Efficiency Evaluation of Interior Permanent Magnet Synchronous Machines using the Synthetic Loading Technique

Abdelaziz Y. M. Abbas
a.abbas@eee.strath.ac.uk
Sudan University of Science & Technology
Electrical Engineering Department
Eastern Daim P.O.Box 72, Khartoum, Sudan

John E. Fletcher
john.fletcher@eee.strath.ac.uk
University of Strathclyde
Electronic and Electrical Engineering Department
Royal College Building, Glasgow, G1 1XW, UK

Abstract - **This paper presents the application of synthetic loading for efficiency evaluation of interior permanent magnet (IPM) synchronous machines and compares it with the standard technique of assessing efficiency and losses. Good agreement is observed between the two techniques. Synthetic loading is a technique of efficiency evaluation that eliminates the need for a mechanical load connected to the test machine. Equations for synthetic loading are developed for the IPM synchronous machine which are then used to simulate the technique using MATLAB. The synthetic loading technique is performed experimentally in the laboratory and a full description of the hardware system is provided. The minimum dc link voltage and volt-ampere requirements of the inverter used to conduct the synthetic loading test are assessed, discussed and compared with the standard efficiency test. Simulation and experimental results demonstrate that the synthetic loading technique is able to evaluate the efficiency of IPM synchronous machines.**

I. INTRODUCTION

The efficiency evaluation of IPM synchronous machines is addressed. A challenge facing electrical machine manufacturers and users is the assessment of efficiency, particularly for larger machines and vertically-mounted machines and also linear machines, both large and small. During operation, an electrical machine is heated as a consequence of the losses during the process of energy conversion. These losses are categorised as electrical and mechanical losses. The electrical losses are due to copper losses in the conductors and hysteresis and eddy-current loss in the ferromagnetic material. The mechanical losses are the result of friction in the bearings and windage loss [1].

During the last two decades, IPM synchronous machine drives have become popular and are gradually replacing brushed dc machine drives and induction machine drives in industrial applications. The growth in use is a consequence of the advantages: high efficiency, compactness and robustness with an improved speed range compared to surface-mount PM machines [2]. Our research addresses assesses the use of the synthetic loading technique to assess the efficiency and losses in IPM synchronous machines.

Testing of electrical machines, to determine the power losses in the form of heat and the resulting temperature rise, is important for both users and manufacturers [3]. High temperatures cause deterioration of insulation materials which affects machine lifetime and high rates of power dissipation imply low efficiency values. The standard method used to perform an efficiency test is to connect a rated load to the test machine shaft. This can be difficult, particularly for large vertical machines [4]. Furthermore, this method requires removal of the test machine from the set, if post-installation tests are required, leading to loss of production. Consequently, an efficiency test that avoids the need of an external load is desirable. Such a test technique is synthetic loading, and this paper reports the application of synthetic loading to IPM synchronous machines. During rated-load efficiency test, the machine must draw it is full load current at rated voltage and speed. Synthetic loading can do this without connecting a mechanical load to the machine drive shaft [4]. With synthetic loading, the electrical machine is accelerated and decelerated in a controlled manner to alternate rapidly between motor-generator action, producing rated rms current and on average, rated speed. This produces average rated copper loss due to the rated current and rated iron (core) loss, friction and windage loss as a consequence of operating at rated speed.

II. SYNTHETIC LOADING TECHNIQUE

Conventional efficiency tests require specialist test facilities, additional load machines and, for large machines, linear machines or vertical mounted machines, floor space. Therefore, synthetic loading is potentially a key technique for solving problems associated with the conventional efficiency test methods. Synthetic loading causes the electrical machine to draw full load current without connecting a mechanical load to the machine drive shaft. The main principle of synthetic loading is to control the machine being tested such that it draws rated current using only the moment of inertia of the rotor as the load [5]. Therefore, synthetic loading offers the advantage that the tested machine is mechanically decoupled from the load, thereby removing the need for special test facilities. During synthetic loading the equipment required to perform the efficiency test is an inverter, appropriate voltage and current sensors and a vector controller. The cost and time associated with performing a synthetic loading test is potentially reduced, as the test equipment can be made portable if multiple sets are to be tested in situ [6].

