2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37158

New Method for Testing Induction Machines in a Teaching Laboratory

Dr. Herbert L. Hess, University of Idaho

Herb Hess is Professor of Electrical Engineering at the University of Idaho. He received the PhD Degree from the University of Wisconsin-Madison in 1993. He is a Fellow of the ASEE. His research and teaching interests are in power electronics, electric machines and drives, and electric power quality. He writes this paper during his fortieth year of teaching electric machines.

Emily M. Conroe
Daniel Taylor

Induction Machine Torque-Speed Curve Testing Methods

Abstract

A testing method for a wound rotor induction machine's torque-speed curve is presented. This method uses two induction machines instead of the conventional method that uses an induction machine and a DC machine. By varying the frequency on one of the two couped induction machines, the intersection of their torque-speed curves varies, allowing collection of torque, speed, current, and voltage data over a full operating range. Energy sources and sinks employed are the public utility and a synchronous machine, though this method is applicable with variable speed drives for both induction machines. The method is used for graduate student instruction in the laboratory.

Introduction

This paper presents a new method for determining the torque-speed curve of a wound-rotor induction machine. Historically, induction machines have primarily been motors. As such, the current method for determining a torque-speed curve uses the squirrel-cage induction machine as a motor to drive a DC generator acting as a load as illustrated in Figure 1. Conventional testing of the machine is performed in this fashion and has long been documented in IEEE Standards.[1]

When a wound rotor induction machine is configured with two voltage sources, its application may be as a Doubly Fed Induction Generator (DFIG). This is how we have configured a wound rotor machine as part of a Type III wind turbine simulation test bed as illustrated in Figure 2. The wound rotor machine is connected to act as a DFIG. Another induction machine, this one a squirrel cage induction machine driven by a synchronous machine or a variable speed drive, mimics a wind turbine. The two machines are coupled at the shaft as a wind turbine and its DFIG would be coupled at the shaft. The entire system as illustrated in Figure 2 forms a test bed. The eventual goal is to do research on methods of electrical protection of the wound rotor machine configured as a DFIG. The configuration for this investigation has our wound rotor induction machine configured as a wound rotor machine of Figure 2.

In the development of the test bed, it became necessary to characterize the operation of wound rotor machine. Due to requirements of the test bed, the conventional method of determining an induction machine's torque-speed curve was less desirable. We paid to have the system aligned professionally, a costly thing for a university laboratory nearly 200km from the nearest alignment contractor. We did not want to decouple the machines because of the cost of realigning them. Therefore, we created a test method to find appropriate machine model parameters without decoupling the machine.

Incumbent Testing Method

The current method to characterize an induction machine's torque-speed curve is represented in Figure 1. In this method induction machine (IM) is operated as a motor and is supplied three-phase AC voltage and current from the utility. The induction motor's shaft couples to a DC machine. The DC machine acts as a generator that varies the load with a resistive bank. Arrows indicate the direction of energy flow. Test procedures are found in IEEE Standard 112 [1] and taught in classes using a textbook[2].

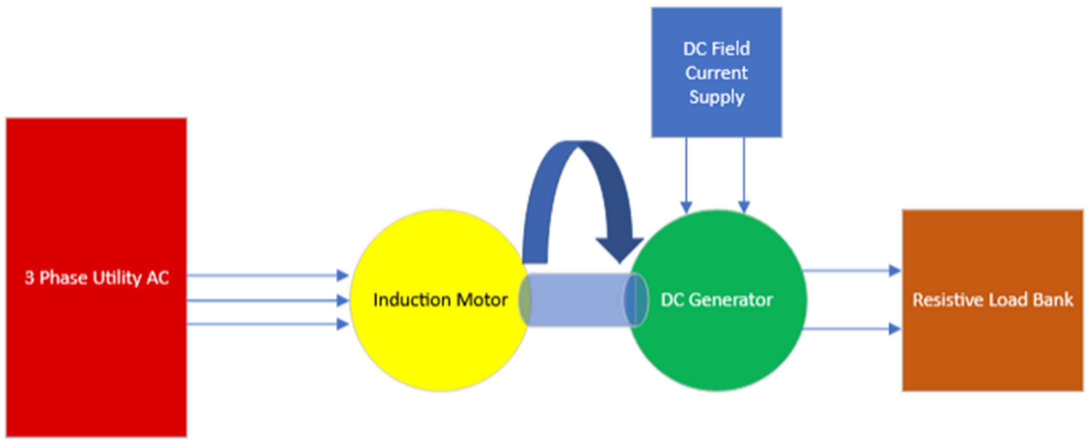

Figure 1: Incumbent Torque-Speed Test Set-Up

This setup is limited to the set voltage and frequency of the Utility provider and the DC generator's load current capability. This results in a narrow band of plottable data points on the torque-speed curve as displayed in Figure 3 with the data shown in Table 1.

