AN ADVANCED APPROACH TO TEACHING PROTECTIVE RELAYING COURSES

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1 INTRODUCTION

The subject of protective relaying is considered quite unique in the power system field due to its great practical importance. The role of protective relaying as a robust and reliable approach to power system contingency operation during fault conditions is well recognised and defined. However, protective relaying is treated differently than other power system disciplines since the approaches to protective relaying scheme designs are considered more of an art than a science. Teaching this subject in the university environment has always been a challenge since practical knowledge base in this area has primarily been developed and maintained within the industry.

A better interaction between industry and university has been recognised as a solution to the general power engineering education problem[1]. Examples of joint research efforts between industry and university have shown significant results regarding the advanced degree education[2]. Practical problems from industry could also be used as quite useful examples for teaching classical relaying topics[3].

The new applications of digital technology in the field of protective relaying are greatly affecting teaching of this subject[4]. As a consequence, new theoretical subjects are introduced[5], new teaching methods are implemented[6,7], and new laboratory facilities are developed[8]. These advancements are suggesting that a new approach to teaching protective relaying should be developed to meet the new challenges.

This paper discusses an advanced teaching approach based on two major innovations. These are the interdisciplinary treatment of the relaying subject and the experimental method used as a major teaching tool. New theoretical and experimental topics for teaching protective relaying are proposed and an example of a graduate course incorporating the new topics is given.

The first part of the paper is devoted to the interdisciplinary aspect of the relaying problem. The next section provides requirements for an extensive experimental approach. An example of theoretical and experimental topics in a computer relaying course are discussed in the following sections. Approaches to overcome major problems associated with lack of appropriate textbooks and interdisciplinary background of the power program students are addressed at the end.

2 INTERDISCIPLINARY APPROACH TO PROTECTIVE RELAYING

2.1 *New developments in protective relaying*

Introduction of digital computer technology to the field of protective relaying dates back to the late 60s[9]. This approach has been explored in the past twenty years to produce numerous new microprocessor-based designs of devices and systems as well as new designs of digital algorithms for relay measurements[10,11]. Major directions of the research and development were toward designing (a) individual relaying devices that functionally correspond to the existing relays and (b) integrated control and protection systems that cover monitoring, control and protection functions in a substation[12].

Another major development that affected protective relaying field is in the area of digital communications. One direction is the use of Local Area Network (LAN) designs in the integrated substation control and protection systems[13]. Yet another direction is the use of fiber-optic technology for both intra-station and inter-station communications[14,15].

The fiber-optic technology is also implemented in the sensor developments for relay applications. Typical examples are non-conventional instrument transformers and measurement sensors for temperature and electrical discharge monitoring[16,17,18].

Another direction of advanced developments is toward new concepts for relaying. One new approach is concernced with adaptive relaying where relay device and system designs are made adaptive in order to accommodate changes in the power system operational conditions[19,20]. A different approach aimed toward development of an inherently adaptive feature for the overall protective relaying system is introduced as a system-wide relaying concept[21]. Finally, an attempt to implement heuristic approaches in the form of an expert system has been pursued in the protective relaying related areas of fault diagnosis and system restoration[22].

2.2 *Advances in the technology and the theory*

All of the mentioned developments are based on some advances in both technology and theory of the specific engineering disciplines.

Major advances in the technology and the theory relevant to the protective relaying field are listed in Table 1 and Table 2 respectively.

As a conclusion, it may be observed that the protective relaying field has indeed become an interdisciplinary one and an advanced teaching approach should accommodate this devolopment.

