Effects of uncompensated vector control on synchronous reluctance motor performance

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Abstract – The performance of a synchronous reluctance motor digital controller based on a saturated dq model without compensation for slotting and iron loss influences is investigated. The model predictions for the machine torque characteristics at various speeds including standstill, and the effects of using simplified control strategies are verified by experimental results. Issues related to the low cost software implementation of the control algorithm are discussed. Quality speed control of an axially-laminated machine has been achieved.

Keywords – Reluctance motor drives, Programmable control, Observers, Estimation, Error analysis.

I. INTRODUCTION

The main limitation of rotor oriented vector controllers for the cageless inverter-fed synchronous reluctance machine (Synrel) using the ideal Park's dq model is the absence of magnetic saturation and iron losses [1]. In a real machine, however, optimal current angles may differ significantly from their ideal values [2]. Furthermore, the model itself ignores stator slotting which is yet another discrepancy with reality. Therefore, in order to achieve optimum machine performance these practical effects have to be considered in the control algorithms. The example Synrel used in this paper has an axially laminated rotor, but the same general principles found in the following discussion carry over to other designs.

Synrels are characterised by minimal saturation along the rotor q -axis, as the flux path is dominated by air. Consequently, the L_q inductance is very small and almost constant under all operating conditions. The high permeance d -axis, on the other hand, usually shows significant saturation, particularly at small current angles, and can substantially reduce

the L_d inductance. While control is more realistic by including L_d variations, it is still uncompensated in terms of core losses and therefore the machine capabilities can not be fully utilised [2].

Iron losses in the Synrel occur in both the stator and rotor core. The stator losses are of similar origin to those in a conventional induction machine. The rotor would ideally be lossless if the flux waveform was a pure sinusoid. In reality, the machine can be subjected to high-frequency flux changes (especially if not optimally designed) as the rotor axial laminations interact with the stator teeth [3, 4]. However, due to difficulties in measuring and modelling high harmonic flux losses, they are normally neglected and only stator losses are accounted for in the saturated model [2, 5]. The use of a real model allows decoupled vector control improving the machine transient performance and efficiency [5–8]. In some of this work L_d is assumed operating point independent [6, 7] or a disadvantage is that the compensated control scheme is not practically implemented [6].

Another side effect of the laminations-teeth interaction, which deteriorates the control model quality, is the inductance harmonics and consequent torque ripple [6, 9]. The control accuracy can be increased by using expressions for dq inductances incorporating the fundamental component of inductance ripple derived from torque measurements [6]. An alternative solution is to precompute the desired optimal torque characteristic of the machine applying the co-energy based finite-element method proposed in [9, 10] and then store the obtained results in a look-up table. An important advantage of this approach over the conventional dq theory is the possibility of predicting the torque fluctuations from the saturation curves.

The purpose of this paper is to examine the practical effects of uncompensated stator slotting and iron losses on control and performance of an axially-laminated machine, and to present a real-time implementation of a Synrel control scheme using software floating point arithmetic. A cost effective control system design has been obtained with the use of a fast PC processor and off-the-shelf digital hardware. A nice feature of this platform is that it allows high quality control at lower cost compared to a DSP based counterpart.

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II. VECTOR CONTROLLER

The Syncrel control algorithm in Fig. 1 relies on a saturated Park's $d-q$ model without iron loss resistors. It is fully implemented in software written in 'C' using a Pentium PC and two I/O boards with interrupt capabilities - the control board and A/D board (for more detail refer to Appendix). The functions carried out by the corresponding interrupt service routines are mainly as follows.

Fig. 1. Syncrel Speed Controller

The 'DMA complete' interrupt routine essentially serves as an interface to the A/D converter hardware which samples the two machine currents (i_{am} and i_{bm}) and dc link voltage (V_{dc}) at 130-kHz (approximately 43-kHz per channel as the board is multiplexed). It sets up the board for the new set of A/D conversions and converts digital measurements, transferred to the PC memory using DMA, into floating point numbers. The use of DMA data transfer has allowed a significant reduction in the control execution time as the processor had to handle only a single interrupt from the A/D card in one control interval.

