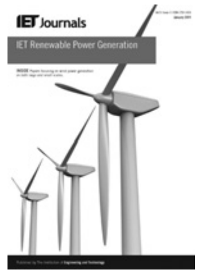
Published in IET Renewable Power Generation
Received on 23rd September 2009
Revised on 17th November 2009
doi: 10.1049/iet-rpg.2009.0146



ISSN 1752-1416

Synthetic loading applied to linear permanent magnet synchronous machines

A.Y.M. Abbas J.E. Fletcher

Department of Electronic and Electrical Engineering, University of Strathclyde, Royal College Building, 204 George Street, Glasgow G1 1XW, UK
E-mail: john.fletcher@eee.strath.ac.uk

Abstract: Linear permanent magnet (PM) machines are applicable to a number of prototype renewable energy devices and therefore are candidates for deployment. Synthetic loading for efficiency evaluation of linear PM synchronous machines is described and evaluated. Synthetic loading is a technique that eliminates the need for an external mechanical load to absorb generated shaft power during rated load efficiency tests. As such it is a technique ideally suited to the large linear PM generators proposed for renewable applications. Mathematical expressions for synthetic loading are derived for the linear PM synchronous machine using the *dq* machine model that includes core loss. Synthetic loading and standard efficiency tests, as methods of efficiency evaluation, are simulated using MATLAB and SIMULINK. Simulation data are verified by experiment for both the synthetic loading test and the standard efficiency test. Simulation and experimental results show that the synthetic loading method is capable of evaluating the efficiency of linear PM synchronous machine under test. The results show good agreement with standard efficiency tests. The key contribution of this work includes the mathematical expressions of synthetic loading applied to linear PM synchronous machines, the hardware and software implementation of the technique and the validation of the synthetic loading as a technique for efficiency evaluation of linear PM synchronous machines.

1 Introduction

Renewable power generation from wave and tidal energy has been a research interest for almost three decades [1–6]. There are a number of candidate devices that could potentially utilise linear generators in the power conversion process. These include such devices as the Oyster, the Archimedes Wave Swing device and Stingray [7–9]. Synthetic loading could be applied to the linear permanent magnet (PM) generators proposed in these devices as it is difficult to find and accommodate a suitable load for efficiency evaluation of the machine using the conventional efficiency test.

Cooling and the removal of heat from electronic systems has become an important issue facing system designers [10]. 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 a suitable method for efficiency evaluation of the linear PM motors proposed for use in the small Stirling cooler-type refrigeration systems used in such systems.

In 1921 Ytterberg introduced the two-frequency or mixed-frequency synthetic loading method for insulation temperature rise tests on induction machines. This method develops the equivalent of a full-load test but is achieved without mechanically loading the induction machine [11–14].

Testing of electrical machines, in order to determine the power losses in the form of heat and the resulting temperature rise, is important for both users and manufacturers [11]. High temperatures cause deterioration of insulation materials and high rates of power dissipation implies low efficiency values that affect machine lifetime, operating costs and revenue. The conventional method used to carry out efficiency tests is to connect a rated load to the test machine shaft. This is difficult, particularly for linear machines and large vertical machines [12]. Furthermore, the method requires removal of the test machine from the system, if post-installation tests are required, leading to loss of production. Post-installation tests may become necessary as part of ongoing condition monitoring. Consequently, an efficiency test that avoids the need for 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 full load current at rated voltage and speed. Synthetic loading can do this without connecting a mechanical load to the machine drive shaft [12]. 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 because of the rated current and rated iron (core) loss, and friction and windage loss as a consequence of operating at rated speed. Synthetic loading has been applied successfully to the induction machine to measure efficiency [11–17]. This paper aims to extend these concepts to linear PM synchronous machines and to assess the equipment ratings required for the test.

Section 2 introduces the principle of the synthetic loading technique. Equations for the linear PM machine under synthetic loading technique are developed in Section 3. Simulation results of the synthetic loading technique and the standard efficiency test for the linear PM synchronous machine under test are presented in Section 4. Section 5 presents the experimental set-up for the standard efficiency test and the synthetic loading test. The experimental results are presented in Section 6 and Section 7 draws conclusions.

2 Synthetic loading technique

Conventional efficiency tests require specialist test facilities, additional load machines and extra floor space. Synthetic loading overcomes these problems. Synthetic loading forces the electrical machine to draw full load current without the need of connecting a mechanical load to the machine drive shaft. The principle of synthetic loading is to control the machine under test such that it draws rated current using only the moment of inertia of the rotor as the load [18]. Therefore synthetic loading removes the need for a load machine. Also, the machine can be tested on-site simply by decoupling it from its load. 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 [19].

During synthetic loading of the linear machine, rms back emf, current and the mover velocity must be equal, on average, to rated values. 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 stored inertial energy back to the supply [18]. In both cases, the machine develops Ohmic loss. If configured correctly synthetic loading will produce rated rms phase current with rated back emf and rated mover velocity. 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, although knowledge of the rotor position is required for the vector controller that is core to the synthetic loading technique described here.

