A NEW CONTROL STRATEGY FOR OPTIMUM EFFICIENCY OPERATION OF A SYNCHRONOUS RELUCTANCE MOTOR

Takayoshi Matsuo, Ahmed El-Antably, and Thomas A. Lipo*

Department of Electrical and Computer Engineering
University of Wisconsin-Madison
1415 Engineering Drive
Madison, Wisconsin 53706
Telephone: (608)262-0287
Fax: (608)262-1267

Abstract

The synchronous reluctance motor has recently attracted the efforts of a number of researchers and is gaining favor as a possible alternative for ac drives. The energy saving is always an important issue for a motor drive system. In this paper, an optimum efficiency control scheme of synchronous reluctance motors is presented. The synchronous reluctance motor is a singly salient machine in which the rotor is constructed so as to employ the principle of reluctance torque to produce electromechanical energy conversion. Only the rotor is constructed with salient poles while the stator inner surface is cylindrical and typically wound in an identical manner to an induction machine. There exists a variety of combinations of d and q-axis current which provide specific motor torque. The objective of the optimum efficiency controller is to seek a combination of d and q-axis current components, which provides minimum input power, that is, minimum losses at a certain operating point in steady state. A small amount of perturbation is added to the d-axis current reference for the purpose of searching a minimum input power operating point. The input power of the inverter is calculated from the measured dc bus current and dc bus voltage of the inverter. A block diagram for implementing the proposed optimum efficiency controller of the synchronous reluctance motor is presented and the overall control strategy for searching the minimum input power is discussed. An optimum efficiency controller of the synchronous reluctance motor drive has been implemented in the laboratory to verify the developed control scheme. An experimental study has been carried out with the implemented drive system.

* Indicates Corresponding Author
For traditional oral presentation

A NEW CONTROL STRATEGY FOR OPTIMUM EFFICIENCY OPERATION OF A SYNCHRONOUS RELUCTANCE MOTOR

DIGEST

INTRODUCTION

The energy saving is always an important issue for a motor drive system. A number of reports have been published on the subject of efficiency improvement for induction motor drives [1, 2, 3]. Induction motor efficiency can be improved by means of reduced voltage operation at light loads in the case of fixed frequency induction motor drives. It is also known that induction motor losses at partial loads can be reduced by operating an adjustable-frequency drive at the optimum slip which yields maximum efficiency.

This energy saving measure can be applied to synchronous reluctance motor drives. The synchronous reluctance motor is a singly salient machine in which the rotor is constructed so as to employ the principle of reluctance torque to produce electromechanical energy conversion. Only the rotor is constructed with salient poles while the stator inner surface is cylindrical and typically wound in an identical manner to an induction machine. In the field oriented control of synchronous reluctance motors [4], d and q-axis components of the stator current vector applied to the motor are independently variable, and a specific torque at any motor speed can be achieved with a variety of different dq current component combinations. Each dq current component pairing defines a particular motor torque characteristic, but motor efficiency may vary widely. If the d-axis current is high, then the motor voltage is increased and consequently, core losses are large. If the d-axis current is reduced excessively, then motor currents and copper losses must increase. Consequently, there is an optimum current vector which gives a specified torque with maximum efficiency at every operating point.

For the practical realization of an efficiency optimized synchronous reluctance motor drive, an optimum efficiency controller may be accomplished with the aid of a loss model for the drive into which complete parameter values, including inductance saturation, coefficients of iron losses, temperature and harmonic effects, must be programmed. At any operating point, the controller performs a computation on optimum efficiency operating conditions and adjusts one, or more, variables in the model until the optimum values are found. These optimized values then become the commanded values for the drive regulator. The effectiveness of this approach obviously depends on the accuracy of the loss model.

Optimization can be accomplished by measuring the power input to the drive and perturbing one variable while seeking the minimum input power at the particular operating point. The minimization of total power input may not be very sensitive procedure for minimization of losses, but accurate loss modeling and precise information regarding parameter values are not required.

