The Synthetic Loading Technique Applied to the PM Synchronous Machine

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***Abstract*—The application of the synthetic loading technique to permanent magnet (PM) synchronous machines is investigated. Mathematical equations for synthetic loading are developed. From the equations, a quadrature-axis current algorithm is proposed from which rotor speed and the stator direct- and quadrature-axis voltage and current equations are derived. The impact that synthetic loading frequency has on the dc-link voltage and the inverter phase-leg volt-ampere rating are analyzed. This shows that the synthetic loading technique requires an increased dc-link voltage and inverter volt-ampere rating compared to the standard efficiency test method. Synthetic loading is verified experimentally using a surface-mount PM synchronous machine. Simulation and experimental results are compared with the standard efficiency test. The simulation and the experimental results show that the synthetic loading technique is capable of evaluating the losses in the PM synchronous machine.**

***Index Terms*—Efficiency test, permanent magnet synchronous machine, synthetic loading.**

I. Introduction

THIS paper addresses the efficiency evaluation of PM synchronous machines. A challenge faced by 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 categorized 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]. If the losses are higher the machine will be less efficient.

During the past two decades, permanent magnet (PM) synchronous machine drives have become popular and are gradually replacing classic dc machine drives and induction machine drives in industrial applications. The growth in use is a consequence of the advantages such as high efficiency, compactness, robustness, and high reliability [2]. Much research has been targeted on control and design aspects. Also, the developments in power electronic technology make the PM synchronous machines useful in industrial processes that need a wide speed range.

The 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 that affects machine lifetime. The current method used to carry out an efficiency test is to connect a rated load to the test-machine shaft. This is difficult, particularly for large machines and vertical machines [4]. Furthermore, this method requires removal of the test machine from the set, leading to loss of production. Consequently, an efficiency test that avoids an external load is desirable. Such a test technique is the synthetic loading technique and this paper addresses the application of the synthetic loading to PM synchronous machines. During a rated-load efficiency test, the machine must draw it is full-load current at rated voltage and rotor speed. Synthetic loading can do this without connecting a mechanical load to the machine drive shaft [5]–[7]. During synthetic loading, the electrical machine is accelerated and decelerated creating motor–generator action, producing on average rated copper loss due to rated current, rated iron (core) loss, and friction and windage loss as a consequence of operation at rated speed.

The paper is organized as follows. Section II presents the synthetic loading technique. The mathematical equations of the synthetic loading technique are developed in Section III, which are then used in Section IV for simulation of the synthetic loading technique and the standard efficiency test for the PM synchronous machine. Section V shows the impact of nonzero direct-axis current on the performance of synthetic loading. Experimental results are presented in Section VI with a comparison with simulation results. Conclusions are drawn in Section VII.

II. Synthetic Loading Technique

Synthetic loading must be configured such that the test machine draws full-load current without connecting a mechanical load to the machine drive shaft. The principle of synthetic loading is to use only the moment of inertia of the rotor as the load [8]. Therefore, synthetic loading offers the advantage that the tested machine no longer requires a load. Also, the machine can be tested on site. During synthetic loading, the equipment required to conduct the efficiency test is a vector controller (inverter, controller, appropriate voltage and current sensors, and position sensor or estimator), and a power analyzer. The cost and time associated with performing a synthetic loading test is significantly reduced as the test equipment is portable [9].

Manuscript received August 17, 2009; revised December 20, 2009, April 26, 2010, and September 20, 2010; accepted September 24, 2010. Date of publication December 10, 2010; date of current version February 18, 2011. Paper no. TEC-00335-2009.

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Digital Object Identifier 10.1109/TEC.2010.2082543

During synthetic loading, the machine accelerates and decelerates alternating between motor and generator action. Under acceleration, the machine operates as a motor and draws current from the supply. During deceleration, the machine regenerates and delivers current back to the supply [8]. In both cases, the machine develops Ohmic loss. If configured correctly synthetic loading will produce rated voltage at the machine's terminal and rated rotor speed with rated rms phase current; therefore, rated flux, frequency, and current conditions prevail with their associated loss components. In our proposed synthetic loading method for the PM machine, a current (or vector) control method is used. The investigation of the impact of synthetic loading on dc-link voltage rating shows that a slightly higher dc-link voltage is required. The current rating of the inverter is also higher. This indicates that synthetic loading requires an inverter with a higher volt-ampere rating than that for the standard efficiency test. This is to be expected as the single inverter in the synthetic loading test is processing the equivalent of the combined power of the drive and the load machine in the standard efficiency test. The principle equations that characterize our proposed technique are now developed. The equations then form the basis for simulation.

III. Mathematical Equations

In this section, mathematical equations of the synthetic loading method are developed for the PM synchronous machine. The proposed perturbation of the quadrature-axis current is introduced that establishes appropriate synthetic loading conditions. The resultant voltage equations, using *d*- and *q*-axis equivalent circuits, including equivalent core loss resistance, are developed. The system of equations provides a mechanism to tune the proposed quadrature current waveform prior to practical tests. The equations also provide a means to assess the impact of synthetic loading frequency on the required inverter dc-link voltage and inverter volt-ampere rating. In addition, the equations allow the potential benefits of additional moment of inertia to be assessed, particularly the effect on the peak-to-peak rotor speed.

The PM synchronous machine model is based on Park's equations. The solutions to the model's equations yield instantaneous currents, which are used to determine the electromagnetic torque developed by the PM synchronous machine. The torque, in conjunction with mechanical and damping torque acting on the rotor, is then used to determine the rotor speed of the PM synchronous machine.

