Integrating the Advantages of Hardware and Software Tools into An Induction Machine Education

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***Abstract*—This paper develops exercises on hardware and software tools for enhancing an induction machine (IM) education. Firstly, the hardware tools mainly consisting of a wound rotor induction motor and a digital oscilloscope are used to demonstrate the operating principles of the IM through an open-circuit, a no-load, and an on-load test. Typically, the teaching of the relationship between stator frequency and rotor frequency is taught by a pure theorem. In this paper, it is directly measured through various exercises. Secondly, the software tools using MATLAB are used to build the simulation tools for IM analysis. Typically, the IM block in Simulink is used to evaluate its performances. In this paper, the simpler simulation IM block is presented for a steady state analysis. It has been proposed with the goals of making it as versatile as possible for students to learn independently about topics such as the effect of voltage input/slip on the performance of the IM. The uses of the proposed exercises on the hardware and software tools have led to a real breakthrough for an IM education. The proposed methods have been successfully integrated into the IM education at Kasetsart University Sriracha Campus.**

Keywords*—*induction motor, MATLAB, Simulink, electrical engineering, hardware tools, software tools

I. Introduction

An induction motor (IM) is widely used in various industries and its principles are taught in electrical engineering curricula at universities. For industry, it is the most popular electrical rotating machine, because of its simple design, easy maintenance, ruggedness, and reasonable price. In universities, it plays very important roles not only in coursework but also as a research area in electric power engineering [1]-[2]. There are basically two types of three-phase IM depending on the rotor type, being either a squirrel cage rotor or a wound rotor. Typically, the squirrel cage rotor has been applied in industry whereas the wound rotor type is used in the research laboratory. A wound-rotor IM has been dramatically proposed in wind energy conversion with an advanced power converter [3]-[4]. Both stator and rotor feed electrical power to the grid and it is called a Doubly Fed Induction Generator (DFIG). The extensive usage of IM in industries makes its fundamental understanding a necessity for students and electrical engineers.

Teaching an IM is somewhat challenging since it requires significant background in multiple areas such as magnetic fields, electromechanical energy conversion, and electric circuit analysis. A further challenge for the lecturer is to enhance teaching effectiveness. The number of software tools proposed for various courses has been growing in the past decade because of the emergence of MATLAB [5].

Currently, MATLAB, including Simulink is considered as the standard program in departments of electrical engineering [6]-[7]. MATLAB has been used as a teaching tool for estimating parameters of IM and it has been successfully integrated into IM education at Drexel University, USA, Nigde University, Turkey, and Oregon State University, USA [8]-[9]. Both references use the IM block in SIMULINK. Under the IM block consists of the complicated mathematical model. The IM model in these approaches is a *d*- and *q*-axis equivalent circuit.

The use of software tools has some advantages compared to hardware tools [10]. With a given software service, many students can simultaneously take part in an activity provided by the lecturer. The students feel safe because any mistake does not destroy the hardware. In addition, the various elements in Simulink such as scope, resistance, and reactance can easily be duplicated. However, simulation tools cannot fully reflect the real world. Thus, the uses of hardware and software tools can provide the best solution.

This paper develops exercises on hardware and software tools for enhancing an induction machine (IM) education at Kasetsart University Sriracha Campus. The hardware tools have been developed to describe the operating principles of an IM. Because of the time consumed, errors in meter reading, and equipment setup of hardware tools, this paper developed software tools to create simulation tools for IM analysis in various exercises. The simpler IM model is used in this paper. This paper is organized as follows: Section II briefly describes the background of an IM, determines the intended outcomes, and designs various exercises. Section III provides the details of the proposed exercises. Student performance and student satisfaction are evaluated in Section IV. Finally, in Section V, conclusions are drawn.

II. Background And Intended Outcomes

A. Background

Figure 1 shows a *d*- and *q*-axis equivalent circuit of an induction machine. The slip (s) is given by [11]-[12]

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$$s = \frac{\omega_1 - \omega_2}{\omega_1} = \frac{f_2}{f_1} \qquad (1)$$

The instantaneous of power output in terms of the d and q components is

$$p_2 = \frac{3}{2}\left[v_{d2}i_{d2} + v_{q2}i_{q2}\right] = \frac{3}{2}\left[\psi_{d2}i_{q2} - \psi_{q2}i_{d2}\right]s\omega_1 \qquad (2)$$

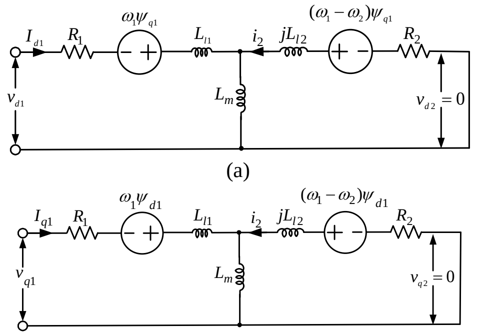

Fig. 1 The *d*- and *q*-axis equivalent circuit of an IM.