It is the purpose of this paper to propose and examine a new control strategy to seek optimum efficiency of a synchronous reluctance motor. The motor torque of synchronous reluctance motors is proportional to two components of the stator current vector, that is, d and q-axis current, i_{ds} and i_{qs}. Hence, there exist various combinations of d and q-axis current which provide a certain amount of motor torque. The objective of the optimum efficiency controller is to seek a combination of d and q-axis current components, which provides minimum input power, that is, minimum losses at a certain operating point in steady state. A small amount of perturbation is added to the d-axis current reference i_{ds}^* for the purpose of searching a minimum input power operating point. The input power of the inverter is calculated from the measured dc bus current and dc bus voltage of the inverter. The obtained input power includes motor output power, motor losses and inverter losses. The motor losses include copper losses, iron losses, and stray load losses. A block diagram for implementing the proposed optimum efficiency controller of the synchronous reluctance motor is presented and the overall control strategy for searching the minimum input power is discussed. An optimum efficiency controller of the synchronous reluctance motor drive has been implemented in the laboratory to verify the developed control scheme and an experimental study has been carried out with the implemented drive system.

IRON AND COPPER LOSSES

When evaluating the core loss, the different behavior of hysteresis and eddy current losses with respect to frequency is taken into account. At fundamental frequency f, the core losses are

$$W_{core} = k_h f \phi^2 + k_e f^2 \phi^2 \tag{1}$$

where ϕ is the mutual flux and k_h , k_e are the hysteresis and eddy current coefficients respectively. Since the air gap voltage is expressed as $V_m = k_c f \phi$, the fundamental core loss is written as

$$W_{core} = V_m^2 \frac{\left(\frac{k_h}{f} + k_e\right)}{k_c^2} = k V_m^2 \tag{2}$$

where

$$k = \frac{\left(\frac{k_h}{f} + k_e\right)}{k_c^2} \tag{3}$$

Copper loss is expressed in terms of stator resistance r_s and stator current I_s as

$$W_{copper} = 3 r_s I_s^2 \tag{4}$$

The loss Wt which includes the fundamental core loss and the copper loss is

$$\begin{aligned} W_t &= W_{core} + W_{copper} \\ &= k V_m^2 + 3 r_s I_s^2 \end{aligned} \tag{5}$$

Using following expressions of V_m^2 and I_s^2,

$$\begin{aligned} V_m^2 &= V_{qs}^2 + V_{ds}^2 \\ &= (r_s I_{qs} + \omega_r L_{ds} I_{ds})^2 + (r_s I_{ds} - \omega_r L_{qs} I_{qs})^2 \end{aligned} \tag{6}$$

$$I_s^2 = I_{qs}^2 + I_{ds}^2 \tag{7}$$

the loss W_t can be expressed in terms of d and q-axis currents as

$$\begin{aligned} W_t &= k V_m^2 + 3 r_s I_s^2 \\ &= k \left((r_s I_{qs} + \omega_r L_{ds} I_{ds})^2 + (r_s I_{ds} - \omega_r L_{qs} I_{qs})^2 \right) + 3 r_s (I_{qs}^2 + I_{ds}^2) \end{aligned} \tag{8}$$

q-axis current, I_{qs}, is expressed as

$$I_{qs} = \frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{ds}} \tag{9}$$

then the loss W_t is expressed as

$$\begin{aligned} W_t &= k\left((r_s I_{qs} + \omega_r L_{ds} I_{ds})^2 + (r_s I_{ds} - \omega_r L_{qs} I_{qs})^2 \right) + 3\, r_s (I_{qs}^2 + I_{ds}^2) \\ &= k\left(\left(r_s \frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{ds}} + \omega_r L_{ds} I_{ds}\right)^2 \right. \\ &\quad \left. + \left(r_s I_{ds} - \omega_r L_{qs} \frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{ds}}\right)^2 \right) \\ &\quad + 3\, r_s \left(\left(\frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{ds}} \right)^2 + I_{ds}^2 \right) \end{aligned} \tag{10}$$

which is a function of d-axis current I_{ds}.

