

Improving Students' Understanding of Electromagnetic Principles with an Alternator Design-Build-Test Project

Dr. Matthew R. Aldeman, Illinois State University

Matt Aldeman is an Assistant Professor of Technology at Illinois State University, where he teaches in the Renewable Energy and Engineering Technology programs. Matt joined the Technology department faculty after working at the Illinois State University Center for Renewable Energy for over five years. Previously, he worked at General Electric as a wind site manager at the Grand Ridge and Rail Splitter wind projects. Matt's experience also includes service in the U.S. Navy as a nuclear propulsion officer and leader of the Reactor Electrical division on the aircraft carrier USS John C. Stennis. Matt is an honors graduate of the U.S. Naval Nuclear Power School and holds a B.S. in Mechanical Engineering from Northwestern University, a Master of Engineering Management from Old Dominion University, and a Ph.D. in Mechanical and Aerospace Engineering from the Illinois Institute of Technology.

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Matthew R. Aldeman

Illinois State University, Dept. of Technology, Normal, IL, 61790

As a required course in the Renewable Energy undergraduate major at Illinois State University, students take *TEC 259: Power Generation: Production, Conversion and Storage*, typically in their junior or senior years. The course covers the fundamental laws governing energy conversion and includes practical applications relating to the design of energy conversion systems. Over an approximately one-month period in the latter half of the course, students design, build, and test their own AC electric alternator or generator. During this time the class lectures include a discussion of electromagnetic principles, Faraday's Law, and real-world generator designs. For materials, students are given a block of wood, wooden dowel rods, shelf support brackets, screws, pairs of ceramic and neodymium magnets, and thirty feet of 24 AWG magnet wire. Students are encouraged to iteratively test and improve their designs. The generators are tested by attaching an electric drill to the input shaft of the generator, and the output is measured with an oscilloscope. The design objective is to maximize the output voltage of the machine. After some experimentation, the instructor for the course has set a benchmark of 300 mV as the target voltage output. Some students have achieved output voltages of more than 3V. The assessment method consists of two parts: i) a quantitative assessment of the machine's output voltage compared to the 300 mV benchmark, and ii) a qualitative assessment of the durability and reliability of the machine. Students have given very positive feedback on the project, saying that it was their favorite part of the course, and have commented that the project greatly improved their understanding of electromagnetic principles and electric machine design. The students' exam scores on related material also show marked signs of improvement.

Introduction and Background

A Bachelor of Science in Renewable Energy (RE) degree program was established by Illinois State University in 2007, and is housed within the Department of Technology. The degree was initially offered in two specialization sequences: i. Technical, and ii. Economics/Public Policy. The two sequences were combined in 2013, and students are now required to choose a minor in one of the following areas: Business Administration, Politics and Government, Economics, Environmental Studies, Geography, and Technology.

The mission of the Renewable Energy program at Illinois State University is "To prepare technically-oriented managerial professionals and leaders for business, industry, government, and education by articulating and integrating competencies in Renewable Energy." The program prepares graduates for jobs in the fields of renewable energy systems as well as regulatory and governmental agencies. To meet this demand for well-rounded graduates who are knowledgeable in both technical and economic aspects of renewable energy systems, a curriculum has been developed consisting of courses from the Departments of Technology, Economics, Physics, Business, and others.

The Renewable Energy Program operates on five goals that align with the strategic goals of the college and university. The five goals of the Renewable Energy program are:

1. Provide students with high quality educational experiences by featuring a modern, up-to-date curriculum that will develop the technical and managerial knowledge, skills, and attitudes that are foundational to success as RE professionals.
2. Recruit and graduate a diverse group of individuals to support companies and organizations that will employ RE professionals in the state and throughout the United States.
3. Provide opportunities for students to interface with RE professionals.
4. Provide service to companies and organizations that employ RE graduates through applied research, consulting/workshops, and participation in professional organizations.
5. Develop industry and RE alumni relationships in support of the program.

To meet Program Goal #1 and ensure that graduates acquire a fundamental understanding of both conventional and renewable power plant systems, a new required course was added for the spring semester of 2017 called *TEC 259: Power Generation: Production, Conversion and Storage*. The course is typically taken by students in their junior or senior years. The purpose of this course is to help students understand the operating principles of many types of electrical generation power plants. The principles are applicable to most types of conventional fossil-fuel based thermal power plants as well as thermal renewable energy power plants such as solar thermal or geothermal plants.