During synthetic loading of the IPM synchronous machine, rms voltage, current and the rotor speed must be equal on average to the rated value. The machine alternates between motor and generator action at the synthetic loading frequency. During acceleration, the machine operates as a motor, draws energy from the

supply and transfers it to the shaft as inertial energy. During deceleration, the machine regenerates and delivers inertial energy back to the supply [5]. In both cases the machine develops Ohmic loss.

III. MATHEMATICAL EQUATIONS

The mathematical model of an IPM synchronous machine is based on the synchronously rotating reference frame. A three phase machine with symmetrical windings is assumed. The three phase *abc* model is then transformed to a two phase *d-q* model, which reduces the complexity in the machine model [7].

Generally, low order mathematical models are used to represent IPM synchronous machines in simulating and analyzing dynamic behaviour. Five nonlinear differential equations, based on Park's *dq* axis representation [8], [9], are used to represent IPM synchronous machines. These equations are arranged in a set of first order differential equations which are derived from the *d-* and *q*-axis equivalent circuit illustrated in Fig. 1.
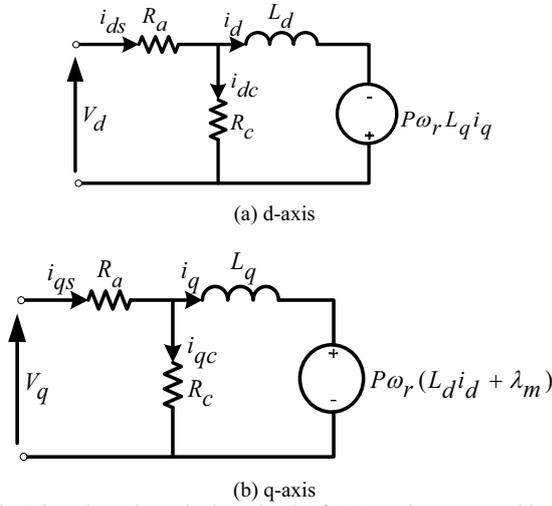

(a) d-axis

(b) q-axis

Fig.1 d- and q-axis equivalent circuit of PM synchronous machines

The voltage equations of the IPM synchronous machine in the *dq* synchronous frame can be expressed as

$$V_d = R_a i_d + L_d \left(1 + \frac{R_a}{R_c}\right)\frac{di_d}{dt} - P\omega_r L_q i_q \left(1 + \frac{R_a}{R_c}\right) \quad (1)$$

$$V_q = R_a i_q + L_q \left(1 + \frac{R_a}{R_c}\right)\frac{di_q}{dt} + \left(1 + \frac{R_a}{R_c}\right)P\omega_r (L_d i_d + \lambda_m) \quad (2)$$

where,

V_d and V_q are *d-* and *q*-axis stator voltages, respectively,
i_d and i_q are *d-* and *q*-axis currents, respectively,
R_a and R_c are stator and core loss resistances, respectively,
L_d and L_q are *d-* and *q*-axis self inductances, respectively,
λ_m is the permanent magnet flux linkages,
ω_r is the rotor speed, and P is the number of pole pairs.

The electromagnetic torque, T_e, developed by the rotor is described by

$$T_e = \frac{3}{2} P \left(\lambda_m i_q + \left(L_d - L_q\right)i_q i_d\right) \quad (3)$$

The dynamic equation of the speed is:

$$\frac{d\omega_r}{dt} = (T_e - T_L - B\omega_r)/J \quad (4)$$

where T_L is the load torque, and J and B are moment of inertia and damper coefficient respectively. The position, θ, is given by

$$\frac{d\theta}{dt} = P\omega_r \quad (5)$$

A. Quadrature Axis Current Equation

The key step in performing a synthetic loading test is the correct choice of quadrature axis current waveform, i_q, in order to produce rated rms phase current at rated rms phase voltage. The reference i_q waveform must be chosen correctly to force the machine to accelerate and decelerate. The drive current, i_q, takes the form

$$i_q = I_m \sin(2\pi f_n t) + I_o \quad (6)$$

where I_m is the magnitude of AC perturbation current, I_o is a dc offset current and f_n is synthetic loading frequency (Hz). Typically I_m is larger than I_o, but all three parameters in (6) need to be chosen to force rated conditions in the machine under test.