3 Equations of the linear machine under synthetic loading

Five non-linear equations are arranged as a set of first-order differential equations to represent the linear PM synchronous machines [20]. These differential equations are derived from the d- and q-axis equivalent circuit illustrated in Fig. 1, where v_x is the translational velocity and the subscripts 's' and 'c' indicate the stator and core branches.

From Figs. 1*a* and *b* the voltage equations in the dq synchronous reference frame for the linear PM synchronous machine are

$$V_d = R_a i_d + L_d\left(1+\frac{R_a}{R_c}\right)\frac{\mathrm{d}i_d}{\mathrm{d}t} - P\frac{\pi}{\tau}v_x L_q i_q\left(1+\frac{R_a}{R_c}\right) \quad (1)$$

$$V_q = R_a i_q + L_q\left(1+\frac{R_a}{R_c}\right)\frac{\mathrm{d}i_q}{\mathrm{d}t} + \left(1+\frac{R_a}{R_c}\right)P\frac{\pi}{\tau}v_x(L_d i_d + \lambda_m) \quad (2)$$

where V_d and V_q are d- and q-axis stator voltages, respectively, i_d and i_q are d- and q-axis torque generating currents, respectively, i_{ds} and i_{qs} are d- and q-axis stator currents, respectively, i_{dc} and i_{qc} are d- and q-axis core branches 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 PM flux linkage and v_x

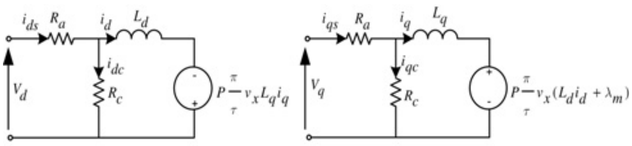


Figure 1 *d- and q-axis equivalent circuits for linear PM synchronous machines*

a *d*-axis
b *q*-axis

IET Renew. Power Gener., 2010, Vol. 4, Iss. 3, pp. 221–231
doi: 10.1049/iet-rpg.2009.0146

is the mover velocity. P is number of pole pairs and τ is pole pitch length.

The electromagnetic force F_e developed by the mover is

$$F_e = \frac{3}{2}\frac{\pi}{\tau}P(\lambda_m i_q + (L_d - L_q)i_q i_d) \quad (3)$$

The velocity equation is

$$\frac{dv_x}{dt} = (F_e - F_L - Dv_x)/M \quad (4)$$

where F_L is the load force. M and D are the mover mass (kg) and the damper coefficient (Ns m^{-1}), respectively. The mover position, x, is given by

$$\frac{dx}{dt} = v_x \quad (5)$$

3.1 Quadrature axis current equation

The correct choice of quadrature axis current (i_q) waveform is essential in order to draw rated phase current at rated phase voltage and velocity during synthetic loading of the linear PM synchronous machine. The reference waveform for i_q forces the machine to accelerate and decelerate. In this research, the 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 the AC perturbation current, I_o is a DC offset current and f_n is the synthetic loading frequency (Hz).

As the linear PM synchronous machine force, F_e, is assumed 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 of the mover velocity (assuming constant mechanical parameters) and the DC offset component, I_o, controls the average mover velocity. As the mover position, x, reaches the end of its travel, the DC component is reversed. It is essential to develop equations relating the synthetic loading parameters I_m, I_o and f_n to the parameters of the drive system in order to predict useful values for the synthetic loading parameters before testing. The next sections derive these relationships.

3.1.1 Determining I_o in terms of machine parameters: The load force, F_L, and the rate of change of mover velocity, on average, are zero during the synthetic loading test. Therefore the electrical force generated balances the force because of friction and windage. Hence, the average electrical force, F_{eav}, can be expressed as

$$F_{eav} = Dv_{xo} = k_f f_n \int_0^{1/f_n} (I_m \sin(2\pi f_n t) + I_o)\, dt \quad (7)$$

where v_{xo} is the rated steady-state mover velocity. The DC offset current, I_o, required to meet a desired average mover velocity, v_{xo}, during synthetic loading is a function of the mechanical parameters. By solving and rearranging (7) the expression for I_o is

$$I_o = \frac{Dv_{xo}}{k_f} \quad (8)$$

where k_f is the force factor of the machine ($k_f = 3/2(\pi/\tau)P\lambda_m$).

3.1.2 Determining I_m in terms of machine parameters: The synthetic loading technique must be configured to force the linear PM synchronous machine to draw rated current. Therefore the magnitude of AC perturbation current, I_m, is a function of the desired rms current, the required DC offset current I_o and the direct axis current i_d. To force rated rms phase current, I_s, the following must hold

$$\frac{(i_q^2 + i_d^2)}{2} = I_s^2 \quad (9)$$

Substituting the quadrature axis current, i_q, from (6) into (9) and averaging over one synthetic loading cycle gives the AC perturbation current as

$$I_m = \sqrt{4I_s^2 - 2I_o^2 - 2i_d^2} \quad (10)$$

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

$$I_m = \sqrt{4I_s^2 - 2I_o^2} \quad (11)$$

This equation provides a means of determining the AC current magnitude to force rated current in the machine for a given I_o required to balance friction and windage force.

