# Implementation of MATLAB Based Flux Linkage Characteristics Model of 8/6 SRM

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**ABSTRACT**

This paper is describes the method of measuring the flux linkage versus current and rotor position of SRM for submersible pump application. The knowledge of flux linkage characteristics of motor is utilized for determination of performance of motor, design of converter and rotor position. Proposed experimental setup is finding the flux linkage characteristics of motor and their modeling in MATLAB is also designed using Fourier cosine coefficients. Developed model is compared with experimental results and validate MATLAB model.



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## 1. INTRODUCTION

Switched reluctance motor drives have become the subject of considerable attention because of their inherent advantages in variable speed motor drive system. Due to lack of any windings or brushes on the rotor, SRM is an exceptionally robust structure, a wide speed range can operate in very hostile environments [1]. The switched reluctance machine (SRM) can be use in a variety of variable-speed applications such as fans, pumps, hand-tools, centrifuges, machining spindles, and electric vehicles.

The submersible pump is an emerging application for agriculture in rural areas. These rural areas are always suffering from poor quality of power supply and this causes the frequent breakdown and poor performance of conventional induction motor. The Switched Reluctance Motor possesses unique characteristics that the motor has fault tolerance capability, ability to continue operation despite faulted windings or inverter circuitry [2, 3]. The magnetic independence of the motor phases and the circuit of the inverter phases permit the Switched Reluctance Motor drive to continue operation with one or more faulted phases with reduced capacity. The SRM is a cost effective and rugged machine due to the absence of any magnetic source in its rotor [4]. The SRM can perform well in the submersible pump application due its unique characteristics.

The standard SR pole number notation will be used, e.g. a 6/4 motor has 6 stator poles and 4 rotor poles, and a classical SR motor is defined as [5]:

a) An inner rotor
b) More stator poles than rotor poles, in particular a three phase motor has a basic pole pattern of 6/4, a four-phase 8/6, etc.
c) One tooth per pole

d) A short pitched winding round each stator pole
e) Possible multiples of the same basic pole pattern, e.g. a 12/10 is two repeats of the 6/4 pole pattern
f) Possible interpole projections (heat spikes) on the stator
g) At least three phases

The knowledge of flux linkage characteristics is necessary for proper design of converter system and performance analysis of the SRM. The flux linkage and inductance profile of the SRM depends on the rotor position and phase current. The family of the flux linkage characteristics (for different rotor positions) can be determined in laboratory using Simpon's ⅓ rule [6]. The MATLAB modeling of same motor is also designed.

## 2. MATHEMATICAL SRM MODEL

Precise computation of the nonlinear magnetic characteristic at an arbitrary rotor position and a current 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. To implement accurate simulation and real-time control, the designers have to develop novel techniques to calculate precisely the nonlinear magnetic characteristics of the SRM both on line and offline [7].

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 self inductance of motor. As a result the self inductance of the motor can be precisely estimate by detecting current slope [8].

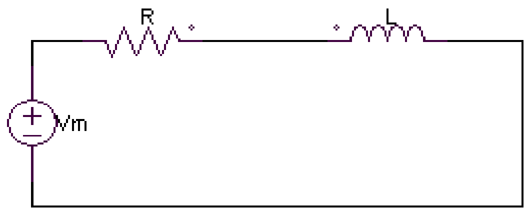


Figure 1. Electrical Model of One Phase of *SRM*

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

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

Where R is phase resistance and $\lambda(i,\theta)$ is magnetic flux is given by Equation (2).

$$\lambda(i,\theta) = L(i,\theta)i \tag{2}$$

Where $L(i,\theta)$ is the phase inductance, which varies as a function of rotor position (due to varying reluctance) and phase current (due to magnetic saturation).

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).

$$\lambda(i,\theta) = \int (v - ir)dt \tag{3}$$

The electrical model of the SRM can be compared with d.c. motor by substituting (2) in (1) as follows:

$$\begin{aligned} v &= ir + \frac{d(L(i,\theta)i)}{dt} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\frac{d(L(i,\theta))}{dt} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\frac{d\theta}{dt}\frac{d(L(i,\theta))}{d\theta} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\omega\frac{d(L(i,\theta))}{d\theta} \end{aligned} \tag{4}$$

There are many approaches for modeling the SRM, such as lookup-table techniques, magnetic equivalent circuit analysis, cubic-spline interpolations and finite-element analysis (FEA). Magnetic equivalent-circuit analysis and FEA are computationally intense and cubic-spline interpolations and lookup-table techniques require numerous flux-linkage current- position data, which are obtained either through experiments or using FEA, which are time-ineffective and tedious [9, 10].

