

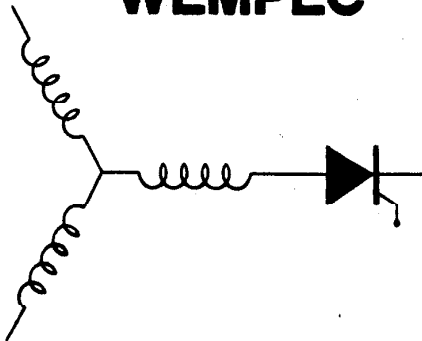
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Vector Control of Synchronous Reluctance Motor Including Saturation and Iron Loss

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# VECTOR CONTROL OF A SYNCHRONOUS RELUCTANCE MOTOR INCLUDING SATURATION AND IRON LOSS

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## Abstract

The application of vector control to a conventional synchronous reluctance motor (VCSynRM) is presented with emphasis on the effects of saturation and iron losses. It is shown experimentally that these parasitic effects can significantly influence the performance of a VCSynRM. A simplified d-q model including saturation and iron losses is presented and experimental results concerning optimal torque/ampere and optimal efficiency operation are shown to be in general agreement with the predictions of the model.

## Introduction

Historically, the performance of the line-start synchronous reluctance machine (SynRM) was regarded as inferior to that of the other types of AC machines and, thus, little attention has been directed to it recently. Although tremendous progress has been made in the variable reluctance motor (VRM) in recent years [1] [2] and the unique attributes of the reluctance machine, such as simple and rugged structure and very good compatibility with the power electronic converter, have been recognized, the application of the more conventional SynRM in converter fed variable speed drives has not been examined in detail.

There are a number of advantages associated with a converter fed SynRM [3]:

- 1) No starting cage is necessary. The rotor therefore can be designed purely for synchronous performance.
- 2) Electronic control makes the motor auto-synchronous and can ensure an optimum torque angle at all loads and speeds. This permits the motor to operate without concern for pullout.
- 3) No damper winding is required to stabilize operation. This makes it possible to design the rotor for the highest possible reactance difference,  $X_d - X_q$ , thus increasing the power density of the motor [2].

It is therefore important that research be conducted regarding the potential of the reluctance motor. In particular, vector control of the conventional synchronous reluctance machine, parallel to the field orientation control of the synchronous or induction machine, deserves special effort so that the capability of a SynRM can be fully utilized.

Issues such as efficiency and torque/ampere are important in evaluating the performance of an electric machine. Such characteristics depend upon the losses and saturation behavior of the machine and therefore require experimental evaluation. However, a model is very useful in understanding the way in which various losses and nonlinearities impact performance. To assist in this regard, a synchronous reference frame model of a SynRM including saturation and iron losses is developed. The behavior of a vector controlled SynRM is analyzed based on the model. It is observed that saturation and iron losses can have a significant effect on the performance of a VCSynRM. To verify the validity of the model for vector control, a DSP based vector controller was built for a 7.5 hp SynRM to experimentally evaluate performance.

## Equivalent Circuit of Synchronous Reluctance Motor

As illustrated in Fig. 1 (a), a synchronous reluctance machine is typically equipped with three phase, symmetrical, sinusoidally distributed windings. Conceptually, a resistor  $R_m$  coupled to the total stator flux is added to incorporate iron losses. For the purpose of analysis, the equations of the sinusoidally operated reluctance machine can be conveniently expressed in the rotor reference frame by the well known d-q transformation [4]. These equations are summarized in Appendix A and the resulting steady state d-q equivalent circuits are shown in Figure 1 (b). Saturation can be

represented by a saturation curve relating  $\lambda_{ds}$  and  $i_{dm}$ . Parameter identification will be discussed in the section on experimental results.

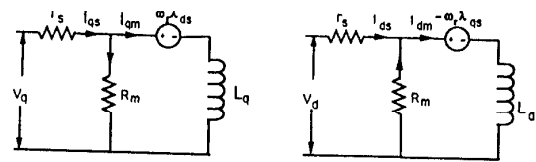
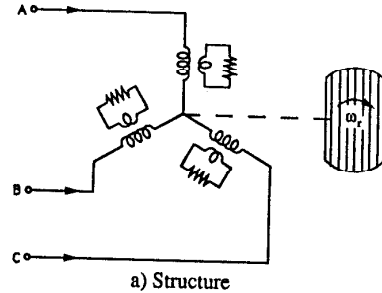


Fig. 1. Structure and Equivalent Circuit of a SynRM.