The task of the control interrupt routine is to compute and output the machine control for the next interval to the control board hardware. This is achieved by running the control scheme in Fig. 1 at the rate programmed to the interrupt timer (see Appendix). The control rate and the number of samples should be appropriately chosen by the user to ensure that both control and DMA interrupt routines are executed before the next control interrupt occurs. The routine performs the following major control actions.

Samples are firstly averaged to enable the dq currents (i_d and i_q) used in the control procedure to be calculated. Note that only two stator currents are measured as the test Syncrel has no neutral connection. The average dq currents are computed by using the rotor d -axis position corresponding to the middle of the previous control interval (this represents the mean value of encoder measurements at the current and

previous control sampling instants, e.g. $\theta_{m,k}$ and $\theta_{m,k-1}$) in order to compensate for the dq frame movement to be discussed later. The use of averages has the advantage of helping filter out the noise effects in the measurements. Furthermore, they are more representative in terms of the machine shaft performance as the machine reacts to the average and not instantaneous torque values.

The angular velocity (ω) is estimated from the rotor position $\theta_{m,k}$ and the electromagnetic torque from the model $\tau = 3[L_d(i_d) - L_q]i_d i_q$ by using a closed-loop load model based observer [11]. An observer is also employed to accurately predict the rotor position (θ) required for generating the PWM waveform for the next interval. It effectively eliminates quantization errors present with incremental or digital absolute position encoders (particularly at low speeds), and more importantly allows almost instantaneous estimates which is essential for high performance control.

Simple Euler's approximations to the machine differential equations are used for the dq current prediction :-

$$\left. \begin{aligned} i_{dp} &= i_d + \frac{u_d - Ri_d + \omega L_q i_q}{L_d(i_d) + L_q(i_d)} \Delta \\ i_{qp} &= i_q + \frac{u_q - Ri_q - \omega L_d i_d}{L_q} \Delta \end{aligned} \right\} \quad (1)$$

where $\Delta \equiv$ time of one control interval, and $L'_d(i_d) = dL_d/di_d$. Note that the dq voltages (u_d and u_q) are the outputs of the conventional anti-windup PI current loops (one for each rotor axis) evaluated in the previous control interval. The Syncrel parameters used in (1) are obtained by off-line testing as outlined in the Appendix. The values of R and L_q are assumed constant whereas the measurement results for the saturation curve, L_d vs i_d and L'_d vs i_d , are stored in a look-up table.

The preceding equations imply that the rotor position remains unchanged over the control interval. This assumption is justified as Δ is usually small ($333\mu s$ in this case), the movement of the dq frame being negligible at low speeds. However, with increasing the speed the movement gets more pronounced (at 1500-rpm it is 6° elec) and causes current prediction errors, as shown in Fig. 2. Controller performance can be improved by using the correct values (i_{dp} and i_{qp}) instead of the uncompensated i_{dp_o} and i_{qp_o} as control variables :-

$$\left. \begin{aligned} i_{dp} &= i_{dp_o} \cos d\theta + i_{qp_o} \sin d\theta \\ i_{qp} &= i_{qp_o} \cos d\theta - i_{dp_o} \sin d\theta \end{aligned} \right\} \quad (2)$$

where $d\theta = \omega\Delta$ is the angular shift of the d -axis over Δ . These currents are then employed for determining the state-feedback voltages $u_{dsf} = -\omega L_q i_{qp}$ and $u_{qsf} = \omega L_d(i_{dp}) i_{dp}$ needed to compensate for a cross-coupling between the dq axes due to machine rotational voltages.

The dq voltages to be applied to the machine (u_d and u_q) in the next control interval are produced by the current regulators with circular voltage limiting. The reference currents (i_{dd} and i_{qd}), required for the machine to develop the desired torque τ_d , are subject to the control strategy being implemented. In this paper, the control objective is the maximum

Fig. 2. Rotor frame movement effects

torque per ampere. The optimal i_{dd} vs τ_d characteristic is precomputed using Matlab® and stored in a look-up table.

A PWM generator is based on the space vector algorithm with double-edged modulation [12] and dead-time compensation [13]. The switching times for inverter legs are programmed into the appropriate timers on the control board as outlined in the Appendix.