Five nonlinear differential equations, based on Park's *dq*-axis representation [10], are used to represent the PM synchronous machine. These equations are arranged in a set of first-order differential equations that are derived from the *d*- and *q*-axis equivalent circuits illustrated in Fig. 1(a) and (b), respectively.

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

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

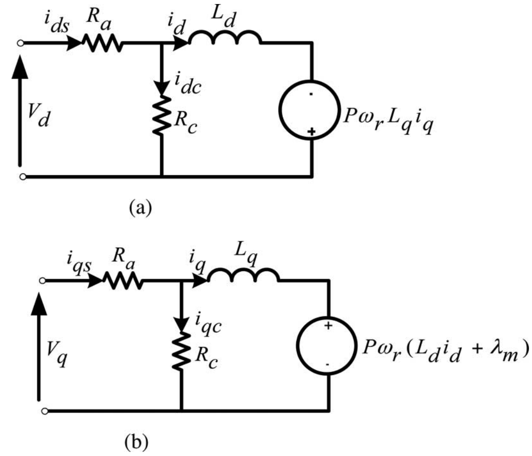

Fig. 1. (a) *d*- and (b) *q*-axis steady-state equivalent circuit of the PM synchronous machine.

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

where

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

The electromagnetic torque, T_e, developed by the rotor is

$$T_e = \frac{3}{2} P(\lambda_m i_q + (L_d - L_q) i_q i_d). \tag{3}$$

The speed equation is

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L - B\omega_r}{J} \tag{4}$$

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

$$\frac{d\theta}{dt} = \omega_r. \tag{5}$$

A. Quadrature-Axis Current

The key step in performing synthetic loading on a PM synchronous machine is the correct choice of the torque producing 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. In this research, i_q, takes the form

$$i_q = I_m \sin(2\pi f_n t) + I_o \tag{6}$$

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

As the machine torque is assumed 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 variation in the rotor speed (assuming constant mechanical parameters) and the dc-offset component controls the average rotor speed.

1) 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 average electrical torque generated, $T_{\rm eav}$, balances only the torque due to friction and windage; hence,

$$T_{\rm eav} = B\omega_{ro} = k_t f_n \int_0^{1/f_n} (I_m \sin(2\pi f_n t) + I_o) dt \quad (7)$$

where $k_t = (3/2)P\lambda_m$ is the machine torque constant in ((Newton meter) per ampere) and *B* is the damper coefficient in (in Newton.meter.second), *P* is the number of pairs of poles, λ_m is the linkage flux, and ω_{ro} is the rated steady-state rotor speed.

Hence, during synthetic loading, the required dc-offset current, I_o, is a function of the average desired machine speed and the mechanical parameters. By solving and rearranging (7), the expression for I_o is

$$I_o = \frac{B\omega_{ro}}{k_t}. \quad (8)$$

Thus, the average dc-offset current required is the friction torque divided by the torque constant of the machine. In the test setup, I_o can be used to independently control the average speed of rotation.

2) Determining I_m in Terms of Machine Parameters: The magnitude of ac perturbation I_m is a function of the target rms current (typically the rated 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

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

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

$$I_s^2 = \frac{f_n}{2} \int_0^{1/f_n} (I_m \sin(2\pi f_n t) + I_o)^2 \, dt + f_n \int_0^{1/f_n} \frac{i_d^2}{2} dt. \quad (10)$$

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

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

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

$$I_m = \sqrt{4I_s^2 - 2I_o^2} \quad (12)$$

which provides the mechanism to determine I_m.

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 algebraic manipulations of (3), (4), and (6) yielding

$$J\frac{d\omega_r}{dt} + B\omega_r = k_t I_m \sin(2\pi f_n t) + k_t I_o. \quad (13)$$

By applying Laplace transforms, partial fraction expansion, and Laplace inverse transforms to (13), the rotor speed is described with respect to time as

$$\begin{aligned}\omega_r = {} & \frac{k_t I_o}{B} + \frac{k_t I_m B/J^2}{(2\pi f_n)^2 + (B/J)^2} \sin(2\pi f_n t) \\ & - \frac{k_t (2\pi f_n) I_m/J}{(2\pi f_n)^2 + (B/J)^2} \cos(2\pi f_n t) \\ & + \left[\frac{k_t (2\pi f_n) I_m/J}{(2\pi f_n)^2 + (B/J)^2} - \frac{k_t I_o}{B}\right] \mathrm{e}^{-(B/J)t}. \quad (14)\end{aligned}$$

In time, the exponential term decays to zero and after further algebraic manipulations the synthetic loading rotor speed is

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

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

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

1) Maximum and Minimum Rotor Speed: From (15), the maximum and minimum rotor speeds can be determined. Using trigonometric identities and algebraic manipulations, the maximum rotor speed is

$$\omega_r(\max) = \frac{k_t I_o}{B} + \frac{k_t I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}. \quad (16)$$

The minimum rotor speed is

$$\omega_r(\min) = \frac{k_t I_o}{B} - \frac{k_t I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}. \quad (17)$$

