The Effect of Direct Axis Current on the Performance of the Synthetic Loading Technique

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***Abstract*—Synthetic loading is a technique that forces the machine under test to operate at rated speed, torque, and flux without the need for the test machine to be connected to an external load. The technique has been successfully applied to permanent magnet machines but it requires an inverter voltampere (VA) rating that is 1.51 pu of the rated value due to the need for instantaneous phase currents and voltages that are higher than the rated value. In order to reduce the VA rating, it is possible to inject direct axis current. This has important consequences. It reduces the ac perturbation current thereby reducing the peak instantaneous phase current. Also, by reducing the ac perturbation current, the rotor speed variation is reduced, thereby reducing the instantaneous phase voltage requirement. Both these effects reduce the VA rating of the inverter. However, this paper demonstrates through simulation and experiment that such a scheme increases the iron losses in the machine. This is important as it alters the distribution of losses which is not a desired consequence. The effect of direct axis current on the iron loss and the machine efficiency during synthetic loading is assessed and evaluated as is the effect on the minimum dc link voltage and the inverter VA requirements used to conduct the synthetic loading technique. Simulation and experimental results are used to demonstrate the effects and validate the conclusions that while direct axis current injection reduces the inverter VA rating, it reduces the accuracy of the synthetic loading technique.**

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

I. Introduction

THE traditional 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 large vertical machines [1]–[4]. Furthermore, the method requires the removal of the test machine from the set, 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 addresses the application of synthetic loading to the permanent magnet (PM) synchronous machines. During rated-load efficiency test, the machine must draw its full load current at rated voltage and speed. Synthetic loading can do this without connecting a mechanical load to the machine drive shaft [5]–[8]. 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 consequence to rated speed.

Synthetic loading has successfully been performed on surface-mount PM machines with the direct axis current forced to zero. The technique then perturbs the quadrature axis current to force rated torque and rated speed, on average, over a synthetic loading cycle. The motor is then operated under rated conditions without the need for an external load. However, a drawback of the technique is that it requires a dc link voltage and inverter current rating higher than the rated value. In this paper, the impact of injecting direct axis current on the machine iron loss and the inverter voltage and current rating is assessed. It is shown that injecting direct axis current reduces the required VA rating of the inverter but affects the distribution of losses in the machine leading to an underestimate of the machine efficiency.

During synthetic loading, the machine terminal voltage and the rotor speed must be equal on average to the rated values. The synthetic loading method discussed here is a current control method; therefore, the knowledge of the rotor speed is not necessary. Section II presents the synthetic loading technique. The mathematical equations of the synthetic loading technique are developed in section III. The experimental setup is presented in section IV. The experimental and simulation results of the synthetic loading technique with direct axis current, and the standard efficiency test, for the PM synchronous machine under test, are presented in Section V. Section VI draws conclusion.

II. Synthetic Loading Technique

Synthetic loading is 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 [9], [10]. 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 [11].

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 [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 rotor speed with rated rms phase current; therefore, rated

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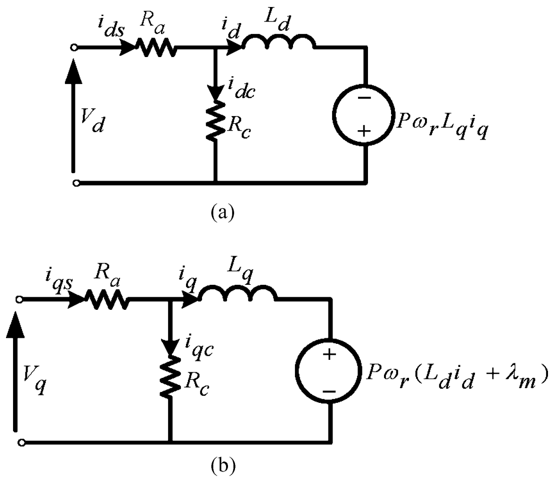

Fig. 1. (a) d- and (b) q-axis steady-state equivalent circuit of the PM synchronous machine.

flux, frequency, and current conditions prevail with their associated loss components. The synthetic loading method for the PM machine is a current control method. The investigation of the impact of synthetic loading on dc link voltage rating shows that a 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 VA 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.

III. Modeling Synthetic Loading

The mathematical model of the synthetically loaded PM synchronous machine is based on the dq equivalent circuits in the synchronously rotating reference frame (see Fig 1) [12]–[17].

