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Teaching Protective Relaying Concepts and Testing Methods

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Teaching Protective Relaying Concepts and Testing Methods

Abstract

This paper covers problems inherent in teaching electrical power system protective relaying concepts and testing methods at the associate degree level in an electrical engineering technology program. In many cases, these problems are also seen at the baccalaureate level in both electrical engineering and electrical engineering technology. The first, and most difficult obstacle is symmetrical components. The mathematics behind symmetrical components involve complex numbers and linear algebra. While the students are exposed to complex numbers in their AC analysis course and, if required by their program, their electrical machinery course, most of the students have not had a linear algebra course. Another obstacle is power system stability. At best they may have a classical controls and/or dynamics course. This is why in most cases protective relaying is taught at the graduate level or via industrial seminars. Without a background in protective relaying concepts, the testing of the protective relay becomes very prescriptive. The student only learns the specific steps outlined by the relay manufacturer, or in some cases the textbook author, to determine if the relay performed one function correctly.

Most utilities and electrical power system operators need protective relay technicians that understand the electrical power system and how the protective relays function to protect the system in the case of abnormal operating conditions. Simply knowing the output X was set when input Y reached a certain level is not sufficient. The methods used to cover protection of generators, transformers, transmission lines, and busses are discussed. The level of detail in symmetrical components: how they are derived, how they can be recombined to form phase quantities; along with what are the characteristics of the different sequence values and what sequence quantities are associated with the different fault types are covered. Finally, zones of protection, communication between protective relays, and the subsequent effect on system integrity are also discussed.

Introduction

This paper describes the problems encountered in teaching a protective relaying course at the sophomore level of an associate engineering technology degree, and offers examples on how those obstacles can be overcome. The course is offered at Northern Michigan University (NMU) as part of the two-year Electric Power Technician Program. This program was developed in response to the needs of local industry and as an offshoot of the successful Electrical Line Technician Program[1]. While the Electrical Line Technician Program (Line Tech) is a pre-apprenticeship, two-semester diploma program; the Electric Power Technician Program (Power Tech) is a two-year, associate degree program. Courses taken in the associate degree program are transferable into a four-year Electrical Engineering Technology baccalaureate degree program.

Background

ET-280 Protective Relay Systems is taken the second semester of the student's second year in the two-year Power Technician Associate Degree Program at NMU. This course looks at protective relay systems that are used to insure dependable distribution of electrical power. The system is developed from the basics of relay operation to modern communication-based relay tripping. Before taking this course, the student has taken courses in AC and DC analysis, an introduction to electrical power systems (all in their first year); transformers and, generally, three-phase power equipment (in the first semester of their second year). All of the courses in the two-year associate degree transfer into a four-year baccalaureate degree, so some of the students continue. Also, some of the students in the four-year program take this course as an elective.

Assessment

The student learning objectives of the course are that upon successful completion of the course, the student will be able to:

1. Understand and be able to calculate values using the per unit system
2. Understand and be able to calculate values using symmetrical components
3. Determine the operating characteristics and proper application of auxiliary transformers used with protective relays
4. Contrast the different types of bus protection schemes and determine the operating characteristics and application of each type
5. Understand the application distance relays and zones of protection

For assessment of the course learning objectives, a metric of 75% passing of the topic areas was used. Winter 2015 was the first time the course was taught by the author (previously, adjunct faculty had taught the course). The class size was small, with only eight students. Almost all the students met this criteria for all areas on the assessment tool (questions on the unit and final exams). The one exception was that one student did not meet the requirement for fifth learning object. Two example questions (specifically for learning objectives 4 and 5, respectively) are shown below:

> For each of the bus arrangements given, draw a one-line diagram showing the bus, circuit breakers, CTs, VTs, and disconnects (including normally open or closed, NO or NC, status). On the completed diagram, show the protection zones.
>
> a. Single bus – single breaker arrangement with three circuits (lines)
> b. Double bus with bus tie – single breaker arrangement with two circuits on Bus A and three circuits on Bus B
> c. Main and transfer bus – single breaker arrangement with four circuits
> d. Ring bus arrangement with four circuits
> e. Breaker and a half arrangement with four circuits

