# A Novel FEA Algorithm for SRM Simulations

Tanvir Rahman, Derek N. Dyck, David A. Lowther
Infolytica Corporation
300 Leo Pariseau, Suite 2222, H2X 4B3, Canada,
Corresponding author: tanvir@infolytica.com

***Abstract*— A new finite element analysis based switched reluctance machine simulation algorithm has been proposed and applied to carry out static and dynamic analysis. The algorithm can be used to approximate the static characteristics of SRMs with as few as six static FEA solves while taking into account the non-linear characteristics of SRMs. For the dynamic analysis, a novel equivalent circuit has been proposed for an H-bridge configuration that can carry out continuous conduction mode, voltage limited current driven dynamical analysis.**

***Index Terms*—Switched reluctance machine (SRM), Finite Element Analysis (FEA), Iterative optimization.**

## I. INTRODUCTION

Recently, the need to lessen dependence on fossil fuel in various industries including transportation has led to a great deal of effort being devoted to the electrification of automobiles and the development of more electric aircraft. This means that a new generation of highly efficient motors and generators that combine the powers of modern electronics, control strategies, novel materials etc. are being developed. Switched reluctance motors (SRM) are one of the motor types that are being considered for many of these applications. SRMs have long been known for their simplicity, robustness, ease of manufacture, fault tolerance (relative to other motor types), lack of permanent magnets etc. On the other hand, some of the drawbacks of the SRM such as high torque ripple, difficulty of control, high acoustic noise and vibration, etc., have meant that limited research has gone into their development. New research is exploring unconventional topologies, drive strategies, loss minimization and many other factors [1, 2] to address some of the drawbacks. An essential aspect of this process is the use of modern electromagnetic simulation tools that can be used to design and simulate the next generation of SRMs.

As in the case of other machine types, SRM design is an iterative process. This means that electromagnetic simulation tools must have capabilities that allow engineers to carry out design iteration and optimization quickly and accurately. As such, from the perspective of computational electromagnetics some of the challenges with regards to SRM design are as follows. It is known that by design, SRMs operate optimally under material saturation. This means that material non-linearities must be taken into account for their analysis and finite element analysis (FEA) based electromagnetic analysis is absolutely necessary for design validation. This is unlike some other numerical approaches such as those using a magnetic circuit based approach in which non-linear materials modeling coupled with design changes can be difficult to implement. Hence, the development of fast and accurate FEA based SRM modeling algorithm can be quite valuable for SRMs.

In this paper, a novel FEA based approach for the design and simulation of SRMs has been presented and the approach has been applied to carry out static and dynamic analysis of an SRM model. Over the years, many different analysis methods have been reported in the literature for designing SRMs (the numbers are too numerous to list but see e.g., [3, 4, 5]). Relatively fast algorithms have always used magnetic circuits based approaches. On the other hand, most previous FEA based algorithms have not optimized simulation times by taking advantage of known geometrical and other characteristics of SRMs that can reduce the amount of computation. The work presented here achieves this objective. In Section II of this paper, a hybrid approach is presented that combines FEA with certain geometrical characteristics of SRMs. In Section II.A, the algorithm for static analysis is presented and in II.B, a novel circuit that can be used to carry out dynamic simulation of SRMs is presented. In Section III, some simulation results using an SRM example are reported. The two approaches together provide a complete design and simulation algorithm for SRMs.

## II. NOVEL FEA BASED ALGORITHM

Static and dynamic simulations are the main analysis that is carried out during the design of an SRM. They can be considered the minimal requirement in any computational electromagnetic tool that is used for designing an SRM. Two new approached to carrying these out are presented below.

### *A. Static Analysis*

Static simulations of SRMs are generally used to calculate the flux linkage and static torque as a function of rotor position and phase current. These entities determine the performance envelope of an SRM. An FEA based approach to determining the flux linkage at a current *i* and position *Θ,* which can be considered an extension of [6] in which the flux linkages on the right hand side are calculated using static FEA solves is given by,

$$\lambda(i,\theta) = [\lambda_a \quad \lambda_u]\begin{bmatrix} 1 & 1-\frac{\pi}{NN_rB_r} & \cdots & 0 \\ 0 & \frac{\pi}{NN_rB_r} & \cdots & 1 \end{bmatrix} \times \vec{C}^{-T} \begin{bmatrix} 1 \\ \cos\theta \\ \vdots \\ \cos N\theta \end{bmatrix} \quad (1)$$

Where $\lambda_a$ and $\lambda_b$ are the flux linkages at the aligned and unaligned positions of the rotor, $N_r$ is the number of rotor poles, $B_r$ is the rotor pole arc angle and $N$ is and order parameter of the algorithm that originates from a Fourier series expansion of the flux linkage waveform of the SRM. The matrix *C* is given by,

$$\vec{C} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & \cos(\frac{\pi}{N}) & \cos(\frac{2\pi}{N}) & \cdots & \cos(\pi) \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & \cos(\frac{n\pi}{N}) & \cos(\frac{2n\pi}{N}) & \cdots & \cos(n\pi) \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & \cos(\pi) & \cos(2\pi) & \cdots & \cos(N\pi) \end{bmatrix}_{(N+1)\times(N+1)} \quad (2)$$

It should be noted with as few as six static solves (at three current levels), an approximation of the SRM performance envelope can be obtained using (1) and (2). Of course, better resolution and accuracy requires higher number of solves. Even though in this report this approach has been used for static analysis, the method can be applied to PWM drive simulations. This work is in progress.