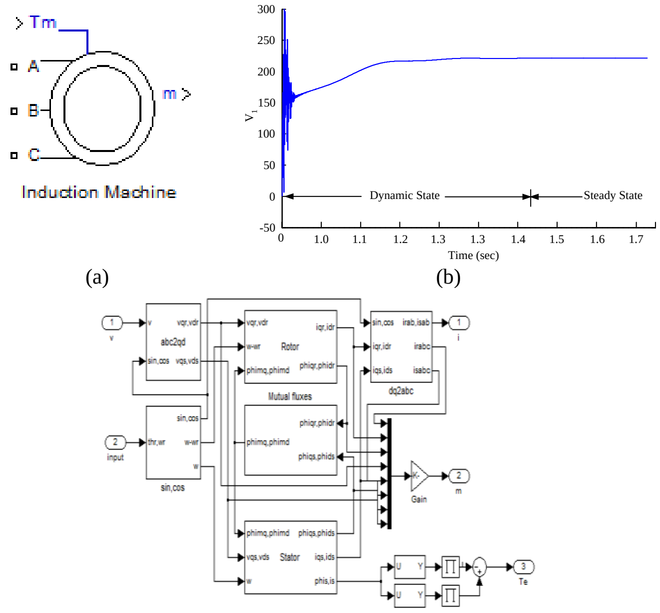

Fig. 2 Simulation of *d*- and *q*-axis equivalent circuit of an IM using SIMULINK. (a) an IM block. (b) voltage input response for an IM with a disturbance. (c) mathematical model under the IM block.

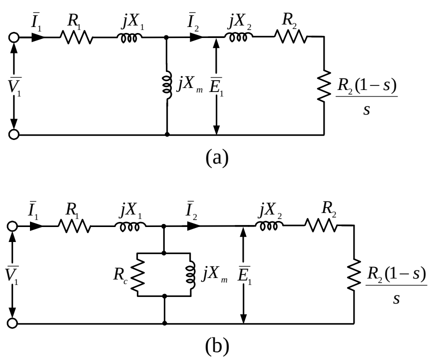

Fig. 3 Steady state equivalent circuits of an IM. (a) An approximated equivalent circuit. (b) An actual equivalent circuit.

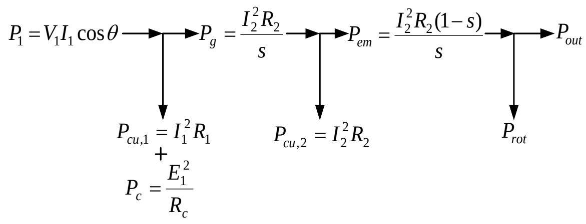

Fig. 4 Power flow diagram of an IM.

Figure 2 shows a simulation of *d*- and *q*-axis equivalent circuit of an IM using SIMULINK. An IM block as shown in Figure 2 (a) is very powerful to determine the behavior of IM machine both dynamic state and steady state as shown in Figure 2(b). In addition, it can be applied to estimate constant parameters of induction machine as proposed in [8]-[9]. When working in this approach, it is very time consuming because under the IM block (look under mask) consists of the complicated mathematical model as shown in Figure 2(c).

For the steady state analysis in the electrical engineering curriculum at the undergraduate level, the modeling of IM can be simpler and then simulation time is faster than in the *d*-and *q*-axis equivalent circuit. The steady state performance of the IM and can be represented by the equivalent circuit as shown in Figure 3 (a) [13]. It is called an approximated equivalent circuit. The core losses (P_c) represented by R_c are approximately constant and included into the rotational losses and stray load losses (P_{rot}). The actual model of an IM is shown in Figure 3(b) and its power flow diagram is shown in Figure 4 [14]. The above background is of central importance and is taught in the IM at the undergraduate level. The author presents exercises based hardware and software tools to reinforce IM teaching.

