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Modeling and Simulation of Induction Motor based on Finite Element Analysis

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Article Info	ABSTRACT
	This paper presents the development of a co-simulation platform of induction motor (IM). For the simulation, a coupled model is introduced which contains the control, the power electronics and also the induction machine. Each of these components is simulated in different software environments. So, this study provides an advanced modeling and simulation tools for IM which integrate all the components into one common simulation platform environment. In this work, the IM is created using Ansys-Maxwell based on Finite Element Analysis (FEA), whereas the power electronic converter is developed in Ansys-Simplorer and the control scheme is build in MATLAB-Simulink environment. Such structure can be useful for accurate design and allows coupling analysis for more realistic simulation. This platform is exploited to analyze the system models with faults caused by failures of different drive's components. Here, two studies cases are presented: the first is the effects of a faulty device of the PWM inverter, and the second case is the influence of the short circuit of two stator phases. In order to study the performance of the control drive of the IM under fault conditions, a co-simulation of the global dynamic model has been proposed to analyze the IM behavior and control drives. In this work, the co-simulation has been performed; furthermore the simulation results of scalar control allowed verifying the precision of the proposed FEM platform.

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1. INTRODUCTION

In order to better understand the physics in a complex machine design, first-order harmonic Finite Element Method (FEM) model embedded within a dynamic simulation seems to suite better the needs of complex control strategies, especially when the control actions to fault cases are taken into consideration. In fact, co-simulation is now a proven way to handle and understand the physics of these complex machine designs and hence facilitate the development of control strategies of complex machines [1], [14].

For maximizing the quality of simulation results of an electric drive, it is therefore essential to use a model which is as detailed as possible. But, making such a detailed is not feasible using a single software tool [2]. This is because, the model which consists of a control structure, power electronics and a machine, is a heterogeneous model.

Generally, simulation of electric drives is realized using reduced order models, where the inverter is represented by a sinusoidal source and the machine is replaced by a simple look-up table [6]. In fact, such a modeling can give reasonable information about the system level performance, but it cannot identify

and investigate certain transient and harmonic effects, switching and increased iron losses etc.., which are necessary for optimization of the drive [4].

Many authors conducted studies on FEA for IM. Moreover, in almost all those previous studies the control part has not taken into account [7], [8]. In the same manner, a lot of strategies of control have been proposed [6]. However, the nonlinearities and magnetic characteristics of IM in control algorithms and especially with fault conditions are rarely discussed. However, to know the actual and accurate behavior of IM in faulty cases and check the validation limits of control drives, simulation need to be performed taking into account the nonlinearities and magnetic characteristics of the machine and to increase the accuracy and reliability of the control drives.

It is known that the machines behavior becomes more nonlinear depending on the drive changing conditions and the effects of magnetic saturation and spatial harmonics should be taken into account [3]. For these reasons, the use of FEA becomes relatively easy because of the capability to import geometry drawings and to give a more realistic representation to the internal machine characteristics. Actually, the FEA is automated to be useful in modern machine design which offering flexibility in the geometrical shape, material properties and boundary conditions in all machine regions [7].

In this work, the co-simulation of an IM is presented and two-dimensional motor model is created in Maxwell which gives acceptable balance between the simulation time and result accuracy. In fact, the aim of the co-simulation is to realize a more realistic and acurate model of the overall electric control system which can be used in the healthy and failure mode operation. Here, the performances of scalar control of IM have been compared under healthy and faulty state considering nonlinearities of both the IM and control drives.

This publication presents the development of a platform for co-simulation. Different simulation environments are integrated in order to approach the maximum from the reality machine state. The simulation results of the IM drive are obtained under normal and failure modes operating conditions.

The paper is organized in six sections. In introduction, the motivation of the co-simulation is presented. In the second section, the FEA theory is presented and the finite element model of the IM using Ansys-Maxwell and the inverter model using Ansys-Simplorer are described. In the third section, The FEM model of the machine is developed on Maxwell and used for co-simulation with Simplorer. The global model structure using the link between Simplorer/Maxwell and MATLAB-Simulink is presented in fourth section. The simulation results of the proposed model are shown and analyzed in healthy and faulty conditions. Finally, conclusions are presented in section VI.