Given a transmission line distance relay with the characteristics shown below. The time delay for Zone 2 is 0.3 seconds.

a. What would happen (will the relay trip, if it does, when will it trip, and why) if the voltage is 50 V at an angle of zero and the current is 20.0A at an angle of -75° for 0.5 seconds?

b. What would happen (will the relay trip, if it does, when will it trip, and why) if the voltage is 70 V at an angle of zero and the current is 10.0A at an angle of -75° for 0.5 seconds?

c. What would happen (will the relay trip, if it does, when will it trip, and why) if the voltage is 70 V at an angle of zero and the current is 10.0A at an angle of -75° for 0.2 seconds?

d. What would happen (will the relay trip, if it does, when will it trip, and why) if the voltage is 60 V at an angle of zero and the current is 5.0A at an angle of -30° for 5 seconds?

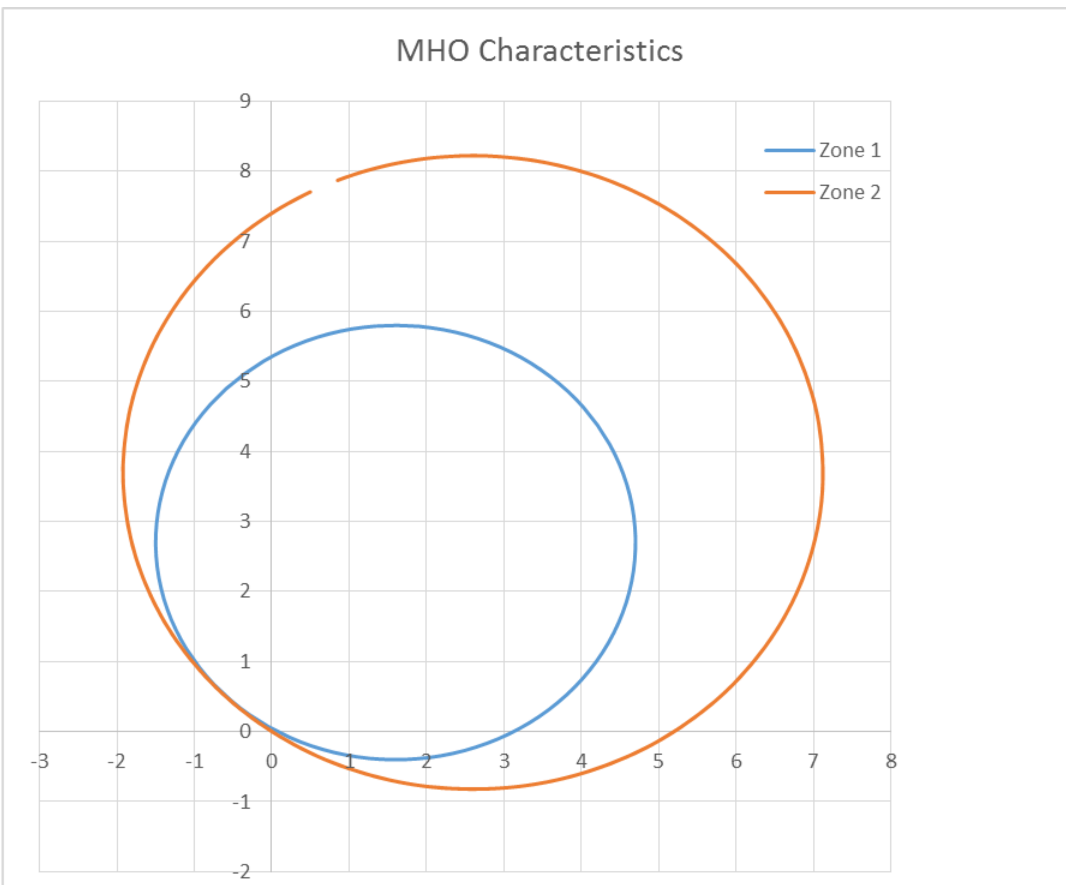

Figure 1. Mho Characteristic for Sample Question

The results for each student and each objective is given in the table below.

Table 1. 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%

For Winter Semester 2016, the class size has increased to 12 students. While the analysis has not been completed, preliminary results are similar to Winter Semester 2015. Feedback from the students to assure correlation to performance in the workforce will be the next step.