The first half of the course focuses on thermal energy, beginning with a review of the fundamentals of work, energy, and power, followed by applications of the Laws of Thermodynamics, with particular emphasis on the First and Second Laws of Thermodynamics and their implications for thermal energy power plants. Next, the course turns to the topic of heat transfer, with an emphasis on Steam Cycles and calculation of heat flux through conduction, convection, radiation, and combined modes of heat transfer.

The second half of the semester takes a turn away from thermal energy processes and moves towards the electrical generation aspect of electric generation power plants. The second half of the semester is applicable to all of the previously-mentioned types of power plants, and is also applicable to wind turbines. The electrical generation section of the course includes the topics of magnetism and electromagnetism, induced voltage (Faraday's Law), and the many variations of generators that are in use today (e.g. synchronous, induction, permanent magnet, doubly-fed induction, full-converter, etc.). The final topic in the class is energy storage. Several storage options are discussed, including traditional electro-chemical batteries of various chemistries, pumped hydro and other gravitational energy storage, flywheels, and compressed gas. A topical outline is given below.

TEC 259: Power Generation: Production, Conversion and Storage

- I. Basic Principles of Energy Conversion
 - A. Work, Energy, Power
 - B. Types of Energy Production, Storage, and Conversion
 - C. Laws of Thermodynamics
- II. Thermal Energy Conversion
 - A. Steam Cycles & Turbines
 - B. Thermal Energy Transfer: Conduction, Convection and Radiation
 - C. Heat Exchangers, Boilers & Condensers
- III. Electrical Energy Conversion
 - A. Review of electrical fundamentals
 - B. Induced Voltage and Faraday's Law
 - C. Alternators and Generators
- IV. Energy Storage
 - A. Electro-chemical Batteries
 - B. Pumped Hydro
 - C. Flywheels
 - D. Compressed Gas

Students in this class are assigned approximately 18 homework assignments during the semester. The homework assignments are short, and are intended to take students approximately 30 minutes to complete outside of class. However, in keeping with the applied nature of this course, the instructor (and author of the present paper) desired to find a hands-on project that would allow the students to apply some of the important principles from the course. The hands-on project should reinforce the topics discussed in class, should be fun, and should allow for friendly competition between the students.

There are a variety of energy-related projects that have been developed for high school and college level classrooms. For example, the NEED Project offers an entire curriculum of K-12 energy education lessons and projects [1]. The KidWind Project, meanwhile, developed a set of interactive wind energy kits [2] and, in collaboration with the National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy, led the development of the annual U.S. Collegiate Wind Competition [3]. The website *Sciencing* has developed a tutorial for students to build homemade electric generators [4], and the website *teacherstryscience.org* has developed a tutorial lesson plan around constructing a wind turbine generator [5]. The *Electrical Construction & Maintenance* magazine recently reported that a Florida high school student has utilized these same principles to develop a \$12 hydroelectric turbine generator made out of recyclable materials [6]. The student was inspired to create the low-cost generator when she learned that her Ethiopian pen pal was living without electricity and running water.

Similar projects have been undertaken at the university undergraduate level. Marshall [7] provides a step-by-step construction procedure for students to build a low-voltage DC motor, and notes that the activity has been used by students as young as eight year old all the way up

through university seniors. The materials consist of a D-cell battery, a rubber band, magnet wire, a ceramic magnet, and sandpaper. Maheswaran [8] reports on a DC motor design and construction project assigned in a freshman-level Engineering Physics course at Northeastern University. Seventy-five percent of the students in the class reported that the motor design project motivated them to learn more about engineering physics concepts. Wendell [9] discusses a freshman seminar class at MIT that includes the construction of an electric motor. In addition to electromagnetic principles, the electric motor project also involved CAD, laser-cutting, and the use of a Raspberry Pi device as a motor controller. Wendell reports that the project was well-received by the class, and all of the students eventually succeeded in creating a functional motor. Williams [10] describes a brushless DC motor project that is built by all students in a first-year electrical engineering orientation course at the Milwaukee School of Engineering. The brushless DC architecture allows the instructors to incorporate a variety of topics into the project, including instrumentation, communications, robotics, and microprocessors. The students reported that they enjoyed the tactile and immediate feedback of the project. Clayton and Stein [11] developed a permanent magnet DC motor project for a 200-level mechanical engineering course at Villanova University. They provide a step-by-step instruction manual for the construction of the motor, including a functional commutator. They also demonstrate that the motor construction project gives students an improved understanding of the underlying principles as compared to theory-based lecture or disassembling an existing motor.

