FAULT TOLERANT CONTROL OF ADJUSTABLE SPEED SWITCHED RELUCTANCE MOTOR DRIVES

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ABSTRACT

Existing position sensorless methods rely on (1) one-one correspondence between magnetic characteristics of SRM and rotor position and (2) access to terminal quantities (i.e. voltage and current) for all phases. The occurrence of a fault in one or more phases will prohibit the necessary access to the phase/s and as such introduces a challenge to successful implementation of existing position sensing technique. This paper introduces a generalized strategy for sensorless operation of SRM under single and multi-phase faults using existing sensorless method. Experimental results of a four phase SRM drive with different numbers of faulty phases are presented to validate the proposed methods.

I. INTRODUCTION

One of the most active research and development areas in the field of power electronics and machine drives is variable speed drives. As power semiconductor devices have become cheaper, faster and more reliable, their use for energy saving approaches in industry and residential applications has been increasing. Today's interest and demand is for compact, inexpensive, reliable and high performance variable speed drives. In the past, direct current (DC) machines were used extensively for variable speed operation, since their torque could be controlled easily by the armature currents. However, DC machines have certain disadvantages due to the presence of commutator and brushes. These machines require periodic maintenance, cannot be used in explosive or corrosive environments and have limited commutator capabilities under high speed, and high voltage operating conditions. In recent years, AC machines have started to replace DC machines due to the enhancements in their control and power electronics. Over the past decade, there have been extensive development efforts of various kinds of brushless AC motor drives. These are induction motor (IM), permanent magnet brushless direct current (PMBLDC) motor, permanent magnet synchronous motor (PMSM) and switched reluctance motor (SRM) based drives. Recently, SRM drives have received considerable attention from the researchers and the drive industry due to their various attractive features. The SRM is a viable candidate for variable speed applications, because of its high torque density, low losses, wide speed range capability, simple control and low overall cost. The absence of permanent magnets or windings in the rotor makes switched reluctance (SR) machine a low-cost machine. Moreover, the SR machine stator windings are electrically separated; hence, the choice of converter topology and control strategy has more flexibility than any other drive system. Both the SR and the PM machines are free of rotor copper loss, but the SR machine phases are independently controlled by the converter which makes the short circuit current decay quickly, while in the PM machine the short circuit current persists as long as the machine continues to rotate due to back-emf generation. The availability of powerful microcontrollers and modern power electronic devices has made a significant improvement in the machine performance, making the SR machine a respectable competitor to PM machines.

II. PRINCIPLES OF SRM DRIVE

SRM drive requires a power converter and associated control system for its basic operation. Advancements in semiconductor technology and high speed digital controllers paved the way for renewed interest in SRM drives. A typical SRM drive system consists of the machine, the power converter and associated control system. The converter is connected to a DC power supply, which can be derived from the utility lines through a front end diode rectifier or from batteries. The controller energizes each phase of the SRM in a sequence and the energization is synchronized with the rotor position in order to produce smooth unidirectional torque. This necessitates a mechanical position sensor, which is usually connected to the shaft of the SRM in order to provide rotor position feedback for the controller. Furthermore, the attractions of SRM drives will be significantly enhanced if the machine position sensor can be eliminated. A typical SRM drive system with position feedback is shown in Fig. 1.