B. Intended Outcomes

The proposed exercises, tool types, and intended outcomes are summarized in Table I. On completion of these proposed exercises, students will gain the following outcomes:

1) A better understanding of the operating principles of an IM
2) A better understanding of equivalent circuits of an IM
3) Ability to create Simulink diagram of an IM using an equivalent circuit
4) Ability to create Simulink diagram of an IM using the power flow diagram
5) A better understanding of the effect of voltage input/slip on the performance of the IM

TABLE I. PROPOSED EXERCISES

Exercise	Tool Type	Intended Outcome
1) Open-circuit test	Hardware	1
2) No-load test	Hardware	1
3) On-load test	Hardware	1
4) IM analysis using the	Software	2 and 3
5) IM analysis using power	Software	4
6) An example	Software	2 and 5

The hardware tools used in exercises 1, 2, and 3 are intended to enhance student learning of the operating principles of an IM. The use of a wound-rotor IM allows us to measure I_2 as given in (2) and rotor frequency as written in (1) for various conditions of the IM. Because of the disadvantages of the hardware tools mentioned earlier, the software tools are used to achieve the other intended outcomes. In exercise 3, a special toolbox named Simulink is used to construct the equivalent of an IM. In exercise 4, the basic toolbox of Simulink is used to create its power flow diagram. In the last exercise, an example is used to study various effects such as the voltage input/slip on the performance characteristics of the IM through the simulation tools as presented in exercises 4 and 5.

III. PROPOSED EXERCISES

This section provides detail of the utilization of the hardware and software tools for enhancing the IM education.

A. *Exercises based Hardware Tools*

The hardware tools consist of the following equipment: a wound rotor induction motor, an eddy current brake, a digital oscilloscope, an adjustable ac voltage source, and an adjustable dc voltage source. The open-circuit test has been used to comprehend the operating principles of an IM and to validate (1) and (2). An open-circuit test diagram is shown in Figure 5 (a). While the rotor is open-circuited, ac voltage input is gradually applied to the stator and V_1, E_2, and f_2 are measured using a digital oscilloscope. The results of the open-circuit test are summarized in Table II. It can be observed from the results that with an open-circuit test, the electrical behavior of an IM is similar to that of a TR and thus E_2 is proportional to V_1. At standstill, ω_2 =0, so that s=1 and f_1=f_2, that is, no energy conversion takes place at the rotor.

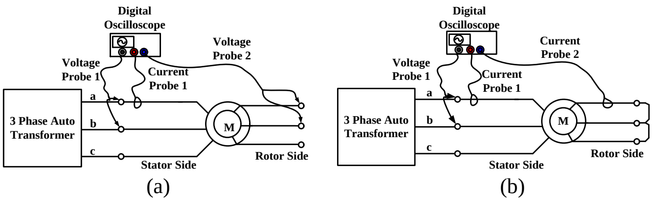

Fig. 5 Open-circuit test and No-load test diagram.

TABLE II. RESULTS OF OPEN-CIRCUIT TEST

V_1(V)	E_2(V)	f_2(Hz)
20	18.73	50
60	59.81	50
100	98.33	50
140	136.47	50
180	174.84	50
220	210.42	50

Similarly, the no-load test is performed with the rotor close-circuited as shown in Figure 5(b). Under this condition, I_2 is generated and I_2 in a rotating megnetomotive force causes rotation of the rotor. With the no-load test, the f_2 and s are inversely proportional to the V_1 as shown in Table III. In other words, the rotor speed is proportional to V_1. However, rotor speed never reaches synchronous speed. Like the on-load of a TR, the on-load of an IM is used here to compare its behavior to the no-load test as summarized in Table III.

TABLE III. RESULTS OF NO-LOAD AND ON-LOAD TEST

V_1(V)	I_2(A)		f_2(Hz)		s (%)	
	No-Load	***On-Load***	***No-Load***	***On-Load***	***No-Load***	***On-Load***
20	3.65	0	50	50	100	100
60	2.97	0	3.15	50	6.30	100
100	2.64	3.46	1.18	2.61	2.36	5.22
140	2.70	2.90	0.63	2.10	1.26	4.20
180	2.64	2.72	0.06	1.48	0.12	2.96
220	2.19	2.38	0.02	0.03	0.04	0.06

B. *Exercises based Software Tools*

In the exercises based software tools, Simulink is used to provide a powerful teaching tool. The simulation block diagram as shown in Figure 6(a) is drawn from Figure 3(b). R_1, X_1, R_c, X_m, R_2, and X_2 are in the *elements* library of Simulink whereas the instruments and display are in the *measurement* and *sink* library, respectively. An ac voltage source of the IM is in the *electrical source* library.

