Simulation Analysis of PI Based Switched Reluctance Motor

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ABSTRACT

Development of switched reluctance motors have revolutionized the industrial drives, aircraft applications, food processors, compressors, fans, pumps, electric vehicle application centrifuges, vacuum cleaners and many more applications because of its simpler design, ruggedness and efficiency. Researchers are highly motivated to declare switched reluctance motor as a substitute of induction motors. In this research, PI based control of switched reluctance motor is developed and analyzed under robust environment. Different performance parameters and characteristics curves are obtained in order to derive conclusions. It is concluded that speed and current are supervised effectively and torque swells are reduced significantly with this controller. Matlab/ Simulink is used for simulation analysis.

Keywords: switched reluctance motor (SRM); PI control; Asymmetrical power converter;voltage and current control mode; Matlab/ Simulink

1. INTRODUCTION

Switched reluctance motor is a type of DC stepper motor which operates on reluctance torque. Power is delivered into the windings of the stator not of the rotor. For the stator, switched reluctance motor (SRM) has wound field coils. However, there is no attachment of coils for rotor. It has salient pole rotor made of soft magnetic material i.e. laminated steel. Poles are projected on the rotor. When power is supplied to stator winding, magnetic reluctance of rotor develops a force that attempts to align the poles of the rotor to the nearest stator poles. An electronic control system (ECS) switches are attached in order to maintain rotation of rotor. With this, the magnetic field of rotor always lags the magnetic field of stator. Further, instead of highly mechanical commutator requiring periodic maintenance for commutation, electronic position sensor is utilized to determine the angle of the shaft of the rotor. Solid state electronics is used for switching of stator windings. Because of this, pulse timing and shaping can be controlled dynamically [24]. Development of highly efficient and cost effective machine i.e., simpler in construction, having easier cooling mechanism and that performs application oriented tasks perfectly even in the harsh environment is a major concern of research nowadays.

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Successful development of this machine will revolutionize the washing machines and private sector of laundries would work 24/7 without any interruption because of its efficiency and ruggedness already proved in many applications such as general purpose industrial drives, aircraft applications, food processors, compressors, fans, pumps, electric vehicle application centrifuges and vacuum cleaners.

Instantaneous torque of two phases can be controlled by torque ripple reduction scheme. When both commutating phases are in their excitation periods, then the self-adaptive phase torque obeys linear distribution law. Outgoing phase is switched off when torque observation is applied. The newly controlled strategy can be effectively smoothed out the torque ripples which are caused by inherent non-linear and phase commutation torque production characteristics of a SRM. The strategy of torque has been experimentally implemented in based drive system (BDS). For on and off angle settings, the torque ripple reduction controller is not sensitive. Acoustic noise level of conventional flat-topped current by hysteresis control strategy as compared to torque ripple reduction control strategy is reduced. The combination of the turn-on angle, the turn off angle and phase torque distribution coefficient “k’ make it possible to achieve torque ripple-free operation for low to medium speed range and at maximum speed [1]. Both stator and rotor has a single stack and is constructed from laminations. The opposite poles of stator carrying coils that are connected in series to give a two pole field pattern, form the simplest design diametrically [2]. From the studies of stepping motor, it is desirable that, mutual inductance between phases is required to eliminate from the point of maximizing machine output. The mutual inductance due to main (air gap) flux will indeed be zero and is the feature of the model [3].

The control functions include feedback control with starting torque loop, speed loop, torque loop, position synchronized angle control and sequencing control. The dedicated digital hardware is implemented by angle control because of the critical timing requirement. The signal of feedback speed was synthesized from the 15° pulse position encoder in the higher speed range. Teledyne type sensor is used in the lower speed range [4].

The topology of switched reluctance motor in existing power electronics employs a converter that can be used to provide power factor correction. With suitable filtering, input sinusoidal current can be drawn and it would be in phase with the supplied voltage. Conventional drive is required with little usage of the power electronic components and increased control complexity. The operation of phases is not fully independent. It requires at least two phases which are fast recovery rectifier diodes. For the limited output range, the power factor of the drive is appropriate. The most cost effective solution is with very low power passive filtering. An extra active rectification or active filtering stage is suitable for higher powers [5].