3.2 Mover velocity equation

The mover velocity must equal, on average, the rated (or desired) mover velocity of the machine. During synthetic loading, the load force, F_L, is zero. Thus the mover velocity can be derived from the solution of (4) yielding

$$M\frac{dv_x}{dt} + Dv_x = k_f I_m \sin(2\pi f_n t) + k_f I_o \quad (12)$$

Solving (12) gives the mover velocity

$$v_x = \frac{k_f I_o}{D} + \frac{k_f I_m D}{(2\pi f_n M)^2 + (D)^2}\sin(2\pi f_n t) - \frac{k_f(2\pi f_n M)I_m}{(2\pi f_n M)^2 + (D)^2}\cos(2\pi f_n t) + \left[\frac{k_f(2\pi f_n M)I_m}{(2\pi f_n M)^2 + (D)^2} - \frac{k_f I_o}{D}\right]e^{-D/Mt} \quad (13)$$

In time the exponential component decays to zero and after further manipulations the synthetic loading mover velocity

doi: 10.1049/iet-rpg.2009.0146

equation is

$$v_x = \frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}} \sin(2\pi f_n t - \varphi) \tag{14}$$

where $\phi = \tan^{-1}(2\pi f_n M/D)$.

This demonstrates that under the synthetic loading technique described by (6) the mover velocity has a DC component and an AC component. During synthetic loading the machine accelerates and decelerates around the rated velocity hence the velocity is in one direction, but is programmed to reciprocate at the end of the translator stroke by changing the sign of I_o. In terms of the mechanical parameters, the DC velocity component depends on the mechanical friction, whereas the AC velocity component depends on the friction and the mover mass.

3.2.1 Maximum and minimum mover velocity:

The synthetic loading frequency can be expressed in terms of a desired value of peak-to-peak mover velocity and from (14) the maximum and minimum mover velocity can be determined.

The maximum mover velocity is

$$v_x(\max) = \frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}} \tag{15}$$

The minimum mover velocity is

$$v_x(\min) = \frac{k_f I_o}{D} - \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}} \tag{16}$$

3.2.2 Determining f_n in terms of machine parameters:

The synthetic loading frequency has an impact on the DC link voltage and inverter volt–ampere rating because of the effect it has on the maximum mover velocity. A higher maximum mover velocity induces a larger back emf. This requires increased line voltages, hence DC link voltage and inverter VA rating. Therefore proper choice of synthetic loading frequency is essential in order to avoid unnecessary VA rating. The peak-to-peak variation of mover velocity, Δv_x, is

$$\Delta v_x = v_x(\max) - v_x(\min) = 2\frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}} \tag{17}$$

The synthetic loading frequency can be determined if a required Δv_x is specified along with I_m, assuming the mechanical parameters are known. The synthetic loading frequency using (17) is

$$f_n = \frac{\sqrt{(2k_f I_m)^2 - (\Delta v_x D)^2}}{2\pi M \Delta v_x} \tag{18}$$

Δv_x can be between zero and twice the rated mover velocity, but for better synthetic loading performance this value should be small to avoid the overrating of the inverter. Also, higher values of Δv_x will lead to changes in the iron loss in the machine. The impact of synthetic loading frequency on DC link voltage and inverter volt–ampere will be discussed in detail in Section 4.

The synthetic loading period is found from (18) to be proportional to the mover mass for a desired value of Δv_x. This means that if the mechanical time constant increases, for example, by attaching additional mass to the mover, a lower Δv_x is produced for a given synthetic loading frequency. This is beneficial as it reduces the inverter volt–ampere requirement.

3.3 Direct and quadrature axis stator current equations

In order to derive equations for the input power and the inverter volt–ampere rating during synthetic loading tests, the direct and quadrature axis stator current equations must be determined. The stator direct and quadrature axis currents are a function of the synthetic loading frequency. Therefore in order to evaluate the stator phase current during synthetic loading, the direct and quadrature axis stator current is transformed to the *abc* reference frame. The stator phase current is also necessary to assess stator copper losses.

3.3.1 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 $i_{dc} = -P v_x \pi/\tau(L_q i_q/R_c)$ and $di_d/dt = 0$. Substituting the expression of i_{dc}, i_q (6) and v_x (14) into (19) gives the direct axis stator current as

$$i_{ds} = i_d - P\frac{\pi}{\tau}\frac{L_q}{R_c}(I_m \sin(2\pi f_n t) + I_o) \times \left[\frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}}\sin(2\pi f_n t - \varphi)\right] \tag{20}$$

3.3.2 Quadrature axis stator current equation:

From Fig. 1*b* the quadrature axis stator current can be

doi: 10.1049/iet-rpg.2009.0146

calculated using Kirchhoff's current law as

$$i_{qs} = i_q + i_{qc} \tag{21}$$

where $i_{qc}=P\pi/\tau\ v_x\ (L_d i_d + \lambda_m)/R_c$. Therefore substituting the expression of i_{qc}, i_q (6) and v_x (14) into (21) the quadrature axis current is

$$i_{qs} = I_m \sin(2\pi f_n t) + I_o + P\frac{\pi}{\tau}\frac{(L_d i_d + \lambda_m)}{R_c} \times \left[\frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}}\sin(2\pi f_n t - \varphi)\right] \tag{22}$$