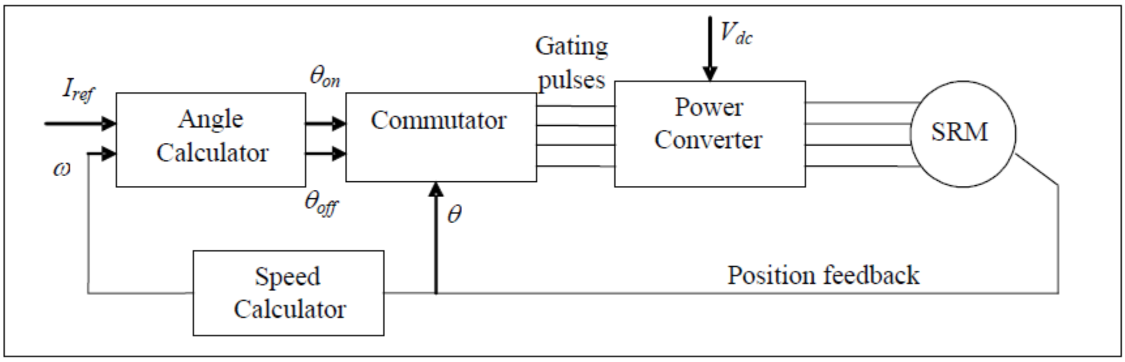

Fig. 1: A Typical SRM Drive System with Position Feedback

The SRM is a doubly salient, singly excited machine with unequal numbers of stator and rotor poles. This is to ensure that the rotor poles are never in a position where the torque, due to the current in any phase, is zero (i.e. all rotor poles are aligned with stator poles). The common stator/rotor pole configurations are 6/4 and 8/6. The stator poles have concentrated windings and the coils on diametrically opposite poles are connected in series to form one phase. Fig. 2 shows the cross-section of 4-phase, 8/6 SRM. The choice of the number of phases of SRM is a compromise between low torque ripple and cost of power converter control circuit.

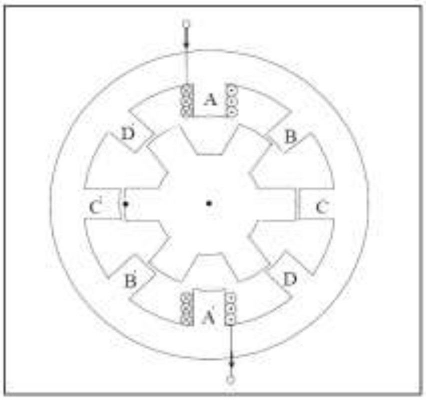

Fig. 2: Cross-Sectional View Of A 4-Phase, 8/6 SRM

The principle of operation of a SRM is based on the tendency of an electromagnetic system to obtain a stable equilibrium position minimizing magnetic reluctance. Whenever diametrically opposite stator poles of a SRM are excited, the closest rotor poles are attracted, resulting in torque production. When these two rotor poles become aligned with the two stator poles, a second pair of stator poles is excited to bring a second pair of rotor poles into alignment. The SRM is integrated with a closed loop control circuit, which is essential to run the machine. The main function of the control circuit is to optimize the switching angles of the applied phase voltage to make the current pulse coincide with the active interval of the motoring inductance profile. The process is controlled mainly by three control parameters; the advance angle (θα) (turn-on angle), the (θβ) (turn-off angle) (conduction angle θc = θβ -θα), and the value of the effective supply voltage. The switching angles are defined for each phase based on the rotor position information provided by a position sensor located on the shaft. The value of θα is chosen to permit the current to grow to an adequate level while the inductance is at its minimum value. After the conduction angle duration, the voltage across the phase winding will be reversed. The entire period must be completed with one rotor pole pitch rpτ, which is related to the number of rotor poles Nr as

$$\tau_{rp} = \frac{2\pi}{N_r}$$

2.1 Converter Topologies

The converter is necessary for SRM operation to supply switched DC voltages that established the current pulses into the windings of the different phases according to control signals from the controller. It was mentioned that the torque developed by the motor could be controlled by varying the amplitude and the timing of the current pulses in synchronism with the rotor position. Unlike other AC machines, the currents in SR machines are unidirectional and the converter configuration should suit this requirement. In the literature, several converter topologies for SRM drives have been proposed. The most flexible and the most versatile four-quadrant SRM converter is the classic bridge converter shown in Fig. 2.8, which requires two switches and two diodes per phase. The main advantage of using a classic converter is the flexibility in control. All the phases can be controlled independently which is very essential for very high speed operation, where there will be considerable overlap between the adjacent phase currents. In the classic converter, both the controlled switches are turned on simultaneously so that the motor winding will be connected to the DC bus voltage. Both the switches are turned off simultaneously when it is desired to turn off the phase. The phase current flows through the freewheeling diodes and returns the trapped magnetic energy into the DC link. During the freewheeling, the SRM phase is subjected to negative of the bus voltage through the freewheeling diodes. In order to provide current feedback to the controller, a current sensor is connected in series with the phase windings. The high cost of power semiconductor devices and the need to reduce the switching losses motivated the researchers to develop several other converter topologies with some design trade-off.

