Multi-domain System Models Integration for Faults Detection in Induction Motor Drives

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Abstract - The power electronic converters, electric machines, and mechanical loads are key parts of the electric drives systems, and these components are usually modeled and analyzed using specific simulation tools. The overall performances of the electric drives are influenced by system's interconnected components. One solution, to investigate the interaction between different parts of these multi-domain systems, is to integrate them into only one simulation environment. This paper presents the development of two integrated models of a three-phase induction motor (IM) drive: one, based on d-q machine model using MATLAB/Simulink-Simscape, the second being based on finite element analysis (FEA) motor model using ANSYS Simplorer/Maxwell software. The goal is to analyze the system models capabilities to simulate the faults detection caused by failures of different drive's components. The motor current signature analysis is used, in this paper, for monitoring the operation of the IM fed through a pulse-width-modulated (PWM) power inverter. Finally, two case studies are presented, one illustrating the effects of a faulty device of the PWM inverter, and the second case demonstrating the influence of the IM's stator fault. Another objective of this study is to provide users a convenient way of instruction in the area of faults detection and power quality of alternating current (ac) machines and drives.

Keywords - PWM inverter, induction motor, FEA co-simulation, faults detection, engineering education.

I. INTRODUCTION

The electric drives are multi-domain systems, with coupled non-linear components involving electric, electromagnetic and mechanical physical domains. The classic analytical design of the electric machines and drives, is now successfully complemented by using more realistic and accurate analysis and design methods based on FEA. The use of finite element method software become affordable, based on recent developments and increase of computational power, and is now a must for modeling, analysis and design of electric machines and drives [1].

The problem is that the electric machines, power electronic converters, and mechanical subsystems of the electric drives are modeled using specific separate software packages. Because the overall system performance is influenced by the interconnected components, the interaction between different parts of the drives must be analyzed. One solution is to integrate the models of all subsystems into only one simulation tool. The goal of this paper is to presents two such integrated models of three-phase IM drives to be used for simulated faults detection and analysis. Two case studies are presented in order to illustrate the capability of the developed simulation platforms to detect faults due to electronic components failures of the drive's PWM inverter, and stator faults of the IM. Another objective of this work is to provide users a convenient way of instruction in the area of faults detection of induction motor drives based on current waveforms signature analysis. The motor current signature analysis is a condition monitoring technique that has been widely investigated in the literature [2], [3], [4].

Relevant advanced studies of the electric machines faults were reported by a team at Regal Beloit Corporation and University of Wisconsin Milwaukee [5]. Our initial work related to faults monitoring and detection, was based on the analysis of voltage and current waveforms distortion caused by failing electronic components of the brushless exciter of a high power wound field synchronous motor. In our preliminary studies [7], [8], FEA advanced machine models have been utilized to illustrate that faults of the ac machines can be also revealed by the magnetic field pattern variation.

The development of the simulation platform, in this paper, is based on two different approaches that can be used for instructional materials in power and energy systems engineering programs. In our first approach, the development of the IM model is based on the state equations governing the motor dynamic operation. The following software products, adopted in this study, are required to build and simulate the overall model of the ac drive: MATLAB®, Simulink®, and Simscape [9]. The SimPowerSystems™, a product of Simscape toolbox, is first employed to model the PWM inverter, and Simulink is used to implement the state space model of the IM.

The second approach, adopted in this study, is dedicated to advanced electric drives models. In this case, the linear simple machine models are not anymore sufficient in the analysis of control algorithms of ac drives with high dynamic performances. The motors’ behavior becomes more nonlinear depending on the drive changing conditions, and the effects of spatial harmonics and magnetic saturation on the control algorithms should be taken into account. In order to include these effects, advanced simulation tools are needed such as those centered on the FEA. The application of FEA for the ac machines simulation and design offers unlimited flexibility in
the geometrical shape, material properties, and boundary conditions in different regions of the machine [1]. In the second approach of this paper, the following products of the ANSYS commercial software are assumed to be available: RMxprt-Maxwell [10], which is required to build the accurate FEA model of the IM, and Simploter [11], which is employed to implement the three-phase PWM inverter, the external electric circuit and the mechanical load.

