

Teaching Power Transformer Testing to Undergraduates

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Glenn T. Wrate received his B.S.E.E. and M.S.E.E. from Michigan Technological University (MTU) in 1984 and 1986, respectively. While attending MTU, he worked for Bechtel Power Corporation on the Belle River and Midland power generating stations. After graduating MTU, he worked for the Los Angeles Department of Water and Power from 1986 to 1992, primarily in the Special Studies and High Voltage DC (HVDC) Stations Group. He returned to MTU in 1992 to pursue a Ph.D. in Electrical Engineering. While completing his research he worked in the relay testing group at Northern States Power Company in Minneapolis. After obtaining his Ph.D., Glenn accepted an appointment as an Assistant Professor in the Electrical Engineering and Computer Science department at the Milwaukee School of Engineering (MSOE). In 1999 he was promoted to Associate Professor, in 2001 he won the Falk Engineering Educator Award and was promoted to head the Master of Science in Engineering (MSE) program. He received the Karl O. Werwath Engineering Research Award in 2003. In 2004 he moved from the MSE program to take over the Electrical Engineering program. After guiding the program through accreditation, he stepped down in 2007. Dr. Wrate has now returned to his boyhood home and is teaching as a full professor at Northern Michigan University. He is a member of HKN and IEEE, a Registered Professional Engineer in California, and is a past chair of the Energy Conversion and Conservation Division of ASEE.

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Abstract

Many educational electrical power laboratories do not have any access to utility-sized three-phase and single-phase power transformers, voltage regulators, and utility-grade instrument transformers. At Northern Michigan University, a local consortium (Lake Superior Community Partnership, The Upper Peninsula Power Company, American Transportation Company, Systems Control, and M.J. Electric) has donated a 2500-kVA, three-phase, General Electric, 32.8-kV – 2,400-V, grounded wye to delta, type OA-T transformer; a 333-kVA, single-phase, McGraw-Edison, 34.4kV – 277-V, type OA transformer; five voltage regulators, and several current and potential transformers. With test equipment obtained from a grant from the Department of Energy (DoE) and other equipment donated by local industry, the students perform insulation resistance, transformer turns ratio, oil breakdown, and power factor (or dissipation factor) testing on these transformers. These tests are in addition to the standard laboratory tests on small transformers: 1) determining the polarity and turns-ratio, 2) finding equivalent circuit parameters via open- and short-circuit tests, and 3) voltage regulation. This paper will discuss the problems encountered running these tests with undergraduates, including safety concerns. It will also discuss the students' interactions and their impressions of the testing; and look at methods to evaluate how well they learned the testing methods and the transformer operational concepts.

Introduction

Papers on power transformer testing typically focus on simulation in MATLAB/Simulink [1] or PSpice [2]. Most universities do not have large power transformers for students to test, and if they do, they are generally used from graduate research such as [3]. Northern Michigan University (NMU) is fortunate to have large power transformers for our undergraduate students to test. Figure 1 shows the General Electric 2500-kVA three-phase transformer donated by a local utility being installed in the mock substation on campus. Figure 2 shows a close-up of the oil temperature gauge and the transformer nameplate. Additionally in the mock substation, we have three voltage regulators and in the lab, we have a signal-phase 333-kVA transformer, one intact voltage regulator, a voltage regulator that has been drained of oil and ports cut in the side to view the mechanism in operation, and several industrial/utility grade instrument transformers.

The tests on the large power transformers are performed in this order:

- 1) A Megger MIT525 is used to perform the insulation resistance and PI tests
- 2) A Megger TTR-320 is used to perform the transformer turns-ratio tests
- 3) A Hipotronics OC-60-A portable oil tester is used to perform a breakdown voltage test on the oil from a Hampden H-OFT-180 oil-filled transformer trainer
- 4) A Megger Delta 3000 is used to perform the power factor (or dissipation factor) tests at 10 kV.

In addition to learning how to use the test equipment safely, the students must also learn the software to run the tests and collect the data. It is hoped that this paper provides insight into testing large power transformers and suggestions for others who are interested in teaching these tests.



