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SIMULATION ANALYSIS OF A FOUR-PHASE SWITCHED RELUCTANCE MOTOR USING A 3D FINITE ELEMENT APPROACH

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Abstract— **Development of switched reluctance motors have revolutionized the industrial drives, aircraft applications, food processors, fans, pumps, vacuum cleaners and many applications because of its simpler design, ruggedness and efficiency. Researchers are highly motivated to declare switched reluctance motor as a substitute of induction motors. This paper deals with a three-dimensional (3D) finite element analysis of a switched reluctance motor. The performance of the motor was analyzed by injecting voltage in the windings of the motor and transient analysis of the model was carried out. Flux density distributions, magnetic field intensity within the motor, the winding currents, flux linkages, induced voltages, total energy and energy error were obtained. It was observed that the winding currents were high because of the high value of the applied excitation voltage (120V). The plot of energy error showed that there was less than 1% error in the simulation which shows that the simulation was accurate.**

Index Terms**—3D Model, Finite Element Method, Switched Reluctance Motor, Transient Analysis and Windings.**

I. INTRODUCTION

Switched Reluctance Motor (SRM) is special machinery with simple robust construction high speed operation, high efficiency, and high degree of independence between phases, high reliability, and high torque to inertia ratio. Its application ranges from low-power servomotor to high power traction drives [1], [2], [3] and [4].Exclusive features of the Switched Reluctance Motor (SRM) such as lack of any coil or permanent magnet on the rotor, simple structure and high reliability make it a suitable candidate for operation in harsh or sensitive conditions. The different aspects of SRM drives have been extensively investigated and carried out in the past decades by several research organizations [5] and [6].SRMs are suitable for applications where high speed and high power are required. Each stator phase is supplied with dc voltage and developed torque tends to rotate the rotor aligned with the energized stator poles. This makes the inductance of the excited coils maximum. Torque production is not dependent of the current direction [7]. If this rotation tendency in the same direction is kept continuously rotational, torque will be produced. A control scheme is required to observe the rotor position and switch the stator phases with respect to these rotor positions by using the power electronic circuit.

There are many advantages of SRMs over a conventional electric motors: easy construction, less copper losses, higher efficiency compared to the motors in the same power ratings, tolerable phase faults, very high speed applications, high torque/Inertia ratio, etc. There are also some disadvantages of SRMs: requirement of rotor position sensor or microcontroller for the sensor less control, complexity of the controller since theproduced torque is also a function of the position beside thephase current, torque has strokes because of the switching, noise, torque pulsations [8].

There are a number of numerical methods which can be adopted for the analysis of electromagnetic field problems. Examples are Moments Method (MM), Monte Carlo Method (MCM), Finite Difference Method (FDM) [9], Boundary Element Method (BEM) [10] and Finite Element Method (FEM) [11].By the introduction of the FEA, numerical field calculation approach has become a strong alternative in the design and analysis of electrical machines and many performance outcomes can be assessed. Intensive knowledge of FEA could be found in [12], [13] and [14].

In this paper, the analysis of the SRM was done using ANSYS Maxwell-3D package. The Magnetic and electric potential was calculated by finite element solution which was made in3D. The ANSYS program supports high frequency electromagnetic analysis which will vary with current. First step of analysis in Maxwell-3D is to assign excitations and boundary conditions to the criti¬cal geometry of the motor. The Geometrical model of a Switched Reluctance motor is meshed up into different polynomial elements. One sample can be analyzed by ANSYS software

II. STRUCTURE CHARACTERIZATION OF SRM

The structure of the SRM is presented in Figure 1,which shows the schematic diagram of an eight-stator pole, six-rotor pole; the stator and rotor laminations are assumed to be made of steel_1008. Stator windings are made up of copper with relative permeability of 0.999991 H/m and bulk conductivity of 58000000 Siemens/m. The stator winding is concentrated and the rotor has no winding or brushes. The rotor has segments which constitute flux guides that serve to bend the flux produced by the current flowing in the coil windings in the stator slots around the slot and back towards the periphery of the rotor. Figure 1 shows layout of the SRM with 4-phase and 8 poles. Table 1 shows the specifications of the SRM.

III. FINITE ELEMENT MODEL

Finite Element Method (FEM) is a numerical technique to get an approximate solution by partial differential equation. FEM is a computational tool used to know the perfor¬mance in engineering applications. The complicated solid structure with moving boundaries can be analyzed over FEM. A field solution can be obtained with time variables and with non-linear materials [15]. The stages involved in the simulation of the motor using 3D FE approach are; design settings, creation of 3D model, assigning of boundaries and excitations, assigning of parameters, mesh operations and analysis setup as outlined in [16].

