The Education and Training of Future Protection Engineers: Challenges, Opportunities and Solutions

C-6 Working Group Members of Power System Relaying Committee

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Abstract **It is getting increasingly clear that electric power systems are undergoing rapid changes due to deregulation, the penetration of new technologies and the adoption of efficient computation, communications and control mechanisms. The primary goal of this paper is to recognize the importance of education and the training of future protection engineers, and, secondly, to suggest course content needed to meet this challenge.**

***Keywords*—power system protection, relaying, deregulation, education and training, engineering curriculum**

I. Introduction and Background

A. Background

Electric energy has not only become a basic necessity for human existence but also has become the backbone for our economic development. We have witnessed electric power systems becoming larger and more complex in the last sixty years due to the unprecedented population growth and higher standards demanded by society. Unfortunately these complex systems are becoming more vulnerable to natural disturbances and external threats. If one analyzes the detailed anatomy of the blackouts that have occurred since 1965, it becomes evident that protection played a significant and crucial role [1, 2].

On the positive side, the advent of computerized relays, Global Positioning Systems (GPS), Phasor Measurement Units (PMU), power electronic control devices, digital communication technologies, and other technical developments have facilitated improved protection of power systems over a wide area. As a result, the monitoring, control, protection and automation of the power systems in real-time is becoming more effective. The protection community should seize this opportunity to make power systems safer, more secure, more reliable and less vulnerable to external threats.

The continuation of the technology explosion of the second half of the 20th century requires the availability of a diverse and highly capable technical workforce. Unfortunately, the education of protection engineers has not kept pace with the technological developments. Only a few universities teach just a single course on relaying and protection without much emphasis on power system automation. Though it is a science that can be covered through sound basic principles, its actual implementation permits alternatives, all of which are technically equal to the task at hand. The alternative that is selected depends upon the relay engineer's experience and the traditions of the electric utility company. In order to capture this aspect of freedom of choice, many view relaying as an art. As a matter of fact, the entire power engineering education curriculum is at a crossroads and needs complete rejuvenation [3-5]. Experience to date has shown that students can be attracted to and retained in power programs if they are exposed early to the joys of creation through design, discovery through research and invention through hands-on experimentation**.**

B. Purpose

The IEEE Power System Relaying Committee (PSRC) recognizes the importance of proper education and training of future protection engineers. With this primary goal, the Committee proposes the development of materials that will enable the successful education of engineers at the university level and the subsequent training in the industry. The education and training should be viewed as a seamless process.

C. Organization of Paper

The history of protection is addressed in Section II. The importance of protection for industry is covered in Section III, which in essence establishes the motivation for developing this paper. The current status of courses at universities, conducted through a survey, is summarized in Section IV. Section V covers the background materials and prerequisites needed for protection course modules. The outline of modules and content are identified in Section VI. The topics recommended are extensive but by no means complete and comprehensive. Section VII identifies effective mechanisms for teaching such courses. The paper includes a summary in Section VIII, a list references in Section IX, and further resources in Section X.

II. Historical Review of Protective Devices

Extensive electrical power distribution systems began to appear towards the end of the 19th century. The interruption of supply during fault location and repair was a secondary consideration to the protection of apparatus in the system. Such apparatus protection was provided in the form of fuses. Selectivity problems arising when using parallel generators on the same busbar led to the development of magnetic "cut-outs" which could operate on "reverse" current flow and hence could detect a faulted machine in preference to an unfaulted machine which was carrying a higher current. Such devices were in fact reverse power cut-outs and employed both a potential and a current coil. These early devices not only had to detect the fault condition, but also had to develop sufficient torque to trip the switch on which they were fitted. The inverse definite time/current characteristic of the fuse coupled with variable time multiplier settings [6] in induction disk relays underpinned the development of time graded overcurrent protection systems. A significant development which took place around 1905 was the introduction of the Merz-Price pilot wire system of protection. This was a differential system that compared the line currents at opposite ends of the protected line. This system found its greatest application in the protection of tie lines, i.e. lines joining generating stations, where power flow could be in either direction. Where grounded systems were in use, a device alternatively referred to as a grounding relay, leakage current detector [7, 8] or a core balance relay was introduced. This is a zero sequence current detector and is still widely used today.

Throughout the 1920's, relays progressed from the original magnetic cut-out "motors" into the realm of measuring instruments with the tripping torque requirements being met by means of an electrical trip coil on the circuit breaker, energized from a station battery through contacts operated by the relay. The network being protected was now of sufficient complexity to involve many of the present-day protection requirements such as detection, discrimination, back-up facilities to cover the failure of a relay or circuit breaker, and simple logic functions in the form of interlocks. Prior to the publication of Fortescue's paper [9] on symmetrical components, there was a general appreciation that application had advanced beyond analysis.

