Practical Power Systems Protection – Course Model

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Abstract

In this paper, a new senior-level Electrical Engineering course in power systems is presented. The demand for this course was first identified by the career service office in a form of feedback obtained from employers and students returning from their co-op and internship assignments. This course is designed to provide strong theoretical and applied knowledge in solid-state relays and protection topologies used in today's power systems based on recent advances in this field. In this course, students perform calculation of short-circuit currents, fuses ratings, circuit breakers, tripping batteries, and relays. Moreover, protection design parameters on medium and low-voltage networks under various system disturbances with sequence coordination involving transformers, switch-gears, and motors will also be covered. Several case studies are embedded in this course including a laboratory component to provide students with real-world applications. Finally, a syllabus outlining the course objectives, topics covered, and the student learning outcomes are also presented in this paper.

Keywords

Protection, Course, Power, control, relays.

Introduction

Power system protection is important especially for students interested to work in the power sector. Sufficient background in all aspects of power systems is required to understand modern power protection and technologies which include extensive hands-on experience in system stability and protection[1,2]. A new course to enhance the power systems concentration in the Electrical Engineering (EE) program at Georgia Southern University (GSU) is presented in this paper. The aim is to introduce students to modern topics in power systems' protections and controls in a senior level course. This 4-credit hour course is designed to satisfy EE elective requirements for students with concentration in power systems. What is unique about this course is that it can fill the technical needs expressed by regional power companies seeking to hire our EE graduates. This need was first identified by the career service office at GSU through feedback from employers and students returning from their co-op or internship assignments. Therefore, faculty of the EE department have seized this opportunity to develop a course to address advanced topics in power systems. These advanced topics primarily deal with system protection and relaying apparatus under various system faults or disturbances. Methods and devices used for system protection such as relays, pilot wires, machines protection, buses, lines, and instrument transformers are usually covered at the senior level in a typical EE program. Therefore, students who complete this course will obtain the skills and technical expertise highly desirable for power engineers.

The ABET accredited EE program at GSU is a relatively new program that was established in 2011. Students enrolled in this program can choose one of four different concentrations currently available in the curriculum. The power systems concentration consists of a sequence of core courses that include electric machines and power systems fundamentals followed by two advanced elective courses in power systems. These electives include Power Electronics, Smart Grids Fundamentals, and the Power System Protection course that is presented in this paper. This course is viewed as an important step towards integrating and strengthening the power system concentration of the EE program. In the following, a brief description of this course sequence is presented.

Electric Machines: The concepts of electric machines and their operational characteristics are covered with emphasis on different types of DC/AC motors and generators including single-phase and three-phase transformers. Finally, an overview of the latest generation machines is introduced. The course also includes laboratory activities to support the instruction.

Power Systems Fundamentals: This course is designed to introduce students to the basic concepts of electric power systems. Single-phase and 3-phase networks, electric power generation, transformers, transmission lines, and power flow analysis including stability and fault analysis are thoroughly covered. Additional topics addressing conventional energy sources, electricity market, and regulations affecting the power sector are introduced and discussed. Students are expected to perform power flow simulation using Power World Software and/or other professional programming tools for power system studies.

Power Electronics: This course provides basic knowledge of power Electronics device characteristics and circuits for the control and conversion of electrical power with high efficiency. This course discusses converters the can change and regulate the voltage, current, or power such as dc-dc converters, ac-dc uncontrolled and phase controlled rectifier circuits, dc-ac inverters, and ac-ac cyclo converters. Applications include electronic switching power supplies, motors, heater systems, and renewable energy systems. Analysis, design, and operation of power electronic circuits are covered by simulation software and laboratory experiments. This course provides students with a theoretical and practical background in power electronic devices and circuits, along with the engineering analytical and design skills.