Figure 1. Placing the 2500kVA Transformer

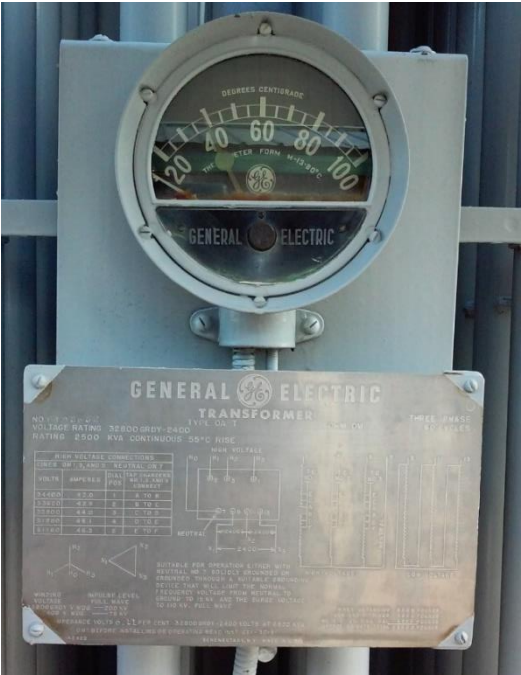


Figure 2. Transformer Nameplate and Oil Temperature Gauge

Basic Tests

The first four labs are tradition transformer experiments. These experiments are intended to help the students gain an understating of the test equipment and how transformers work.

1. Basic Power Measurements
2. Transformer Ratio, Polarity, and Open Circuit Tests
3. Winding Resistance, Leakage Reactance, and Voltage Regulation
4. Three-Phase Transformer Connections

The basic power measurement lab is intended to familiarize the student with the measurement tools they will be using in the three subsequent experiments. The transformer turns ratio and polarity tests and performed on a small (120 VA) benchtop transformer, similar to most power labs. For the open and short-circuit tests we switch over to an industrial-sized transformer (1.5 kVA) to get more realistic values. Finally, for the three-phase transformer connections lab we switch back to small benchtop three-phase transformers.

Insulation Resistance and Polarization Index Tests

For the labs where we perform the insulation resistance (IR) and polarization index (PI) tests, we use utility-sized transformers. If weather permits, we test the 2500-kVA three-phase transformer in the mock substation outside. If it is raining or snowing, we test the 333-kVA single-phase transformer inside. For either transformer, a Megger MIT525, shown in Figure 3, is used to perform the tests.



Figure 3. Insulation Resistance Tester Used for Testing

The following insulation resistances are found:

- a. High-voltage winding to low-voltage winding and to ground
- b. High-voltage winding to ground
- c. Low-voltage winding to high-voltage winding and to ground
- d. Low-voltage winding to ground
- e. High-voltage winding to low-voltage winding

The test connections are shown in Figure 4.



a. High-voltage winding to low-voltage winding and to ground



b. High-voltage winding to ground



c. Low-voltage winding to high-voltage winding and to ground



d. Low-voltage winding to ground



e. High-voltage winding to low-voltage winding

Figure 4. The five test connections used for the IR and PI tests

The students are broken into groups so that more students get a hands-on experience with the test equipment, rather than just recording values taken from someone else, as shown in Figure 5. On the outside transformer, the groups perform a single test, e.g. the high-voltage winding to low-voltage winding and to ground test. On the transformer inside, the groups arrange a time to perform all five tests on a given tap. In either case, the students report their results via a Learning Management System (LMS) blog. This allows each student access to the entire data set to right their test report on the transformer. An example of student-recorded data is shown in Figure 7.



