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Open Loop Control of Switched Reluctance Motor Using Theta Position Sensing

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***Abstract*— The switched reluctance motors had gained more attention among the variable speed drives due to its inherent simplicity and low cost. It is an electronically commutated motor and need to be driven from a converter. The excitation of the different phases of the converter is dependent on the rotor position. This paper presents the simulation of the open loop control of a 6/4 switched reluctance motor driven with the conventional asymmetric converter using theta position sensing. Here the gate signals are derived from the theta output of the motor.**

***Keywords*— Switched reluctance motor, Asymmetric bridge converter, Theta position sensing, Open loop control.**

I. INTRODUCTION

Switched reluctance motor is increasing great acceptance in industry due its inherent simplicity, low cost, ruggedness, and extensive development over the past two decades. Each phase is largely independent physically, magnetically and electrically from the other machine phases. It can achieve very high speeds (20000 to 50000 rev/m) because of the lack of conductors or magnets on the rotor. However, It must always be electronically commutated and thus cannot run directly from a dc bus or an ac line Its salient structure causes strong nonlinear magnetic characteristics, complicating its analysis and control [1].

The conventional converter used to run the switched reluctance motor is the asymmetric converter and is the most flexible one. When power is applied to the stator windings, the rotor magnetic reluctance creates a force that attempts to align the rotor pole with the nearest stator pole. In order to maintain rotation, an electronic control system switches on the windings of successive stator poles in sequence so that the magnetic field of the stator leads the rotor pole. The excitation of the phase windings of the machine is dependent on its rotor position. Gate signals are derived from the rotor position. In this paper theta signal is used to generate the switching signal for the converter rather than integrating the speed signal.

II. SWITCHED RELUCTANCE MOTOR

A. Basic Features of Switched Reluctance Motor

The switched reluctance motor (SRM) is a type of synchronous machine in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximized. The stator houses a set of coils or windings per salient pole, which are typically connected in series between opposing poles. The coils are wound concentrically with no overlap between phases, resulting in little mutual inductance between phases, and ensuring a greater portion of copper is used as active length in the windings. The rotor is similarly constructed of laminated magnet steel with salient poles, but has no windings or permanent magnets, thus requiring no brushes or slip rings, and allowing a higher operating temperature and increased durability. Hence the machine is a doubly salient, singly excited machine with both the stator and rotor having salient pole structure [2].

The basic concept of operation is that a DC current is applied to a phase which creates a magnetic flux that travels through the rotor. The rotor tends to position itself in a way that minimizes the reluctance of the flux path thereby maximizing the inductance of the excited winding and creating a torque that aligns the salient poles of the rotor and stator as shown in Fig. 1. As a result of its inherent simplicity, the SRM promises a reliable and a low-cost variable-speed drive.

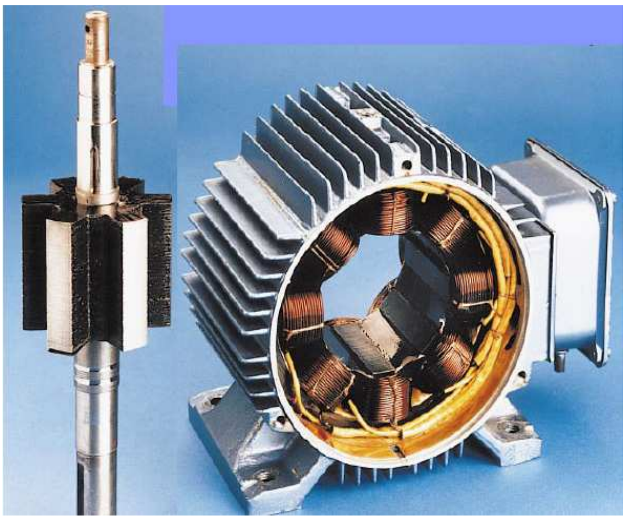

Fig.1. Stator and rotor of switched reluctance motor

The energy conversion in a SRM depends on the magnetic interaction of the rotor and stator, which changes with relative angular position. The aligned position occurs for a given phase when a pair of rotor poles is exactly aligned with the stator poles of that phase [3]. When the axis equidistant between the pairs of rotor poles (interpolar axis) is exactly aligned with stator poles of a given phase rotor poles, it is said to be in the unaligned position. Any other position is referred to as a misaligned position. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be the unaligned position and at this position the phase has minimum inductance [4] as shown in Fig. 2.