3 EXPERIMENTAL METHODS FOR PROTECTION RELAY EVALUATION

3.1 *Requirements for experimental study*

As is well known, power system faults produce significant distortions in the voltage and current signals. The fault signals contain, besides the funda-

Technology	Advances
Microprocessors	16-bit and 32-bit, bipolar and C-MOS designs, self checking
VLSI design	Custom designed chips for implementation of relaying algorithms
Analog circuit design	Low pass filters; high speed 12-bit and 16-bit A/D conversion with auto-calibration and auto-ranging; fiber-optic sensors
Fiber-optic communication	Bidirectional comm., rugged cable designs, easy splicing and terminating
LAN communications	10 MB/sec Ethernet, Token Ring and Token bus designs, Fiber-optic LANs

TABLE 2 *Advances in the theory*

Field	Advances
Signal processing	Application of the following techniques: FFT, Haar transform, Walsh transform
Control theory	Application of the following techniques: Kalman filtering, minimum least square error
Artificial intelligence	Application of expert systems and neural networks
System theory	Application of distributed concepts to processing, decision making, and control
Protective relaying	Adaptive relaying concept for setting coordination, relay operation, and inherently adaptive schemes; relaying as a part of EMS

mental component, several other components such as d.c. offset, higher harmonics and subharmonics. Another important characteristic is a very high amplitude of the fault current which can exceed even 60 times the nominal value. The fault-distorted waveforms are measured using instrument transformers designed for relaying purposes. Those transformers represent a nonlinear filter for the spectra of the fault signals. Once the signals are converted to the low level signals available at the secondary terminals, they are transmitted over secondary wiring into the relays. The relay front-end usually contains auxiliary transformers which are used for galvanic isolation.

The whole process of signal acquisition and measurement represents specific processing of the signal components. A detailed analysis of the transient response of all of the mentioned measurement and communication components has to be performed in order to better understand the overall performance of the relaying system. The final step in the signal processing is the measurement performed by the relay. In order to verify performance of the relay measurement logic, it is also necessary to analyze transient response of the relay itself.

Therefore, a general requirement for experimental study of relays and relaying systems is a capability to produce transient conditions similar to the ones that are present in the actual system during system faults.

3.2 *Approaches to experimental study*

Due to the fact that the main developments in protective relaying field have taken place within the manufacturing industry in the past, the most extensive test facilities were developed by the manufacturers. Another group that had a need for elaborate test facilities were utility research personnel located at research centers of the national utility companies. It is only in the recent past that universities have played an important role in the development of micro-processor-based relay designs. Therefore a need for inexpensive and yet quite powerful testing tools has recently originated within the academic environment as well.

Different approaches to the experimental study of protection relays are summarized in Table 3. The desirable approach for university implementation is the least expensive and yet sufficiently powerful configuration. The obvious choices in this respect are digital simulators[8].

4 NEW TEACHING APPROACH

4.1 *Goals and objectives*

The main goal is to shift teaching focus from the classical to the new protective relaying issues. In the areas of fault studies, the analysis method of symmetrical components should be extended with the study of electromagnetic transients. Coverage of the relaying schemes should be augmented by the coverage of new approaches such as adaptive and system wide relaying. The issue of relay designs should be explored by giving an overview of both hardware and software design techniques. Impact of new technologies such as fiber optics, LANs and expert systems should be extensively discussed. New relaying system solutions should be illustrated with analysis of the integrated system design concept. Major emphasis should also be given to the relay evaluation and test issues.

TABLE 3 *Experimental approaches*

Approach	*Characteristics*
High power labs	Excellent performance, limited test flexibility, very costly
Scaled physical models of a power system	Good dynamic performance, limited transients performance; costly to build, maintain and use
Transient network analyzers	Limited capability for overall system modelling, excellent transient performance, moderate cost
Analog electronic simulators	Excellent performance, good flexibility, moderate cost
Digital simulators	Excellent transients performance, limited dynamic performance, very flexible, low cost

analysis, development and evaluation. On the analysis side, the transient behaviour of power systems, instrument transformers and relays at the moment of the fault should be emphasized. Development problems should be related to design of hardware, software and communications for relay devices and systems. Special attention should be given to definition of digital algorithms for relay signal measurement and logic implementation. Extensive coverage of relay standards and test facilities for evaluation of new designs should also be provided.