In the three dimensional finite element analysis adopted in this paper, a regular polyhedron element, with dense meshes at places where the field variations are being changed rapidly has been used. Each phase of the motor has two coils which are shown in different colours as presented in figure 1. There are 150 turns which are made up of stranded conductors. The windings were excited using voltage type of excitation. Also, the usual assumption that the magnetic field outside of an air box in which the motor is placed is considered to be zero. Figure 2 shows the shape of the boundary with the model while figure 3 shows the finite element mesh of the SRM.

IV. RESULTS AND DISCUSSIONS

In the previous sections, the model of the four-phase Switched Reluctance Motor was obtained and implemented in Maxwell 3D environment. The simulation produced a number of results. The objective of this section is to discuss the obtained results and pave way for an informed conclusion.

The Total Energy, Energy Error (%) and Delta Energy were plotted against Adaptive Solution Pass as shown in figures 4, 5 and 6 respectively. This is primarily to evaluate the convergence of these quantities versus the mesh. The maximum number of passes used in this analysis is nine (9). This is the maximum number of mesh refinement cycles which Maxwell-3D performed. This value is a stopping criterion for the adaptive solution.

Figure 4 shows that the total energy was decreasing down during the simulation. It stopped at 5.39 J at the last adaptive pass.

Figure 5 shows the Energy Error (%). This is the error energy as a percentage of the total energy. From the figure 5, the percentage is less than 1% at the last adaptive pass. This shows that the simulation/solution is accurate.

The Delta Energy (%) plot is presented in figure 6. It can be observed that the value at the last adaptive solution pass is 0.19%. This shows that further mesh refinement will probably not change the solution, which further proves that the solution is accurate.

It should be noted that at each step in the adaptive process, the energy and error energy are computed, and the most recent solutions can be viewed as soon as they are completed. After the mesh is refined, the matrix is calculated on the refined mesh. The relative change between the previous matrix and the current matrix will then be computed and reported as the matrix delta; the target matrix delta is the Percent Error.

The magnitude of magnetic flux density and magnitude of vector potential were monitored during the simulation as presented in figures 7 and 8 respectively.

Figure 7 shows the flux density on the stator and rotor of the motor. It can be observed that there are enough magnetic fields on the stator than the rotor.

Figure 8 is the field plot of the magnitude of vector potential showing the direction of concentration. The vector potential lines link all the slots of modeled motor.

The transient simulation results are shown in figures 9, 10, 11 and 12. The stop time is 20 ms while the time step is 2 ms.

Figures 9 and 10 are the plots of the winding currents versus time. It can be observed that the maximum current that is going through each of the windings is approximately 59 amps. The maximum currents for winding1, winding2, winding3 and winding4 are 58.9442 amps, 58.9250 amps, 58.8975 amps and 58.7703 amps respectively. The reason for these high currents is because of the high value of the applied excitation voltage of 120 volts.

The induced voltage recorded a transient of 62.5 volts at 2 ms before settling at 0 volt as presented in figure 11. The maximum flux linkage recorded in the windings of the motor is 0.29 Wb as shown in figure 12.

V. CONCLUSION

In this work, a complete model of Switched Reluctance Motor was developed and the simulation analysis of the motor was carried out using Maxwell 3D software. The motor has four phases in which each of the phases has two coils. The coils are in series with each other. The stator has eight poles while the rotor has six poles. The stator windings are made up of copper with relative permeability of 0.999991 H/m and bulk conductivity of 58000000 Siemens/m. Using Finite Element Approach, finish element mesh of the model was obtained. The performance of the motor was analyzed by injecting voltage in the windings of the motor. Flux density distributions, magnetic field intensity within the motor were monitored. Transient analysis was carried out which produced results such as flux linkages (0.29 Wb), induced voltages (62.5 V), winding currents of the four windings (58.9442 amps, 58.9250 amps, 58.8975 amps and 58.7703 amps respectively). It was observed that the winding currents were high because of the high value of the applied excitation voltage. Adaptive solutions of the model were obtained and it was shown that there was less than 1% error in the simulation.