2. FINITE ELEMENT ANALYSIS (FEA)

FEA is a computer based numerical technique for calculating the parameters of electromagnetic devices. It can be used to calculate the flux density, flux linkages, inductance, torque; induced emf etc., in the FEM, the large electromagnetic device is broken down into many small elements. The behavior of an individual element can be described with a relatively simple set of equations [11]. The computer can solve this large set of simultaneous equations. From the solution, the computer extracts the behavior of the individual elements.

In fact, FEA offers unlimited flexibility in the geometrical shape, material properties and boundary conditions in different regions of the machine [13]. It provides also detailed information about the machine nonlinear effects (based on its geometry and material properties). This modeling approach is capable of obtaining an accurate and complete description of an electrical machine [10]. The magnetic circuit is modeled by a mesh of small elements. The field values are then assumed to be a simple function of position within these elements, enabling interpolation of results. The time required to calculate the field distribution may be very long, depending on the number of elements considered. A compromise must be reached between using finer meshes to achieve higher accuracy and the processing resources needed to achieve reasonable simulation times. The FEA is very flexible, especially for new designs incorporating new shapes. However long time simulation requirements reduce its attractiveness for a case when a control algorithm needs to be incorporated [5].

This work presents the development of a simulation platform of a three-phase squirrel cage induction motor drive control system. The machine models are first created in ANSYS Maxwell 2D, a template-based electric machine design tool fully integrated into Maxwell, then imported in Simplorer for co-simulation, enabling the implementation of the electromechanical parts of the drive [4]. Finally, a two way interface is established between Simplorer and Matlab-Simlulink. The co-simulation is done by adding first a Simulink component to Simplorer circuit, followed by the creation of an S-Function in Simulink using the Sim2Sim Link interface.

2.1. Finite Element Model of Induction Motor

The Maxwell is one of the Ansoft Corporation software well known for Finite Element Method modeling [3]. Because it has many features which altogether make analysis of machine models. The models generated in Maxwell can also be inter-linked to Simplorer for co-simulation. It can also make simulation by itself which can make possible to observe the machine parameters and performances.

In the process of imputing the design data in the RMxprt, a user has to specify the dimensions of the stator and rotor of the machine and related parameters such as machine type, number of poles of the machine and control type. Furthermore, a user has to specify the rated parameters such as winding, slot, wire, conductors, insulation and some other related parameters [12].

A model of the IM was constructed using Maxwell 14. The RMxprt model of an IM is shown in Figure. There are four steps involved in FEA which are:
a. Definition of geometrical parameters and construction of 2D model.
b. Definition of physical parameters such as regions, materials etc.
c. Construction of electric circuit model.
d. Meshing of the study domain and solving of problem.

Figure 1 shows the RMxprt model and Figure 2 illustrates the complete geometrical 2D model of the IM. The parameters of the machine are detailed in Tables 1, 2 and 3.
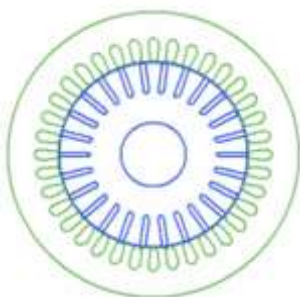

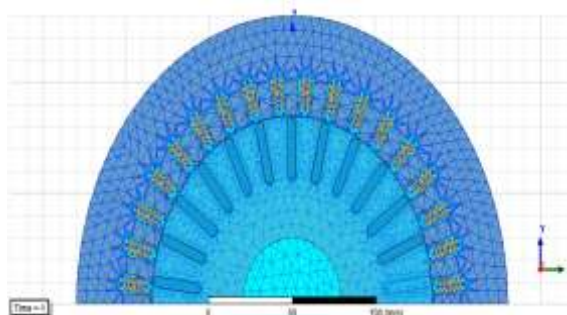Figure 1. RMxprt Model of the induction motor

Figure 2. 2D Finite Element Model of the induction motor

2.2. Power Inverter Model

Figure 3 shows the three-phase inverter of the simulation structure which implemented in Ansys-Simplorer. In fact, Simplorer is a circuit modeling software which is also used in this work. It present a simulation package for electric circuit simulations that allows one to easily and quickly model all Power electronic components of an application. It can be used to design and model electric, electronic, control and mechanical components [9]. It has user friendly graphical interfaces making even complex models easy to define [10]. Due to its ability to inter-link with Maxwell and Simulink, Simplorer was the best choice to be used as the interface engine in the co-simulation of this paper.