As the machine torque is linearly related to i_q, the generated torque alternates between positive and negative values. The frequency and magnitude (f_n and I_m respectively) of the AC component effectively controls the AC variations in the rotor speed (assuming constant mechanical parameters) and the dc offset component controls the average rotor speed.

(i) Determining I_o in terms of machine parameters

During synthetic loading the machine should run, on average, at rated speed. In addition, as the load torque T_L equals zero (there is no load) the electrical torque generated balances only the torque due to friction and windage.

$$T_{eav} = B\omega_{ro} = (k_t + k_r i_d) f_n \int_0^{\frac{1}{f_n}} \left(I_m \sin(2\pi f_n t) + I_o\right)dt \quad (7)$$

where $k_t = 3/2 P\lambda_m$ is the machine torque constant in (Nm/A), $k_r = 3/2 P(L_d - L_q)$ is IPM synchronous machine reluctance torque constant, and B is damper coefficient in (Nms), P is number of pairs of poles, λ_m is linkage flux, and i_d is direct axis current.

During synthetic loading the required dc offset current I_o is a function of average desired machine speed and the mechanical parameters. T_{eav} is the average electromagnetic torque during synthetic loading and ω_{ro} is rated steady state rotor speed.

By solving and rearranging (7) the expression for I_o is described by

$$I_o = \frac{B\omega_{ro}}{k_t + k_r i_d} \quad (8)$$

That is the average dc offset current required is the friction torque divided by the torque factor of the machine. In the test set-up, I_o is used to independently control the average speed of rotation.

(ii) Determining I_m in terms of machine parameters

The magnitude of AC perturbation I_m is a function of machine rated rms current I_s, the dc offset current I_o and the direct axis current i_d. In order that the machine draws rated current during synthetic loading

$$\frac{\left(i_q^2 + i_d^2\right)}{2} = I_s^2 \tag{9}$$

Substituting (6) into (9), and taking the average for one synthetic loading cycle

$$I_s^2 = \frac{f_n}{2} \int_0^{\frac{1}{f_n}} \left(I_m \sin(2\pi f_n t) + I_o\right)^2 dt + f_n \int_0^{\frac{1}{f_n}} \frac{i_d^2}{2} dt \tag{10}$$

Solving and rearranging (10) gives the AC perturbation current as

$$I_m = \sqrt{4I_s^2 - 2I_o^2 - 2i_d^2} \tag{11}$$

where I_s is the rated rms current of the IPM synchronous machine under test. When vector control is applied the reference value of the direct axis current will be zero therefore:

$$I_m = \sqrt{4I_s^2 - 2I_o^2} \tag{12}$$

B. Speed Equation

During synthetic loading the machine accelerates and decelerates. However, the rotor speed must equal, on average, the rated rotor speed. The rotor speed, ω_r, is determined from the solution of dynamic equation (4). Substituting (6) into the torque equation (3), then substitute the electromagnetic torque into the dynamic equation and rearranging yields:

$$J\frac{d\omega_r}{dt} + B\omega_r = k_t I_m \sin(2\pi f_n t) + k_t I_o - k_r i_d I_m \sin(2\pi f_n t) - k_r i_d I_o \tag{13}$$

Using Laplace transforms to solve (13) for ω_r gives:

$$\omega_r(s) = \left[\frac{(k_t + k_r i_d)(2\pi f_n)I_m}{J\left(s + \frac{B}{J}\right)\left(s^2 + (2\pi f_n)^2\right)}\right] + \left[\frac{(k_t + k_r i_d)I_o}{Js\left(s + \frac{B}{J}\right)}\right] \tag{14}$$

By applying partial fraction expansion and Laplace inverse transformation to (14), the rotor speed is described with respect to time as

$$\omega_r = \frac{(k_t + k_r i_d)I_o}{B} + \frac{(k_t + k_r i_d)I_m/J}{\sqrt{(2\pi f_n)^2 + \left(\frac{B}{J}\right)^2}} \sin(2\pi f_n t - \phi) \tag{15}$$

where $\phi = \tan^{-1}\left[\frac{2\pi f_n}{B/J}\right]$

The equation demonstrates that the speed has a dc offset term plus a sinusoidal variation at the synthetic loading frequency.