In conclusion, the goals and objectives should be geared toward providing students with detailed insight into possibilities for new designs of relaying equipment based on the interdisciplinary approach that is the basis for the advanced developments.

4.2 *Experimental environment*

The existence of an extensive experimental facility is essential in meeting the mentioned teaching goals and objectives. An example of a suitable experimental set-up is given in Fig. 1[8].

As can be observed, this facility enables generation of fault transients from two sources. One source is different electromagnetic transient programs (EMTPs), which in the case given in Fig. 1 can be executed on different machines such as DEC VAX, SUN workstation or IBM PC. Another source is recorded fault signals captured by either analog or digital fault recorders. These signals can now be used to analyze transient response of power systems and instrument transformers. The signals can also be used to evaluate digital algorithms for relaying by feeding the signal samples into digital models and observing responses obtained by the simulation.

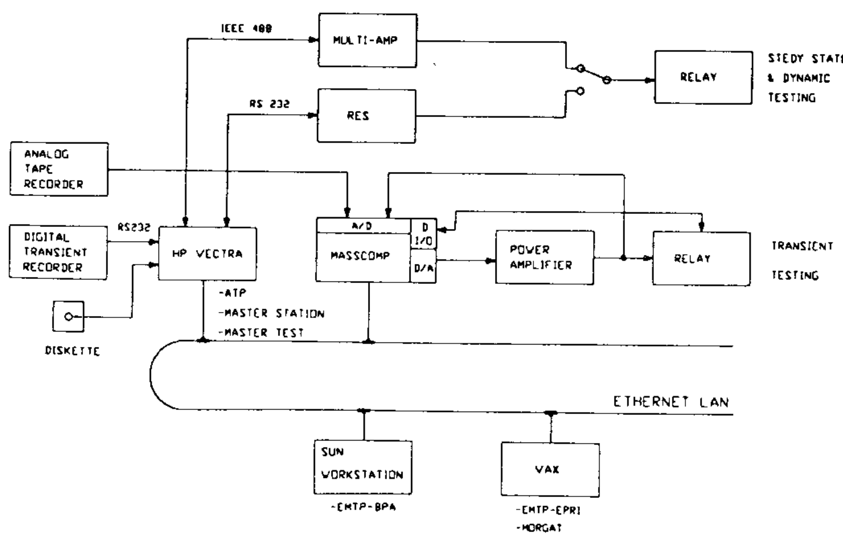

FIG. 1 DYNA-TEST simulator configuration.

Another option is to use any of the generated fault signals for the evaluation of existing or new relay devices. In this case fault signals have to be converted from sampled form into analog form. Then, analog signals have to be amplified to match the signal levels obtained at the instrument transformer secondaries. This is achieved as shown in Fig. 1, by bringing all the required signals from the signal sources over the LAN connection into the power amplifier controller. A MASSCOMP computer is used for this purpose, and it acts as a D/A conversion controller.

Finally, this configuration can be utilized to evaluate the steady state test concept vs. the new dynamic test concept. In this case some type of conventional relay test equipment may be connected in parallel to the configuration shown in Fig. 1 (Multi-Amp and RES equipment).

5 CASE STUDY: COMPUTER RELAYING COURSE

5.1 *Selection of topics*

A course covering this subject can be organized in a number of different ways. This author has taught such a course four times over a span of three years and each time some changes in the selection of topics have taken place. The main reason was the fact that the course was taught to both graduate and undergraduate classes. Another reason was the rapid change that was observed in industrial developments and it was felt that this change should be reflected in the teaching topics.

Regardless of the mentioned topic variations, a core of the topics was defined and taught each time around. The main variations were made in the level of detail and the emphasis of different topics. The list of the core topics is given in Table 4.