Due to its ability to inter-link with Maxwell and Simulink, Simplorer was the best choice to be used as the interface engine in the co-simulation of this paper. Here, ideal switches are used, but it is also possible to replace them with exact models of IGBTs. The PWM signals (Sa, Sb, Sc) can be generated from the control scheme in MATLAB-Simulink and received through an interface and fed to the inverter switches S1 to S6 built up in Simplorer. In this work, the inverter is controlled by PWM signals generated with Simplorer.

Besides the inverter, the model includes the concentrated phase end-winding inductances Lend and phase winding resistances Rs. These components are included in this model as it is not possible to integrate them in a two dimensional FEM based motor model. Figure 4 and 5 give the PWM signals and the PWM output for one phase.

It is important to use Simplorer because in Simulink software, a power electronic switch like Mosfet has modeled with an ideal switch and a resistant that named Rd and determined from Mosfet datasheet [15]. This model cannot simulate behavior of a real Mosfet like noise, switching losses, temperature and many other details. In fact, Simplorer calculates two groups of features for a switch. First group is electric features like DC current (A), Energy and time calculation, capacities and parasitic elements [16], [17].
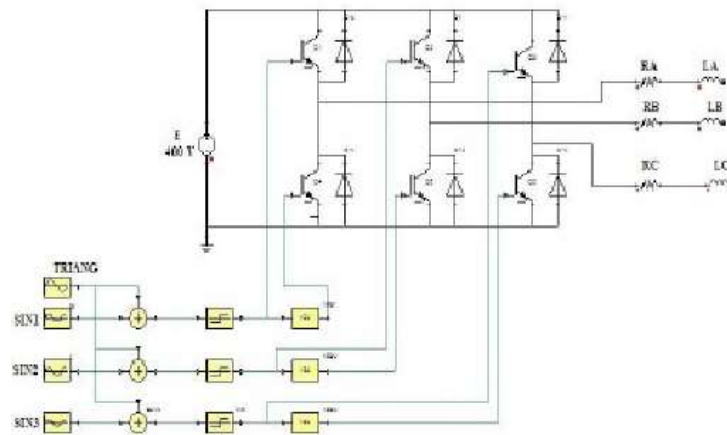
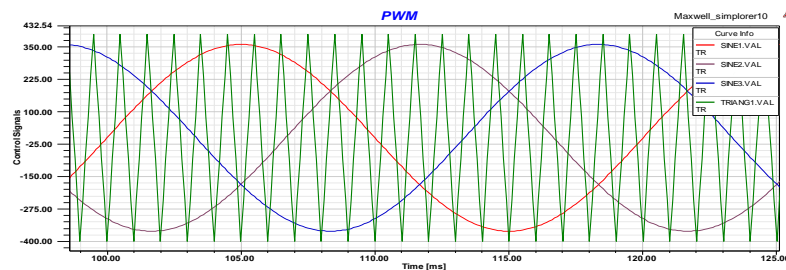Figure 3. A three phase Power Converter with additional resistance and end-winding inductance

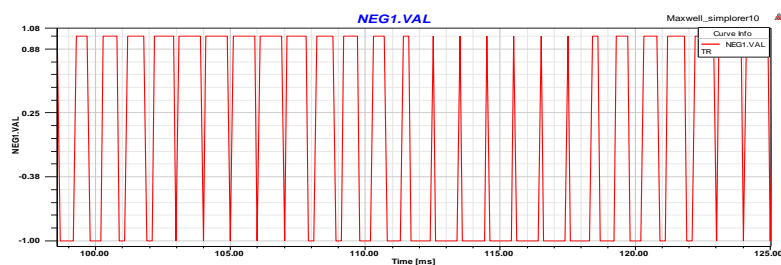Figure 4. 2-Level PWM Comparison Signals

Figure 5. 2-Level PWM Output

3. IM DRIVE MODEL: CO-SIMULATION MAXWELL/SIMPLORER

In this section, we propose to feed the machine with a three-phase PWM inverter. The FEM model of the machine is developed on Maxwell and used for simulation with Ansys-Simplorer in order to have the simulation results of the complete system.

When the IM is completely built in Maxwell and analyzed, then it will be prepared for co-simulation with Simplorer. The excitation is previously defined with current sources. In order to use Maxwell in co-simulation with Simplorer, the user needs to do some modifications on the Maxwell model. The 2D FEM machine model created and analyzed in Maxwell cannot be exported directly to Simulink. A necessary intermediate step using Simplorer program, here we choose to include the inverter, and it is possible to include a simple three phase source. Figure 6 shows the principle diagram of the proposed co-simulation.