In the early 1920's, the need for more sensitive fault settings on relays rapidly came into conflict with the accuracies at high current values of available current transformers. The difference in accuracy between two such transformers used in a differential scheme placed a lower limit on the difference current at which the device could be allowed to trip. This problem was largely overcome by using a bias or restraining force proportional to the primary current magnitude.

The application of a restraining force, to an overcurrent induction disc type relay, that is proportional to system voltage produced a time of operation roughly proportional to the distance to the fault from the relaying point [10, 11]. The development of distance protection in the form of impedance relays had thus commenced as far back as 1923.

Electronics made no significant impact on relaying until 1948 when Warrington et al. [12] designed an electronic mho relay and gave results of its application [13]. All such relays were at a grave disadvantage with respect to their electromagnetic counterparts, due to the relatively short life of thermionic valves. The advent of the transistor lent considerable impetus to the development of electronic or "static" relays as they are now known [14-15]. Voltage and current signals were phase shifted and "mixed" before being applied to electronic phase or amplitude comparators. The parameters of the mixing process could be chosen to provide a particular shape of trip zone.

Static relays offered the possibility of making instantaneous comparisons and this led to the realization that before making an instantaneous comparison it was necessary to remove all non-power frequency components in the signal. As digital computers became available in the early 1970's, researchers began to look at ways to use digital algorithms for protection purposes. Throughout the 1970's and 1980's, while they waited for digital technology to mature, researchers examined many different relay algorithms. The most common algorithms used in today's digital relays are based on abstracting the fundamental components of voltage and current using a Discrete or Fast Fourier Transform. References [16 - 19] give an excellent account of this period of relay development.

Digital technology did allow some new techniques to be investigated; in particular, the use of "incremental signals" [20] for directional comparison and "traveling-wave" [21] or "echo" techniques for distance measurement. Incremental signals are formed by subtracting values taken an integral number of cycles ago from the present samples.

Artificial Intelligence techniques in the form of Artificial Neural Networks (ANN's) and genetic algorithms have been applied to many relaying functions [22] but have not been adopted in practice. Advanced simulation is also providing a better appreciation of the application scenarios leading to more effective protection systems. "Smart" substations are now evolving in which hierarchies of computers or computing instruments perform the instrumentation, protection, control and communication within the substation [23, 24]. Mobile "agents" may be applicable within the computer hierarchies and communication systems of modern substations. While this improves the automation of substation control and operation, it also facilitates the possibility of the system being compromised by software insecurity.

The legacy devices employed in today's power systems maintain the identity of the stand-alone relay. As new equipment is introduced, the protection function will become embedded in the overall control/communication system. Wide-Area protection [25] is becoming necessary to avoid cascading failures and communication will play a vital role in the process. The developments of Phasor Measurement Units (PMU), fast communication channels, and high precision signal transducers have made wide-area protection a reality [26-29]. However, the algorithms performing the protection functions are based on the same principles as have been developed over the last 100 years but the availability of these new technologies accelerated these new possibilities.

III. IMPORTANCE OF PROTECTION FOR INDUSTRY

Power system protection is ordinarily considered the problem of the electric utility and the associated manufacturers. However, the effect on and by the industrial sector cannot be overlooked. The obvious relationship incorporates the utilities' protective relay practices that are established to maintain the integrity of the utilities' responsibilities to insure uninterrupted production facilities. To this extent, the education and training of engineering students, including the basics of power system protection, would seem to be the sole responsibility of the utility organization, including, of course, those manufacturing entities that service the utility. It should be apparent, however, that this is a severely limited point of view. From the purely economic point of view, in negotiating the specifics of the interconnection, the industrial sector must have knowledgeable engineers on its side of the table; engineers who are intimately familiar with both the production facilities and problems that may be mitigated or exacerbated by the application of protective devices. They must also be keenly aware of the ever-increasing competition between electric utilities so they can determine the most desirable specification.

From the more technical viewpoint, utility protection engineers are well aware of the impact of relay performance and its effect on the electric system, of abnormalities in frequency and voltage associated with the industrial production equipment and practices. However, this concern is primarily with system performance. The individual industrial response may not be sufficiently considered by these engineers. All engineering students, therefore, regardless of their ultimate career paths, should be exposed to protection theory and practice.

From the international point of view the importance of evaluating power system education, and in particular, power system protection education and training engineering is vital. A recent National Academy of Engineering (NAE) publication [30] states that the globalization we are experiencing today is unprecedented in its magnitude and reach. Universities must recognize that it is within their power, and, indeed it is their responsibility, to prepare the next generation for this fundamental transformation where technical expertise will be the key to success. Less than 5% of U.S. College students go into engineering (as opposed to 12% in Europe and 40% in Asia). This sets the agenda for the university curricula. Courses in power system engineering are essential. In designing these courses the designers of curriculum should seek proper input from both the electric utility and its associated manufacturing organizations and the wide-ranging industrial community where electronics, computer, communication and sophisticated control technology are so essential. Thus there is a dire need to identify and develop the material needed for the education and training of future protection engineers.

