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Innovations in Teaching Energy Systems Utilizing an Integrated Simulation with Hardware in the Loop

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Abstract

This paper presents the latest efforts by the authors in the development of integrated drive simulation environment. Furthermore, we will present the utilization of these research developments into the classroom and how it can be integrated into lectures. We want to help students acquire the knowledge related to actual operations of integrated power systems, for example, the physical behavior of various electrical components, interactions of the individual components with each other during dynamic operations. We could also show component reactions to changes in system parameters or operational conditions as well as study the effects of design changes.

The development of physical component modeling and the integrated coupling of these realistic physical modeling with the over all system have led to the creation of realistic practical system that is capable of simulating dynamic operations. This environment also includes hardware-in-the-loop ability along with distributed simulation in order to achieve research innovations in addition to the associated education benefits.

Keywords

Dynamic simulation, finite element, hardware-in-the-loop simulation, integrated power system, physical modeling.

1. Introduction

In teaching energy systems, the general rule is to explain the basic principles of electrical components such as machines as idealized models in addition to power electronics switches and control components. Practical effects are generally treated as correction factors of standard component models rather than true coupling of the physical component modeling. For example, the *dq* model used to describe rotating machines ignores slotting and saturation effects of laminated iron cores. Furthermore, ideal transformer model is generally adopted to represent transformers, which neglects the nonlinear magnetization, magnetostriction effects and winding arrangements, etc.

Introducing changes in component designs, operational frequency as well as voltage and current levels and switching patterns presents a major challenge in evaluating practical effects using simplified modeling.

In addition, each component is modeled and introduced individually. The interactions between each component with the integrated system are not taken into consideration during course teaching due to limited teaching hours. These effects are generally left to be gained after graduation.

The feedback from students shows that the knowledge of physical modeling of various components and their effects in the integrated system are also important to their industry career or graduate studies. For example, they need to understand the origins of machine torque pulsations, the influences of PWM on machine performances, the consequences of faults, the effects of different machine designs on the system, etc. Investigations indicate that graduate students could move to practical research projects much faster if they acquired related knowledge during their undergraduate study. Practicing engineers can use this knowledge to improve product quality effectively, diagnose problem accurately as well as study the effects of design operations and actual changes. An integrated simulation environment was developed to meet the demands mentioned above.

The FE-based physical phase variable model is a newly developed circuit model for electrical machines, transformers, and cables, etc. It considers the effects of geometry and saturation by using the inductance profiles, obtained from nonlinear transient FE analysis as well as loss and capacitance effects. Such a model can provide the same performance as the full utilization of FE electromagnetic model but with much faster simulation speed, which is suitable for classroom demonstration. As an example, the FE-based phase variable model of a PM synchronous machine and a BLDC motor are presented here.

The coupling of FE model and external circuits are studied. To show the machine's operation under fault conditions, the FE model is necessary because in this case the inductance profiles are unpredictable. In addition, FE modeling is the only way to describe the winding internal fault in machines and transformers. The coupling of FE model and external circuits are performed to demonstrate the transformer's behavior under internal and external fault conditions.

Hardware-in-the-loop simulation is implemented. Utilizing this technique, the professor can show students the effectiveness of the developed FE-based phase variable model and demonstrate the influences of controller parameters on the actual hardware and the overall system.

In this paper, some of our research efforts and their applications in teaching are presented. It includes the FE-based phase variable model of PM synchronous machine and BLDC, demonstration of transformer internal and external faults, the effect of the pole number on the machine torque pulsations, effects of PWM drive on the machine, simulation of integrated system, hardware-in-the-loop simulation, and introduction of power electronics experiment simulation, etc.

2. Examples

2.1. FE-based phase variable model of PM synchronous motor

The dq-model, a simplified description of rotating machines can't meet the requirements such as torque ripples minimization, current harmonics analysis, high frequency effect evaluation, etc. The full FE model can take into consideration all geometrical, material and operational details of electrical machines. But it is computationally intensive when such a model is used for control and drive studies. A FE-based phase variable model is developed, which combines the accuracy of the full FE model of the machine with fast computational speed.

The physical FE-based phase variable model for the PM synchronous motor utilizes the rotor position dependence of inductance and back EMF obtained from sequential FE solutions at rotor positions covering a complete ac cycle. By adding the cogging torque, the proposed FE-based phase variable model performed at the same accuracy level as the full FE model [1]. The cogging toque and the rotor position dependent inductance profiles are shown in Fig.1 and Fig. 2. Fig. 3 shows the comparison of the dq, FE and the FE-based physical phase variable model. A commonly-used PWM vector control speed regulation system is built in Simulink. Fig. 4 shows the simulation results obtained using the proposed phase variable model. These results help students have a better understanding of the assumptions made in the dq model, the characteristics of FE analysis and the advantage of the developed FE-based model.