The learning of the static conditions of the motor are carried out from the feed forward compensator. Stator actual current passing in circuit is different and learning processes of current controller and the feed forward compensator are not at all connected to each other. The desired current profile goes on whenever a torque demand is specified. The torque is computed using the non- linear model at the indicated rotor position and requirement of rotor positions for this learning is not at all related to the actual speed of the motor [6].

The outline of the switch reluctance motor torque/speed characteristic makes a switch reluctance motor strong competitor to induction motor drives. On the other hand, the drawbacks of switch reluctance motor are the presence of position sensor and torque ripple. The reason behind these drawbacks is because of the basic principle of its construction and operation [7]. The switch reluctance motor is designed with two phases excited at the same time. Phase excitation can be applied to four and five phase machines. This results in increase in its overall performance. Fully and fractionally pitched windings are obtained by mutual coupling. These winding models lead to increase in motor’s torque density as compared to switch reluctance motor with single tooth winding, but in the same time, the useless end-turns are also increased [8].

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The dynamic response (torque and speed) is monitored by investigating by many electrical machines which minimizes the cost, torque ripples, increased performance and reliability of switched reluctance motor [9] [27].

To suppress torque ripples, current waveforms are evaluated. The current of each phase and the rotor positions are affected by the torque of switched reluctance motor. Therefore, the fuzzy iterative approach (FIA) is proposed and waveforms of current are generated by FIA based rule with two inputs, i.e., error in torque and rotor position [10] [25].

There are numerous advantages of SRM due to its simple power electronic drive requirements, low cost and simpler construction. Motor's main components (stator and rotor) are electrically, physically and magnetically independent from each other and these machines are very reliable. The reason behind this is the absence of any coil or magnets on the rotor of SRM and due to this, high speed is achieved. Speed may reach up to 100000 rpm.

Salient structure of switched reluctance motor causes very strong nonlinear magnetic characteristics. Therefore, it is difficult to analyze and control. For the machine, the key requirement is to develop fine and simple control with no compromise over perfection [11].

A single phase SRM is found to be competitive for low-cost, variable-speed applications with a two – switch – based asymmetric converter and a two-phase SRM with two – switch – based split supply converter [12].

A test of vibration measurement with the rotor stationary is conducted in order to fix the frequencies for the natural mode. With a short voltage pulse, one phase of the motor is excited, which causes a triangular pulse of current. The pulse repetition frequency of 30 hz with the pulse duration of 5ms allows specific time for the vibrations to die out between pulses [13]. There is an analytical method for 1-phase and 2-phase switched reluctance motors to compute maximum and minimum inductances. A good correlation is shown with finite data analysis and experimental measurements. Computation has also been presented for an equivalent circuit model for inductance of motor. End core effects must be accounted to achieve improved accuracy between results from two dimensional modeling and experimental data. To convert energy efficiently, SRM is designed in a variable reluctance stepping motor. With an unequal number of rotor and stator poles, the motor is double salient and has the tendency to produce the torque. The excited stator phase poles are aligned with rotor poles which are not dependent on the direction of the phase current. Only one main switching device per phase is required by power circuit with a unipolar current. Further, the SRM has no winding of any kind and its rotor is brushless [14 15].

The switched reluctance motor is tested in a typical situation by an average values for the global model. The number of electrical equations is equal to the number of machine phases that is typically used in the SRM models. In this new model, only electrical equation is used. This model was designed in two steps. The first one was reduction of the number of the system dynamic equations [16].

The lower cost and higher efficiency are known advantages of SRMs which offer manufacturers the most attractive cost/benefit ratio. SRM possesses highly robust structure and drive circuitry. Therefore, it works properly in some faulty conditions e.g., when it is used in electric vehicles (EV) applications. In comparison to conventional motors, SRM is the best candidate for reliable variable-speed drive applications and rugged environment. There is self-starting torque in SRM with more than two-phase windings. Although, due to low cost driving circuits, both 1 – phase and 2 – phase SRMs are smarter, structural robust, lightweight and compact yet they characteristically suffer from the dead-zone issues [17].

Significant properties of the large coefficient matrix of finite element model are not explored by using the indirect coupling circuit equations. Thus, more effective solution methods may be obtained with the direct coupling for handling the large field matrix. When the finite element

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model is treated as a separate system, the progress of a simulator program is flexible by the aid of coupling coefficients which interacts with the circuit analyzer routines [18].