Note the difference between the current pair  $(i_{qm}, i_{dm})$  compared to  $(i_{qs}, i_{ds})$ . If the iron loss is neglected, i.e.  $R_m$  approaches infinity, these two current pairs become equal. In this case, the stator MMF is aligned with the stator current. When  $R_m$  is finite, however, a phase difference between the stator current and MMF occurs due to the current in  $R_m$ . The relation between vectors  $i_{dq}$ ,  $i_{qm}$  and  $\lambda_{dq}$  is shown in Fig. 2.

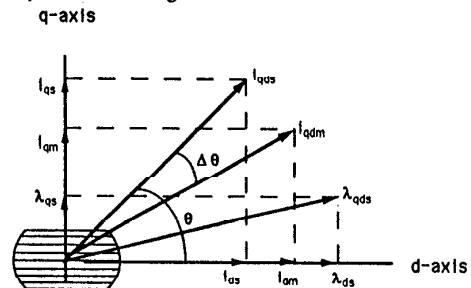


Fig. 2. Vector diagram for finite  $R_m$

The electromagnetic torque produced can be simply derived from energy balance and the induced speed voltage as

$$T_e = \frac{3}{2} i_{dm} i_{qm} (L_d - L_q) \\ = \frac{3}{2} (\lambda_{ds} i_{qm} - \lambda_{qs} i_{dm}) \quad (1)$$

The torque can be interpreted as the interaction between the flux

linkage  $\lambda_{dq}$  and the current  $I_{dqm}$ . The torque equation and the circuits of Fig. 1 b form a useful conceptual and first order analytical model to assist in understanding saturation and core loss impacts on SynRM performance.

### Vector Control of a SynRM without Saturation and Iron Losses

When saturation and iron losses are neglected,  $R_m$  approaches infinity. The d-q quantities are decoupled in this case and vector control of the machine becomes trivial.

It is often desirable to achieve optimal efficiency operation of a SynRM. This can be achieved by selecting an appropriate current angle  $\theta$  with respect to the rotor d-axis. It can be easily shown from the circuit model that the optimal angle is 45° when the saturation and iron losses are neglected. This is also the angle for maximum torque/ampere operation because the only losses are the winding I<sup>2</sup>R losses.

### Effects on Vector Control Caused by Saturation and Iron Loss

An approach to including the saturation effect of the iron is to assume that the torque equation remains true except that the inductances in the d-axis and q-axis are excitation current dependant. Note in particular that the saturation effect in the d-axis is expected to be very different from that of the q-axis because the nature of the magnetic paths are different. In the d-axis, the magnetic path is iron dominant and excitation sensitive, while in the q-axis the magnetic path is air dominant and not excitation sensitive. Hence an unequal saturation effect occurs on the d-axis and the q-axis respectively as the current increases. Under such a circumstance, to properly control the angle  $\theta$  so as to optimally allocate the components  $i_{ds}$ ,  $i_{qs}$  becomes complex.

While saturation alone increases the complexity of vector control, the iron loss will further complicate the situation. As illustrated by the d-q transformation, to represent the effect of the iron loss, an additional resistor  $R_m$  needs be added to the equivalent circuit. It is of importance to realize that in the vector controlled reluctance motor, the shunting resistor will share the input stator current. Hence, the physical stator currents are no longer the currents which directly govern the electromagnetic torque. In effect, a new magnetizing current  $I_{qdm}$  is defined by the component currents  $I_{qm}$  and  $I_{dm}$  as shown in Fig. 2. Comparing vectors  $I_{qds}$  and  $I_{qdm}$  shows an additional angle shift  $\Delta\theta$  is generated due to the iron loss. In effect,  $R_m$  adds an additional coupling mechanism to the d and q circuits which can aggravate the misplaced stator current vector. It is evident that to control the current components  $i_{dm}$ ,  $i_{qm}$  via vector control of the stator MMF for optimal torque/amp or optimal efficiency operation becomes more complex.

### Configuration of Experimental System

Vector control of the experimental synchronous reluctance machine is implemented on a DSP based system. Fig. 3 shows a diagram of the system. The experimental machine has an axially laminated rotor and a conventional three phase stator winding. Appendix B describes the machine and the induction machine from which it was derived. The core losses of the machine are relatively large which serves to enhance the evaluation of their impact on VCSynRM performance and on the validity of the dq circuit model.