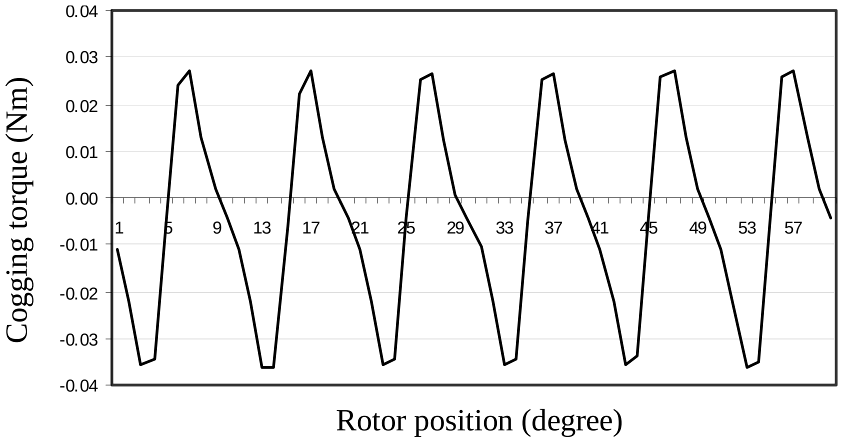


Fig. 1 Cogging torque profile of a 2-hp 6-pole PM synchronous motor

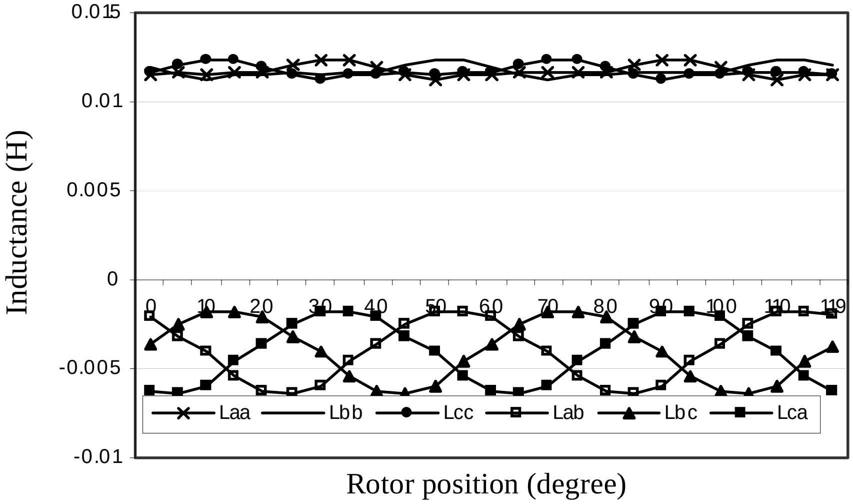


Fig. 2 Rotor position dependence of inductance of a 2-hp 6-pole PM synchronous motor

2.2 FE-based phase variable model of BLDC

BLDC has a trapezoidal back EMF and requires rectangular stator currents to produce constant torque. The variation of the self and mutual inductances of the stator windings is non-sinusoidal. There is no particular advantage exists in transforming the *abc* equations to the *dq* frame. The commonly-used *abc* model assumes that the self and mutual inductances are constant. Due to the physical rotation of the rotor and the nonlinear magnetization property of stator iron, the inductance varies with rotor position and winding current.

The FE-based phase variable model of BLDC is developed [2]. It provides an equivalent circuit model of BLDC motors for utilization in simulation environments because the dq model is not applicable to BLDC machines. Fig. 5 shows the accuracy of the developed phase variable model by comparing it with the full FE model. With the developed model, the working principle of BLDC can be explained to students conveniently.