Equation 10 can be written as

$$W_t = a\, I_{ds}^2 + b\, I_{ds}^{-2} + c \tag{11}$$

$$\begin{aligned} \frac{dW_t}{dI_{ds}} &= 2a\, I_{ds} - 2b I_{ds}^{-3} \\ &= 2\, a\, I_{ds}^{-3}\left(I_{ds}^4 - \frac{b}{a} \right) \\ &= 2\, a\, I_{ds}^{-3}\left(I_{ds}^2 + \sqrt{\frac{b}{a}} \right)\left(I_{ds} + \left(\frac{b}{a}\right)^{1/4} \right)\left(I_{ds} - \left(\frac{b}{a}\right)^{1/4} \right) \end{aligned} \tag{12}$$

where

$$a = \frac{\left(\frac{k_h}{f} + k_e\right)}{k_c^2}\left((\omega_r L_{ds})^2 + r_s^2 \right) + 3\, r_s \tag{13}$$

$$\begin{aligned} b = \frac{\left(\frac{k_h}{f} + k_e\right)}{k_c^2} &\left(\left(r_s \frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})} \right)^2 + \left(\omega_r L_{qs} \frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})} \right)^2 \right) \\ &+ 3\, r_s \left(\frac{T_e^*}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})} \right)^2 \end{aligned} \tag{14}$$

$$c = \frac{\left(\frac{k_h}{f} + k_e\right)}{k_c^2}\left(\frac{2\, r_s\, T_e^*\, \omega_r\, L_{ds}}{\frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})} \right)(L_{ds} - L_{qs}) \tag{15}$$

Equation 12 indicates that $dW_t / dI_{ds} < 0$ when $I_{ds} < \left(\frac{b}{a}\right)^{1/4}$ and $dW_t / dI_{ds} > 0$ when $I_{ds} > \left(\frac{b}{a}\right)^{1/4}$, which means that there exists minimum W_t at specific I_{ds}.

OPTIMUM EFFICIENCY CONTROLLER

A control configuration of the optimum efficiency controller of a synchronous reluctance motor drive with torque and speed controllers is shown in Fig. 1.