In each of these cases, it is clear that electric motors or generator systems have captured the imaginations of teachers and students from across the country. If they present an interesting challenge to general populations of students as described in some of the references previously described, then it is likely that they will be even more engaging to students that have demonstrated a motivation to learn about these topics by choosing to major in Renewable Energy. To make the project more challenging and open-ended, the students in TEC 259 are provided only with raw materials – which they are permitted to add to – and are told to build a functioning generator. The students are not given step-by-step instructions.

Beginning in the spring semester of 2017, students in the TEC 259 class were assigned to design, build, and test an electric alternator or generator. Immediately upon beginning Section III of the course (Electrical Energy Conversion), the students were informed of the project. Students are given approximately one month (4 ½ weeks) until the final testing day. Each student is given a set of materials to build their alternator or generator, but they are told that they are free to add their own materials. The materials provided to each student consist of:

- Block of wood, approximately 3” x 6” x 0.75”
- Wooden dowel rod, 0.25” diameter x 6” long
- Wooden dowel rod, 0.75” diameter x 6” long
- Pair of metal shelf support brackets
- Pair of round ceramic permanent magnets, 0.75” diameter x 0.25” thick
- Pair of round neodymium permanent magnets, 0.75” diameter x 0.125” thick
- 30 feet of 24 AWG magnet wire

- Miscellaneous screws and fasteners

The governing law for the alternator project is known as Faraday's Law of Induced Voltage, named after British scientist Michael Faraday. A convenient form of Faraday's Law is given as:

$$E_{ind} = -N \frac{d\Phi_B}{dt} \quad \text{Eqn. (1)}$$

where E_{ind} is the induced voltage, N is the number of turns in the coil of wire, and Φ_B is the magnetic flux through the coil of wire. Through calculations, guided discussion and experimentation, students quickly realize that "generator action" (i.e. induced voltage) requires three components: i. a magnetic field, ii. a conductor, and iii. relative motion between the magnetic field and the conductor. In the case of the student project, the magnetic field is provided by the permanent magnets, the conductor is provided by the coiled magnet wire, and the relative motion is provided by the rotation of the magnetic field relative to the wire coil. Images of several examples of completed student generators are given in Figures 1-3.