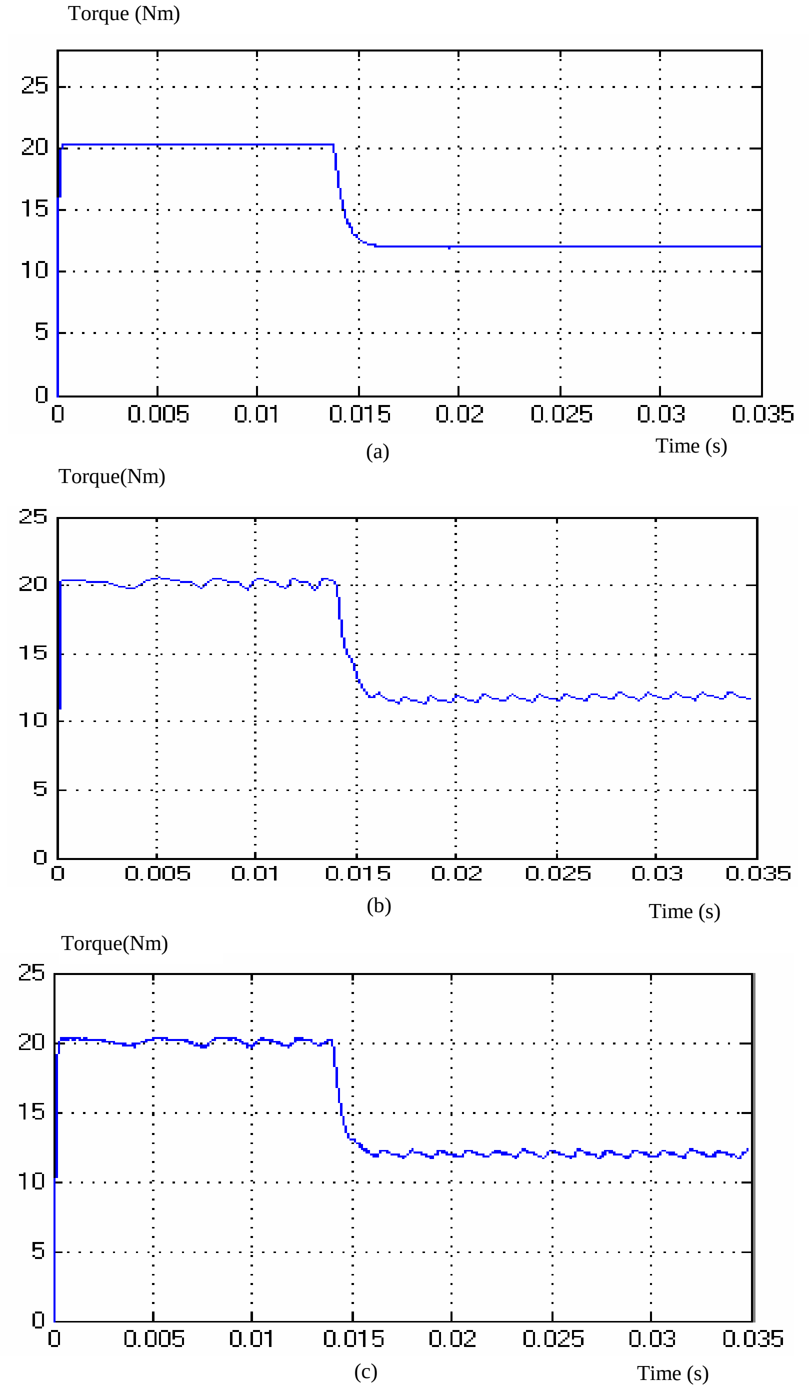
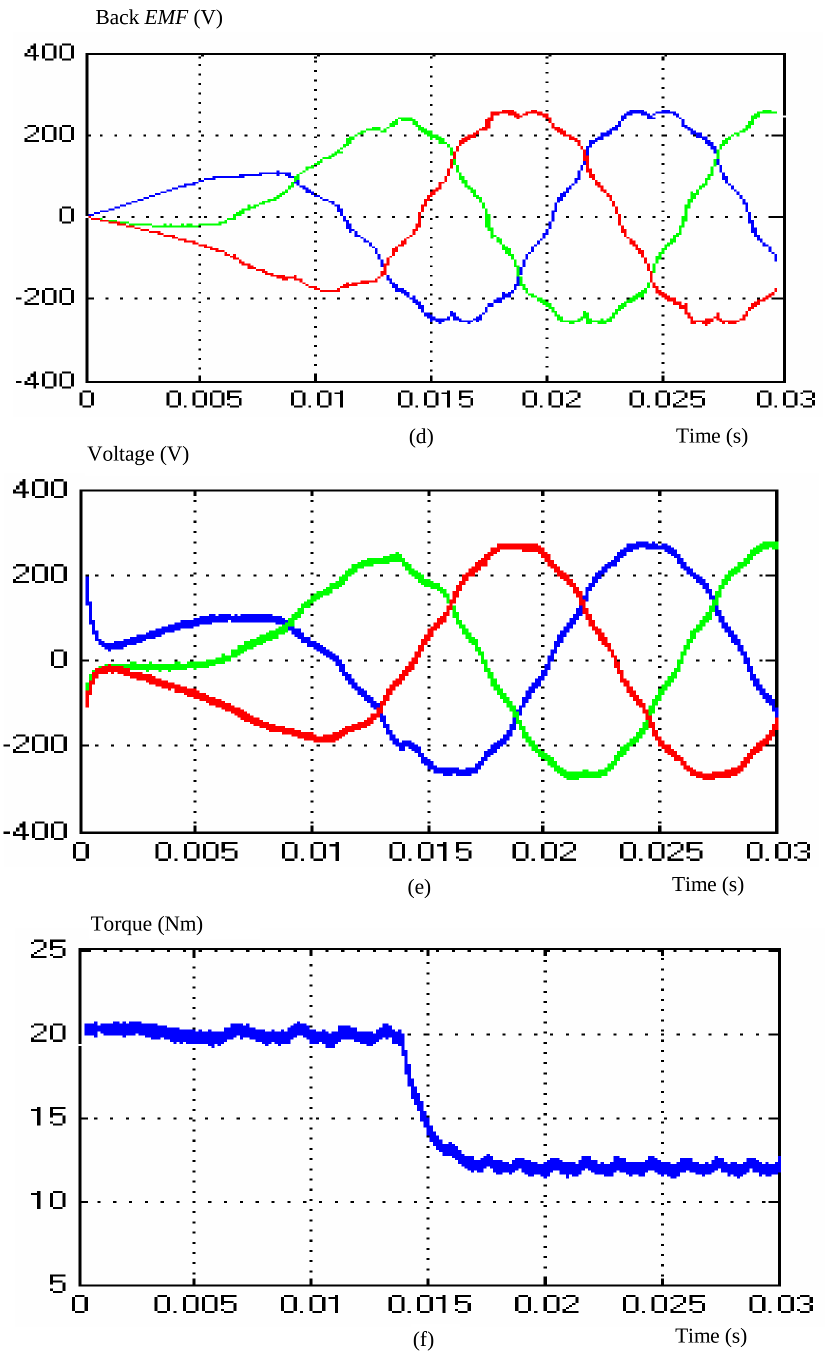


Fig. 3 Torque profile obtained by (a) dq-model, (b) FE model, (c) FE-based phase variable model



(d)

(e)

(f)

Fig. 4 Results obtained using a physical phase variable model in a PWM drive system, (d) back EMF, (e) voltage, (f) torque

2.3 Effects of the pole number on torque pulsations

Fig. 6 shows the geometry and field picture of two PM motors which have different number of poles. The FE-based phase variable model of these two machines are developed and inserted in motor drive simulation. Fig. 7 shows the obtained torque profiles, which demonstrate the effect of pole number on the torque pulsations.

