STATE OF THE ART OF SWITCHED RELUCTANCE MOTOR FOR TORQUE RIPPLE MINIMIZATION

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Abstract- Switched Reluctance Motor (SRM) is a type of synchronous AC machine that converts the reluctance torque into mechanical power. Torque pulsations are inherent in SRM due to the doubly salient structure of the machine. The SRM offers similar overall efficiency to an induction motor of the same rating since the windage and friction losses are comparable. Indirect torque control methods using Torque Sharing Functions (TSF) is applied for the minimization of the torque ripple in switched reluctance motor. The most classical and easily implemented controller is the hysteresis controller. The increase of the current ripples at steady state and the production of a variable switching frequency in hysteresis controller can be reduced by using sliding mode controller. This paper reviews their merits and limits based on a survey of the available literature to minimize torque ripple in Switched reluctance motor.

Keywords- Switched Reluctance Motor, Asymmetric Bridge Converter, Hysteresis Current Controller, Sliding Mode Control.

I. INTRODUCTION

Switched reluctance motor is gaining importance in both industrial and domestic applications in the last two decades due to their inherent simplicity, ruggedness, and extensive development. The reluctance principle for torque production is utilized in these machines, where the phases operate independently and in succession. The machine torque is essentially defined by the nonlinear phase torque-angle–current characteristics and the magnetization of the phases.

There are primarily two approaches for reducing the torque ripple. One method is to improve the magnetic design of the motor, while the other is to use sophisticated electronic control techniques. The torque pulsations can be reduced by changing the stator and rotor pole structures, but only at the expense of some specific motor outputs. The electronic control techniques is based on optimizing the control parameters, which include the supply voltage, turn-on and turn-off angles, and current level. This may lead to a reduction in the average torque, since the motor capabilities are not being fully utilized at all power levels.

Iqbal Husain introduced a hybrid torque ripple minimizing controller infusing the balanced commutator with torque sharing over an extended region. Although the results are for a particular four-phase SRM, it was suggested that the torque ripple minimization up to a reasonable desired level is possible if the issue is dealt with starting from the machine design phase. A direct torque controller using sliding mode control was proposed by S K Yahoo et al. in 2005. Torque ripple reduction up to a certain range was achieved where the upper speed limit, with accurate torque control, was decided by the controller bandwidth which in turn depends on the sampling frequency and DC link voltage.

Xue et. Al proposed two improved torque sharing functions, dependent on turn on angle, overlap angle and the expected torque using genetic algorithm was used to optimize these torque sharing functions. Exponential torque sharing function is found to give better results if maximum speed with torque control is considered as the evaluating target.

Vujicic introduced a family of TSFs by using different secondary objectives, such as power loss minimization and drive constraint consideration. However, the consideration of linear magnetic characterization and a simple torque equation may reduce drive efficiency and performance. Rajib Mikail et. al. proposed a novel method of profiling the phase currents to minimize the torque ripple of a switched reluctance machine. The method is a combination of machine design and control algorithm designed to function from zero speed to the maximum speed for the application.

II. SWITCHED RELUCTANCE MOTOR

A. Constructional Features

SRM has wound field coils of a dc motor for its stator windings wound concentrically on salient pole structures. The rotor is laminated steel structure shaped as projecting poles without any coils or magnets on it. Both the stator and rotor have salient poles, hence the machine is referred to as a doubly salient machine. The diametrically opposite stator phase windings are connected together in series or parallel to form an independent phase. The rotor is said to be aligned whenever diametrically opposite
Stator poles are excited. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation. When current flows in a phase, the resulting torque tends to move the rotor in a direction that leads to an increase in the inductance. Provided that there is no residual magnetization of steel, the direction of current flow is immaterial and the torque always tries to move the rotor to the position of highest inductance.

While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment. Likewise, by sequentially switching the currents into the stator windings, the rotor is rotated. The movement of the rotor, hence the production of torque and power, involves switching of currents into stator windings when there is a variation of reluctance and this variable speed motor drive is referred to as a switched reluctance motor drive.

The number of poles in the stator of SRM is usually unequal to the number of the rotor to avoid the possibility of the rotor being in a state where it cannot produce initial torque, which occurs when all the rotor poles are aligned with the stator poles. These phase windings can be excited separately or together depending on the control scheme or converter.

B. Advantages and Limitations
The SRM offers low cost manufacturing, very high speed operation, and robustness due to its simple construction and material composition. The physical form of the motor is simple and rugged, although the electromagnetic behavior is very non-linear and external control is more complex than comparable induction and DC motors. Concentrated phase windings on the stator and no windings on the rotor ease the cooling requirement of the machine. The lack of permanent magnets lowers reliance on imported rare-earth materials and improves the heat tolerance of the motor.