On the basis of the assumption that the SRM phase inductance profiles have triangular shapes, a new useful and simple method to model the SRM is developed. In this method, peak values depend on the electrical current through the phase windings due to magnetic saturation.

In this research, switched reluctance motor is simulated in Matlab/ Simulink and different electrical characteristics of motor is analyzed in order to derive conclusions for its usage in rugged environment.

This research paper consists of following sections: Section II covers the basics of PI Controller. Section III contains the mathematical formulation for switched reluctance motor. Section IV concludes the Proposed block diagram is given in section IV. Matlab/ Simulink environment for SRM is presented in section V. Section VI is the conclusion.

2. PI CONTROL

To reduce the steady state errors and to refine the speed of response, the combination of proportional and integral terms is necessary. The performance of proportional integral controller can be improved by giving feedback to the converter and to overcome the disturbance. Proportional controller and ON – OFF controller can eliminate the steady state errors and forced oscillations respectively.

2.1. Working

In PI controller, a reference current signal I_{ref} with the help of speed controller is generated. A sensor which is embedded into switched reluctance motor to sense the actual current coming from motor, both actual and reference currents are compared in current comparator. After comparison, the required signal goes to the current controller. A position sensor senses position of excited pole and feeds its derivative value to speed comparator so that speed could be controlled by speed controller. Different sets of logic switches are also used for this purpose [19].

In this way, speed and current of SRM can be supervised by using PI controller. This system is not applicable at that place where continuous variation in values is necessary. The reason is that it takes some time to change their parameters.

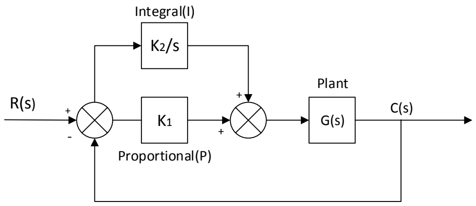

Fig. 1. PI Controller [23]

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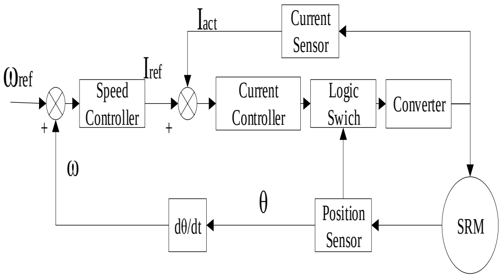

Fig. 2. Closed loop of PI controller for SRM [23].

First, the reference speed is applied to the speed controller. The speed controller compares the actual speed which comes from the switched reluctance motor with required speed to minimize the speed error. Similarly, the current controller is used to minimize the current error between the reference current and actual current which also comes from the SRM. As in SRM, the stator has winding and the rotor has no winding. The rotor has a position sensor which is used to sense the energized current and to align the rotor pole with the energized stator pole [20].

2.2. Torque Ripple Reduction

There are various factors to impact the torque swell, for instance, rotor or conceivably stator shape, air length, correspondence procedure, control framework and the essential factor of organizing current. This paper presents diverse techniques to reduce torque swell for a switched reluctance motor. In the first technique, a system is developed to restrict the torque with the help of alignment of inside torque and current with true objectives. The electromagnetic torque which is obtained from the motor is used to get the reference current from the association.

$$T \propto I^2 \tag{1}$$

Fig 7 shows the square outline for torque swell diminishing. In the second technique, the rotor post roundabout fragment plan is changed. In this way, the torque swell is reduced. As a result, the curves of rotor shaft and stator shaft are proportional when the two posts are aligned where the inductance is generally large. Along these alignments, it is vital to interrupt the current even before it absolutely modifies position of rotor post.

In this manner, to utilize the torque-conveying positive inductance inclined region absolutely, it is important that the current should be kept up in the locale. If the current continues advancing towards positive inclination area, then a negative torque is conveyed in SRM with proportional twisting of stator and rotor post with the fact that there is no zero slope inductance region [21] [26][28][29].

