On the Importance of Using Correct Saturated Steel B/H Curves for Performance Predictions in Induction Motors for Modern Electric and Hybrid Vehicular Drives

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Abstract —This digest investigates the importance of modeling steel *B-H* curves accurately, well into saturation, when simulating induction motors that are run into saturation (such as in variable-speed vehicular drives that use a wide field weakening region). Most steels are only tested just beyond the knee point which is insufficient without correct extrapolation. The results show, for a particular example, a 15 % increase in line current and 4.2 % reduction in torque when a good extrapolation is used and compared to a poor B/H curve.

I. INTRODUCTION

Modern hybrid and electric vehicles use high performance motor drives. The Toyota Prius is the most popular hybrid car and the drive in this has been developed for larger cars such as the Toyota Camry. The brushless permanent magnet (BPM) motors for these were detailed by Oak Ridge Laboratories [1] and the main performance envelope of the Prius 2004 motor is shown in Fig. 1. This illustrates that it operates with a very wide field weakening range, with the main operation likely to be from zero up to about 2000 rpm which is the acceleration/deceleration urban cycle. Over this range, efficiency is very important; also the machine is operating at high torque but low frequency so that copper loss is the dominant loss. In this study, a key point is highlighted as an example in the urban cycle.

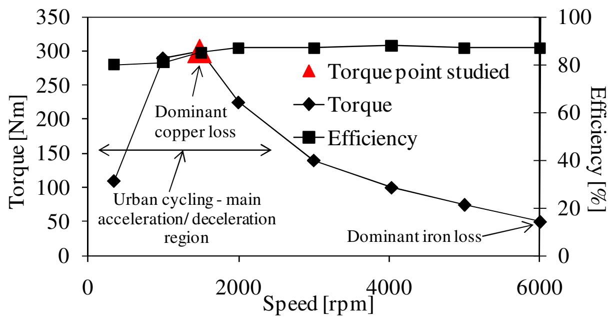

Fig. 1. Torque and efficiency envelopes for 2004 Prius PM drive motor.

While BPM drives are utilized in the Prius and Camry, there is an interest in the application of induction motors (IMs) in hybrid and electric vehicles, and they too require high efficiency and wide speed range. A first-pass IM design was carried out in [1]. The selected operating point in this study was shown to be a demanding operating point. There is high copper loss and flux levels are deep into the steel saturation region. To obtain correct simulation then the *B-H* curve has to be used. It is shown here that normal measured curves often do not go to sufficiently high flux density levels so that they need to be extended in a correct manner up to 2.5 to 3 T to enable an accurate finite element analysis (FEA).

II. MODELING *B/H* CURVES

When carrying out an FEA analysis one of the important issues is to define the correct *B-H* curve together with associated iron loss data. However, many curves are only defined to a point just above the knee point (say 1.7 to 1.9 T). In Fig. 2 M19 steel is quoted and the data requires extrapolation above 1.8 T, which is the maximum quoted from measured curves. There are many ways to do this but they should all lead to the incremental permeability (slope of B/H curve) tending towards μ_0 as H tends towards infinity. Fig. 2 plots manufacturers BH data for 29 Gauge M19, together with 3 curves used in FEA analysis. Case 1 has constant gradient above the maximum measured point. Case 2 uses smoothing to trend towards μ_0. Case 3 assumes incremental permeability close to μ_0 once the measured data is exceeded.

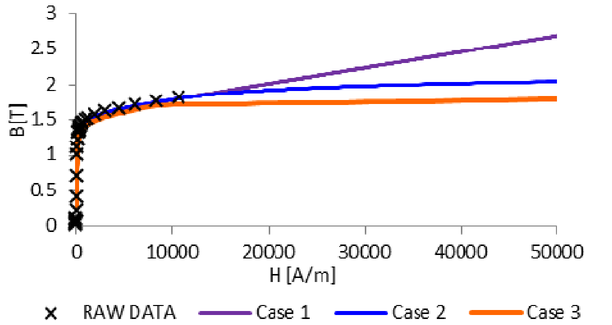

Fig. 2. B/H curves for different measured and simulated steels M19.

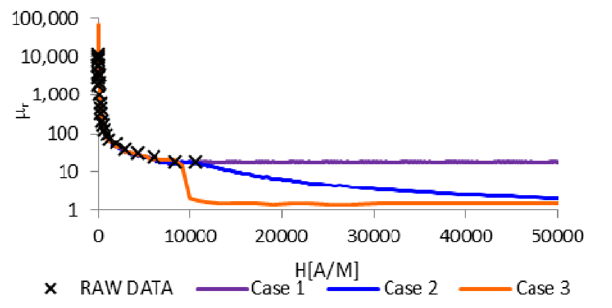

Fig. 3. Incremental relative permeability curves for measured and simulated steels M19.

Both Cases 1 and 2 in Figs. 2 and 3 utilize the same algorithm to extend the B-H curve beyond the maximum data value provided. In Case 2, manual user intervention was applied to graphically extend the *B-H* curve by maintaining the rate of change of $\delta B/\delta H$ until the curve passes 2.2T. The algorithm predicts the absolute reluctivity using

$$\upsilon_{abs} = \upsilon_{(\text{last point})} + 2\left(1 - \frac{\sqrt{B^2_{(\text{last point})}}}{B^2}\right)\left(\frac{\delta\upsilon}{\delta B^2}\right)_{(\text{last point})} \quad (1)$$

to give absolute reluctivity with respect to the square of the flux density where:

$$\frac{\delta\upsilon_{abs}}{\delta B^2} = \frac{\sqrt{B^2_{(\text{last point})}}}{\left(B^2\right)^{3/2}}\left(\frac{\delta\upsilon}{\delta B^2}\right)_{(\text{last point})} \quad (2)$$

There are few measured *B-H* curves in the literature which run heavily into saturation, examples include 50A470 in the rolled L and cross C directions [3] and also C1010 [4].