2) Determining f_n in Terms of the Machine Parameters: The synthetic loading frequency, f_n, is important as it has an impact on the dc-link voltage and inverter volt-ampere rating. Hence, proper choice of synthetic loading frequency is essential in order to avoid needlessly over rating the power converter components. Also, it is preferable that the swing speed is small to reduce the required dc-link voltage and the inverter volt-ampere rating. The synthetic loading frequency can also be determined to provide a desired peak-to-peak rotor-speed variation, therefore, provides a design method for choosing the synthetic loading frequency. The peak-to-peak speed variation, $\Delta\omega_r$, is

$$\begin{aligned}\Delta\omega_r &= \omega_r(\max) - \omega_r(\min) \\ \Delta\omega_r &= 2\frac{k_t I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}. \quad (18)\end{aligned}$$

From (18), the synthetic loading frequency can be determined if a required $\Delta\omega_r$ is specified along with I_m from (11) and the mechanical parameters

$$f_n = \frac{\sqrt{(2k_t I_m)^2 - (\Delta\omega_r B)^2}}{2\pi J \Delta\omega_r}. \quad (19)$$

The value of $\Delta\omega_r$ can be between zero and twice the rated rotor speed ($0 < \Delta\omega_r \leq 2\omega_r$); nevertheless, for better synthetic loading performance, $\Delta\omega_r$ should be as small as possible. A high value of $\Delta\omega_r$ leads to a higher inverter volt-ampere rating and dc-link voltage. The designer can select f_n in order to achieve a desired $\Delta\omega_r$ using (19).

From (19), the synthetic loading period is proportional to the moment of inertia for a given value of $\Delta\omega_r$. This means that if the inertia is increased, a lower synthetic loading frequency will achieve the same $\Delta\omega_r$. The moment of inertia can be increased by attaching additional mass to the motor shaft. The increase in inertia leads to a reduced dc-link voltage and inverter volt-ampere rating required for a given value of synthetic loading frequency. This is potentially beneficial.

C. Direct- and Quadrature-Axis Voltage Equations

The direct- and quadrature-axis voltages in PM machines are primarily a function of rotor speed; and hence, are affected by the synthetic loading 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. Substituting (6) and (15) into (1) and (2) determines the direct- and quadrature-axis voltages during synthetic loading as

$$V_d = -PL_q\left(1 + \frac{R_a}{R_c}\right)\left(I_m \sin(2\pi f_n t) + I_o\right) \times \left[\frac{k_t I_o}{B} + \frac{k_t I_m / J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}} \sin(2\pi f_n t - \phi)\right] \quad (20)$$

$$V_q = R_a I_m \sin(2\pi f_n t) + R_a I_o + L_q I_m (2\pi f_n)\left(1 + \frac{R_a}{R_c}\right)\cos(2\pi f_n t) + P\left(1 + \frac{R_a}{R_c}\right)(L_d i_d + \lambda_m) \times \left[\frac{k_t I_o}{B} + \frac{k_t I_m / J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}} \sin(2\pi f_n t - \phi)\right]. \quad (21)$$

Using Park's transformation, we have

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (22)$$

where V_a, V_b, and V_c are the stator phase voltages of the PM synchronous machine, the instantaneous phase and line voltage requirements can be determined; hence, the minimum dc-link voltage can be identified.

D. Direct- and Quadrature-Axis Stator-Current Equations

The direct- and quadrature-axis stator-current equations are necessary to calculate input power. Furthermore, from them the stator phase current can be determined hence the stator copper loss and the inverter volt-ampere rating.

1) Direct-Axis Stator-Current Algorithm: From Fig. 1(a), the direct-axis stator current is

$$i_{ds} = i_d + i_{dc} \quad (23)$$

where $i_{dc} = -P\omega_r(L_q i_q / R_c)$ and $di_d/dt = 0$. Therefore, by substituting the equations for i_{dc}, i_q, and ω_r from (6) and (15) into (23), the direct-axis stator current is then

$$i_{ds} = i_d - P\frac{L_q}{R_c}k_t\left(I_m \sin(2\pi f_n t) + I_o\right) \times \left[\frac{I_o}{B} + \frac{I_m / J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}} \sin(2\pi f_n t - \phi)\right]. \quad (24)$$

2) Quadrature-Axis Stator-Current Equation: From Fig. 1(b), the quadrature-axis stator current is

$$i_{qs} = i_q + i_{qc} \quad (25)$$

where $i_{qc} = P\omega_r\left(L_d i_d + \lambda_m\right)/R_c$. Therefore, substituting the equations for i_{qc}, i_q, and ω_r from (6) and (15) into (25) gives

$$i_{qs} = I_m \sin(2\pi f_n t) + I_o + P\frac{(L_d i_d + \lambda_m)}{R_c}k_t \times \left[\frac{I_o}{B} + \frac{I_m / J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}} \sin(2\pi f_n t - \phi)\right]. \quad (26)$$

Park's transformation can then be used to calculate stator phase 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. Simulation of Synthetic Loading

Simulation is used to predict the losses and confirm the required synthetic loading frequency, f_n, and associated parameters I_o and I_m given a moment of inertia, *J*, and damper factor, *B*. This then provides an estimate of the required peak current rating, minimum dc-link voltage requirement and inverter VA rating. During synthetic loading, only the input power to the PM synchronous machine is measured. The dynamic model for the PM synchronous machine including iron loss resistance in the *dq* model is used [3]–[5], [11]–[14]. Based on this model, synthetic loading is simulated and evaluated for determining the losses and the efficiency of the PM synchronous machine. Synthetic loading is simulated using MATLAB and Simulink

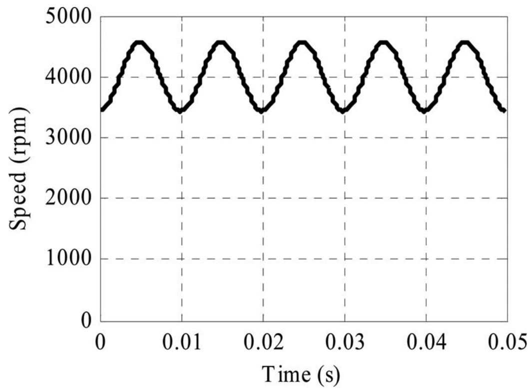

Fig. 2. Speed variation during synthetic loading for 100 Hz under full-load-torque condition.

