Efficiency Evaluation of Linear Permanent Magnet Synchronous Machines Using the Synthetic Loading Method

Abdelaziz Y. M. Abbas, John E. Fletcher
University of Strathclyde, Department of Electronic and Electrical Engineering,
Royal College Building, 204 George Street, Glasgow G1 1XW, UK
a.abbas@eee.strath.ac.uk

Abstract - **In this paper, the concept of efficiency evaluation of linear permanent magnet synchronous motors using the synthetic loading method is described and evaluated. Synthetic loading is a method of efficiency evaluation that eliminates the need for a mechanical load to absorb generated shaft power. A mathematical model for synthetic loading is derived for the linear machine using the d-q machine model that includes core loss. The implication of synthetic loading frequency on the required inverter DC link voltage and inverter volt-ampere rating is discussed. In addition, the effect of additional mover mass on the synthetic loading frequency is described in order to get constant swing velocity. Synthetic loading and standard efficiency tests, as methods of efficiency evaluation, are simulated using MATLAB and SIMULINK. Simulation data is verified through the experiment for synthetic loading and the standard efficiency tests. Simulation and experimental results show that the synthetic loading method is capable of evaluating the efficiency of linear permanent magnet synchronous motor under test.**

I. INTRODUCTION

One of the more difficult challenges facing electrical machines manufacturers and users is how to perform efficiency evaluation tests, particularly for larger machines and vertical mounted machines but also for linear machines, both large and small. During the operation of electrical machines, losses during the process of energy conversions manifest themselves as machine heating. These losses are categorised as electrical and mechanical losses. The electrical losses are a combination of Ohmic loss, due to conductor resistance, and iron loss which can be predicted. The mechanical losses are a result of bearing friction and windage loss [1]. Losses give an indication of machine efficiency; if the losses are higher the machine will be less efficient.

During the last two decades, permanent magnet (PM) 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, robustness and high reliability [2]. Therefore, a target of research is the design, losses and efficiency, and control of PM machines. Also, developments in power electronic technology, and their control, make the PM synchronous machine useful in industrial processes requiring a wide speed range. This research addresses the efficiency evaluation of linear permanent magnet machines. Historically, linear machines have been used in actuation applications where efficiency tends not to be a priority. However, linear machines are now finding applications with continuous duty, for example refrigeration, and also at high power levels for direct-drive wave energy conversion therefore an effective and rapid method of efficiency evaluation is a useful tool.

Exploiting the wave energy in the seas and oceans has been a research interest for almost three decades particularly due to world events such as the oil crisis in 1973 [3]. There are a number of candidate wave energy conversion devices that could potentially utilize linear generators in the power conversion process. These include such devices as the Oyster, the Archimedes Wave Swing device and Stingray [4]-[6]. Synthetic loading used for efficiency evaluation is useful for the linear generators proposed in these devices because it is difficult to find and accommodate a suitable load for the machine. This is one significant driver for this research.

Cooling and the removal of heat from electronic systems has become an important issue facing system designers [7]. Particularly as conventional cooling systems no longer provide adequate cooling for sophisticated electronic systems such as high performance computers. Hence the application of compact refrigeration systems is growing. Synthetic loading is suitable method for efficiency evaluation of the small PM linear motors proposed for use in small Stirling cooler-type refrigeration systems.

Testing of electrical machines for these applications, to determine the power losses in the form of heat and the resulting temperature rise is important for both users and manufacturers [8]. High temperatures cause deterioration of insulation materials and high rates of power dissipation implies low efficiency values which affect machine lifetime. The current method used to carry out efficiency test is to connect a rated load to the test machine shaft. This is difficult, particularly for linear machines and large vertical machines [9]. 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 linear PM machines. During a rated-load efficiency test, the machine must draw it is full load current at rated voltage and speed.

978-1-4244-1668-4/08/$25.00 ©2008 IEEE

Synthetic loading can do this without connecting a mechanical load to the machine drive shaft [9]. 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

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 the problems associated with the conventional efficiency test methods. Synthetic loading forces 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 [10]. Therefore, synthetic loading offers the advantage that the machine tested is mechanically decoupled from the load, thereby removing the need for special test facilities. Also, the machine can be tested on site. In synthetic loading the equipment required to carry out 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 [11].