Table 1: Collected Data for Incumbent Torque-Speed Curve Test

Speed (rpm)	Speed (rad/s)	Power-Induction (kW)	Mech Power (kW)	Torque (Nm)	Armature Current (ADC)
1802	188.6	1.63	1.58	0.877	1.10
1770	185.3	2.70	1.65	1.5	1.30
1753	183.5	3.50	3.45	1.97	1.50
1745	182.6	3.80	3.75	2.15	1.60
1732	181.3	4.00	3.95	2.49	1.80
1721	180.1	5.10	5.05	2.93	1.90

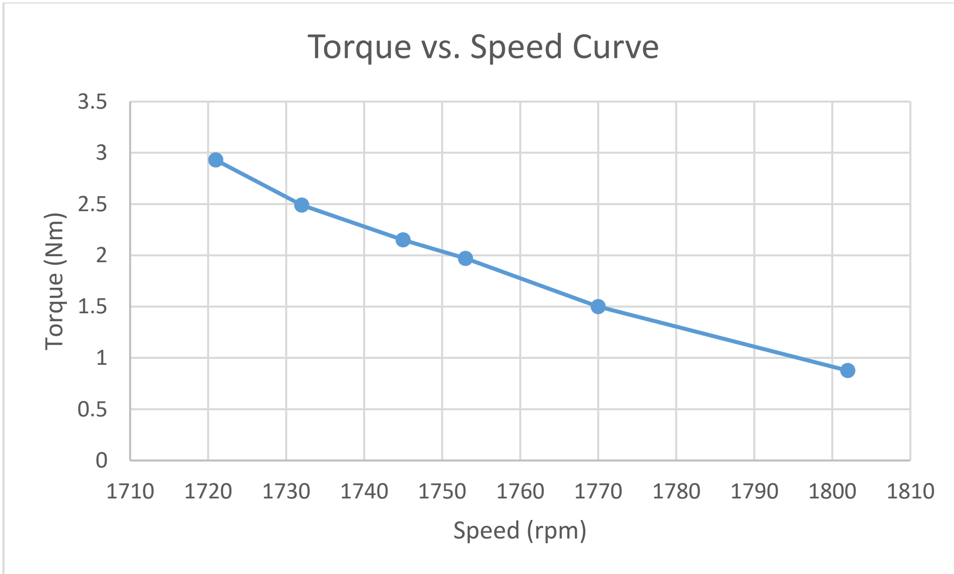

Figure 2: Incumbent Torque-Speed Testing Curve Results

For testing and demonstrating a squirrel-cage induction motor as a motor to students under normal utility provided power conditions this method is acceptable [1,3]. However, to save the cost of realigning the two test machines on more than one occasion, as mentioned previously, we developed a method to determine the wound rotor machine's circuit model parameters without decoupling the two induction machines.

Testing Method

The incumbent testing method is based appropriate tests to determine circuit model parameters of a squirrel-cage induction machine or a wound rotor induction machine.[1] As introduced, we have two induction machines, a squirrel cage machine and a wound rotor machine, both capable of operating at variable frequencies in a test bed designed to mimic Type III wind turbine operation.[3] As shown in Figure 3, a squirrel-cage induction machine couples via the rotor shaft to the wound-rotor machine instead of a DC generator and resistor bank to provide load. The squirrel-cage induction machine is driven by a synchronous machine instead of a variable speed drive for better noise performance [4]. This test set-up and our reluctance to decouple it for conventional testing required this change in testing method. Figure 3 illustrates the test method set-up. Figure 4 illustrates the Type III Wind Turbine test bed platform containing the two machines and, in the configuration in the photo, variable speed drives.