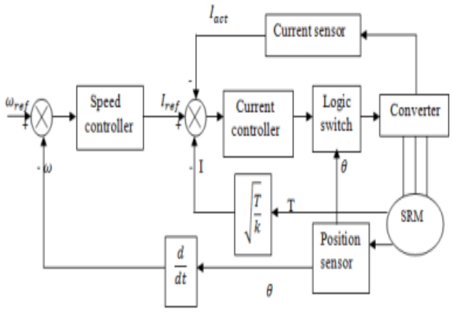

Fig. 3. Closed loop of speed control of SRM with torque ripple reduction

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3. MATHEMATICAL FORMULATION

The output equation is linked with bore diameter, speed, length, electric and magnetic loading to machine's output. Usually designs of conventional motors start from the equation of output. SRM design will be systematic if equation of output is derived. Output equation of design of SRM can be derived with the design values of conventional motors. Although SRM is different from other motors yet they have some similarities.

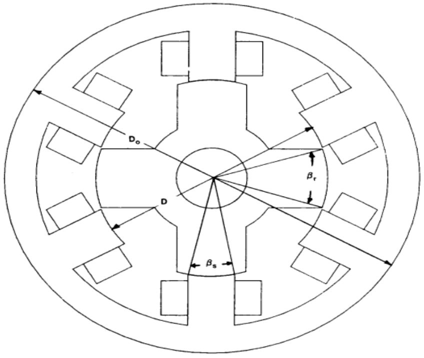

Fig. 4. Schematic of switch reluctance motor

Here is a schematic diagram of 6/4 SRM where stator poles are six and rotor poles are four. Flux linkage and current characteristics at aligned and unaligned positions of stator poles and rotor poles are shown in Fig.4. If the center of stator poles is between two poles of rotor, then it is unaligned position of stator poles and rotor poles. One stroke output mechanical energy of the motor is denoted by enclosed area of 0, A, B, C, 0. The equation for a flat-topped phase current relationship with volt-second is given as [22]

$$(L_a^s - L_u)\mathrm{i} = \mathrm{V\,t} \tag{2}$$

Where $L^{s}{}_{a}$ is saturated per phase aligned inductance, L_u is per phase unaligned inductance, V is supplied voltage and t is time taken by rotor to rotate from unaligned to aligned position

$$t = \frac{\beta_s}{\omega} \tag{3}$$

Where β_s is stator pole arc and ω is rotor speed.

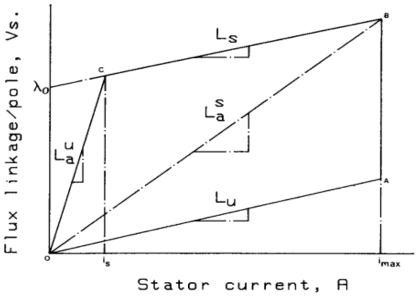

Fig. 5. Flux linkage verses Stator Current

It defines:

$$\alpha = \frac{L_a^s}{L_a^u} \tag{4}$$

$$\lambda_u = \frac{L_a^u}{L_u} \tag{5}$$

From (3) and (4)

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$$V = \frac{\omega_m}{\beta_s} L_a^s i(1 - \frac{1}{\sigma\lambda_u}) \quad (6)$$

For aligned position, equation will become

$$L_a^s = B.A_s.T_{ph} \quad (7)$$

where $A_s.D.L.\frac{\beta_s}{2.0}$ is stator pole area, D is diameter of bore, L is stator pole's axial length, B is flux density on aligned position and $T_{ph}$is no. of turns per phase.

The stator current can be calculated from specific electric loading A_{sp} given as:

$$A_{sp} = \frac{2T_{ph}i_m}{\pi D} \quad (8)$$

In this equation, *m* represents the number of phase conducting simultaneously. Power is delivered when only one phase is conducting of motor (6/4) and is given as:

$$P_d = k_e.k_d Vim \quad (9)$$

In this equation, V and i are peak phase values. Duty cycle and efficiency are represented by k_d and k_e respectively. Duty cycle can be given as:

$$k_d = \frac{\theta_{\mathrm{i}}.qP_{\mathrm{r}}}{360} \quad (10)$$

In this equation, angle of current conduction for rising inductance profile is denoted by θ_{i}. Number of phases is denoted by $q = \frac{P_s}{2}$ and number of rotor poles is represented byP_{r}. Comparing (6) and (7)

$$P_d = k_e.k_d.\left(\frac{\pi^2}{120}\right).\left(1 - \frac{1}{\sigma\lambda_{\mathrm{u}}}\right).B.A_{sp}.D^2.L.N_{\mathrm{r}} \quad (11)$$