According to each module of all above built, the PWM inverter fed IM system can be composed of the entire systematic model. Figure 6 shows the simulated system model for the study of inverter fed induction motor. In the systematic model, motor rotation speed is given rated speed 1500 rpm by V_ROTB1 module.
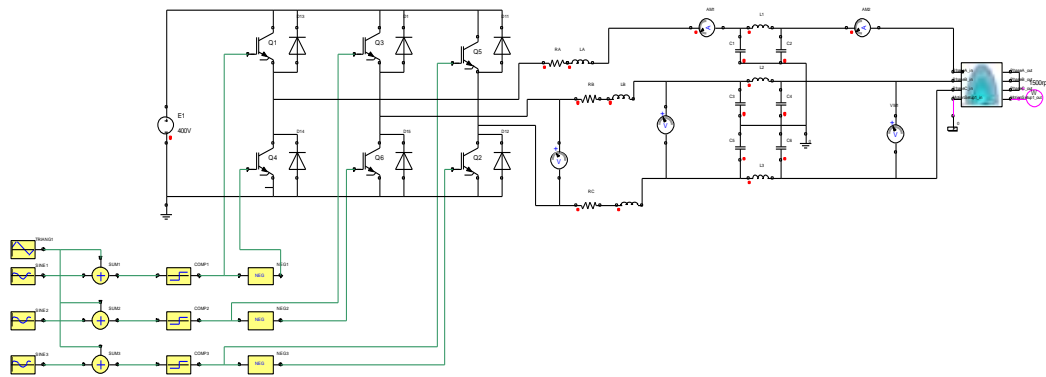

Figure 6. 2D dynamic model of the induction motor drive imported in Simplorer drive simulator

4.   GLOBAL MODEL STRUCTURE

After verifying the control scheme with the simulation model of IM in Simulink, the next step was to link the control system to Simplorer. This was done by replacing the machine in the Simulink "S-function" with a generic IM in Simplorer. The IM and the inverter which will be linked to Simulink voltage were placed in Simplorer worksheet. The Simulink control system was then imported to Simplorer as shown in the complete coupled model of Simplorer IM and Simulink control system in Figure 7.
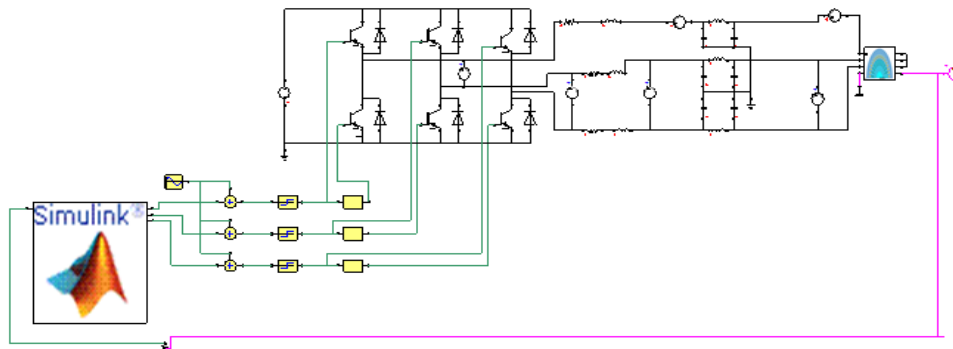

Figure 7. Maxwell/Simplorer/Simulink co-simulation of an induction motor drive with V/f speed control

Using the "SiM2SiM"interface link generated in Simulink by a special S-Function known as « AnsoftSFunction » as shown in Figure 8. Information from the FEM model can then be connected to the Simulink control system ready for co-simulation. Figure 8 displays the Simulink block diagram of a standard open loop Volt/Hertz control system of an induction motor drive that is used in this study for the co-simulation validation.
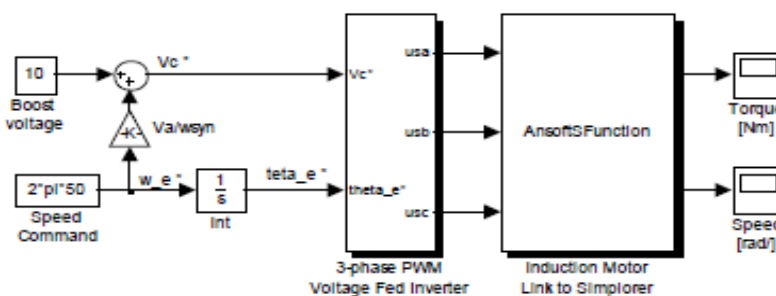