Smart-grid Fundamentals[5]: The course is designed to introduce new topics related to distributed generation, micro-grids, renewable energy sources, and smart homes applications to students. Topics covered include design, modeling, control, and analysis to provide students with working knowledge of smart-grid systems. Furthermore, concepts dealing with computational intelligence, decision support systems, smart metering, optimization, and renewable energy sources are presented. The automation and computational techniques used to ensure smart-grid are also introduced and discussed. The laboratory component associated with this course provides students with the hand-on experience in the utilization of smart-grid technologies and equipment.

Therefore, this course fits the overall objective of providing a well-rounded education and enable students to build a solid background in all aspects of power systems. When developing this course, an intensive search was conducted to explore similar power systems courses offered at other universities. What is unique about our EE program is having embedded laboratory component in most courses within the curriculum. This has the advantage of blending theory with practice so students can immediately gain hands-on experience and reinforce concepts being learned.

System Protection Description

When dealing with engineering problems, trade-offs between reliability, selectivity, speed, simplicity, and economy are considered in any practical applications assuming different options. The first option is to implement a robust system of components that requires minimal maintenance. The second option is to predict all possible failures that may occur in order to design around these failures[1]. The protection system must have several features such as to provide: selectivity in the sense to detect and isolate the faulty item; stability to ensure continuity or supply; sensitivity to detect even the smallest abnormalities; and speed to operate quickly when needed[1,2].

A typical topology of a power system protection chain is shown in Figure 1. It covers the complete protection scheme from the main power systems[1,4].

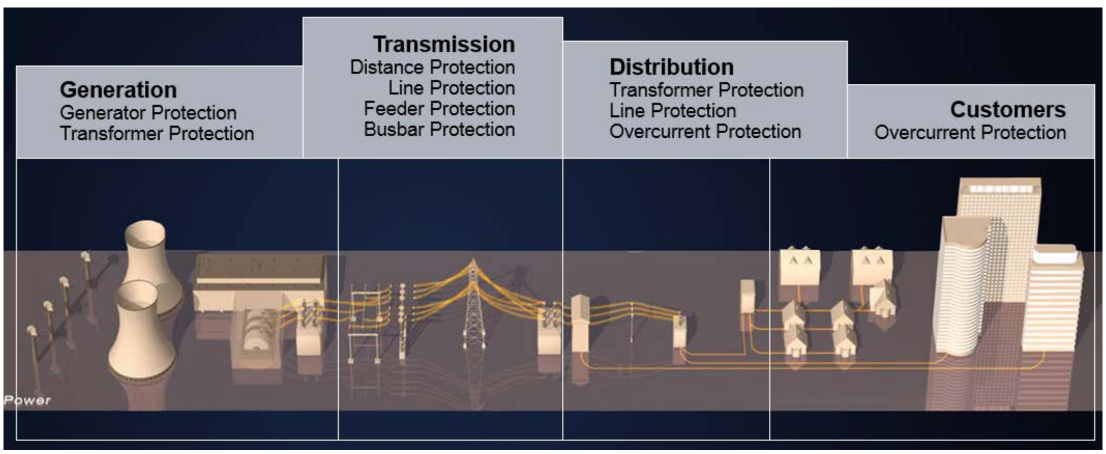

Figure 1- Complete Power System Protection Chain[4]

The logic representation of an electric relay is presented in Figure 2. There are several basic components of protection. For instance, fuses are self-destructing devices and are normally independent or stand-alone protective components in an electrical system unlike a circuit breaker. Voltage and current measurements give feedback to whether a system is operating under normal conditions or not. Measured values are converted to analog or digital signals intended to operate the relays and isolate the circuits. Time is another important factor when opening faulty circuits. Circuit breakers carry the fault currents until they are totally cleared. The operation of relays and circuit breakers require power sources that should not be interrupted by the faults in the main distribution. Radial system distributions offer the advantage of isolating faults that occur within one radial branch so other consumers are not affected. The disadvantage of this system is that when a radial conductor fails, supply to this particular consumer is completely lost and cannot be restored until the conductor is repaired or replaced.