Figure 5. Students (and faculty member) recording data while other students performed testing

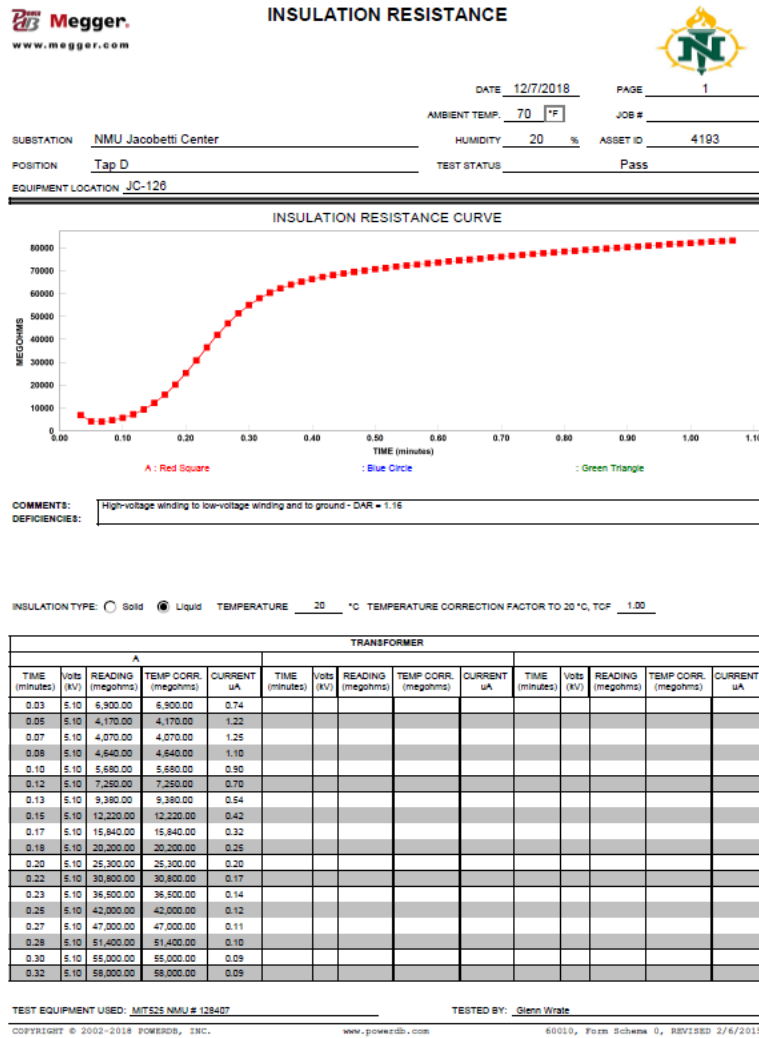


Figure 6. Insulation Resistance (IR) Test Report

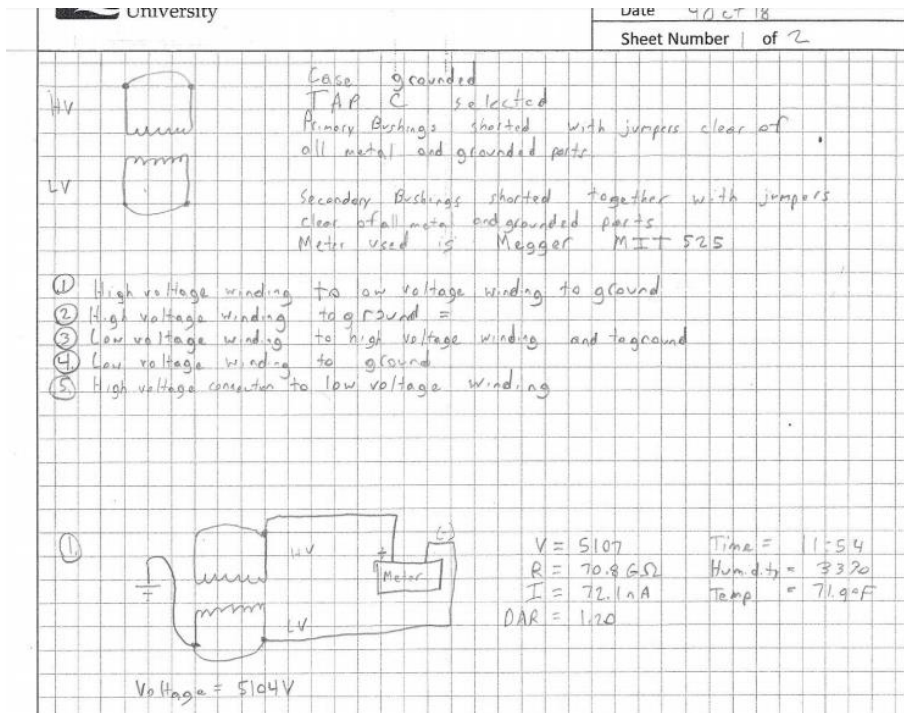


Figure 7. Example IR Data Sheet from a ET 255 Student

Transformer Turns-Ratio Tests

Transformer turns ratio tests are performed on the 333-kVA transformer, a series of window CTs and bushing CTs, and, in most semesters, a voltage regulator. A Megger TTR-320 is used to perform the tests.