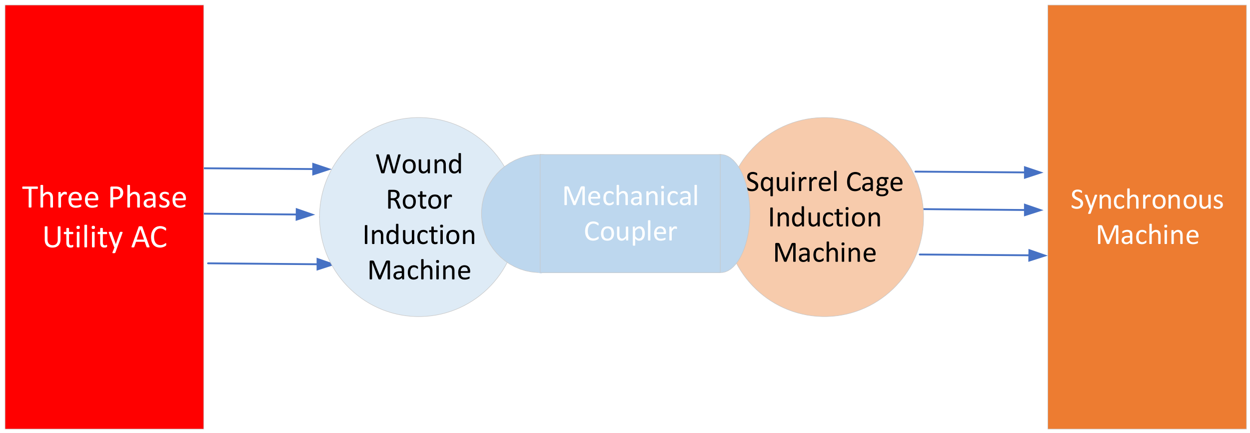

Figure 3: New Torque-Speed Curve Test Set-Up

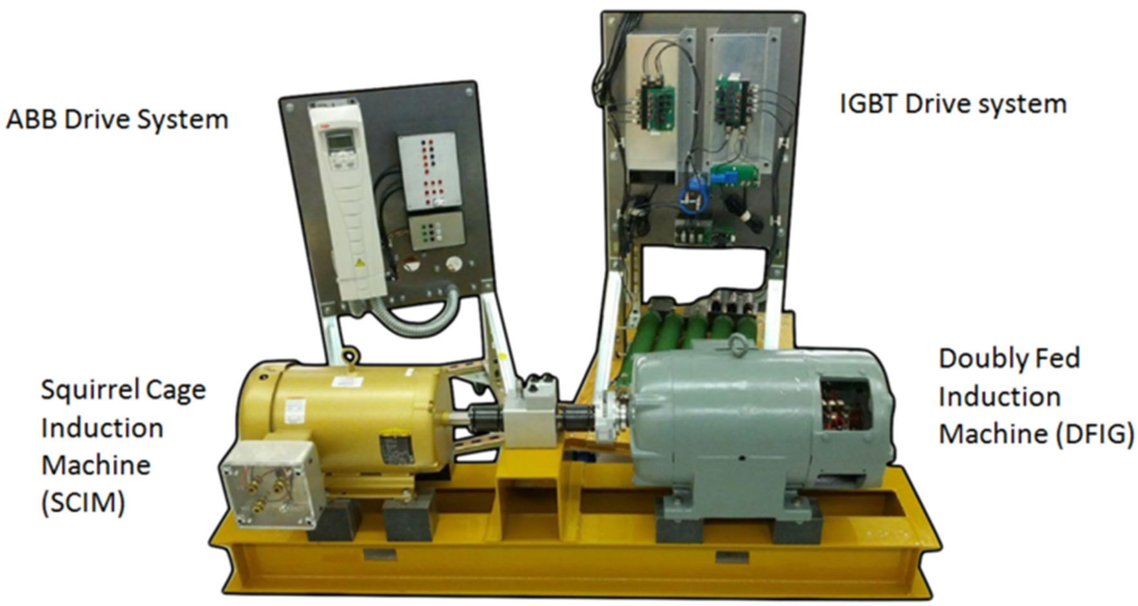

Figure 4. Squirrel Cage and Wound Rotor Induction Machines
Configured to Mimic a Type III Wind Turbine

Both the wound-rotor and squirrel-cage induction motors have their own unique torque-speed curves. There are two different methods that can move the two different torque-speeds curves relative to each other. The first is by varying the frequency supplied to the wound-rotor machine while holding the squirrel-cage machine's frequency steady. The second is by varying the load provided by the squirrel-cage induction machine while holding the wound-rotor machine steady.

The wound-rotor machine is a high slip machine. The squirrel-cage induction machine is a high efficiency, low slip machine…Figure 5(a) displays a visualization of the first method while Figure 4(b) shows the second method. In Figure 5 (a) and (b), the red torque-speed curve is the wound-rotor induction motor and the blue is the squirrel-cage induction machine. In the application of this new testing method, the second approach was used as the machine under-test was the wound-rotor induction machine.