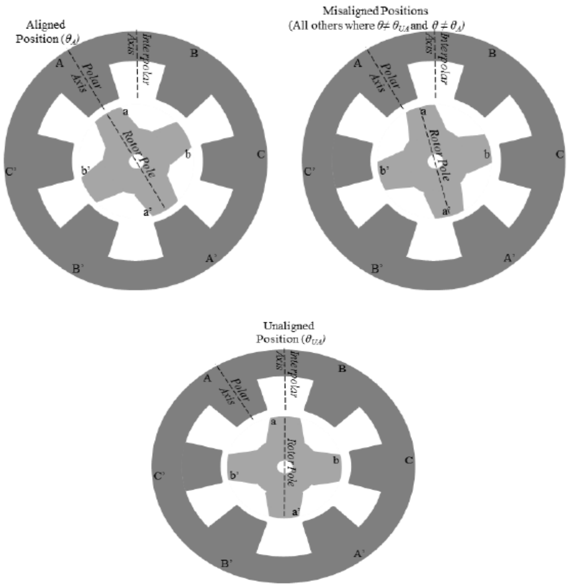

Fig. 2 Misaligned, aligned and unaligned positions for SRM

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 cancelled out, and the shaft torque becomes zero. As a result, to achieve an effective rotating power, switching excitation must be synchronized with the inductance profile shown in Fig. 3.

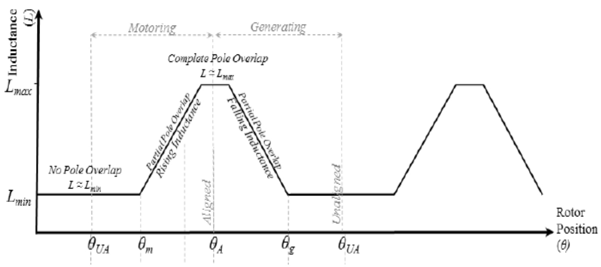

Fig. 3 Inductance profile

The 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. 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.

A minimum of rotor losses and low switching losses in the controller create high overall system efficiency over an extreme wide control range. Hence, SR motors are not designed and optimized to a fixed synchronous speed. Due to the high efficiency and the minimum losses of an SR motor it can, as general rule, produce a higher power (torque) to weight relation as standard ac or dc motors. Due to the low rotor losses extremely high starting torque is realizable permitting prolonged operation in the stall condition. The simple construction of the magnet-free, brushless SR Motor enables integration with the driven machine easier than with more conventional motor.

Disadvantages of the SRM can include torque ripple, acoustic noise and 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 (two per phase vs. one per phase in wye-connected induction motors). The highly non-linear nature of the SRM operating in saturation makes analytical modeling extremely difficult.

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.

B. Mathematical Modeling

- The voltage equation for the equivalent circuit of SRM is given by,

$$V = iR + L(i,\theta)\frac{di}{dt} + i\,\frac{\partial L(i,\theta)}{\partial \theta}\omega$$

$$e = i\,\frac{\partial L(i,\theta)}{\partial \theta}\omega$$

Where V is the voltage applied to phase winding, i is the phase current, $L(i,\theta)$ is the phase inductance (function of phase current and rotor position, θ), R is phase resistance, ω is rotor speed and e is the electromotive force [5].

- The Electromagnetic torque equation is given by,

$$T_e(i,\theta) = T_L + B\omega + J\frac{d\omega}{dt}$$

Where T_e is electromagnetic torque, T_L is the load torque, B is viscous coefficient and J is moment of inertia.

- Electromagnetic torque is dependent on phase current and rotor position

$$T_e = \frac{1}{2} i^2 \frac{dL(i,\theta)}{d\theta}$$

- Mechanical equation is given by,

$$\frac{1}{2} i^2 \frac{dL(i,\theta)}{d\theta} - T_L = B\omega + J\frac{d\omega}{dt}$$