## 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 2.

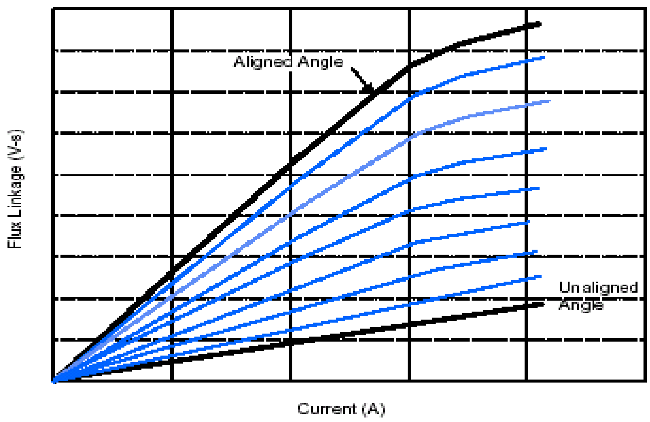


Figure 2. Ideal Flux Linkage Characteristics of SRM

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 [11, 12].

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 denergized.

A simplified measurement circuit for SRM flux linkage characteristics is shown in Figure 3.

When a voltage pulse applied to any phase of the SRM while all other phases are open the voltage given by Equation (5) [9].

$$V_m = iR_m + \frac{d\lambda}{dt} \tag{5}$$

$$\lambda = \int (V_m - iR_m)\, dt \tag{6}$$

Where '$V_m$' voltage across phase winding
'$R_m$' resistance of the phase winding
'$\lambda$' is flux linkage

From the Equation (6) flux linkage can be calculated from any numerical integration technique the above equation is performed by using Simpson's 1/3 rd rule.

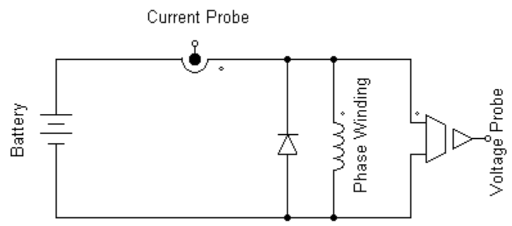


Figure 3. Simplified Measuring Circuit for SRM Flux Linkage Characteristics

### 3.1. Simpson's ⅓ Rule

Simpson's 1/3 rule is one of the popular method of numerical integration and it is used for the measurement of definite integrals.

$$\int Y(x)dx = h/3[Y0+4Y1+2Y2+4Y3+\text{---------------------} 2Yn\text{-}2+4Yn\text{-}1+Yn] \quad (7)$$

In Equation (7) Y(x) is the function and Y0, Y1………… the values of function at specified intervals and h is the interval period.

The proposed method has been tested using an experimental 0.5-kW 42-V four-phase 8/6 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 3.321ohms.

Table 1. Motor Specifications of SRM Submersible Pump

| Parameter | Value |
|---|---|
| Number of phase | 4 |
| Number of Stator poles | 8 |
| Number of rotor poles | 6 |
| Stator Inner diameter | 50 mm |
| Rotor outer diameter | 49mm |
| Stack length | 102mm |
| Stator arc | 10mm |
| Rotor arc | 08 mm |
| Airgap length | 0.3mm |
| Shaft Diameter | 19mm |

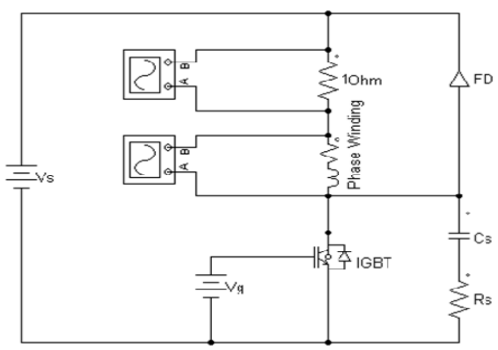


Figure 4. Experimental Setup

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. The current and voltage waveforms across the phase winding are capture is DSO as shown in Figure 5 and Figure 6. Digitally stored voltage and current waveform is applied in Equation (6 & 7) to calculate the flux linkage at different current levels of a 0.5kw 8/6 SRM is obtained.