5.2 *Theoretical considerations*

The major theoretical issue is a definition of digital algorithms for relaying. As is well known, a number of different algorithms for relaying have been introduced in the past twenty years[11,23]. The main teaching goal is to provide students with basic knowledge about the different theoretical approaches available for algorithm definition.

The main objectives are to demonstrate the fundamental properties of the algorithms by going through analysis, synthesis and evaluation steps. One approach to this problem was developed by the author and his colleagues in the course of an industrial development of a microprocessor-based distance relay[24]. A common form for algorithm presentation was developed and used to classify the known distance relaying algorithms. This form was also used to synthesize some new algorithms for relaying and other measurement applications[25–27].

TABLE 4 *Core topics for Computer Relaying course*

Topic	*Content*
Protection function requirements	Response time, selectivity/dependability, availability/reliability, cost/performance
Computer relay hardware and software	Sampling and filtering, A/D conversion, self-checking, assembler and high level programming
Digital algorithms for relaying	Fundamental frequency algorithms, traveling wave algorithms; fault detection, classification, verification
Approaches to design of relaying equipment	Individual devices, integrated systems, communication facilities
New concepts for relaying	Integrated control and protection systems, adaptive and system wide relaying, expert system applications
Fiber-optic applications	Inter-station and intra-station communications, non-conventional transducers and sensors
Relay testing and evaluation	Industry standards, steady state vs. dynamic evaluation

The basic algorithm form can be represented as a bilinear form of samples of voltage and current signals[25]:

$$BF_n = \sum_{k=0}^{N-1} \sum_{m=0}^{N-1} h_{km} u_{n-k} i_{n-m} = U^T H I \tag{1}$$

where H is a weight matrix.

Distance relaying algorithm is based on one of the following forms:

$$Z = \frac{U}{I} \quad \text{or} \quad Z = R + jwL \tag{2}$$

Using bilinear form representation given by equation (1) the following expressions for impedance measurement are obtained:

$$R = \frac{U^T A I}{I^T B I} \qquad wL = \frac{U^T C I}{I^T D I} \tag{3}$$

As can be observed, the bilinear forms depend on selection of the weight matrices A, B, C and D. Further analysis can be developed to show that distance relaying algorithms can be obtained by selecting proper coefficients of the weight matrices[25]. New optimal algorithms can be derived by selecting some new combinations of the coefficients mentioned[26,27].

Another major topic are the traveling wave algorithms[11]. This is still a research area and as far as the digital relaying implementations are concerned, the topic of traveling wave algorithms can be divided into several categories: distance relaying, directional discrimination, relaying of 'T' feeders[11]. Particular attention should be given to the understanding of the high speed relaying requirements that are the basis for this theoretical development.

5.3 *Design issues*

The main design issue is related to digital processing for relay measurement and logic. The first important step in understanding digital implementation is to study filtering and A/D conversion requirements. This asks for full understanding of the sampling theorem and antialiasing filtering as well as carefull analysis of the synchronized sampling of several input signals and multiplexing them to one A/D converter. The A/D conversion accuracy for a wide dynamic range of input signals and the conversion time have to be studied together with the errors of the finite precision arithmetic that is performed by the processing unit of a relay. Finally, relay sampling rates have to be matched with the algorithm performance characteristics and processing requirements.

Another set of design issues is related to the allocation and distribution of relay functions to the microprocessor hardware. Previous designs were enforced with a straightforward implementation strategy of having one relaying function represented with one device. Digital technology enables implementation of several relaying functions in one design. Typical example of functions of a complex distance relay implemented using single microprocessor-based design is shown in Table 5.

New design approaches are also suitable for mixing of relaying, monitoring and control functions in one design. Typical example of a new design approach in this direction is an integrated substation control and protection system. This design brings a number of different functions in one multiprocessor-based distributed system design. A list of functions of such a system is given in Table 6.

