A Simplified Design and Control of Switched Reluctance Motor

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***Abstract* — The simplified sensor and sensor less control of Switched Reluctance Motor (SRM) drive is done here. The proposed sensor less excitation position is based on the amplified detecting phase current by the short dc pulse voltage according to the rotor position during detecting period. In the proposed sensor less scheme, a phase winding has excitation, detecting and non-excitation period respectively. The turn-on and turn-off positions of SRM are determined by the detecting period of the previous excited and next exciting windings with detecting phase current levels that are inverse-proportional to rotor position. During the detecting period of a phase, the different phases turn-on and turn-off position are determined by the envelope of detected current level. After then detecting period is ended. In order to get the linear relationship of rotor position and detected phase current, a short test voltage is applied during detecting period. Since the proposed sensor less scheme does not use the complex inductance calculation and any look-up table of flux and position, the excitation pattern for SRM can be easily determined.**

This paper presents a simplified approach of sensor less control of SRM without a complex calculation of rotor position from estimated inductance. Since the output torque is dependent on excitation position and excited current, the proposed sensor less scheme determines the only excitation pattern from the detected current of unexcited phase winding in the detecting period.

***Index Terms* — SRM, rotor position, inductance calculation, MATLAB/ SIMULINK**

I. INTRODUCTION

Among the electrical machines, the Switched Reluctance (SR) Motor is relatively a new entrant. This motor is quite rugged, reliable, inexpensive, simple to construct and offers a relatively high torque-to-inertia ratio. SR motor drives are basically used for simple power electronic converter requirement, fault tolerance, high efficiency and capability for very high speed operations. A switched reluctance motor (SRM) stator has salient poles with concentric windings on it. The rotor has no winding or permanent magnet. The number of stator and rotor poles depends on the selection of number of phases.

A switched reluctance motor (hereinafter referred to as an"SRM") is a power drive device which can be easily manufactured, be inexpensively manufactured, and have relatively high reliability since it is proved against drive accidents. switched reluctance motor (SRM) has been receiving attention for industrial and domestic applications due to its simplicity, low cost, fault tolerance and high efficiency over a wide speed range. Hence, an SRM drive system has some characteristics comparable with an existing induction motor or a permanent magnet motor, in view of high torque, a high output density, a high-efficient variable speed drive, and an economic inverter power in applied fields such as industrial machinery, airplanes, automobiles, consumer devices, and others.

This sensor less method is very simple to detect excitation position estimation and gives on efficient control of drive system. In the control of SRM, on accurate information of rotor position is essential to correct phase winding excitation. Since the output torque of SRM is dependent on the excitation period and excited phase current, the accuracy of rotor position is very important. In general speed control system, optical encoder is widely used for detecting of rotor position. Recently, sensor less Control and position detecting techniques are interested in the practical applications due to the problem of optical encoder in harsh environment and cost. In the sensor less control of SRM it removes the complex calculation of rotor position from estimated inductance which eases its control.

This is a simplified approach of sensor less control of SRM without a complex calculation of rotor position from estimated inductance. Since the output torque is dependent on excitation position and excited current, the proposed sensor less scheme determines the only excitation pattern from the detected current of unexcited phase winding in the detecting period. In the proposed sensor less scheme, a phase winding has excitation, detecting and non-excitation period, respectively. The turn-on and turn-off positions are determined by the detecting period of the previous excited and next exciting windings with detecting phase current levels that are inverse-proportional to rotor position.

In the sensor less control of SRM it removes the complex calculation of rotor position from estimated inductance. In order to get the sensor less rotor position of

SRM, mathematical based observer and flux detecting method are used. Since the accuracy of estimated rotor position of observer is dependent on mathematical model of SRM and electrical parameters, the estimation error is large in the low speed range. And it is very difficult to get the rotor position in standstill. Although the flux detecting method can easily estimate the rotor position without any complex mathematical model of SRM, the look-up table of flux and rotor position is required. And the relationship of flux and rotor position has non-linear characteristic due to the saturation effect. Recently, fuzzy logic and ANN(Artificial Neural Networks) have been used in speed estimation.

The simplified approach of sensor less control of SRM without a complex calculation of rotor position from estimated inductance. Since the output torque is dependent on excitation position and excited current, the proposed sensor less scheme determines the only excitation pattern from the detected current of unexcited phase winding in the detecting period. In the proposed sensor less scheme, a phase winding has excitation, detecting and non-excitation period, respectively. The turn-on and turn-off positions are determined by the detecting period of the previous excited and next exciting windings with detecting phase current levels that are inverse-proportional to rotor position.