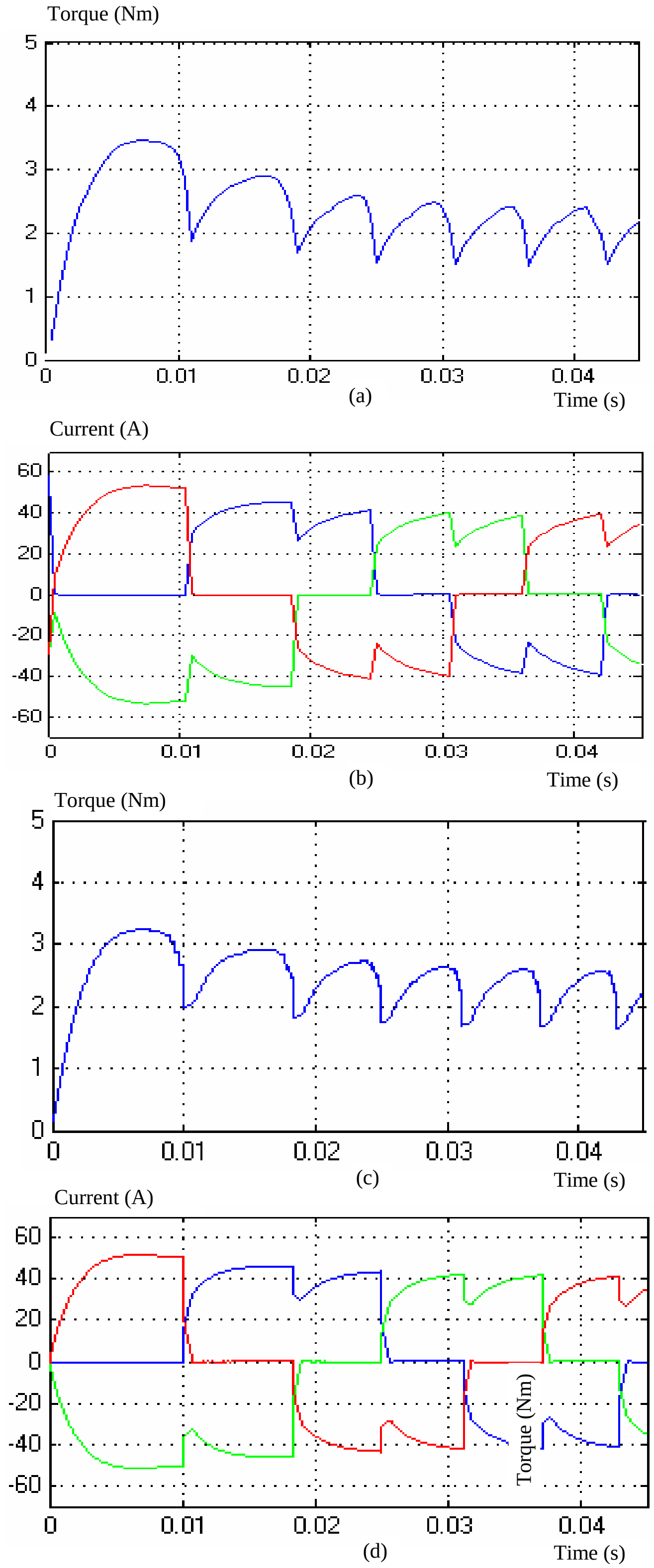
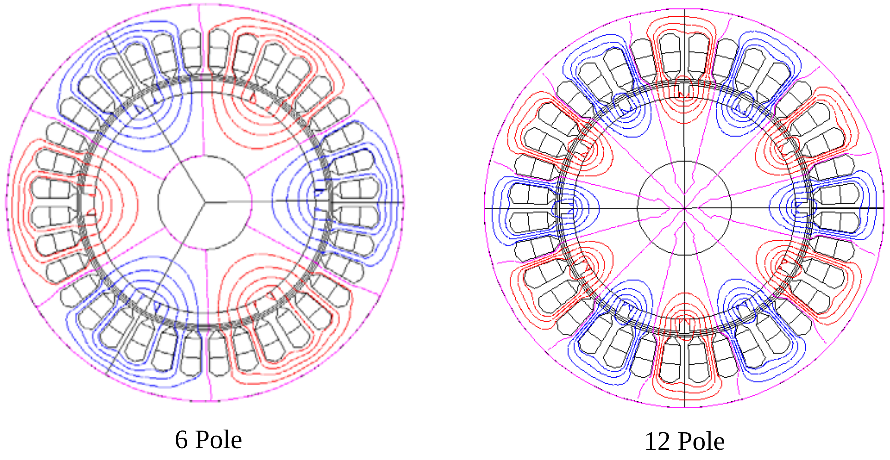


Fig. 5 BLDC torque and current profiles obtained by (a), (b) full FE model; (c), (d) FE-based phase variable model