Figure 8. Simulink block diagram linked to Simplorer

For simulation, the reference speed of 2*50*pi was converted in position angle and provided to the inverter with the reference voltage V*$_C$. After that, the simulation was started in Simplorer which calls control system. The intention of this simulation step is to verify co-simulation between Simulink and Simplorer. The responses were as shown in the following Figures. Figure 9 shows the simulation results of the co-simulation of the IM in normal operating conditions. This Figure gives the stator voltages, currents, flux and the electromagnetic torque.
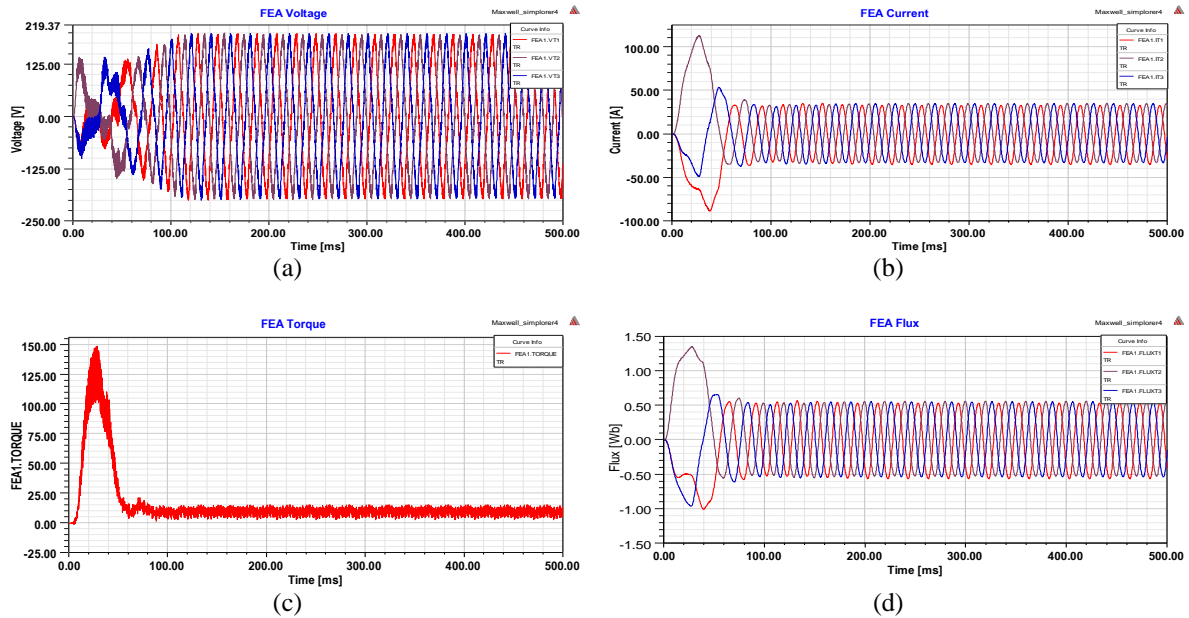

(a)

(b)

(c)

(d)

Figure 10. Simulation results of co-simulated IM in normal operating conditions: (a) stator voltages, (b) stator currents, (c) electromagnetic torque, (d) stator Flux

Figure 9 present the three phase stator voltages, currents which are non sinusoidal at the start-up and then stabilize with a regular form and phases. The electromagnetic is given when the simulation is realized without load torque. Figure 10 shows the distribution of the magnetic flux line of the machine in healthy case. In this case, we note that the flux distribution is symmetrical.
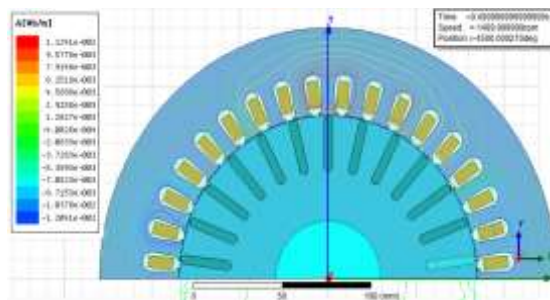

Figure 10. Magnetic Flux lines in healthy case

5. INDUCTION MOTOR MODEL WITH FAULT OPERATING CONDITIONS

The IM drive circuit model is constituted of the nonlinear elements, the circuit breakers, and power electronics components. In this section, the effects of power electronics faulty components are simulated and discussed. The machine, used in simulation of two fault case studies, is a three-phase, 2 poles, squirrel cage induction machine, without load torque and a maximum speed of 1500 rpm. In this work, two types of fault are presented and discussed: one fault is occurring at the machine terminals and the second one is due to faulty power transistor.