The stator *abc* phase current can be calculated from *dq*-axis stator current using Park's transformation

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\left(P\frac{\pi}{\tau}x\right) & \sin\left(P\frac{\pi}{\tau}x\right) \\ \cos\left(P\frac{\pi}{\tau}x - \frac{2\pi}{3}\right) & \sin\left(P\frac{\pi}{\tau}x - \frac{2\pi}{3}\right) \\ \cos\left(P\frac{\pi}{\tau}x + \frac{2\pi}{3}\right) & \sin\left(P\frac{\pi}{\tau}x + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{23}$$

where i_a, i_b and i_c are the stator phase current of the linear PM synchronous machines, and x is the mover displacement. The peak phase current can then be identified, which then provides a means of calculating the inverter VA rating in conjunction with the DC link voltage.

3.4 Direct and quadrature axis voltage equations

The direct and quadrature axis voltages are a function of the synthetic loading frequency. Therefore equations for the *dq*-axis voltages are essential in determining the machine's peak phase and line voltages; hence, DC link voltage and inverter volt–ampere rating are required for the synthetic loading test. The direct and quadrature axis voltages are derived from (1) and (2) after substituting the equations of quadrature axis current, i_q, (6) and mover velocity, v_x, (14).

The direct axis voltage of linear PM synchronous machine during the synthetic loading test is

$$V_d = R_a i_d - L_q P\left(1 + \frac{R_a}{R_c}\right)(I_m \sin(2\pi f_n t) + I_o)\frac{\pi}{\tau} \times \left[\frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}}\sin(2\pi f_n t - \varphi)\right] \tag{24}$$

The quadrature axis voltage of the linear PM synchronous machine during synthetic loading is

$$V_q = R_a I_m \sin(2\pi f_n t) + R_a I_o + L_q I_m (2\pi f_n) \times \left(1 + \frac{R_a}{R_c}\right)\cos(2\pi f_n t) + P\left(1 + \frac{R_a}{R_c}\right)(L_d i_d + \lambda_m)\frac{\pi}{\tau} \times \left[\frac{k_f I_o}{D} + \frac{k_f I_m}{\sqrt{(2\pi f_n M)^2 + (D)^2}}\sin(2\pi f_n t - \varphi)\right] \tag{25}$$

The Park transformation allows the instantaneous values of phase voltages to be calculated. Hence the peak line voltages can be determined. The minimum DC link voltage and inverter VA rating can then be determined.

4 Simulation of synthetic loading

During synthetic loading the machine is decoupled from the load. The simulation results are obtained using a MATLAB m-file that solves the expressions developed in Section 3 with the machine data detailed in the Appendix, Table 3. Ideally, Δv_x should be as small as possible during synthetic loading. An increase in speed variation leads to an increase in inverter volt–ampere rating and DC link voltage. The impact of the synthetic loading frequency on the inverter volt–ampere and DC link voltage is presented in this section in order to assess quantitatively the impact that the synthetic loading frequency has on the inverter VA rating.

Fig. 2 shows the effect of synthetic loading frequency on the inverter VA rating and the DC link voltage. These graphs are derived using the machine parameters given in the Appendix for the laboratory linear PM machine. The graph shows the general trend and identifies specific optimum synthetic loading frequencies based on the machine parameters. The inverter VA rating and the DC link voltage requirement rises as the synthetic loading frequency decreases below 20 Hz as shown in Fig. 2. For

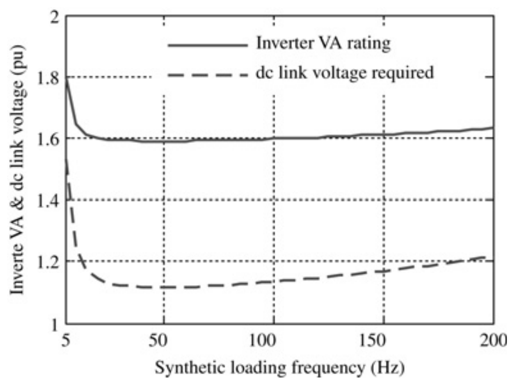


Figure 2 *Impact of synthetic loading frequency on the required DC link voltage and inverter volt–ampere rating during synthetic loading*

example, the inverter VA rating and the DC link voltage required are 1.8 and 1.53 pu with a 5 Hz synthetic loading frequency. The inverter VA rating and the DC link voltage gradually decreases as the synthetic loading is increased falling to a minimum of 1.51 and 1.1 pu, respectively, with synthetic loading frequencies between 20 and 60 Hz. As the synthetic loading frequency rises from 60 to 200 Hz, the inverter VA rating and the DC link required gradually increases. Therefore an optimum synthetic loading frequency for the linear PM synchronous machine tested is between 20 and 60 Hz. These optimum synthetic loading frequencies are used to simulate the synthetic loading technique for the linear PM synchronous machine in this section and to execute synthetic loading experimentally in Section 6.