The output torque is dependent on excitation position and excited current, the proposed sensor less scheme determines the only excitation pattern from the detected current of unexcited phase winding in the detecting period. In the proposed sensor less scheme, a phase winding has excitation, detecting and non-excitation period respectively. During the detecting period of a phase, the different phases turn-on and turn-off position are determined by the envelope detected current level. After then detecting period is ended. In order to get the linear relationship between rotor position and detected phase current, a short test voltage is applied during detecting period.

This sensor less method is very simple to detect excitation position estimation and gives on efficient control of drive system. A switched reluctance motor (hereinafter referred to as an "SRM") is a power drive device which can be easily manufactured, be inexpensively manufactured, and have relatively high reliability since it is proved against drive accidents. Hence, an SRM drive system has some characteristics comparable with an existing induction motor or a permanent magnet motor, in view of high torque, a high output density, a high-efficient variable speed drive, and an economic inverter power in applied fields such as industrial machinery, airplanes, automobiles, consumer devices, and others. The flux detecting method can easily estimate the rotor position without any complex mathematical model of SRM, the look-up table of flux and rotor position is required.

Since the proposed sensor less scheme does not use the complex inductance calculation and any look-up table of flux and position, the excitation pattern for SRM can be easily determined. This sensor less method is very simple to detect excitation position estimation and gives efficient control of drive system Experimental tests. The suggest method is verified with the help of simulation.

II. MATHEMATICAL MODEL OF THE SRM

Let us consider an elementary reluctance machine as shown in fig 1, the machine is single phase exited; that is, it carries only one winding on the stator. The excited winding is wound on the stator and the rotor is free to rotate.

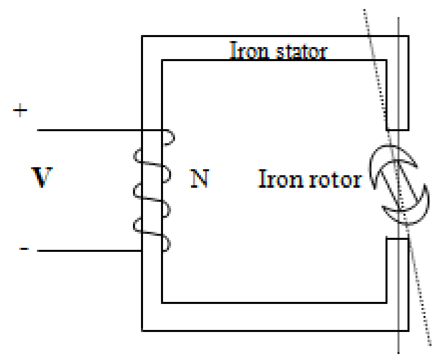

Fig 1 Single Phase SRM

The flux linkage is

$$\lambda(\theta) = L(\theta)i \quad \text{........... (1)}$$

where i is the independent input variable, i.e. the current flow through the stator. The general torque expression is given by

$$T_e = \left[\frac{\partial W'}{\partial \theta}\right] i = constant\ t \quad \text{...........(2)}$$

where W' is the co-energy which is varying with respect to position of the motor. At any position the co-energy is the area below the magnetization curve as shown in the Figure 1.

In other words, the definite integral

$$W' = \int_0^i \lambda(\theta, i)di \quad \text{...........(3)}$$

Where λ (θ, i) is the flux linkage with respect to angular position θ and current 'i'. So the torque equation becomes

$$T_e = \int_0^i \frac{\partial\lambda(\theta,i)}{\partial\theta} di \quad \text{...........(4)}$$

The mechanical work done

$$\Delta W_m = \Delta W^2 \quad \text{...........(5)}$$

Where W m is the mechanical energy and W is the stored magnetic energy. At any rotor position θ, the co-energy and the stored magnetic energy are equal and is given by

$$W_r = W' = \frac{1}{2}L(\theta)i^2 \quad \text{...........(6)}$$

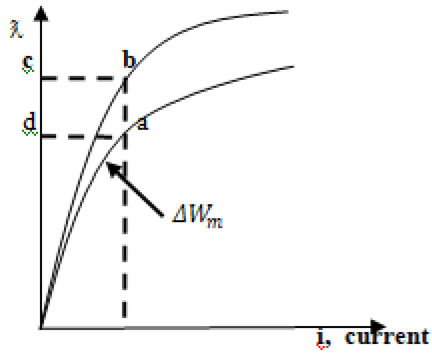

Fig 2. Flux Linkage Chart

The instantaneous torque reduces to

$$T_e = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \quad \text{...........(7)}$$

As most SRM is multiphase, the torque equation becomes a summation of torques produced by each phase. For m phases, the total torque is given by

$$T_e = \sum_{j=1}^{m} T_{ej} \quad \text{...........(8)}$$

Where T_{ej} is the torque due to single phase.