IV. Current Status of Protection Courses At Universities

In order to assess the current status of course offerings in protection, the academic members of the Power Engineering Education Committee (PEEC) were contacted by e-mail and they were requested to respond to the following two simple questions:

1. Does your institution regularly teach a course in power system protection?

2. Does your institution include some protection in another course?

A total of 75 institutions predominantly from the North American continent were contacted. Additional data was collected from the most recent PEEC resource survey [31]. Appendix A identifies the list of institutions that offer some form of protection courses. Of the 50 schools that responded, 21 offer a course with protection component included. The other 29 respondents offer one or more courses devoted entirely to protection. The current emphasis of these courses is on fault calculations, relay settings and coordination for major power system components. System protection is also emphasized at graduate level courses.

The following sections offer suggestions for designing protection courses.

V. Background Materials and/or Prerequisites

A course in power system protection is recommended for seniors and graduate students in Electrical Engineering. Typically, most universities require one or two courses dealing with the analysis of power systems as prerequisites at junior/senior levels. The background covered in the prerequisite course(s) should include:

(1) Adequate mathematical skills, such as use of trigonometric functions, complex variables and vector algebra.
(2) Per unit representation of power system
(3) Principles and modeling of power system components: transformers, generators, motors, transmission lines
(4) Formation of bus impedance matrix (Z_{bus}) and bus admittance matrix (Y_{bus})
(5) Power flow analysis
(6) Symmetrical and unsymmetrical fault analysis
(7) Principles of power swing equation and equal area criterion for stability.

VI. Education Modules and Course Content

A. General Requirements

In recent years, educational modules for self-teaching or guided learning have become quite popular. Educational modules are pre-packaged instructional aides which can be made available to prospective students on CD's or accessed through the web. Quite often these modules are created by experts in particular fields and they can then be used as instructor's aides at other institutions or as self-study guides by students.

The subject of an educational module should be a well-defined topic analogous to a chapter in a text book. A module should be able to stand on its own merit in terms of contents and should be complete to allow a student learn the intended topic with some level of proficiency. There is a logical development of the subject through the module, and although other reference materials and modules are referred to, it should be possible to master the material in a module without excessive dependence on these other sources.

The organization of a module, of course, depends upon the nature of the subject and the inclination of the author of the module. However, it is possible to single out some elements which are essential components of a good module.

(1) Introduction: The introduction should provide the reason why the material is relevant and important to the general field of study. For example, when the module deals with a topic in the protection of power systems, the purpose of protection systems, how they act in conjunction with other protection systems, and the characteristics of a well-designed protection system should be defined. A few illustrative examples without too much detail are useful in getting these ideas across. The Introduction should also show the relationship of a particular module to other modules which make up the complete subject under consideration.

(2) Theory: Sufficient self-contained discussion of underlying theory should be provided wherever it is needed. The author of the module should be careful not to include too much of the basic material, which is covered in the well-defined pre-requisites.

(3) Numerical examples: With each important concept developed, there should be well-chosen numerical examples which would further reinforce the understanding of the theory. Some of the numerical examples should be formulated in an interactive format so that the student could experiment with different initial conditions or constraints in the problem. Examples of practical applications help students gain a more in-depth understanding of the module content and prepare them for assignments in the module.

(4) Visual aids: It is generally expected that visual aids in the form of figures and animations will be included as they are all useful teaching tools.

(5) Homework: A set of exercises for the student as homework should be included in those modules where appropriate.

(6) Summary: A set of concluding remarks or summary of the module purpose is useful and helps the student validate their understanding of the material with the author's or instructor's intent.

(7) Reference list: Finally, a reference list and how to best access or obtain copies should be provided.

The modules may consist of graphic pages with accompanying notes such as the teacher's comments on the slides. In addition commonly used engineering and mathematical tools such MATLAB or SIMULINK should be used throughout both for problem solving, animations, and interactive student work. A number of educational modules in power system engineering have been developed by many individuals and universities, and should be consulted for additional insight into the design of educational modules [32, 33].

B. Course Material

Power system protection has changed remarkably in the past twenty years due, in particular, to the development of numerical relays. Therefore, it is necessary that undergraduate and post-graduate level modules of power system protection provide adequate training in this technology. Because the relays designed with older technologies (electromechanical, electromagnetic and solid-state) continue to be used, sufficient training in those technologies should also be included in the teaching modules.

It is not possible to teach all the details of power system protection in one course at a university. Proper understanding of the basics of the techniques, devices and the underlying principles should be sufficient to give the students a good start in becoming competent protection engineers [34]. Such training is sufficient for them to understand the development of newer technologies and technique. However, a solid preparation cannot cover all the aspects, but allows the student to attain a functional knowledge provided that further training is offered in the respective workplace.