The power electronic control allows the torque and speed profiles to be programmed, allowing operational flexibility. The unidirectional phase current reduces the number of switches decreasing the component counts and expense. The SRM is fault tolerant, and allows high speed operation and low inertia, making it an excellent candidate for actuators and traction drives. The predominant source of loss in SRM is in the windings of the stator coils, but high current density is limited by the large cross-section of the coils. Iron losses due to saturation occur, particularly at high speeds due to higher switching frequencies, but the motor uses a relatively small amount of iron.

Fault tolerance is a key advantage of the SRM. Each phase in the machine is electrically independent, so a short circuit fault on one phase does not affect the other phases. The unfaulfted phases will have full operating capacity and full source voltage may still be applied with no electrical imbalance. Due to the varying phase inductance, there is a significant delay time in the current rise under a short circuit condition, allowing protection circuitry to detect and isolate the fault in an early stage to minimize damage. The converter only needs to conduct unidirectional current, so only one switch is required in series with the phase windings. This prevents the possibility of a shoot through fault (short circuiting the DC source will arise when both the switches of the same one leg of a full H-bridge circuit are closed simultaneously) that is a common failure mode in the bidirectional converters required by other types of motors.

Disadvantages of the SRM can include torque ripple, acoustic noise, electromagnetic interference generation, and excessive bus current ripple, and the converter must be carefully matched to a given motor for maximum performance. These motors also require more conductor connections than induction motors (one per phase in Y-connected induction motors). The highly non-linear nature of the SRM operating in saturation makes analytical modeling extremely difficult. Thus, measurements or finite element predictions for magnetization curves are required to formulate control schemes and predict performance during the design process.

These complexities can limit flexibility and customization of motors for specific applications. In general, the fixed speed SRM only appears competitive with induction motors for low cost, high volume applications such as vacuum cleaners and other commercial products. For larger fixed speed applications, the SRM is not typically cost efficient.
However, for variable speed, fault tolerant applications, the SRM is a viable alternative to induction and permanent magnet motors, with the inherent advantage of ruggedness and fault tolerance.

III. TORQUE RIPPLE MINIMIZATION

C. Torque Control

The electromagnetic torque in SRM is generated towards the direction such that the reluctance is minimized. The magnitude of torque generated in each phase is proportional to the slope of inductance and the square of the phase current, which is controlled by the converter or drive circuit, and the torque control scheme. The drive circuit and torque control scheme directly affect the performance and characteristic of the SRM. Since the torque is proportional to the square of current, it can be generated regardless of the direction of the current. And also because the polarity of torque is changed due to the slope of inductance, a negative torque zone is formed according to the rotor position. To have a motoring torque, switching excitation must be synchronized with the rotor position angle.

The inductance profile is classified into three regions, increasing, constant and decreasing period. If a constant exciting current flows through the phase winding, a positive torque is generated, when the machine is operated in inductance increasing period and in inductance decreasing period, torque is produce is negative. In the case of a constant excitation, no torque is generated, because the positive torque and negative one are canceled out, and the shaft torque becomes zero.

![Fig. 2. Classification of inductance regions](image)

As a result, to achieve an effective rotating power, switching excitation must be synchronized with the inductance profile. The three regions of inductance profile are bounded by \( \theta_{on1} \), \( \theta_1 \), \( \theta_2 \), \( \theta_{off2} \). The \( \theta_{on1} \) and \( \theta_{off2} \) are the on angles of the incoming and the following phases, which will depend on speed and load, respectively. \( \theta_1 \) is the starting point of the overlap between the stator and the rotor. \( \theta_2 \) is the aligned position of inductance in the outgoing phase. The entire range of the regions in a 3-phase electric motor is 120 electrical degrees. Here, phase A is the input and phase B is the output. In region 1, the inductance of phase A rises while that of phase B will be near its minimum value. The inductance of phase B has a very mild slope and thus, phase A will provide the greatest portion of the torque required. In region 2, the rotor position is such that its phase is in an aligned position where both the inductance slope and the torque decrease for phase A. Although the inductance of phase B is rising in this case, it cannot provide the required torque, hence both phases should be on.

In order for the negative torque of phase A to decline in the third region, its current should decrease and the greatest portion of the torque must be provided by phase B. In region 3, the torque generated by phase A will become negative and need to be reduced in order to enhance machine efficiency. This, in turn, requires phase A to become demagnetization. In this case, the inductance of phase B will be rising and it will be capable of generating the required torque.