6 Pole

12 Pole

Fig. 6 The effect of switching frequency on machine properties

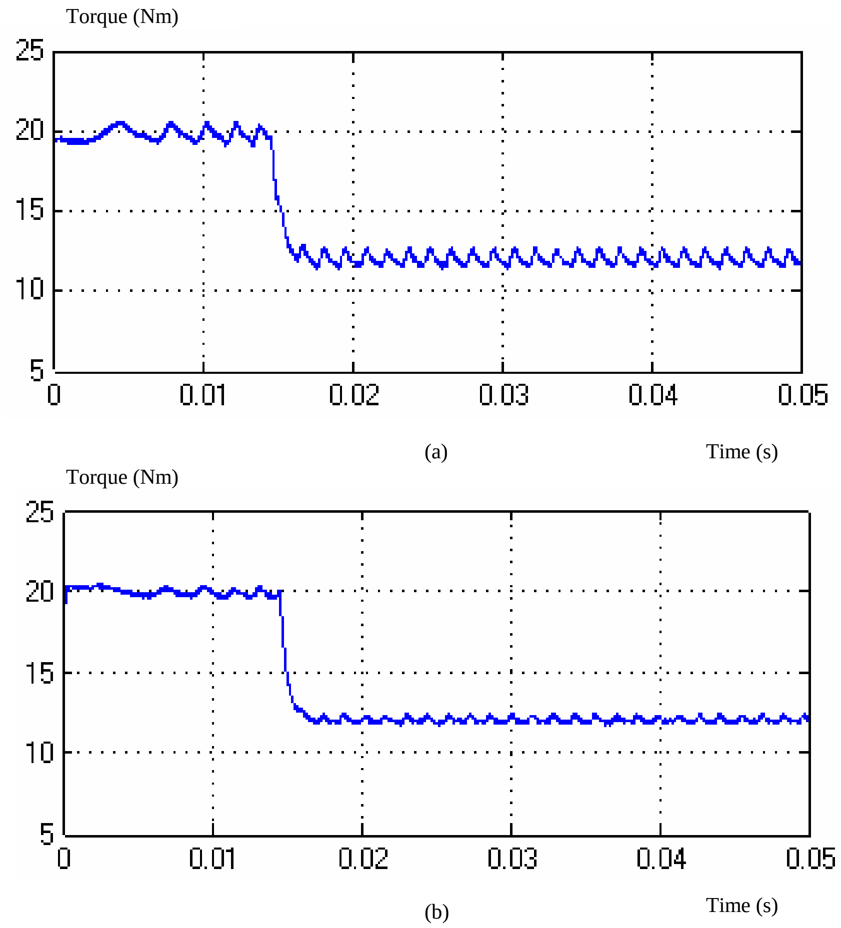


Fig. 7 Torque profiles (a) of 12- pole motor; (b) of 6-pole motor

2.4 Simulation of transformer fault using FE modeling

Having the knowledge of faults, which commonly happen in electrical machines, transformers, etc. is very helpful to the fault diagnosis and removal. In addition to the physical modeling under normal operating conditions, the physical modeling of electrical machines under fault conditions is also studied by the authors [3].

Since the inductances are unpredictable under the fault condition, both the simplified model and the FE-based physical phase variable model are not applicable to this case. Therefore, for the external faults, the coupling of the FE model and circuits needs to be performed; for the internal winding faults, the short circuit or open circuit fault needs to be described at the stage of establishing the FE model.

As an example, Fig. 8 and Fig. 9 show the procedures for transformer external fault and internal fault studies. The obtained results are given in Fig. 10. The explanation and the demonstration of this transformer fault problem help student to understand the function of FE model in fault studies and the corresponding procedures.

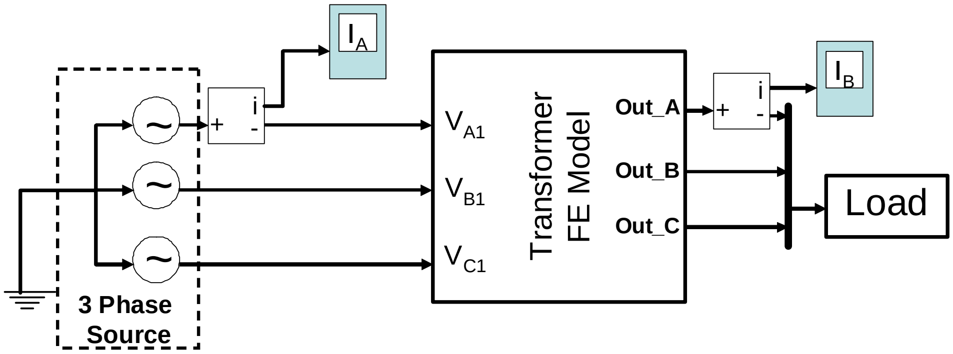


Fig. 8 Linkage of FE transformer model to external circuit

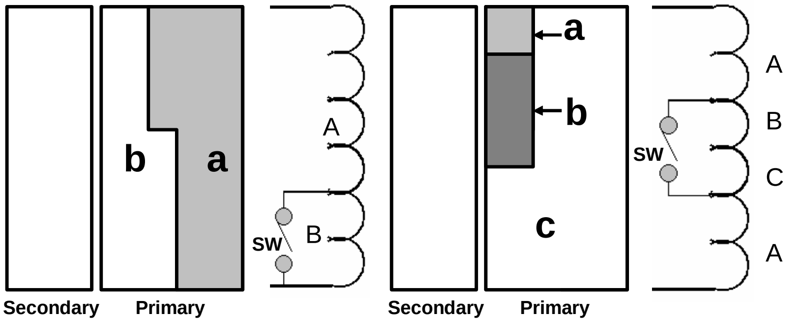
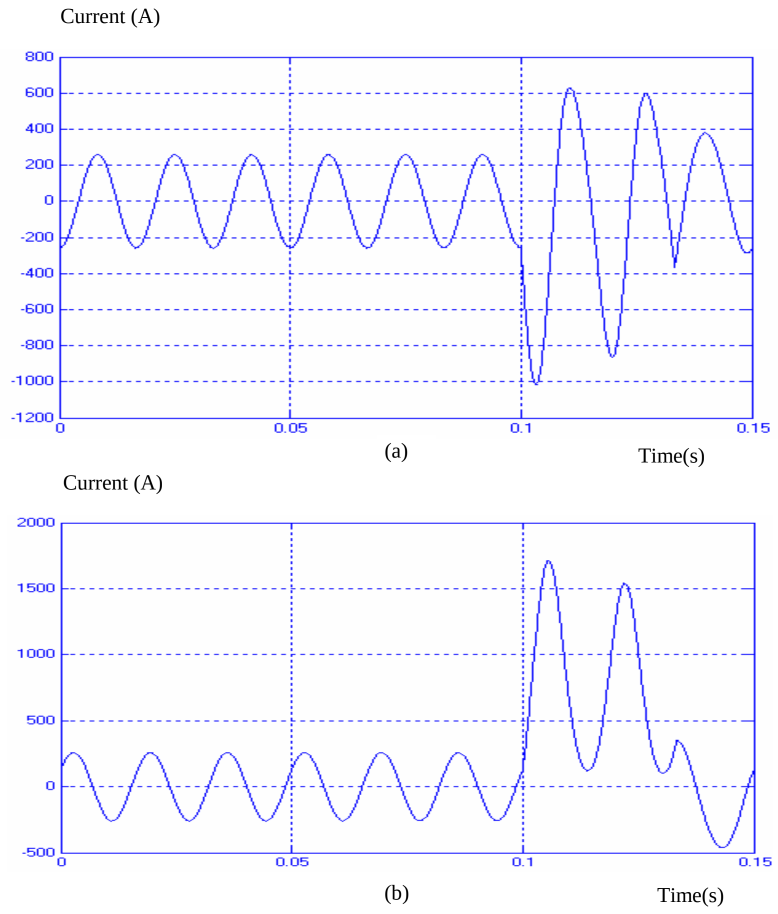