Where N_{r} represents speed of rotor in revolution per minute. Equation is further modified as:

$$P_d = k_{\mathrm{e}}.k_d.k_1.k_2.B.A_{sp}.D^2.L.N_{\mathrm{r}} \quad (12)$$

Where $k_1 = \frac{\pi^2}{120}$, $k_2 = 1 - \frac{1}{\sigma\lambda_{\mathrm{u}}}$

Torque is calculated by:

$$P_d = k_e.k_d.k_3.k_2.(B.A_{sp}).D^2.L \quad (13)$$

Where $k_3 = \frac{\pi}{4}$

4. FLOW CHART OF PROPOSED ALGORITHM

Flow chart of proposed PI based algorithm for switched reluctance motor

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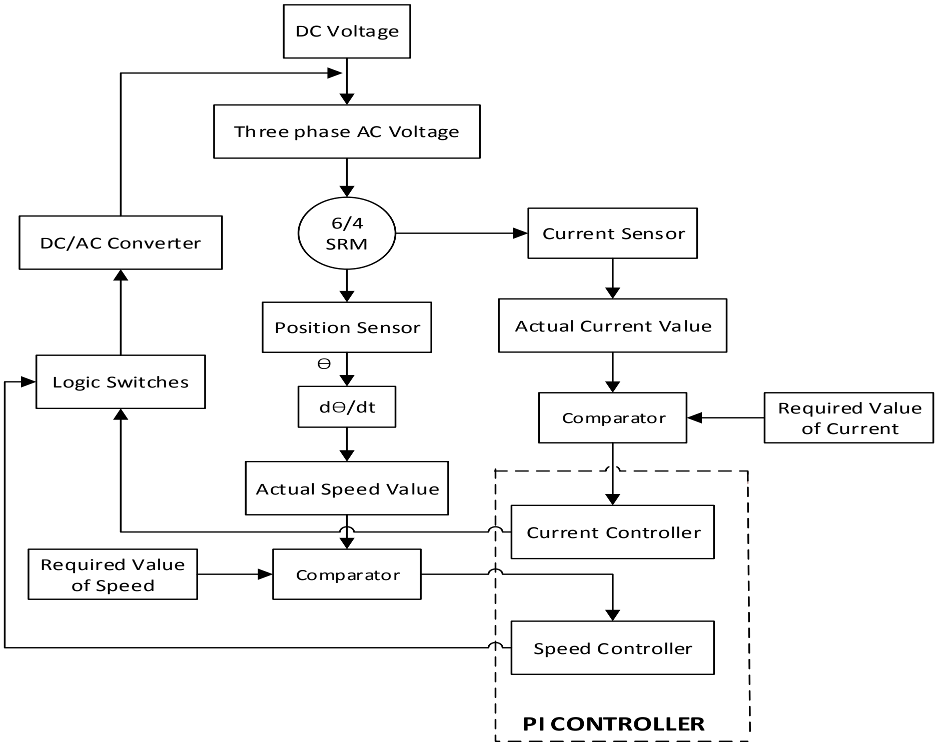

Fig. 6. Proposed flow chart of PI based algorithm for SRM

5. MATLAB / SIMULINK IMPLEMENTATION

The model of switched reluctance motor is designed in MATLAB / Simulink. The model of SRM is based on three phase asymmetrical power converter. This power converter consists of three legs. Each leg consists of two freewheeling diodes and two IGBTs. The stator winding of the switched reluctance motor is connected to positive source voltage through the IGBTs in active mode. During the period of conduction, positive current will flow into the phase windings. During the period of non-conduction, negative voltage gives to the winding and stored energy returns back to the DC source via diodes. In this way, the fall time of the current can be decreased. Turning off and on phases of the motor windings are controlled by the position sensor. Torque waveforms are under control of turning off and on angle of the phase windings. In this model as shown in fig. 7, DC voltage source of 240 volt is used. Position sensor angles for turning on and off of converter are 45 degrees and 75 degrees respectively. Reference current of 200 A is taken for hysteresis controlling of three phase currents. Motor is started on by applying a step reference to a motor. Motor will speed up according to the load attached. Therefore, it can be said that mechanical parameters and dynamics solely decide the speeding up of motor. There are basically two operating modes of motor and these modes are dependent upon value of speed. Motor operates in a current controlled mode up to speed of 3000 rpm. Current is regulated by the reference value of the current. Afterwards, motor operates in a voltage fed mode for speed above 3000 rpm. In this mode, current cannot be regulated by the reference value of the current and motor's emf is high so that there is no switching. Switches remain closed in the active or conduction period. Therefore, DC source directly feeds the motor in a voltage fed mode.