5.1. One IGBT Short Circuited

Figure 11 present the system model with a short circuit of the one IGBT of the inverter first leg. The simulation results are obtained in this case by injecting the fault when the speed reached the steady state operation. Then at t=0.2s, closing the switch S1, the top transistor of the first power pole of the inverter is short circuited between the IGBT and the source terminal. The waveforms of the motor's stator currents in phase A are shown in Figure 12.

The simulation based on FEA motor model indicates an initial increase of the torque pulsations, immediately after the fault occurs at t=0.2s. This followed by oscillations in the electromagnetic torque, meaning that the motor cannot operate under the same rated load condition. Figure (12.b) shows that the stator current of the circuited IGBT has very high amplitude with disturbances in all currents phases. We can notice a difference in the flux lines distribution in the healthy and default cases. Color gradation gives an idea of the concentration areas of the magnetic flux.
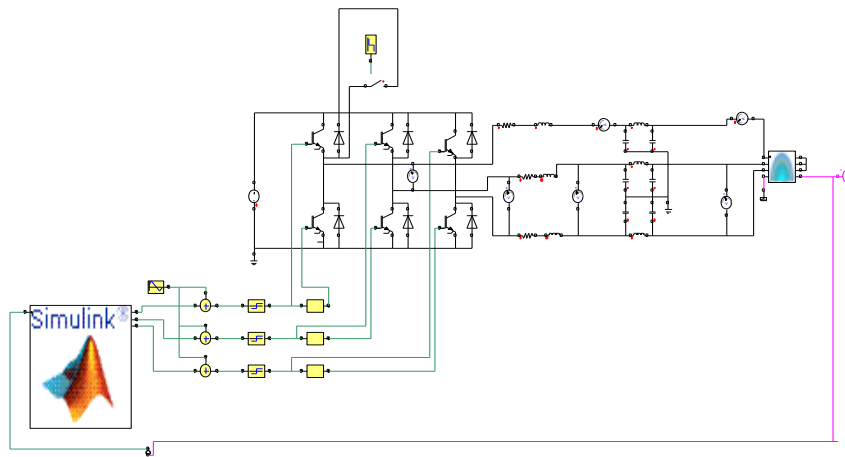

Figure 11. Induction motor drive diagram with one IGBT short circuit
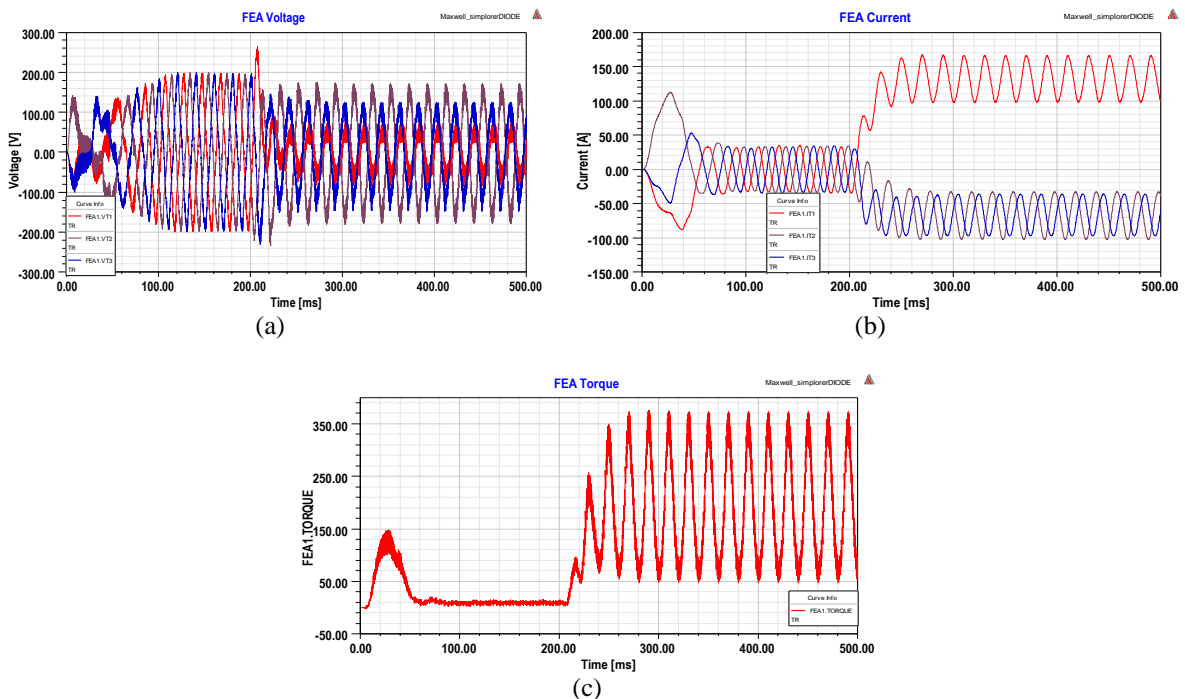

