A New Energy Optimizing Control Strategy for Switched Reluctance Motors

Philip Carne Kjaer, Student Member, IEEE, Peter Nielsen, Student Member, IEEE,
Lars Andersen, Student Member, IEEE, and Frede Blaabjerg, Member, IEEE

Abstract—This paper describes a new and machine-independent method to minimize the energy consumption of a speed controlled Switched Reluctance Motor (SRM). The control strategy is to vary the duty cycle of the applied dc voltage in order to obtain the desired speed quickly and when operating in steady-state vary the turn-on angle ($\alpha_{on}$) of the phase voltage to minimize the energy consumption. The power flow is measured in the dc-link and used to control the turn-on angle. Simulations carried out on a three-phase 6/4 pole SRM justify the algorithm and the physical implementation in a Siemens SAB 80C517A microcontroller is described. Measurements on two different load systems show it is possible to minimize the energy consumption on-line in a speed controlled Switched Reluctance Motor without losing the dynamic performance. A comparison with an ordinary mode-shift controlled SRM shows more than an 8% increase in overall efficiency for some operation points. The algorithm is fully applicable to other Switched Reluctance Motors at other power levels or with other pole configurations.

I. INTRODUCTION

The Switched Reluctance Motor (SRM) experiences a revival due to improvements in power devices, low-cost microcontrollers and computer-aided design tools. In comparison with ac motors or commutated dc motors, the SRM is less expensive in production and design. It is also very suitable for high-speed applications. The disadvantages are the need for position feedback sensors, the produced torque-ripple, and the emitted acoustic noise when the stator and rotor attract each other.

An important factor in electrical drives is high efficiency and low cost. Some papers have considered energy optimized control of ac machines like minimizing the energy consumption by adjusting the rotor slip frequency [1, 2] which gives a high dynamic performance. Another strategy is to minimize the energy consumption by measuring the dc-link current and voltage and in steady-state adjusting the voltage/frequency ratio [3]. Very few papers have considered such strategies for SRM but this paper will deal with a new developed control strategy based on a dc-link current measurement.


P. C. Kjaer is with the SPEED Laboratory, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8LT, U.K.

P. Nielsen is with the Transmission Division, Danfoss A/S, DK-6300 Graasten, Denmark.

L. Andersen is with Niftisk A/S, DK-2605 Brondby, Denmark.

F. Blaabjerg is with the Department of Electrical Energy Conversion, Institute of Energy Technology, Aalborg University, DK-9220 Aalborg East, Denmark.

IEEE Log Number 9412787.

The SRM is usually voltage controlled or current controlled. Voltage control means applying a phase voltage consisting of a chopped dc voltage with constant duty cycle $D$. The duty cycle is thus the control signal and no current control loop is used. In current control, the phase current is compared to a reference current and the phase voltage is controlled by a hysteresis control. The reference current is then the control signal.

Apart from the duty cycle (or the reference current) and the angular speed, two other parameters determine the electromagnetic torque production. These two are the turn-on angle $\alpha_{on}$ and the turn-off angle $\alpha_{off}$, which are angles defined in relation to the rotor position of the SRM. A traditional control of the firing angles is presented in [4]–[6]. The firing angles are moved in steps depending on the speed and the same firing angles are then used for a wide speed range. This control strategy is referred to as Mode-Shift Control. Few papers have treated optimized control of the SRM. Reference [4] treats microcomputer control of the SRM where the turn-on and turn-off angles are varied but not in the sense of optimizing the efficiency. In [5] the torque/current ratio is theoretical, maximized by adjusting the turn-off angle when the converter and the SRM operate in current control. Results are only validated by simulation and the efficiency is not optimized. Another paper [6] treats a simple energy optimization control scheme by adjusting both the turn-on and turn-off angle according to experimental obtained optimization points. The limits of this strategy are that it can only be used for one load condition at one specific speed and it is necessary to do many experiments. Another strategy is used in [7] concerning energy optimized control which is specially developed for high power SRM's, where the number of transistor switchings in the converter is essential in order to reduce the converter losses, and this is used in an energy optimizing scheme. However, a detailed system knowledge is necessary to do this optimization. This paper suggests an energy optimizing (EO) control strategy for the SRM which is independent of machine parameters and where no measurements are necessary in order to perform the control. The strategy is based on an on-line adjustment of the turn-on angle in a voltage controlled closed-loop speed controlled SRM.