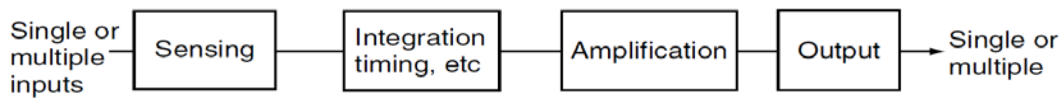

Figure 2- Logic representation of an electric relay

A typical single-line AC connection of a protective relay with DC trip circuit is illustrated in Figure 3. As shown, the CS seal is not required for modern circuit breakers equipped with solid-state units and lower-trip circuit currents[2,3]. The most favored type is the ring system in which each consumer has two feeders connected in different paths to ensure power continuity. The main drawback is that fault current is fed via two parallel paths which essentially reduce the impedance from the source to the fault location and the fault current is much higher when compared to the radial system [1-3].

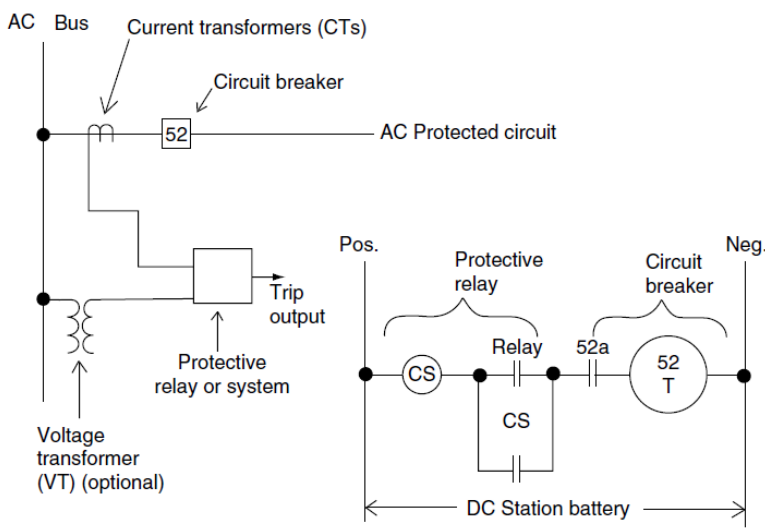

Figure 3- Typical single-line AC connections of a protective relay with its DC trip circuit [2,3]

Specific designs and features vary widely with application requirements, different manufacturers, and the time required for each particular design. Originally, all protective relays were of the electromechanical type. Electromechanical type relays are still in widespread use and continue to be manufactured [1-4]. Figure 4 shows a typical 3-phase system protection scheme with a set of ground relays which can either be separated or combined together in one unit[1].