C. Direct and Quadrature Axis Voltage Equations

The direct and quadrature axis voltages are a function of the synthetic frequency. Therefore, the determination of direct and quadrature axis voltages is essential in order to understand the impact of synthetic loading frequency on volt-ampere rating of the inverter. From the voltage equations in (1) and (2) the direct and quadrature axis voltage during synthetic loading can be calculated using quadrature axis current in (6) and rotor speed in (15) for IPM synchronous machines.

(i) Direct axis voltage equation
The direct axis voltage for the IPM synchronous machine is found to be

$$V_d = R_a i_d - L_q P\left(1 + \frac{R_a}{R_c}\right)\left(I_m \sin(2\pi f_n t) + I_o\right)$$
$$\times \left[\frac{(k_t + k_r i_d)I_o}{B} + \frac{(k_t + k_r i_d)I_m/J}{\sqrt{(2\pi f_n)^2 + \left(\frac{B}{J}\right)^2}} \sin(2\pi f_n t - \phi)\right] \tag{16}$$

(ii) Quadrature axis voltage equation
The quadrature axis voltage for the IPM synchronous machine is:

$$V_q = R_a I_m \sin(2\pi f_n t) + R_a I_o + L_q I_m (2\pi f_n)\left(1 + \frac{R_a}{R_c}\right)\cos(2\pi f_n t)$$
$$+ P\left(1 + \frac{R_a}{R_c}\right)\left(L_d i_d + \lambda_m\right)\left[\frac{(k_t + k_r i_d)I_o}{B} + \frac{(k_t + k_r i_d)I_m/J}{\sqrt{(2\pi f_n)^2 + \left(\frac{B}{J}\right)^2}} \sin(2\pi f_n t - \phi)\right] \tag{17}$$

The resultant stator abc voltage can be calculated from dq axis voltages by:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{18}$$

where V_a, V_b, and V_c are the stator terminal voltage of the permanent magnet synchronous machine. Using (18), and appropriate equations from (16)-(17) the instantaneous phase and line voltage requirements can be determined. From this the minimum dc link voltage can be identified.

D. Direct and Quadrature Axis Stator Current Equations

The stator direct and quadrature axis current are also a function of the synthetic loading frequency. The direct and quadrature axis stator current equation is determined to evaluate the stator phase current during synthetic loading. Furthermore, the stator phase current is important for the evaluation of stator copper losses, and inverter volt-ampere rating, and the direct and quarature axis stator current equations are necessary for input power calculations.

(i) Direct axis stator current equation
From Fig. 1 (a) the direct axis stator current can be calculated using Kirchhoff's current law as:

$$i_{ds} = i_d + i_{dc} \tag{19}$$

where $i_{dc} = -P\omega_r \frac{L_q i_q}{R_c}$ and $\frac{di_d}{dt} = 0$. Therefore by substituting the equations for i_{dc}, i_q and ω_r from (6) and (15) for the IPM synchronous machines into (19), the direct axis stator current is then

$$i_{ds} = i_d - P\frac{L_q}{R_c}\big(I_m\sin(2\pi f_n t)+I_o\big)$$

$$\times\left[\frac{(k_t+k_r i_d)I_o}{B}+\frac{(k_t+k_r i_d)I_m/J}{\sqrt{(2\pi f_n)^2+\left(\frac{B}{J}\right)^2}}\sin(2\pi f_n t-\phi)\right] \qquad (20)$$

(ii) Quadrature axis stator current equation

From Fig. 1 (b) the quadrature axis stator current can be calculated using Kirchhoff's current law as:

$$i_{qs} = i_q + i_{qc} \qquad (21)$$

where $i_{qc} = P\omega_r\dfrac{(L_d i_d+\lambda_m)}{R_c}$. Therefore by substituting the equations for i_{qc}, i_q and ω_r from (6) and (15) for IPM synchronous machines into (21) gives

$$i_{qs} = I_m\sin(2\pi f_n t)+I_o+P\frac{(L_d i_d+\lambda_m)}{R_c}$$

$$\times\left[\frac{(k_t+k_r i_d)I_o}{B}+\frac{(k_t+k_r i_d)I_m/J}{\sqrt{(2\pi f_n)^2+\left(\frac{B}{J}\right)^2}}\sin(2\pi f_n t-\phi)\right] \qquad (22)$$

Park's transformation can then be used to calculate stator phases current from the *dq* axis stator current and therefore the peak current rating of the inverter phase leg. This then assists in determining the VA rating of the power converter.