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

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

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

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 loss resistances, respectively;
L_d and L_q	d- and q-axis inductances, respectively;
λ_m	permanent magnet flux linkage;
ω_r	rotor speed and P is the number of pole pairs.

The electromagnetic torque, T_e, developed by the rotor is

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

The speed equation is

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

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

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

A. Quadrature Axis Current

The torque producing current, i_q, is designed to have a small dc offset, I_o, with a much larger ac perturbation of magnitude I_m with a (synthetic loading) frequency f_n

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

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_{eav}, balances only the torque due to friction and windage; hence,

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

where $k_t = 3/2P\lambda_m$ is the machine torque constant in (N·m/A) and B is the damper coefficient in (N·m·s), P is the number of pairs of poles, λ_m is the linkage flux, and ω_{ro} is the rated steady-state rotor speed.

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

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

That is, 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 the rated current during synthetic loading, assume that the magnitude of i_{dc} and i_{qc} is small compared to i_d and i_q

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

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

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

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 phase current, i_d is the chosen value of the injected direct axis current, and I_o is the quadrature axis current required to achieve the rated speed. The direct axis current, i_d, is typically zero, but in this research, nonzero values are investigated in order to understand the impact it has on the accuracy of the synthetic loading technique. As i_d is increased, the value of I_m required to force the rated phase current decreases.

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

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

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

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

C. Direct and Quadrature Axis Current and Voltage Equations

From the PM synchronous machine-equivalent circuits and the required *dq* axis currents, equations for the rotor speed and the direct and quadrature axis voltage are derived using the machine's electrical and mechanical parameters. Expressions for the average input power, copper, iron, and mechanical losses during one synthetic loading cycle can then be derived. The average input power is equal to the sum of the losses. The core loss current components, i_{dc} and i_{qc}, are

$$\begin{aligned}i_{dc} &= -P\frac{L_q}{R_c}k_t (I_m \sin(2\pi f_n t) + I_o)\\ &\quad \times \left[\frac{I_o}{B} + \frac{I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \phi)\right]\\ &\approx \frac{-P}{R_c}\frac{I_o}{B}k_t [L_q (I_m \sin(2\pi f_n t) + I_o)] \quad (16)\end{aligned}$$

and

$$\begin{aligned}i_{qc} &= P\frac{(L_d i_d + \lambda_m)}{R_c}k_t\\ &\quad \times \left[\frac{I_o}{B} + \frac{I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \phi)\right]\\ &\approx \frac{P}{R_c}\frac{I_o}{B}k_t [L_d i_d + \lambda_m] \quad (17)\end{aligned}$$

and the core loss is

$$P_{co} = \frac{3}{2}R_c(i_{dc}^2 + i_{qc}^2). \quad (18)$$

From (17), i_{qc} increases as i_d increases which leads to increased core loss associated with the q-axis circuit. From (16), i_{dc} is a function of the ac perturbation, I_m, and I_m decreases as i_d increases. Therefore, the contribution to core loss from the d-axis circuit reduces as i_d is increased, but the reduction d-axis core loss is much less than the corresponding increase in q-axis core loss (the q-axis back electromagnetic motive force (emf) is much larger than the d-axis back emf due to the permanent magnet flux); therefore, there is an increase in the total core loss. This is an important consequence of injecting i_d as it increases the total core loss, and therefore, alters the distribution of copper and core loss in the machine.

If the i_{qc} component increases, it is expected that V_q and i_{qs} will also increase (see Fig. 1). On the d-axis, if i_{dc} decreases, V_d and i_{ds} would be expected to decrease. Equations for V_d and V_q can be derived

$$\begin{aligned}V_d &= R_a i_d - PL_q\left(1 + \frac{R_a}{R_c}\right)(I_m \sin(2\pi f_n t) + I_o)\\ &\quad \times \left[\frac{k_t I_o}{B} + \frac{k_t I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \varphi)\right]\end{aligned} \quad (19)$$

and

$$\begin{aligned}V_q &= R_a I_m \sin(2\pi f_n t) + R_a I_o\\ &\quad + L_q I_m (2\pi f_n)\left(1 + \frac{R_a}{R_c}\right)\cos(2\pi f_n t)\\ &\quad + P\left(1 + \frac{R_a}{R_c}\right)(L_d i_d + \lambda_m)\\ &\quad \times \left[\frac{k_t I_o}{B} + \frac{k_t I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \varphi)\right] \quad (20)\end{aligned}$$

with the peak phase voltage given by

$$V_{\text{phase,peak}} = \sqrt{V_d^2 + V_q^2}. \quad (21)$$

In a similar fashion to the core loss current components, i_{qc} and i_{dc}, as i_d is increased, the peak V_q required also increases, leading to a higher peak phase voltage requirement.