### *B. Dynamic Analysis*

The dynamical analysis is carried out based on the following novel representation of an H-bridge configuration for SRMs (Figure 1). This circuit can be used to simulate the position based phase on/off characteristics that is particular to SRMs. It has the advantage of being applied using a current driven but voltage limited approach. FEA solves at each time step ensure that mutual induction and continuous conduction modes are taken into account during the simulations. Being current driven, the transients of the simulation are relatively short compared to a voltage driven approach. This makes this approach faster than other equivalent FEA based dynamical simulation methods for SRMs.

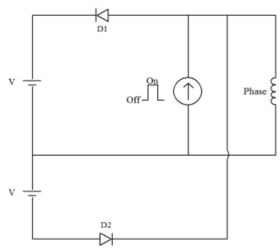


Figure 1: Per-phase equivalent H-bridge SRM circuit

## III. RESULTS AND VALIDATION

The algorithm has been validated using a 12/8 SRM with the following parameters: 400 V Bus, 2500 RPM, 200 Amps max. phase current, 30 and 18.5 inches outer and inner diameters. l The results of static analysis are shown in Figure 2 and the dynamic analysis results are shown in Figures 3-5. Both analyses show the expected qualitative behaviour. The static analysis has been verified by comparing against complete FEA based solves. The dynamic analysis has been validated by comparing against a magnetic circuit based analysis.

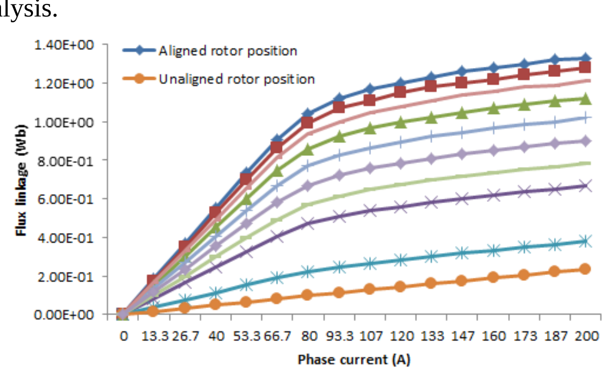


Figure 2: Flux linkage vs. static phase current at various rotor positions from aligned to unaligned.

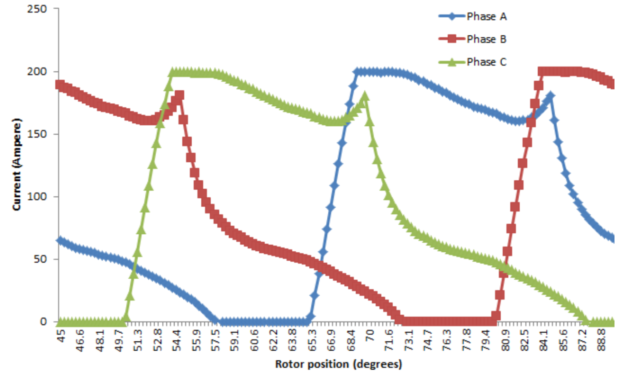


Figure 3: Current vs. rotor position in steady state

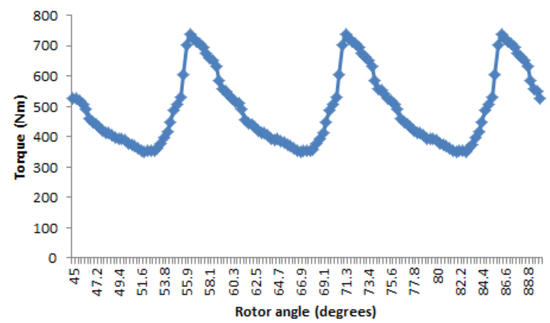


Figure 4: Torque vs. rotor position in steady state

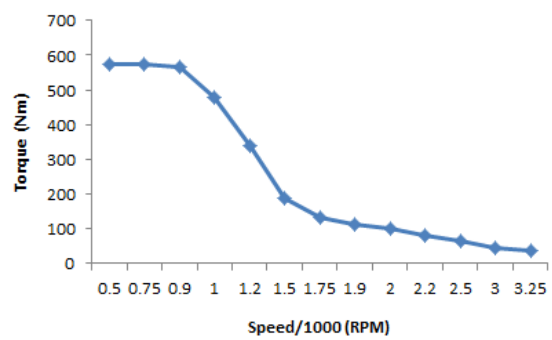


Figure 5: Torque-speed curve

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