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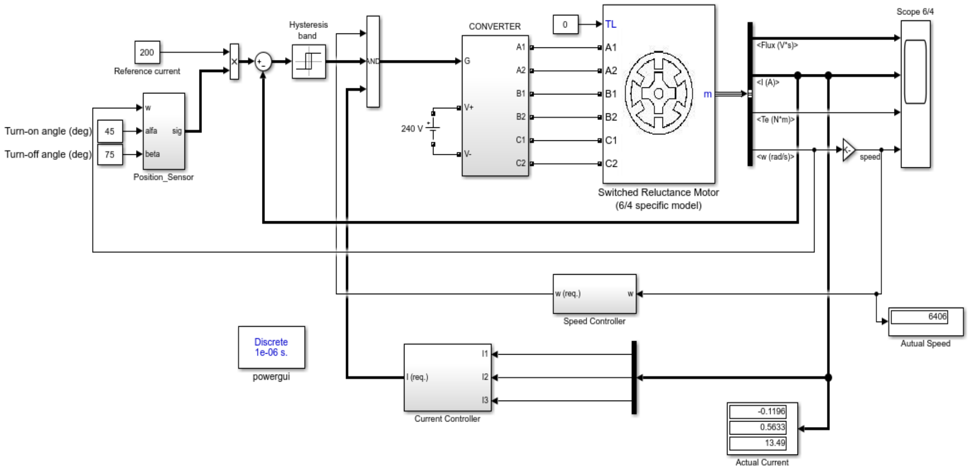

Fig. 7. Switched Reluctance Motor Using PI

Desired output is obtained by application of PI controller for 6/4 SRM. Speed controller contains a comparison based circuit between actual and reference values to get desired speed by using PI logic. Similarly, current controller also compares the actual and reference value to get desired value based on PI logic. Thus, speed of SRM can be controlled by changing current or by speed controller based on PI logic.

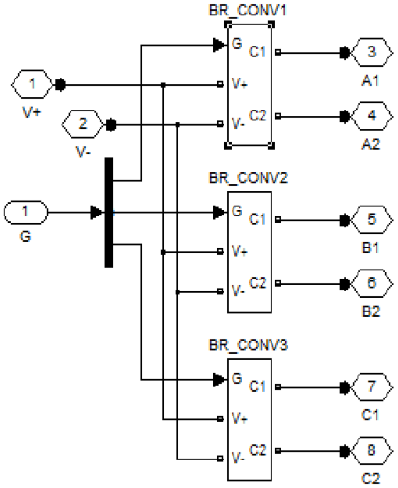

Fig. 8. Internal circuit of converter

The power converter used to convert the power supply is “asymmetrical converter”. In this converter, IGBTs are used because of their good current ratings. The converter used in this model with IGBTs is shown in fig 8.

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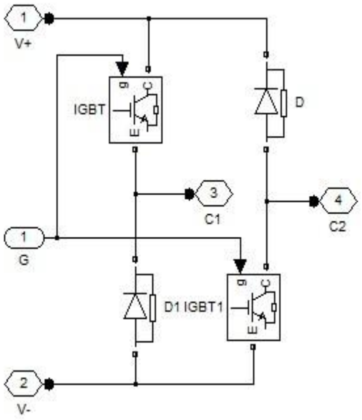

