



## Reduce Torque Ripple Using Novel Torque Distribution Function for High-Speed Applications Using Embedded System Technology

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**Abstract:** In this paper presents real-time simulation results of a switched reluctance motor (SRM) drive with a novel Torque Distribution Function for high-speed applications, in order to reduce torque ripple. The SRM is fed by a 3-phase unidirectional power converter having three legs, each of which consist of two IGBTs and two freewheeling diodes. The SRM model incorporates all nonlinearities between excitation currents, rotor position and flux linkages. For the purpose of control SRM drives, an improvement of the Torque Distribution method is proposed for high-speed applications, in order to reduce torque ripple. The real-time simulation of the drive is conducted on the real time simulation platform. Since the converter is current controlled, simulator latency is critical to achieving good accuracy and avoiding current overshoot. The paper demonstrates that this type of drive with simple hysteretic current control can be simulated in real-time at a time-step of 15 $\mu$ s, with good accuracy. **Torque Distribution Function Index Terms - Switched reluctance motor (SRM), Torque Distribution Function, real-time simulation.**

**Keywords:** Switched reluctance motor (SRM), Torque Distribution Function (TDF), real-time simulation

### I. INTRODUCTION

Nowadays before using a motor controller with a real motor drive, it is a common industrial engineering practice to test a controller against a simulated motor model running in real-time. This has several advantages. For example, the simulated motor drive can be tested with borderline conditions that would damage a real motor, often a costly prototype. The motor itself may be under development in parallel to the controller and therefore not available for testing. While testing, a controller is interfaced with the real-time simulated motor drive through a set of proper I/Os: this approach is called hardware-in-the-loop (HIL) simulation. Such motor drive simulation is required by hybrid vehicle OEMs and other power electronic motor drive manufacturers to speed up development and testing time by using real-time simulation before conducting tests on physical prototypes. At the production stage, HIL simulation can also be used to verify code integrity with automated correlation tests. The switched reluctance motor drive is interesting because of its low manufacturing costs, rugged construction and simplicity of controller design. Since the rotor has no windings and no magnets, it is a good candidate for drive operation at high speed and in adverse environments. Position sensor reliability poses a more important problem in the latter case. A developer or integrator of such drives will want to test the behavior of the drive in case of a position sensor malfunction, for example. A real-time simulator is the ideal tool to safely test this scenario. Sensorless drive designs pose other challenges related to sensor accuracy that could be overcome through the use of a real-time simulator.

High speed drive systems are much interested in the industrial application such as blower, compressor, pump and spindle due to the compact size and high efficiency. In recent, the demands of high speed drives are much increased due to the mechanical advantages of high speed system. SRMs (Switched Reluctance Motors) have simple structure and inherent mechanical strength without rotor winding and permanent magnet. These mechanical structures are suitable for harsh environments such as high temperature and high speed applications. Although SRMs have many advantages for the high speed applications, high torque ripple is still main problem to be applied to a high speed drives. SRM (Switched Reluctance Motor) has been researched in last 150 years. A typical 6/4 pole SRM is shown in Fig. 1. In an SRM, the rotor is aligned whenever diametrically opposite stator poles are excited. At the same time, when two rotor poles are aligned to two stator poles, another set of stator poles is out of alignment with a different set of stator poles.

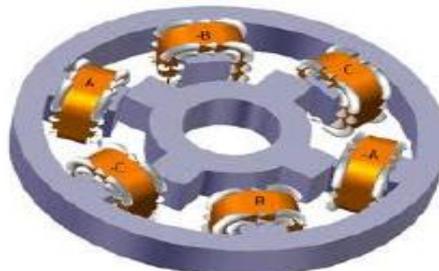


Fig1: Switched Reluctance Motors

## II. TORQUE FABRICATION STRATEGY

In SRM control strategies, each phase winding is excited separately in the rising slope of the inductance for the positive torque, and in the falling slope for negative torque. The overall torque of the motor is the sum of the phase torques. The inductance profile, phase current and voltage are shown in Fig. 2.

### A. Model of the SRM

In the SRM, there is a three-dimensional relationship between excitation current, rotor position and flux linkages. Therefore, electromagnetic torque depends on both excitation current and rotor position

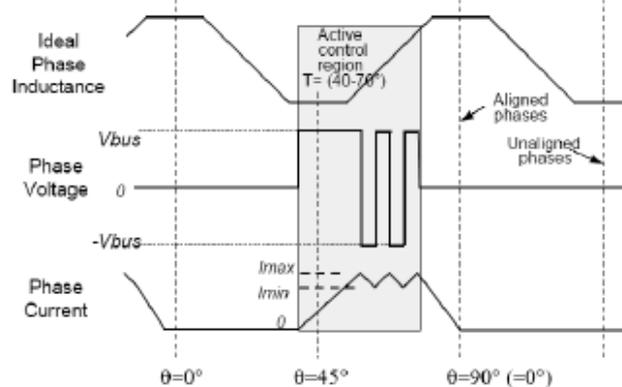


Fig. 2. Inductance profile, phase current and voltage

### 2.1 Statistical SRM model

Precise computation of the nonlinear magnetic characteristic at an arbitrary rotor position and acurrent is critical when performance predictions, simulations, computer-aided designs, torque control and sensorless control of the switched reluctance motor (SRM) drives are carried out. The nonlinear magnetic characteristics in the SRM are the functions of both the rotor position and the current.