Course Content

As with many courses on this topic, Protective Relaying: Principles and Applications, 4th Edition by J. Lewis Blackburn and Thomas J. Domin is the required textbook[2] for the course. The lecture topics for the course include:

1. System Protection Overview
2. Per unit and percent values
3. Phasors and Polarity
4. Introduction to Symmetrical Components
5. Sequence elements and networks
6. Sequence fault calculations
7. Relay inputs
8. Basic Design Principles
9. Generator or Intertie Protection
10. Transformers
11. Reactors
12. Capacitor Banks
13. Bus Protection
14. Line Protection
15. Pilot Protection
16. Stability

Symmetrical Components

The first, and most difficult obstacle for the students to overcome is symmetrical components. The mathematics behind symmetrical components involve complex numbers and linear algebra.

While the students are exposed to complex numbers in their AC analysis course and, if required by their program, their electrical machinery course, most of the students have not had a linear algebra course. To overcome this problem, graphical analysis is used. The process is as follows:

- Define the sequence components:
  - Zero Sequence is a set of three vectors all of the same length with each pointing in the same direction.
  - Positive Sequence is a set of three vectors all of the same length and separated each by 120 degrees. The order of the vectors is A B C.
  - Negative Sequence is a set of three vectors all of the same length and separated each by 120 degrees. The order of the vectors is A C B.
- Claim that any unbalanced set of three-phase voltages and currents can be converted into three balanced sets of zero, positive, and negative sequence quantities.
- Show graphically that an unbalanced set of three-phase voltages or currents can be broken into sequence components by adding up the individual components to get the phase values. An example is given in the following figures. In the figures that follow the abscissa is the real part of the complex voltage phasor and the ordinate is the imaginary part of the complex phasor voltage.