During synthetic loading of the linear machine, rms terminal voltage, current and the mover velocity must be equal, on average, to the rated value. The machine accelerates and decelerates alternating, at the synthetic loading frequency, between motor and generator action. Therefore, under 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 [10]. In both cases the machine develops ohmic loss. If configured correctly synthetic loading will produce rated voltage at the machine's terminal and rated mover velocity with rated rms phase current. The synthetic loading method discussed here is a current control method, so that the knowledge of the mover velocity is not necessary when carrying out synthetic loading.

A. Determination of i_q Profile:

The key step in performing a synthetic loading test on a permanent magnet linear machine is the correct choice of quadrature axis current i_q waveform in order to produce rated rms phase current at rated rms rated phase voltage. The reference value of i_q must be chosen correctly to force the machine to accelerate and decelerate. The reference value of the direct axis current is zero. Therefore, the drive current, i_q, is designed to have a small dc offset, I_o, with a much larger AC perturbation of magnitude I_m and frequency f_n.

$$i_q(t) = I_m sin(2\pi f_n t) + I_o \qquad (pu) \qquad (1)$$

Where, I_m is the magnitude of AC perturbation current (pu), I_o is a dc offset current (pu) and f_n is synthetic loading frequency (Hz).

As the machine force is linearly related to i_q, the generated force alternates between positive and negative values. The frequency and magnitude (f_n and I_m respectively) of the AC component effectively controls the AC variation in the mover velocity (assuming constant mechanical parameters) and the DC component controls the average mover velocity.

In order that the machine draws rated current during synthetic loading, the magnitude of AC perturbation I_m is a function of machine rated current I_s and the dc offset current I_o and is derived from:

$$I_s^2 = \left[\frac{f_n}{2} \int_0^{\frac{2}{f_n}} \left(I_m sin\left(2\pi f_n t\right) + I_o \right)^2 dt \right] + \left[\frac{f_n}{2} \int_{\frac{2}{f_n}}^{\frac{1}{f_n}} \left(I_m sin\left(2\pi f_n t\right) + I_o \right)^2 dt \right] \qquad (2)$$

Solving and rearranging (2) gives the AC perturbation current $I_m = \sqrt{4I_s^2 - 2I_o^2}$ where, I_s is rated rms current of the machine under test (pu).

During synthetic loading the machine will move at its rated velocity on average. In addition the load force F_L equals zero, as there is no load, and the electrical force generated balances the force due to friction and windage. F_{eav} is the average electrical force during synthetic loading.

$$F_{eav} = \frac{Dv_x}{K_f I_{Base}} = f_n \int_0^{\frac{1}{f_n}} \left(I_m sin\left(2\pi f_n t\right) + I_o \right) dt \qquad (3)$$

The dc offset current I_o is a function of average machine velocity and mechanical parameters during synthetic loading (3).

By solving and rearranging (3) the expression for I_o is

$$I_o = \frac{D v_x}{k_f I_{Base}} \qquad (pu) \qquad (4)$$

Where, $k_f = \frac{\pi}{\tau} \frac{3}{2} P \lambda_a$ is the machine force constant in (N/A), D is damper factor in (Ns/m), P is number of pairs of poles, τ is pole pitch in (m) λ_a is linkage flux and I_{Base} is base current.

B. Determining Maxima and Minima of Shaft Velocity

During synthetic loading the machine accelerates and decelerates. The mover velocity, v_x, resulting from the application of $i_q(t)$ in (1) is derived from the mechanical equation $M\frac{dv_x}{dt} = F_e - F_L - Dv_x$. During the application of synthetic loading $F_L=0$. After normalizing the electrical force and mechanical equations then $F_e(t) = i_q(t)$ therefore the mechanical equation can be expressed as:

$$\frac{M}{D} I_o \frac{dv_x(t)}{dt} + I_o v_x(t) = I_m \sin\left(2\pi f_n t\right) + I_o \qquad (5)$$

Using the Laplace Transformation to solve (5) for v_x gives:

$$v_x(t) = 1 - \frac{I_m(2\pi f_n)}{I_o} \frac{1/\tau_m}{(2\pi f_n)^2 + \left(\frac{1}{\tau_m}\right)^2} \cos(2\pi f_n t) + \frac{I_m}{I_o} \frac{(1/\tau_m)^2}{(2\pi f_n)^2 + \left(\frac{1}{\tau_m}\right)^2} \sin(2\pi f_n t) \quad (pu) \qquad (6)$$

Where, τ_m is mechanical time constant, $\tau_m = \frac{M}{D}$, and M is the total mass of the mover.