*C. Fields included in teaching of protection cour*ses

Universities should consider that engineers working in power system protection may have to work in one of the following aspects of the discipline.

(1) Define appropriate protection schemes
(2) Undertake designs of ac and dc schematic drawings as well as wiring diagrams for installation purposes. (This activity may be the primary function of a design group but engineers should have sufficient input to be supportive or critical.)
(3) Carry out power system studies to define settings and parameters of relays to guarantee the required levels of reliability and selectivity.
(4) Implement parameters, test and commission protection installations.
(5) Analyze relay performance under events and interpret COMTRADE.

D. Topics for power system protection courses

The following topics, if adequately covered in a power system protection course, provide satisfactory knowledge to the students.

(1) Introduction: Objectives of the course, need for protection, history of development of power system protection, definition of terms used in the discipline, protection zones, classification of relays, interfacing of relays with the power system (use of Cut's and VT's), types of faults and their relative frequencies, overview of protection principles and identification of technologies used in protection, automation and substation control, and trip circuit logic.

(2) Overcurrent and directional overcurrent relays: Instantaneous and inverse time overcurrent relays, their principle of operation and application to protect radial distribution circuits and equipment such as motors. Need for directionality, basic design of a directional relay, torque equation, maximum sensitivity angle, displaying relay operating principles on the impedance (R-X) plane and application of directional overcurrent relays for protecting networked distribution circuits. Connection angle and selection of connection angle for application in overload and/or protection during faults, typical connections of directional relays in the three-phase environment. Ground directional relays, negative sequence directional relays and designs of electromechanical, solid-state and numerical directional relays.

(3) Distance relays: Definition, need for distance relays, types of distance relays, characteristics of distance relays plotted on the R-X plane (impedance, offset impedance, mho, offset mho, quadrilateral, lenticular, quadrilateral and blinders), inputs for achieving those characteristics, electromechanical, solid-state and numerical designs of distance relays. Application of distance relays for protecting transmission lines, primary and backup protection zones using step distance approach. Use of communication channels along with distance relays for increasing protective coverage and fault clearing time. Voltages and currents applied to distance relays for detecting multi-phase and single phase to ground faults. Performances of phase-fault distance relays during phase-to-phase and single phase to ground faults. Multi-phase distance relays, and symmetrical components approaches. Impact of arc resistance on the performance of distance relays during phase faults and single phase to ground faults. Use of distance relays for field failure protection of generators as well as for power swing identification.

(4) Differential protection: Basic principle and percentage bias differential protection. Application to the protection of generators, delta-wye, and autotransformers.

(5) Major components of a numerical relay, need for anti-aliasing filters, filter designs using operational amplifiers, basic principle of analog to digital conversion, different types of A/D converters, commercial successive approximation and flash converters. Errors caused by conversion process. Algorithms for converting quantized samples of voltages and currents to Phasors, Discrete Fourier Transform, Least Squares approach, Kalman filtering neural network and Wavelet transform approaches. Adaptive protection of transmission lines and distribution systems; Microprocessor and Digital Signal Processors used in numerical relays. Basic functioning, programming and suitability issues; impact of numerical technology on the application of transformer and transmission line protection.

(6) System protection: System protection issues are becoming increasingly important as the response of traditional protection devices to system-wide disturbances are coming under special scrutiny, and it is being recognized that system protection should be handled in a more organized manner. Examples of system protection devices with which students must be familiar include various System Integrity Protection Systems (SIPS), also known as Remedial Action Schemes (RAS). Protection systems designed for load shedding and restoration, generation dropping, islanding schemes, protection against voltage instability are some of the emerging technologies which should be discussed. A more recent development is that of using wide area measurements (Synchronized Phasor Measurements) to improve protection system response to catastrophic failures and service restoration.

VII. Effective Mechanism for Teaching

In order to impart effective instructions to students, the following procedures could be used in power system protection courses.

A. Standard classroom sessions and lectures

Teachers should present the entire material by means of lectures using as far as possible computer-aided instruction materials. However extensive and exclusive computer-aided presentations can make sessions very tedious and so case study analysis is advised. The instructors should cover general relay concepts including theory, application and setting variants and options offered by the manufacturers. This is because the internal operation of relays, especially in numerical devices, is beyond the scope of protection courses. Forty contact hours are recommended for a one-semester course.

B. Laboratory sessions

In order for the students to get a real sense of the operation and setting of relays, especially undergraduate courses, working in laboratory sessions is essential. These sessions should illustrate among several aspects, the different types of relays, the checking of characteristic curves and the meaning of selectivity operation of non-unit protection type as that given by overcurrent and distance relays. The acquisition of protective relays for laboratory usage is essential but may be often costly and difficult to acquire. The laboratory sessions also should give a good idea of the operation of testing equipment, analysis of postmortem operation and the use of COMTRADE files. Fig 1 shows a typical relay testing set-up. This set-up allows testing of most characteristics of electromechanical and numerical relays.