III. EFFECTS ON MOTOR SIMULATIONS

An FEA model of the first-pass IM design in [2] was developed using JMAG from JRI Solutions Ltd, Japan. The point illustrated in Fig. 1 was the focused upon. Space restraints prevents motor detailing, however, it is a 48 stator slot, 40 rotor bar, 8 pole machine designed to fit into the same space as the Prius 2004 machine in [1]. The key point is at a speed of 1475 rpm with a synchronous speed of 1548 rpm; the required line voltage was about 350 V.

To understand the effects of using the different M19 curves shown in Fig. 2, synchronous speed conditions were simulated at 103.2 Hz (1548 rpm) with 350V line voltage. In this case the phase currents can be assumed to be equal to the magnetizing current. The line currents are shown in Fig. 4. It is clear that the extrapolation approach has significant impact on the magnetizing current predictions.

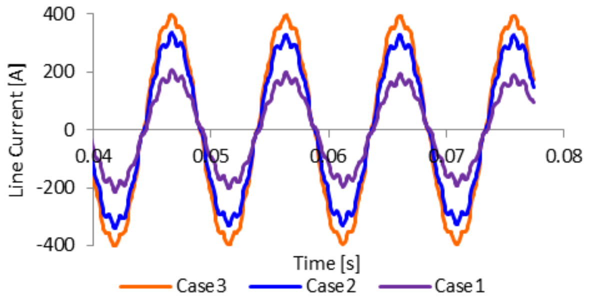

Fig. 4. Line currents from simulations of synchronous speed at 1548rpm.

Next, simulations of the variation of line voltage when using the Case 2 curve are presented in Fig. 5. The current and torque are shown. To illustrate the non-linear nature of the simulations due to saturation, a line through the origin is also included which corresponds to the first point at 250 V, where saturation effects are beginning to take effect. The torque/peak current ratio is also shown. This is a good indicator that the maximum practicable torque is being reached at 350 V since the torque/peak current ratio has begun to fall. To illustrate the saturation in the machine a flux plot is shown in Fig. 6. Much of the machine remains below 2 T, however, tooth and back iron regions are approaching 2.2 T. The final simulations address direct comparison between Case 2 and Case 3, with results shown in Table I. It can be seen that there is an increase of 14.3 % for the current and a reduction of 4.2 % in torque, this leads to a reduction of 7.4 % in efficiency. Since the machine is working at a high efficiency this represents a significant reduction in actual losses, and this will produce less stress on the cooling system.

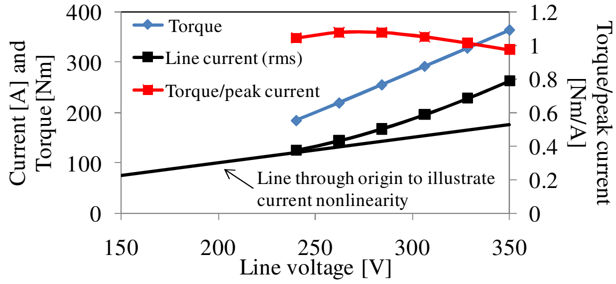

Fig. 5. Variable voltage at 1475 rpm, s = 0.047 using two different M19 *B/H* curves in Fig. 2.

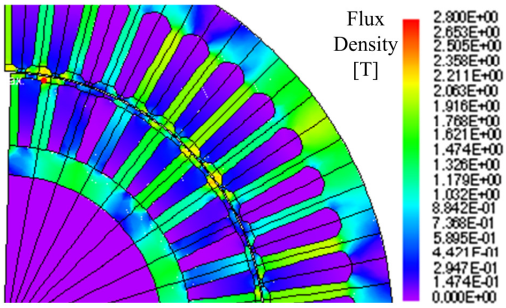

Fig. 6. Flux plot at 350 V (line) and full load for load point.

TABLE I
COMPARISON OF PERFORMANCE AT 350 V (LINE) AND 1475 RPM WITH SLIP = 0.047 WITH SMOOTHED AND LINEAR EXTRAPOLATION FOR M19 STEEL MEASURED UP TO 1.7 T

Extrapolation method	I_{Line} [A]	P_{in} [kW]	P. F. [p.u.]	Torque [Nm]	Eff. [%]
Smoothed	262.9	75.8	0.48	362.7	73.9
Linear extrapolation	300.4	78.4	0.43	347.4	68.4
(actual and % change)	+14.3	+3.4	-10.4	-4.2	-7.4

IV. CONCLUSIONS

Numerical simulations of electrical machines operating in transient or extreme conditions require magnetization data to represent operating regions beyond what is normally provided by manufacturers. Unfortunately, high field test facilities and data are rare. The paper highlights the importance of understanding the impacts of data extrapolation choices and the fact that modern numerical methods are still limited by the availability of good input data and understanding of these limitations by the user.

V. REFERENCES

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