When the synthetic loading method is applied, the knowledge of maximum and minimum velocity is important. The difference of maximum and minimum velocity gives indication of the velocity swing, which is preferable to be as small as possible. Also, the synthetic loading frequency can be expressed for different values of peak to peak velocity variation. From (6) the maximum and minimum velocities can be determined.
The maximum velocity is

$$v_x(max) = 1 + \frac{I_m(2\pi f_n)}{I_o} \frac{1/\tau_m}{(2\pi f_n)^2 + \left(\frac{1}{\tau_m}\right)^2} \quad (pu) \qquad (7)$$

And the minimum velocity is

$$v_x(min) = 1 - \frac{I_m(2\pi f_n)}{I_o} \frac{1/\tau_m}{(2\pi f_n)^2 + \left(\frac{1}{\tau_m}\right)^2} \quad (pu) \qquad (8)$$

Additional mass could be added to the mover. This increases τ_m thereby reducing the AC variation of mover velocity hence reducing the velocity swing.

C. Determining the value of synthetic loading frequency:

The synthetic loading frequency is important. The synthetic loading frequency has an impact on the DC link voltage and inverter volt-ampere rating hence proper choice of synthetic loading frequency is essential. The peak to peak velocity variation Δv can be determined.

$$\Delta v = v_x(max) - v_x(min) = 2\frac{I_m}{I_o}(2\pi f_n) \frac{1/\tau_m}{(2\pi f_n)^2 + \left(\frac{1}{\tau_m}\right)^2} \quad (pu) \qquad (9)$$

From (9) the synthetic loading frequency can be determined if a required Δv is specified along with I_m and assuming the mechanical parameters are known:

$$f_n = \frac{\left(\frac{2}{\tau_m}\frac{I_m}{I_o}\right) + \sqrt{\left(\frac{2}{\tau_m}\frac{I_m}{I_o}\right)^2 - 4\left(\frac{\Delta v}{\tau_m}\right)^2}}{4\pi \Delta v} \qquad (10)$$

The value of Δv can be between zero and twice the rated velocity ($0<\Delta v \le 2v_x$), but for better synthetic loading performance this value should be as small as possible. The high value of Δv leads to a higher inverter VA rating and dc link voltage.

Fig. 1 shows the impact of synthetic loading frequency on dc link voltage. Based on the simulation results shown in Fig. 1, the dc link voltage is higher for lower synthetic loading frequency. The dc voltage requirement is around 1.5pu for a 4 Hz synthetic loading frequency. The dc link voltage gradually decreases as the synthetic loading frequency is increased. For example a dc link voltage of approximately 1.14pu is required for a synthetic loading frequency between 20Hz to 70 Hz.

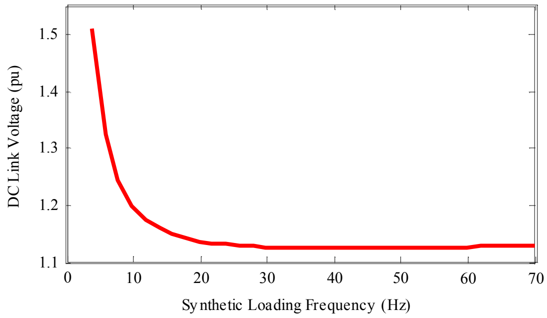

Figure 1. The impact of synthetic loading frequency on DC link voltage

The volt-ampere rating of inverter is also higher. This indicates that synthetic loading requires a higher VA rating than the VA rating of the machine. This is demonstrated in Fig. 2. The higher volt-ampere value at lower synthetic loading frequencies is due to the higher dc link voltage requirement. The inverter volt-ampere rating at 4 Hz synthetic loading frequency is about 1.83pu and then decreases with increase of synthetic frequency stabilising at 1.64pu with a synthetic loading frequency between 20 Hz to 70 Hz. In general, the higher value of inverter volt-ampere rating for synthetic loading frequencies between 20 Hz to 70 Hz is a consequence of the higher value of AC perturbation current I_m, rather than a higher dc link component.

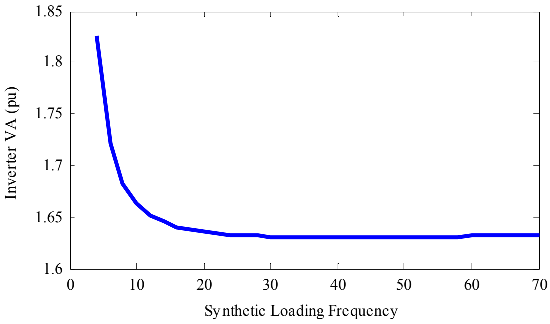

Figure 2. The effect of synthetic loading frequency on inverter VA rating

During investigation of synthetic loading, it is found that the synthetic loading period is proportional to the mover mass. This means that when the mechanical time constant increases a lower synthetic loading frequency is required for the same Δv. Fig. 3 illustrates the implications of mover mass on synthetic loading frequency with constant value of Δv. Based on simulation results Fig. 3 has shown that for $\Delta v = 0.186$pu the mover mass is inversely proportional to the synthetic loading frequency.