At least three sessions of three hours each is adequate for the students to get a fairly good idea of what working with relays in the field means. A visit to a real facility, either power plant or an electrical substation, is advisable but not strictly required. This gives the students a much better idea of the use of relays and the installation options.

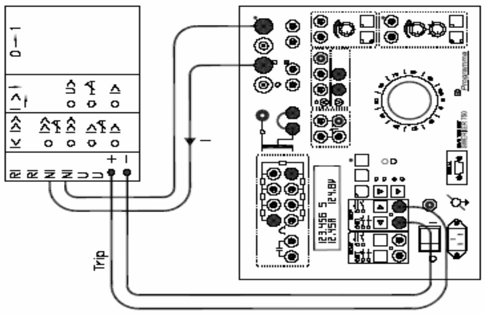

Fig. 1 Typical relay testing equipment

C. Software handling

Most manufacturers of numerical relays provide software packages that help to illustrate the courses very well. These software packages illustrate the operation of relays, to the implementation of settings and parameterization.

Fig 2 shows, for example, how a part of a system set up is carried out in a generator protection relay manufactured by a major vendor.

On the other hand it is very important that students taking courses in protection are capable of running power system software and especially power flow and short circuit modules. It is important that they have a good command of transient stability modules too, if setting of distance, out of step and loss of field relays is required.

D. Homework

Homework is important to help the students learn the topic material in the courses better. In these homework assignments simple cases of relay application, relay setting and relay coordination could be assigned.

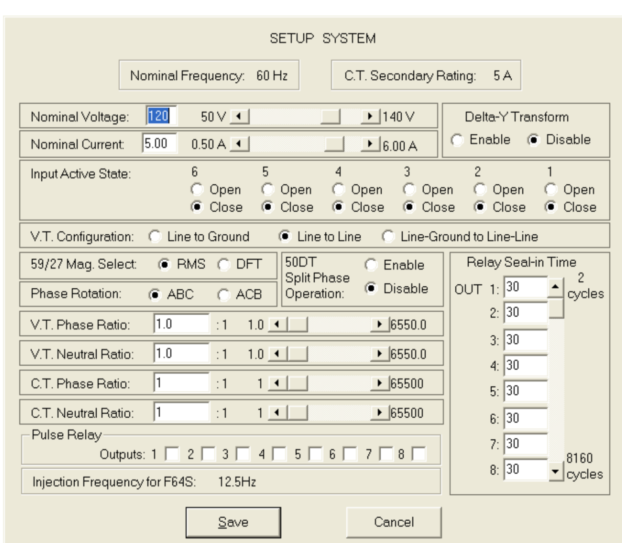

Fig 2 Setup system configuration of a numerical relay

E. Case study

At the end of the course a project should be assigned where a comprehensive analysis is needed. This allows for a consolidation of the knowledge imparted during the course. A recommended approach is to take a typical power system with different types of relays and ask students to define the protective scheme, to specify relays, to calculate settings and parameters and to draw the coordination and relay characteristic curves. Power flow and short circuit analysis should at least be part of the project [35].

VIII. SUMMARY

This paper presents a comprehensive discussion of the need for, suggested methods of instruction, and a detailed list of applicable course material that would allow university sufficient information to educate and train potential protection engineers. A survey of courses now being offered is included in addition to a wide-ranging list of reference material.

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X. Additional Resources

Additional information can be found in the following resources: Bibliography of Relay Literature published every year in January in the Transactions on Power Delivery. From time to time IEEE PSRC Committee Reports and IEEE Guides and Standards for Protective Relaying Systems are also published and updated. Many other publications and reference papers may be obtained from the manufacturers and from many professional societies throughout the world. Useful search engines include IEEE Xplore and Google Scholar.

Appendix A: Detailed Response on Current Offerings in Protection

University	Number of courses with some protection	Number of courses entirely devoted to protection
Akron	0	2
Alabama	0	1
Alabama-Birmingham	0	1
Alaska-Fairbanks	0	1
Alberta	0	1
Arizona State	0	2
Auburn	1	0
Cairo University	1	1
Cal State-Long Beach	0	1
Cal State-Sacramento	0	1
Calgary	1	1
Clemson	1	0
Colorado	0	1
Dalhousie	0	1
Drexel	2	1
FAMU-FSU	0	1
George Washington	0	1
Georgia Tech	1	1
Hartford	0	1
Houston	0	1
I. I. T., Chicago	1	1
Idaho	2	1
Illinois	0	1
Kansas State	2	0
Louisiana State	1	0
Michigan Tech	1	1
Minnesota	0	1
Miss. State	1	0
Missouri	1	1
Montana	0	1
Nevada-Reno	0	1
New Mexico State	1	1
New Orleans	0	1
Newfoundland	0	1
Ohio State	0	2
Penn. State-Harrisburg	1	0
Penn. State-State College	1	0
Polytechnic University	0	2
RPI	0	1
San Diego State	0	1
Saskatchewan	1	2
Southern Illinois	0	1
Texas A&M	0	3
Texas-Arlington	0	1
University of B. C.	0	2
Virginia Tech	2	1
Washington	1	1
Washington State	1	2
Wichita	0	1
Widener	1	0

Appendix B: Utility Training Programs

The following outline describes the topic material that can be presented to electrical engineers to introduce them to system protection. It is a comprehensive list of skills needed for an engineer charged with the responsibility for power system protection and control including associated automation functions.