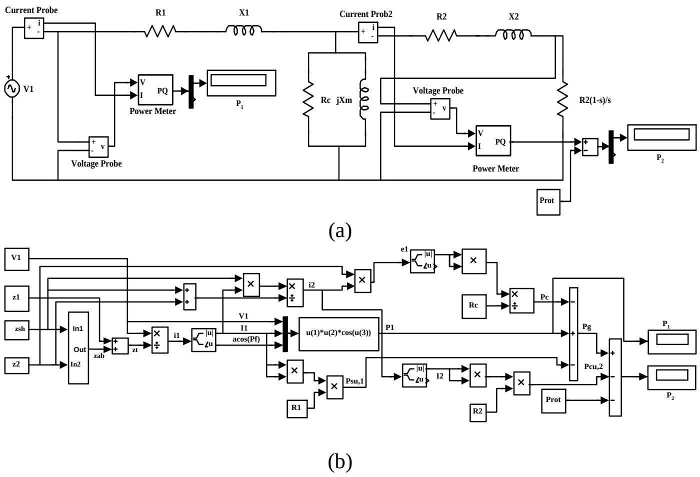

Fig. 6 Simulation block diagram of an IM. (a) Equivalent circuit. (b) Power Flow diagram.

We now consider the method of IM analysis by using a power flow diagram. Figure 6(b) shows the Simulation block diagram representing the power flow of an IM as shown in Figure 4. The arithmetic operations are in the *math operations* library. With more complicated equations such as P_1, the use of the *user-defined functions* library is more suitable than the *math operations* library. It may be mentioned here that the IM model as shown in Figure 2 and Figure 6 must provide the same results of the steady state analysis. However, the IM model as shown in Figure 6 is much easier than Figure 2. By changing V_1 and s, the simulation results are compared for various cases and summarized in Table IV. The simulation results of an induction motor with wye connection (V_1=220 V) and delta connection (V_1=380 V) are compared and shown in

Figure 7. Figure 7(a), and Figure 7(b) and help us to explain the wye-delta starting method of an IM. It can be observed from the figures that in the starting period (high slip), I_1 is relatively high, with the wye connection I_1 able to be reduced in direct proportion to the decrease in V_1 by a factor of $\sqrt{3}$, and it follows that the P_{out} decreases to one-third of the delta connection. Thus, to fully utilize the IM, the delta connection should be replaced near an operating slip.

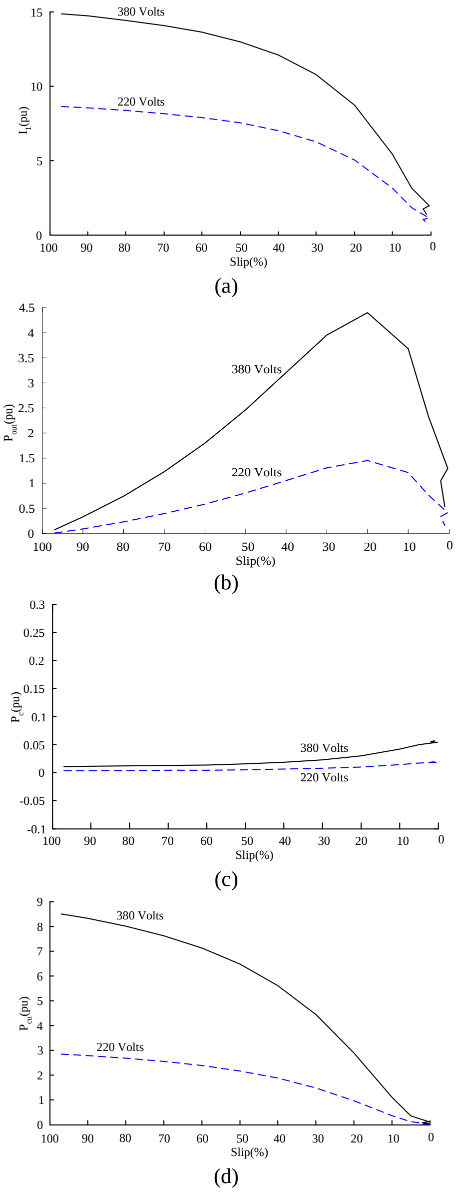

Fig. 7 Simulation results of an induction motor with wye connection (V_1=220 V) and delta connection (V_1=380 V). (a) I_1 versus *s*. (b) P_{out} versus *s*. (c) P_c versus *s*. (d) P_{cu} versus *s*.