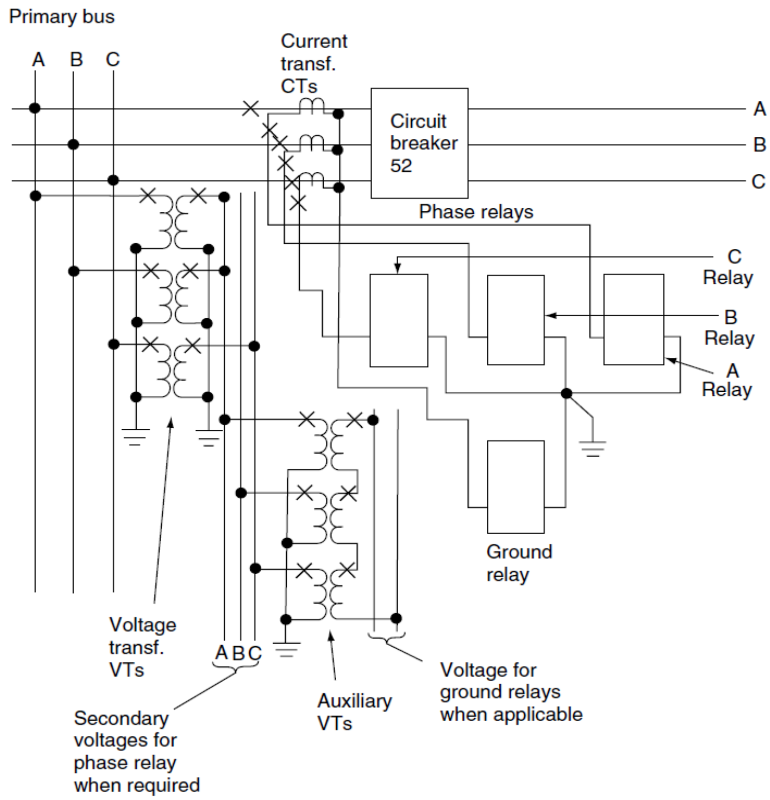

Figure 4- Typical three-phase AC connections of a set of phase and ground relays[1]

Moreover, a distance relay has the ability to detect a fault within a pre-set distance along a transmission line or power cable from its location. As shown in Figure 5, every power line has a resistance and reactive impedance per Kilometer as a function of length or distance.

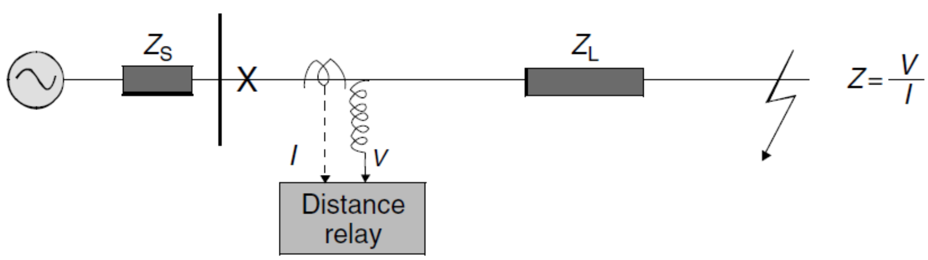

Figure 5- Basic principle of distance relay operation[1,4]

For illustration purposes, a complete schematic consisting of a busbar, feeder, transformer, and motor protection is shown in Figure 6.

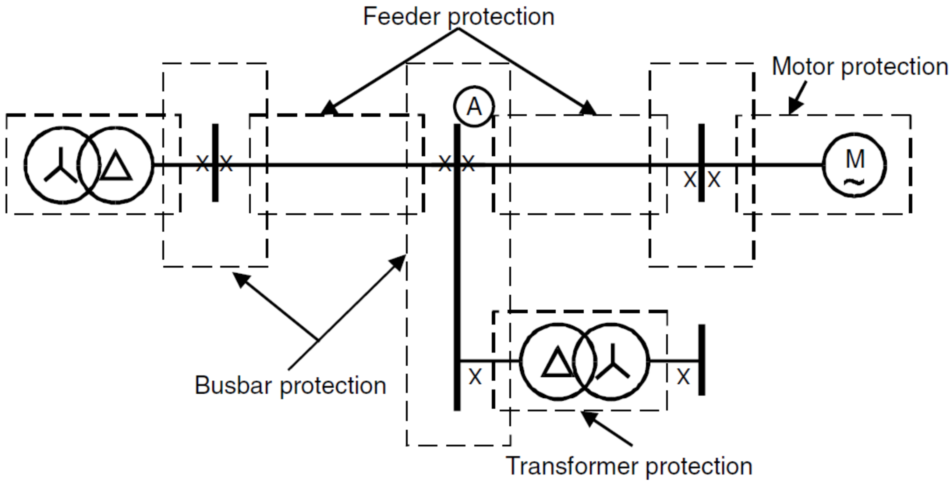

Figure 6- Overall schematic indicating busbar, feeder, transformer and motor protection

Course Description

As mentioned earlier, this course is intended to be offered at the senior level as an undergraduate EE elective which can also be dual-offered with the graduate level. This 4-credit hour course is designed to be taught as a 3-hours lectures and 2-hours laboratory component per week. The catalog description of this course is given as follow:

Power Protection: This course offers a comprehensive study of methods and devices used in power system protection including relay types and responses, pilot wire and carrier systems, transmission lines and transformers, machines protection, and modern trends in protection technology. After reviewing the need for protection of power system elements, the course proceeds to explore the development and regulations of smarter, more flexible protective systems applied to modern power grids. Students learn the trade-offs between reliability, selectivity, speed, simplicity, and economy using real world case studies. A hands-on lab project, using state of the art equipment, is also completed during the course.