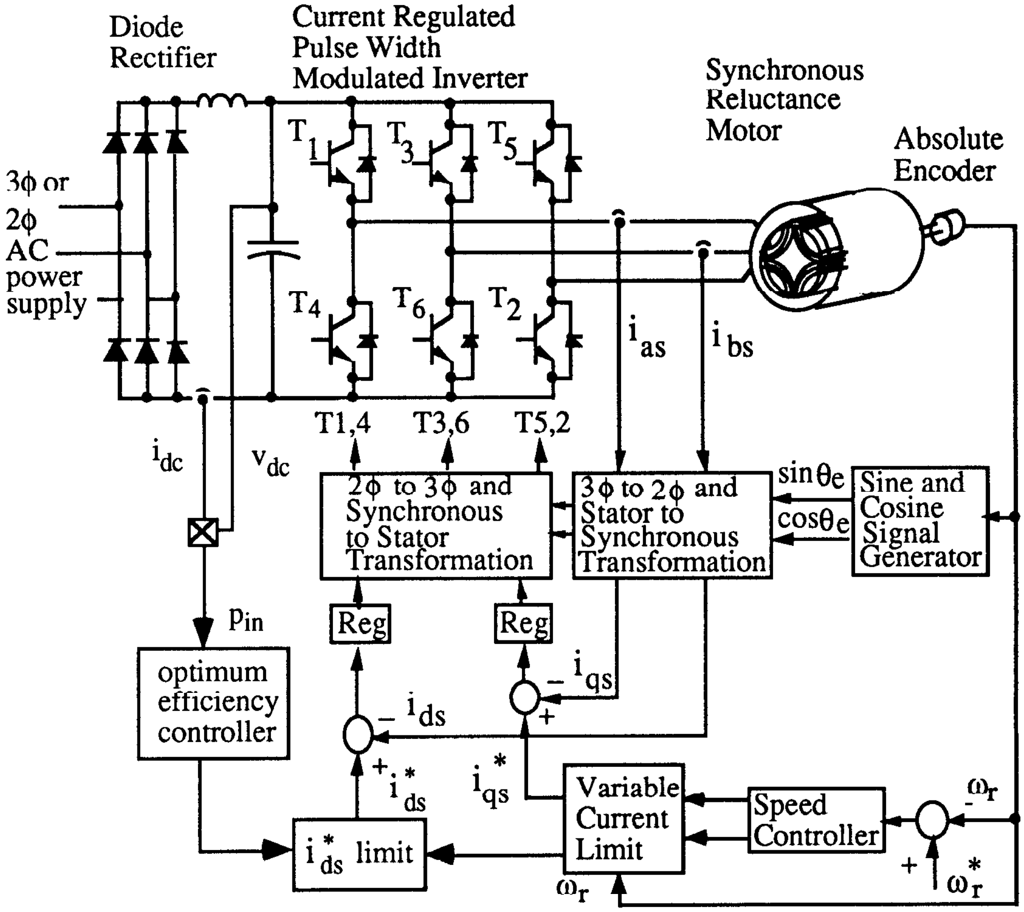


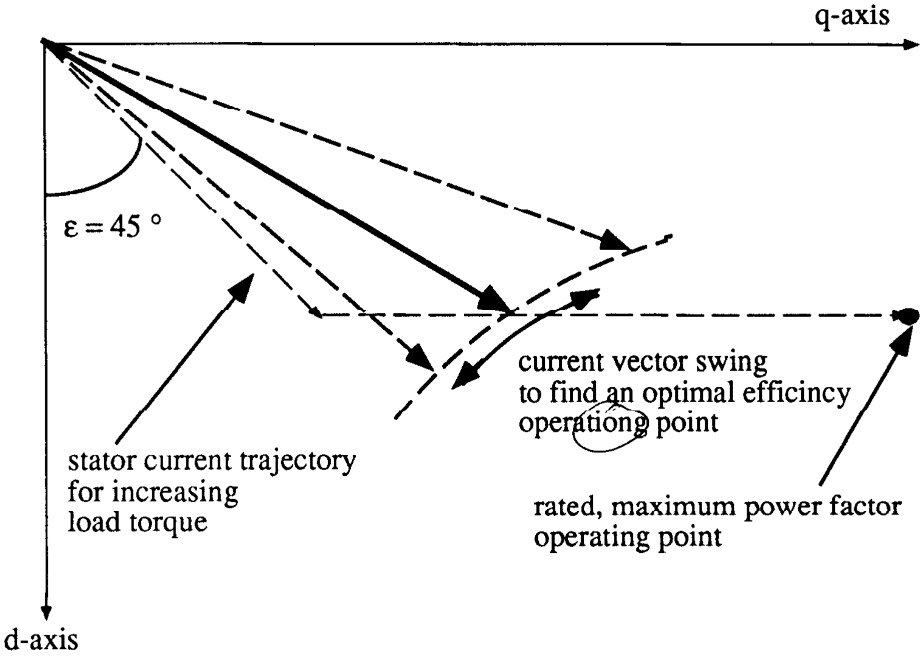
Fig. 1 An optimum efficiency control configuration for a synchronous reluctance motor drive.

By means of an absolute encoder or resolver, the sine and cosine of the angular position of the rotor is established. These sinusoidal components are used to refer those physical stator currents from the physical (stationary) reference frame to the rotating (d-q) axes. The encoder is also used to measure speed and, based on the speed measurement, the desired (command) values of i_{ds} and i_{qs} are established. Current regulators guarantee that the desired and actual values of the d-q currents are obtained. The voltage command signals which are obtained in the synchronously rotating d-q frame are finally referred back to the stator frame before being used to switch the voltage source PWM inverter.