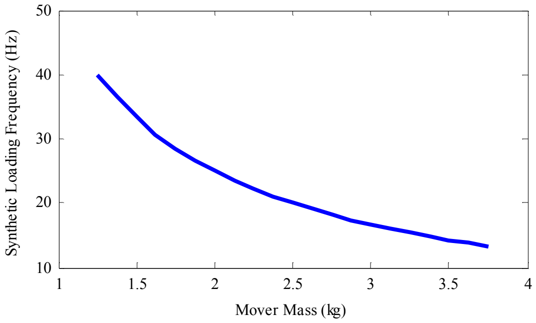

Figure 3. The impact of mover mass on synthetic loading frequency for a constant Δv

III. MODELING AND SIMULATION

The mathematical model of a linear permanent magnet synchronous machine used here is in the synchronously translating reference frame. A transformation is used to transform three phase components, which can be currents or voltages, into two variable quantities. To develop a model of a permanent magnet machine, 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 modeling the machine [12]. From the linear permanent magnet synchronous machine equivalent circuit, which is in an arbitrary synchronously translating *d-q* axis reference frame, the synthetic loading equation for direct axis and quadrature axis voltage have been derived using quadrature axis current from (1) and velocity from (5) and the machine parameters. The equations are complex so are not reported in full here. Using these equations the average input power, copper, iron and mechanical losses during one synthetic loading cycle can be calculated. The average input power is equal to the sum of the losses.

A standard efficiency test and a synthetic loading test for efficiency evaluation of linear permanent magnet synchronous machine have been simulated using MATLAB and SIMULINK. Fig. 4 shows the velocity profile during synthetic loading which confirms that the machine accelerates and decelerates during synthetic loading. The synthetic loading frequency in the simulation is 20Hz. The average velocity is 1.0pu with a velocity swing of 0.187pu, the test uses I_m=4.81 Amps (1.41pu), I_o=0.023Amps (0.0068pu) and the mechanical parameters are M=1.25 kg, D=0.14 Nsm^{-1}.

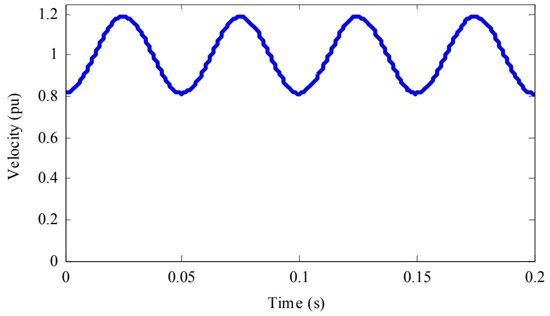

Figure 4. Velocity during synthetic loading method

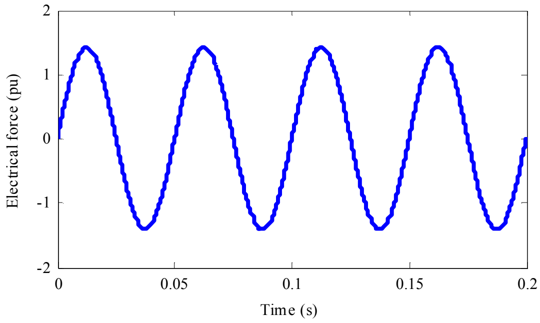

Figure 5. Electrical force during synthetic loading method

Fig. 5 illustrates electrical force and confirms alternation between motor-generator actions during the synthetic loading cycle $1/f_n$ (s). The synthetic loading frequency used in the simulation of Fig. 5 is 20 Hz. The peak acceleration and deceleration forces are 1.47 pu and -1.4pu respectively, which are higher than the rated force (1.0pu). This clearly indicates that the machine is heavily loaded by synthetic loading method, the machine acting as a motor for half a cycle of force variation and as a generator for the other half cycle. Note that the velocity is positive during the synthetic loading cycle. The average value of force over one synthetic loading cycle will be a positive value proportional to the friction and windage losses, and this can be used to separate the mechanical losses from the total losses.