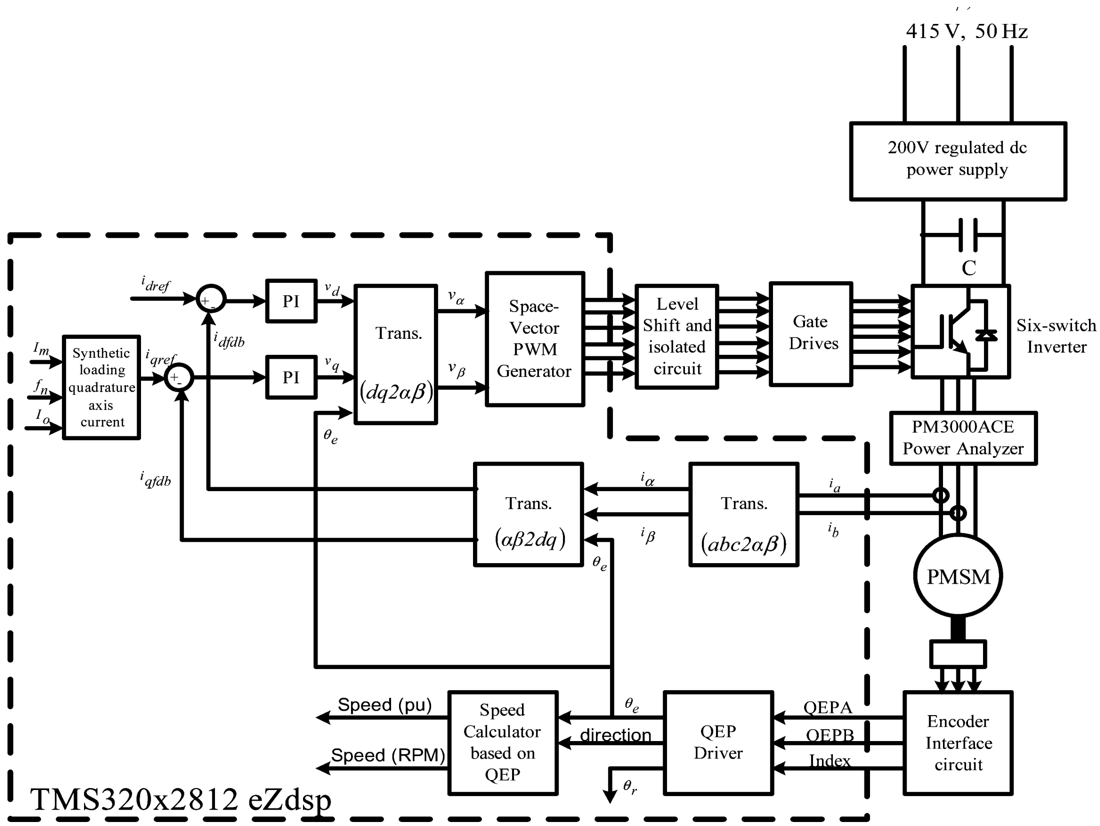

Fig. 2. Block diagram of vector control system for conducting the synthetic loading technique.

A similar argument holds for the peak phase current where

$$i_{ds} = i_d - P\frac{L_q}{R_c}k_t\left(I_m\sin(2\pi f_n t) + I_o\right) \times \left[\frac{I_o}{B} + \frac{I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \phi)\right] \quad (22)$$

and

$$i_{qs} = I_m\sin(2\pi f_n t) + I_o + P\frac{(L_d i_d + \lambda_m)}{R_c}k_t \times \left[\frac{I_o}{B} + \frac{I_m/J}{\sqrt{(2\pi f_n)^2 + (B/J)^2}}\sin(2\pi f_n t - \phi)\right]. \quad (23)$$

The dependences of core loss, $|V_{dq}|$, and $|i_{dq}|$ on i_d are demonstrated by (17)–(23). As i_d increases, the i_{qc} current, the peak quadrature axis voltage, V_q, and the stator quadrature axis current, i_{qs}, increase, respectively. This leads to higher core loss and higher dc link voltage. However, the ac perturbation, I_m, decreases leading to lower inverter VA rating and lower variation in peak-to-peak speed, rms voltage, and current.