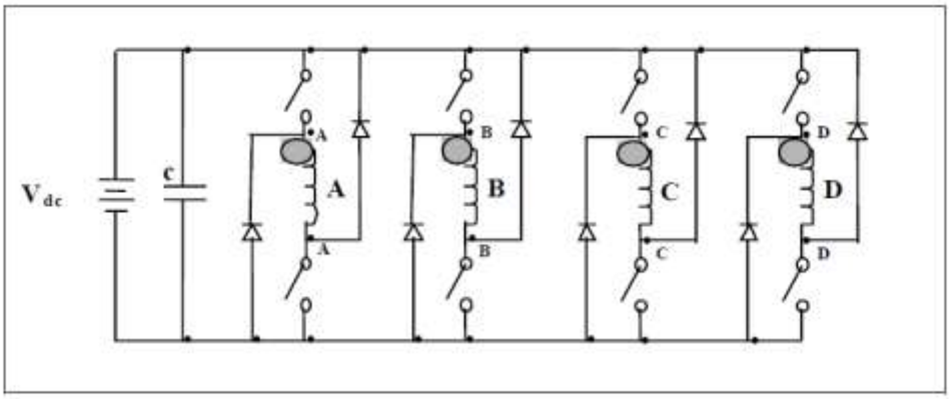

Fig. 3: Classic Bridge Power Converter For A 4-Phase, 8/6 SRM

III. FAULT TOLERENT OPERATION

By definition, the fault tolerance is a fundamental characteristic of a system that ensures its continuous function even after a fault occurs, that would cause a normal similar system to malfunction. In safety-critical systems faults can cause life losses, environmental degradation or significant financial losses. Hence the fault tolerant design of complex electrical systems is becoming nowadays a requirement for a growing number of companies, far beyond its traditional application areas, like aerospace, military, automotive, medical, etc.., The switched reluctance machine (SRM) based electrical drive systems are ideal for such critical applications. The phase independence characteristics of the SRM enable it to operate also under partial phase failure conditions in its classical construction. Its reliability can be improved by applying special fault tolerant designs, respectively monitoring its condition and applying fault detection techniques. The SRMs used in such safe electrical drive systems have to be fed from power converters which also have fault tolerant capabilities, and respectively they have to be controlled by systems that can auto-reconfigure if a fault occurs in the machine or in the power converter.

3.1 Principles of Fault Tolerant Operations

The main concerns in designing and constructing any fault tolerant system are the potential added cost and feasibility issues. The increased cost of incorporating fault tolerant capabilities into the existing system should always be compared with the cost of damage to the motor-load system when functioning with the existing configuration without such fault tolerant capabilities under faulty conditions. It would not make sense to implement a fault tolerant capability to the existing technology if the added components and manufacturing costs are higher than either the cost of having system redundancy, or the cost of damage to the overall system, when operating under a faulty condition with no remedial action being taken. Several faults can appear also in power converters. When a switch in the converter is open-circuited it does not lead to any catastrophic failure; it only stops supplying current to the corresponding phase winding. This case is similar to the open phase case. It practically means that the corresponding phase stops generating any torque. A more frequent and much more dangerous fault is when a switch in the converter is short-circuited. The winding faults of the SRM can be sensed by several failure detectors. One of the most simple fault detection devices is the over-current detector given in Figure 4. Its efficiency is limited due to insufficiently fast response time and the inability to detect all types of faults.

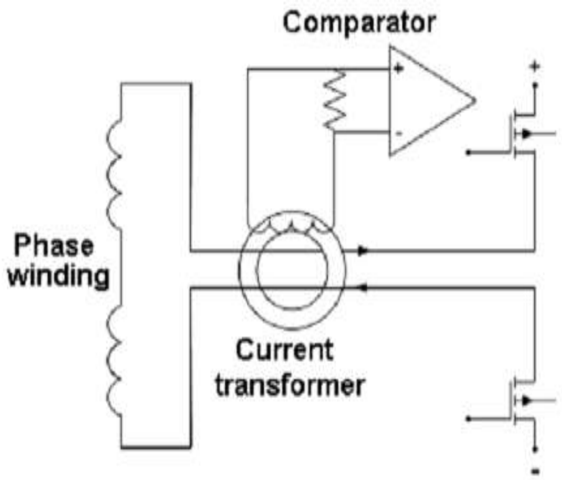

Fig 4: The Current Differential Detector

It requires additional search coils wrapped around the stator poles. The search coils of each phase are connected in series opposing, similarly to the connections of the main coils of the machine. During normal operation (without winding faults) the voltages induced in the two search coils are equal and opposite. Hence zero voltage will be at the input of the comparator. When a winding fault occur the imbalance in the pole fluxes induces different voltages in the two search coils. This voltage difference can be detected with the bidirectional comparator.