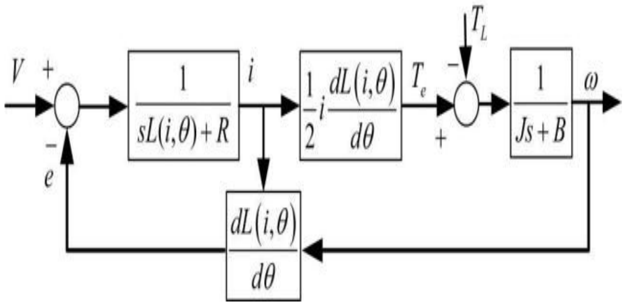

Fig. 4 Block diagram of single phase of SRM

III. Control of Switched Reluctance Motor

The purpose of a switched reluctance motor drive is to apply current in each phase in coordination with the rotor position to achieve the desired operating mode and torque output. As mentioned, one of the chief advantages of the SRM is that it simply requires unidirectional current to operate in all four quadrants, which entails fewer semiconductor switches to be used in the converter design and opens up the range of drive circuit options as compared to other motor types requiring bi-directional or sinusoidal current. Because of the inductive nature of each phase winding, the switches must be protected from transients due to the induced voltages after commutation occurs and current must always be provided a conduction path, so freewheeling diodes (so named because they allow current to circulate or "freewheel" within the circuit after turn-off) or some other type of clamping mechanism will also be required. The selection of converter topology for a certain application is an important issue. Basically, the SRM converter has some requirements, such as:

- Each phase of motor has at least one switch to be able to conduct independently.
- The converter should be able to excite the phase before it enters the generating or demagnetizing region.
- The converter energy can be supplied to one phase while extracting it simultaneously from the other phase. So, the converter should be able to allow phase overlap control.
- The demagnetization energy from the outgoing phase should be fed back to the dc source (dc-link capacitor) or using it in the incoming phase
- The converter has to be single rail of power source in order to reduce the voltage stress across the semiconductor switches.

A. *Conventional 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 [6]. The three states, modes of operation are

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

During the magnetization or energization 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. There is zero volts 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. 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.

IV. Open loop control of Switched reluctance motor

The switched reluctance motor need to be operated with a power electronic converter as this is an electronically commutated machine. The conventional asymmetric converter is used for simulation. DC supply can be used to excite the phase windings. The open loop control of the three phase 6/4 switched reluctance motor is performed with the help of computer simulation in MATLAB software. Fig. 5 shows the Simulink model of the open loop control of switched reluctance motor. The excitation of the windings is dependent on the rotor position. Hence the theta output from the motor is used to sense the position of the rotor and to derive the switching signals to drive the motor [7].

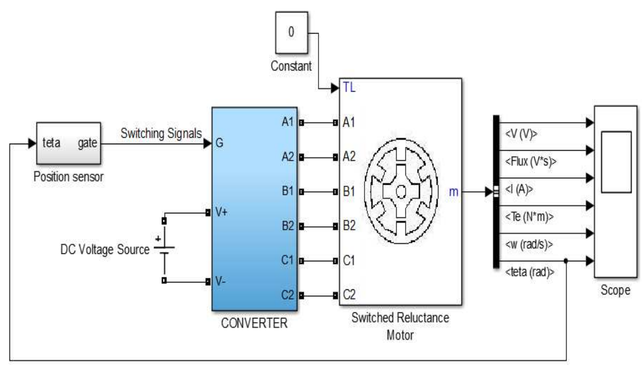

Fig. 5 Simulink model of open loop control of SRM

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The switched reluctance motor used for simulation has been taken from MATLAB software with the block parameter specification given in table 1. The SRM block input is the mechanical load torque in Nm which is positive for motoring and negative for generating operation. The block output of SRM is a vector containing stator voltage in volts, flux linkage in Vs, stator current in A, electromagnetic torque in N-m, rotor speed in rad/s and rotor position in rad respectively. Simulation run in discrete mode and the turn on and turn off angles are kept constant at 40 and 75 respectively.

Table 1: Block parameters of switched reluctance motor

Parameter	Value
Stator resistance (ohm)	0.05
Inertia (kg.m^2)	0.05
Friction (N-m.s)	0.02
Initial speed and position (rad/s and rad)	0,0
Unaligned inductance (H)	0.67e-3
Aligned inductance (H)	23.6e-3
Maximum current (A)	450
Maximum flux linkage (Vs)	0.486

A. *Asymmetric converter*

The Asymmetric converter has two diodes and two IGBT switches for each phase. Each phase is excited according to the gate pulses given according to the rotor position such that each phase is excited in every 90 degree rotation of the rotor as there are 4 rotor poles. Same gate pulse is given to both the switches of the corresponding phase. When the gate pulses are high the switches of the corresponding phase are in conduction and the supply voltage appears across the supply. An input voltage of 250 V is given to excite the phase windings [8]-[9]. Fig. 6 shows the Simulink model of asymmetric converter.