First, the existence of an optimum turn-on angle, which minimizes the rms phase current (and thus the dc-link current) for constant load torque and speed is discussed. Next, a conventional control strategy for an SRM drive will be described. The new energy optimizing strategy will be explained and a
detailed implementation given. Finally, different test results will be shown which are obtained on two different load systems. Especially, a comparison will be done between an ordinary control scheme and an energy optimization control scheme.

II. MODELLING OF THE SRM

In order to develop an energy optimization strategy for an SRM, a dynamic model has been used. The characteristics of the SRM have been determined by the model developed in [11]. The model has been the basis of a computer program, which simulates the instantaneous current \( i \), the flux-linkage \( \psi \), the speed \( \omega \), and the electromagnetic torque \( T_{em} \).

The produced electromagnetic torque can be described as

\[
T_{em} = \int_{0}^{\alpha \cdot \theta} \psi \, d\theta
\]

where \( T_{em} \) is the electromagnetic torque, \( i \) is the current in a phase, \( \psi \) is the flux-linkage in the SRM, and \( \theta \) is the rotor-position. The torque calculated by (1) includes iron losses.

Simulations have been used to determine rms current and torque production as functions of turn-on and turn-off angles as well as speed and duty cycle. Fig. 1 shows the profile of the 6/4-pole SRM and the converter used for control.

A conventional converter is used for the SRM. Fig. 2 shows the idealized profile of the flux-linkage versus rotor position at constant current and at different rotor positions.

Simulations have been carried out to investigate the relationship between the electromagnetic torque and the phase current. To illustrate how the average electromagnetic torque \( T_{em} \) and rms phase current \( I_{rms} \) depend on the turn-on angle \( \alpha_{on} \) and duty cycle \( D \) at speed of 1500 r/min. (a) Electromagnetic torque \( T_{em} \), (b) RMS phase current \( I_{rms} \).

Fig. 3 shows that the torque and current do not behave equally for changes in the turn-on angle and the duty cycle. Therefore, the current is not constant for any set of \( (D, \alpha_{on}) \) that produces the same torque, and an optimum operating point can be expected, providing maximum efficiency.

The power losses in the SRM are not only determined by the rms current but also the iron losses. The motor losses \( P_{loss} \) can be characterized by

\[
P_{loss} = P_{cu} + P_{hy} + P_{ed}
\]

where \( P_{loss} \) is the total power loss in motor, \( P_{cu} \) is the copper losses, \( P_{hy} \) are the hysteresis losses, and \( P_{ed} \) are the eddy current losses.

The copper losses are dependent on the rms current in the stator and are given by

\[
P_{cu} = m \cdot R_{SRM} \cdot I_{rms}^2
\]

where \( m \) is the number of stator poles and \( R_{SRM} \) is the resistance in a stator pole winding.

In a voltage controlled SRM, the rms phase current will increase as a function of the turn-on angle \( \alpha_{on} \) and the conduction angle \( (\alpha_{off} - \alpha_{on}) \). However, if \( \alpha_{on} \) is moved too close to \( \alpha_{off} \) the desired torque will not be available.
The hysteresis losses $P_{hy}$ and the eddy current losses $P_{ed}$ depend on the excitation frequency as well as the level of magnetization. Approximately, the losses can be characterized by

$$P_{hy} = k_1 \cdot f \cdot \psi^2$$  \hspace{1cm} (4)
$$P_{ed} = k_2 \cdot f^2 \cdot \psi$$  \hspace{1cm} (5)

where $f$ is the excitation frequency of flux-linkage and $k_1, k_2, k_3$ are the empirical constants.

The iron losses are not uniformly distributed in the SRM. In the rotor poles, a high-frequency flux waveform will appear compared with the stator poles. A detailed loss model can be very hard to estimate and use. However, a general approach is to model the iron losses increase with higher speed [12] and that the copper losses will be dominant at lower speed which can also be seen from (3)~(5). Therefore, it is possible to determine an operating point where the power losses are minimized and the efficiency maximized.

### III. CONVENTIONAL CONTROL STRATEGY

A typical way to control the firing angles of the SRM is a Mode-Shift Controller (MSC) as shown in Fig. 4. To remain capable of controlling the SRM at high speed, the turn-on angle must be changed with the speed. Traditionally, this is done in steps and special ASIC circuits are available for this type of control [4]. A typical way to control the firing angles is shown in Fig. 5 with appropriate mode-names. “Normal” mode is used at low speed, “Long Dwell” mode is used at medium speed and “Advanced Long Dwell” mode is used at high speed. The main disadvantage of this control method is that excessive current is drawn when turning on earlier than necessary to achieve the current needed to produce the demanded torque. Fig. 6 shows an example of two phase currents, where the same average torque is produced but the rms currents are significantly different.