Table 2. Flux Linkage Characteristics

| Current in | Flux Linkage in mWb at Different Rotor Position | | | | |
|---|---|---|---|---|---|
| Amp | 0 deg | 8 deg | 16 deg | 25 deg | 30 deg |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 1.2 | 1.8 | 2.4 | 2.7 | 4.8 |
| 0.948 | 2 | 3 | 3.9 | 4.8 | 6.8 |
| 1.481 | 3.3 | 3.9 | 5 | 6.6 | 9.8 |
| 2.104 | 4.5 | 5 | 7.2 | 9.3 | 13.4 |
| 2.667 | 5.7 | 6.6 | 8.7 | 11.7 | 16.1 |
| 3.289 | 6.6 | 7.8 | 11 | 14.4 | 19.5 |
| 3.763 | 7.5 | 8.5 | 12.3 | 16.8 | 22.2 |
| 4.44 | 8.7 | 10 | 15 | 20 | 26.7 |
| 5.03 | 9.6 | 11 | 17.4 | 23 | 30 |
| 5.68 | 10.7 | 12.6 | 19.2 | 26 | 35.1 |
| 6.45 | 11.7 | 13.5 | 22.8 | 30.8 | 39.8 |
| 7.04 | 13 | 15.2 | 25 | 34 | 44.6 |
| 7.51 | 14 | 16.6 | 26.9 | 37 | 47.3 |
| 8.01 | 15 | 17.9 | 28.5 | 39.7 | 50 |
| 8.51 | 16 | 19.3 | 30 | 41.8 | 52 |
| 9.01 | 16.5 | 20.5 | 31.5 | 43.5 | 54 |
| 9.51 | 17 | 21 | 33.1 | 45 | 55.8 |
| 10 | 18.1 | 22.4 | 34 | 46 | 57.3 |
| 10.5 | 19.1 | 22.9 | 35.6 | 46.8 | 58 |
| 11 | 19.6 | 24 | 36.5 | 47.5 | 58.5 |
| 12.68 | 22.2 | 27.2 | 38.2 | 48.5 | 58.8 |

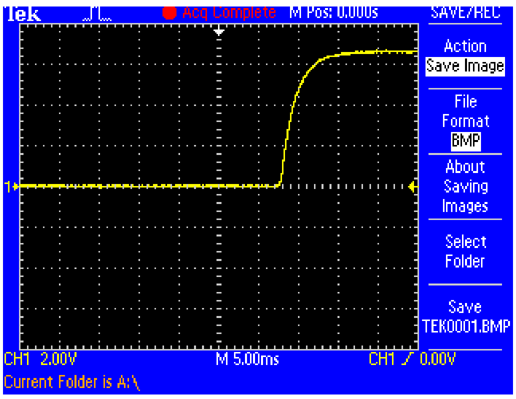


Figure 5. Current through the Motor Phase Winding

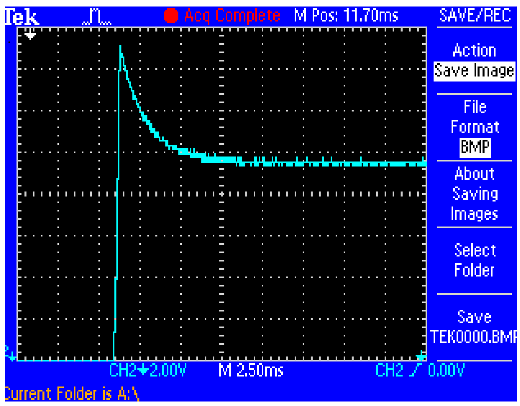


Figure 6. Voltage Across the Motor Phase Winding

The flux linkage at equally spaced rotor positions between unaligned to aligned positions are recorded as given in Table 2. The flux linkage characteristics of the motor based on experiments is shown in Figure 7.

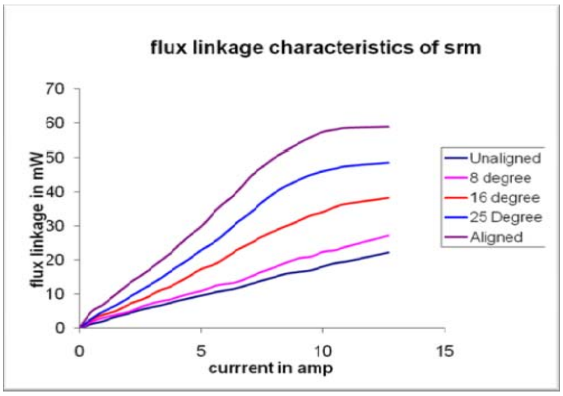


Figure 7. Experimental Flux Linkage Characteristics of SRM

## 4. MODELLING OF 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 modeling the drive is the analytic representation of the motor, which contains spatial and magnetic nonlinearities. The modeling 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 derive [10].