Fig. 9. Internal scheme of IGBTs in a bridge converter

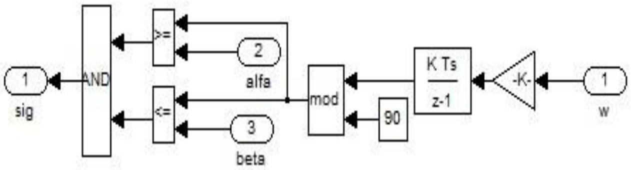

Fig. 10. Logical operation of position sensor

TABLE I. Values of flux and current

Time	Torque	Speed
T ***x10^{-6}s***	***Te*** ***Nm***	***ω*** ***rad/s***
0	7.24E-06	0
1.00	0.028183166	1.38E-09
2.00	0.055617043	5.38E-06
3.00	0.082310938	1.60E-05
4.00	0.108276301	3.17E-05
5.00	0.13352577	5.24E-05
6.00	0.158073066	7.79E-05
7.00	0.1819329	0.000108
8.00	0.205120872	0.000144
9.00	0.227653387	0.000182
1.00	0.249547564	0.000225
0	0.27082115	0.000273
1.00	0.29149244	0.000324

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TABLE 2. Values of speed and torque

Time	Flux			Current		
*T*x10^{-6} *s*	***Φ1 mVs***	***Φ2 mVs***	***Φ3 mVs***	***I1 A***	***I2 A***	***I3 A***
0	-0.249	-0.241	-0..241	0	0	0
1.00	-0.478	-0.360	-0.470	-0.013	-0.036	-0.036
2.00	-0.717	0.234	-0.687	-0.026	-0.001	-0.071
3.00	-0.936	0.472	-0.891	-0.039	0.035	-0.104
4.00	-1.165	0.710	-1.083	-0.052	0.072	-0.136
5.00	-1.378	0.948	-1.264	-0.065	0.108	-0.165
6.00	-1.597	1.186	-1.433	-0.077	0.144	-0.193
7.00	-1.798	1.424	-1.590	-0.089	0.181	-0.218
8.00	-2.000	1.66	-1.736	-0.101	0.217	-0.242
9.00	-2.198	1.900	-1.872	-0.112	0.253	-0.265
1.00	-2.389	2.138	-1.997	-0.123	0.29	-0.286

Table 1 shows the electrical values of flux and time with respect to time and the table 2 shows the mechanical values of speed and torque with respect to time.