Fig. 6 shows the resulting phase current and voltage during synthetic loading. Fig. 6a illustrates the instantaneous phase current when synthetic loading method is used for loading the linear permanent magnet synchronous machine. The instantaneous phase current varies in amplitude with a synthetic loading frequency of 20 Hz. Fig. 6b shows the instantaneous phase voltage, during synthetic loading for 20 Hz synthetic loading frequency. The instantaneous phase voltage is amplitude modulated with constant frequency (the 20 Hz synthetic loading frequency).

From standard efficiency test simulation results the peak voltage and peak current are 1.0pu and 1.0pu respectively and the peak voltage and peak current during different values of synthetic loading frequency are 1.0pu and 1.0pu respectively. The results of standard efficiency test and the synthetic loading method correlate. This confirms that synthetic loading method has potential as an efficiency test.

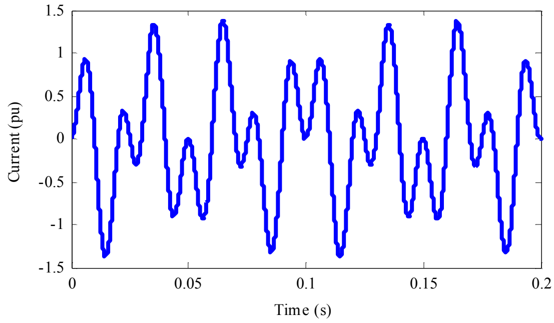

Figure 6a. Phase current

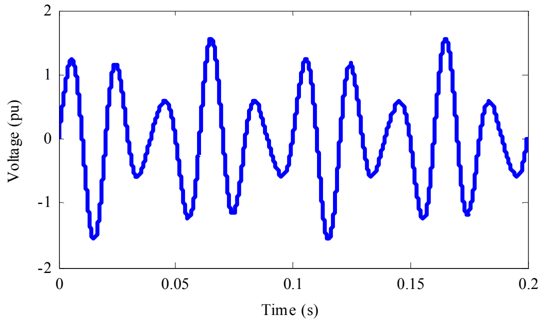

Figure 6b. Phase voltage

Figure 6. Phase current and voltage during synthetic loading method

Fig. 7 shows the variation of the instantaneous rms current and voltage with time during synthetic loading. The value of actual machine rms current and voltage is calculated using the synthetic loading cycle $1/f_n$ (s). Fig. 7a illustrates the variation of instantaneous rms current for 20Hz synthetic loading frequency. The amplitude of the positive half cycle is slightly higher than the amplitude of the negative half cycle. This is a consequence of the dc offset current. The instantaneous rms current varies between dc offset (I_o) minimum and AC perturbation plus dc offset current (I_m+I_o) maximum. The instantaneous rms voltage is varying with time for 20 Hz synthetic loading frequency as shown in Fig 7b. The instantaneous rms voltage is higher in half cycle than the machine rated rms value when the machine accelerates and lower for other half cycle when the machine decelerates.

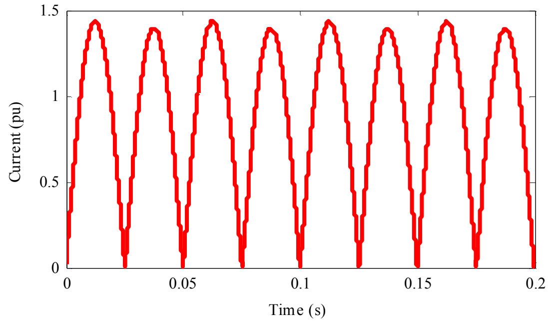

Figure 7a. . Instantaneous RMS current

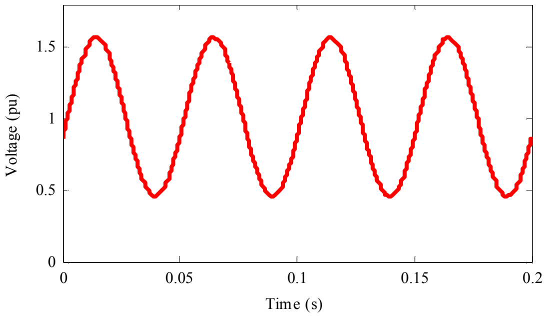

Figure 7b. Instantaneous RMS voltage

Figure 7. Instantaneous RMS current and voltage during synthetic loading method

Fig. 8 shows the variation of input power and total losses with time during synthetic loading. The input power is positive while the mover is accelerating and negative while the mover is decelerating. During the synthetic loading test the maximum power draw from the supply (1.64pu) is higher than maximum power returned back to the supply (-0.54pu), in both cases the machine delivers total losses as shown in Fig. 8. The average of input power over one synthetic loading cycle is equal to the total losses (0.4012pu), which confirms that efficiency can be evaluated using synthetic loading method.