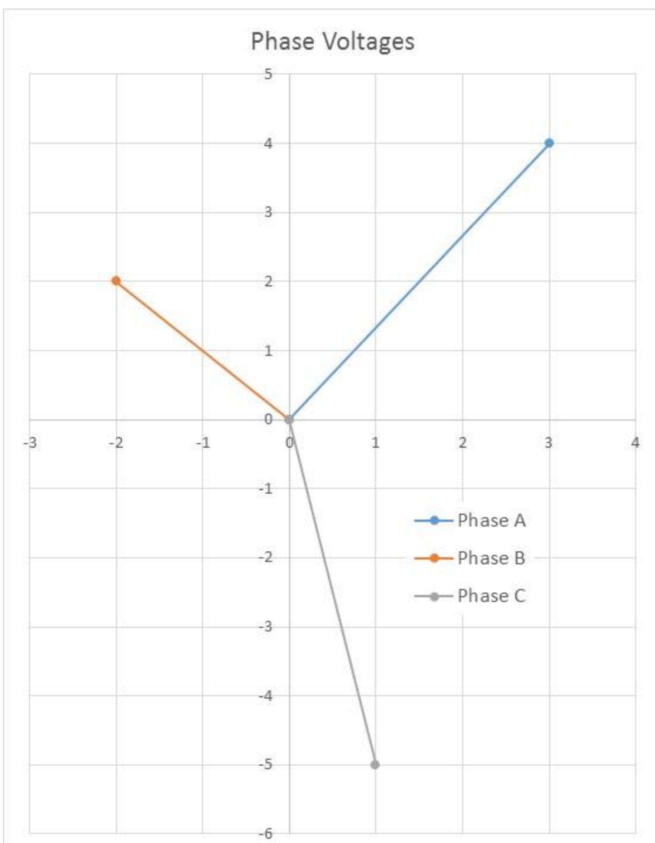

Figure 2. Unbalanced Phase Voltages

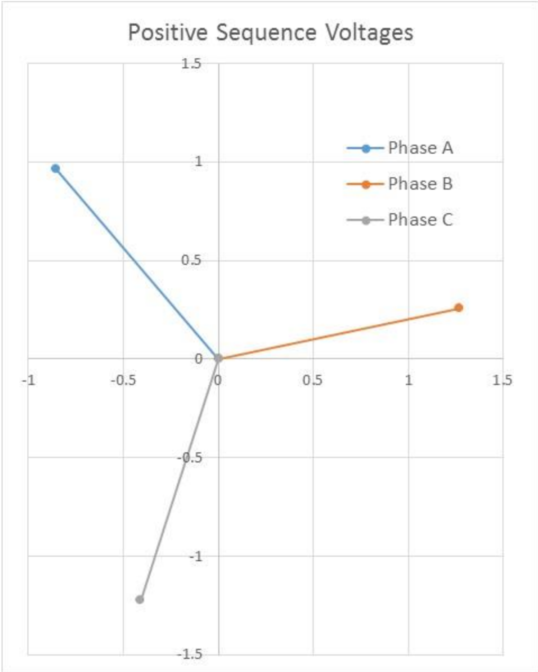

Figure 3. Positive Sequence Voltages

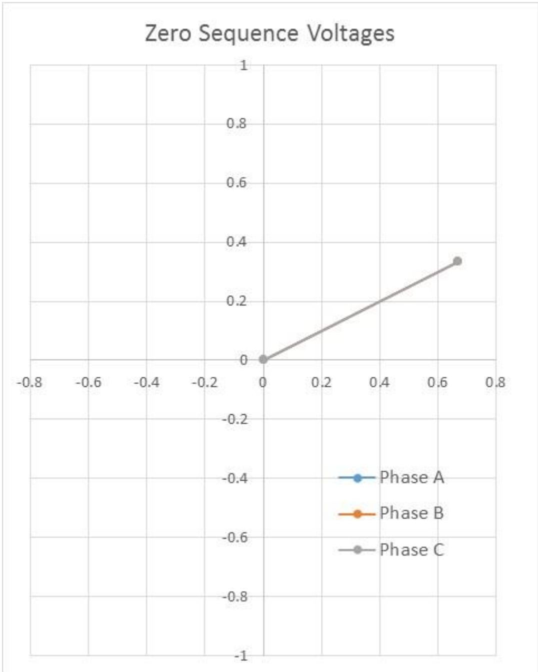

Figure 4. Zero Sequence Voltages

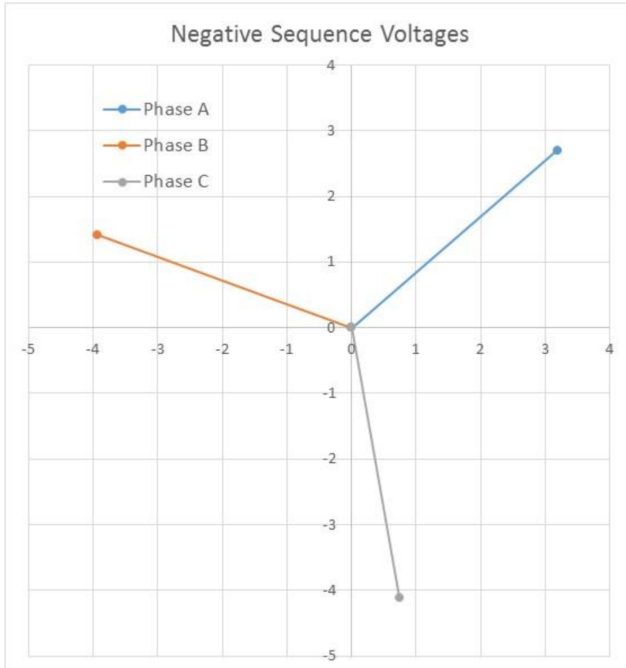

Figure 5. Negative Sequence Voltages

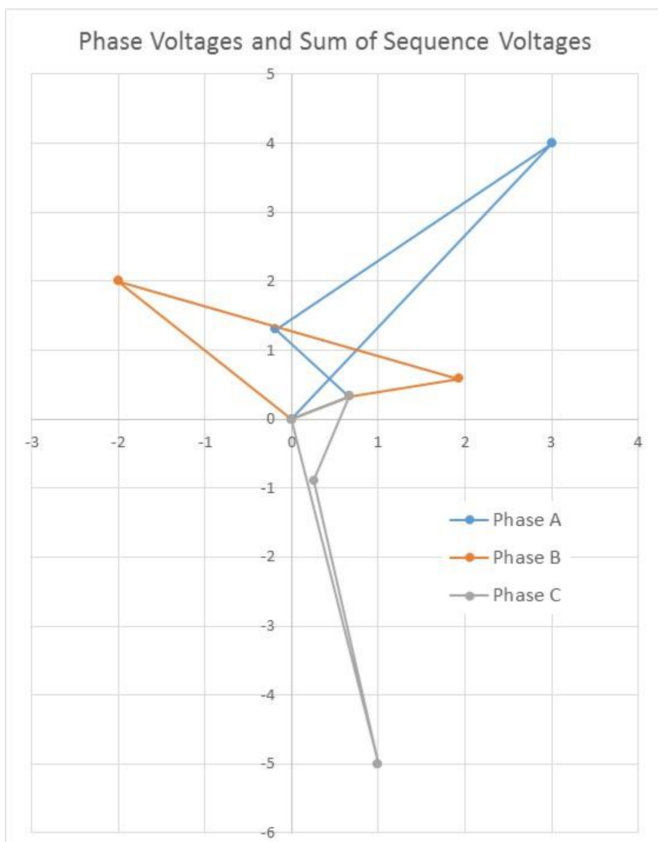

Figure 6. Phase Voltages and Sum of Sequence Voltages for Each Phase

Once the students have a clear grasp of what symmetrical components are, sequence networks are introduced. A three-phase circuit with a single-phase fault is solved using the methods the students learned in AC analysis, and then solved via symmetrical components and sequence networks. The sequence network interconnection for double line, double-line to ground, and three-phase faults are then presented.

Power System Stability

Another obstacle is power system stability. At best the students may have had a classical controls and/or dynamics course. In the ET program at NMU, our controls course is usually taken in the final semester of the fourth year, so typically none of the students have taken this course. Again, graphical methods are used here. One method is to show the generator rotor angle increasing without bound. Another method is to use the equal area criterion. An example is given below:

> Using the equal area criterion, determine if the system will be stable if the mechanical power suddenly changes from $P_1 = 1.5$ pu to $P_2 = 4.5$ pu. The generator has an internal voltage of 1.3 pu and is attached to an infinite bus with a voltage of 1.05 pu. The total impedance from the generator to the infinite bus is 0.25 pu.