As can be seen in Figure 5(b), this movement of torque-speed curves results in two unique intersection points – one in the stable region and one in the un-stable region of the torque-speed curves. The unique intersection points in the stable region, from here on referred to as the stable point, is utilized for measurements. The stable point provides current, voltage, power input, and speed in rpm. From these measurements torque, energy efficiency, and power factor can be calculated for each point.

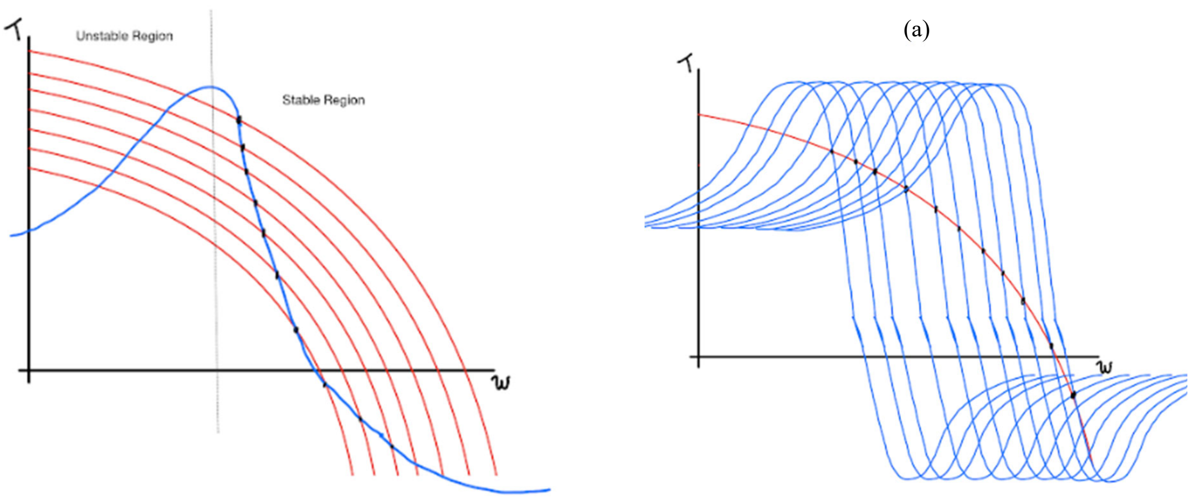

Figure 5(a) Sweeping Wound-Rotor Curve

Figure 5(b) Sweeping Squirrel-Cage Curve

Figure 5: Visualization of Intersecting Two Torque-Speed Curves, Sweeping One of Them

A wound-rotor induction machine has voltage and current connections to both stator and rotor windings. When utilizing the wound-rotor with this testing method, the wound-rotor machine was tested twice: Once with the rotor windings shorted and three-phase utility AC voltage applied to the stator windings and a second time with the stator windings shorted and three-phase utility AC voltage applied to the rotor windings. This provided two distinct torque-speed curves for the tested wound-rotor induction machine, one for the rotor side and one for stator side of the machine. The collected data and resulting torque-speed curve for the rotor side can be found in Figure 6. While the collected data and resulting torque-speed curve for the stator side can be found in Figure 7. Because the wound-rotor induction machine is a high-slip machine, the slopes of the curves tends to help accuracy. For the torque-speed curves at hand, the contrast between flatter and steeper slopes illustrates this. An advantage of using a synchronous machine or variable speed drive is the ability to obtain data at supersynchronous speed while maintaining excitation.