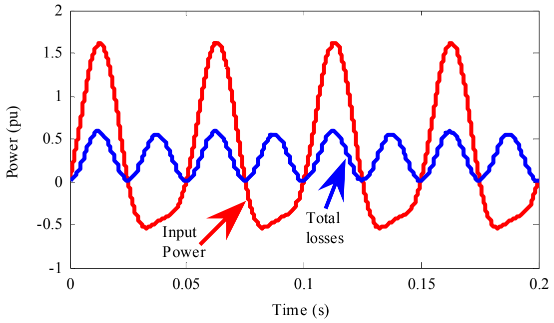

Figure 8. Input power and total losses during synthetic loading method

Different values of synthetic loading frequency have been simulated and are summarized in table I. The parameters of the motor are, armature resistance R_a=3.01Ω, quadrature axis inductance L_q=1.95mH, direct axis inductance L_d=1.95mH, damper factor D=0.14 Ns/m, mover mass M=1.25kg, number of poles P=4 and permanent magnet linkage flux λ_a=84.75 mWb.

Simulation results show that the losses, current and velocity using synthetic loading are consistent with the standard efficiency test method. This indicates that synthetic loading could be used in the efficiency evaluation of linear permanent magnet synchronous machines. The low efficiency (~70%) in table I is typical of linear machines designed for actuation applications operated below rated velocity (2.56ms^{-1}, around 50% of rated velocity). From table I the synthetic loading efficiency result is under estimated by 0.29% from the standard efficiency test.

TABLE I
SIMULATION RESULTS FOR LPMSM EFFICIENCY TESTS

	Standard Efficiency Test Method	Synthetic Loading Frequency (Hz)			
		20	25	30	35
Peak voltage (pu)	1.0000	1.004	1.004	1.004	1.004
Peak current (pu)	1.0000	1.000	1.000	1.000	1.000
Mover velocity (pu)	1.0000	1.000	1.000	1.000	1.000
Output power (pu)	0.9809	-	-	-	-
Input power (pu)	1.3824	0.4012	0.4010	0.4010	0.4010
Stator copper loss (pu)	0.3773	0.3815	0.3815	0.3815	0.3815
Iron loss (pu)	0.0129	0.0128	0.0127	0.0127	0.0126
Friction & windage loss (pu)	0.0069	0.0069	0.0068	0.0068	0.0068
Total losses (pu)	0.3971	0.4012	0.4010	0.4010	0.4009
Efficiency (%)	71.27	70.98	70.98	70.98	70.98

VI. EXPERIMENTAL RESULTS

To confirm that synthetic loading is an accurate method for efficiency evaluation for linear permanent magnet synchronous machines, the synthetic loading has been performed experimentally for different values of synthetic loading frequency and compared with experimental standard efficiency test.

A. Standard Efficiency Test:

This section describes the standard efficiency test for evaluating the efficiency of linear permanent magnet synchronous machines and requires a second machine to be mechanically coupled to the linear machine's mover. This second machine acts as a load causing the machine under test to draw rated current at rated voltage and move at rated velocity. The linear PM motor has trapezoid velocity waveform with positive velocity 2.56ms^{-1} when the machine is in forwards direction and negative velocity -2.56ms^{-1} when the machine is in backwards direction. Under these conditions the test machine produces rated losses. When the linear machine is operating in this condition, measurements are made of the input power to the linear machine and the output power of the load machine in order to determine the rated efficiency. Typically, a linear permanent magnet synchronous generator is used to load the test machine with the power absorbed in a resistive load. The linear permanent synchronous generator must be capable of handling the output power of the linear machine undergoing the test.

A practical standard efficiency test has been performed on the linear permanent magnet synchronous motor using a linear synchronous permanent magnet generator as a load. The motor load current and terminal voltage are depicted in Fig. 9. Fig. 9a shows the rated current drawn by linear permanent magnet synchronous machine when it is full loaded by linear permanent magnet synchronous generator. The load current waveform is approximately a sine wave with a maximum value 3.33 Amps (0.98pu) and frequency 50 Hz. Fig. 9b illustrates the line voltage of the linear machine when the machine is fully loaded and draws rated current. The voltage waveform is sine wave with a peak value 60.5 volts (1.03pu) and 50 Hz frequency. The experimental results have been normalized and are summarized in table II. In detail, the simulated standard efficiency test over-estimates the efficiency by 1.77% compared with experimental standard efficiency test.