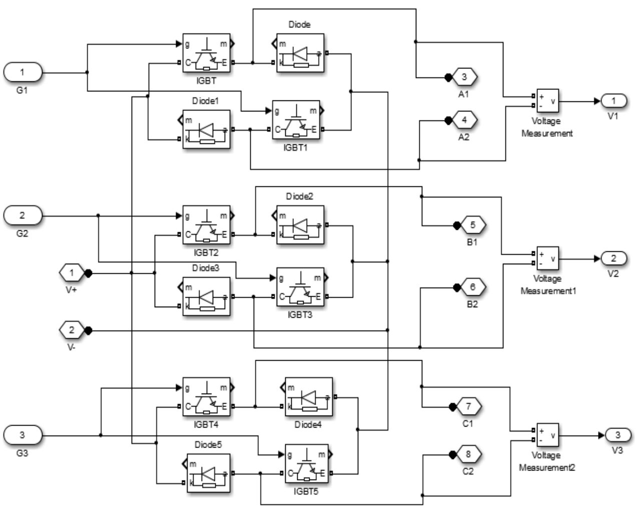

Fig. 6. Simulink model of Asymmetric converter

The gate signals for the switches of the corresponding phases are produced depending upon the rotor position. Fig. 7 shows the gate signals for the individual phases and Fig. 8 shows the output voltage waveforms of the asymmetric converter. This voltage appears across the phase windings of the corresponding phases. There are three output voltage levels including positive V_{dc}, negative V_{dc} and zero voltage level.

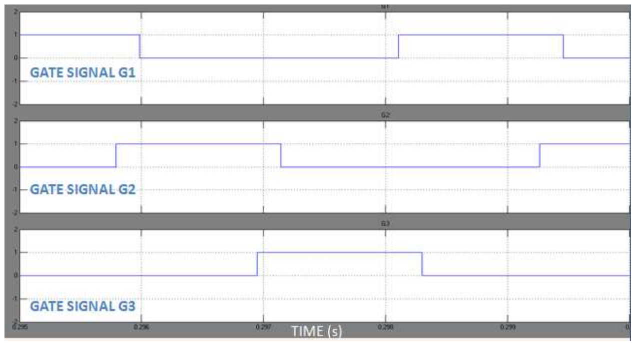

Fig. 7 Gate signals for the asymmetric converter

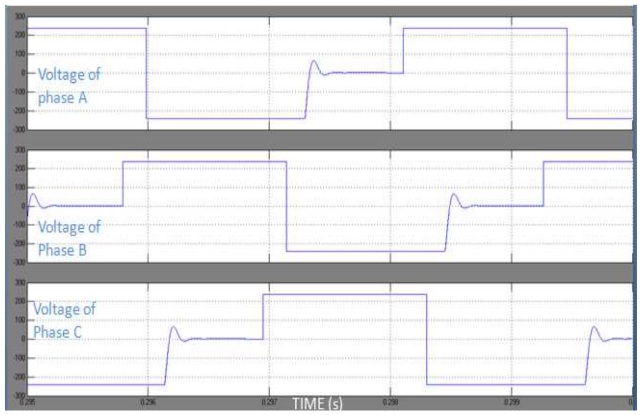

Fig. 8 Output voltage waveforms of asymmetric converter

B. *Phase Activation through Theta Position Sensing*

Fig. 9 shows the position sensor block using the theta position sensing and Fig. 10 shows the waveforms at different stages of the sensing [4].

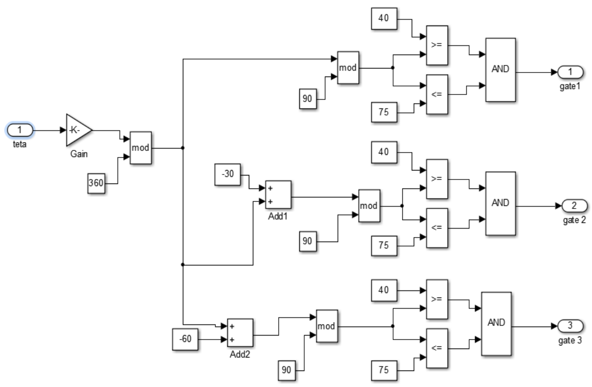

Fig. 9 Simulink model of theta position sensing

The theta output from motor is continuously increasing with time shown in waveform 1 of Fig. 10. It is initially converted into degrees and then the angle position is reset to 0^0 to 360^0 using modulus operator and dividing with 360 as shown in waveform 2 and is done to relate the absolute rotor position to position relative to the stroke. This signal is again divided by 90 using the modulus operator as the cycle repeats after each 90 degrees and is distributed for the individual phases.