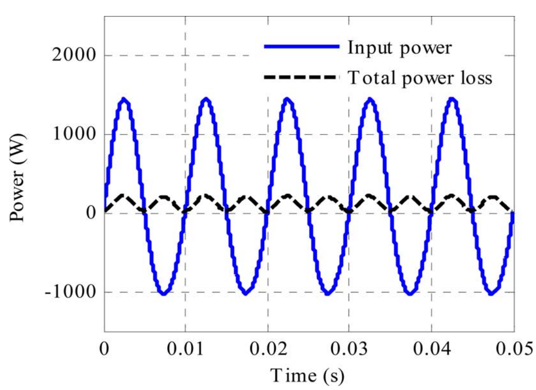

Fig. 3. Input power and total losses during synthetic loading for 100 Hz synthetic loading frequency.

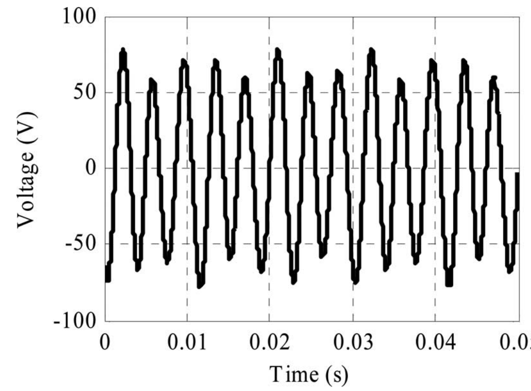

Fig. 4. Phase voltage during synthetic loading for 100 Hz synthetic loading frequency.

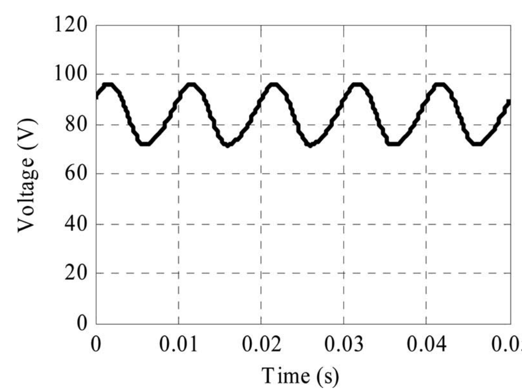

Fig. 5. RMS line-voltage variation during synthetic loading for 100 Hz under full-load-torque condition.

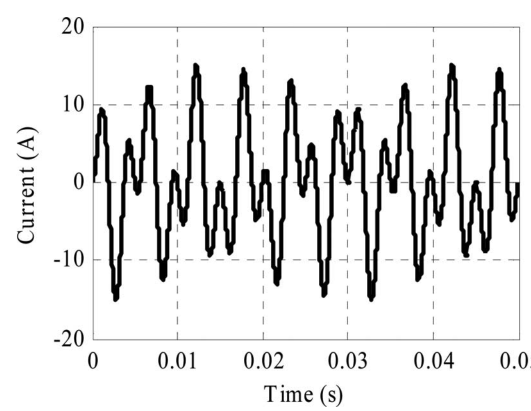

Fig. 6. Phase current during synthetic loading at 100 Hz.

at rated speed and compared with the standard efficiency test method. The parameters of the PM synchronous machine are provided in the Appendix (see Table IV). Different synthetic loading frequencies that force full-load-torque conditions are compared with the standard efficiency test.

Figs. 2–7 illustrate machine waveforms with the machine perturbed with a synthetic loading frequency of 100 Hz. According to (3) and (6), torque is perturbed at 100 Hz, which causes the machine to accelerate and decelerate at this frequency. This is clearly shown in Fig. 2 with the speed varying between 3500 and 4500 r/min at 100 Hz. Although the PM synchronous machine speed varies, the average speed is the rated value, 4000 r/min (1.0 pu). During the acceleration phase, the machine consumes energy from the dc link, as shown in Fig. 3, with energy returned during the deceleration phase. The instantaneous power swings between 1500 and –1000 W during the synthetic loading cycle and has a dc offset that is indicative of the total losses in the machine. Fig. 7 also illustrates the power loss in the machine calculated during the simulation. This is always positive and its average value is controlled by selection of parameters I_o, I_m, and f_n. The average input power over one synthetic loading cycle is equal to the average of the total losses, from which the efficiency can be readily evaluated.

The machine speed is varying, and hence, the magnitude and frequency of the back EMF generated by each phase will also vary. This is predicted by (20)–(22). Fig. 4 clearly illustrates the amplitude modulation whose envelope varies at the synthetic loading frequency. The variation in the frequency component is less obvious but must be occurring due to the change in speed sown in Fig. 2. Fig. 5 shows the instantaneous rms line-voltage variation. Rated rms voltage is 90 V; hence, the instantaneous rms voltage when synthetically loading the machine is exceeds 1.0 pu during the acceleration phase. The machine rms voltage varies according to synthetic loading frequency (100 Hz) and has an average value of 83.2 V (0.93 pu).