IV. Experimental Setup

Fig. 2 shows the hardware required for synthetic loading. Two stator currents i_a and i_b are measured by current sensors. A *dq* transformation is applied to obtain the rotating reference frame quantities i_d and i_q. i_d and i_q are compared to their reference values i_{qref} and i_{dref} and corrected by means of PI current controllers. The "reference current generator" block calculates the required i_{ds} and i_{qs} components using the desired synthetic loading parameters (i_{dref}, I_m, f_n, and I_o). The reference values reflect the quantities in (22) and (23).

The outputs of the current controllers v_d and v_q are transformed and a new stator voltage vector is impressed on the motor using the space vector modulation technique. The pulse width modulation (PWM) signals are generated by the PWM modules with a 20 kHz switching frequency and a 2-μs deadband. The sample frequency is also 20 kHz. A TMS320×2812 DSP is used as the core of the drive system.

Two 12-bit analog to digital converter channels are used to sample the two phase currents. One of two available quadrature encoder channels is used for the position encoder. The digital signal processing is programmed using the Spectrum Digital eZdsp development environment with Code Composer Studio. The block diagram of the vector controller implementation is shown in Fig. 2.

V. Experimental and Simulation Results

In order to assess the effect of direct axis current, the synthetic loading technique is performed experimentally with a range of direct axis currents (0–1 pu). These are then compared with simulation results and with the standard efficiency test.

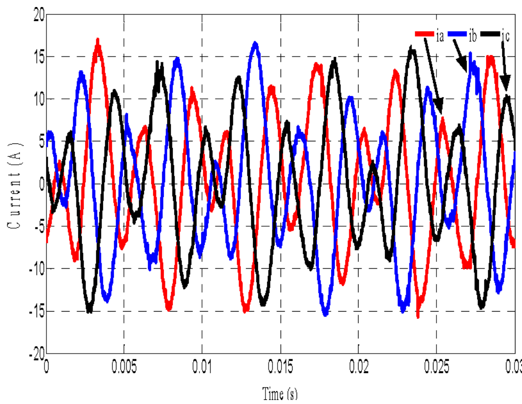

Fig. 3. Instantaneous phase currents with $i_d = 0$ A during synthetic loading at full load and 100 Hz synthetic loading frequency.

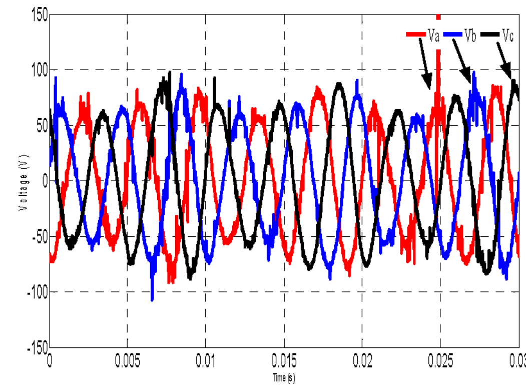

Fig. 4. Instantaneous phase voltage with $i_d = 0$ A during synthetic loading at full load and 100 Hz synthetic loading frequency.

Comparison between the simulation and experiment results shows that the iron loss increases with direct axis current increase. Consequently, the efficiency is underestimated. The required dc link voltage increases but the inverter VA rating decreases. The parameters of the PM synchronous machine are provided in the Appendix.

In order to compare synthetic loading simulation results with experimental results, the simulated quantities for iron loss, required inverter VA, and required dc link voltage are superimposed onto the experimental results. Fig. 3 shows the instantaneous phase current with zero direct axis current; it has a peak value of 15.2 A (1.42 pu) and the average rms current is 7.52 A (1.0 pu). The instantaneous phase currents with $i_d = 10.5$ A are sinusoidal and have no variation in frequency or amplitude. They have a peak value of 10.5 A (1 pu) and an average rms current of 7.5 A (1.0 pu). This clearly shows the decrease in peak phase current (from 1.42 pu to 1 pu) that is achieved by injecting i_d. This leads to a lower inverter VA rating required during synthetic loading.