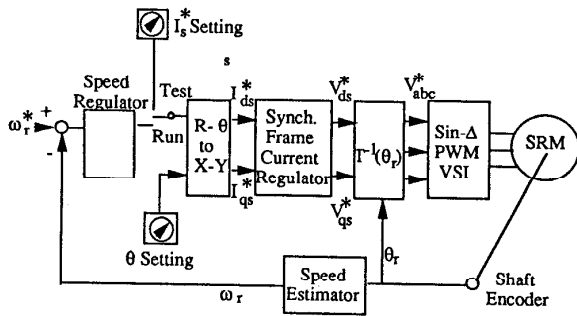


Fig. 3. Block diagram of the experimental system

## Experimental Results

### 1. Parameter identification

In order to identify  $L_q$ ,  $R_m$  and the saturation curve, we need to align the actual stator flux to the d and q axes of the rotor respectively. The alignment of stator flux with one of the axes can be determined by detecting zero shaft torque. In the experiment, the selecting switch in the block diagram is switched to the position of "test". Hence, the speed loop is opened and the magnitude of the stator current,  $I_s$ , becomes an independent input variable. The speed is held constant by a DC dynamometer (800 rpm). For a given  $I_s$  input, the angle  $\theta$  is adjusted around 0° (for d-axis alignment) or 90° (for q-axis alignment) until zero torque is reached. Phase current, fundamental input voltage and input power are then measured. The parameters are calculated from the measured quantities.

The saturation curve ( $\lambda_{ds}$  vs.  $i_{dm}$ ) and iron loss resistor  $R_m$  are identified with the flux aligned with d- axis. In this case the following equations can be derived from the equivalent circuit (neglecting the stator resistance):

$$V_s \approx V_{qs} = \omega_e \lambda_{ds}; \quad (2)$$

$$I_{dm} = I_{ds} = I_s \cos(\theta); \quad (3)$$

$$P_{iron} = P_{in} - \frac{3}{2} I_s^2 R_s; \quad (4)$$

$$R_m = \frac{3(\omega_e \lambda_{ds})^2}{2P_{iron}}; \quad (5)$$

The measured results are summarized in Table 1.

Table 1. d-Axis Alignment Test for  $\omega_r = 800$ rpm  
( $\omega_e = 26.67$  rad/sec)

$\theta^\circ$	$I_{spk}$	Fund. $V_s$	$P_{in}$	$I_{dm}$	$\lambda_{ds}$	$R_m$
26.15	3.15	18.62	45	2.831	0.1111	12.65
20.52	8.27	52.17	267	7.75	0.3114	17.02
18.49	12.84	75.07	504	12.18	0.4480	19.27
13.65	21.37	91.28	775	20.77	0.5447	21.04
12.24	25.31	93.90	862	24.74	0.5603	21.74
11.36	28.61	97.00	950	28.05	0.5788	22.55

Note that  $R_m$  is not constant but varies with  $\lambda_{ds}$ . This happens because the actual iron loss varies less rapidly than  $\lambda_{ds}^2$  because of the hysteresis loss. If the actual iron loss varied as  $\lambda_{ds}^2$ ,  $R_m$  would be a constant.

Information concerning  $L_q$  can be obtained by aligning the flux to the q-axis. In this case, the stator resistance can no longer be neglected since the voltage is comparable to the IR drop. Realizing that  $\theta = 90^\circ$  and  $I_s \approx I_{qs}$ , an approximation of  $L_q$  can still be derived from the equivalent circuit:

$$L_q^2 \approx \frac{V_s^2 - R_s^2 I_s^2}{\omega_e^2 I_s^2}; \quad (6)$$

This equation suggests that measurement of  $L_q$  is sensitive to the error in  $R_s$ . To minimize the sensitivity, the test should be conducted at a higher speed. At 800 rpm,  $L_q$  is estimated to be 0.0055 Henry for the tested machine.

### 2. Comparison between measured performance and model prediction

With the parameters identified as above, we can use the equivalent circuit model to predict the performance of a SynRM. For simplicity, a fixed value of 18  $\Omega$  is used for  $R_m$  in the model, despite the variation in the actual  $R_m$ . The prediction is made for constant output speed (800 rpm) and constant output torque. The current angle  $\theta$  is varied and the corresponding stator current, input voltage and input power are calculated.

An experiment was conducted to confirm the calculated performance. In this experiment, the speed loop is closed to maintain constant output speed. The load torque is maintained constant with a DC generator with a fixed load resistor and fixed field excitation. The magnitude of stator current now becomes a dependant variable. Current angle is adjusted and corresponding stator current, input fundamental voltage and input power are

measured. The measured and calculated performance are compared in Figs. 4 and 5.