B.1 Program content

I. Phasor Notation and Network Modeling
II. Symmetrical Components
III. Sensors – Current Transformers (CT) and Voltage Transformer Theory
IV. Protective Relaying Devices
V. Settings and Coordination of High Voltage Transmission and Subtransmission System Back-up Ground Relaying
VI. Setting and Coordination of High Voltage Transmission and Subtransmission Step Distance Phase Relays
VII. Transformer Differential Relay Protection
VIII. Protection for a Transmission/Distribution Substation
IX. Breaker Failure Relay Protection
X. High Speed Relaying for High Voltage Systems
XI. High Speed Relaying for Extra High Voltage Systems
XII. Generating Station Equipment Protection
XIII. Industrial and Commercial Protection
XIV. Power Component Thermal Protection
XV. Power System Stability and Relaying
XVI. Advances in Substation and Line Protection
XVII. Wide Area System Protection
XVIII. Relay System Testing

Practical experience may be gained by performing several laboratory experiments. The topics could include, but not limited to, the following topics:

A. Short Circuit and Symmetrical Component Fault Calculation Program
B. Power System Protection Design and Setting
C. Relay Testing
D. Substation Control System Design
E. Generator and Motor Protection
F. IED's Configuration and Setting
G. Relaying for Stability
H. Open Loop and Closed Loop testing using Real-Time Digital Simulation Technology

B.2 Detailed Outline

I. Phasor Notation and Network Modeling
  A. Voltage and Current Conventions in a Three Phase System
    1. Phasors and the Operators "j" and "a"
    2. Percent and Per Unit Calculations
  B. Three Phase Transformer Modeling
    1. Transformer Delta and Wye Connections
    2. Conversion of Delta Impedances to Equivalent Wye Impedances for Three Winding Transformers
    3. Transformer Impedance Calculations from Nameplate Data
  C. Transmission Line Impedance Modeling
  D. Delta Network to Wye Network Conversions

II. Symmetrical Components
  A. Symmetrical Component Equations and Network Models
    1. Convert Unbalance Phasors into Symmetrical Components
    2. Development of Sequence Networks
    3. Sequence Current Flow Through a 3-Phase Transformer including relationship to Phase Shifts
    4. Generator Impedance Models
    5. Transmission Line Models
    6. Sequence Network Modeling Example
  B. Symmetrical Component Analysis of an Unbalanced System
    1. Symmetrical Component Network Connections by Type of Fault
    2. Arc Resistance modeling
    3. Radial System Fault Current Example
    4. Network System Fault Current Examples
    5. Open, short, and simultaneous circuits
  D. Symmetrical Component Computer Programs
    1. Short circuit calculation programs
    2. Relay coordination computer programs
    3. Relay coordination curve plotting programs
  E. Symmetrical Components as Measured by Relays
    1. $3I_0$ and $3V_0$ Filters
    2. Negative Sequence Voltage and Current Filters
    3. Mixed Excitation (I_2 –I_1/K) Current Filter for Phase Comparison
    4. Other Examples of Composite Sequence Filters

III. Sensors - Current Transformer and Voltage Transformer Theory
  A. Current Transformers
    1. (CT) Construction and Design
    2. CT Models
    3. CT Saturation
    4. CT Circuit Testing
    5. CT Insulation, polarity, ratio, excitation, winding and lead resistance and burden measurement testing
  B. Capacitive Voltage Transformer (CVT)
    1. Construction and Design
    2. CVT Models
    3. Transient Responses of a CVT
    4. CVT Testing
  C. Non-conventional/Optical instrument transformers

1. Performance and conformance

IV. Protective Relaying Devices

A. Device Function Numbers and the Need for Standardizing Protection Systems
B. Stand Alone Relay Principles of Operation
C. Polarized and Direction Ground Overcurrent Relays
D. Polyphase Distance Protection
E. Distance Ground Electromechanical
F. Methods of Phase and Ground Impedance Relay Polarization
G. Static Phase and Ground Impedance
H. High Impedance Bus Differential
I. Transformer Differential
J. Breaker Failure Relays
K. Digital Relay Protection
   1. Digital Integrated Circuit Design
   2. Digital Systems Design
   3. Digital Signal Processing and Filtering
   4. Techniques
   5. Limitations of Protection
   6. Settings Examples
   7. Firmware Revision Control
L. Transmission Line Teleprotection Communication Media
   1. Lease Phone Lines
   2. Direct of Fiber Optics
   3. Sonet Based Multiplexing
   4. Power Line Carrier