We now wish to validate the approximated equivalent circuit of an IM because it is very important for the student's perception of teaching in the IM. In addition, it is very difficult for the lecturer to provide the mathematical justification of using the approximated equivalent circuit instead of the actual equivalent circuit. Figure 7(c) indicates that with constant V_1, P_c is almost constant. For simplicity of IM analysis, P_c is combined in P_{rot} and then the representation of R_c is omitted. However, P_{cu} is dramatically changed in every slip as shown in Figure 7(d). Then $P_{cu,1}$ and $P_{cu,2}$ represented by R_1 and R_2 are carefully considered.

IV. EVALUATION

This section provides detail of the evaluation of student performance in understanding the IM and student satisfaction with the proposed method. The participants were 85 students who attended the electromechanical energy conversion II course. An anonymous survey was given to all participants. The participants, 85 students, were asked to fill out a questionnaire as shown in Table IV. The questionnaire uses a five-point scale: 1—very poor; 2—poor; 3—satisfactory; 4—good; and 5—very good.

Pre- and post-testing were used to appraise how well students had achieved the 5 intended outcomes. The pre-and post-tests were given to students after they had completed the lecture course and exercises, respectively. Table V shows the student performance on understanding an IM. The majority of the students agreed that they understood the theory better after they have done the proposed exercises. The mean pre-test score for all 85 students was 2.63 whereas the mean post-test score increased to 3.65. The average student response was enhanced by 42.38%.

Student satisfaction is increasingly becoming an important indicator in the evaluation of university management performance and it was also used to validate the success of this proposed method. Student satisfaction is summarized in Table V which shows that the impact of the proposed method based on students' feedback was very positive.

V. CONCLUSION

This paper develops exercises on hardware and software tools for enhancing an induction machine (IM) education at Kasetsart University Sriracha Campus. The exercises on hardware tools were used to explain the operating principles of an IM. The distinctive characteristics of a wound-rotor IM allow us to measure the frequency of the rotor's electrical quantities. Then, the slip under various conditions of the IM (such as an open-circuit, no-load, and on-load test) can be assessed. These exercises help students to comprehend the behavior of the IM.

One of the course's stated goals is to help the students create simulation tools for IM analysis. Simulink is very popular software tools which have been applied in many courses in the electrical engineering curriculum. They are applied to analyze the IM for various cases and are explained in detail with the corresponding proposed exercises.

The proposed methods have contributed to student learning and to lecturer teaching in the Electrical Engineering Department. The methods have produced a favorable response from the students.

TABLE IV. STUDENT PERFORMANCE

Question	Test	Response					Mean	Enhancement (%)
		1	2	3	4	5		
1) Describe the operating principle of an IM and the behavior of the IM	Pre-Test	12	29	35	6	3	2.52	44.86
	Pro-Test	2	17	9	38	19	3.65	
2) Draw the various equivalent circuits of an IM	Pre-Test	9	22	34	4	16	2.95	55.78
	Pro-Test	0	0	11	12	62	4.6	
3) Draw the power flow diagram of an IM	Pre-Test	17	18	38	7	5	2.59	31.36
	Pro-Test	11	10	17	28	19	2.89	
4) Explain how the voltage input and slip affect on the performance of the IM?	Pre-Test	17	28	29	11	0	2.4	42.16
	Pro-Test	10	13	17	22	23	3.41	
5) Explain why the IM starts with a wye connection and operates with a delta connection?	Pre-Test	19	14	28	23	1	2.68	37.72
	Pro-Test	5	13	12	28	27	3.69	

TABLE V. STUDENT SATISFACTION

Question	Student	Response				
		1	2	3	4	5
1) The exercises on hardware tools are helpful to comprehend the operating principles of an IM.	Number	0	0	20	28	37
	%	0	0	23.53	32.94	43.53
2) The exercises on software tools provide benefits/are useful to analyze IM.	Number	0	0	0	37	48
	%	0	0	0	43.53	56.47
3) It is necessary to use both exercises on hardware and software tools for the IM education.	Number	0	0	0	31	54
	%	0	0	0	36.47	63.53
4) The proposed laboratory contributed to my overall academic growth.	Number	0	3	25	35	22
	%	0	3.53	29.41	41.18	25.88
5) I have gained an impression of these proposed methods.	Number	0	0	0	20	65
	%	0	0	0	23.53	76.47

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