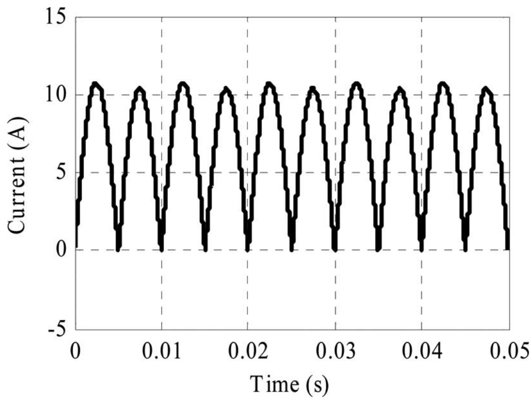

Fig. 7. Instantaneous rms line-current variation during synthetic loading at 100 Hz under full-load-torque condition.

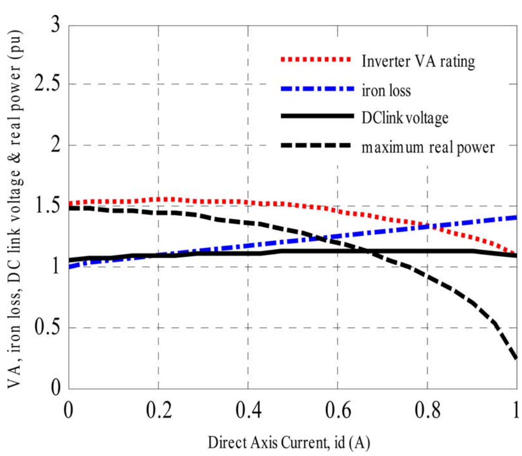

Fig. 8. Impact of direct-axis current on the synthetic loading performance.

Instantaneous phase current and rms line current are shown in Figs. 6 and 7. The phase current is frequency and amplitude modulated, as predicted by (6). The depth of modulation of phase current (see Fig. 6) is much greater than that of the phase voltage as i_q is forced between ± 1.42 pu, whereas the voltage variation due to changes in speed is much smaller. Due to amplitude and frequency modulation of the phase current, the instantaneous rms current is varying with time (see Fig. 7). The average of the instantaneous rms current is the rated rms current of the machine, 7.45 A (1.0 pu) and this ensures rated copper loss. From Fig. 5, the peak of first half cycle of instantaneous rms current (associated with acceleration) is higher than the peak during deceleration. This is a consequence of the dc-offset current. The asymmetry in the peaks of the rms current increases as the configured load is reduced as the dc offset, I_o, becomes a larger proportion of I_m.

Five synthetic loading frequencies that establish full-load-torque conditions are summarized in Table I. In each case, $I_m = 14.9$ A and $I_o = 0.074$ A. Efficiency I is calculated using the input power from the standard efficiency test minus the total losses measured using synthetic loading divided by the input power. Efficiency II is calculated using the rated output power from the machine nameplate divided by the rated output power plus the total losses. The simulation results show that the losses, rms current, and average speed using the synthetic loading technique are consistent with the standard efficiency test method, which indicates that synthetic loading could be used for the evaluation efficiency of the PM synchronous machine.

TABLE I
COMPARISON OF THE STANDARD EFFICIENCY TEST AND THE SYNTHETIC LOADING TECHNIQUE SIMULATION RESULTS UNDER FULL-LOAD-TORQUE CONDITIONS

	Standard Efficiency Test	Synthetic Loading Frequency (Hz)				
		100	105	110	115	120
Rms line voltage (V)	90.0	83.4	83.4	83.5	83.5	83.5
Rms line current (A)	7.45	7.45	7.45	7.45	7.45	7.45
Speed (rpm)	4000	4000	4000	4000	4000	4000
Inverter peak current(A)	10.5	14.9	14.9	14.9	14.9	14.9
Phase-leg volt-ampere (VA)	1365	2086	2086	2086	2086	2086
Minimum dc link voltage (V)	130	140	140	140	140	140
Output power (W)	843.0	-	-	-	-	-
Input power (W)	962.0	117.7	117.7	117.7	117.7	117.7
Stator copper loss (W)	91.6	91.7	91.7	91.7	91.7	91.7
Iron loss (W)	19.8	19.8	19.8	19.8	19.8	19.8
Friction and windage loss (W)	6.1	6.2	6.1	6.1	6.1	6.1
Total losses (W)	117.5	117.7	117.6	117.6	117.6	117.6
Efficiency I (%)	87.8	87.8	87.8	87.8	87.8	87.8
Efficiency II (%)	87.8	87.8	87.8	87.8	87.8	87.8

The stator copper loss, iron loss and friction and windage loss are the same as the standard efficiency test method. This is expected because the stator rms currents and the speed are at rated values. The rms voltages during synthetic loading are lower than the voltage during the standard efficiency test. This is 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 PM synchronous machine is still running at rated electromagnetic motive force (EMF) during synthetic loading.