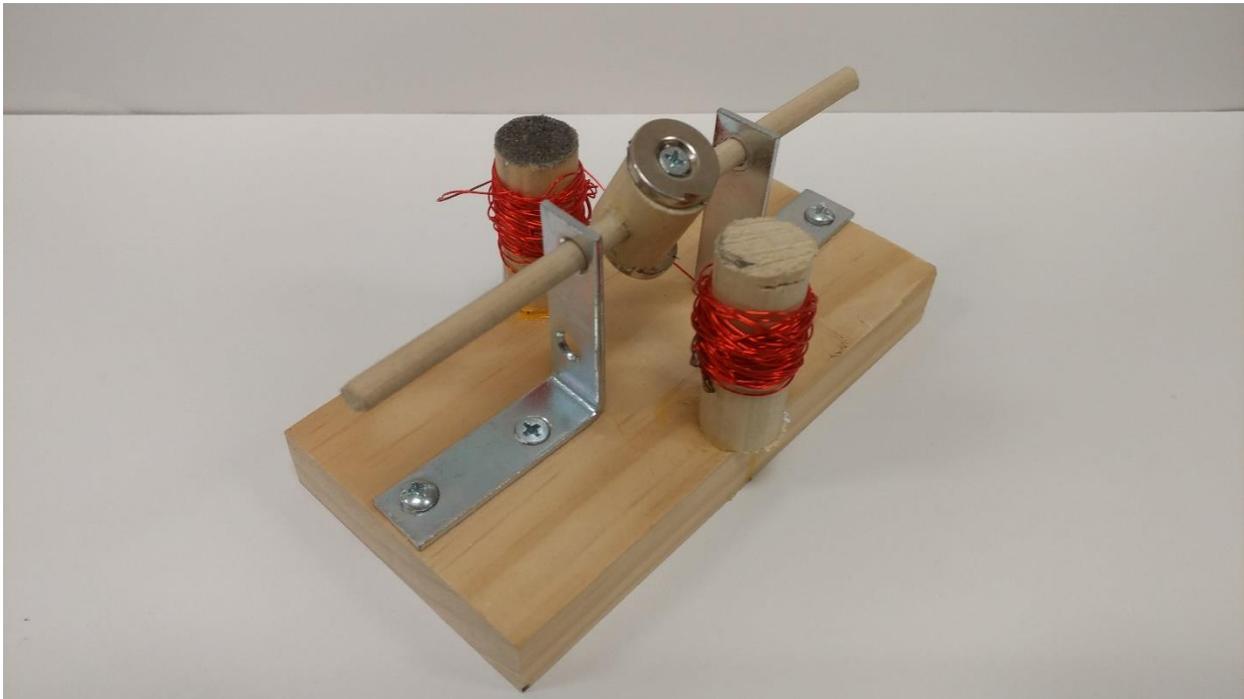


Figure 1. Example of student-built generator project

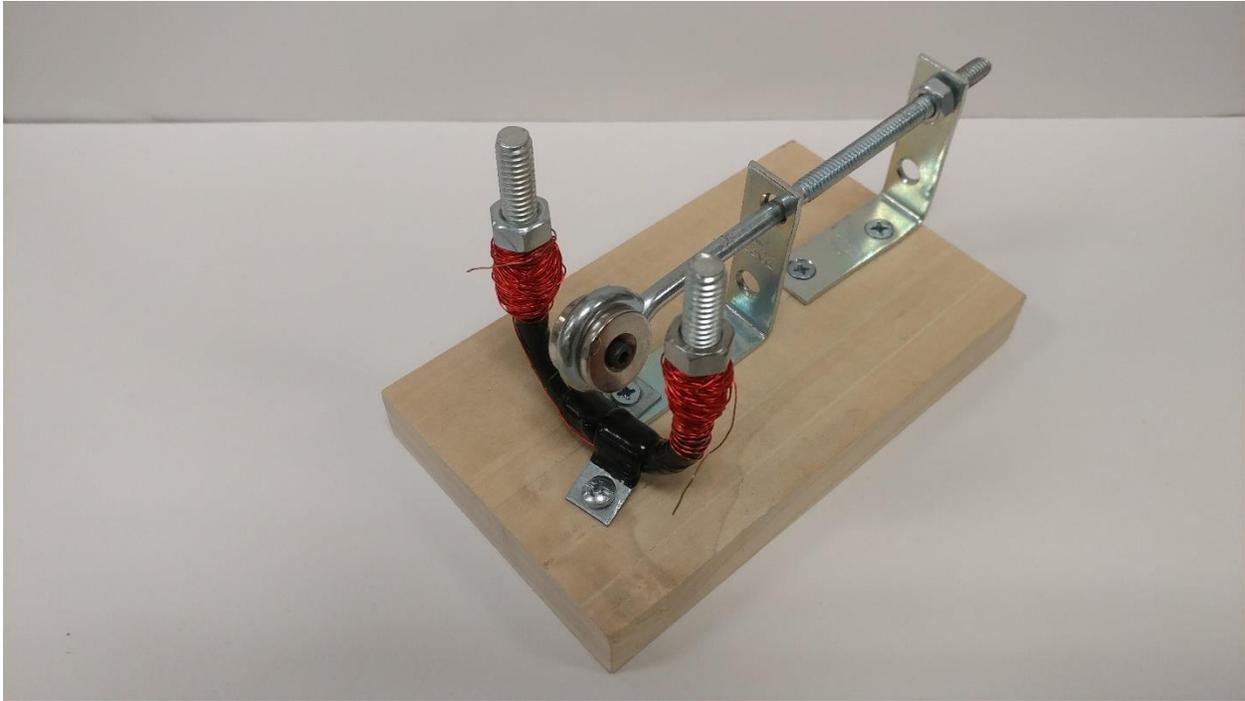


Figure 2. Example of student-built generator project

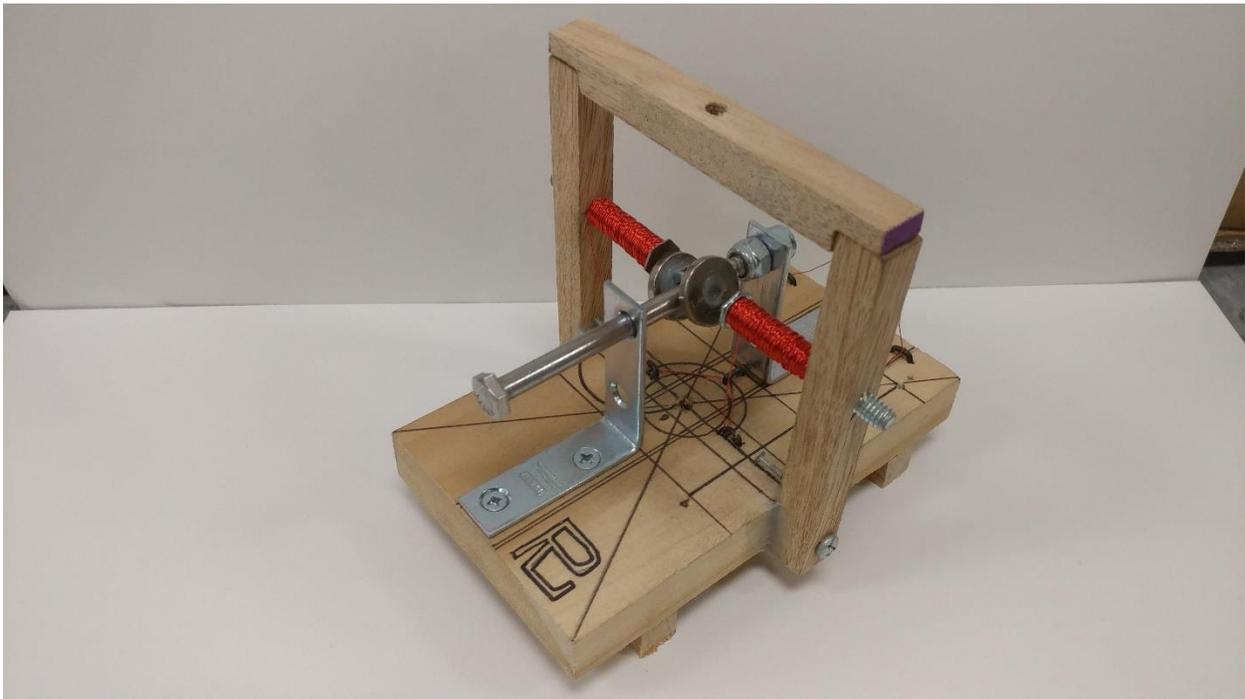


Figure 3. Example of student-built generator project

Testing and Assessment

Students are given approximately one month to design, construct and test their generator. They are also warned that the project typically requires some trial-and-error, necessitating design iteration. Testing of the generator is available throughout the one-month window, so students do not have to wait until the due date to test their generators. Many of the students take heed of this opportunity to iterate their design, and begin construction well in advance of the due date. Students that take advantage of this opportunity to iterate their design usually end up with higher-performing generators.

To test the generators, the students place their generators inside a plastic enclosure that is approximately 4 feet x 4 feet x 4 feet. The enclosure is closed on all but one side. This is to ensure that if the generators fly apart during testing (which happens occasionally), the flying pieces will be contained by the plastic enclosure. Students connect the input shaft of their generator to a corded electric drill, and the generator's electrical output wires are connected to an oscilloscope without any electrical load attached. The instructor monitors the oscilloscope and calls out the measurements while the student operates the corded drill. The evaluated metric is the peak open-circuit output voltage of the generator, measured from the horizontal axis to the peak of the voltage waveform.

The results for the spring 2017 and spring 2018 sections of the class are given in Table 1 and Table 2, and histograms of the results are given in Figure 4 and Figure 5. In both sections, there was one student who chose not to build a generator. The tables below show "N/A" for those students, and this data is not represented in Figure 4 or Figure 5.