The solution is shown in Figure 7. First the area between the green power curve and blue P_2 line starting where the red P_1 line crosses the green generator power curve is found. This is the acceleration area. This area is then compared to the area above the blue P_2 line and below the green generator power curve. This is the deceleration area. If the deceleration area is greater than the acceleration area, the system is stable.

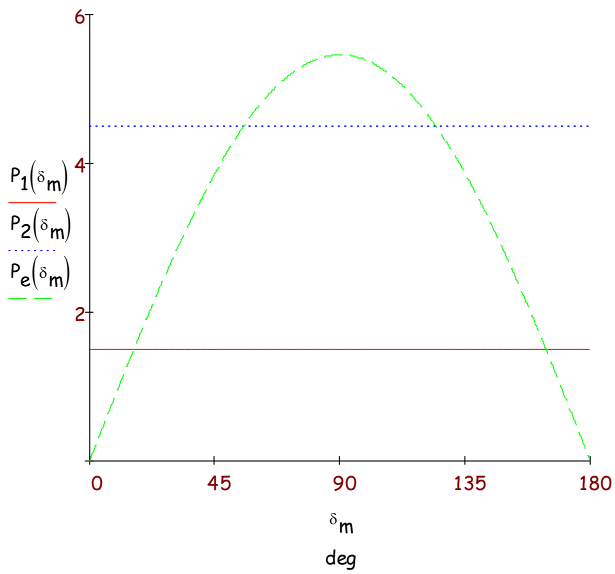

Figure 7. Example of the Application of the Equal Area Criterion

Protective Relay Testing

Most utilities and electrical power system operators need protective relay technicians that understand the electrical power system and how the protective relays function to protect the system in the case of abnormal operating conditions. Simply knowing the output X was set when input Y reached a certain level is not sufficient. Because of this, relay schemes for the protection of generators, transformers, transmission lines, and busses are discussed and detailed examples are given. In addition, zones of protection, communication between protective relays, and the subsequent effect on system integrity are also discussed. In the Winter Semester 2015 offering of the course the students were given laboratory projects where they used a Doble F6150e Power System Simulator to test either a Schweitzer Engineering Labs SEL-221F microprocessor-based relay or a Westinghouse (ABB) Type CO electromechanical relay. The test setup for testing the SEL -221F is shown in Figure 8 below.