The SRM drive system simulation is much more complex than ac & dc motor drives because its operational region is mostly nonlinear. The nonlinearity is introduced by the following three factors:

1. The nonlinear B-H characteristics of the magnetic material.
2. The dependence of phase flux linkages on both the rotor position and current magnitude while in other machines it is dependent only on current magnitude.
3. The single source of excitation.

By using the proposed method a deviation of the current slope, which is not influenced by the motor speed can be derived. The deviation of the current slope is only related to input d.c. voltage and selfinductance of motor.

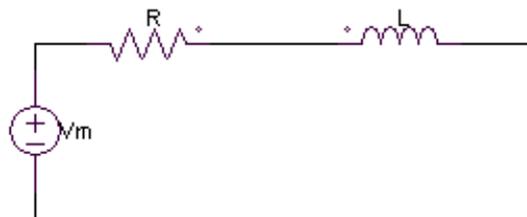


Fig: 3 Electrical Model of One Phase of SRM

SRM models are generally made up of three parts: the electrical model, torque characteristics and mechanical model. The electrical circuit for one phase of SRM is shown in Figure 3

Applying Kirchhoff voltage law thus voltage given by Equation (1).

$$v = ir + \frac{d\lambda(i, \theta)}{dt} \quad (1)$$

Where R is phase resistance and is magnetic flux is given by Equation (2).

$$\lambda(i, \theta) = L(i, \theta)i \quad (2)$$

Solve Equation (1) to calculate magnetic flux at various rotor angles and current magnitudes from measures stator voltages, currents and resistance as given in Equation (3).

$$\lambda(i, \theta) = \int (v - ir) dt \quad (3)$$

### DIRECT FLUX LINKAGE METHOD

The flux linkage characteristics of SRM depend on the rotor position and the excited stator phase current. The ideal flux linkage characteristics of SRM are represented in Figure 4

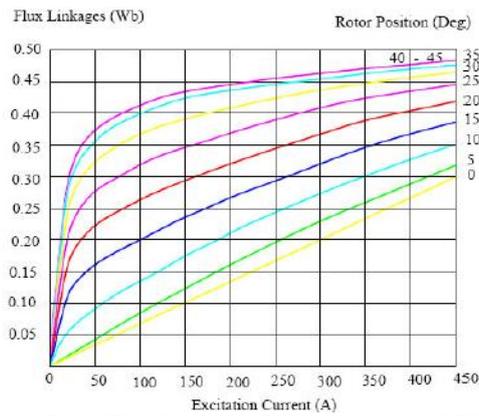


Fig :4 Ideal Flux Linkage Characteristics of SRM

The flux linkage characteristics at aligned position are represented, when the stator interpolar axis coincides with the rotor interpolar axis and the flux linkage characteristic at unaligned position is also represented. The flux linkage characteristics at the intermediate position shown, as the rotor position is changed from unaligned position to aligned position till the overlap of the pole approached.

The phase inductance of the SRM depends on both the excitation current and rotor position. The measurement of inductance can be performed while the phase winding is excited with the appropriate d. c. current. The measurement of flux linkages can be implemented in two ways:

1. By applying a constant voltage to phase winding and measuring the rising current.
2. First establishing a steady state d. c. current in the winding and then measuring the decaying current when the circuit is demagnetized.

A simplified measurement circuit for SRM flux linkage characteristics is shown in Figure 5

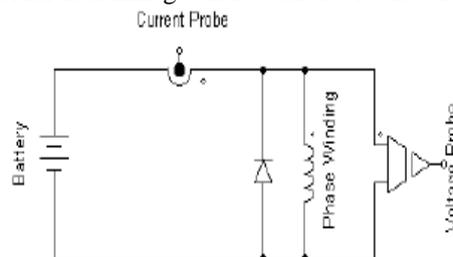


Fig: 5 Simplified Measuring Circuit for SRM Flux Linkage Characteristics

### III. SRM FLUX LINKAGE CHARACTERISTICS IN MATLAB

The modeling is motivated by the need for accurate drive performance estimate to support optimized excitation and control. In this regard one of the most challenging aspects of modelling the drive is the analytic representation of the motor, which contains spatial and magnetic nonlinearities. The modelling approach used here is based on characteristics of existing motor. Once the SRM is modeled analytically, a general expression for torque, power production and losses can be deriving.

The flux linkage current characteristics are used to represent the coupling between the electrical and mechanical terminals of the motor. The magnetic saturation is very important to the high performance of the SRM drive.

The piece wise linearization of the magnetic characteristics has accuracy limitations and the SRM drive modeling requirements makes sense to find an analytic expression for flux linkage/current/position data. The goal of this analytic expression is to provide all of the flux linkage current information for every rotor position in one summary equation that is simple, matches the experimental data can be connected to a physical interpretation. The flux linkage current relationship for each phase of the motor is the same except for the angular dependence takes into account the physical interpolar spacing.