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. From the experimental data of SRM, a function of flux linkage is chosen as summary Equation (8). The coefficients a, b and c in Equation (8) to vary with rotor position, considering the physical significance that can be attached to each of these coefficients [10].

$$\lambda(i,\theta) = a(\theta)\left(1 - e^{b(\theta)i}\right) + c(\theta)i \quad (8)$$

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. The inherent periodic structure of the SRM is given in the variations of the coefficients a, b and c may be represented by Fourier cosine series of the form in Equations (9, 10, 11).

$$a = \sum_{k=0}^{\infty} a_k \cos(k \propto \theta) \quad (9)$$

$$b = \sum_{k=0}^{\infty} b_k \cos(k \propto \theta) \quad (10)$$

$$c = \sum_{k=0}^{\infty} c_k \cos(k \propto \theta) \quad (11)$$

Where $a_k$, $b_k$ and $c_k$ represents the $k^{th}$ Fourier coefficient of the fitting coefficient. The periodicity of the Fourier series is dependent on α, which is the number of electrical cycles seen by each phase. For the experimental SRM, α= 6. The Fourier coefficients listed in Table 3 are used to generate the coefficient a, b and c as described at all rotor positions. Therefore Fourier coefficient in Table 3 described the magnetic structure of the experimental SRM. Equation (8) is applied for experimental SRM with coefficients a, b and c as shown in Figure 8. The simulated flux linkage characteristics of experimental SRM are presented in Table 4.

Table 3. Fourier Coefficients for Experimental SRM

| k | a | b | c |
|---|---|---|---|
| 0 | 43.3091 | -0.0792 | 1.2648 |
| 1 | 33.8727 | -0.0415 | -0.6771 |
| 2 | -3.4927 | 0.0211 | -0.0168 |
| 3 | -0.7585 | -0.0124 | 0.0376 |
| 4 | -0.141 | 0.0039 | 0.0027 |
| 5 | -0.8969 | -0.0021 | 0.0307 |
| 6 | 0.1335 | -0.0013 | 0.0107 |
| 7 | -0.2167 | 0.0011 | -0.0016 |
| 8 | 0.3225 | -0.0014 | -0.0038 |

Table 4. Simulated Flux Linkage Characteristics

| Current | Flux Linkage in mWb at Different Rotor Position | | | | |
|---|---|---|---|---|---|
| I | Unaligned | 8 Degree | 16 Degree | 25 Degree | Aligned |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1.92 | 2.355 | 5.41 | 7.78 | 8.59 |
| 2 | 3.25 | 4.56 | 10.32 | 15.36 | 17.15 |
| 3 | 5.69 | 6.67 | 14.71 | 20.69 | 23.01 |
| 4 | 7.57 | 9.45 | 19.13 | 25.94 | 28.95 |
| 5 | 9.53 | 11.17 | 23.12 | 31.17 | 34.33 |
| 6 | 11.46 | 13.33 | 26.94 | 35.87 | 39.51 |
| 7 | 13.3 | 15.49 | 30.33 | 40.26 | 43.94 |
| 8 | 15.46 | 17.55 | 33.73 | 44.38 | 48.05 |
| 9 | 16.99 | 19.64 | 36.89 | 47.74 | 51.73 |
| 10 | 18.95 | 21.85 | 39.88 | 51.24 | 55.22 |
| 11 | 20.8 | 23.93 | 42.62 | 54.12 | 58.16 |

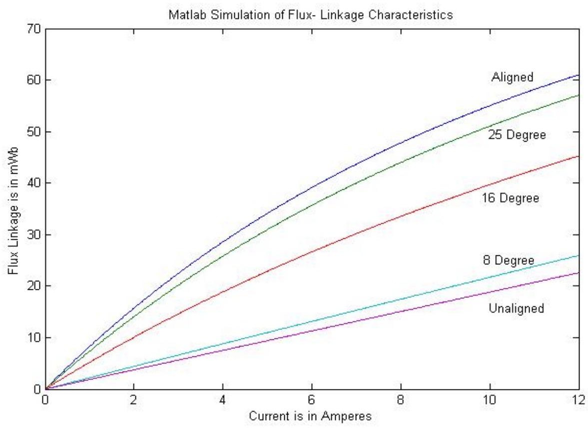


Figure - 8 Simulation result of Experimental SRM

## 5. 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 gives the characteristics of induction motor, dc shunt motor or series motor or combination of motors.

This paper has been 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 developed using Fourier series cosine coefficients. The accuracy of the model has verified with experimental results and they have validated the model.

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