In the case studies presented in the paper the same three-phase squirrel-cage induction motor is used for analysis. This is similar to the machine that has been adopted for use in the electric drives laboratory experiments proposed by the University of Minnesota within the nationwide consortium of universities CUSP [12]. The simulation results of the IM drive under normal and failure modes operating conditions are presented and compared using both proposed modeling methods.

The paper is organized in five sections. In Introduction, the motivation of the simulation platform development is presented, and the work in progress elsewhere is discussed. In the second section, the two modeling approaches of the IM drive are presented. In the third section, the simulation results are displayed and analyzed. In fourth section, the use of simulation platforms for instruction in electric power engineering curriculum is shortly discussed. The fifth section outlines the concluding remarks and future work considerations.

II. MODELING THE INDUCTION MOTOR DRIVES

A. IM Drive Model in MATLAB/Simulink-Simscape

In this section, a brief description of the state-space IM model is presented along with the corresponding block diagram realization in the Simulink-Simscape environment. The induction machine dynamic model chosen here is based on the space vectors theory and the following simplifying assumptions: three-phase symmetrical stator windings, constant air gap, squirrel cage rotor, sinusoidal distribution of the air gap magnetic field (space harmonics neglected), machine operation in the linear region of the B-H curve (magnetic saturation neglected), and constant motor parameters. The rotor variables and parameters are referred to the stator winding, and the core losses are neglected. A fifth order dynamic state space model of the induction machine has been applied, in d-q synchronously rotating reference frame, and using the components of the stator and rotor flux space vectors and the rotor angular speed, [13], [14], [15].

The general state space IM model is conveniently used in studies of vector control and dynamic regimes of ac drives with induction motors. The best way to implement the IM mathematical model is based on Simulink block diagrams. The advantage is the easy access to all machine's state and output variables available in the internal structure of the built block diagram. For the open loop IM model implementation employed in this paper, the reference frame is stationary, fixed to the stator.

Fig.1 illustrates the Simulink-SimPowerSystems block diagram realization of the open loop induction motor drive. The SimPowerSystems blocks are utilized for the nonlinear elements of the PWM inverter model: the MOSFET power transistors and the breakers (ideal switches) that are used to simulate a set of failure modes of the IM drive. The Simulink blocks are mainly utilized in the linear part of the diagram in Fig.1, for the state space induction motor-mechanical load subsystem model realization.

Simulink blocks are also employed in the diagram of Fig.1 to generate the control gate signals of the three-phase PWM inverter. The three control voltages are compared with a switching-frequency triangular waveform to generate the switching functions for all six power transistors forming the switch-mode power electronic ac converter with three poles [15].

The Powergui block on top of the diagram in Fig.1 is necessary for simulation of any Simulink model containing SimPowerSystems blocks. The Powergui block also allows it to perform a FFT analysis of recorded signals to obtain the frequency spectrum signatures of the current waveforms for different types of faults. The three Voltage Measurement

![Diagram](Image)

Fig. 1. Induction motor drive block diagram realization in Simulink-SimPowerSystems.
blocks are used in the three-phase output of the PWM inverter acting as an interface between the SimPowerSystems blocks (power transistors) and the Simulink blocks (stator three phase voltage inputs). Notice that these Schematic blocks feature both, electrical input ports (●) to connect the special electrical connection lines, and normal Simulink output ports (►) to connect directional signal lines.

The normal operation of the IM drive is simulated with the switches Sw1, Sw2, and Sw4 opened and Sw3 closed, in Fig.1. These are implemented with the Breaker blocks from SimPowerSystems library. The Breaker blocks implement circuit breakers where the opening and closing times are controlled from an internal control mode in Fig.1, the block diagram.

Various faults can occur in the three-phase IM drives. Several failure modes are simulated using switching operations in the drive's block diagram shown in Fig.1:

(1) two lines short circuited fault at the machine terminals-with Sw1 closed, (2) single line to ground fault-with Sw2 closed, (3) open drain fault of a MOSFET-with Sw3 opened, and (4) power transistor short circuit fault-closing Sw4. The IM drive fault simulation results are presented in the third section.

B. IM Drive Model in Simplorer/RMxpert-Maxwell

In this section, the IM advanced model development is briefly discussed and the block diagram structure of the IM drive is presented using the ANSYS RMxpert-Maxwell 2D software components. The Maxwell specific features for the co-simulation platform will be shortly presented.