D. Minimization of torque ripple

The causes of the torque ripple include the geometric structure including doubly salient motor, concentrated windings around the stator poles and the working modes which are necessity of magnetic saturation in order to maximize the torque per mass ratio and pulsed magnetic field obtained by feeding successively the different stator windings. Minimization of torque ripple can be achieved by improving the magnetic design of the motor and by using sophisticated electronic control techniques. The torque pulsations are reduced by changing the stator and rotor pole structures, but only at the expense of some specific motor outputs. The electronic approach is based on optimizing the control parameters, which include the supply voltage, turn-on and turn-off angles, and current level. The minimization of torque ripple through electronic control may lead to a reduction in the average torque, since the motor capabilities are not being fully utilized at all power levels. The control techniques can be broadly classified as indirect torque control techniques and direct torque control techniques.

E. Indirect Torque Control Methods

In AC machines, it is quite common to control the torque of the motor by converting torque reference into equivalent phase current references. Similar approach is followed in SRM, where torque is indirectly controlled by controlling the current. Hence, these methods are known as indirect torque control techniques. In SRM, torque to current conversion is not straight forward due to torque dependence on rotor position. The coupled nonlinear relationship between the torque, current and rotor position makes it infeasible to formulate an analytical expression between them.
To achieve this conversion, two methods are available in the literature. One method is to store the static T-i-θ characteristics in a look-up table and the other is to use Artificial Neural Networks (ANN). Look-up table approach requires large online memory whereas ANN requires intensive online computation. However, look-up table approach is the most commonly used technique due to its simplicity and ease of implementation.

The torque controller shown in the block diagram generates individual phase torque references such that the sum of phase torques is equal to the reference torque. Subsequently, reference currents are generated for each phase from the lookup table and assigned to a current controller. The current controller either consists of a hysteresis-controller or a fixed frequency Pulse Width Modulation (PWM) controller.

**F. Direct Torque Control Methods**

The indirect methods involve torque to current transformation, which is subjected to inaccuracies due to variations in the motor characteristics during operation. Thus, the concept of Direct Torque Control (DTC) has evolved, where the torque is directly controlled avoiding to this conversion. The motor torque for feedback is estimated in most of the cases from the static T-i-θ characteristics. Due to the nonlinear characteristic of switched reluctance machines, the instantaneous torque can be rather estimated only from the stored profile.

For this purpose, the torque profile is determined from rotor position and current or flux linkage and current. At low speeds, it will be difficult to estimate the flux linkage. The estimated torque is compared with the reference torque. But the direct control methods require large online memory. Though the structure is simple, but its implementation implies the complex switching rules, uncontrolled switching frequency and high sampling rate.

**IV. IMPLEMENTING TORQUE RIPPLE MINIMIZATION**

Indirect torque control methods using torque sharing functions (TSF) is applied for the minimization of the torque ripple in switched reluctance motor. The torque sharing functions is used to produce reference torque for the individual phases from the total reference torque. The individual phase reference torques are converted to corresponding phase current references using artificial neural network or static T-i-θ characteristics and the rotor position is sensed by the means of hall effect sensors. The conventional current controllers used are hysteresis controller or the pulse width modulated controller. The figure shows the block diagram of torque control.

**G. Torque sharing functions**

In SRM, torque ripple is generated mainly during the commutation period when multiple phases conduct together. A convenient electronic approach for minimizing torque ripple is to coordinate the torque production of the individual phases so that the total torque tracks the reference value generated by the position or speed control loop. The total torque sharing among the phases is governed by the phase T-i-θ characteristics of the SRM. A high bandwidth current regulator is necessary to regulate the phase currents or phase fluxes, which, in turn, maintain the desired phase torque it will directly affect the performance parameters like copper loss, peak current, back emf.

The input torque, \( T^* \) is divided into individual torque references, \( T^*_k \) for each phase through TSF block with respect to rotor position. The reference phase torque of each phase is obtained by the proper shifting of the pre defined torque sharing functions. This region can be divided into two major areas as commutation and single conduction mode. In the commutation area, two adjacent phases should produce positive torque based on the distinctive functions. In single conduction mode, only one phase must provide the reference torque. Here, excitation of not more than two phases in overlap region is considered.

According to the torque sharing curve in overlap region, the conventional torque sharing functions can be classified as linear, sinusoidal, cubic and exponential TSFs. The phase \( k \) is energized between the turn on, \( \theta_{on} \) and turn off angles, \( \theta_{off} \). According to the torque production capability these angles must satisfy conditions: \( \theta \leq \theta_{on} \leq \theta_{off} \leq \theta_{TOR} \). Overlap angle, \( \theta_{ov} \) denotes the interval when phase \( k \) shares torque with incoming phase or outgoing phase.