When using the control strategy shown in Fig. 5, the actual turn-on angle has only one optimum operating speed for each mode. The approach dealt with in this paper is to minimize the rms current and the power losses by adjusting $\alpha_{on}$ continuously. Fig. 5 also shows that the turn-off angle $\alpha_{off}$ is changed for higher speeds due to the fall-time of the current when turning off a phase winding. At lower speed, $\alpha_{off}$ can be kept constant. Again, significant current should be avoided at the negative edge of the flux profile ($\phi > 90^\circ$) to avoid negative torque production. The approach used here does not adjust the turn-off angle $\alpha_{off}$ continuously because the influence on the efficiency is primarily affected by the turn-on angle $\alpha_{on}$ when the SRM operates in voltage control. This is validated later by experiments.

### IV. ENERGY OPTIMIZING CONTROL STRATEGY

In order to get an optimized operating point at all speeds and all loads, it is necessary to use the turn-on and turn-off angles as control parameters. The proposed strategy to minimize the power consumption is based on the principle shown in Fig. 7.

Instead of measuring and using the rms phase current for an energy optimization, the dc-link current $I_{dc}$ is used. $I_{dc}$ reflects the active power fed into the converter. In order to minimize the power consumption which includes both the converter and the SRM, the dc-link current is measured and the dc-link voltage is assumed to be constant. The Mode-Shift Control in Fig. 4 is substituted with a Floating Angle Control (FAC), where $\alpha_{on}$ follows a first order function of speed determined by the optimum turn-on and turn-off angles at low and high speed. The turn-on and turn-off angles used in the FAC are given by

$$n < 1400 \text{ r/min}: \quad \alpha_{on} = 55^\circ$$
$$n > 1400 \text{ r/min}: \quad \alpha_{on} = 55^\circ - \frac{n - 1400}{3000} \cdot 30^\circ \quad (6)$$
$$n < 3200 \text{ r/min}: \quad \alpha_{off} = 82^\circ$$
$$n > 3200 \text{ r/min}: \quad \alpha_{off} = 82^\circ - \frac{n - 3200}{3000} \cdot 30^\circ \quad (7)$$

$$\alpha_{on_{,\min}} = 25^\circ \quad \alpha_{off_{,\min}} = 70^\circ \quad (8)$$
where \( n \) is the rotational speed, \( \alpha_{on} \) is the turn-on angle, \( \alpha_{off} \) is the turn-off angle, \( \alpha_{on,min} \) is the minimum turn-on angle, and \( \alpha_{off,min} \) minimum turn-off angle.

The functions for the firing angles can be explained by simulations. They can represent the firing angles which provide almost maximum efficiency. Achieved by experimental observations, the functions will only be an initial guess and can easily be machine and load-independent. Equations (6)–(8) can also be derived by the fact that a minimum conduction angle \((\alpha_{off} - \alpha_{on})\) is necessary to obtain maximum torque. At low speed, these firing angles are adequate. For speeds exceeding 1400 r/min, \( \alpha_{on} \) is adjusted due to the back-EMF to maintain full torque capability. The minimum turn-on angle \( \alpha_{on,min} \) is specified for high speed operation, to avoid negative torque production at the beginning of the conduction interval.

In this paper, \( \alpha_{off} \) is chosen relatively low initially and could be increased at lower speed. However, due to simplicity of the control algorithm \( \alpha_{off} \) is kept fixed below 3200 r/min and adjusted for higher speeds to avoid negative torque production. A minimum turn-off angle is specified in order to have a minimum conduction angle at higher speeds. Fig. 8 shows the turn-on and turn-off angles for the FAC as a function of speed.

Another obvious initial guess for the turn-on angle as a function of speed could be that the current should reach a commanded value before the rotor moves into the magnetic overlap position (\( \alpha_1 \)). The turn-on angle can be given as in [7]

\[
\alpha_{on} = -I_c \cdot \frac{L_u \cdot \omega}{D \cdot V_{dc}} + \alpha_1
\]

where \( I_c \) is the commanded/wanted current, \( L_u \) is the inductance in unaligned position, \( V_{dc} \) is the dc-link voltage, and \( \omega \) is the angular speed.