Figure 8. Megger TTR320 Turns Ratio Tester [From Megger TTR 320 User's Guide]

The test setup must be changed when testing current transformers, but the general setup for all other transformers is shown in Figure 9. An example of student data is shown in Figure 10.

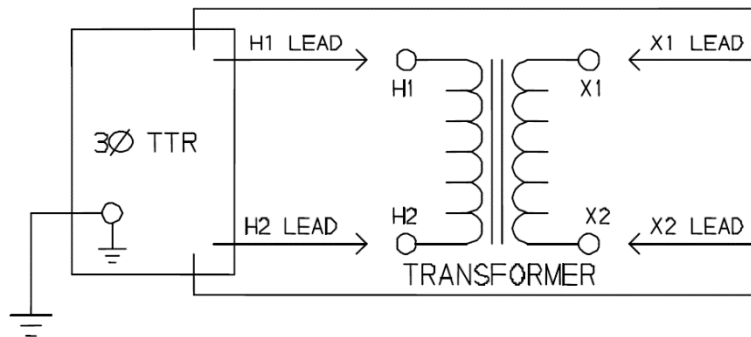


Figure 9. TTR320 Connections for Testing a Single-Phase Transformer [From Megger TTR 320 User's Guide]

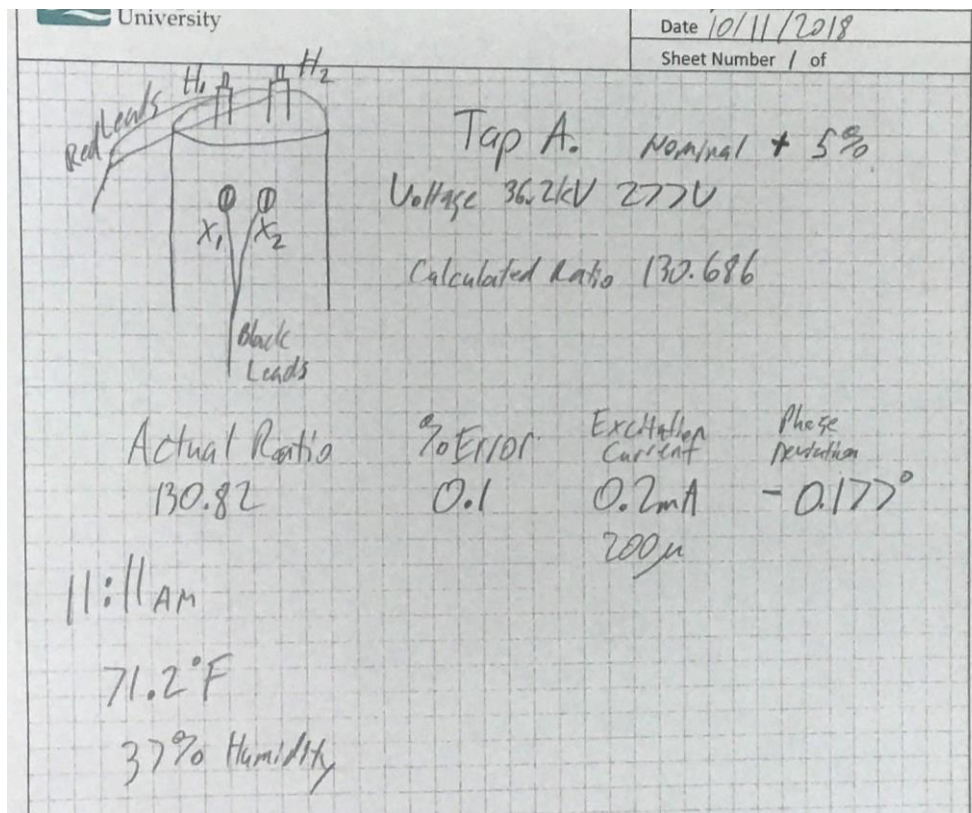
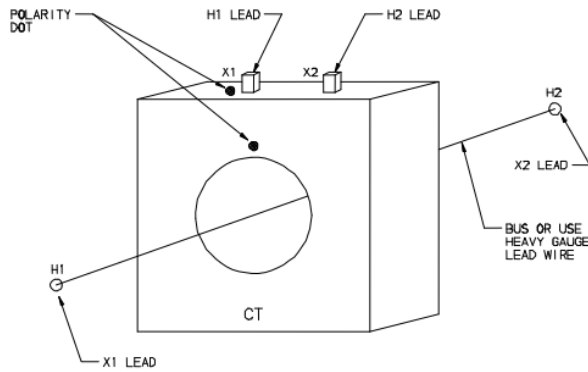