The motor torque of synchronous reluctance motors is proportional to two components of the stator current vector, that is, d and q-axis current, i_{ds} and i_{qs}. Hence, there exists various combinations of d and q-axis current which provide a certain amount of motor torque. The objective of the optimum efficiency controller is to seek a combination of d and q-axis current components, which provides minimum input power, that is, minimum losses at a certain operating point in steady state. A small amount of perturbation is added to the d-axis current reference i_{ds}^* for the purpose of searching a minimum input power operating point. The input power of the inverter is calculated from the measured dc bus current and dc bus voltage of the inverter. The obtained input power includes motor output power, motor losses and inverter losses. The motor losses include copper losses, iron losses, and stray load losses.

Figure 2 illustrates stator current vectors to which small perturbations are superimposed to find an optimum efficiency operating point. First, d-axis current reference i_{ds}^* is changed by small amount Δi_{ds}^*. If d-axis current is decreased, then the motor torque decreases and the motor speed is decreased, where it is assumed that the load torque is constant. The error between speed reference and speed feedback increases and then the output of the speed controller, that is, the torque command i_{qs}^* increases. The motor torque increases as q-axis current i_{qs} increases up to the same amount of the load torque. The torque at two operating points are expressed as

$$\begin{aligned} T_e &= \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, i_{ds}\, i_{qs} \\ &= \frac{3}{2}\frac{P}{2}(L_{ds}' - L_{qs})\,(i_{ds} - \Delta i_{ds})\,(i_{qs} + \Delta i_{qs}) \qquad (16) \end{aligned}$$



X

Fig. 2 Illustration of current vector swing to find an optimum efficiency operating point where current vectors provide same motor torque.

Figure 3 illustrates a pattern of d-axis current perturbation to find an optimum efficiency operating point. It is assumed that the motor is generating a partial load torque at certain speed, where d-axis current reference is $i_{ds}^*{}_1 = i_{ds}^*(5)$ at an operating point. In this pattern, first, d-axis current reference i_{ds}^* is decreased five steps, Δi_{ds}^* each step. Then, d-axis current reference i_{ds}^* is increased ten steps, again, Δi_{ds}^* each step. The input power is measured at each step while d-axis current reference i_{ds}^* is increased from $i_{ds}^*(0)$ to $i_{ds}^*(10)$ and then the optimum efficiency controller determines at which step the input power has a minimum value. The controller decreases d-axis current reference to the current level where the input power

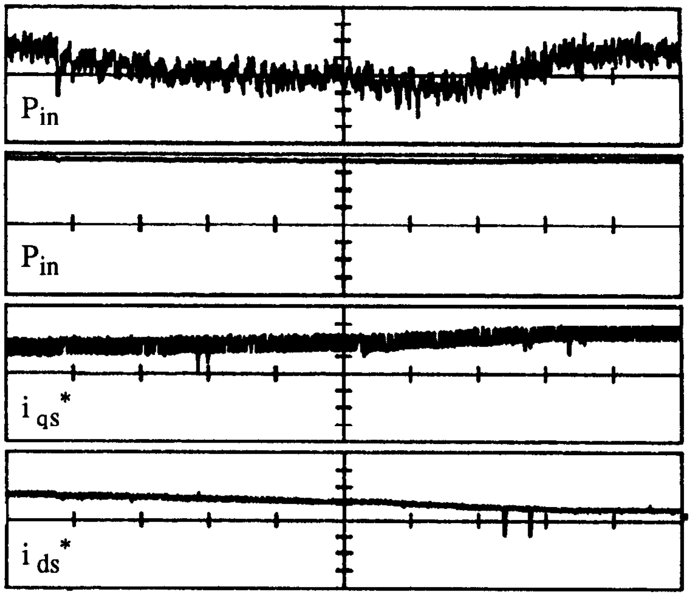


Fig. 4 Experimental result of a behavior of input power P_{in} for continuous change of d-axis current i_{ds}, while the rotor speed is controlled at 1800 rpm and dc dynamometer provides the load torque of 0.55 N-m. From top to bottom: (i) the measured input power (1.865 watts/div.), (ii) the measured input power (37.3 watts/div.), (iii) the q-axis current (1.0 A/div.), (iv) the d-axis current (1.0 A/div.), and the time scale is 5 sec./div.