Table 1: Specifications of the 4-phase SRM

Materials	**Descriptions**	**Dimensions in mm**
	Core diameter on gap side	70
ROTOR	Core diameter on yoke side	30
	Core length	66
	Number of poles	6
	Yoke thickness	9
	Pole embrace	0.5
	End extension	0
	Region length	200
	Core diameter on gap side	75
STATOR	Core diameter on yoke side	120
	Core length	65
	Number of poles	8
	Yoke thickness	9
	Pole embrace	0.5
	End extension	1
	Region length	200

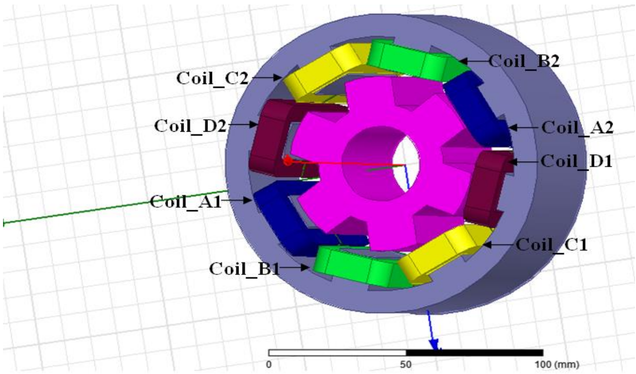

Figure 1: 4 Phase-8 Poles SRM Layout