The standard efficiency test and the synthetic loading test on the linear PM synchronous machine are simulated under full-load force and rated speed conditions. Five different synthetic loading frequencies are used and simulation allows the optimum synthetic loading parameters to be determined. Figs. 3 and 4 show examples of the simulation results of the synthetic loading technique using a synthetic loading frequency of 20 Hz.

The instantaneous phase voltage and current are simulated during synthetic loading using (24). Fig. 3*a* shows the instantaneous phase voltage and Fig. 3*b* shows the instantaneous phase current during synthetic loading. The instantaneous phase voltage and current are amplitude

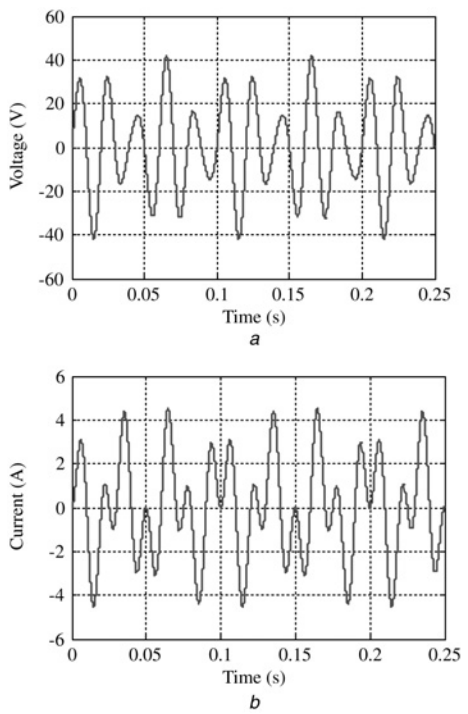


Figure 3 *Simulated synthetic loading configured to produce rated conditions ($I_m = 4.64$ A, $I_o = 0.023$ A, $f_n = 20$ Hz)*

a Phase *a* voltage
b Phase *a* current

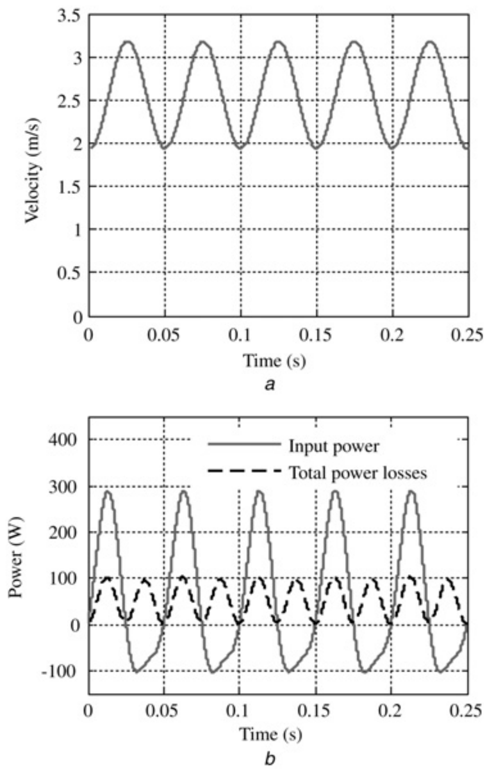


Figure 4 *Simulated synthetic loading configured to produce rated conditions ($I_m = 4.64$ A, $I_o = 0.023$ A, $f_n = 20$ Hz)*

a Mover velocity
b Input power and total losses

and frequency modulated during synthetic loading. The phase voltages and currents have more than one frequency component, whereas the *q*-axis current (and voltage) is modulated only by the synthetic loading frequency, the phase quantities are transformed from *dq* quantities using rotor position leading to multiple frequency components as shown in Fig. 3 (and Fig. 5 for the experimental system). The instantaneous rms line voltage is higher during the half cycle when the machine accelerates and lower for that during the half cycle when the machine decelerates. The amplitude of the instantaneous rms current during the acceleration half cycle is slightly higher than the amplitude of the deceleration half cycle. This is a consequence of the DC offset current.

The quadrature axis current of the linear PM synchronous machine during synthetic loading in (6) has a peak value of 4.64 A (1.42 pu). However, the average value of the quadrature axis current is 0.066 A. This average value is equal to the no-load current that compensates the no-load friction losses. The peak value of the electromagnetic force is 72.7 N (1.42 pu). The average value of the electromagnetic force over one synthetic loading cycle is 0.36 N to compensate the friction loss.