IV. SENSORLESS CONTROL OF SRM

With the advent of high speed digital signal processors (DSPs) specialized for machine control applications, it has become possible to control machines without mechanical (speed or position) sensors. This is achieved by algorithms that estimate the desired quantities in real time, based on the electrical signals in the machine windings. Under single phase faulty condition, the synchronization between rotor position and excitation will be lost due to lacking of position information. This could possibly be recovered by introducing a motion estimator to estimate the rotor position when there is no phase in position diagnostic state. The motion estimator is different from a motion observer in the sense that it is an open loop system. Since it only works for a short duration of one electrical cycle, under steady state and low dynamic condition, the drift error due to integration would be relative small. Thus continuous operation of the machine can be maintained.

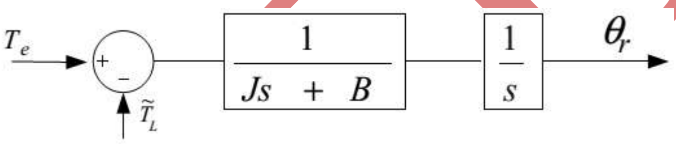

Fig.5: The Block Diagram of Motion Estimator

For a system which utilizes idle phase sensorless method initially, the system state transition with motion estimator incorporated under single phase fault can be described by fig.5. In this figure, phase D is assumed to be the faulty phase and disabled. From this figure, the estimator functions in the time interval which is originally taken by the phase D diagnostic state. This ensures continuously obtaining of position information for correct commutation. The T_e in the estimator is set as phase D torque which is zero in faulty condition and (T_L)̃ is set as the average torque of the other phases in their conduction band.

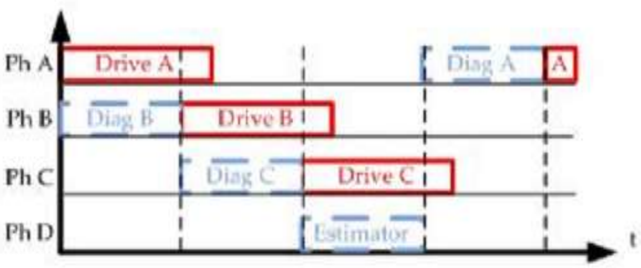

Fig.6: State Transition with Estimator for Idle Phase Method under Phase D Fault

V. MATLAB/SIMULINK RESULTS

The proposed sensorless methods are simulated for the 3phase SRM drive and 4 phase SRM drive for single phase faults.