Table 1. Generator Peak Output Voltage Results

2017 Student-Built Generator Output [mV]			
Student 1	1,000	Student 11	400
Student 2	1,600	Student 12	100
Student 3	350	Student 13	328
Student 4	120	Student 14	3,900
Student 5	75	Student 15	550
Student 6	150	Student 16	400
Student 7	250	Student 17	400
Student 8	400	Student 18	300
Student 9	N/A	Student 19	150
Student 10	400	Student 20	350

Table 2. Generator Peak Output Voltage Results

2018 Student-Built Generator Output [mV]			
Student 1	175	Student 11	275
Student 2	50	Student 12	350
Student 3	1,200	Student 13	150
Student 4	250	Student 14	320
Student 5	300	Student 15	375
Student 6	325	Student 16	350
Student 7	1,500	Student 17	200
Student 8	400	Student 18	450
Student 9	900	Student 19	N/A
Student 10	400		

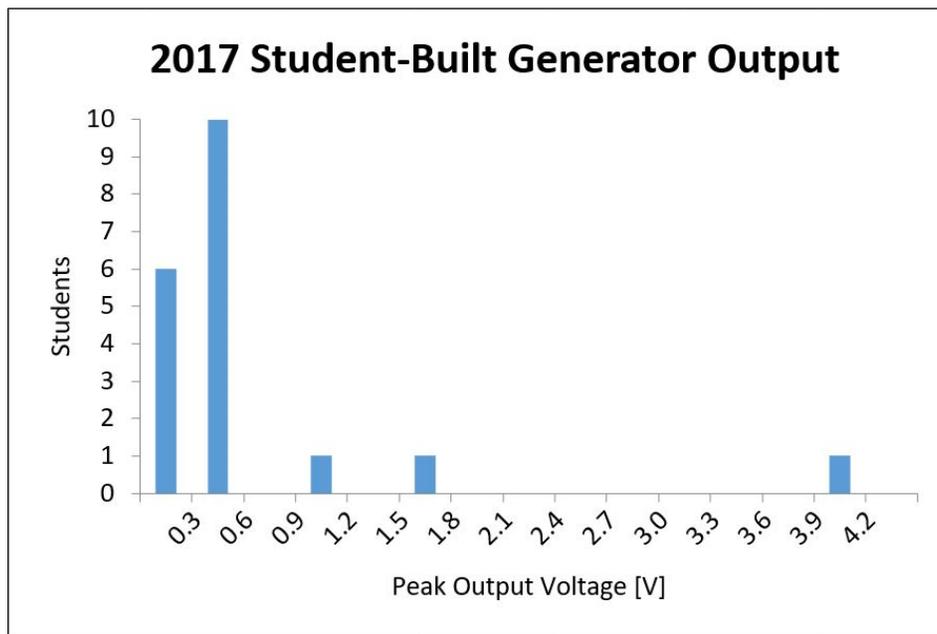


Figure 4. Histogram of Peak Student-Built Generator Output Voltage (TEC 259, Spring 2017)

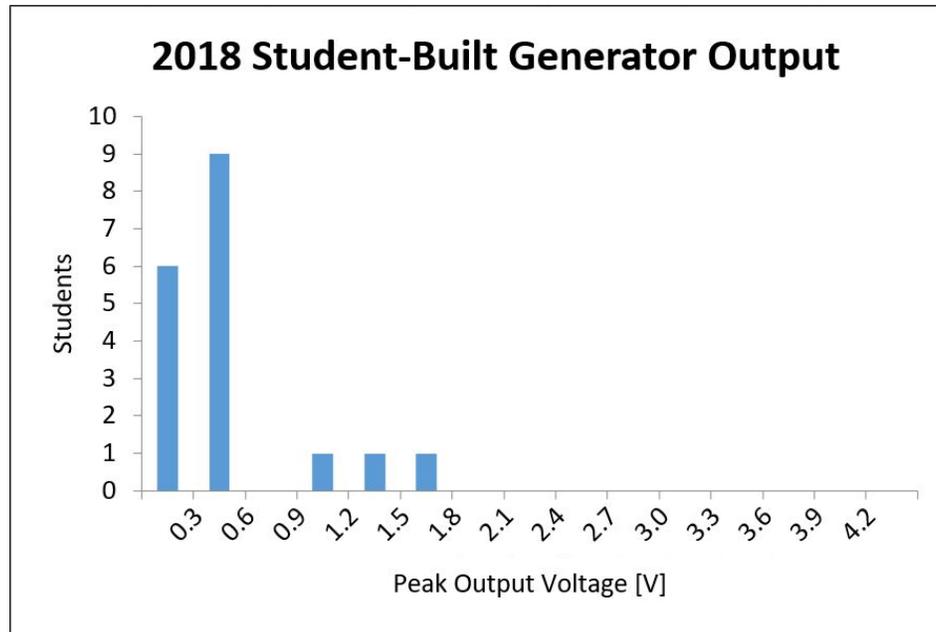


Figure 5. Histogram of Peak Student-Built Generator Output Voltage (TEC 259, Spring 2018)