5.4 *Impact of new technologies*

The teaching of such a subject should point out new relaying concepts that can be supported by the new technology. As is well known, the basic relaying concept of a distributed on-off automaton is still the only concept

TABLE 5 *Functions of a complex digital distance relay design*

Directional Inverse Time Overcurrent Protection (back-up)
Phase and Ground Distance Protection
Directional Comparison Carrier Blocking
Three Zone Stepped Distance Protection
Local Breaker Failure Protection
High Speed Reclosing Initiation (3-phase or 1-phase)
Automatic Reclosing with Sinchro check
Sequence of Events Recording
Transient Recording
Fault Locating

TABLE 6 *Functions of an integrated control and protection system design*

Protection	Line, transformer, bus, shunt reactor, out-of-step, local back-up
Monitoring	Pilot channel, transformer, line overload, self checking, breakers and switches
Controls	V/Var, load shedding, switching sequences, synchro check, autoreclosing
Data Acq	Sequence of events, alarms, oscillography, revenue metering, fault location
Interfaces	Man-machine, SCADA/EMS, protection engineer, communication channels

implemented in practice. Most of the developments in the last twenty years have been concentrating on ways to utilize the new technology to design better relays and relaying systems. However, the main relaying concept has remained unchanged.

Discussion of the technology impact should concentrate on the two fundamental issues. One relates to the cost/performance benefits that can be identified by comparing microprocessor-based designs with designs implemented using electromechanical and solid state technology. Another issue is the impact that the introduction of new technology may have on the development of new relaying concepts. In this sense it is important to cover such new developments as adaptive and system-wide relaying. The expert system applications and possibility for interactions between relaying system and Energy Management System (EMS) functions should also be pointed out.

Finally, a close look at the consequences that the new technology may have on the test practice and implementation of the test equipment should also be taken.

6 EXPERIMENTAL STUDY

6.1 *Example 1: Evaluation of fault transients*

This experiment provides the student with an understanding of the fault transient characteristics and the system response performance under these transients. The experiment is carried out using the test configuration shown in Fig. 1.

The experiment consists of several steps including fault transients generation, representation and analysis. Transients are generated using both an EMTP model and an actual fault file captured by a digital fault recorder. The actual fault is recorded in a substation. A specific section of the power system including fault zone is modeled using the EMTP technique. The model of the system is shown in Fig. 2. Both signals from the DFR and EMTP have to be converted to an appropriate file format in order to be displayed. Display of fault voltages is shown in Fig. 3. It should be noted that the voltage signal was recorded from two different types of voltage transformers. The voltage signal shown in Fig. 3(b) is taken by a bus potential transformer (PT), while the signal in Fig. 3(a) is taken by a capacitor coupling voltage transformer

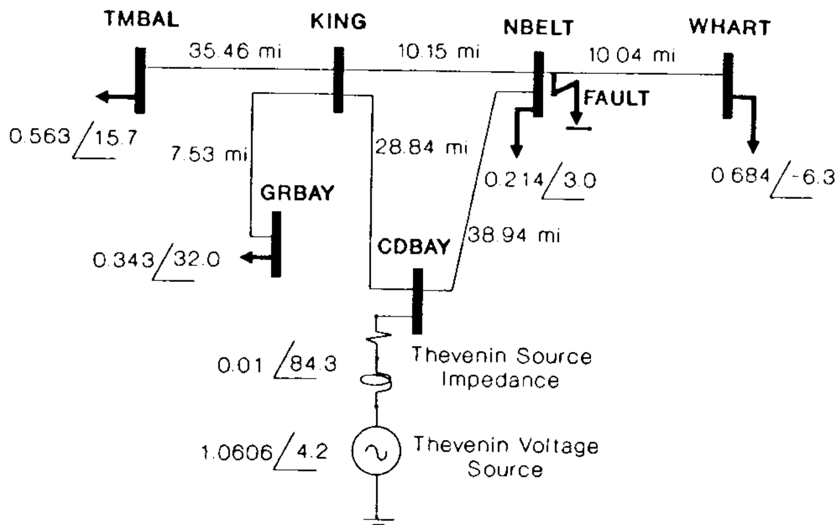

FIG. 2 EMTP model of a power system section.