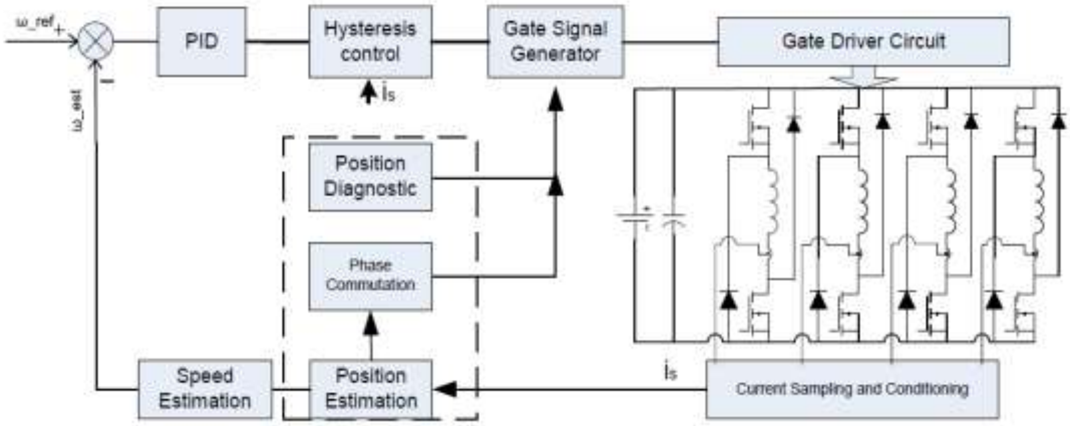

Fig.7: System Diagram of the Simulated 4 Phase SRM Drive System

Case I: Three phase Switched Reluctance Motor Drive

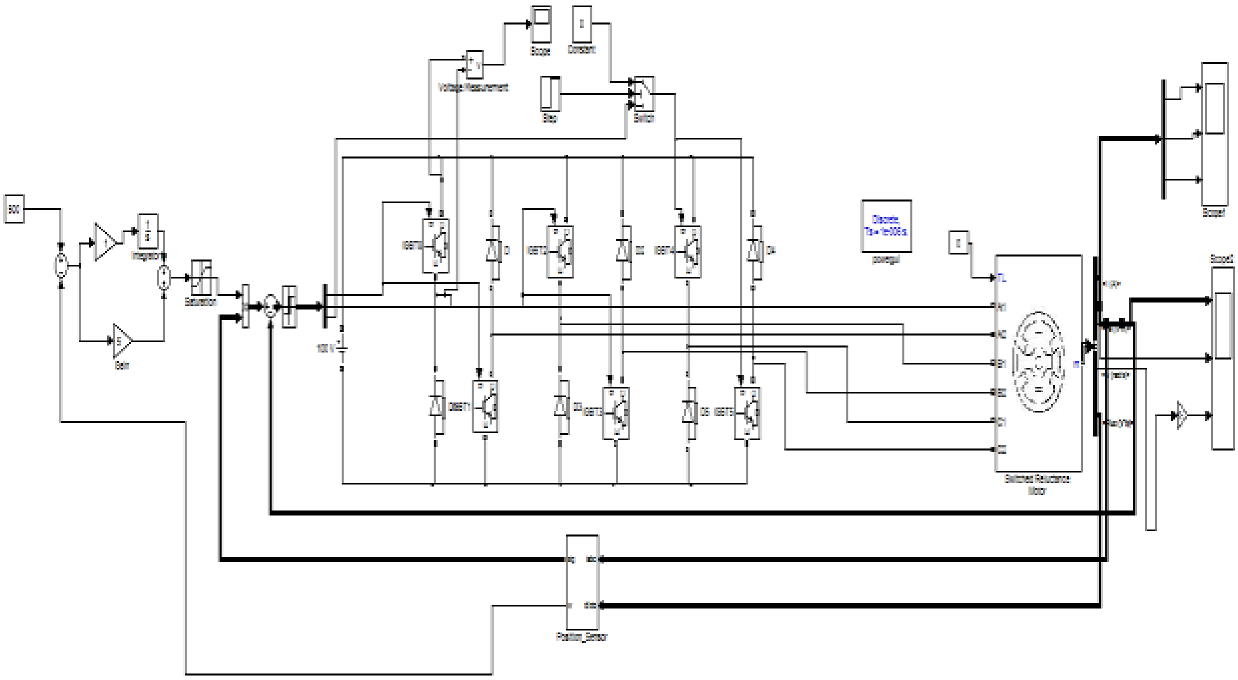

Fig.8: Matlab/Simulink Model of Proposed three phase Switched Reluctance Motor Drive