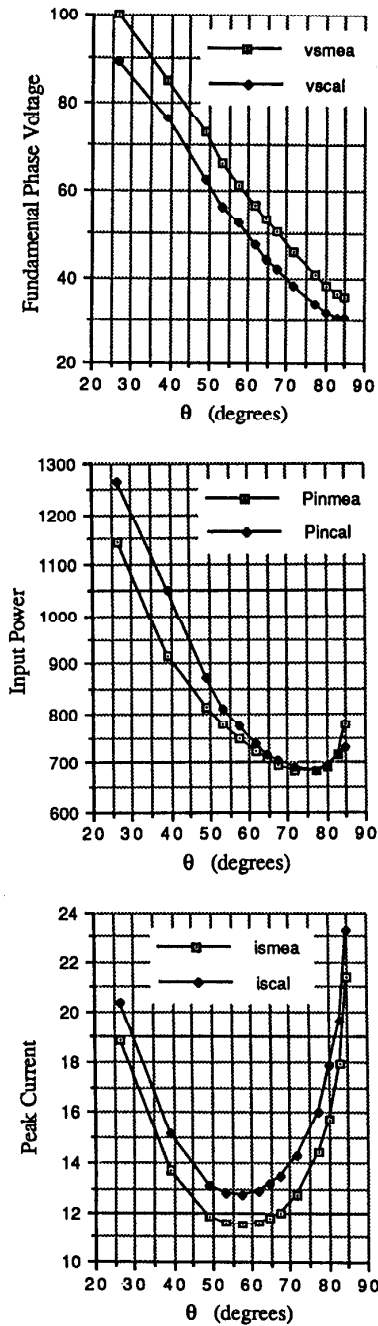


Fig. 4. Performance of VCSynRM ( $\omega_r=800\text{rpm}$ ,  $T_e=6.07 \text{ Nm}$ ).

It is important to observe that the rotor angle for maximum torque per ampere and maximum efficiency is significantly different than the idealized value of  $45^\circ$  for both levels of loading. Note also that the predicted values of these optimal angles are in very good agreement with the measured values and that there is reasonable overall agreement between predicted and measured performance.

The reasons the actual angle differs from the idealized  $45^\circ$  for optimal torque/ampere can be understood as follows. Recall in Fig. 2 that torque is generated when the flux  $\lambda_{qds}$  interacts with the current  $i_{qdm}$ . However, the flux  $\lambda_{ds}$  does not increase linearly with

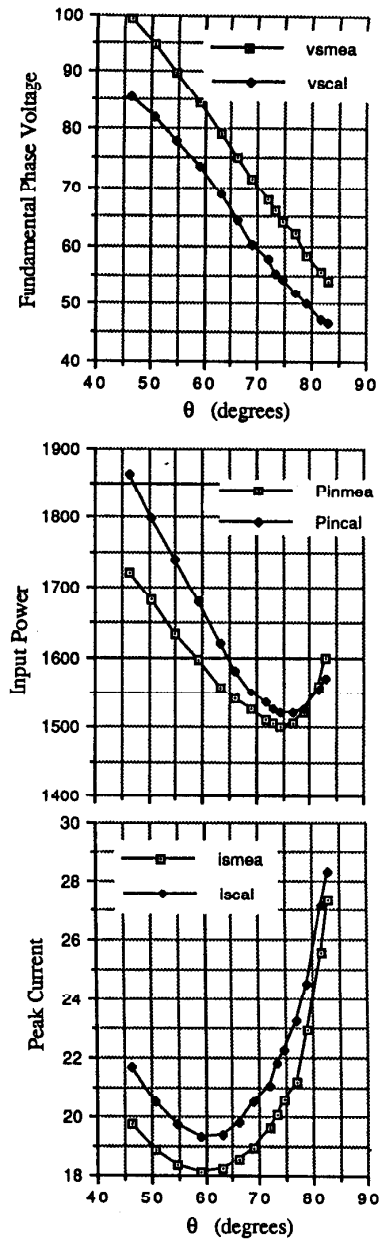


Fig.5. Performance of VCSynRM ( $\omega_r=800\text{rpm}$ ,  $T_e=13.5 \text{ Nm}$ ).

$i_{dm}$ , the magnetizing current component. The best choice of the magnitude of the magnetizing current is such that the iron of the machine does not saturate significantly. This implies that the angle of the current needs to be controlled to ensure that the iron is at such a flux level. This requires an increased value of  $\theta$ , which also increases  $i_{qm}$ , the armature current component in the q-axis, and favors torque production for a given terminal current excitation.