The turn-off angle \( \alpha_{off} \) could similarly be determined by

\[
\alpha_{off} = -I_{ph} \cdot \frac{L_a \cdot \omega}{V_{dc}} + \alpha_a
\]

where \( I_{ph} \) is the actual or maximum phase current and \( L_a \) is the inductance in aligned position.

In (10), it is assumed the converter applies negative voltage across the phase winding during turn-off. If a maximum current should be available to give the maximum torque, (6) can be calculated according to (9) and \( n_1, n_2, \) and \( n_3 \) can be estimated according to the previous specifications.

EO Algorithm

1. The speed controller assures the desired speed by varying the duty cycle \( D \) at an initial turn-on angle and a fixed turn-off angle, which are both controlled by the FAC.
2. In steady-state, the load torque remains constant and the power flow is measured in the dc-link \((V_{dc}, I_{dc})\) by the EO.
3. The turn-on angle is initially changed \( \Delta \alpha_{on} \) in either direction.
4. The speed controller changes the duty cycle \( D \) to reassure the desired speed.
5. When steady-state is reached again, a new set of \((\alpha_{on}, D)\) is obtained which exactly produces the necessary torque and gives a different power flow.
If the power flow has decreased, \( \Delta \alpha_{on} \) is moved further in the same direction (the sign of \( \Delta \alpha_{on} \) is unchanged).

If the power flow has increased, the sign of \( \Delta \alpha_{on} \) is changed.

This is repeated until the change in power flow is too small to encourage any change in angle and the turn-on angle will alternate between two or three angles which all give the highest efficiency. Fig. 9 shows a flow chart of the energy optimizer algorithm.

The time interval between two power flow measurements is determined by the time constants of the mechanical part of the system and the capability of the speed controller. The energy optimization principle is illustrated in Fig. 10 by simulations. By cutting the electromagnetic torque versus \((\alpha_{on}, D)\) curve at a constant torque (see Fig. 3(a)), a trajectory for \((\alpha_{on}, D)\) appears. The same trajectory implies an rms current corresponding to the constant torque, which is shown in Fig. 10(b). It can be seen that there exists a set of coordinates of \((\alpha_{on}, D)\) which defines the minimum rms-current and thereby a minimum power consumption. The optimum coordinates will move as a function of speed.

V. IMPLEMENTATION

All control parts are performed by a Siemens SAB 80C517A 8-b high-speed microcontroller. It receives position sensing signals from the motor and calculates speed and firing angles. The speed is calculated by the use of an edge-triggered timer. It produces firing pulses for all six power switches and also performs the speed control. The switching frequency of the converter is 16 kHz. By means of a Hall sensor the dc-link current is measured and thus the energy optimization is realized.

The speed is detected every 5 ms and the sample time for the Energy Optimizer is 2 s. Different tests are done to validate the proposed strategy. The tests are:

1) dynamic test of speed controller,
2) energy optimizing on piston pump load system,
3) validation of global minimum power consumption with dc machine load system,
4) influence from turn-on and turn-off angle adjustment,
5) comparison between MSC and EO.

VI. TEST RESULTS

Two load systems have been used for tests. One consists of a piston pump which circulates hydraulic oil in a closed pipe system. The other load is a permanent magnet dc-machine, used for fast load changes and accurate load torque control. The sample time for the speed controller is 5 ms and the sample time for the Energy Optimizer is 2 s. Different tests are done to validate the proposed strategy. The tests are:

1) dynamic test of speed controller,
2) energy optimizing on piston pump load system,
3) validation of global minimum power consumption with dc machine load system,
4) influence from turn-on and turn-off angle adjustment,
5) comparison between MSC and EO.

The first test is done for validation of the speed controller. Fig. 12 shows a step response where the speed controller assures reference speed in about 150 ms, which is fast compared to the time between two power flow samples.

---

**Fig. 11.** Implementation of FAC and energy optimizing control of SRM.

**Fig. 12.** Measured system response with speed controller by a step in reference speed from 1000 to 3000 rpm with hydraulic load.

**Fig. 13.** Measured values of power flow, turn-on angle, and speed with hydraulic system as load.
The next test shows the energy optimizer in operation. In Fig. 13, results are shown when the energy optimizer is used with the hydraulic load.