Fig. 4 shows the variation of the mover velocity and the input power and the total losses during synthetic loading.

doi: 10.1049/iet-rpg.2009.0146

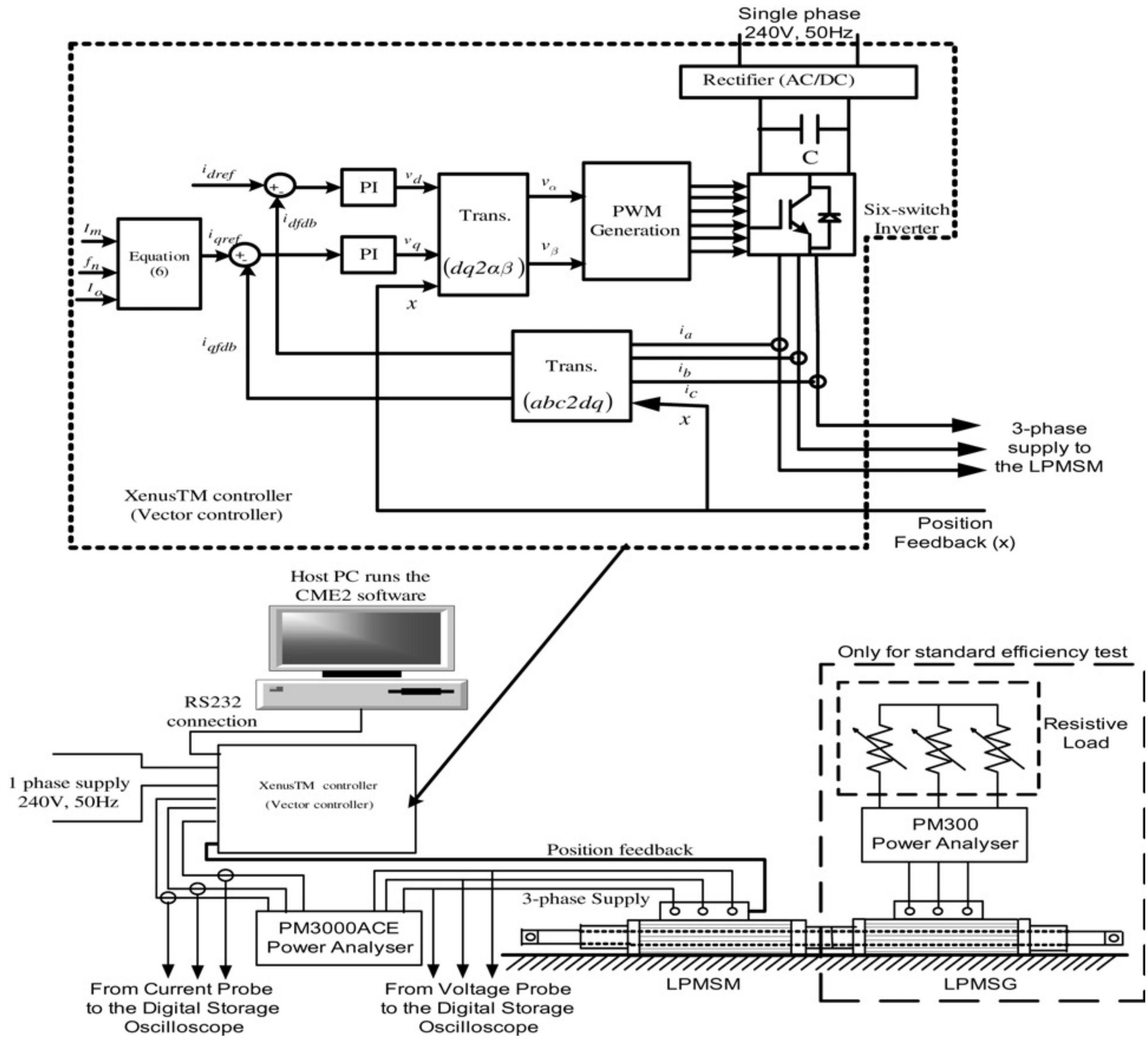


Figure 5 *Block diagram for performing synthetic loading technique and standard efficiency test on the linear PM synchronous machine*

The linear PM synchronous machine velocity during synthetic loading is simulated using (15). The results in Fig. 4*a* confirm that the linear PM synchronous machine accelerates and decelerates during synthetic loading with a velocity swing (peak to peak) of 1.24 ms^{-1} (0.48 pu). The average value of the mover velocity over one synthetic loading cycle is 2.56 ms^{-1} (1.0 pu).

Fig. 4*b* shows the variation of the input power and the total losses during synthetic loading. During acceleration periods the power absorbed by the motor peaks at 290 W, Fig. 4*b*, during deceleration periods it peaks at 100 W. The average input power over one synthetic loading cycle is 51.3 W and is equal to the average of the total losses from which the efficiency can be readily evaluated.