The iron losses require an additional angle advance to ensure optimal torque/ampere operation. This is clearly shown in the vector diagram in Fig. 2. Because of the iron losses, the effective current vector  $i_{qdm}$  is pushed back towards the d-axis by an angle  $\Delta\theta$ . In order to have optimal torque/ampere operation, the physical current  $i_{qds}$  needs to be adjusted to an angle which is even larger than the one when saturation is considered alone. To have optimal efficiency operation, an even larger increase in the current angle  $\theta$  is required to further reduce the flux and hence the core loss. The optimum occurs when the additional  $I^2R$  loss associated with the increased q-axis current required to produce the torque offsets the reduction in core loss.

### 3. Effect of the Operating Frequency on the Optimal Current Angle

The equivalent circuit of the SynRM indicates that the iron loss is dependent on the operating frequency due to the speed voltage  $\omega \lambda_{qm}$ . The higher the operating frequency, the larger the current through  $R_m$  and hence, the iron loss is larger. Therefore, to implement vector control for the purpose of optimal efficiency or torque/ampere operation of the SynRM, the effect of frequency needs to be considered.

The machine model was utilized to calculate the current angle  $\theta$  needed for optimal efficiency and torque/ampere operation with variable speed. The results are shown in Figure 6 and 7.

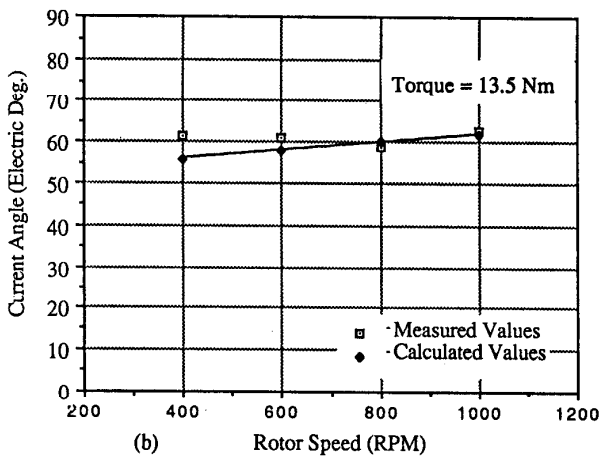
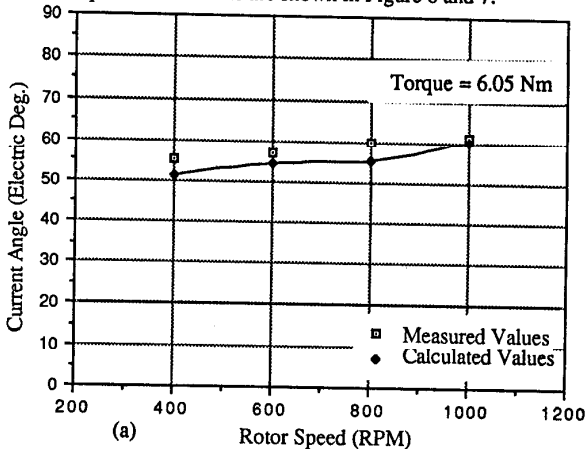


Fig. 6 Current Vector Angle for Maximum Torque/Ampere

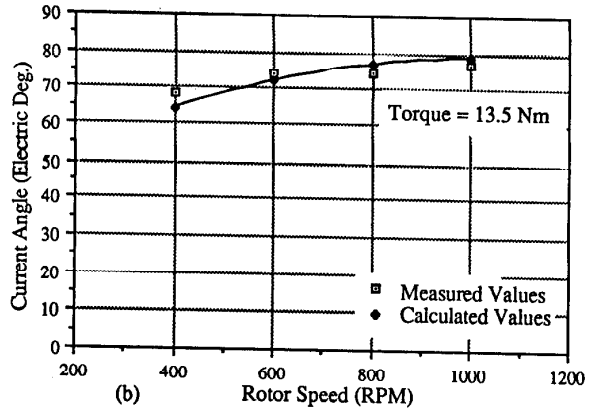
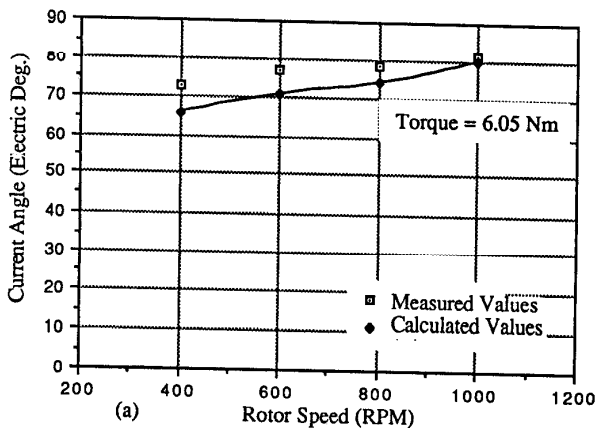