IV. HARDWARE AND SOFTWARE IMPLEMENTATION

Fig. 2 shows the hardware for synthetic loading. The stator currents i_a and i_b are measured via the current sensors. The transformation is applied to the measured current to transform the stator current into the stationary reference frame currents i_α and i_β. Then using a transformation to obtain the rotating reference frame quantities i_d and i_q. i_d and i_q are compared to their reference values i_{qref} derived from (6) and i_{dref} (set to zero) and corrected by means of PI current controllers. The outputs of the current controllers v_d and v_q are passed through the transformation to yield v_α and v_β and a new stator voltage vector is impressed on the motor using the Space Vector Modulation technique. The PWM signals are generated by the PWM modules with a 20 kHz switching frequency and a 2μs dead-band. The interrupt frequency is 20 kHz [10], [11]. A TMS320X2812 DSP is used as the core of the drive system.

Implementing a vector control algorithm in a digital processing system requires time critical software capable of calculating and loading timer information into the PWM timers efficiently in order to attain a reasonable switching frequency [12]. The six PWM channels available in event manager module A of the DSP are used to drive the three-phase inverter. The event manager module A is configured to operate with 50μs period resulting in 20 kHz PWM frequency given the 75MHz system clock. The dead-band module is configured to give 2.0μs under-lap to avoid cross-conduction. Two of the available 16 analog channels of the 12 bit ADC are used to sample the two phase currents. One of two available
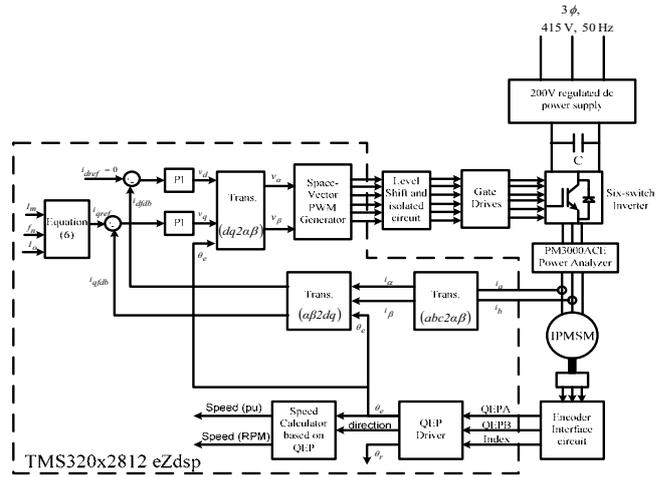

Fig. 2 Block diagram of vector control system for conducting the synthetic loading technique

quadrature encoder channels is used for the position encoder. The DSP is programmed using the Spectrum Digital eZdsp development environment with Code Composer Studio. The block diagram of the vector controller implementation is shown in Fig. 2.

V. SIMULATION AND EXPERIMENT RESULTS

In order to confirm that synthetic loading is an accurate method for efficiency evaluation of IPM synchronous machines, the technique is performed experimentally for different values of synthetic loading frequencies and compared with the standard efficiency test. The standard efficiency test method produces rated operating conditions of the IPM synchronous machine under test, consequently, this method is used as a basis of the IPM synchronous machine under investigation. Comparison between the tests will confirm the accuracy of efficiency evaluation using the synthetic loading technique. The parameters of the IPM synchronous machine are provided in the Appendix.