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The reference torque of phase k can be defined as,

\[ T_k^r(\theta) = \begin{cases} 0, & 0 \leq \theta \leq \theta_{on} \\ T^* \cdot f_{rise}(\theta), & \theta_{on} \leq \theta \leq \theta_{on} + \theta_{ov} \\ T^*, & \theta_{on} + \theta_{ov} \leq \theta \leq \theta_{off} - \theta_{ov} \\ T^* \cdot f_{fall}(\theta), & \theta_{off} - \theta_{ov} \leq \theta \leq \theta_{off} \\ 0, & \theta_{off} \leq \theta \leq \theta_{al} \end{cases} \]

During commutation intervals function, \( f_{rise} \) must rise from 0 to 1 and function \( f_{fall} \) must fall from 1 to 0.

### Linear TSF

![Linear TSF](image)

### Sinusoidal TSF

![Sinusoidal TSF](image)

**Fig. 6. Conventional Torque sharing functions**

### H. Generation of current references

The static T-i-0 characteristics or the artificial neural networks are conventionally used to make the torque to current conversions. Reference torque can be transformed to current references at low torque level using the equation,

\[ i_k^*(\theta) = \begin{cases} \frac{T_k^r(\theta)}{a_k(\theta)}, & a_k(\theta) > 0 \\ 0, & a_k(\theta) \leq 0 \end{cases} \]

At high torque levels using the equation

\[ T_k(\theta, i_k) = \frac{a_k(\theta) i_k^2}{1 + b_k(\theta) i_k^3} \]

The angular functions, \( a_k \) and \( b_k \) depends on the motor geometry and magnetic property of the iron. They can be experimentally obtained on the available motor. The torque function \( T_k(\theta, i_k) \) is invertible as it can be rearranged as current function \( i_k(\theta, T_k) \).

Thus the reference torque can be directly converted to the reference current as,

\[ i_k^*(\theta, T_k^r) = \frac{T_k^r}{a_k} \left[ \frac{b_k}{2} + \frac{b_k^*}{4} + \frac{a_k}{T_k^r} \right]^{\frac{1}{3}} \]

Instead of using the 3D lookup table of the static T-i-0 data for the reference torque to current translation, only the data of the two angular functions are stored in memory to be used for calculation of reference current.

### I. Asymmetric bridge converter

Asymmetrical converters are commonly used in switched reluctance drives. There are two main switches and two flywheel diodes in per phase circuit. During the period of chopping, one main switch is turned on and the other switch is turned off, the phase current flows through the turned on main switch and the flywheel diode. During the period of commutation, the main switches are turned off and the stored magnetic energy in the motor is released with the flywheel diodes by the continuing current. The three states, modes of operation are

- **Mode 1**: Magnetization mode
- **Mode 0**: Freewheeling mode
- **Mode -1**: Demagnetization mode

During the magnetization or energisation mode, both switches (\( S_1 \) and \( S_2 \)) are on and the current rises rapidly in the phase winding. During the second mode, the freewheeling state, only one switch and one diode are on. Zero voltage applied across the phase winding and the current continues to flow through one switch and one diode, although it is gradually decaying. No energy is transferred to or from the supply in this mode. The third mode, demagnetization, occurs when both switches are off and the energy in the phase winding is returned to the supply via the freewheeling diodes. The voltage is reversed across the phase winding which forces the current to rapidly decay to zero.

**Fig. 7. Asymmetric converter**

The rest of the phases are similarly connected. Turning on transistors \( S_1 \) and \( S_2 \) will circulate a current in phase A of the SRM. If the current rises above the commanded value, \( S_1 \) and \( S_2 \) are turned off. The energy stored in the motor winding of phase A will keep the current in the same direction until it is...
When the current error exceeds $-\Delta i$, the switches $S_1$ and $S_2$ are turned off simultaneously. Hysteresis current controller is considered here due to its simplicity in concept and implementation. At that time, diodes $D_1$ and $D_2$ take over the current and complete the path through the dc source. The voltage of phase A is then negative and will be equal to the source voltage, $V_{dc}$. During this interval, the energy stored in the machine inductance is sent to the source, thus exchanging energy between the load and source repeatedly in one cycle of a phase current. After the initial startup, during turn-on and turn-off of $S_1$ and $S_2$, the phase machine winding experiences twice the rate of change of dc link voltage, resulting in a higher deterioration of the insulation. This control strategy hence puts more ripples into the dc link capacitor, thus reducing its life and also increasing the switching losses of the power switches due to frequent switching necessitated by energy exchange.