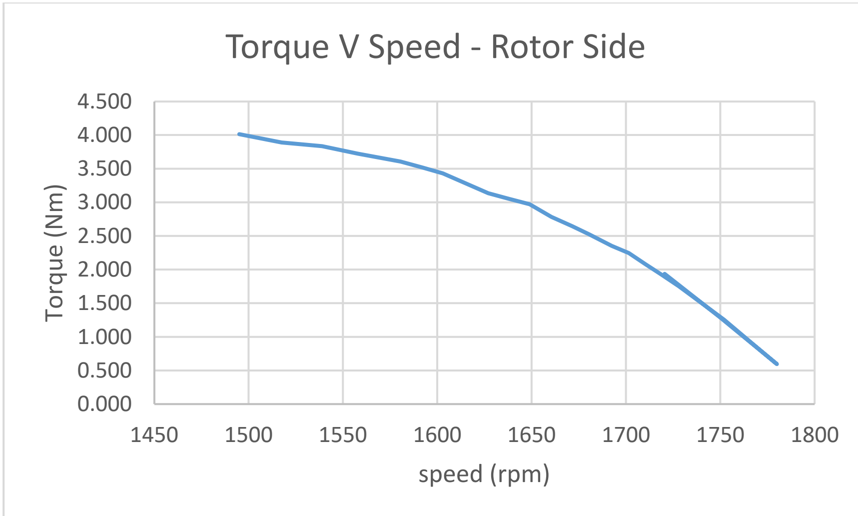

Figure 6: Torque-Speed Curve for Rotor Side of Wound-Rotor Induction Motor

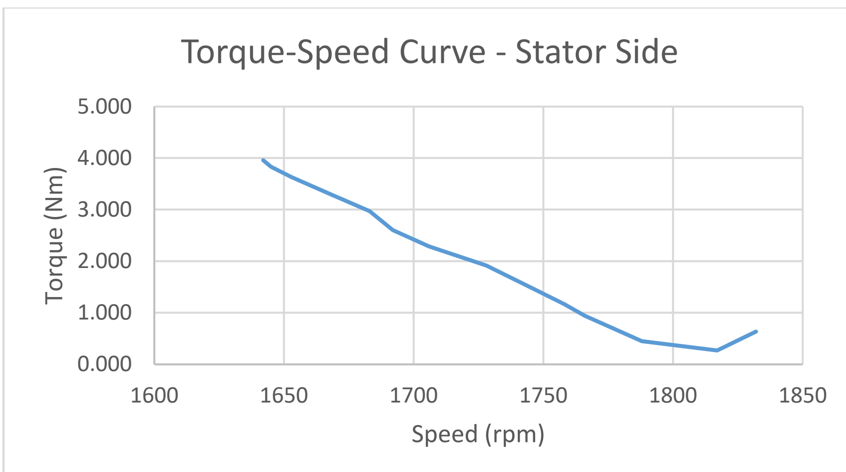

Figure 7: Torque-Speed Curve for Stator Side of Wound-Rotor Induction Motor

Steady-state circuit model parameter testing was also performed on the wound-rotor and squirrel-cage induction machines by conventional means.[1] From these circuit model parameters, torque-speed curves were also calculated. To verify this new testing methods torque-speed curves, the model derived torque-speed curves were compared to the test derived torque-speed curves. These torque-speed curves over similar ranges can be seen in Figures 7 and 8. respectively.

Torque Calculated from Model

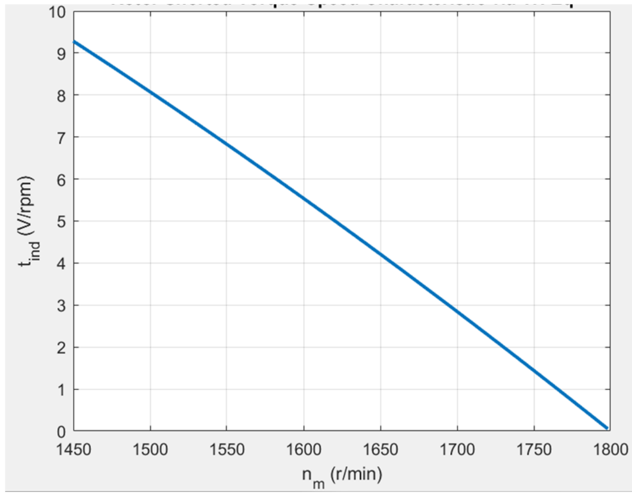

Figure 8: Torque-Speed Curve from Steady-State Parameters for Rotor Side of Wound-Rotor Induction Motor

Torque Calculated from Model

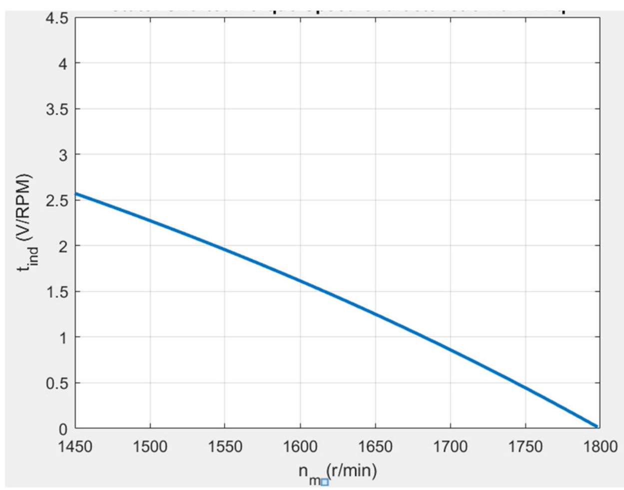

Figure 9: Torque-Speed Curve from Steady-State Parameters for Stator Side of Wound-Rotor Induction Motor