V. IMPACT OF NONZERO DIRECT-AXIS CURRENT

Generally, the synthetic loading technique for PM synchronous machines would be performed using a vector control technique with the direct-axis current, i_d, set to zero. However, direct-axis current can be used to increase the Ohmic loss; this reduces the I_m requirement in the q-axis current that

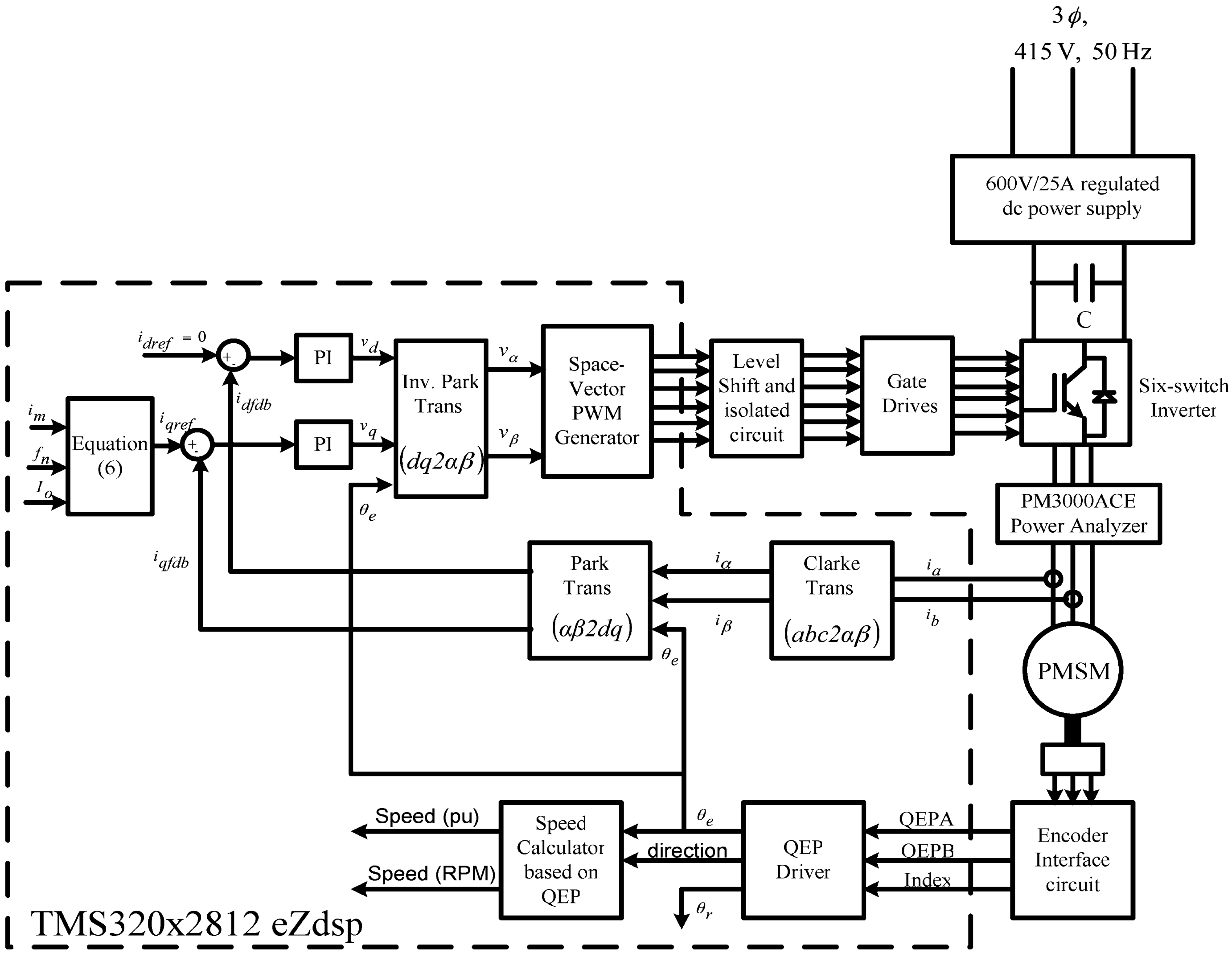

Fig. 9. Block diagram of vector control system for conducting synthetic loading technique.

reduces speed swing. However, if a positive i_d component is injected the iron losses are higher than rated value. Fig. 8 shows how direct-axis current component affects the inverter volt-ampere rating, the dc-link voltage, the maximum real power absorbed, and the iron loss for the test PM synchronous machine. The inverter volt-ampere rating with zero direct-axis current is 1.52 pu, and this gradually decreases as the direct-axis current component is increased. The VA rating falls to a minimum value of 1.13 pu when the direct-axis current is the same as the machine rated current. The dc-link voltage required is 1.1 pu with $i_d = 0$, and then gradually increases to 1.13 pu when the direct-axis current reaches 1.0 pu. This is a consequence of the higher EMF due to the significant contribution direct-axis current makes to the direct-axis flux. Consequently, the iron loss increases by 0.41 pu.

The maximum real power decreases, as shown in Fig. 8. Therefore, injection of direct-axis current decreases the inverter volt-ampere rating required. However, the dc-link voltage required increases and, more importantly, the iron loss exceeds rated value, which leads to an underestimate of the efficiency of the machine. If a negative i_d component was injected the opposite effect would occur with the iron loss underestimated and the efficiency overestimated.

VI. Experimental Results

The simulations show that the synthetic loading technique is a candidate for efficiency evaluation. The experimental tests will confirm this conclusion. The synthetic loading technique is performed experimentally at different values of synthetic loading frequencies and compared with the standard efficiency test. The results demonstrate the accuracy of efficiency evaluation using the synthetic loading technique. The input power, rms line voltage, rms current, the speed of the machine under test, and the output of the load machine are measured. The efficiency of the PM synchronous machine is then calculated.