The educational objectives of this course enables students to demonstrate knowledge and understanding of:

- The various types of protection systems.
- The types of protective relays.
- Performance and design calculations for transformers and generator protection schemes.
- Instrument transformer design and selection.
- Types of protective devices and their choices.
- Unit and non-unit protection systems.
- Appreciate the importance of protective relays in power systems.
- Compare and contrast the operation of different types of protective schemes.
- Derive equations related to the different protection methods.
- Formulate relevant equivalent circuits of the protection schemes to calculate their actual behavior.

- Identify different types of protective relays and their applications.
- Analyze simple problems related to protection schemes.
- Choose among the different types of protection schemes to suit a given application task.
- Explain the operation and performance of different types of protective relays.
- Apply engineering studies for different types of power system protection.

Topics covered in this course include the following:

- Fundamental concepts of protection, protection schemes for various power system configurations.
- Review on fault current calculations: study of sequence components, symmetrical and unsymmetrical faults.
- Protection devices: fuses, circuit breakers, relays; operating principles, device rating determination, relay setting and coordination.
- Instrument transformers (CTs and VTs): selection, transient performance. Distance protection; Differential protection; Overcurrent protection and its coordination; Directional overcurrent protection.

The course contents consist of the following:

1. Introduction to power system protection
2. Review on fault analysis
3. Relaying: operating principles
4. Current and voltage transformers and circuit breakers and fuses
5. Overcurrent protection and its coordination
6. Directional overcurrent protection
7. Differential overcurrent protection
8. Distance protection
9. Islanding detection, distributed and renewable power generation protection and load shedding
10. IEC61850 based substation automation including protection

Topics covered are organized on lecture basis as follows:

<u>Module 1</u> : Fundamentals of Power System Protection

- **Lecture 1** : Introduction
- **Lecture 2** : Protection Paradigms - Apparatus Protection
- **Lecture 3** : Protection Paradigms - System Protection
- **Lecture 4** : Desirable Attributes of Protection

<u>Module 2</u> : Current and Voltage Transformers

- **Lecture 5** : Introduction to CT
- **Lecture 6** : CT Tutorial
- **Lecture 7** : CT Saturation and DC Offset Current

- **Lecture 8** : Introduction to VT
- **Lecture 9** : VT Tutorial

Module 3 : Sequence Components and Fault Analysis

- **Lecture 10** : Sequence Components
- **Lecture 11** : Sequence Components (Tutorial)
- **Lecture 12** : Sequence Modeling of Power Apparatus
- **Lecture 13** : Sequence Modeling (Tutorial)

Module 4 : Overcurrent Protection

- **Lecture 14** : Fuse Protection
- **Lecture 15** : Fundamentals of Overcurrent Protection
- **Lecture 16** : PSM Setting and Phase Relay Coordination (Tutorial)
- **Lecture 17** : Earth Fault Protection using Overcurrent Relays

Module 5 : Directional Overcurrent Protection

- **Lecture 18** : Directional Overcurrent Relaying
- **Lecture 19** : Directional Overcurrent Relay Coordination (Tutorial)
- **Lecture 20** : Directional Overcurrent Relay Coordination in Multi-loop Systems

Module 6 : Distance Protection

- **Lecture 21** : Introduction to Distance Relaying
- **Lecture 22** : Setting of Distance Relays
- **Lecture 23** : Pilot Protection with Distance Relays