In order to compare synthetic loading simulation results with experimental results, the simulated quantities for instantaneous phase voltage, current, speed and input power are superimposed onto the experimental results. Fig. 3 shows the variation of the phase voltage during synthetic loading with a synthetic frequency of 4 Hz. The phase voltage magnitude during synthetic loading depends on the rotor speed and the air-gap flux. Therefore, any variation in the rotor speed and air-gap flux affects the phase voltage variation. Hence, the higher peak-to-peak values of rotor speed and air-gap flux in the IPM synchronous machine directly affects the variation in the phase voltage envelope. Fig. 3 shows that there is a large variation in the phase voltage. Fig. 4 illustrates the variation of instantaneous phase current during synthetic loading at 4 Hz. The peak current during synthetic loading is 2.84 A (1.41pu) and the average rms current is 1.42A (1.0pu). This confirms that the PM synchronous machine is fully loaded. Good correlation is observed in magnitude and waveform. The main differences between the results are caused by the difficulty of forcing identical operating conditions in both simulation and experimental systems, particularly synchronising rotational and synthetic loading angles in both time and space.
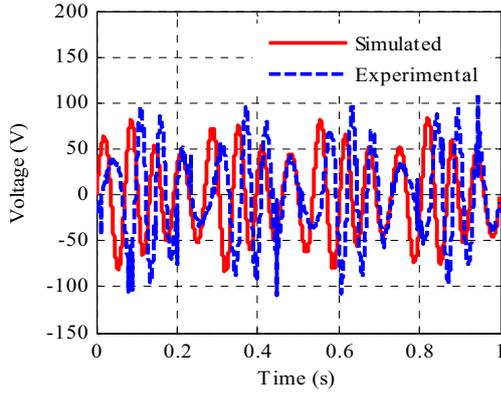
Fig. 3 phase voltage during synthetic loading with 4 Hz synthetic loading frequency
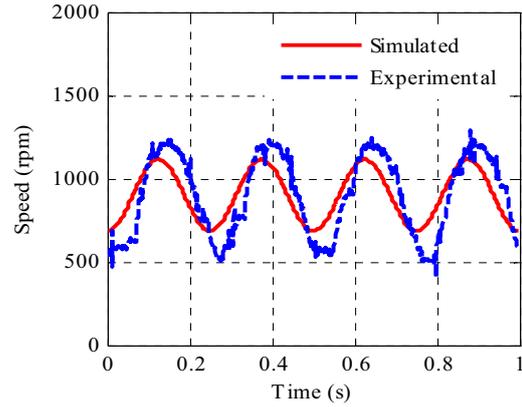

Fig. 4 phase current during synthetic loading with 4 Hz synthetic loading frequency

Fig. 5 Speed variation during synthetic loading at 4 Hz under full-load torque conditions
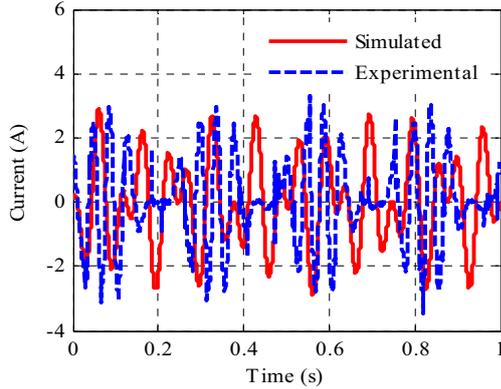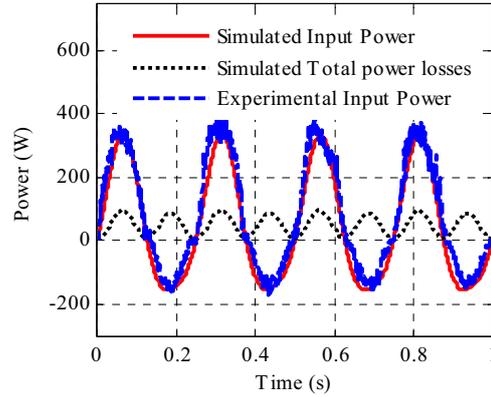

Fig. 6 Input power variation during synthetic loading at 4 Hz under full-load torque conditions

Fig. 5 shows the variation of speed with time during synthetic loading for both experiment and simulation with a synthetic loading frequency of 4Hz. The experimental rotor speed is in agreement with the simulated speed in terms of shape but the peak to peak is around 28% higher in the experiments. Fig. 6 illustrates the experimental and simulated input power and total power loss variation with time during synthetic loading for a synthetic loading frequency of 4Hz. It shows that during synthetic loading the IPM synchronous machine draws power from the supply when the machine is accelerating as a motor and regenerates when the machine decelerates.