Table 1 summarises the simulation results for synthetic loading applied to the linear PM synchronous machine for five different synthetic loading frequencies that all produce rated rms voltage and rated rms current. These are compared to simulations of the standard efficiency test. The individual losses are calculated during synthetic loading and compared with the standard efficiency test. The iron loss and friction loss are the same as the standard efficiency test. This is because the linear PM synchronous machine is running at rated mover velocity, on average, during synthetic loading. The copper loss for the standard efficiency test is higher than the copper loss for the five synthetic loading frequencies. This is as a result of slightly higher rms current during standard efficiency test: during the standard efficiency test the machine is loaded to rated output power and the current drawn by the machine is slightly higher than the rated current; during synthetic loading the current is controlled to be equal to the rated value. Therefore the calculated efficiencies during synthetic loading are underestimated by 0.2%, on average. The rms terminal voltages during synthetic loading are lower than the voltage during the standard efficiency test. This is

Table 1 Comparison of the standard efficiency test and the synthetic loading technique configured to produce rated conditions ($I_m = 4.64$ A, $I_o = 0.023$ A)

	Standard efficiency test	Synthetic loading frequency, f_n,Hz				
		20	25	30	35	40
rms line voltage, V	45.1	35.4	35.3	35.2	35.2	35.2
rms line current, A	2.32	2.32	2.32	2.32	2.32	2.32
average speed, ms^{-1}	2.56	2.56	2.56	2.56	2.56	2.56
peak inverter current, A	3.27	4.64	4.64	4.64	4.64	4.64
phase-leg volt–ampere, VA	229.0	348.0	348.0	348.0	348.0	348.0
required DC link voltage, V	70	75	75	75	75	75
output power, W	128.5	–	–	–	–	–
input power, W	179.5	51.3	51.3	51.2	51.2	51.2
stator copper loss, W	48.3	48.6	48.6	48.6	48.6	48.6
iron loss, W	1.72	1.72	1.72	1.72	1.71	1.71
friction loss, W	0.92	0.93	0.93	0.93	0.93	0.92
total losses, W	51.0	51.3	51.3	51.3	51.2	51.2
efficiency, %	71.6	71.4	71.4	71.4	71.4	71.4

because the average voltage drop across R_a and L_q over one synthetic loading cycle is close to zero unlike during the standard efficiency test. Even though the rms voltage is lower, the linear PM synchronous machine is operating with rated back emf during synthetic loading, hence producing rated iron loss. It is observed that the required DC link voltage and peak inverter current are higher for the synthetic loading technique leading to an increased VA rating for the inverter.

5 Experimental set-up

The synthetic loading technique and standard efficiency test for the linear PM synchronous machine are performed using an off-the-shelf vector controller for the linear machine. In this case, a Copley Controls amplifier controlled via Copley Controls CME2 software is utilised. The amplifier can be configured with current, velocity and position control loops, to control the motor.

In order to perform synthetic loading for the linear PM synchronous machine the current control loop is utilised. With current control, the reference quadrature axis current is set up by configuring the peak current, I_m, the DC offset, I_o, the synthetic loading frequency, f_n, and the PI controller parameters k_i and k_p in the control software. To perform the synthetic loading, two of 16 user-definable sequences are chosen, one for forward motion and the other for backward motion of the mover. In each sequence the distance of the movement, the acceleration and the deceleration of the mover is configured. The block diagram of the practical set-up is shown in Fig. 5. The load machine and the resistive load are required only for the standard efficiency test.

The standard efficiency test is performed by configuring the reference current at the desired value. In the sequences for the forward and the backward motion, the distance of movement, the movement velocity of the mover and the acceleration of the mover are configured to 100 mm, 2.56 ms^{-1} and 5.2 ms^{-2}, respectively. The mover of the linear PM synchronous motor is mechanically coupled to the mover of the linear PM synchronous generator and the generated power is dissipated in the resistive load as shown in Fig. 5. The resistive load is adjusted to give rated current in the linear PM synchronous motor.

The phase currents and voltages of the linear PM synchronous machine under test are captured using a digital storage oscilloscope. These are then processed off-line to obtain the input power waveform. The PM3000ACE power analyser measures power input, rms current, voltage and system frequency. For the standard test configuration the PM300 measures the output power.

6 Experimental results

Synthetic loading has been performed experimentally for different values of synthetic loading frequency and compared with the experimental standard efficiency test. In this case the synthetic loading technique and the standard efficiency test for the linear PM synchronous machine are performed for the full-load force condition at rated velocity. Five different

doi: 10.1049/iet-rpg.2009.0146

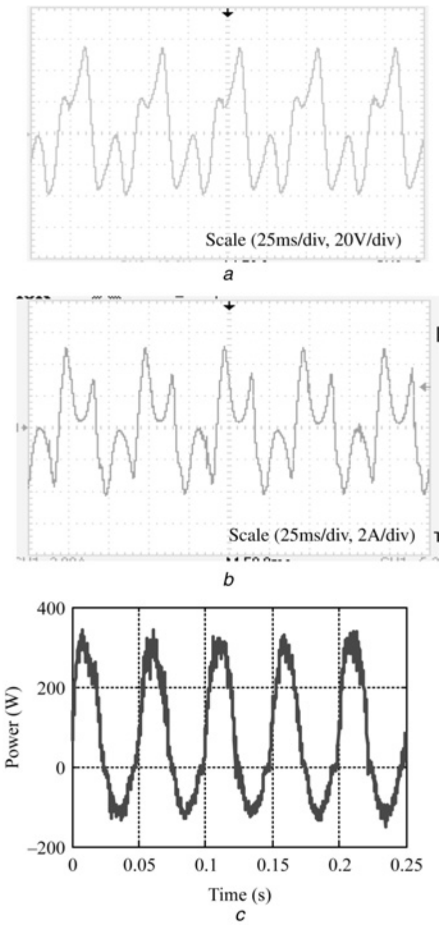


Figure 6 *Experimental synthetic loading configured to produce rated conditions ($I_m = 4.81$ A, $I_o = 0.043$ A, $f_n = 20$ Hz)*