Fig. 9 Representation of internal faults on primary coils for, (a) turn to ground fault simulation (b) turn to turn fault simulation

2.5 Simulation of integrated power systems

Fig. 11 shows the diagram of an integrated power system, which provides students an over all picture of the actual power system constitution. Fig. 12 shows the voltage or current waveforms of the transformer, rectifier and the voltage waveform, speed and torque profiles of the motor in an actual integrated system [4].



(a)

(b)

Fig. 10 Three phase fault secondary currents from full FE model,
(a) "a" phase current, (b) "c" phase current

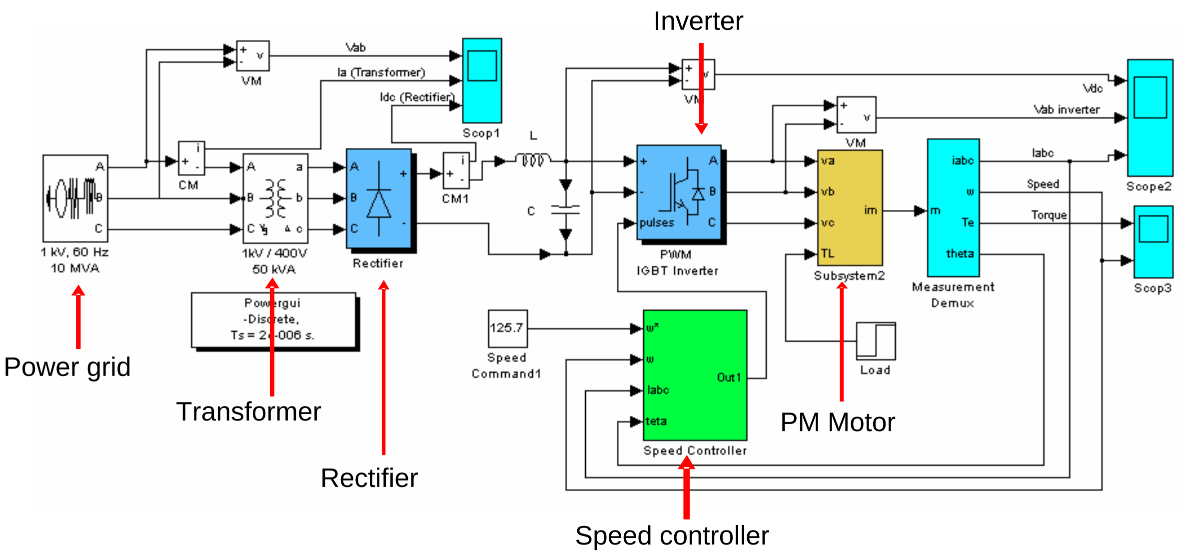


Fig. 11 Integrated power system

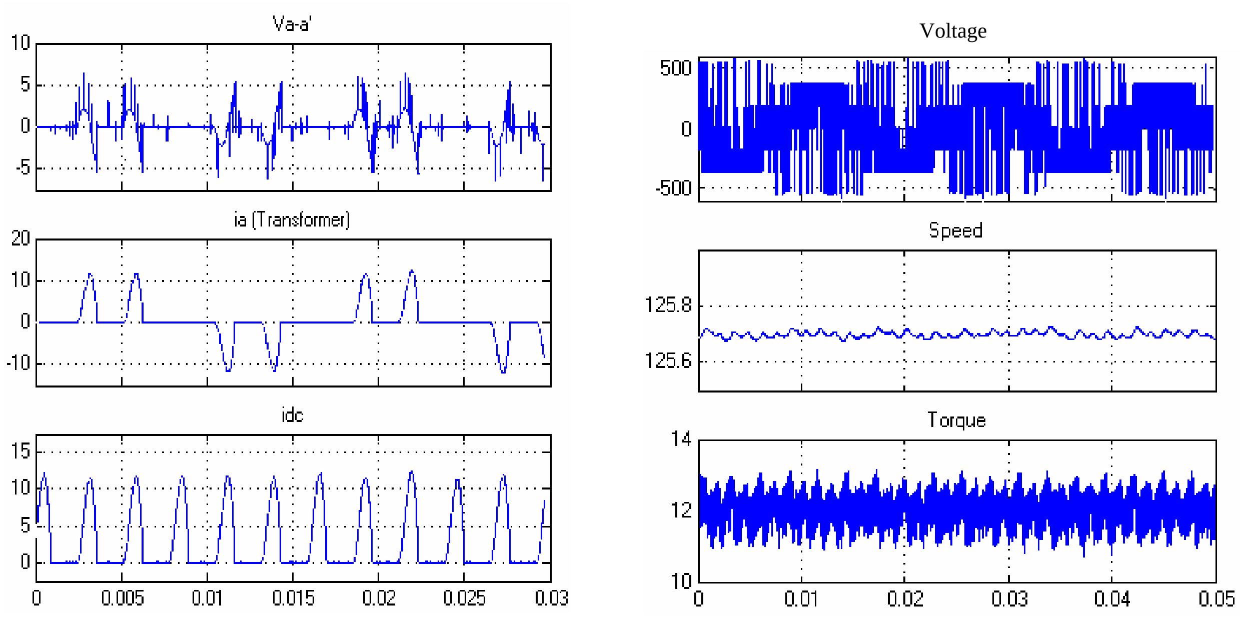


Fig. 12 Terminal voltage profile of the cable, current profiles of the transformer, rectifier and simulation results obtained using the FE-based phase variable model