1. FEA Model of the IM Created in Maxwell

The investigation of using Maxwell software for the co-simulation platform in this study was possible based on the installed licenses for ANSYS software. The renewal of the license includes Maxwell, Simplorer, RMxpert, and PE xpert software components. The license allows five concurrent tasks (five users) to run programs simultaneously.

The ANSYS software components provide multiple methods to create the geometry and to perform detailed finite element calculations of the machine models. Maxwell can import geometry files from various external sources, or the machine models can be created by using the Maxwell's own geometry utilities.

Another convenient way is the use of ANSYS RMxpert, which is a template-based electric machine design tool and is fully integrated into ANSYS Maxwell to further perform a detailed motor design and analysis based on FEA (method applied in this paper). The geometry of the simulated three-phase induction motor based on the provided template is shown in Fig.2. RMxpert can also help the user to calculate initial machine performances, make first sizing decisions, and perform multiple analyses variants in a short simulation time.

The Maxwell 2D design (Fig.2b) is created from the RMxpert environment. Then, the required settings for FEA are specified, which are: (i) the motion setup of the motor shaft and rotor (Fig.3a), (ii) the appropriate excitations (Fig.3b) for electromagnetic transient analysis, (iii) the assigned materials, and (iv) the boundary conditions. Once these settings are completed, the mesh is generated and the analysis is completed. The IM drive simulation results, using the FEA model, are presented in the third section.

2. Simplorer Implementation of the IM Drive Simulator

The ac machines and drives represent complex multi-domain dynamic systems. In this paper, the modeling and co-simulation of the overall IM drive require tools from distinct programming environments: (1) the advanced IM model is using FEA based ANSYS Maxwell software, and (2) the power electronic converters and the drive's mechanical load are modeled using the ANSYS Simplorer specialized circuit simulator.

Fig.4 illustrates the block diagram realization of the open loop induction motor drive for co-simulation in Simplorer-Maxwell (see Fig.1 for comparison). First, the machine model created in RMxpert is exported to Maxwell for a rigorous finite element analysis to generate the expected results. Second, an RMxpert dynamic coupling link allows the FEA machine model created in Maxwell to be imported in Simplorer for co-simulation.

Finally, a two way interface is established between Simplorer and Maxwell for the overall electric drive control system implementation and simulation.

The same failure modes to those proposed in the first approach (Fig.1) are considered and simulated for comparison. Thus, the switching operations create the following simulated faults in the IM drive's block diagram shown in Fig.4: (1) two lines short circuited at machine terminals-with Sw1 closed, (2) single line shorted to ground-with Sw2 closed, (3) open drain fault of a MOSFET-with Sw3 opened, and (4) power transistor short circuited-closing Sw4. The simulation results of the IM drive faults using this second approach are presented and discussed in the next section.
III. SIMULATION RESULTS

The IM drive circuit model, containing nonlinear elements, the circuit breakers, and power electronics components, require stiff solvers for more accurate simulation in Simulink-SimPowerSystems. The best accuracy and fastest simulation speed is usually achieved with ode23tb solver set in the simulation configuration parameters, with relative tolerance $10^{-4}$, and the Solver reset method set to ‘robust’, in Simulink.

First, the two IM drive modeling methods presented in the previous section (Fig. 1, and Fig.4) allow users to perform the simulation of the system in normal operating conditions.

Second, the effects of power electronics faulty components and faults due to the motor itself are simulated and discussed. The machine, utilized in simulations of two fault case studies, is a three-phase, 4 poles, 120 Hz, squirrel-cage induction motor, with a constant load (rated) torque of 0.6 Nm, and a maximum speed of 4000 rpm.

1. IM in Normal Operating Conditions

The time waveforms of the phase current, the electromagnetic torque, and the motor shaft speed, obtained with the simulation platform in MATLAB Simulink-SimPowerSystems (Fig.1), are shown in Fig. 5.

The similar waveforms obtained with the co-simulation platform in Simplorer/RMxprt-Maxwell (Fig.4), are depicted in Fig. 6. Comparing the simulation results for normal operating conditions, obtained with both simulation methods, observe that the differences between the speed characteristics are negligible. In Fig.6, notice that the torque ripples are smaller, while the phase current is larger, with the motor advanced model.

Next, two type of faults are presented and discussed: one fault is occurring at the machine terminals and the second one is due to a faulty power transistor.