a Phase voltage
b Phase current
c Input power variation

synthetic loading frequencies are investigated. These are between 20 and 40 Hz as this frequency range minimises the VA rating of the inverter as explained in Section 4. Fig. 6 shows examples of the experimental results using a synthetic loading frequency of 20 Hz. Fig. 6*a* shows the experimental waveform of the instantaneous phase voltages. The average of the instantaneous rms voltage over one synthetic loading cycle is equal to the rated terminal voltage of the linear PM synchronous machine. The instantaneous phase currents for the same conditions are shown in Fig. 6*b*. The experimental phase current and voltage during synthetic loading are amplitude and frequency modulated and show good agreement with the simulation results. Fig. 6*c* shows the input power. The experimental and the simulation input power waveforms are in good agreement with the simulation results in Fig. 4.

There is a difference in the component frequencies of the simulated and experimental results shown in Figs. 3 and 6. This is primarily due to the variation of mover velocity of the simulated systems being different to the experimental systems as a result of mismatch in the mechanical parameters.

Table 2 compares the standard efficiency test and synthetic loading test under rated conditions. The inverter used to carry out synthetic loading test must deliver a peak current of 4.81 A (1.41 pu), which is higher than the inverter rating used to conduct the standard efficiency test. Table 2 illustrates that the efficiency of the linear PM synchronous machine assessed using synthetic loading technique, under rated conditions, is between 70.1% and 70.5%. Therefore the synthetic loading experimental result underestimates the efficiency by 0.1% at best and 0.5% at worst compared to the standard efficiency test. This indicates that the synthetic loading technique can be used to evaluate the efficiency of the linear PM synchronous machine. Also, during synthetic loading, the results show that the machine draws rated rms current and moves at rated velocity on average.

The comparison between the simulation and the experimental results in Tables 1 and 2 show that there is an additional loss during the experiment. This additional loss is due to harmonic currents at the PWM switching frequency. These harmonic currents are not modelled during

Table 2 Experimental comparison of the standard efficiency test and the synthetic loading technique under full-load force conditions ($I_m = 4.81$ A, $I_o = 0.023$ A)

	Standard efficiency test	Synthetic loading frequency, f_n,Hz				
		20	25	30	35	40
rms line voltage, V	47.3	47.0	46.8	47.1	47.0	47.2
rms line current, A	2.4	2.42	2.4	2.4	2.41	2.42
minimum inverter peak current, A	3.4	4.81	4.8	4.8	4.81	4.81
speed, ms^{-1}	2.56	2.56	2.56	2.56	2.56	2.56
input power, W	197.4	58.4	58.8	58.2	58.5	59.1
output power, W	139.6	–	–	–	–	–
total losses, W	57.8	58.4	58.8	58.2	58.5	59.1
efficiency, %	70.6	70.4	70.2	70.5	70.4	70.1

doi: 10.1049/iet-rpg.2009.0146

simulation. The harmonic currents contribute additional core loss (hysteresis and eddy current) arising from the changing flux density in the iron of the machine and additional Ohmic loss caused by the rms value of the current ripple at the switching frequency. Additionally, non-linearities such as magnetic saturation, skin effect and damper factor for calculating friction losses are assumed to be constant but may not be constant during the experiment. This leads to an underestimate of the losses in the simulation.

7 Conclusions

Synthetic loading as a technique for efficiency evaluation of 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 simulation technique is used to determine an optimum operating point for synthetic loading that minimises the required DC link voltage and inverter VA rating. Synthetic loading causes the machine to produce rated losses. The losses can be calculated over one synthetic loading cycle and can be determined by calculating the input power and take the average over one synthetic loading cycle. Synthetic loading has been carried out experimentally for five different synthetic loading frequencies. The synthetic loading simulation results and experimental results agree with the standard efficiency test results and it can be concluded that the synthetic loading technique is an appropriate method for determining losses at rated conditions.

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9 Appendix

See Table 3

Table 3 Electrical and mechanical parameters of the linear PM synchronous machine

Parameters	Values
rated output power	130 W
maximum rated current	3.27 A
rated velocity	2.56 ms^{-1}
maximum bus voltage	220 V
armature resistance, R_a	3.01 Ω
core loss resistance, R_c	625 Ω
quadrature axis inductance, L_q	1.95 mH
direct axis inductance, L_d	1.95 mH
mover mass, M	1.25 kg
damper coefficient, D	0.14 Nsm^{-1}
total PM flux linkage, λ_m	84.75 mWb
pole pitch, τ	51.2 mm
number of poles	4

doi: 10.1049/iet-rpg.2009.0146