Fig. 13 shows that the optimum turn-on angle is found in about 40 s (20 power flow samples). The search time will strongly depend on the initial turn-on angle and in many cases the optimum value will be reached quickly due to the Floating Angle Control. The power measurement is performed every 100 ms, but a filtered value is used only every 2 s in the energy optimizer. Fig. 13 shows also the change in turn-on angle and the resolution of 1° can be seen. The resolution can easily be increased by software if necessary. The speed is also measured and is kept constant by the controller.

In the next tests, a dc machine has been used as load. This has been done to demonstrate the abilities of the energy optimizer with different types of load and different load torque-speed characteristics. It is also demonstrated that a global power minimum is found by the optimizer. Fig. 14 shows three different operating conditions with an active energy optimizer which is enabled after 10 s and with different initial guesses of the turn-on angles.

For the six tests, the initial turn-on angles have been set very low or very high. This is a worst case situation (lowest efficiency) but it illustrates the EO principle very well. The optimizer finds in both cases almost the same optimum turn-on angle with a maximum variation of 3°, and it is concluded that
a global optimization point is estimated in all cases. Fig. 14 shows the actual speed during operation, and it can be seen that it remains constant when the optimizer is active.

Previously it has been stated that the influence on the efficiency by adjusting the turn-on angle is much more dominant than the turn-off angle in voltage control and different tests are performed to validate this. Tests are performed at different speeds and different load torques. In Fig. 15(a), the efficiencies are shown when the turn-on angle is kept fixed and the turn-off angle is varied. The turn-on angle is varied according to the FAC-control specified in (6) and (7). Fig. 15(b) shows when the turn-off angle is kept fixed and the turn-on angle is varied. Where data points are missing, the converter is saturated ($D = 1$).

Fig. 15 shows the efficiency is very dependent on the turn-on angle while the adjustment of the turn-off angle does not change the efficiency significantly if it is chosen below $82^\circ$ for the test conditions. However, it should also be stated that the freedom of changing the turn-on angle in voltage control is much higher than the turn-off angle, because the turn-off angle is dependent on the turn-on angle. The test results also show a small adjustment of the turn-off angle can give a small increase in efficiency, but then the energy optimization control strategy becomes much more complex because then there are two parameters in the optimization scheme.

Finally, an efficiency comparison of the Mode-Shift Controller and a Floating Angle Control with an energy optimizer is done. The SRM runs with fixed torque at different speeds and the efficiencies are measured. The measured efficiencies include both the converter and the SRM. The measurement procedure has been that the SRM runs at one speed and one load for Mode-Shift Control, and after some time the control strategy has been changed to Energy Optimized Control and a new measurement is performed. This ensures comparative measurements. Fig. 16 shows the measured efficiencies for the two control strategies and their difference.

Fig. 16 shows that a significant improvement can be obtained by using Floating Angle Control together with an energy optimizer compared with an ordinary Mode Shift Controller. In some operating points, 8% absolute efficiency are gained by using the proposed strategy. Fig. 16(b) shows also that an efficiency higher than 82% for the whole system can be obtained with the EO-control.

VII. CONCLUSION

A new control approach to minimize the power consumption of a voltage controlled Switched Reluctance Motor when it runs at steady-state has been introduced. It requires regular measurement of the power flow in the dc link, control of the turn-on angle $\alpha_{on}$, and a fixed turn-off angle $\alpha_{off}$ as a function of speed. An internal control loop with a speed controller, which uses the duty cycle of the applied phase voltage as a control parameter, assures the desired speed, regardless of the firing angles. The energy optimizer has no influence on the dynamic behavior of the SRM because it is only enabled during steady-state operation. It only requires the possibility to control the firing angles in a continuous way which is realized by an 8-b microcontroller and a stable and fast speed controller.
Tests have shown that an 8% increase in absolute efficiency can be obtained in some operation points by using an Energy Optimizing algorithm compared with an ordinary control scheme.

The algorithm used for energy optimization is applicable to any Switched Reluctance Motor and the strategy also takes the characteristics of the converter into account.

APPENDIX

MOTOR RATINGS

The data of the three-phase, 6/4 pole SRM used for tests are:

dc-link voltage 80 V,
rated current 25 A,
rated power 1.0 kW,
rated shaft torque 4 N·m,
rated speed 2500 r/min,
max. speed 10,000 r/min, and
stator pole resistance $R_{SRM}$ 0.3 Ω at 25°C.

ACKNOWLEDGMENT

The authors thank F. Jensen, Danfoss A/S, for converter and switched reluctance motor design.

REFERENCES