Figure 10. Example TTR Data Sheet from a ET 255 Student Team

The configuration for CT testing is shown in Figure 11. An example of the test results is shown in Figure 12. The .pdbxml files for each test from the PowerDB program used in conjunction with the Megger test equipment was made available to the students via EduCat (NMU's Learning Management System). The students have a copy of PowerDB on their laptops, so that they can review and export the data.



NOTE: TEST PER DIAGRAM NO. 1 FOR ANSI, CEI/IEC & AUSTRALIAN STANDARDS

Figure 11. Setup for Testing Current Transformers (From Megger TTR 320 User's Guide)

Table 1. Results for Lone Current Transformers

Asset ID	Test #	Ratio	Test V	Ratio Nameplate	Ratio Actual	% Error	Excitation Current (mA)	Phase Angle (deg)	Result
3221981	Test 1	600:5	8V	120	119.385	-.51%	21.8	-.12	Fail
3226424	Test 2	600:5	8V	120	119.412	-.49%	21.8	-.13	Pass
3226410	Test 3	600:5	8V	120	119.346	-.54%	21.7	-.14	Fail
E653324	Test 4	400:5	80V	80	78.009	-2.49%	253.8	.01	Fail

Table 2. Results for CT's on Recloser

Asset ID	Test #	Ratio	Test V	Ratio Nameplate	Ratio Actual	% Error	Excitation Current (mA)	Phase Angle (deg)	Result
5630	Test 5	600:5	80V	120	120.031	.03	62.2	-.13	Pass
5630	Test 6	500:5	80V	100	100.027	.03	84.7	-.14	Pass
5630	Test 7	450:5	80V	90	90.038	.04	109.6	-.14	Pass
5630	Test 8	400:5	80V	80	80.041	.05	176.8	-.13	Pass
5630	Test 9	100:5	8V	20	20.045	.023	295.6	.06	Pass

Figure 12. Results for Current Transformer Testing from an ET 255 Student's Report

Transformer Oil Breakdown Voltage Tests

Transformer oil breakdown voltage tests are performed on the oil a from a Hampden H-OFT-180 oil-filled transformer trainer. Either a Megger OTS60PB or a Hipotronics OC-60-A portable oil tester is used for these tests. The Megger OTS60PB is an automated tester, so there is very little for the students to do after the sample of oil is taken. After the students confirm the gap spacing between the electrodes and place the sample container in camber, the OTS60PB performs the complete ASTM D877 [4] test and displays the result.