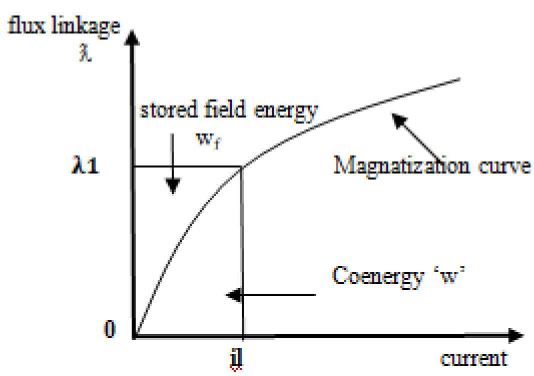

Fig 3 Energy Exchange

III. GENERAL PRINCIPLES OF SRM

Fig. 4 shows the general drive system and torque characteristics of SRM. In the Fig. 4, SRM has 6/4 stator and rotor structure, and the output torque is produced in the inductance variation region shown as Fig. 5.

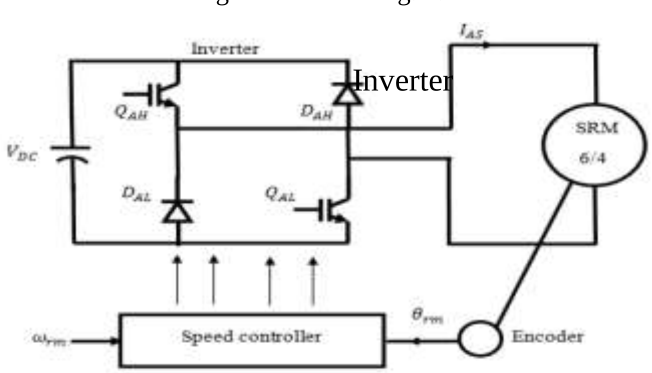

Fig 4 The general drive system of SRM

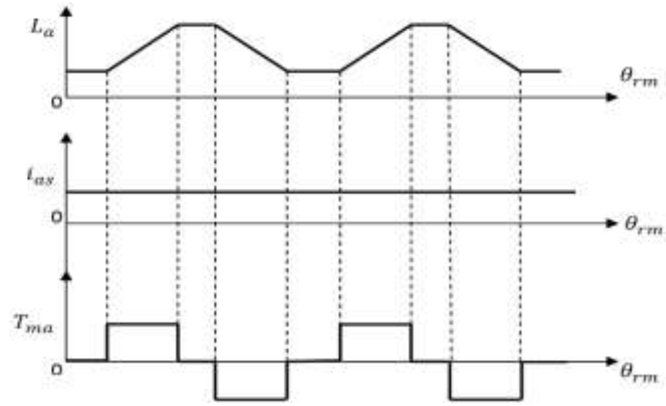

Fig 5 The general Torque characteristics

The output torque can be explained by the relationship of current and inductance as follows.

$$T_e = \frac{1}{2} . i^2 . \frac{dL}{d\theta_{rm}} \quad \text{...........(1)}$$

Shown as Fig 5, the inductance profile of SRM is dependent on electromechanical structure of SRM and rotor position. For this reason, sensor less position of rotor is derived by the estimated inductance from above equations.

In order to estimate the phase inductance, phase current excited by switching test pulse voltage is used at every sampling period shown as Fig 6.

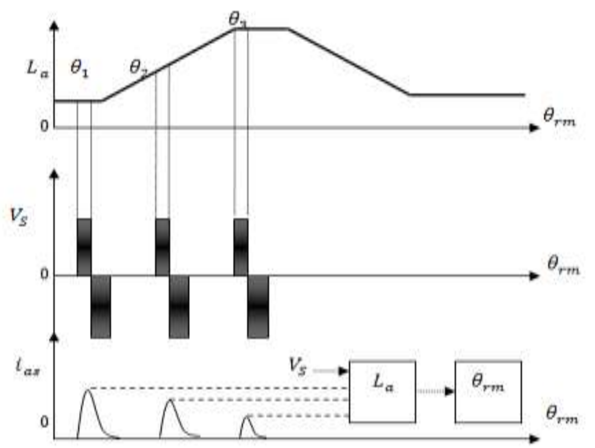

Fig 6 Waveform of test pulse voltage and phase current for inductance estimation

The voltage equation for estimating of phase inductance can be derived with disregarding of voltage drop of phase resistance and back emf.

$$V_s = L(\theta_{rm}) . \frac{di}{dt} \quad \text{...........(2)}$$

$$\hat{L}(\theta_{rm}) = V_s . \frac{dt}{di} \quad \text{...........(3)}$$

From the above equation, the phase inductance that is function of rotor position is calculated, and the rotor position is estimated from the calculated inductance. In spite of a complex calculation, the estimated rotor position from the calculated inductance has some error due to the saturation effect including the non-linear characteristics of inductance and voltage drop of phase resistance.