(a)

(b)

(c)

Figure 12. Simulation Results with one Shorted IGBT: (a) Stator Voltages, (b) Stator Currents,
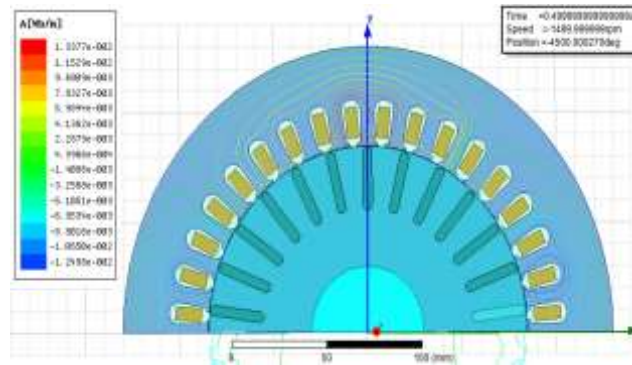(c) Electromagnetic Torque

Figure 13. Magnetic flux lines in faulty case: short circuit of IGBT

5.2. Two Phases Short Circuited

Figure 14 shows the simulation results of the faulted machine when the phase A and B are short-circuited. The simulation is done by starting the drive under rated load and then, at t=200ms, the two lines are short circuited at the machine terminals by closing a switch in parallel with the IGBT. The simulation results are obtained with motor already running in steady state conditions.
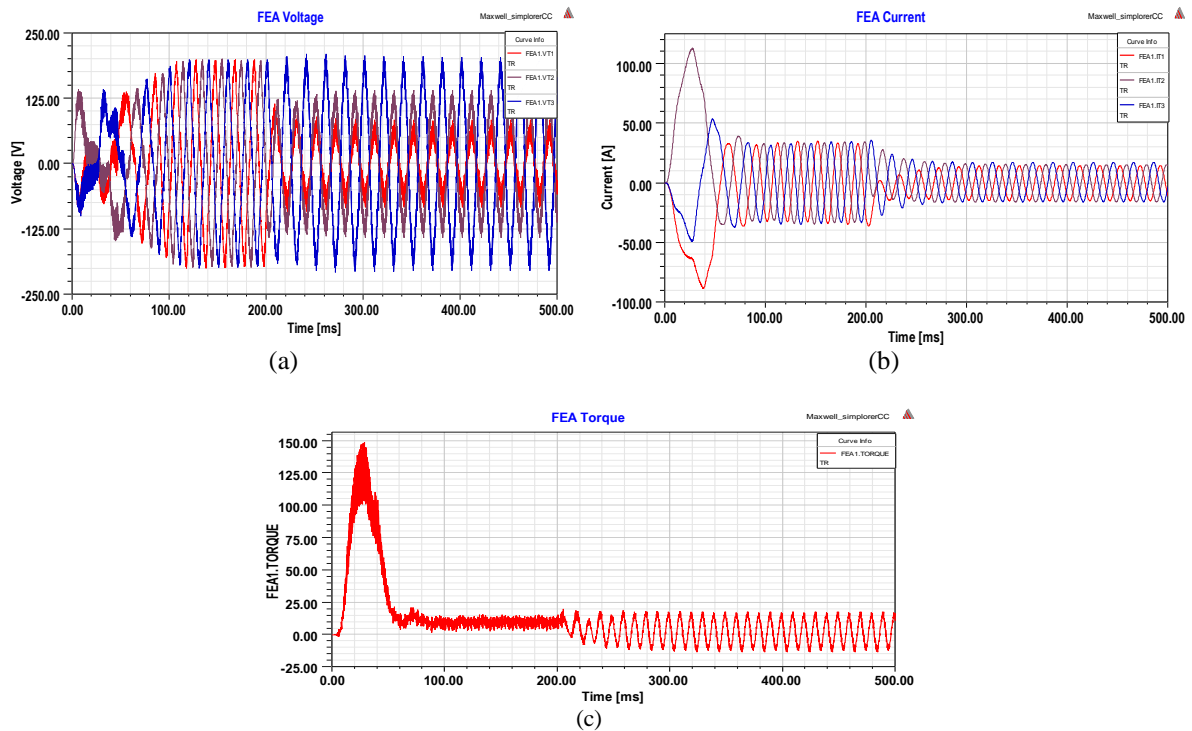