Fig. 7 Current Vector Angle for Minimum  $P_{in}/P_{out}$

As indicated in Figure 6 (a) and (b), the angle variation for optimal torque/ampere operation for different rotor speeds (frequencies) is small. This small angle change can be understood by inspecting the derived equivalent circuit and equations for parameter estimation. The calculated results have been compared to those obtained from experimental tests and shown in the same figure. The calculated results are, in general, correlated well with the experimental ones.

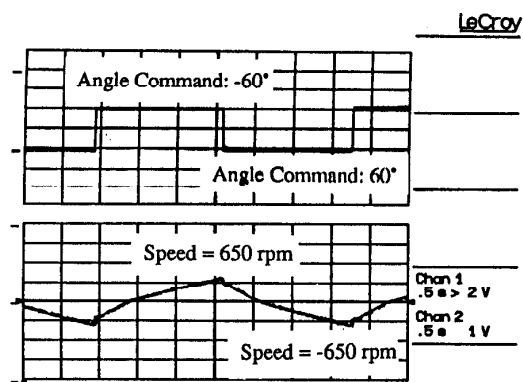
On the other hand, as illustrated in Fig. 7 (a) and (b) the current vector for optimal control of efficiency varies about 10 electrical degrees for rotor speed ranging from 400 to 1000 rpm. This significant change of the angle of the stator current vector results from the iron loss of the machine. In order to have a minimum input power for a given output power, the iron loss and copper loss should be optimally allocated or, equivalently, the magnetizing and armature current components be properly controlled. Since the iron loss is nearly proportional to the square of the operating frequency, a large reduction of the flux linkage is required at high rotor speed to reduce the iron loss to an appropriate value. As shown in Figure 7, when the machine is under light load, the current angle shift is still large because the magnetizing current component is dominant under this condition.

### 4. Transient Torque Control of the VCSynRM

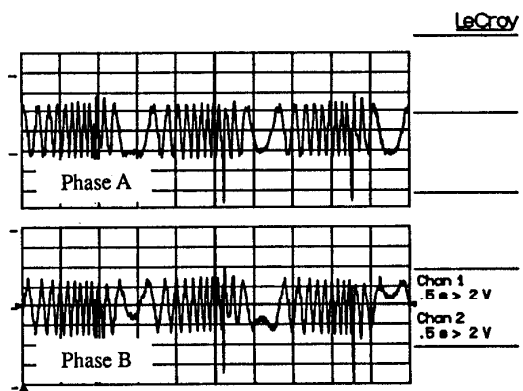
Transient response to a torque command is always an important performance aspect to be considered for a converter fed variable speed drive. It is clear that in the VCSynRM the magnitude and polarity of the torque can be changed rapidly by just shifting the current vector to a proper position with respect to the rotor saliency. For example, if the machine is initially rotating in forward direction, by shifting the stator current vector to a negative angle with respect to the rotor d-axis, the electromagnetic torque changes polarity and the rotor will be braked to zero speed and then accelerated in reverse direction.

A control algorithm was implemented in the experimental drive system to ensure that for a given current a maximum torque is produced. To implement the control algorithm, the optimal torque/ampere angle is calculated by the machine model and stored in a look-up table in the DSP microprocessor. During VCSynRM operation, the microprocessor keeps accessing the table so that the current angle is always such that torque/ampere is maximized.

The transient response of the VCSynRM for both positive and negative step torque commands is shown by the rotor speed curve in Figure 8. As shown in the figure, the SynRM is accelerated and decelerated alternatively with a controlled stator current vector. Note that this current vector has a constant magnitude but a positive angle in one direction and negative angle in the other direction. Therefore, the torque is expected to change polarity repetitively. Under such a circumstance, the machine experiences four quadrant operation, that is, two quadrant operation is in the motoring mode while another two in the regenerative mode. The recorded rotor speed traces show that the system responds very quickly to the command indicating that the step torque command is followed properly.



a) Angle Command and Speed Response



b) Phase Current during Torque Transient

Fig. 8 Experiment Results of Transient Torque Response

However, it has been observed from the experiment that the torque is not totally symmetric when the VCSynRM is operated in the motoring mode compared to that when it is in the generating mode. That is, with the same value of stator current the machine operating as a motor (positive current angle  $\theta_0$ ) a different value of torque is produced from the machine operating as a generator (negative current angle  $-\theta_0$ ). The unsymmetrical torque response is clearly shown by the different speed slope of the machine when it is in the generator and motor mode respectively.