IV. SIMPLE SWITCHING

If the poles A0 and A1 are energised then the rotor will align itself with these poles. Once this has occurred it is possible for the stator poles to be de-energised before the stator poles of B0 and B1 are energized. The rotor is now positioned at the stator poles b. This sequence continues through c before arriving back at the start. This sequence can also be reversed to achieve motion in the opposite direction. This sequence can be found to be unstable while in operation, under high load, or high acceleration or deceleration, a step can be missed, and the rotor jumps to wrong angle, perhaps going back one instead of forward three as shown in the Fig 7.

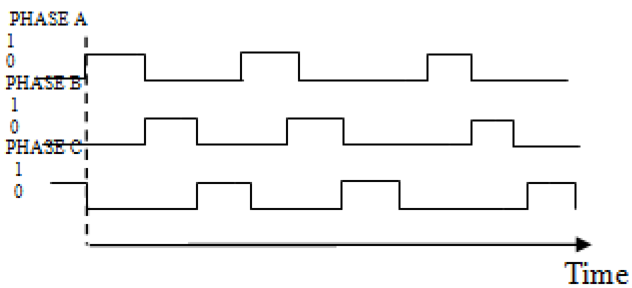

Fig 7 switching sequence

Improved Sequence

A much more stable system can be found by using the following "quadrature" sequence. First, stator poles A0 and A1 are energized. Then stator poles of B0 and B1 are energized which pulls the rotor so that it is aligned in between the stator poles of A and B. Following this the stator poles of A are de-energized and the rotor continues on to be aligned with the stator poles of B, this sequence continue through BC, C and CA before a full rotation has occurred. This sequence can also be reversed to achieve motion in the opposite direction. As at any time two coils are energized, and there are more steps between positions with identical magnetization, so the onset of missed steps occurs at higher speeds or loads.

In addition to more stable operation, this approach leads to a duty cycle of each phase of 1/2, rather than 1/3 as in the simpler sequence as shown in the Fig 8.

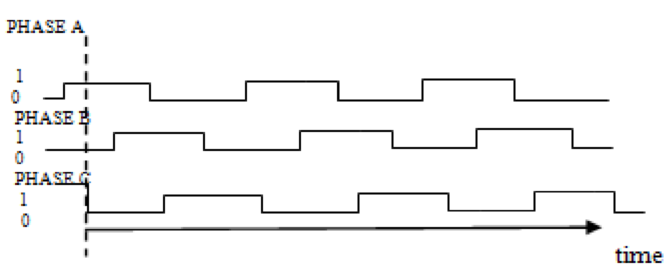

Fig 8 improved sequence

V. SIMULATION MODULE AND RESULTS

In order to verify the proposed sensor less scheme, 6/4 SRM is used in SIMULINK software. The specifications of SRM are given below as follows.

Stator poles = 6

Rotor poles = 4

Power = 3kW

Voltage = 240V

Current = 10A

Speed = 3000rpm

The simulation module for the control of switch reluctance motor is done with and without the use of sensor and the outputs for both sensor and sensor less control is obtained as shown below.

(A) Simulation Module for Control of SRM With Sensor:

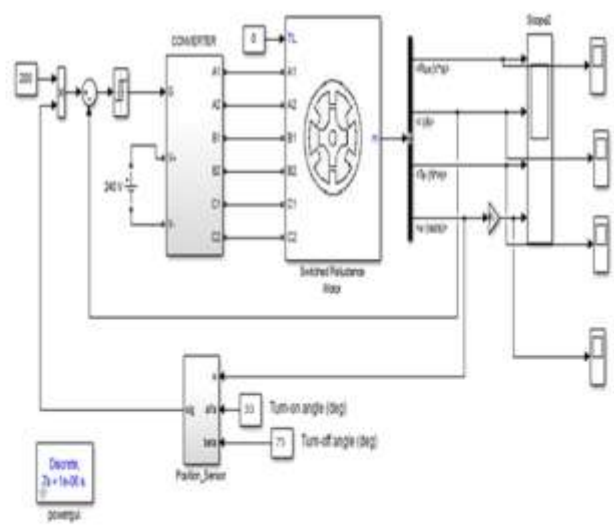

Fig 9 SIMULINK module for control of SRM with sensor.