The Hipotronics OC-60-A is an older unit, and has been used for the last two years. After the electrode gap spacing is set, the students pour oil into the test cup and carefully place it into the unit. Each student performs one test, while other students assist with recording the breakdown voltage, measuring the time between individual tests, and the overall test time. The ASTM D877

test requires a 3 kV/second voltage rise, five breakdowns, and a one-minute wait time between the breakdowns. The average of the five tests is then considered the breakdown voltage of the sample. The Hipotronics OC-60-A is shown in Figure 13.



Figure 13. Hipotronics OC-60-A Portable Oil Tester

Power Factor/Dissipation Factor Tests

If the weather permits, we test the power factor ($\cos \phi$) or dissipation factor ($\tan \delta$) of the 2500-kVA three-phase transformer in the mock substation outside. If it is raining or snowing, we test the 333-kVA single-phase transformer inside. A Megger Delta 3000 is used to perform the tests at approximately 10 kV.



Figure 14. Megger Delta 3000 Power Factor / Dissipation Factor Test Set

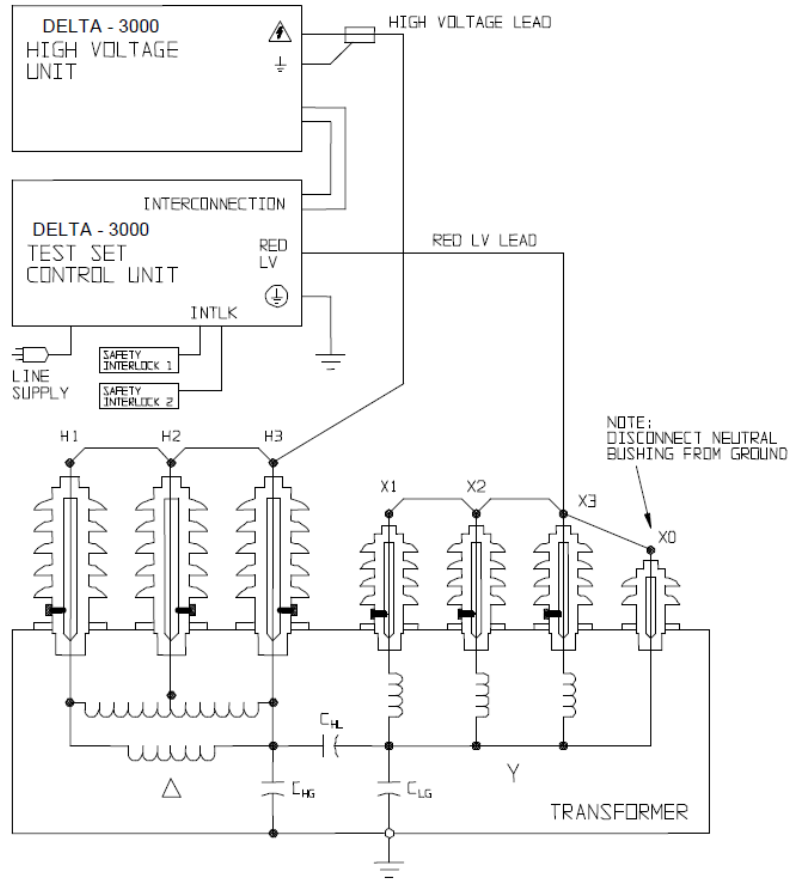


Figure 15. Typical Test Setup for AC Insulation Testing on a Three-Phase Power Transformer
[From Megger Delta 3000 Users Guide]

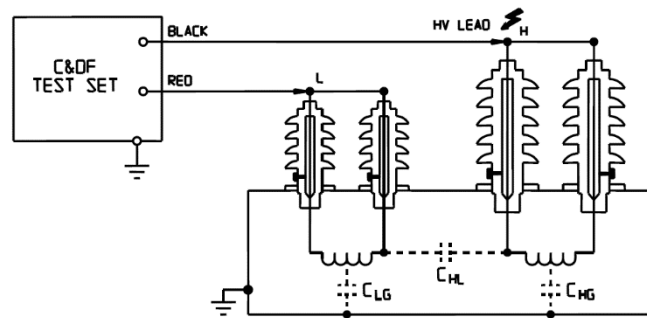


Figure 16. Typical Test Setup for AC Insulation Testing on a Single-Phase Power Transformer

The tests performed on a two winding transformer are shown in Table 1. The table includes a calculated check that helps to eliminate measurement errors.