Figs. 3-6 illustrate that the experimental results are in agreement with the simulation results in terms of characteristic shape. The simulation model does not account for magnetic saturation and skin effect. This leads to small disagreement between the experimental and simulated waveform. Also, it is difficult to precisely synchronise both the rotor and synthetic angular positions.

The simulation results for the IPM synchronous machine for five different synthetic loading frequencies are summarised and compared with the standard efficiency test method in Table I. The simulation result shows the power loss distribution in the IPM synchronous machine and confirms that synthetic loading can be used for efficiency evaluation. The efficiency calculated from the synthetic loading simulations is 77.5%. In general, if the IPM synchronous machine draws the rated current at a speed of 900 rpm, the efficiency is overestimated by 0.1% during synthetic loading compared to the standard efficiency test.

Table I Comparison of the standard efficiency test and the synthetic loading technique simulation results under full-load torque condition (I_m=2.83A, I_o=0.028A)

	Standard Efficiency Test	Synthetic Loading Frequency (Hz)				
		4	6	8	9	10
Rms line voltage (V)	90.8	75.4	75.5	75.5	75.6	75.6
Rms line current (A)	1.42	1.41	1.41	1.41	1.41	1.41
Speed (rpm)	900	900	900	900	900	900
Inverter peak current (A)	2.0	2.83	2.83	2.83	2.83	2.83
Phase-leg volt-ampere (VA)	280.0	438	433	438.0	443.0	449.0
DC link voltage (V)	140	154.5	153	154.8	156.5	158.5
Output power (W)	165.4	-	-	-	-	-
Input power (W)	213.7	48.0	48.0	48.0	48.0	48.0
Stator copper loss (W)	42.4	42.0	42.0	42.0	42.0	42.0
Iron loss (W)	3.53	3.54	3.53	3.6	3.6	3.6
Friction and windage loss (W)	2.41	2.5	2.43	2.4	2.4	2.4
Total losses (W)	48.3	48.0	48.0	48.0	48.0	48.0
Efficiency (%)	77.4	77.5	77.5	77.5	77.5	77.5

Table II Comparison between the standard efficiency test and the synthetic loading technique experimental results under full-load torque conditions

	Standard Efficiency Test	Synthetic Loading Frequency (Hz)				
		4	6	8	9	10
Rms line voltage (V)	91.3	91.8	91.6	92.0	91.8	91.6
Rms line current (A)	1.41	1.41	1.41	1.41	1.41	1.41
Inverter peak current (A)	2.0	2.83	2.83	2.83	2.83	2.83
Phase-leg VA rating (VA)	292.0	457.0	457.0	460.0	461.3	461.3
DC link voltage (V)	146.0	161.5	161.5	162.5	163.0	163.0
Speed (rpm)	900	900	900	900	900	900
Input power (W)	217.7	51.2	51.5	51.3	51.0	51.3
Output power (W)	167.2	-	-	-	-	-
Total losses (W)	50.2	51.2	51.5	51.3	51.0	51.3
Efficiency (%)	76.8	76.5	76.3	76.4	76.6	76.4

11

Table II presents the experimental results of the standard efficiency test and synthetic loading technique for the full load torque condition. The total losses are evaluated and then the efficiency calculated. The inverter phase-leg VA rating and peak current required during synthetic loading technique are 460VA (1.57pu) and 2.83A (1.41pu) respectively. The efficiencies of the five different synthetic loading frequencies are between 76.3% and 76.6%, which shows that synthetic loading underestimates the efficiency by 0.2% at best, 0.5% at worst and 0.4% on average compared with the standard efficiency test.

An inverter is used during the standard efficiency test and the synthetic loading test. This inverter has minimum requirements in terms of dc link voltage, peak current and peak VA. All these quantities are higher than that required for the standard efficiency test. The minimum dc link voltage required is 161.5V (1.1pu compared with the standard efficiency test), the minimum peak current required is 2.83A (1.41pu) and the minimum inverter phase-leg required is 457VA (1.56pu) at 4 Hz synthetic loading frequency.