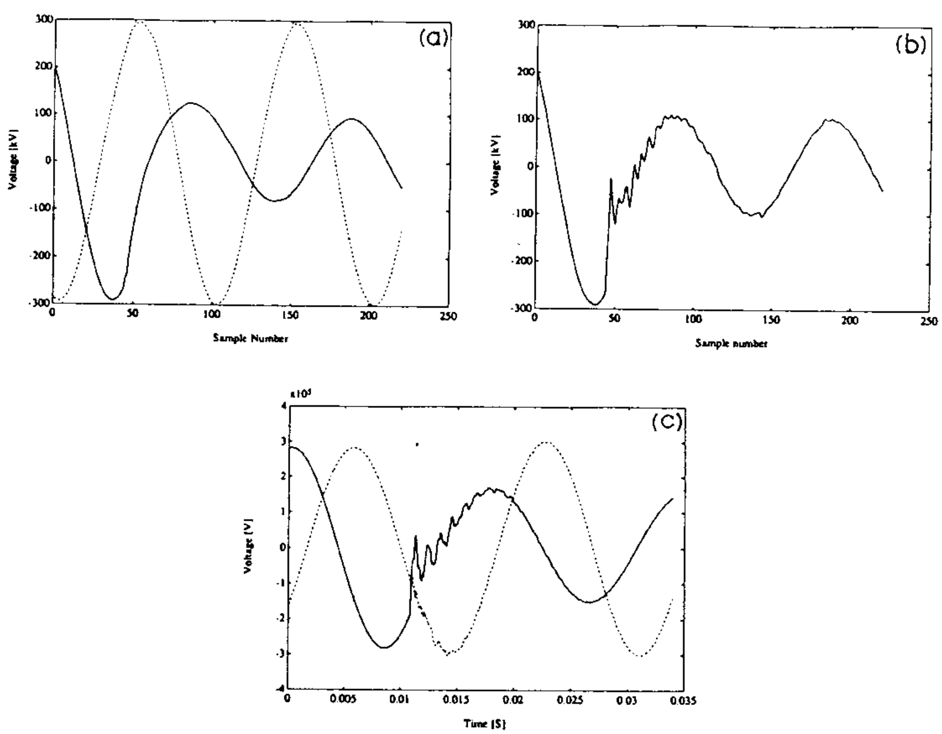

FIG. 3 (a) DFR fault transients (voltage recorded by a CCVT), (b) DFR fault transients (voltage recorded by a PT) and (c) EMTP generated fault transients.

(CCVT), located on the faulted line. The difference in the voltage transients shown in Fig. 3(a) and (b) is due to the filtering performed by the CCVT. The same signal obtained by EMTP, shown in Fig. 3(c) indicates similar transients as obtained by the PT device. The EMTP generated signal corresponds to the primary signal and should be similar to the secondary signal on the PT since the PT does not filter out any relevant transients. This may be observed by comparing voltage transients shown in Fig. 3(b) and (c).

As it can be concluded from this experiment, students are exposed to the experimental methodology of studying fault transients. This experiment can be extended to include study of the fault response of any power apparatus including different types of instrument transformers and different power system configurations.

6.2 *Example 2: Evaluation of digital relaying algorithms*

A large number of experiments can be developed to illustrate to the students the transient behaviour of various digital relaying algorithms. Such a study has been performed by the author in order to evaluate some of the best known digital algorithms for impedance measurements[24]. Similar methodology has been applied to evaluate some new impedance measurement algorithms invented by the author and his colleagues[26,27]. To illustrate the experimental procedure and the type of results obtained, an example of the algorithm sensitivity study is described as follows.