V. Settings and Coordination of High Voltage Transmission and Subtransmission System Back-up Ground Relaying

A. Current and Voltage Polarizing Circuits and Sources
B. Effect of Mutual Induction on Ground Relaying
C. 138 kV Back-up Ground Relay Settings Example
D. Impacts of mis-coordination

VI. Settings and Coordination of High Voltage Transmission and Subtransmission Step Distance Phase Relaying

A. Introduction to Phase Relay Principles of Operation
B. General Torque Equations
C. R-X Diagrams and Phase Impedance Relays
D. Relay Loadability/Load Encroachment
E. Phase Relay Settings Theory
F. Theory of Apparent Impedance Calculations
G. Step Distance Phase Relay Settings Example
H. Impact of series compensation in impedance computations, protection set points, and coordination
I. Special Coordination Considerations
   1. Two adjacent line sections with one being very long and the other being very short

VII. Transformer Differential Relay Protection

A. Two and Three Winding 3 Phase Transformers
B. Phase Angle Regulating Transformers (PARS)

VIII. Protection for a Transmission/Distribution Substation

A. Protection of Transformers
   1. Basics of Transformer Design
   2. Differential Relay Protection
   3. Sudden Pressure Relay
   4. Transformer Loading Philosophy
   5. Transformer and Bus Back-up Relaying
   6. Transformer Automatic Paralleling Circuitry
B. 12.5 kV radial feeder protection
   1. Overcurrent relay settings
   2. Fuse coordination
C. Interlocking Scheme Logic to Facilitate Transformer Loading and Equipment Restoration
D. Breaker Failure Protection
E. Circuit Switcher Protection
F. Undervoltage and Underfrequency Load shedding Applications and Schemes
G. Substation Equipment Thermal and Overload Protection
H. Capacitor Bank Protection

IX. Breaker Failure Relay Protections

A. Circuit Breaker Mechanisms
B. Breaker Failure Relay Circuit Designs
C. Breaker Failure Relay Timer Setting Considerations
D. Variations in Breaker Failure Relaying for HV and EHV Applications

X. High Speed Relaying for High Voltage Systems

A. High Speed Relaying Philosophies for High Voltage Systems
B. Directional Comparison Relay Fundamentals
C. Direct Transfer Trip
D. Permissive Overreach Transfer Trip
E. Current Differential Transfer Trip
F. Traveling wave theory applied to line protection
G. Automatic Reclosing
H. Protection Requirements in an Urban 138 kV Cable Network
   1. Limitation of fault damage
   2. Need for backup relay coordination
I. Local versus Remote Breaker Failure Protection
J. Relay Loadability and Dependability

XI. EHV Transmission System Protection

A. Protection Philosophy
B. Two Systems of Relaying
   1. Redundancy advantages and disadvantages
   2. Current Only High Speed Relaying
   3. Phase and Ground Distance Relaying
   4. Impedance Based Direct Underreaching Line Transfer Trip
C. High Speed Communication Systems
   1. Power Line Carrier

2. Microwave
3. Fiber Optics
4. Relay Loadability

D. Fully Complimentary High Speed Scheme Logic
E. Stability Ramifications of Relaying
F. EHV Line Characteristics
G. Effect of line capacitance on relaying
H. Autotransformer Protection
   1. Differential Protection
   2. Polarizing Current Sources
   3. Transformer and 138 kV System Backup protection
   4. Transformer Relay loadability
   5. Transformer Transfer Trip

XII. Generating Station Equipment Protection

A. Configurations of Generating Stations
B. Auxiliary Power Protection
   1. Fault Current Calculations at Medium and Low Voltage Levels
   2. Low Voltage Protective Devices
   3. Low Voltage Unit Substation and Motor Control Center Protection
   4. Medium Voltage Protection for Auxiliary Power Unit Substations
   5. Medium Voltage Motor Protection
      a. Motor Design
      b. Induction Motors
      c. Principles of Synchronous Machines
      d. Variable Speed Motors
      e. Speed vs Torque Curves
      f. Thermal Limit Curves
      g. Locked Rotor
      h. Duty Factor Ratings of Motors
      i. Current and Impedance Relay Applications
      j. Motor Protection Settings
      k. Specialty Application Motors
   6. Medium Voltage Bus Protection
   7. Diesel Generator Protection
   8. Auxiliary Power System Settings and Coordination Examples
   9. Settings and Coordination Computer Programs
   10. Nuclear Station Safety Related Protection Requirements
C. Generating Unit Protection
   1. IEEE Standard C37.102 and the need for Standard Unit Protection
   2. Device Numbers and Function
   3. Need for system coordination
      a. Impacts of miscoordination
      b. Impacts of overexcitation protection during
      c. system swings
D. Protection Guide for Units and Auxiliaries
      a. High Voltage connected units
      b. EHV Connected units
      c. Independent Power Producers