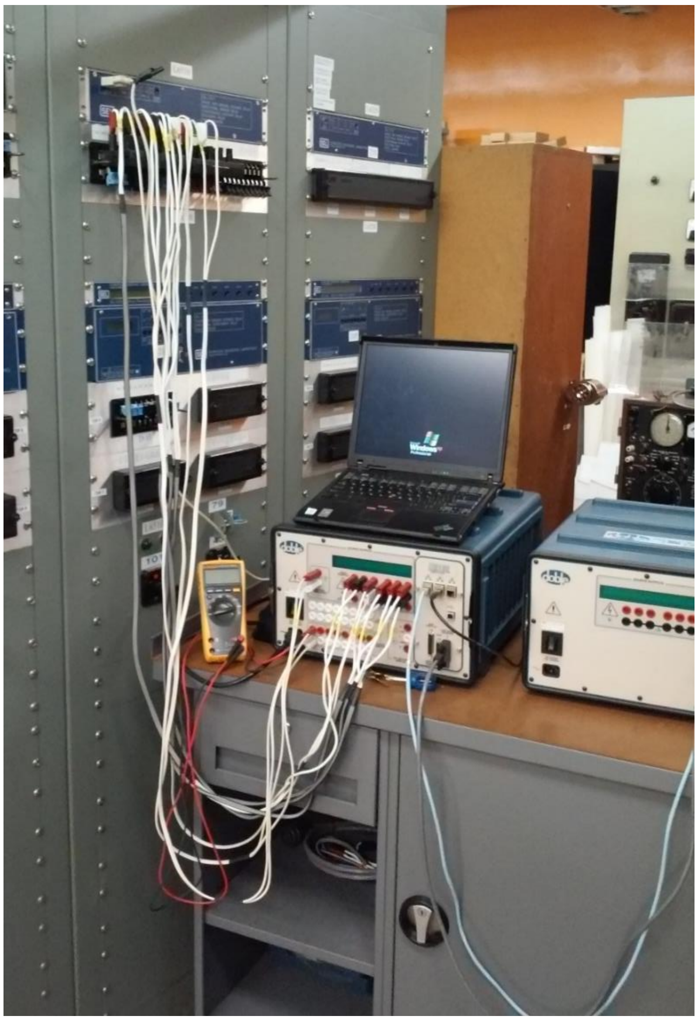

Figure 8. Protective Relay Testing Lab Setup

Based on employer input, the electromechanical relays were not included in the Winter Semester 2016 lab assignments, and will not be included in the future. Also based on employers' comments, the students performed the tests individually rather than in teams. This allowed the students to gain experience in all aspects of testing – setting parameters on the relay, connecting the test leads, developing the test plan in the Doble software, and running the tests. Based on preliminary feedback, the students also prefer this arrangement. The only drawback to this is coordinating individual student testing times, since setup and running the tests can sometimes take two hours (more if the students run into problems).

In the future, the plan is to add SEL-321 relays (already in the lab) along with a SEL-311 (in the process of being donated by a local utility), to match the protection schemes of local utilities. While this lab is similar to laboratories at some universities[3], it does not have the advanced communication capabilities or other advanced features of some of the premier laboratories[4, 5].

Conclusions

The teaching of protective relays at the associate engineering technology degree level is a daunting task. Symmetrical components: how they are derived, how they can be recombined to form phase quantities, what are the characteristics of the different sequence values, and what sequence quantities are associated with the different fault types are usually covered in a senior-level electrical engineering course, or at the graduate level. Using graphical techniques, this material is made accessible to sophomore level students. Similarly, graphical techniques can be used to explain system stability. Once they have this knowledge, the students can more easily understand the reasons behind the protection schemes they are testing.

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