Fig. 4 shows the phase voltage waveforms when the direct axis current is zero. During synthetic loading, the instantaneous phase voltage varies in amplitude and frequency. The amplitude envelope of the instantaneous phase voltage varies according to synthetic loading frequency, which in the experimental case is 100 Hz. The peak phase voltage is 72.5 V.

The phase voltages when the direct axis current is 10.5 A during synthetic loading are sinusoidal; there is no variation in amplitude and frequency. However, the peak phase voltages are higher at 90.5 V compared to the case with zero direct axis current. This occurs as the direct axis current induces additional direct axis flux, thereby, increasing the air-gap flux.

During a synthetic loading cycle with no direct axis current, the rotor speed varies sinusoidally at 100 Hz with a peak-to-peak variation of 780 rpm and an average value of 4000 rpm. With 10.5 A direct axis, there is no speed variation around the rated speed of 4000 rpm. Therefore, injecting a direct axis current component results in a reduction in the speed swing. With rated direct axis current, there is no speed variation.

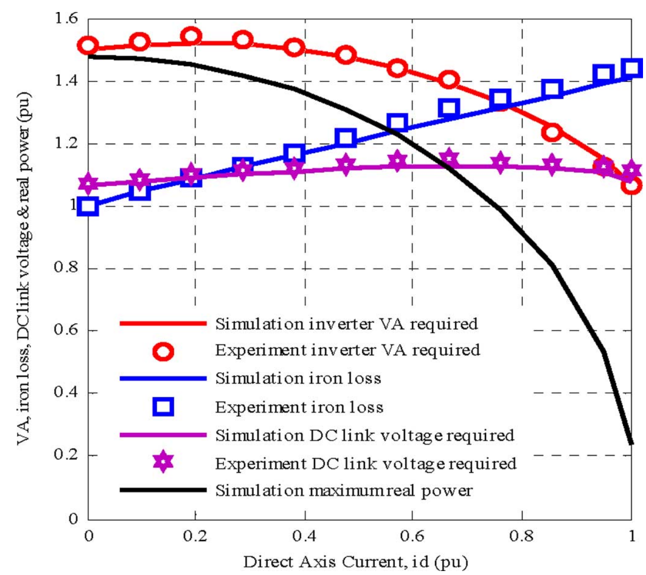

Fig. 5. Impact of direct axis current on the iron loss, inverter VA, inverter dc link voltage and inverter power.

Typically, the synthetic loading technique for PM synchronous machines would be performed $i_d = 0$. However, i_d can be used to reduce I_m that reduces speed swing. However, this results in iron losses higher than the rated value.

Fig. 5 shows the impact of the direct axis current, i_d, on the inverter VA rating required, the dc link voltage, the maximum real power absorbed, and the iron loss for the test PM synchronous machine. Fig. 5 shows that the inverter VA rating and the maximum real power decrease as the direct axis current, i_d, increases. The dc link voltage also increases to a peak and then decreases. The iron loss increases as the direct axis current, i_d, increases.

The inverter VA rating required with zero direct axis current is 1.51 pu for both simulation and experiment and this gradually decreases as the direct axis current component is increased. The VA rating falls to a minimum value of 1.06 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

TABLE I
SYNTHETIC LOADING EXPERIMENTAL RESULTS AT FULL-LOAD TORQUE AND RATED SPEED WITH THE IMPACT OF DIRECT AXIS CURRENT i_d AT 100 HZ SYNTHETIC LOADING FREQUENCY FOR THE PM SYNCHRONOUS MACHINE

	Standard Efficiency Test	Direct axis currents (A) at Synthetic loading frequency 100Hz											
		0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.5
Rms line voltage (V)	95.4	94.7	96.9	98.1	101.1	103.1	105.8	108.2	110.1	111.2	111.2	110.8	110.8
Rms line current (A)	7.45	7.42	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Inverter peak current (A)	10.5	14.85	14.8	14.7	14.4	14.1	13.7	13.2	12.8	12.4	11.85	11.1	10.5
Phase-leg VA rating (VA)	1601	2421	2442	2470	2448	2411	2370	2303	2246	2133	1979	1802	1704
Minimum dc link voltage (V)	152.5	163.0	165.0	168.0	170.0	171.0	173.0	174.5	175.5	172.0	167.0	162.3	162.3
Speed (rpm)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Input power (W)	988.1	130.3	131.8	133.0	134.5	136.2	137.6	138.8	140.0	140.8	141.6	144.8	145.5
Output power (W)	859.5	-	-	-	-	-	-	-	-	-	-	-	-
Total losses (W)	128.6	130.3	131.8	133.0	134.5	136.2	137.6	138.8	140.0	140.8	141.6	144.8	145.5
Iron losses (W)	23.1	24.8	25.3	26.5	27.5	28.7	30.1	31.3	32.5	33.3	34.1	35.3	36.5
Efficiency (%)	87.0	86.8	86.7	86.5	86.4	86.2	86.1	86.0	85.8	85.8	85.7	85.4	85.3