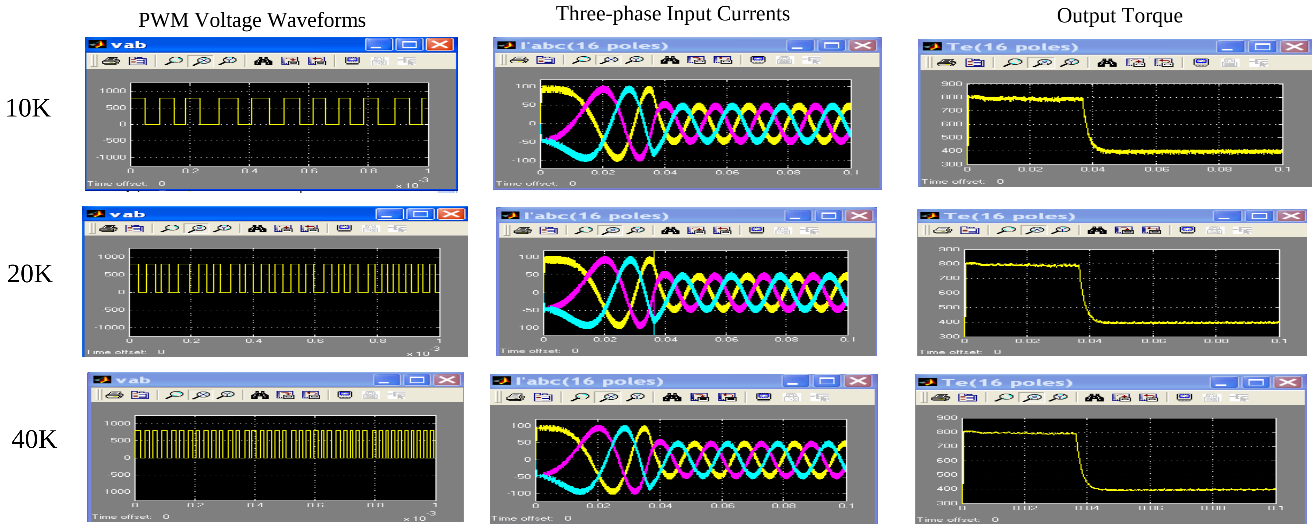
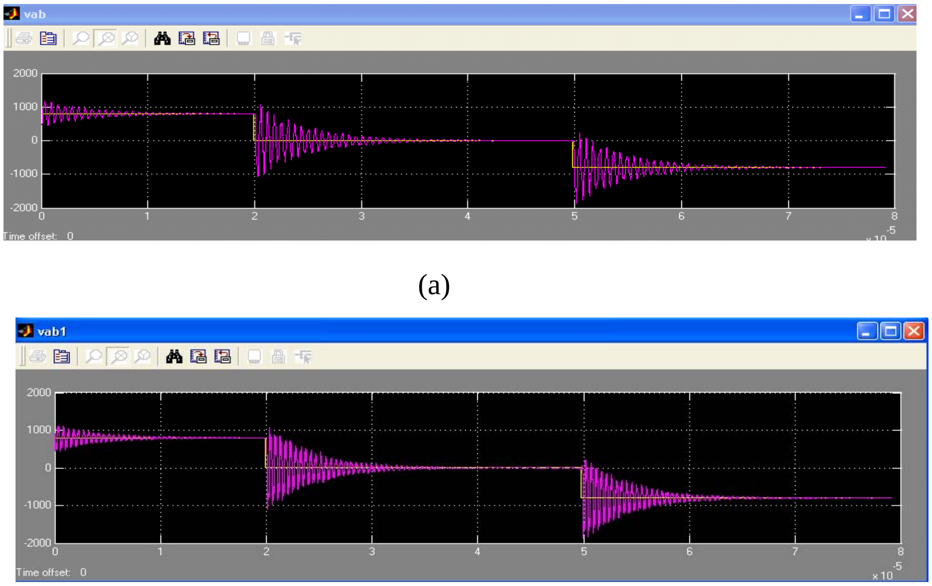


Fig. 13 Effect of switching frequency on machine properties

2.6 Effects of PWM drive on machine behavior

Modern drives use PWM-fed. It is important to investigate the machines' behavior under PWM excitation conditions. Demos shown in Fig. 13 are prepared to help student gain the knowledge of PWM drive and the influence of PWM switching frequency on the current waveform and torque profile of a PM synchronous motor.

Fig. 14 Demonstrates the over voltage phenomenon existing at the winding terminal of motors fed by a long cable, which is one of the important phenomena in PWM drive.