XIII. Unit Transformer Protection

XIV. Generator Protective Functions

A. Generator Differential
B. Stator Ground Fault
A. $3V_0$ Methods
B. Neutral Transformer Protection Methods for Stator Protection
C. 100% Stator Ground Fault Protection Methods
   3. Overexcitation Protection
   4. Negative Sequence Protection
   5. Exciter Circuitry Basics and Protection
   6. Loss of Field Protection
   7. Reverse Power Turbine Protection
   8. Load Rejection
   9. Inadvertent Energization
   10. Underfrequency
   11. Out-of-Step Protection
   12. Overall Settings Examples
   13. Integrated Digital Protection Systems
   14. Generating Station Interface Protection

XV.Power System Stability and Relaying

A. Power Angle Equation
   1. Simplified Power Angle Curve
   2. Equal Area Criteria
B. Solution of Power Swing Equation and Inertia
   1. General Equation and piecewise linear solution
   2. Stable swing studies (units, in particular)
C. Steady State and Dynamic Stability
D. Transient Stability under Balance Fault Conditions
E. Multi-Machine Stability
F. Underfrequency Load Shedding Protection
G. Effects of Protection Systems of Stability
H. Breaker Failure Protection as related to Stability
I. Relay Schemes to Maintain System Stability
J. Critical Clearing Time Determination
K. Unit Stability Tripping
   1. Bus Sectionalizing as Related
   2. to Stability
   3. Load Rejection Tripping
   4. Multiple Line Outage Unit
   5. Trip Schemes
   6. Fault and Path Mode Schemes
A. Impact of Automatic Reclosing on System Stability
   1. Synchronism Check
   2. High Speed Reclosing
   3. System Swing Detection
   4. Impedance based detection

XVI. Industrial and Commercial Protection

A. Interface Protection
B. Transformer Protection
C. Distributed Generation Protection
D. Equipment Protection

XVII. Wide Area System Protection

A. Remedial Action Schemes
B. Power System Stressed Conditions and associated challenges - Stability (thermal or angular), voltage collapse, etc.
C. Wide Areas Measurement Systems
D. Phasor Displays and Phasor Measurements
E. Wide Area Control and Advance Warning Systems
F. Total Visibility
G. Possible considerations for automatic recovery systems when feasible - Application needs to be correct
H. Prevention of System Cascades and Blackouts
I. Real Time Predictors of Cascades – Phase Angle and Voltage
J. System Restoration Protection Issues

XVIII. Power components thermal protection

A. Thermal modules for Hot spot monitoring of power transformers;
B. Microprocessor based relay for overhead lines thermal protection;
C. Power cables overload protection units based on Distributed Temperature Sensors

XIX. Advances in Substation and Line Protection

A. Substation Automation Communication Methods
   1. Automation fundamentals and understanding of basics of interface protocol for use in protection and associate interlocking controls.
   2. What is ModBus, DNP, and UCA/IEC-61850
   3. Inter-substation communication methods for data gathering and integration
   4. Inter-substation communication methods for tripping and closing of circuit breakers
   5. Network communication and traffic management - Industry trend for communication based networking (either at the substation or between substations)
   6. IED's managed by wireless communication links (i.e. employing GSM/GPRS or satellite based communication units).
B. Substation LAN Management
C. Impacts of GPS input selection – Understanding of modulated vs. de-modulated signals.

XX. Relay System Testing

A. Stand Alone Relay Tests using Phase Shifter Test Kit
B. Substation and Transmission Line Protection Functional Testing
C. Automatic testing and troubleshooting
D. System Testing and hidden failures (manufacturing, relay settings, coordination studies, etc.)

XXI. Protection Lab

A. Short Circuit and Symmetrical Component Fault Calculation Program
B. Requires a short circuit computer program, a relay coordination and curve drawing program and a cad program
C. Power System Protection Design and Settings Module
D. Requires a short circuit computer program, a relay coordination and curve drawing program and a cad program
E. Relay Testing Module
F. Requires electromechanical phase and overcurrent relays, Digital Relay (transmission line preferred) and a three phase test instrument
G. Substation Control System Design Module
H. Requires an digital relay and programmable logic controller
I. Generator and Motor Protection Module
J. Requires a digital relay, three phase current and voltage test device and rotating machine simulator
K. IED Configuration and Settings Module
L. Requires a digital relay and three phase test instrument
M. Relaying For Stability Module
N. Requires a system simulator
O. Open loop and closed looped testing using Real-time Digital simulation technology

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