The unsymmetrical torque response can be explained well by the d-q model of the SynRM in Figure 2. Note, in particular, that when the defined terminal current vector reverses the angle while keeping the magnitude unchanged, the current source which supplies the circuit in the d-axis will be unchanged and the one powering the circuit in q-axis will have its direction reversed. With the defined terminal current, it can be shown that the resulting currents,  $I_{qm}$  and  $I_{dm}$ , which directly govern the torque production will make the torque value larger when the machine acts as a generator. This is actually a dual characteristic of a voltage excited machine with a finite armature resistance.

To illustrate the discussion above, a vector diagram is drawn in Figure 9. In this diagram, the imposed current vectors to the machine have the same magnitude but opposite angle. Note that due to the iron loss current through equivalent resistor  $R_m$ , in the generator case the effective current vector  $i_{qdm}^G$  will change, in both magnitude and angle, to a point which favors the torque production. A control algorithm and implementation which compensate this unsymmetrical effect is being developed. It should also be mentioned that the unsymmetrical torque response in the motoring and regenerative mode caused by the iron loss is a common problem in other types of machine drives powered by a current source.

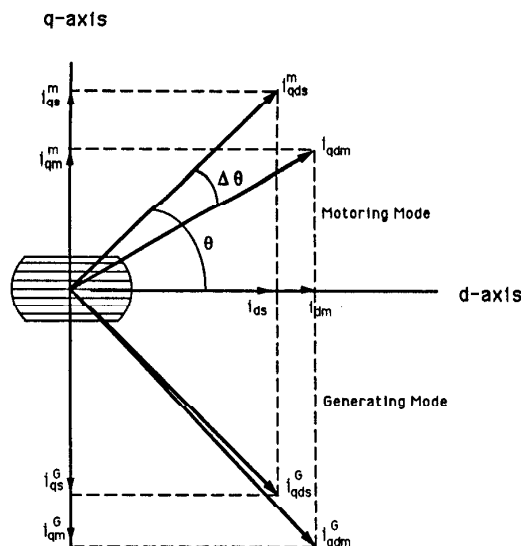


Fig. 9 Vector diagram of SynRM Showing motoring and regenerative current vectors

### Conclusion

The results presented in this paper clearly show that saturation and iron loss can have a significant role in establishing optimal rotor angles for vector control of a SynRM. In general, the optimal angles for maximum torque/ampere and maximum efficiency are larger than the theoretical  $45^\circ$  angle predicted by a linear, lossless model. A simple first order model incorporating the core losses as a shunt resistor and allowing saturation in the d-axis yields useful insight into performance and provides a means for implementing control strategies to compensate for these effects.

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### Appendix A

#### d-q transformation of the phase equations for the sinusoidally excited reluctance motor

##### 1) Phase description of the SynRM and current source

The machine discussed in the paper is assumed to have the structure shown in Figure 1 (a). Under this assumption, the self and mutual inductances of the machine can be described as a function of the rotor position and expressed by the matrix:

$$[L_{abc}] = \begin{pmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{pmatrix} \quad (A-1)$$

$$\begin{aligned}
\text{with } L_{aa} &= L_0 - L_m \cos 2\theta_r \\
L_{bb} &= L_0 - L_m \cos 2(\theta_r - 2\pi/3) \\
L_{cc} &= L_0 - L_m \cos 2(\theta_r + 2\pi/3) \\
L_{ab} &= L_{ba} = -L_0/2 - L_m \cos 2(\theta_r - \pi/3) \\
L_{ac} &= L_{ca} = -L_0/2 - L_m \cos 2(\theta_r + \pi/3) \\
L_{bc} &= L_{cb} = -L_0/2 - L_m \cos 2(\theta_r + \pi)
\end{aligned}$$

To include the effect of the stator iron loss, a resistor  $R_m$  is placed in parallel with the magnetizing inductance in each phase. Further, if the machine is powered by a three phase balanced sinusoidal current source:

$$[i_{abc}] = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} I_m \cos \theta \\ I_m \cos(\theta - 2\pi/3) \\ I_m \cos(\theta + 2\pi/3) \end{pmatrix}, \quad (\text{A-2})$$

then the armature resistance and stator winding leakage inductance can be excluded from the current equation. The phase current equation becomes, in matrix form,

$$[i_{abc}] = [i_{abc}^m] + \frac{1}{R_m} p[\lambda_{abc}^m] \quad (\text{A-3})$$

where the current vector  $[i_{qdn}^m]$  and flux linkage  $[\lambda_{abc}^m]$  correspond to the quantities in Figure 1.