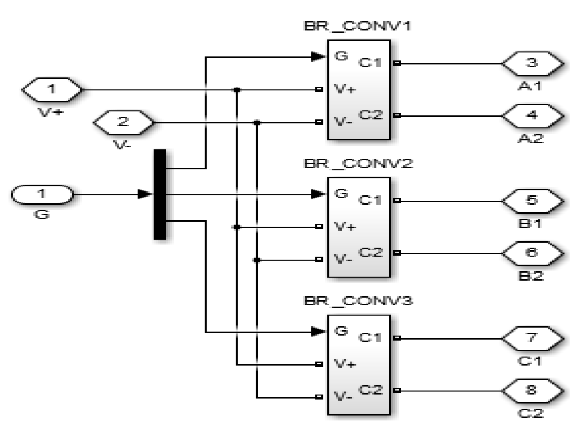

Fig 9.1 Sub system for converter

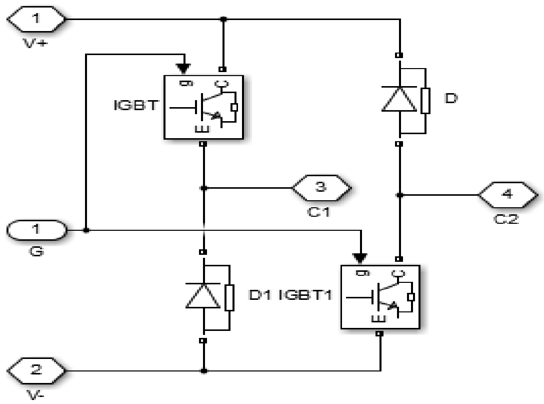

Fig 9.2 Sub system for each phase of converter

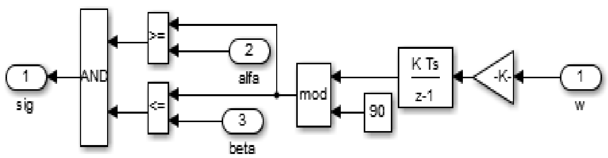

Fig 9.3 Sub system for position sensor

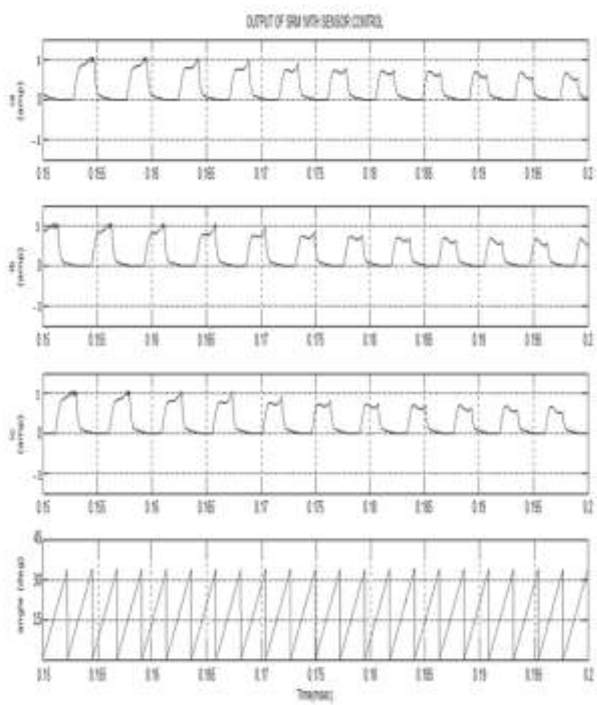

Fig. 9.4 Output waveforms for control of SRM with sensors

In the above figure shows output waveform for the control of SRM using sensor. The output waveform for the three phases is shown. Here the current for three phases a, b, c is shown and the obtained current is 2amps. The speed of the SRM is 2500rpm. The simulation time considered is 0.2m.sec.