Module 7 : Out of Step Protection

- **Lecture 24** : Power Swings and Distance Relaying
- **Lecture 25** : Analysis of Power Swings in a Multi – Machine System
- **Lecture 26** : Power Swing Detection, Blocking and Out-of-Step Relays

Module 8 : Numerical Relaying I : Fundamentals

- **Lecture 27** : An Introduction
- **Lecture 28** : Sampling Theorem
- **Lecture 29** : Least Square Method for Estimation of Phasors - I
- **Lecture 30** : Least Square Method for Estimation of Phasors - II
- **Lecture 31** : Fourier Algorithms

Module 9 : Numerical Relaying II : DSP Perspective

- **Lecture 32** : Fourier Analysis
- **Lecture 33** : Discrete Fourier Transform
- **Lecture 34** : Properties of Discrete Fourier Transform

- **Lecture 35** : Computation of Phasor from Discrete Fourier Transform
- **Lecture 36** : Fast Fourier Transform
- **Lecture 37** : Estimation of System Frequency

Module 10 : Differential Protection of Bus, Transformer and Generator

- **Lecture 38** : Bus Protection
- **Lecture 39** : Transformer Protection
- **Lecture 40** : Generator Protection

Weekly hands-on experience is conducted using computer simulation and experimental laboratories. Modeling involves using simulation tools such as MATLAB, Power Systems toolbox, Simulink, Power World, and LabVIEW. Teaching methodology used include "smart" classroom to deliver lectures and interactive practice examples. Students are required to work independently on homework assignments and exams. Oral and/or written presentations are assigned toward the end of the semester. Potential student research projects will mainly be dealing with topics related to power system stability for distributed generation, different types of alternative energies (Solar, Wind, Hydro, Fuel Cell, etc.), or hybrid control of these systems with the aid of artificial intelligence. Other topics may include new technology for smart inverter, smart relays, system optimization, PMUs, dynamic transmission lines problems, new flexible ac transmission problems, and finally some implementation protection devices. The laboratory component of the course employs commonly used tools to formulate and solve engineering problems.

Typical course materials consist of the following textbook and reference books:

- L. Hewitson, M. Brown, B. Ramesh and S. Mackay, "Practical Power Systems Protection," Elsevier, Amsterdam, 2004. (Textbook)
- P. M. ANDERSON, "Power System Protection", Wiley, 2012. (Reference Book)
- Power Systems Stability and Control, Edited by Leonard L. Grigsby, CRC Press, Second Edition 2007. (Reference Book)

Student learning outcomes will be assessed through weekly practical homework assignments, Lab reports, periodic exams, research project, and a comprehensive final exam. For graduate level students, the instructor requires additional assignments related to their dissertations research work. Moreover, circuit implementations related to the course topics are required from graduate students. Total student grade in the course is based on two exams (15% each), a final research project (15%) to test student understanding of recent advancement in power system protection applications, a (5%) credit for attendance and participation, weekly Lab projects (20%), and a final comprehensive exam (30%).

Conclusion

In this paper, a new course in power system protection is presented. This course is designed to introduce students to modern topics in power systems' protections and controls. The goal of adding this course is to enhance the power systems concentration so EE graduates can find jobs in the power industry. Topics covered in this course are designed to provide students with a strong theoretical and applied knowledge in solid-state relays and protection topologies used in today's power systems based on recent advances in the field. This course was developed to fill special regional power companies' need to hire EE graduates with the appropriate power systems background. A complete course outlines and catalog description were provided including weekly topics and laboratory experiments. Topics developed also cover coordination by time grading for protection design parameters on medium and low-voltage networks with sensitive earth fault protection, as well as, protection applied to transformers, switchgears, and motors. Several case studies are embedded in this course to provide students with real-world applications related to power systems protection with the presence of alternative energy sources in the form of laboratory component. The hands-on experience provided in this course is designed to offer students the necessary skills to design, simulate, and practice in the utilization of protection systems and equipment.

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