Table 1. Two Winding Transformer Test Connections [From Megger Delta 3000 Users Guide]

Test No.	Insulation Tested	Low Voltage Lead Configuration				Test Connections To Windings			Remarks
		Test Mode	Measures	Grounds	Guards	Black	Red	Blue	
1	$C_{HG} + C_{HL}$	GST GND		Red & Blue		H	L	—	L Grounded
2	C_{HG}	GST			Red & Blue	H	L	—	L Guarded
3	C_{HL}	UST	Red	Blue		H	L	—	
4	C_{HL}	—	Test 1 minus Test 2			—	—	—	Calculated intercheck
5	$C_{LG} + C_{HL}$	GST GND		Red & Blue		L	H	—	H Grounded
6	C_{LG}	GST			Red & Blue	L	H	—	H Guarded
7	C_{HL}	UST	Red	Blue		L	H	—	
8	C_{HL}	—	Test 5 minus Test 6			—	—	—	Calculated intercheck

Student Learning and Perceptions

The instructional objectives for the course are that the student will be able to:

- Determine the operating characteristics and proper application of single-phase transformers and three-phase transformer banks
- Calculate maximum fault current available on the secondary winding of a transformer in amperes and per unit
- Understand the maintenance procedures necessary for proper operation of dry-type and liquid-filled transformers
- Understand the methods used to test dry-type and liquid-filled power transformers
- Determine the operating characteristics, proper application, and testing of instrument transformers

The results for each student and each objective is given in Table 2, on the next page. The results were obtained from specific questions on testing and the test equipment on the unit exams or final exam. Two examples are given below:

- What are three things you should do when preparing to do a dielectric breakdown test?
- What rate of voltage rise is required for the ASTM D877 dielectric breakdown test?

Table 2. Assessment Results for Each Student and Learning Objective

	#1	#2	#3	#4	#5
Student #1	100.0%	100.0%	100.0%	92.0%	100.0%
Student #2	100.0%	100.0%	84.0%	96.0%	96.0%
Student #3	88.0%	80.0%	96.0%	96.0%	72.0%
Student #4	100.0%	100.0%	100.0%	90.0%	76.0%
Student #5	80.0%	92.0%	100.0%	96.0%	100.0%
Student #6	96.0%	100.0%	100.0%	88.0%	100.0%
Student #7	88.0%	84.0%	100.0%	80.0%	100.0%
Student #8	100.0%	100.0%	100.0%	80.0%	80.0%

The last two objectives are looking at testing. They are closely monitored each semester the course is run (the course is only run once a year). In addition to the traditional student (ABET) assessment, we actively solicit input from our graduates and their employers. Based on employer feedback, and some alumni feedback, the equipment testing was changed from group to small group or individual. The complaint was that while the students knew the concepts, they were unsure about using the test equipment in the field. From alumni feedback, the reports required for the tests were changed from just a table of results to a test report similar to test reports generated in industry.

Student Comments have been very positive about this testing. We rarely see any negative comments. When we do, it is usually about problems with the test equipment. With generally only one piece of test equipment of each type of test, when the test equipment is not working properly we cannot perform the lab. The equipment does cost a significant amount to maintain. Currently, the Megger OTS60PB needs to be repaired, this is in addition to two other test devices used by classes in the program (a Doble TDR 900 CB Travel Time tester and a PowerDV Micro-Ohm meter). The university's instrument technicians usually cannot perform repairs on this type of specialized test equipment, so the devices must be sent back to the manufacturers for repair.

Conclusions

According to both our students and their employers, the use of actual utility and industrial sized transformers in the teaching of power transformers is definitely a positive thing. The students get real-world experience, and are much more likely to take the lab experiments seriously. Individual or small group testing is preferred. The employers and other industry visitors are very impressed with the labs the students perform and the capabilities of our graduates. It is hoped that this paper will help other programs develop similar labs.

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