The test hardware is shown in Fig. 9, which is a simple vector control system. The stator currents i_a and i_b are measured via current sensors and transformed into 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 the errors

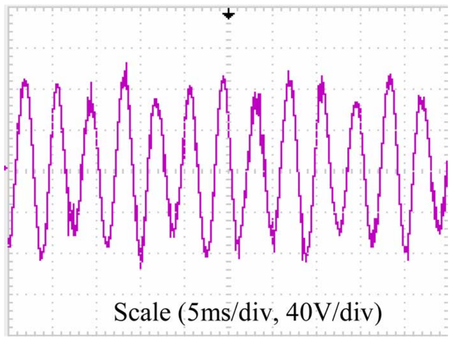

Fig. 10. Phase voltage during synthetic loading for synthetic loading frequency 100 Hz.

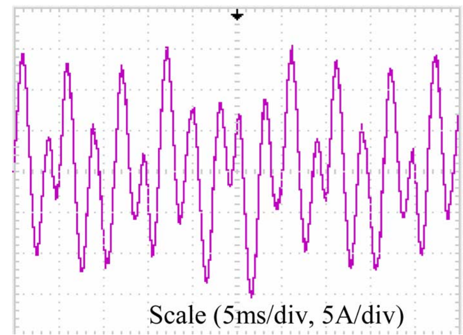

Fig. 11. Phase current during synthetic loading for synthetic loading frequency 100 Hz.

corrected by means of PI current controllers. The outputs of the PI current controllers v_d and v_q are passed through an inverse Park transformation to yield v_α and v_β, and a new stator voltage vector is impressed to the motor using the space-vector modulation technique. The pulsewidth-modulated (PWM) signals are generated by PWM modules that have been configured at 20 kHz with a 2 μs dead band. The interrupt frequency is 20 kHz. The software control is embedded in a TMS320F2812 DSP processor. Measurements are made using a Voltech PM3000 A power analyzer and high bandwidth Hall-effect current and voltage sensors.

Figs. 10–13 show phase voltage, phase current, shaft speed, and input power during synthetic loading with a frequency of 100 Hz. Many of the salient features identified in the simulation results are evident in the practical waveforms with good correlation between simulation and experimental results. The amplitude and frequency modulation of the phase voltage and phase currents is clear. The phase voltage is amplitude modulated at 33.3 Hz. Note that with this set of conditions the shaft speed varies between 233.3 Hz minimum and 300 Hz maximum [4], and this speed variation takes place at 100 Hz. The resultant apparent modulating frequency during synthetic loading at 100 Hz is then 33.3 Hz. In the phase-voltage reference frame, synthetic loading is similar to frequency modulation as the phase voltage frequency is linearly dependent on the rotor speed which itself is being sinusoidally modulated. Similarly, the phase-voltage magnitude is linearly dependent on the rotor speed. Hence, the phase voltage is both amplitude and frequency modulated. The experimental results in Fig. 10 correlate well with the simulation results in Fig. 4.

The instantaneous phase current during synthetic loading for a synthetic loading frequency of 100 Hz is illustrated in Fig. 11. The peak current during synthetic loading is 14.85 A (1.42 pu) and the average rms current is 7.5 A (1.0 pu)—this confirms that the PM synchronous machine is developing rated torque. The characteristics of the phase currents are the same as the simulated instantaneous currents, Fig. 6 particularly that the depth of modulation is large compared to the phase voltage.

The speed and instantaneous input power during the synthetic loading experiment are shown in Figs. 12 and 13 both of which vary at the synthetics loading frequency. The average

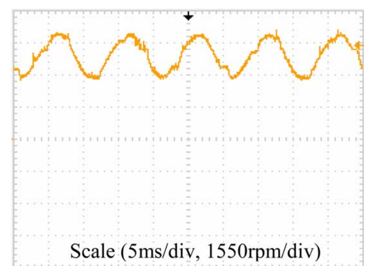

Fig. 12. Speed variation during synthetic loading for synthetic loading frequency 100 Hz.

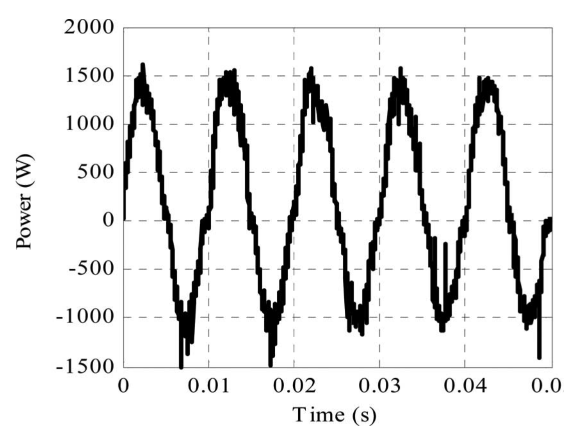

Fig. 13. Input power variation during synthetic loading for synthetic loading frequency 100 Hz.

rotor speed over one synthetic loading cycle equals the rated speed (4000 r/min). The peak value of accelerating power is higher than the peak value of decelerating power; hence, the average input power over one synthetic loading cycle is positive and equals the total losses.