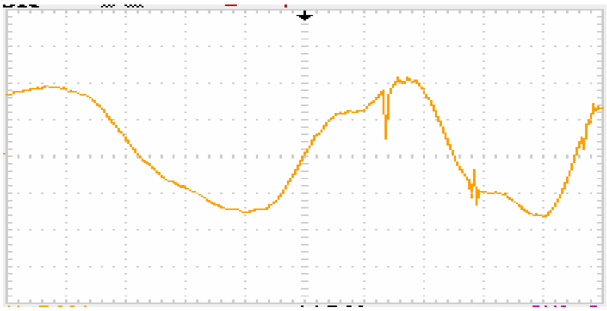

Figure 9a. Experimental phase current during standard efficiency test Scale (5ms/div, 2.0A/div)

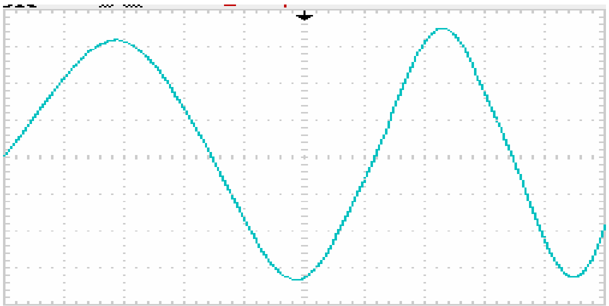

Figure 9b. Experimental line voltage during standard efficiency test scale (5ms/div, 20V/div)

Figure 9. Experimental phase current and line voltage during standard efficiency test

B. Synthetic Loading Test:

Fig. 10 shows the experimental rig. The experimental rig comprise of inverter, vector controller, linear permanent magnet synchronous motor and generator. Synthetic loading tests have been performed experimentally for different value of synthetic loading frequency. Fig. 11 illustrates the permanent magnet synchronous machine current and voltage during synthetic loading. Fig. 11a shows the current waveform during synthetic loading for a 20 Hz synthetic loading frequency. The voltage waveform is also varying in magnitude with a synthetic loading period, as shown in Fig. 11b. The results of the experimental synthetic loading frequency test have been normalized and are summarized in table II. Table I and table II show that voltage, current and mover velocity are in good agreement. The practical synthetic loading results show overestimation the efficiency by 0.05% on average compared with simulated synthetic loading test. The experimental synthetic loading results are in agreement with standard efficiency test results. This confirms that synthetic loading method could be used as a machine efficiency test method. Linear machines are typically designed for actuation applications using below rated power and velocity, therefore synthetic loading tests should be performed at different velocities and load conditions to confirm its validity and this is further research work currently being undertaken.

It notices from table II there is a different of 1.5% on average between efficiency using standard efficiency test method and synthetic loading method. This is a consequence of nonlinearity of the magnetic flux density when the machine is loaded, that is loss due to armature reaction during the standard efficiency test is higher than during the synthetic loading test.

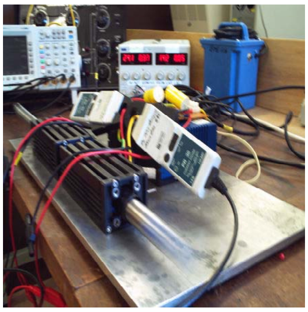

Figure 10. Experimental Rig

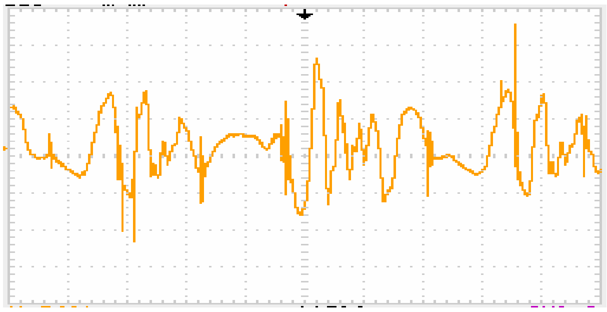

Figure 11a. Experimental phase current during synthetic loading test Scale (25ms/div, 2.0A/div)