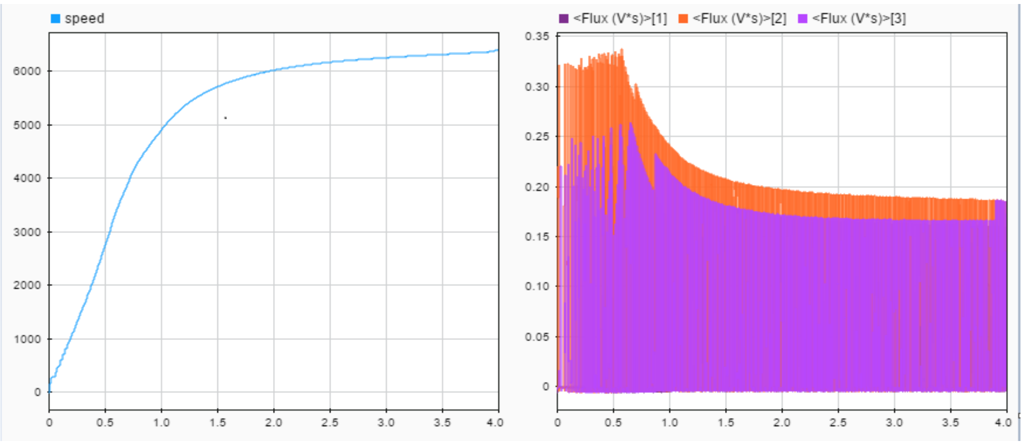

Fig.11. Speed and Flux Relationship

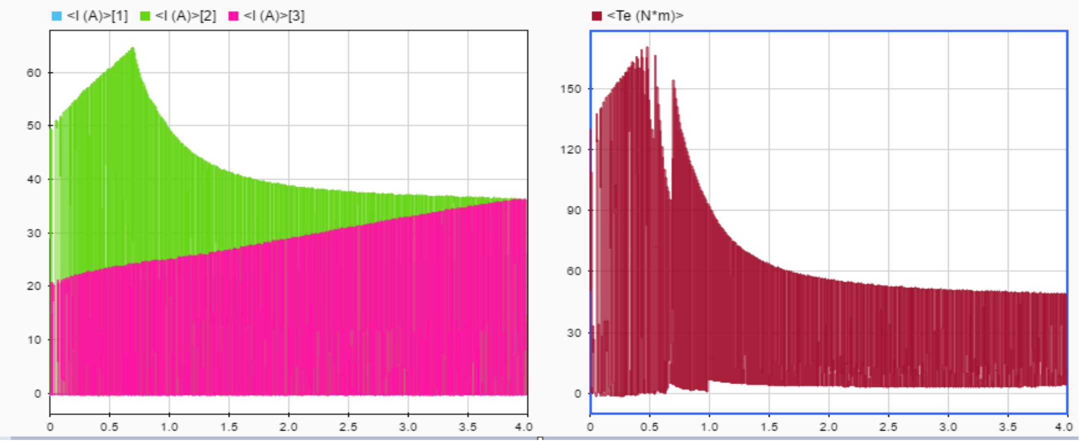

Fig. 12. Torque and Current Characteristics

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When speed increases, flux starts decaying and becomes saturated at the point where speed becomes constant. This will differentiate between motor characteristics of starting and running as shown in fig 12.

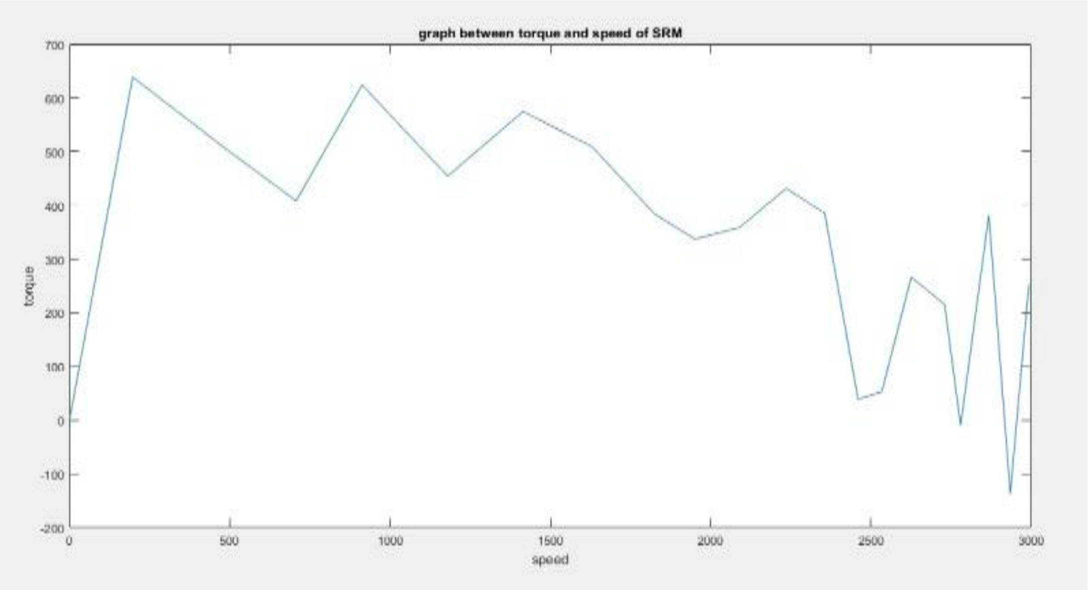

Fig. 13. Torque and Speed Characteristics

In most of convention motors, torque is directly proportional to square of current while, in case of SRM, torque is directly proportional to current as shown in fig 13.

6. Conclusion

Switched reluctance motor is simulated and different relationships are analyzed to write a hypothesis about the motor. It is found out that torque and speed relationships are exactly what the theory interprets. Initially, torque is high to start the motor from rest position and then with the development of speed, torque is reduced. This is the relationship satisfying most of the motors and SRM is also satisfying. Therefore, it can replace any induction machine installed in any application that has the same characteristics because of its simplicity in construction. Further, in most of the motors, it is found that torque is directly proportional to square of the current. SRM has somewhat torque directly proportional to the current. Therefore, this motor utilizes less power as compared to any machine of same size and capacity. This result will revolutionize the load reconfiguration industry.

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