The standard efficiency test and the synthetic loading technique at five different synthetic loading frequencies are compared in Table II. The efficiency obtained from the synthetic loading technique is comparable to the standard efficiency test. Efficiency I for the standard efficiency test under full-load conditions is 87.0%. The synthetic loading technique produces efficiencies between 86.7% and 86.9% when the input power of the standard efficiency test is used to calculate the efficiency. Therefore, synthetic loading underestimates the efficiency by

TABLE II
COMPARISON OF THE STANDARD EFFICIENCY TEST AND THE SYNTHETIC LOADING TECHNIQUE RESULTS UNDER FULL-LOAD-TORQUE CONDITION

	Standard Efficiency Test	Synthetic Loading Frequency (Hz)				
		100	105	110	115	120
Rms line voltage (V)	95.4	94.7	94.4	94.6	95.1	95.4
Rms line current (A)	7.45	7.42	7.4	7.4	7.43	7.42
Inverter peak current (A)	10.5	14.85	14.85	14.85	14.85	14.85
Phase-leg VA rating (VA)	1601	2421	2443	2450	2465	2480
Minimum dc link voltage (V)	152.5	163.0	164.5	165.0	166.0	167.0
Speed (rpm)	4000	4000	4000	4000	4000	4000
Input power (W)	988.1	130.3	129.6	129.0	131.1	130.5
Output power (W)	859.5	-	-	-	-	-
Total losses (W)	128.6	130.3	129.6	129.0	131.1	130.5
Efficiency I (%)	87.0	86.8	86.9	86.9	86.7	86.8
Efficiency II (%)	86.8	86.6	86.7	86.7	86.5	86.6

less than 0.1% at best, 0.3% at worst, and 0.2% on average. Efficiency II for the standard efficiency test is 86.8% and for the synthetic loading technique are between 86.5% and 86.7%. From Table II, Efficiency II, using rated output power to calculate the efficiency, is lower than the Efficiency I measure by 0.2%.

An inverter is used during both the standard efficiency test and the synthetic loading technique. This inverter has minimum requirements in terms of minimum dc-link voltage, minimum peak current, and minimum peak VA. As predicted through simulation, these are all higher than that required for the standard efficiency test. For example, the minimum dc-link voltage required is 165.0 V (1.1 pu compared with the standard efficiency test), the minimum peak current required is 14.85 A (1.41 pu), and the minimum inverter phase-leg VA rating required is 2450 VA (1.53 pu) at 110 Hz.

The efficiency figures from the experiment and from simulation are compared in Table III. The results show that the simulated efficiencies are higher than the experimental efficiencies in each case. The simulation does not model some important loss components associated with switching-frequency-induced current ripple and core loss, and this is the primary contribution to the difference between the results. For this technique, however, close correlation between simulation and experiment is not a requirement.

TABLE III
COMPARISON OF THE SYNTHETIC LOADING SIMULATION AND EXPERIMENTAL RESULTS FOR THE PM SYNCHRONOUS MACHINE UNDER FULL-LOAD-TORQUE CONDITIONS

Synthetic Loading Frequency (Hz)	Full Load Conditions Efficiency (%)	
	Simulation results	Experiment results
100	87.8	86.8
105	87.8	86.9
110	87.8	86.9
115	87.8	86.7
120	87.8	86.8
Standard efficiency test	87.8	87.0

The simulated waveforms for the current, voltage, input power, and rotor speed are close to experimental quantities for this PM synchronous machine. The surface-mount machine considered in this paper is a high-speed, low-power machine with an inverter and controller, which operates at a high switching frequency (20 kHz). However, for high-power and lower speed machine, an inverter and controller with lower switching frequencies are typically used. This leads to higher losses related to switching frequency current harmonics that distort the current waveform [15]–[17]. Furthermore, the parameters of large machines can be more difficult to obtain with the accuracies needed for the precise vector control required.

The technique, therefore, requires further assessment with higher power machines. The power generated by the machine during deceleration is stored in the dc-link capacitor and can be returned to the supply if an active front end is utilized. This further reduces the losses associated with the test. Often, the capacitor is sized sufficiently to absorb the regenerated energy but, if not, the power swing in higher power machine drives may interfere with the source bus which is usually not acceptable to utilities [15].

VII. CONCLUSION

Synthetic loading as a technique for efficiency evaluation of PM synchronous machine has been assessed through simulation and experiment. The technique is able to identify the total losses in the machine. The simulation technique using the developed equations can determine the optimum synthetic loading frequency. It is shown that synthetic loading causes the machine to produce rated power losses. The individual loss components 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.

The effect of direct-axis current on the inverter volt-ampere rating, the dc-link voltage required, maximum real power, and iron loss during synthetic loading has been investigated. The effect of direct-axis current on the synthetic loading performance shows that increasing the direct-axis current results in a lower inverter volt-ampere rating, but leads to a higher dc-link voltage requirement during synthetic loading, hence higher iron loss. This leads to a significant underestimate of the efficiency during the synthetic loading technique. Synthetic loading simulation and experimental results give excellent agreement with the standard efficiency test method.

APPENDIX

TABLE IV
ELECTRICAL AND MECHANICAL PARAMETERS OF THE SURFACE-MOUNT PM SYNCHRONOUS MACHINE

Parameters	Values
Rated output power	843 W
Rated peak current	10.5 A
Rated speed	4000 rpm
Maximum Bus Voltage	340 V
Armature resistance, R_a	0.55Ω
Core loss resistance, R_c	300Ω
Quadrature axis inductance, L_q	0.65 mH
Direct axis inductance, L_d	0.65 mH
Moment of inertia, J	7.85×10^{-5} kg.m^2
Damping coefficient, B	3.47×10^{-5} Nms^{-1}
Total Permanent magnet flux linkage, λ_m	37.7 mWb
Number of poles	8

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