III. EXPERIMENTAL RESULTS

Experimental results have been generated for a 5.8-kW axially-laminated Synrel by executing the control with and without the angular velocity feedback at a 3-kHz rate as illustrated in Fig. 1. The desired orientation of the current phasor in the dq frame is specified on-line by assigning its magnitude and an angle relative to the high permeance d -axis. In order to evaluate the accuracy of the machine model used in the torque controller, the computer results (estimates) from the control algorithm are also presented.

Fig. 3 plots the torque transducer measurements obtained by conducting a locked rotor test in various d -axis positions (θ) with respect to the phase-a axis. The dashed line is a constant estimated torque (36.4-Nm) from the model. The machine current magnitude is controlled at 20-A (rated) and the current angle at the maximum torque per ampere value for 1500-rpm (see Table I in the Appendix).

Despite the inherent advantage of axially-laminated Synrels in terms of low slotting torques compared to other Synrel designs and the switched reluctance machine [9, 10], it can be seen from Fig. 3 that torque ripples can be as much as 20% of the predicted value (36.4-Nm). This is probably not a surprise as the stator is unskewed and the number of slots per pole-pairs is relatively small (18). Consequently, the model prediction is underestimated by about 6% relative to the machine average torque over one cycle (38.7-Nm). The same effect is demonstrated by the following plots for the running machine.

The Synrel torque vs current angle characteristics at different speeds, including rest, are presented in Fig. 4. The mechanical losses are negligible and therefore the shaft torque and electromagnetic torque are approximately equal. The standstill test is similar to that previously described the difference being that the rotor is now locked in the d -axis align-

Fig. 3. Slotting torque at standstill for 20A and 60° current angle position ($\theta = 0$) and the current angle is changed on-line. For rotating tests, the speed is maintained by adjusting the torque of a dc load machine fed from a Ward Leonard based supply without electronic control (Fig. 7).

Fig. 4. Estimated and measured machine torque at 20-A

The influence of stator slotting is obvious from Fig. 4. The machine standstill torque is much higher than estimated as expected considering Fig. 3. The fact that the dq model is generally not very good for predicting the machine torque at rest is not a serious limitation since the machine zero-speed performance is usually of little practical interest, unless position control is required. The model effectiveness in estimating an optimal current angle is however substantially better. The computed angle for the lossless machine is 57.5° whereas the value derived from the measurements is approximately 60°. Note also the considerably improved model accuracy at non-zero speeds compared to the stand-

still case. Estimation errors at larger current angles, when the measured torque is higher than calculated, are mainly due to slotting as previously predicted. The reasoning is that at higher angles the stator teeth and rotor laminations are mostly unsaturated and hence their impact is more significant than at lower angle values when they are saturated.

Other relevant observations about Fig. 4 are related to the effects of torque control without iron loss compensation. Iron losses effectively shunt some of the terminal input currents away from the torque producing branch of the model, resulting in the machine developing less torque at higher speeds and lower current angles [2]. This has two immediate implications: firstly, the estimated torque is higher than the actual torque; and secondly, unlike the lossless machine, the real one is producing a negative (stalling) torque at a zero current angle operating as a generator [14]. There is also a machine dynamic performance trade-off in the motoring compared to the generating mode as shown in Fig. 5 [5, 7]. It can be seen that the transient response of the inertially-loaded Syncrel is very smooth but nonlinear and unsymmetrical the rate of change of speed being higher while braking than during starting. One should also emphasise the accurate speed control at the desired values (± 1500 -rpm) using the maximum torque per ampere strategy.

Fig. 5. Syncrel response while speed reversal between ± 1500 -rpm

If the measured characteristics at 300-rpm and 1500-rpm in Fig. 4 are compared, it can be observed that the torque reduction at 1500-rpm is not that significant at full load current (20-A), indicating that this particular Syncrel has relatively small core losses. The variation of the maximum torque angle from the ideal value (45°) is therefore predominantly due to magnetic saturation. At the current angles above optimal most of the mmf is in the high reluctance q -axis, the resultant flux and iron losses in the machine are low and consequently the experimental torque curves almost coincide.