The signal for the first phase is phase shifted by 0^0 shown in waveform 3, for the second by -30^0 shown in waveform 4 and for the third phase by -60^0 shown in waveform 5 of Fig. 10 respectively. These signals are compared with the turn on and turn off angles to generate the gate signals for different phases. When theta is between the turn on and turn off angle the gate signal is high triggering the IGBT switches of the particular phase. The generated gate signals are shown in Fig. 11.

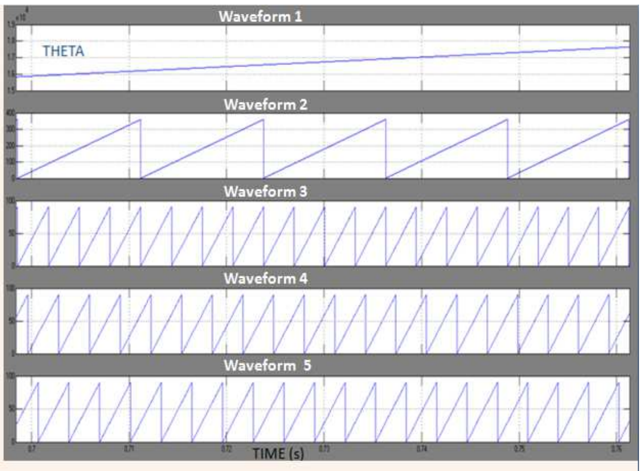

Fig. 10 Different stages of theta position sensing

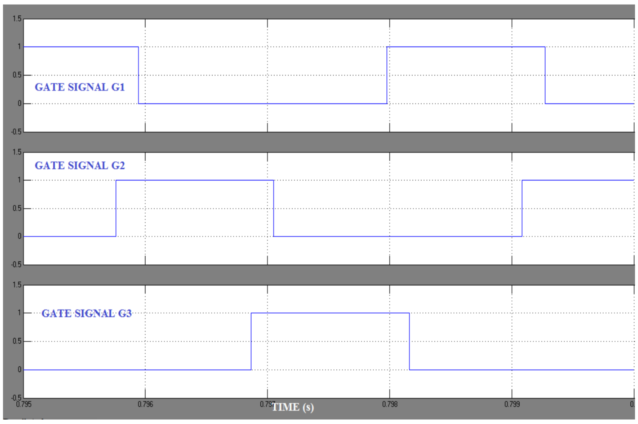

Fig. 11 Gate signals generated through theta position sensing

Fig. 12 shows the motor performance parameters of the open loop control of switched reluctance motor with phase activation through theta position sensing. The output voltage has three states coinciding with the output of the asymmetric converter which is fed to the phase windings [10]. The current waveform shows a peak while the phase rotor position is between the turn on and turn off angle. Speed and theta increases continuously with time as the time proceeds.

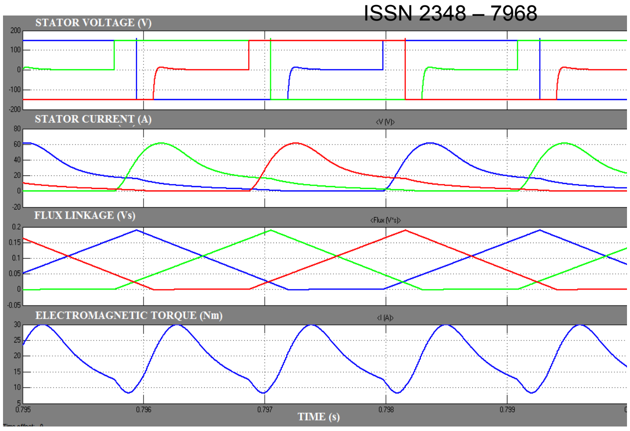

Fig. 12 Motor output waveforms of open loop control

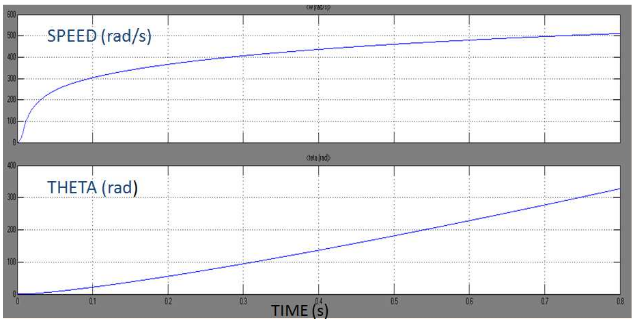

Fig 13 Speed and theta waveforms using theta position sensing

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