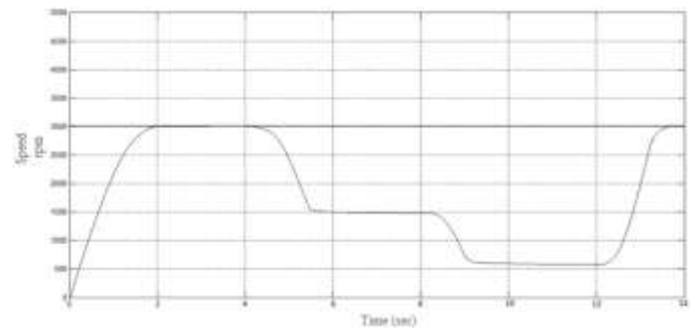

Fig 9.5. Output Speed waveforms for the control of SRM using sensor.

In the above figure shows output speed waveform for the control of SRM using sensor. The output speed for the three phases is shown here and the speed for the each phase obtained is as follow.

Time	speed
t=0 to 4 sec	3000rpm
t=4 to 8 sec	1500rpm
t=8 to 12 sec	600 rpm

(B) Simulation Module for Sensorless Control of SRM:

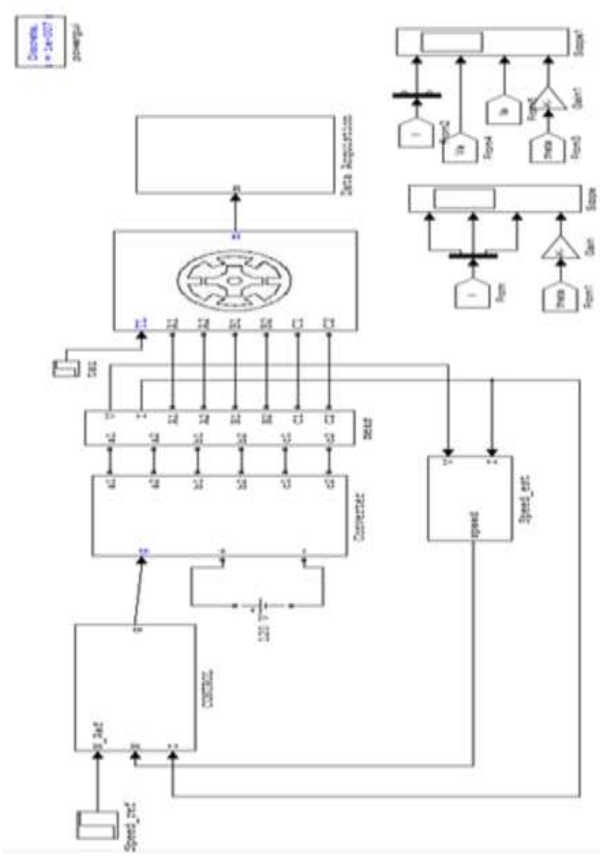

Fig. 10.1 SIMULINK module for the sensor less control of SRM.