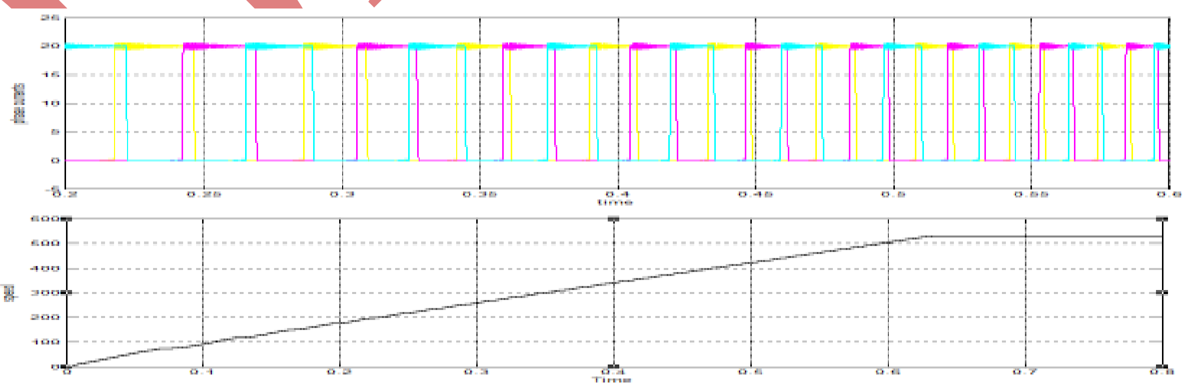

Fig.7: Three phase SRM Phase Currents, Speed without fault condition

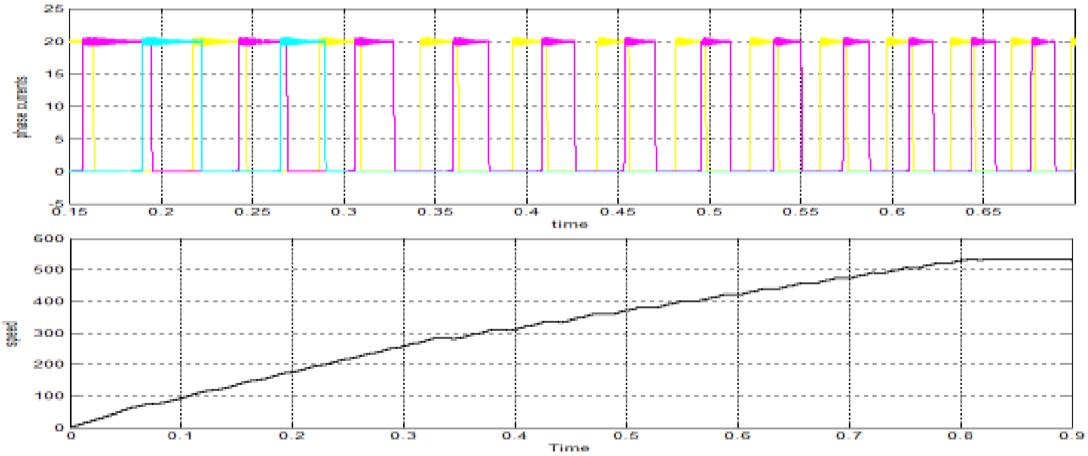

Fig.8: Three phase SRM Phase Currents and speed under Phase C Fault Condition

In this case the fault will be occurred at the middle of the operation, the faulty phase is isolated from the healthy system. In single phase fault condition the SRM derive provides the rated output with the help of remaining phases, the sensorless method provides the rotor position information and according to the rotor position the signals to be send to the respective phases so it can provide continuous output power to the system.