Assessment

The student-built generators are assessed on several different evaluation metrics. First, the instructor decided that only a portion of the assessment would be based on the generator's peak output voltage performance. Because this was a brand new project, the instructor did not know how successful the students would be at achieving high-performing generators, and was wary of setting a performance standard that was too high. Therefore, most of the evaluation weighting was based on the instructor's evaluation of the generator design and quality of construction.

In order to determine the objective performance-based portion of assessment, however, a baseline was needed against which to compare the performance of the students' generators. To produce a baseline output measure, the instructor built a generator himself. However, the performance of the instructor-built generator was intentionally handicapped by using only half as much wire (15 ft.) as was given to the students. Therefore, most students should be able to achieve an output voltage at least as high with 30 feet of wire. The open-circuit output voltage recorded by the instructor's generator with only 15 ft. of wire was 300 mV. Students receive a prorated amount of performance-based points based on their generator's performance relative to the instructor's generator. If the student's generator produces a higher output voltage than the instructor's generator, then the students receive extra credit (via a separate extra-credit calculation). The rubric for the project is given in Table 3.

Table 3. Rubric for generator construction project

Item	Description	Points
Performance	$25 \times \frac{\text{your generator's peak output voltage}}{300 \text{ mV}}$	/25
Instructor Evaluation	The design of the generator should show evidence of 1) an understanding of generator operating principles, 2) quality of construction, 3) durability and reliability. If you wish, you may submit one page of notes/sketches/description along with your generator for the purpose of demonstrating the operating principles of your generator.	/75

It is evident from Tables 1 and 2 and Figures 4 and 5 that most students were able to achieve the 300 mV performance threshold. Therefore, in the future the instructor may consider raising the output voltage goal, and/or increasing the weighting of the objective performance in the assessment of the project.

Evidence of Student Learning

Because the generator project was introduced in the first semester that TEC 259 was taught, there is no way to compare learning outcomes from before and after the project was introduced into the course. However, there is another course in the same department that is taught by the same instructor. This second course is called *TEC 240: Electrical Circuits and Machines*, and it also includes a section of the course devoted to generators and alternators. However, the TEC 240 course does not include the hands-on generator construction task. Therefore, comparing the student performance on exam questions relevant to generator theory and generator design could be a good way to compare the effectiveness of these two instructional approaches: one with a hands-on generator construction activity, and one without. There was no overlap in students between the two courses (for example, students did not take one course followed by the other). Both courses spent a similar amount of time covering generators, and very similar homework assignments were given in both classes.

To compare student exam scores only on questions relevant to generator theory and generator design, the tests from the most recent sections of both classes were reviewed (unfortunately, question-level exam details are not available for course sections prior to the ones reviewed). Because there is overlap in the material covered by these two courses, there is also overlap in the exam questions. In many cases, only the numbers were changed between the questions on the exams in the two courses. Some examples of exam questions that were asked on both exams include calculation problems involving Faraday's Law, drawing diagrams of

magnetic fields, and applying Fleming’s “Right Hand Rule” for generator action. All questions that were asked on the exams that were not directly related to generator principles were excluded from further analysis. A summary of results is given in Table 4.

Table 4. Summary of generator-related exam question scores

Course	<i>n</i> (number of students)	Number of generator-related exam questions	Score on generator-related exam questions
TEC 240 (without generator construction activity)	22	7	71.8%
TEC 259 (with generator construction activity)	18	11	77.4%

As can be seen in Table 4, the score on generator-related exam questions was higher in the course that included the generator construction activity. This is probably because the students were consciously or even subconsciously thinking about generator operating principles as they designed, built, tested, and iterated their generator. In order to meet the design objective of the generator project, students were forced to make sense of Faraday’s Law and apply it as they constructed their own machine, rather than simply plugging numbers into the equation in homework problems.

