	10.5	10.5
P_{Torque}	---	---	---	---	84.8	109.6
Calc P_{FE}	---	---	---	---	14.0	11.0

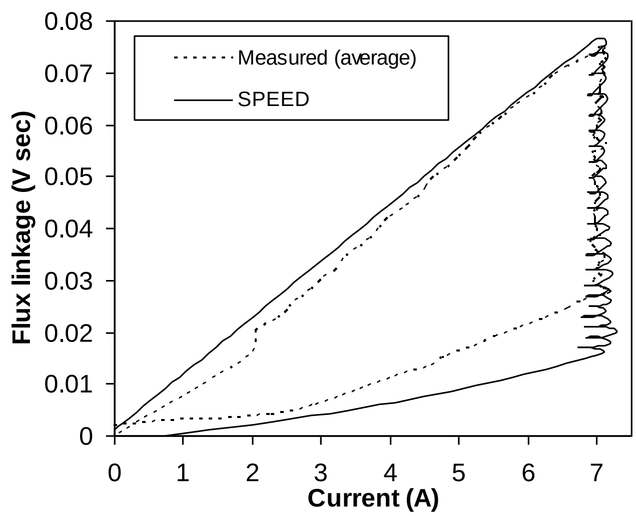

Fig. 6. Comparison between mean-measured and *SPEED*-calculated flux linkage loops at Th0 = 35° and ThC = 55

VI. Conclusion

This paper illustrates that iron loss can affect the performance of a switched reluctance machine and details a method for measuring the iron loss. The paper also validates the *SPEED* design software and highlights the importance of obtaining good magnetizing curves in order to obtain accurate torque calculations.

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