(a)

(b)

(c)

Figure 14. Simulation Results with Two Phases Short Circuited: (a) Stator Voltages, (b) Stator Currents, (c) Electromagnetic Torque.

In this fault condition, the machine cannot operate with electromagnetic torque damping slowly to zero as both time waveforms of Figure 14 shows. At the time of the application of the fault at t=0.2s, we note that the stator voltage are not balanced and the magnitudes are decreased. Same thing for the stator currents which have low magnitudes compared as to these before appliying the fault. Figure 15 shows that there is a big difference between the magnetic flux lines from the high to low values in healthy and faulty case.
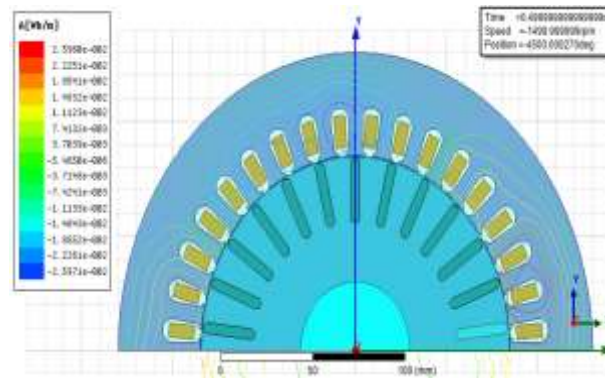
Figure 15. Magnetic flux lines in faulty case: two phases short circuited

6. CONCLUSIONS

The advantage of co-simulation in Simplorer/Maxwell is that it provides advanced displays of the simulation results, including the visualization of the electric machine's magnetic fields. This feature allows users to capture new phenomena, unseen in the other simulation tools, including the faults effects on the machine's field's distribution. A co-simulation method has been proposed for the simulation of the non-linear model of IM and control drives. Furthermore, the scalar control was simulated under healthy and fault condition and finally the results were illustrated and compared.

In this work, a dynamic model coupling 2D finite element method in Maxwell and equivalent circuit simulation in Simplorer is proposed to compute the performances of an IM fed by PWM inverter. The nonlinear magnetization characteristics have been considered and calculated by FEM. The circuits of the inverter are built by using the circuit components in Simplorer. The magnetic fields, the winding characteristics and the torque of the IM are presented. The performances of the IM fed by sinusoidal voltage are computed as comparison with that of fed by PWM inverter. The FEM is performed for the study of the IM with faults introduced in the inverter and the machine. In fact, Fault can be detected online by observing the sequence current and electromagnetic torque. Specifications of the induction machine, the stator, and the rotor as shown as in Table 1,2,3.

Table 1. Specifications of the Induction Machine

Parameters	Values
Rated Voltage	380V
Number of poles	2
Speed	1462rpm
Frequency	50
Number of Stator slots	36
Number of rotor slots	26
Out Put Power	11KW

Table 2. Specifications of the Stator

Parameters	Values
Number of slots	36
Stator inner diameter	170mm
Stator outer diameter	260mm
Slot type	2
Length of stator core	155mm
Type of steel	D23_50
Stacking Factor of stator core	0.95

Table 3. Specifications of the Rotor

Parameters	Values
Number of slots	26
Rotor inner diameter	60mm
Rotor outer diameter	169mm
Slot type	2
Length of rotor core	155mm
Type of steel	D23_50
Stacking Factor of stator core	0.95
Air gap	0.5mm

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