Conclusions and Students’ Lessons Learned

After discussion with the students following the project, most students seem to have legitimately enjoyed the experience of building and testing their own generator. Some students have kept their generators at the end of the semester as mementos of their accomplishments. Some of the most salient instructor observations from the project include:

One of the first design decisions that students must make is whether to use the permanent magnets provided to them, or a wound magnetic field instead. During the course the instructor describes a multitude of different alternator and generator designs. Because of the inherent simplicity of the permanent magnet generator design (and the fact that they are provided with permanent magnets), all students thus far have chosen to build permanent magnet designs. The second design choice that students must make is whether to place the magnetic field of the machine on the rotor or the stator. Most students have chosen to place the permanent magnets on the rotor and the armature windings on the stator. This eliminates the need for the students to build slip rings. However, some students have successfully built designs with the armature placed on the rotor using makeshift slip rings.

The concept of the “rate of change of magnetic flux” (given by the derivative in Eqn. (1)) is a difficult concept for many students to grasp. It is difficult for two reasons: first, the concept of a derivative is not always firmly etched in all student’s minds. Second, magnetic flux itself is difficult to envision, because it is not a tangible object. Putting these two concepts together,

therefore, is challenging for many students. To help students understand these concepts, the instructor invests time in class discussions about what each of them mean.

If they have not already understood the $\frac{d\Phi_B}{dt}$ term in Eqn. (1) before they begin constructing their generator, then the students quickly begin to understand the meaning of the term once they begin experimenting with generator designs. Students quickly realize that the generator output voltage increases proportionally to the speed of the generator's rotor, which in turn depends on the rotational speed of the drill. The output voltage increases as the rotor speed increases because the rate of change of the magnetic flux through the generator coil(s) increases.

Also related to the derivative term in Eqn. (1) is the strength of the permanent magnets in the generator design. Students are given two pairs of permanent magnets: a pair of two ceramic magnets, and a pair of two neodymium magnets. Through experimentation, students learn that the neodymium magnets produce a stronger magnetic field. As the stronger magnetic field rotates on the rotor of the generator, the rate of change of magnetic flux through the wire coil is greater, resulting in a higher peak output voltage than would be achieved by the same generator design utilizing the ceramic magnets. In addition to the strength of the magnetic field, students also find that in order to maximize the derivative term in Eqn. (1) that it is necessary to place the rotating magnetic field as physically close as possible to the stationary coils of wire. This requires careful construction of the machine so that the components do not interfere as the rotor rotates. Because they are quite brittle, it is not uncommon for the neodymium magnets to break in half if the stationary components of the alternator interfere with the rotating neodymium magnets.

Students that begin their generator construction process early and are thus able to iterate their design almost always eventually achieve higher output voltages than students who wait to begin their construction until shortly before the due date. Although this is a self-evident truth for most coursework, it is particularly true for this project because the concepts are challenging to grasp. It is therefore rare for students to "get it just right" on their first construction attempt.

Another concept that students pick up on is the effect of adding more turns of wire to the coil of their generator windings. As seen from Eqn. (1), the number of turns in the coil is directly proportional to the output voltage. Because the length of wire given to the students is a fixed length (30 feet), they soon realize that to increase the number turns in the coil, the coils need to be tightly wound in a small diameter. This is one way that some of the students have achieved output voltages greater than 1.0 Volts, as shown in Figures 4 and 5.

The generator construction project has proven to be a popular activity with students. Students have repeatedly commented that the project was their favorite activity in the class. From an instructor's standpoint, it is rewarding to watch students engage in healthy competition as they seek to build the highest-performing generator. In the two sections that the course has been offered so far, six students (out of 39 enrolled in the courses) have achieved output voltages greater than 1.0 volts. This is truly impressive performance, and required significant time and

dedication. In addition, the project has had a positive effect on exam performance related to generator theory and design. This is shown by the increased scores on generator-related exam questions for this course as compared to a similar course where a generator construction project is not part of the course activities. It seems apparent that this project has engaged students and enabled them to better understand the theory and operation of electric generators.

In future years, this project could be expanded to include several new factors. For example, a cost could be assigned to each material that is provided. The objective for the students could be to design the highest-performing generator possible with the lowest cost achievable. Another possible extension is to measure the real-time power produced by the generator over a given time interval, and then compare the energy produced by the generator over the specified time interval. This could replace the current metric, which is the peak open-circuit voltage. The energy produced by the generators will likely be very small, but it should be able to be measured with data acquisition systems and Labview software. If the energy consumed by the electric drill is also measured, then the conversion efficiency of the generator could be calculated as well.

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