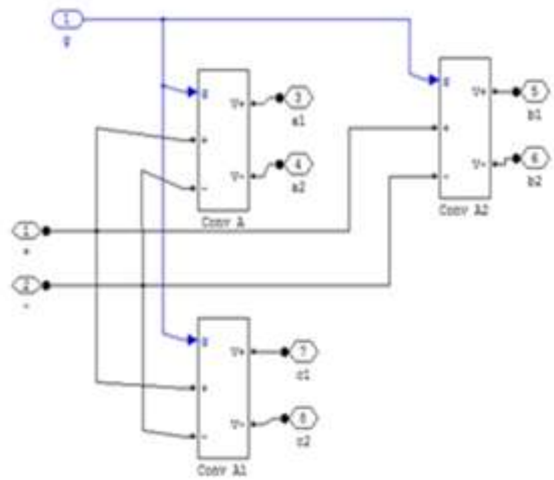

Fig. 10.2 sub system for converter

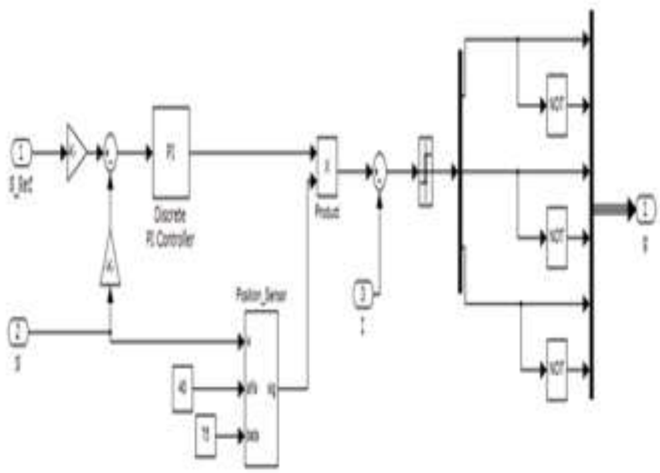

Fig. 10.3 sub system for controller

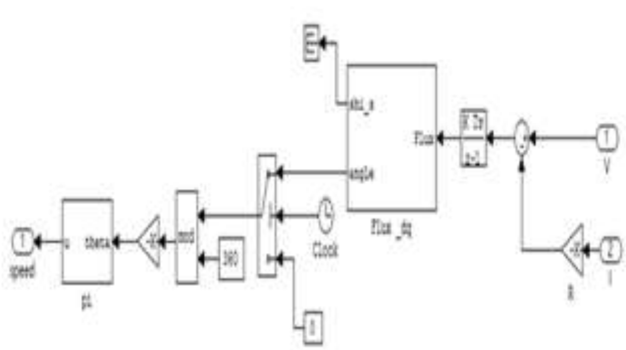

Fig 10.5 sub system for PI controller.

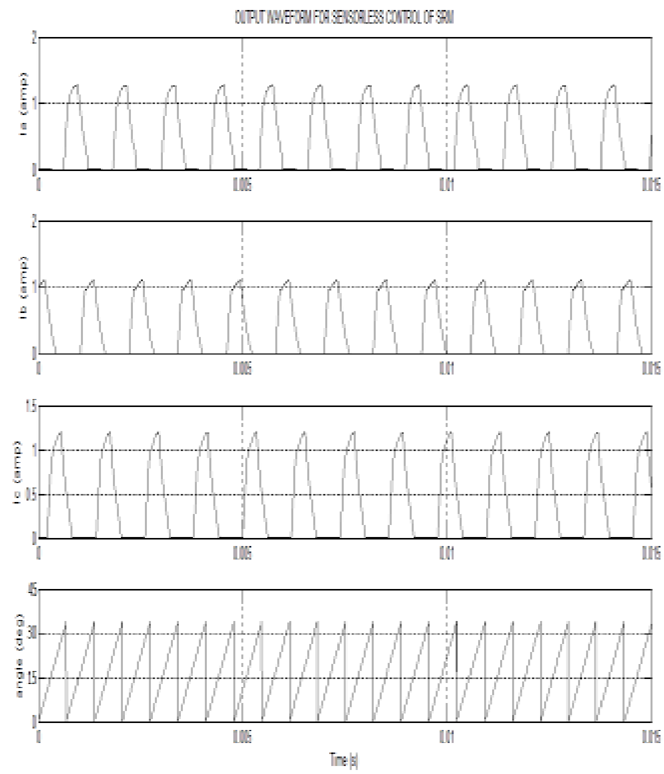

Fig. 10.6 Output 3 phase current and rotor angle waveforms for sensor less control of SRM

In the above figure shows output waveform for the sensor less control of SRM. The output waveform for the three phases is shown. The phase current has excitation and detected current. The excitation current produces the operating torque of SRM. And the detected current shaped pulse is used for rotor position estimation and excitation sequence of other phases. Here the current for three phases a, b, c is shown and the obtained current is 1.2amps. The rotor position angle of the SRM obtained is 30deg. The simulation time considered is 0.015sec.

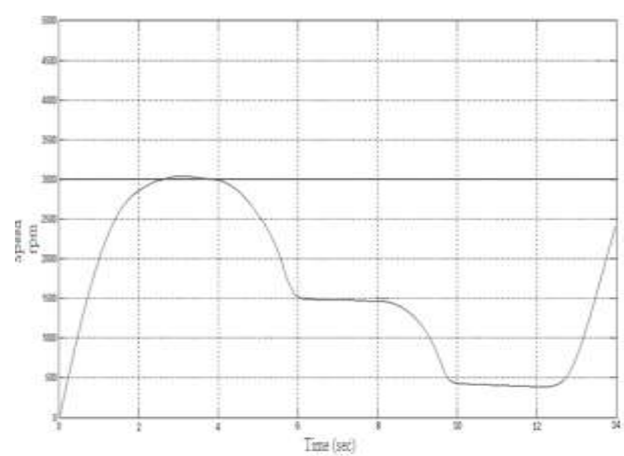

Fig. 10.7 Output Speed waveforms for sensor less control of SRM

In the above figure shows output waveform for the sensor less control of SRM. The output speed for the three phases is shown here and the speed for the each phase obtained in the waveform is as follows