(a)

(b)

Fig. 14 Terminal voltage of motor driven by PWM, (a) obtained by using HF motor model, (b) obtained by using LF motor model

2.7 Simulation with hardware in the loop

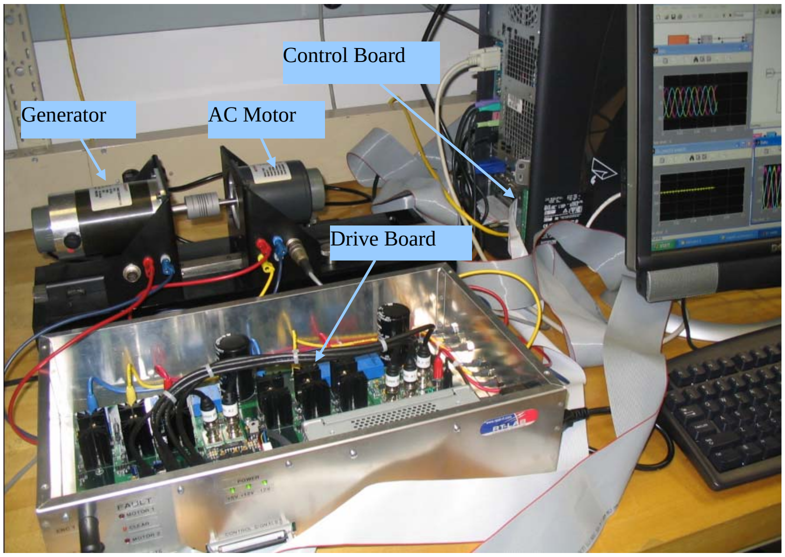


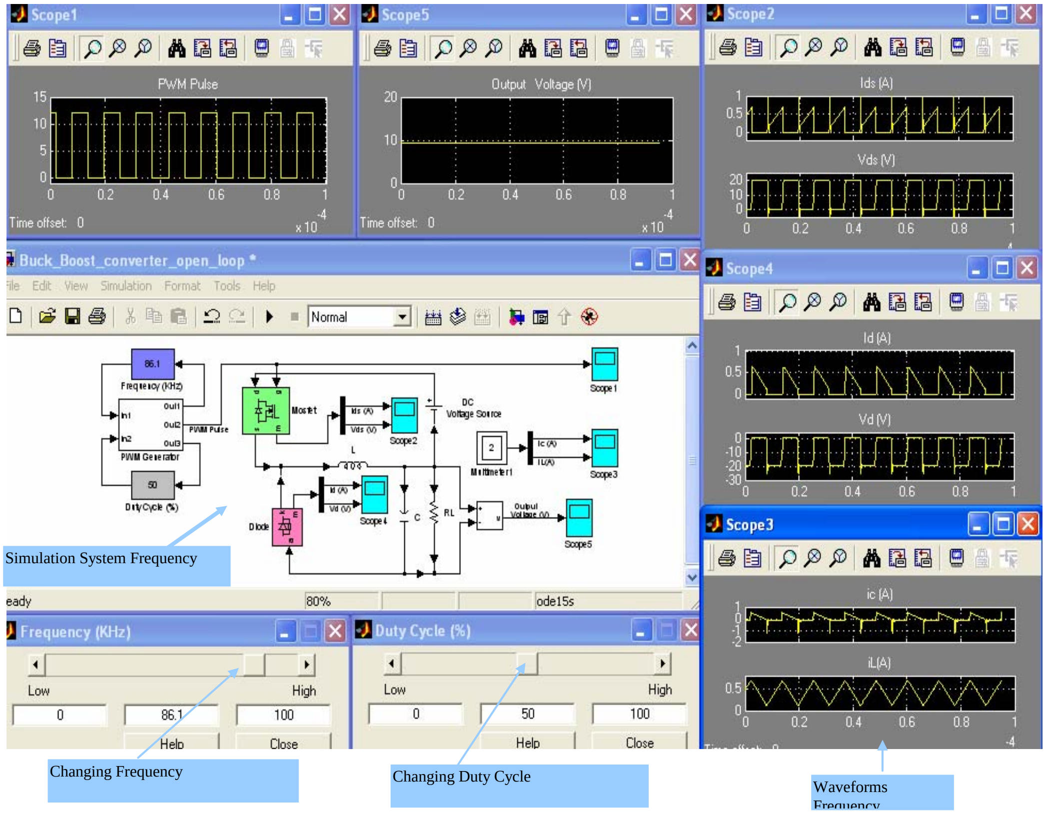
Fig. 15 Hardware in the loop simulation

Hardware-in-the-loop is a new technology which plays an important role for design and optimization. We introduced this technology in our teaching practices mainly for two purposes. One is to provide students an opportunity to access state-of-art simulation technology; the other is to provide a controller design environment for students who don’t have background of computer control technology. Fig. 15

shows the configuration of an ac motor control system. The controller board is inserted in the computer, the simulation experiment is setup via the computer interface.

2.8 Simulation of power electronics experiments

The Simulink simulation of power electronics experiments is developed. Such a simulation environment has the following advantages. First, students can use it to preview before the experiment and review after the experiment. Second, the influences of parameter variations on system performances can be studied. Third, it provides the possibility to observe simultaneously many voltage and current signals. Fig. 16 shows an example of fly back converter experiment.



Simulation System Frequency

Changing Frequency

Changing Duty Cycle

Waveforms Frequency

Fig. 16 An example of software simulation of power electronics experiment

3. Conclusion

In this paper, our research efforts on physical modeling of electrical machinery are presented. They are the FE-based physical phase variable model of various electrical components, FE and circuit coupling for transformer fault studies, the simulation of the integrated system for studying the interactions of components and the influences of different designs, etc., in which the geometry, saturation magnetization property, high frequency effects, etc, are considered. The applications of these research efforts in energy system teaching are introduced.

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Biographic Information

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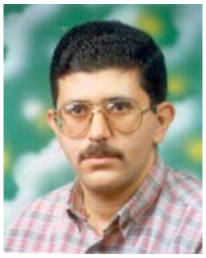

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