Assessment

To date, this method has been used for teaching first year graduate students. The teaching is part of their research work. They teach each other, beginning with the graduate student who developed the method, and spreading to other graduate students as they take their first graduate induction machines course. Undergraduates have not yet used it. The material underlying this is taught here at the graduate level. We are revising the curriculum to include this but such a change requires a year to get into the catalog. The graduate students who used the tests were of two types: one had only a single introductory electrical energy course that addressed machines, power systems, power electronics, and renewable energy. The other had a sequence of three courses: introductory electrical energy with DC machines, an AC machines course, and a power systems course up to and including power flow.

Both sets of graduate students were able to perform the tests: synchronous speed test, blocked rotor test, DC resistance test, and load tests (torque-speed, power factor-speed, and efficiency-speed). Their data were comparable and consistent. Curves shown earlier in this paper are from the work of a student with a single introductory course. Quality of work was good, though the sample size was too small to draw significant conclusions. The same student completed a Master's thesis degree with an excellent thesis.

The students with three or four courses likewise performed well, though their data was not of a higher quality. Their theses were of excellent quality. Their work when performed with a DC machine took less time to set up and execute. The resulting analysis was of a lesser quality, though the sample size is too small to justify conclusions yet. Accuracy was comparable to that experienced from students in similar situations with DC machines. It is evident from the curves in Figure 4 that unlike induction machines, i.e., a high slip induction machine coupled to a low slip induction machine, are likely to produce more accurate results more accurately than induction machines that are more similar. Our DFIG machine is a high slip motor while the other induction machine is a high efficiency, low slip machine. The intersection of their torque-speed curves is likely to deviate less from measurement errors of similar magnitude.

The method was created when facing the expense of aligning motor generator sets, a costly procedure at this university. To bring a technician from Spokane, a 400km round trip, costs $1000 per day. Two motor-generator sets can be aligned to tolerance in one day. The motor generator set at hand has two induction machines, as described earlier in this paper. This method saves the expense of two alignments on separate days: disassembling the motor-generator set to replace one induction machine with a DC machine and then reassembling after testing is completed. That saves about $2000, though the expense can be mitigated if other motor-generator sets in the same laboratory need alignment. Obviously, had the machines to be tested already been in a DC-induction configuration initially, this savings would have been tilted in favor of using DC machine for testing.

Setup takes more time if a synchronous machine sets the frequency. A variable speed drive requires less time for setup and operation.

Student learning is greater with this method because students must learn and employ a squirrel cage induction machine, a wound rotor machine, and a synchronous machine. The method was effective in teaching students to set up, operate, and sample data from machines. Learning is comparable to student performance with DC machine loads, though this method uses more machine types and hence provides opportunity to learn more distinct machine types. Students successfully completed their testing and drafted this paper.

Conclusions

A new test method was developed that allows for variable frequency testing of a wound-rotor induction machine. The previous test method only worked for a limited speed due to constraints for the DC machine load. The requirements of a wound rotor induction machine made a larger range of speed operation necessary. The new method's torque-speed results are like the old method but with the extended range in speed which matches expectations. The new method torque-speed results were also verified with steady-state parameter testing on the wound-rotor induction machine. We saved money in expenses to configure the tests. This savings applied only in favor of the incumbent configuration. Student learning improved due to the greater range of machines to learn from. In conclusion, the new torque-speed testing method works and is a viable teaching method on the fundamental operation of a wound-rotor induction machine.

References

[1] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators," IEEE Standard 112, 1991.
[2] Stephen Chapman, *Electric Machinery Fundamentals*, 5th ed. New York, NY: McGraw-Hill, 2012.
[3] Bin Wu, Yongqiang Lang, Navid Zargari, and Samir Kouro, Power Conversion and Control of Wind Energy Systems, New York, NY: Wiley, 2011.
[4] Amirnaser Yazdani and Reza Iravani, Voltage Sourced Converters in Power Systems, New York, NY: Wiley, 2010.