Time	speed
t=0 to 4 sec	3000rpm
t=4 to 8 sec	1500rpm
t=8 to 12 sec	400 rpm

VI. CALCULATIONS

For the given 6/4 poles switched reluctance motor we know that

Number of stator poles N_s =6

Number of rotor poles N_r =4

Number of phases n =6

Speed of the motor N =3000rpm

The step angle of the motor is given as $\varepsilon = \frac{N_s - N_r}{N_s * N_r} * 360 = \frac{6-4}{6*4} * 360 = 30°$

Stator pole pitch = $\frac{2\pi}{N_s} = \frac{360}{6} = 60°$

Rotor pole pitch = $\frac{2\pi}{N_r} = \frac{360}{4} = 90°$

Rotor pole arc β_r = 32°

Stator pole arc β_s =32-2 = 30°

Form the paper[8] inductance in aligned position L_a=10mH and for inductance in unaligned position L_u=1mH.

Rotor slot angle $\alpha_r = \frac{2\pi}{N_r} - \beta_r$= 90-32 = 58°

For the L-θ value

$$\frac{\alpha_r - \beta_r}{2} = \frac{58-30}{2} = 14°$$

So the torque of the motor is given as

$$T = \frac{1}{2} i^2 \frac{dl}{d\theta}$$

Where $\frac{dl}{d\theta} = \frac{10*10^{-3} - 1*10^{-3}}{44-14} = \frac{9*10^{-3}}{30}$ and i = 2A

$$T = \frac{1}{2} * 2^2 * \frac{9*10^{-3}}{\pi/6}$$

T= 1.5x10^2N-m

Torque calculation for different speeds is given as

$$P = \omega_m . T$$

$$T = \frac{P}{\omega_m}$$

Where p is the power of the motor and ω_m is the speed of the motor

So for different speeds the torque obtained is

P= 3 HP = 3 x 746 = 2238 W

For ω_m =3000rpm

$$T = \frac{P}{\omega_m} = \frac{3 X 746}{3000} = 0.746x10^2 N/m$$

For ω_m =1500rpm

$$T = \frac{P}{\omega_m} = \frac{3 X 746}{1500} = 1.5x10^2 N/m$$

For ω_m =500rpm

$$T = \frac{P}{\omega_m} = \frac{3 X 746}{500} = 4.47x10^2 N/m$$

The obtain output results for SRM with and without the use of sensor are

Variables	**SRM With sensor**	**SRM Without sensor**
Current	1.2A	1.2A
Voltage	240V	240V
Speed	3000rpm	3000rpm
Torque	1.5x10^2N\m	1.5x10^2N\m
Rotor position angle	30deg	30deg

VII. CONCLUSION

In this paper the control of SRM is shown with and without the use of sensor and their outputs obtained are same in both cases but the use of sensor in the SRM causes mechanical strain on the motor, decreases the reliability, increases the size of motor and also increases the cost. These factors can be overcome by the use of sensor less control of SRM. So the sensor less control of SRM is more advantages when compared to the control of SRM with sensor.

In this method sensor less control of SRM using detected peak current at unexcited phase winding. Due to a simple current comparator for the excitation sequence determination, a complex calculation for rotor position estimation is not required. Without any look-up table of flux and rotor position, excitation sequence of each phase can be changed by the comparison of detected peak current in detecting period of other phases. For speed estimation, the peak value of detected current is used and a filtered estimated speed is used in the speed controller. Since the peak value of detected current is limited, saturation effect can be ignored. And the detected current has somewhat linear relationship with rotor position. It has been shown that the effect of sensor less control of SRM is the same as that of sensor control. Hence, such sensor less control of SRM is amenable in harsh environments. The complexity in computation is much reduced without compromising drive robustness.

In future, the sensor less control of SRM can be improved by the use of Fuzzy-PID controller in the controlling part instead of PID controller because Fuzzy controllers have the advantage that can deal with nonlinear systems and use the human operator knowledge. The most important is to make a good choice of rule base and parameters of membership functions. When the parameters are well chosen, the response of the system has very good time domain characteristics. One of the most important problems with fuzzy controller is that the computing time is much more long that for PID, because of the complex operations as fuzzification and particularly defuzzification. PID controller cannot be applied with the systems which have a fast change of parameters, because it would require the change of PID constants in the time. It is necessary to further study the possible combination of PID and fuzzy controller. It means that the system can be well controlled by PID which is supervised by a fuzzy system.

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