increases to 1.15 pu when the direct axis current reaches 0.67 pu and then decrease again to 1.1 pu at 1.0 pu direct axis current. This is a consequence of the higher emf due to the significant contribution of direct axis current to the direct axis flux. Consequently, the iron loss increases by 0.41 pu (simulation) and 0.47 pu (experiment). The increase in direct axis current results in a decrease in the quadrature axis current perturbation in order to force the rated current.

Fig. 5 indicates that the maximum real power decreases as i_d increases. However, the dc link voltage increases due to the increased peak phase voltage (a consequence of the increase in iron loss). Hence, the efficiency of the machine is underestimated and the distribution of losses in the machine altered.

Table I presents the experimental results of the standard efficiency test and synthetic loading technique for the rated torque and speed condition and different values of direct axis current (0–10.5 A). The total losses are evaluated and the efficiency is calculated. The iron loss is calculated by subtracting the temperature-compensated ohmic loss and the mechanical loss from the total input power. The inverter phase-leg VA rating required during synthetic loading technique is 2421 VA (1.51 pu) with zero direct axis current. This gradually decreases as the direct axis current increases and falls to 1704 VA (1.06 pu) at 1 pu direct axis current. The efficiency with zero direct axis current is 86.8% and this falls to 85.3% with 1 pu direct axis current. Injection of direct axis current underestimates the efficiency of the machine compared with standard efficiency test and the synthetic loading technique with zero direct axis current.

The inverter has minimum requirements in terms of dc link voltage, peak current, and peak VA and these quantities are higher than that required for the standard efficiency test. However, injecting direct axis current decreases the requirements. The minimum dc link voltage required is 162.3 V (1.1 pu compared with the standard efficiency test), the minimum peak current required is 10.5 A (1.0 pu), and the minimum inverter phase-leg required is 1704 VA (1.06 pu) at 100 Hz synthetic loading frequency and 1 pu direct axis current. However, the iron loss increases from 24.8 W with zero direct axis current to 36.5 W at 1 pu direct axis current. From Table I, the rms line voltage increases as the direct axis current increases. The rms line voltage at 10.5 A (1.0 pu) direct axis current is 110.8 V compared to 94.7 V at 100 Hz synthetic loading frequency with $i_d = 0$. This is due to higher air-gap flux as the result of increasing direct axis current, because i_d contributes an additional flux (18.5%) in the air gap at 10.5 A (1.0 pu). This leads to higher emf voltage thereby higher dc link voltage required for the same synthetic loading frequency 100 Hz.

These experimental results demonstrate the impact of injecting an i_d on the iron losses in the machine. In general, an increase in iron losses is predicted by (16)–(18), but the precise impact needs to be assessed for each machine and is dependent on the machine parameters. The analysis detailed in Section III provides a framework to determine the impact.

VI. CONCLUSION

The effect of direct axis current on the performance of synthetic loading technique has been assessed. It has been shown that increasing the direct axis current component reduces the VA requirement of the inverter to a value that is similar to the standard technique. However, through simulation and experiment, the iron loss is higher when the direct axis current is injected and this leads to an underestimate of the machine efficiency. This reduces the accuracy of the synthetic loading technique when compared with the standard efficiency test. The increase in iron losses is due to an increase in machine flux caused by the direct axis current. The increase in flux also requires an additional voltage component that has to be provided by an increased dc link voltage. However, there is no speed variation when the direct axis current equals to the rated value of the machine under test. This is as a result of almost no ac perturbation current. Therefore, there is no variation in the peak-to-peak phase voltage and current, but there is higher peak-to-peak phase voltage and lower peak-to-peak phase current compared with that of zero direct axis current. Experimental and simulation results verify this conclusion.

APPENDIX

TABLE II
ELECTRICAL AND MECHANICAL PARAMETERS OF THE PM SYNCHRONOUS MACHINE

Parameters	Values
Rated output power	843 W
Rated peak phase 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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