## 2) d-q transformation and equivalent circuit

Equation (A-3) can be conveniently expressed in the rotor synchronous reference frame by the well known d-q transformation [4]. The transformation is done by multiplying both sides of Equation (A-3) with transformation matrix

$$T = \frac{2}{3} \begin{pmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (\text{A-4})$$

After the transformation, the matrix equation becomes

$$[i_{qdn}^m] = [i_{qdn}^m] + \frac{1}{R_m} \left\{ \omega \times [\lambda_{qdn}^m] + \frac{d[\lambda_{qdn}^m]}{dt} \right\} \quad (\text{A-5})$$

where  $[i_{qdn}^m] = T [i_{abc}]$

$$[i_{qdn}^m] = T [i_{qdn}^m]$$

$$\text{and } \frac{1}{R_m} \left\{ \omega \times [\lambda_{qdn}^m] + \frac{d[\lambda_{qdn}^m]}{dt} \right\} = T \frac{1}{R_m} p[\lambda_{abc}^m]$$

or in scalar form:

$$i_{qs} = i_{qm} + \frac{1}{R_m} \left\{ \omega \lambda_d^m + \frac{d\lambda_q^m}{dt} \right\}$$

$$i_{ds} = i_{dm} + \frac{1}{R_m} \left\{ -\omega \lambda_q^m + \frac{d\lambda_d^m}{dt} \right\}$$

The voltage equation of the circuit is

$$[v_{qdn}^m] = \omega \times [\lambda_{qdn}^m] + \frac{d[\lambda_{qdn}^m]}{dt} \quad (\text{A-6})$$

For the machine described in Figure 1, if the armature resistance and stator leakage is considered, the voltage equation is

$$[v_{abc}] = r_s [i_{abc}] + L_s p [i_{abc}] + [v_{abc}^m] \quad (\text{A-7})$$

where the voltage vector  $[v_{abc}^m]$  is the voltage across the magnetizing inductance and  $L_s$  is the inductance associated with the leakage flux linkage. Similarly, the voltage equation can be transformed into d-q reference frame and becomes

$$[v_{qdn}^m] = r_s [i_{qdn}^m] + L_s p [i_{qdn}^m] + [v_{qdn}^m] \quad (\text{A-8})$$

The d-q equivalent circuit suggested by (A-8) is shown in Figure 1 (b). If the rotor iron loss of the machine is considered, it can be shown that an additional resistance needs to be in parallel with the magnetizing inductance in the d-q equivalent circuit. A more detailed equivalent circuit of a SynRM which includes stator and rotor iron losses is shown in Figure A-1.

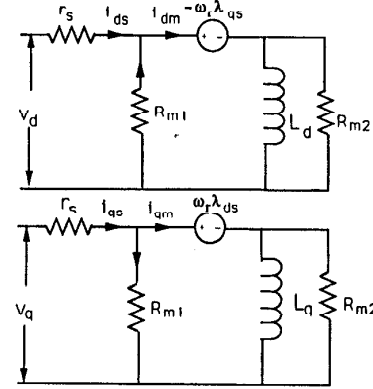


Fig. A-1 Equivalent Circuit of a SynRM Including Stator and Rotor Iron Losses in Synchronous d-q Reference Frame

## Appendix B

### Description and Specifications of the Experimental Synchronous Reluctance Motor

The experimental SynRM tested and discussed in this paper consists of a three phase double layer wound stator and an axially laminated rotor. When the stator is excited with three phase sinusoidal current, a rotating field will be created in the airgap. The stator is actually standard for 7.5 hp three phase induction machine.

The rotor is divided into four segments, and each segment is a stack of axially laminated common steel sheets sandwiched by nonmagnetic material. When the rotating field is aligned with the rotor laminations, the rotor provides maximum permeance, and thus the airgap flux is maximized. Otherwise when the rotating field is unaligned with the field, large reluctance is encountered which minimizes the airgap flux.

The specifications for the equivalent induction machine is listed in the following:

Ratings	
Power rating:	7.5 hp
Rated Speed:	1750 rpm
Rated Voltage:	230 volts
Rated Current:	10 amps
Power Factor at Rated Load:	0.8

Geometry	
Stator Lamination OD:	9.001 in
Stator Lamination ID:	4.954 in
Effective Length of Stator Stack:	4.00 in