### IV. SIMULATION & RESULTS

The proposed method has been tested using an experimental 0.5-kW 42-V four-phase SRM drive, which is design for submersible pump and further specification of motor is mentioned in Table 1. The dc resistance of motor phase winding is measured using Voltmeter-Ammeter method and it is found 3.321 ohms.

Table 1. Motor Specifications of SRM Submersible Pump

parameter	Value
Number of phase	4
Number of Stator poles	8
Number of rotor poles	6
	50mm

Stator Inner diameter	49mm
Rotor outer diameter	102mm
Stack length	10mm
Stator arc	08mm
Rotor arc	0.3mm
Airgap length	19mm
Shaft Diameter	

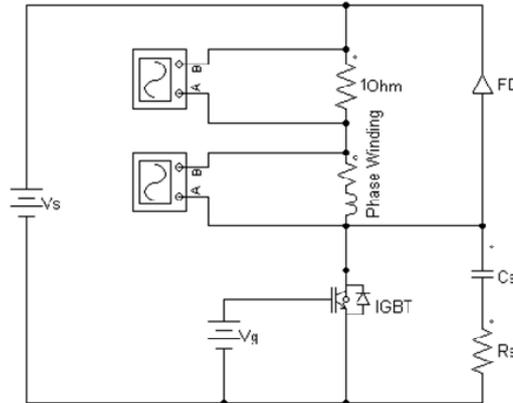


Fig 6: Experimental Setup

The experimental setup is shown in Figure 4. An IGBT is used as a switching device in each phase of SRM. Freewheeling diode is connected across the motor winding for dissipates the stored energy and an R-C snubber circuit is used for the protection of the switching device IGBT. A voltage pulse applied by turning on the switch and the voltage and current waveforms are recorded during short duration through digital storage oscilloscope. A digital storage oscilloscope (TDS 2100 TEKTRONIX) is used to acquire and store the current and voltage waveforms digitally. A mechanist's dividing head (indexing head) is used to hold the rotor in position against high torque produced during the experiment current. Any one of the phase is connected to dc supply while all other phases open.



Fig 7: Current through the Motor Phase Winding

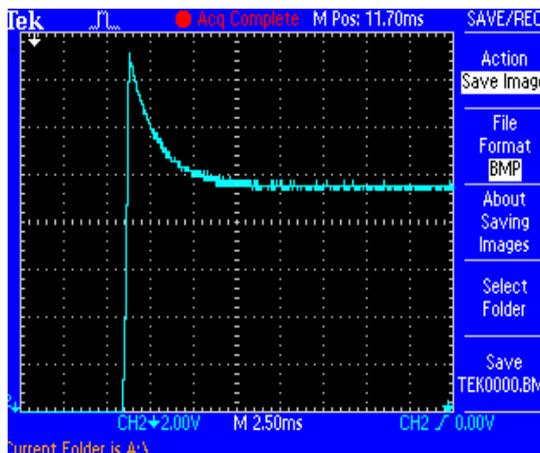


Fig :8 Voltage Across the Motor Phase Winding

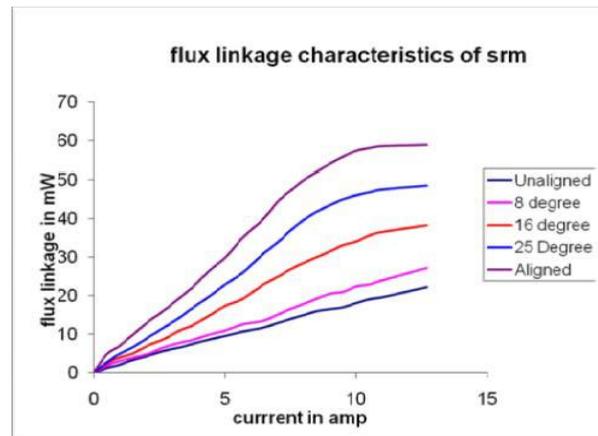


Fig 9: Experimental Flux Linkage Characteristics of SRM

## V. CONCLUSION

The Switched Reluctance Motor drive has excellent performance characteristics with variation in speed, phase current, number of stator and rotor poles. The motor is able to give the characteristics of induction motor, dc shunt motor or series motor or combination of motors. The SRM is fed by a 3-phase unidirectional power converter having three legs, each of which consists of two IGBTs and two freewheeling diodes. The SRM model incorporates all nonlinearities between excitation currents, rotor position and flux linkages. For the purpose of control SRM drives, an improvement of the Torque Distribution method is proposed for high-speed applications, in order to reduce torque ripple. This paper has presented experimental flux linkage characteristics of submersible pump SRM. Obtained results are acceptable for simulation of SRM drive and its control strategy in submersible pump application. Further MATLAB model for same motor has been developed using Fourier series cosine coefficients. The accuracy of the model has been verified with experimental results and they have validated the model.

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