Fig. 6 presents the machine torque performance limitations for a variety of currents. A very good overall agreement of the estimated and measured torque is clearly visible especially at small currents when they are virtually the same. At higher current levels, on the other hand, slotting ripples are more significant leading to the machine optimal torque being somewhat larger than predicted. The same figure also shows the possibility of reducing the influence of slotting on the model predictions at standstill as compared to the alignment test situation (Fig. 4). This is accomplished by running the locked rotor test at $\theta \approx 12^\circ$ which is, according to Fig. 3, one of the positions with the minimum deviations of the measured torque from the calculated value (36.4-Nm). Discrepancies between the maximum torques at 300-rpm and zero-speed at 20-A are obviously much less than in Fig. 4.

Fig. 6. Maximum torque per ampere - estimated and measured

IV. CONCLUSIONS

This paper has presented the design and practical implementation aspects of an observer based vector controller for the Syncrel and the experimental results demonstrating its performance on an axially-laminated machine with low core losses. The control algorithm is suitable for a fully digital implementation using software (PC) or hardware (DSP) floating point arithmetic. The first solution has been chosen mainly because of its low cost and the possibility of achieving the control quality competitive with DSP controllers.

The importance of the paper is also the discussion of effects of applying a saturated dq model neglecting iron losses for torque control. The model effectiveness at standstill has been shown to be rotor angle dependent. It has given poor estimates of optimum dq currents (in magnitude but not in angle) except in the minimum slotting torque ripple positions. This can be a problem in applications where position control is needed. The slotting ripples have manifested

inverter leg being turned off/on. In addition, a PAL circuit performs the address decoding, accepts and processes the output signals from the timers and ports and generates the resultant control signals which are then transferred to the inverter hardware.

The drive signal generation timers, unlike the previous ones operating in square wave mode, is programmed in software triggered strobe mode. They are used in pairs to produce the desired firing waveforms each pair being associated with a single transistor of the inverter (except for the regeneration): one serves to switch the top device on and the bottom off, and the other is vice-versa. The gate inputs of the timers couples are connected to complementary outputs of a toggling flip-flop which allows a low signal into the appropriate timer upon a control interrupt. This design ensures that there is no timing skew in the PWM generation.

The input ports bits on the 8255A chip are used to monitor the state of the inverter power devices and hardware trip condition and can be read at anytime. The output ports bits, on the other hand, are dedicated for: opening / closing contactors, IGBT drive signal enable, regeneration transistor control, gate control flip-flop clear signal and triggering an oscilloscope.

A regeneration strategy, executed within the control interrupt service routine, is fairly simple. The corresponding bit on the output port is pulsed high to switch the regeneration transistor on whenever the measured dc link voltage exceeds a user specified value. The device is turned off once a user assigned lower voltage level is reached.

The bottom part of Fig. 8 is a block diagram of the interface system of the encoder and oscilloscopes to the PC bus. Two octal buffers with common enable gates are used to transfer the 10-bit encoder measurement signals to the 16-bit data bus. The translation of the Gray code input to its binary equivalent is done by software using a look-up table (due to noise problems with a PAL based translator). The purpose of 8-bit DACs is to allow displaying of selected software variables on an oscilloscope.

The machine currents and inverter dc link voltage are measured by Hall-effect transducers (HEME's) and precise potential dividers. The hardware has been designed so that all important measurements are isolated with a bandwidth of about 40-kHz, allowing easy connection of oscilloscopes and data acquisition equipment. A LabVIEW® package, that will enable one to determine Syncrel iron losses and therefore implement a compensated control algorithm, has been recently installed.

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TABLE I
Test Syncrel Parameters

Power	5.8-kW
Current (rms)	14.3-A
Current angle	60°
Speed	1500-rpm
L_q	9.8-mH
L_d/L_q unsaturated	9.1
L_d/L_q saturated	7.8
Inertia J (total)	0.23-kgm ²
R_{dc}	0.6-Ω
Air-gap	0.48-mm
Rotor diameter/length	126/175-mm
Insulator thickness	0.38-mm
Lamination thickness	0.35-mm
Lamin-insul. layers	43
Pole arc/piece	120° elec/brass

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