The energy stored in the phase A can be effectively circulated in itself by turning off, say, $S_2$ only. In that case, the current will continue to flow through $S_1$, phase A and $D_1$, the latter having forward biased soon after $S_2$ is turned off. The voltage across the winding becomes zero if the diode and transistor voltage drops. That will take the phase current from $I_p + \Delta i$ to $I_p - \Delta i$ in a time greater than had it been forced against the source voltage using the previous strategy. This particular fact reduces the switching frequency and hence the switching losses. When the current command goes to zero, both $S_1$ and $S_2$ are turned off simultaneously.

During this interval, the voltage across the winding is $-V_{dc}$ as long as $D_1$ and $D_2$ conduct (i.e., until $i_a$ goes to zero) and thereafter the winding voltage is zero. The voltage across $S_1$ during its off time and when $S_1$ is on is equal to the source voltage, $V_{dc}$.

\[ J. \text{ Hysteresis Current Controller} \]

The most classical and easily implemented controller is the hysteresis controller. The only control parameter is the hysteresis band $\Delta i$. In the case of an analog implementation, this parameter ensures that the instantaneous current is bounded between $i \pm \Delta i/2$, where $i$ is the desired current. In this case, the current ripple is equal to $\Delta i$ and the current controller output takes only two distinct values $\pm V_{dc}$.

In the hysteresis switching based current controller, the current control is much simpler. The current error is computed from which the switching is generated depending on its relationship to the hysteresis current window. The on time of the switches corresponds to the phase winding energisation and off time corresponds to demagnetization of the winding.

The freewheeling corresponding to the interim off-times during phase conduction time have to be discriminated and coordinated with the current command and outputs of the hysteresis current controller. The modeling is as follows: The current command will be compared to the motor phase current, $i_a$.

The switching logic of the hysteresis controller is summarized as:

- If $(i_a^+ - i_a^-) \geq \Delta i$ then $V_e = V_{dc}$
- If $(i_a^+ - i_a^-) \leq -\Delta i$ and $i_a^+ > 0$ then $V_e = 0$
- If $(i_a^+ - i_a^-) \leq -\Delta i$ and $i_a^+ \leq 0$ then $V_e = -V_{dc}$

where $\Delta i$ is the hysteresis window and $V_{dc}$ is the link voltage. It is assumed that the power devices in the converter are ideal in this illustration, hence their voltage drops and switching times are neglected. The applied voltage is 0 or $-V_{dc}$, depending on the converter configuration and switching strategy for negative current error. When the current error is less than the negative of the hysteresis current window, the applied voltage to the machine phase is zero when the current command is positive, and the applied voltage to the machine phase is negative when the current command is negative.

The two main drawbacks of this controller are the increase of the current ripples at steady state and the production of a variable switching frequency, which generate additional acoustic noise in SRM. To reduce these ripples, the hysteresis band $\Delta i$ must be reduced but it increase the switching frequency of the converter, and therefore increase the power converter
losses. However, in practice, the current controller is implemented on a processor. To reduce these ripples as much as possible, the sample time \( T \), must be small. Therefore, this latter is limited according to the processor capacities.

K. Sliding Mode Controller

The increase of the current ripples at steady state and the production of a variable switching frequency in hysteresis controller can be reduced by using sliding mode controller (SMC). Sliding mode controller is an attractive feedback control technique that can guarantee the stability of nonlinear systems. The main idea is to employ a discontinuous control input to force the state trajectory of a nonlinear system to "slide" along a pre-specified surface in the state space. This surface, called a sliding manifold, represents the properties of desired plant dynamics, such as stability to the origin and tracking. SMC is generally robust to external disturbances and changes in system parameters because the direction of a state trajectory depends only on the position of the state with respect to the sliding manifold.

V. COMPARISON

The two main drawbacks of this controller are the increase of the current ripples at steady state and the production of a variable switching frequency, which generate additional acoustic noise in SRM. To reduce these ripples, the hysteresis band \( \Delta i \) must be reduced but it increase the switching frequency of the converter, and therefore increase the power converter losses. Sliding Mode Control can be used to obtain smooth electromechanical torque from SR motors, provided that SMC function is well chosen. Furthermore, it is observed that the current waveforms are not fast changing and do not have peaky waveforms, contributing to the reduction of noise. SRM shaft torque could be controlled to follow the reference level and the torque ripple is very small.

VI. SUMMARY

Switched reluctance motor have the attraction of simple and robust construction, high-speed and high-temperature performance, low costs, and fault tolerance control capabilities large variety of schemes are available for practical applications. The robustness of switched reluctance motor can be improved by adequate control structures such as sliding mode control.

REFERENCES