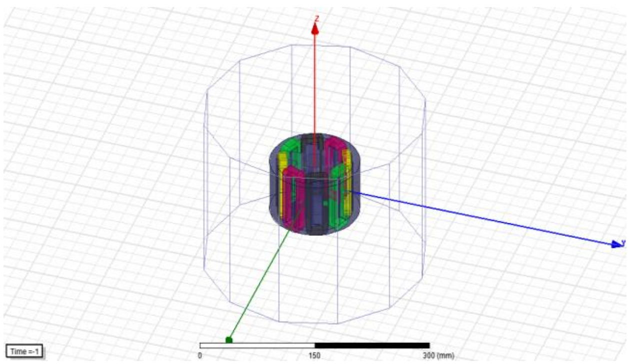

Figure 2: Shape of the boundary with the Model

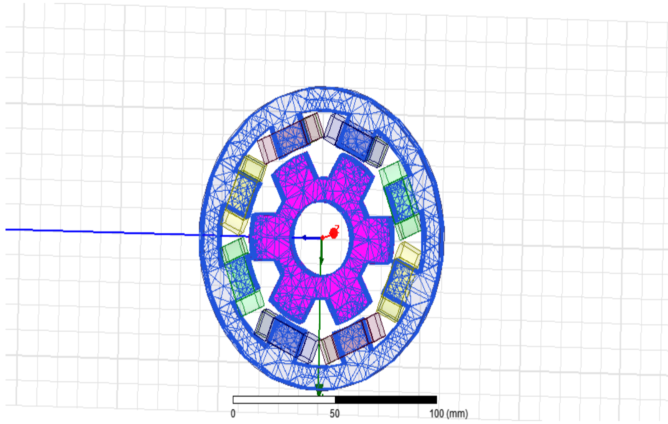

Figure 3: Finite Element Mesh of the SRM

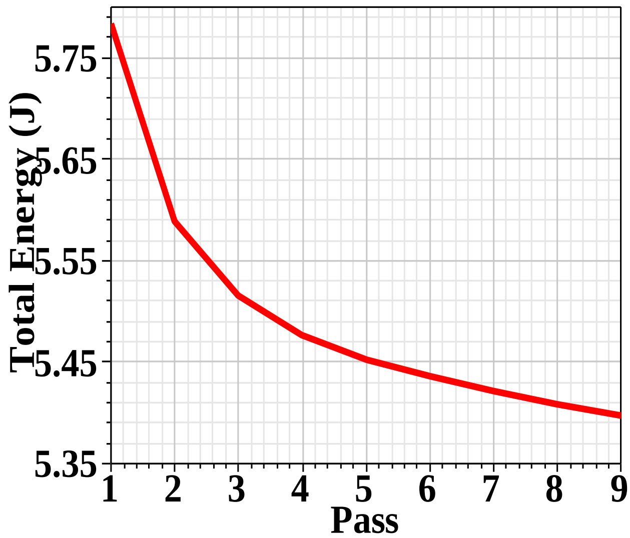

Figure 4: Total Energy versus Adaptive Solution Pass

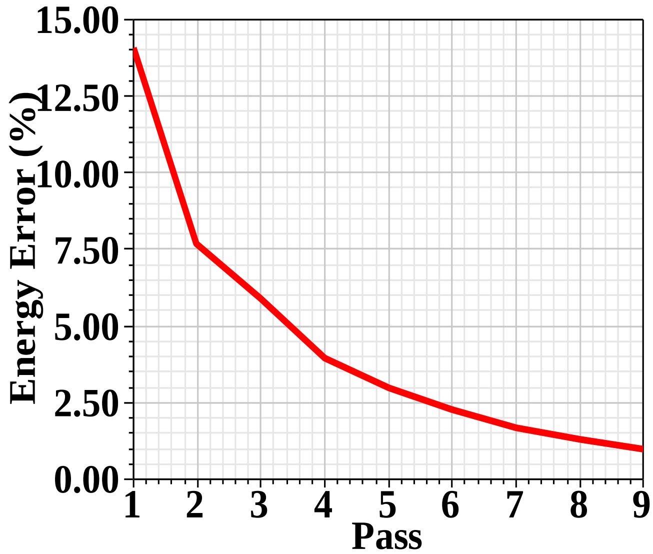

Figure 5: Energy Error (%) versus Adaptive Solution Pass

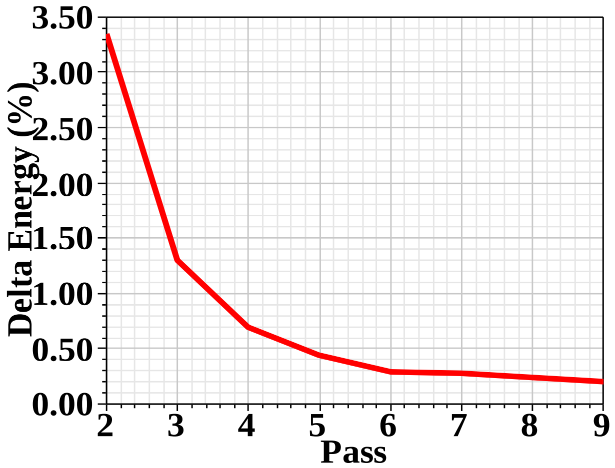

Figure 6: Delta Energy (%) versus Adaptive Solution Pass

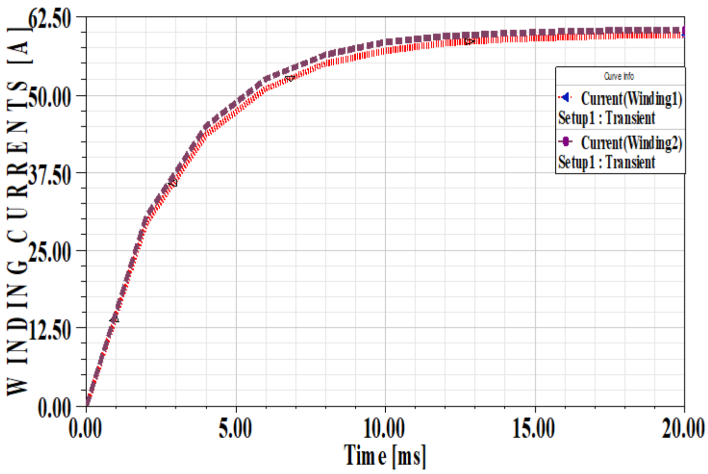