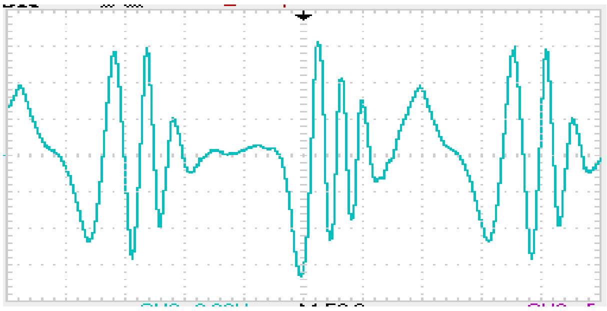

Figure 11b. Experimental line voltage during standard efficiency test scale (25ms/div, 20V/div)

Figure 11. Experimental phase current and line voltage during synthetic loading test

TABLE II
EXPERIMENTAL RESULTS FOR LPMSM EFFICIENCY TESTS

	Standard Efficiency Test Method	Synthetic Loading Frequency (Hz)			
		20	25	30	35
Peak voltage (pu)	0.9800	1.0200	1.0100	1.0000	1.0300
Peak current (pu)	1.0300	1.0000	1.0000	1.0000	1.0000
Mover velocity (pu)	1.0000	1.0000	1.0000	1.0000	1.0000
Output power (pu)	0.9702	-	-	-	-
Input power (pu)	1.3960	0.3975	0.4058	0.4028	0.4110
Total losses (pu)	0.4258	0.3975	0.4058	0.4028	0.4110
Efficiency (%)	69.50	71.50	70.93	71.15	70.55

V. CONCLUSION

Synthetic loading as a method of efficiency evaluation for linear PM electrical machines, has been assessed using MATLAB and SIMULINK. The method is accurate and able to identify the total losses in the machine. The effect of synthetic loading frequency on dc link voltage and inverter VA rating has been assessed. Moreover, the relation between mover mass and synthetic loading frequency is also derived. The simulation technique is used to determine an optimum operating point for synthetic loading. Synthetic loading causes the machine to produce rated losses. The individual losses can be calculated over one synthetic loading cycle. Also the total losses can be determined by calculating the input power and taking the average over one synthetic loading cycle. Synthetic loading test has been carried out experimentally. The synthetic loading simulation results and experimental results agree with the standard efficiency test results.

REFERENCES

[1] C. Grantham and H. Tabatabaei-Yazdi “A Novel Machineless Dynamometer for Load Testing ThreePhase Induction Motors”, *IEEE 1999 Interna-tional 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] N. J. Baker, M. A. Mueller and E. Spooner “Permanent Magnet Air-Core Tubular Linear Generator for Marine Converters”, *Power Electronics, Machines and Drives, 2004. (PEMD2004). Second - International B Conference B on B (Conf. B Publ. B No.498*) Vol. 2, 31 March-2 April 2004, pp. 862-867.

[4] S. Lee, S. Hong, S. Kim,Y. Yamaguchi and J. Won, “Polarimetric Features of Oyster Farm Observed by AIRSAR and J ERS-1”, *IEEE Transaction on Geoscience and Remote Sensing*, Vol. 44, No. 10, October 2006, pp. 2728-2735.

[5] H. Polider, B. C. Mecrow, A. G. Jack, P. G. Dickinson and M. A. Mueller, “Conventional and TFPM Linear Generators for Direct-Drive Wave Energy Conversion”, *IEEE Transaction on Energy Conversion*, Vol. 20, Issue 2, June 2005, pp. 260-267.

[6] Z. Yong-hua, Z. Shi-wu, Y. J ie and K. H. Low, “Morphologic Optimal Design of Bionic Undulating Fin Based on Computational Fluid Dynamics” *Proceeding of the 2007 IEEE International Conference on Mechatronics and Automation, Harbin, China,* 5-8 August, 2007, pp. 491-496.

[7] A. Heydari, “Miniature Vapor Compression Refrigeration Systems for Active Cooling of High Performance Computers” *Thermal and Thermomechanical Phenomena in Electronic Systems, 2002. ITHERM 2002. The Eighth Intersociety Conference on* Volume, Issue, 2002 pp. 371 – 378.

[8] 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.

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

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

[11] C. Grantham and M. Sheng, “The Synthetic Loading of Three-Phase Induction Motors Using Microprocessor Controlled Power Electronics”, *Power Electronics and Drive and Systems, 1995. Proceedings of 1995 International Conference*, Vol.1, on 21-24 February 1995, pp. 471-476.

[12] 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.