2. Two Phases Short Circuited

Fig.7 illustrates the faulted machine's torque when the phases A and B are short-circuited. The simulation is done by starting the drive under rated load and then, at t=300 ms, the two lines are short circuited at the machine terminals by closing the switch Sw1 (see Fig.1, and Fig.4), with the motor already running in steady state conditions. In this fault condition, the motor cannot operate with the electromagnetic torque damping slowly to zero as both torque time waveforms of Fig.7 correctly depicts.
3. One MOSFET Short Circuited

The simulation of the fault due to the short circuit of one of the power transistors, is done in the following way: the IM drive is first started under a rated load until it reaches the steady state operation. Then at $t=0.4$ s, closing the switch Sw4 (see Fig.1 and Fig.4), the top transistor of the first power pole of the inverter is short circuited between its drain and source terminals. In Fig.8a and Fig.9a, the waveforms of the motor's stator current in phase C are shown. Observe that the linear state space model of the IM in Simulink is not able to predict the increase of the phase C stator current during this fault (Fig.8a), while the FEA model in Maxwell shows a significant increase of the current magnitude equal with the starting current (Fig.9a).

In Fig. 8b, the state space model in Simulink is showing an increase of the electromagnetic torque pulsations that are unrealistically kept constant during the transistor short circuit fault. The simulation based on the FEA motor model indicates, in Fig.9b, a similar initial increase of the torque pulsations, immediately after the fault occurs at $t=0.4$ s. This is followed by a slow damping process, meaning that the motor cannot operate under the same rated load condition.

4. Fault Detection Based On Fourier Analysis

A Fourier analysis was applied to determine the specific current waveforms specific signatures generated with the more realistic and accurate model of the IM drive in Simplorer/RMxprt-Maxwell (Fig.4).

The currents' magnitude spectrum of each of the various IM drive operation conditions were plotted and shown in Fig.10 and Fig.11. The harmonic content of the dc link current of the PWM inverter, is shown in Fig. 10(a), and the motor's stator phase current spectrum is plotted in Fig.11(a), under normal rated operation conditions. In Fig. 10(b) and Fig. 11(b), the harmonic content of the dc link and stator phase currents, respectively, are shown for the study case of two phases short circuited with no current limit restriction. The harmonic Fourier analysis, performed in this case, revealed a different pattern of the dc link current waveform, compared to normal operation, with a significant increased of the amplitude of harmonics around 93 Hz. In Fig. 10(c) and Fig. 11(c) the harmonic content of the dc link current and stator phase current, respectively, is presented for a new case study with one MOSFET transistor short circuited and no current limit restriction. In this last case, the harmonic Fourier analysis, compared to normal operation, revealed a new different pattern indicating the appearance of a 23 Hz significant harmonic in both currents waveforms.
IV. PROPOSED USE OF SIMULATION PLATFORM FOR INSTRUCTION

Another goal of this work is to integrate the developed model of the IM drive in SimploM/Mxlink/Mx Maxwell into the existent instructional materials for engineering education in Power and Energy Systems programs.

In the first stage, the Maxwell 2D design of AC machines will be required for projects within Advanced Electric Drives type of course. In addition, the study of the interactions of Maxwell-Simplorer-Simulink platform with real-time simulators, such as dSPACE [16], will be performed for electric vehicle applications. In the second stage of the simulation platform integration, 3D Maxwell designs will be generated from the created 2D designs of the AC machines. An unique advantage of the co-simulation in Simplorer/RMxprt-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 2D world, including the faults effects on the machine's fields distribution.

V. CONCLUSION

In this paper, two variants of a simulation platform development in the area of faults detection in electric drives were presented. An inverter-fed three-phase induction motor drive has been modeled using two different approaches, and simulation results have been analyzed and compared. The case studies included the drive's normal operation, two failure modes of the power converter and the IM, and the results of harmonic analysis based on motor current signature were presented. One objective of this work was to provide a basis for developing new instructional materials to enhance teaching and learning effectiveness in power engineering education.

One future research goal is to post-process the data generated by the simulation platforms using the advanced virtual reality visualization and simulation technologies installed in the Center for Innovation through Visualization and Simulation (CIVS) at Purdue Calumet. On this basis, virtual labs will be created for effective undergraduate and graduate education in Electric Drives and Power Systems.

REFERENCES

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