Figure 9: Winding1 and Winding2 Currents with Time

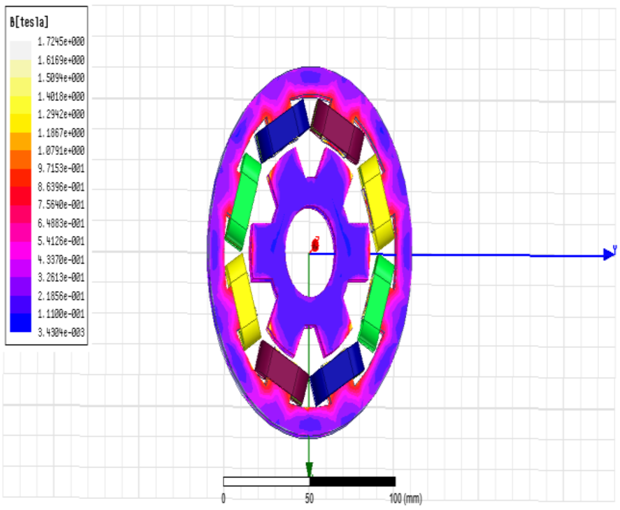

Figure 7: Magnitude of Magnetic Flux Density

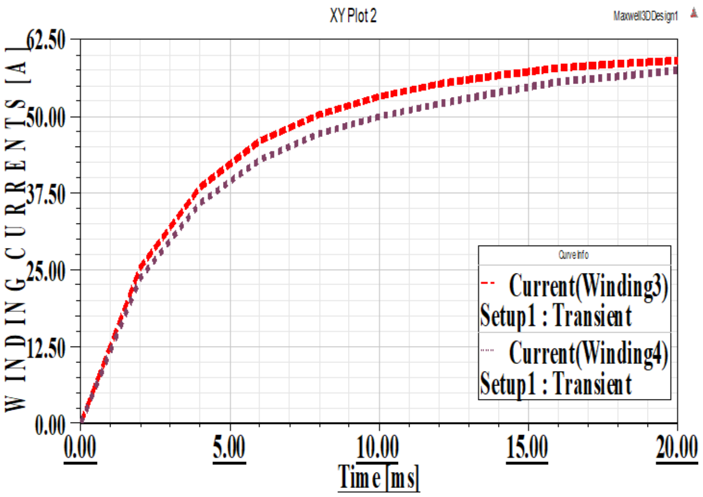

Figure 10: Winding3 and Winding4 Currents with Time

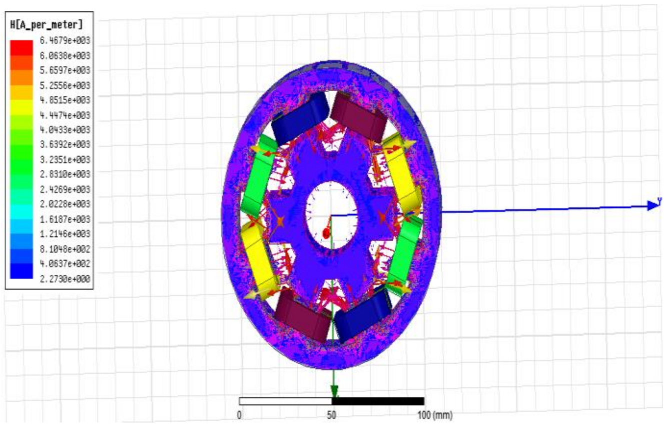

Figure 8: Magnitude of Vector Potential

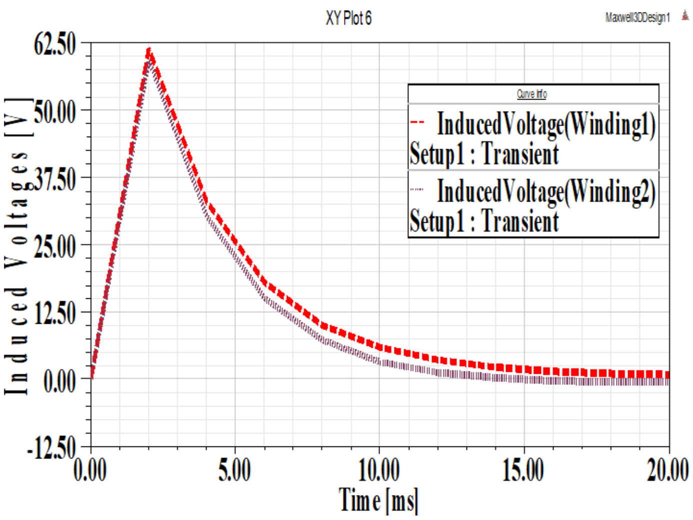

Figure 11: Induced Voltage versus Time

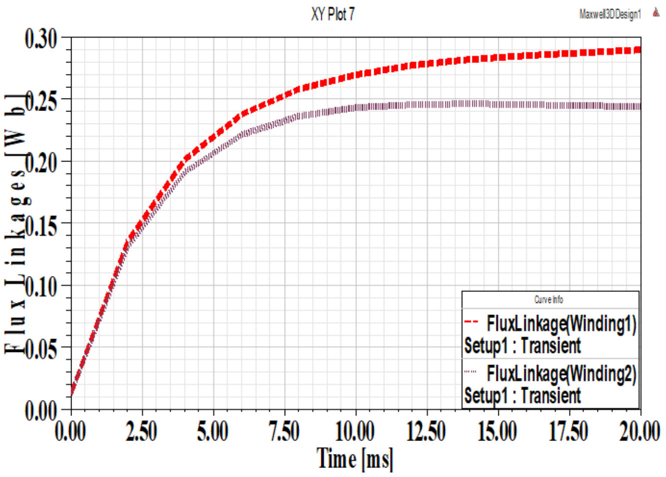

Figure 12: Flux Linkage versus Time

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