Figures 5 shows a process of the optimum efficiency control, where the input power is gradually minimized. The counter 1 counts up from zero to ten as the d-axis current reference is increased stepwise at every perturbation cycle, which is described in Fig. 3. The number of steps is ten in this case. The counter 2 counts down to the d-axis current reference where the input power is minimized among the perturbation at a specific perturbation cycle. The rotor speed is controlled at 1800 rpm and dc dynamometer provides the load torque of 0.55 N-m while the optimum efficiency controller proceeding the minimization of the input power. In this case, the improvement of the input power is about 6-7 watts. The motor output power is 104 watts and at this speed, the motor full power is 415 watts.

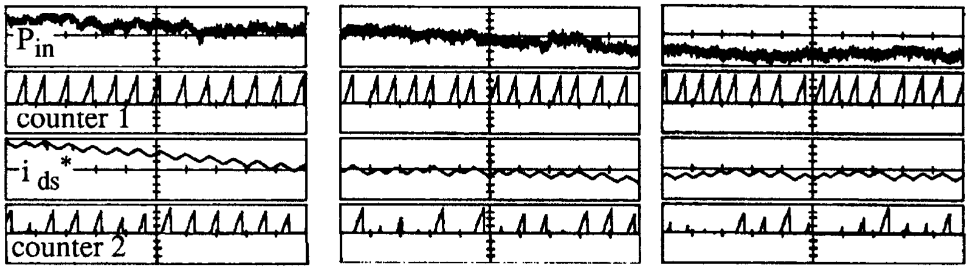


Fig. 5 Experimental results of the optimum efficiency control of a synchronous reluctance motor. The rotor speed is controlled at 1800 rpm and dynamometer provides the load torque of 0.55 N-m. From top to bottom: (i) the measured input power (1.865 watts/div.), (ii) the counter 1, (iii) the d-axis current reference (0.125 A/div.), (iv) the counter 2, and the time scale is 50 sec./div.

CONCLUSIONS

In this paper, an optimum efficiency control scheme of synchronous reluctance motors is presented. There exists a variety of combinations of d and q-axis current which provide specific motor torque. The objective of the optimum efficiency controller is to seek a combination of d and q-axis current components, which provides minimum input power, that is, minimum losses at a certain operating point in steady state. A block diagram for implementing the proposed optimum efficiency controller of the synchronous reluctance motor is presented and the overall control strategy for searching the minimum input power is discussed. An optimum efficiency controller of the synchronous reluctance motor drive has been implemented in the laboratory to verify the developed control scheme. An experimental study has been carried out with the implemented drive system.

REFERENCES

[1] Alexander Kusko and Donald Galler, "Control means for Minimization of Losses in AC and DC Motor Drives", IEEE Transactions on Industry Applications, Vol. IA-19, No. 4, July/August 1983, pp. 561-570.

[2] Daniel S. Kirschen, Donald W. Novotny, and Thomas A. Lipo, "On-Line Efficiency Optimization of a Variable Frequency Induction Motor Drive", IEEE Transactions on Industry Applications, Vol. IA-21, No. 4, May/June 1985, pp. 610-616.

[3] J. M. D. Murphy and V. B. Honsinger, "Efficiency Optimization of Inverter-fed Induction Motor Drives', Conference Record, IEEE Annual Meeting, 1982, pp. 544-552.

[4] T. Matsuo and T. A. Lipo, "Field Oriented Control of Synchronous Reluctance Machine", Conference Record, IEEE Power Electronics Specialists Conference, June 1993, pp. 425-431.