Case II: Four phase Switched Reluctance Motor Drive

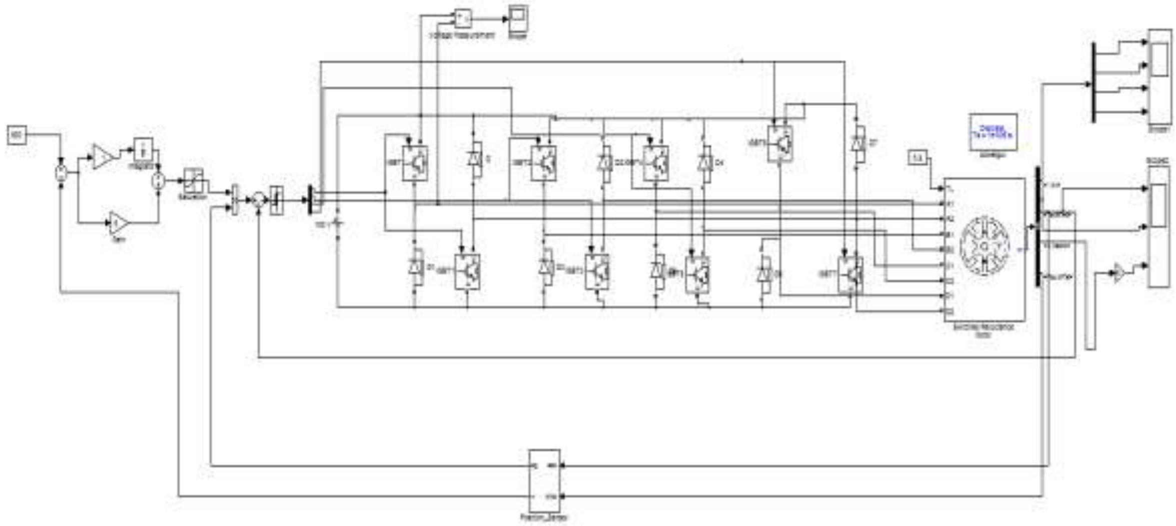

Fig.9: Matlab/Simulink Model of four phase Switched Reluctance Motor Drive

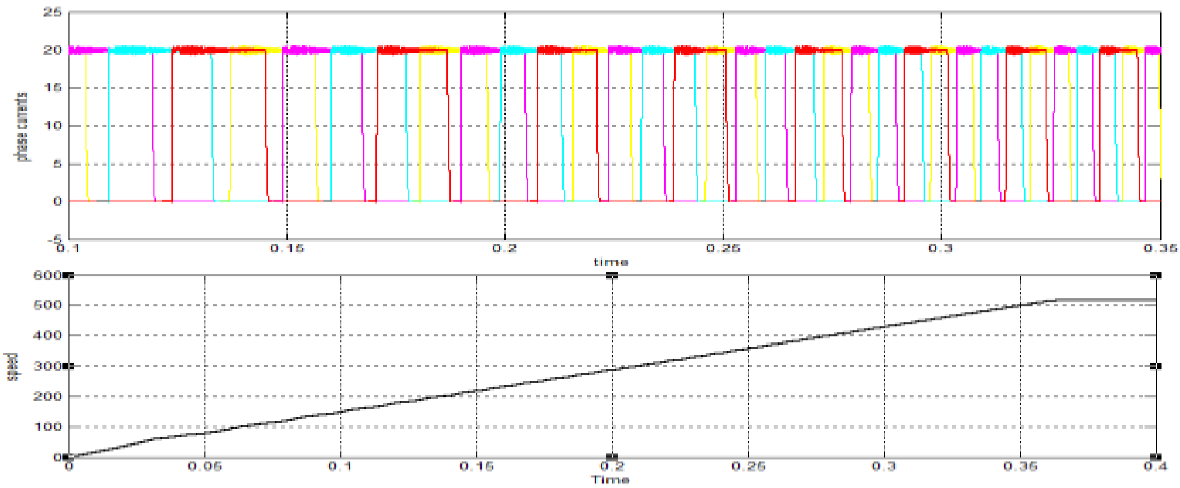

Fig.9: Four phase SRM Phase Currents, Speed without Fault Condition

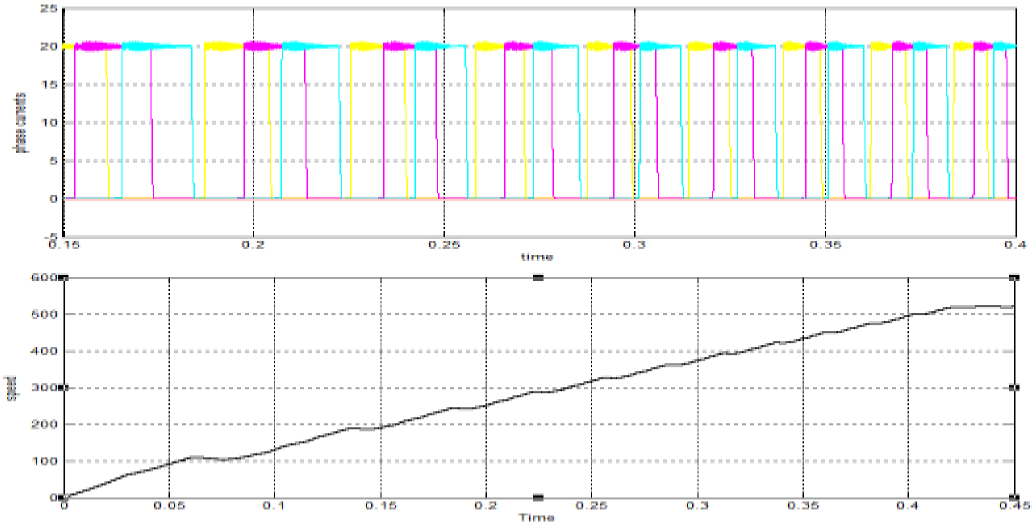

Fig.10: Four phase SRM Phase Currents, Speed under Phase D Fault Condition

From the above results it can be conclude that the performance of sensorless technique in three phase and four phase SRM drive is better compared to position sensors. The performance of the four phase SRM drive is better than the three phase SRM drive. So it says that the fault tolerance of the SRM can be improved by increasing the number of phases.

VI. CONCLUSION

Due to attractive features such as low cost and highly robust, the demand for switched reluctance motors has reached an all-time high .This paper provides a systematic classification for the Existing position sensorless techniques used in SRM drives. A family of techniques for sensorless operation of SRM drives under single phase faults is presented. The proposed fault tolerant techniques are implemented in MATLAB simulink and simulink results are verified.

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