VI. CONCLUSIONS

Synthetic loading as a technique for efficiency evaluation of IPM synchronous machine has been simulated using MATLAB and confirmed by experiment. The technique is able to identify the total losses in the machine. The simulation technique is important as it provides a means of determining an optimum operating point for the synthetic loading experiment. Synthetic loading causes the machine to produce rated power losses. The individual power losses can be calculated over one synthetic loading cycle. Also the total power losses can be determined by calculating the input power and averaging over one synthetic loading cycle. Synthetic loading has been performed experimentally for five different synthetic loading frequencies. Synthetic loading simulation and experiment results give excellent agreement with the standard efficiency test method.

VII. APPENDIX

Table III Electrical and mechanical parameters of the IPM synchronous machine

Parameters	Values
Rated output power	165 W
Rated peak current	2.0A
Rated speed	900rpm
Maximum Bus Voltage	200 V
Armature resistance, R_a	7.0Ω
Core loss resistance, R_c	1580Ω
Quadrature axis inductance, L_q	120 mH
Direct axis inductance, L_d	65 mH
Moment of inertia, J	4.5×10^{-3} kg.m^2
Damping coefficient, B	2.7×10^{-4} Nms^{-1}
Total permanent magnet flux linkage, λ_m	0.6 Wb
Number of poles	2

REFERENCES

[1] C. Grantham and H. Tabatabaei-Yazdi "A Novel Machineless Dynamometer for Load Testing Three-Phase Induction Motors", *IEEE 1999 International Conference on Power Electronics and Drive Systems, PEDS'99*, July 1999, Hong Kong, pp. 579-584.

[2] M. Kadjoudj, M. E. Benbouzid, C. Ghennai and D. Diallo "A Robust Hybrid Current Control for Permanent-Magnet Synchronous Motor Drive", *IEEE Transactions on Energy Conversion*, Vol. 19, No. 1, March 2004, pp. 109-115.

[3] C. Grantham, H. Tabatabaei-Yazdi and M. F. Rahman, "A Novel Method for Rapid Efficiency Measurement of Three Phase Induction Motors", *IEEE Transactions on Energy Conversion*, Vol. 14, No. 4, December 1999, pp. 1236-1240.

[4] D. J. McKinnon and C. Grantham "Improved efficiency Test Methods for Three-Phase Induction Machines", *Conference Record of the Fourthieth IAS Annual Meeting*, Vol. 1, 2-6 October 2005, pp. 466-473.

[5] D. J. McKinnon and C. Grantham, "On-Site Efficiency Evaluation of Three-Phase Induction Motors Using Synthetic Loading Methods", *Second IET International Conference on Power Electronics, Machines and Drives 2004, Conf. Publ. No. 498,* Vol. 1, 31 March-2 April 2004, pp. 291-296.

[6] C. Grantham and M. Sheng, "The Synthetic Loading of Three-Phase Induction Motors Using Microprocessor Controlled Power Electronics", *Proceedings of 1995 International Conference on Power Electronics and Drive and Systems*, Vol.1, February 1995, pp. 471-476.

[7] M. A. Rahman and P. Zhou, "Analysis of Brushless Permanent Magnet Synchronous Motors", *IEEE Transaction on Industrial Electronics*, Vol. 43, No. 2, April 1996, pp. 256-267.

[8] Y. A. I. Mohamed and E. F. El-Saadany, "A Current Control Scheme with an Adaptive Internal Model for Torque Ripple Minimization and Robust Current Regulation in PMSM Drive Systems", *IEEE Transactions on Energy Conversion*, Vol. 23, No. 1, March 2008, pp. 92-100.

[9] C. –K. Lin, T. –H. Liu and S. –H. Yang, "Nonlinear Position Controller Design With Input-Output Linearisation technique for an Interior Permanent Magnet Synchronous Motor Control System", *IET Power Electronics*, Vol. 1, No. 1, March 2008, pp. 14-26.

[10] E. Simon, "Implementation of a Speed Field Oriented Control of 3-phase PMSM Motor using TMS320F240", *Texas Instruments, Digital Control Systems*, Application Report SPRA588, September 1999.

[11] Texas Instrument, "Digital Signal Processing Solution for Permanent Magnet Synchronous Motor", *Application Note, Literature Number*: BPRA044, 1997.

[12] D. G. Holmes and T. A. Lipo, "Pulse Width Modulation for Power Converters: Principle and Practice", *IEEE Press*, 2003.