The experiment consists of fault transients generation, filtering and decimation, and the sensitivity study. An example of the sensitivity study is selected to illustrate effect of the change in fundamental frequency on the accuracy of digital algorithms. Two different algorithms for line inductance measurement are selected for this purpose. Represented in terms of the notation given in equation (3), the algorithms have the following forms[27]:

Algorithm 1

$$C = \frac{1}{2\sin\psi}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \qquad D = \frac{1}{2\sin^2\psi}\begin{bmatrix} 1 & 0 \\ -2\cos\psi & 1 \end{bmatrix} \tag{4}$$

where: $\psi = \dfrac{2\pi\omega_o}{\omega_s}$ is an electrical angle between two samples, ω_s is the sampling frequency, and ω_o the system fundamental frequency.

Algorithm 2

$$C = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 2 & 0 \\ -1 & 0 & 0 \end{bmatrix} \qquad D = \begin{bmatrix} 0 & a & b \\ -a & 0 & 0 \\ -b & 0 & 0 \end{bmatrix} \tag{5}$$

where coefficients a and b can be selected in the following way so that the algorithm is not sensitive to frequency change:

$$a = \frac{-2\psi_o + \sin 2\psi_o}{\psi_o \sin \psi_o} \qquad b = \frac{-\sin \psi_o + \psi_o \cos \psi_o}{\psi_o \sin \psi_o} \tag{6}$$

Algorithm 1 is a known algorithm already proposed in the literature[28]. Algorithm 2 is a new algorithm invented by the author and his colleagues[27].

This experiment is carried out by generating test signals using an EMTP model of a long transmission line[24]. A software package for filtering and decimation of EMTP outputs is utilized to reduce the sampling rate to the desired sampling rate of $96s/c$ and $32s/c$ used by the algorithms. Several values of the fundamental frequency are selected for different EMTP simulations. Results representing mean value of the inductance L calculated by the given algorithms are shown in Tables 7 and 8. As can be observed from Table 7, the change in the mean value for Algorithm 1, for $32s/c$ sampling frequency, is approximately $\pm 5\%$ for a change in frequency of $\pm 5\%$. However, Algorithm 2 has an almost constant mean for the same test conditions. This illustrates the different sensitivity of the selected algorithms.

TABLE 7 *L-mean of the known alogrithm under frequency change*

$\frac{s}{c}$ \ Hz	57	59.4	60	60.6	63
96	28.95	29.09	29.16	29.25	29.86
32	20.26	21.27	21.49	21.70	22.58

TABLE 8 *L-mean of an optimal algorithm under frequency change*

$\frac{s}{c}$ \ Hz	57	59.4	60	60.6	63
96	22.06	22.11	22.07	22.01	22.06
32	21.73	21.73	21.74	21.76	21.76

various power system conditions and algorithm design constraints. As indicated earlier, the evaluation study can be easily extended to much more complex evaluation study of both existing and new algorithms[24,27].

7 PRESENT STATUS AND FUTURE NEEDS

The advanced teaching approach proposed in this paper is quite difficult to implement due to some basic teaching constraints. The first constraint is the lack of textbooks on the subject. Even though there are a number of excellent books covering the field of protective relaying, there are very few texts that treat the computer relaying topic[10,11,23]. The situation can be corrected by using some of over 1000 published papers that deal with almost any subject mentioned in this paper. Another constraint is the lack of interdisciplinary background among students attending power system protection classes. This is even more evident with undergraduate classes than with graduate ones. An obvious way to overcome this problem is to spend some time covering the basics of the background needed to continue with the major points raised in this paper. Obviously, a proper balance between all the different topics has to be maintained so that students do not loose track of the protective relaying being the major subject of the course.

The emphasis on experimental study given in this paper is felt to be critical in providing students with the flavor of the design problems. Most of the schools may not have an experimental set-up to accommodate this activity. However, it is the author's experience that an adequate set-up can be easily implemented using commercial software and hardware. The cost of a minimal computer configuration should not be much more than what is spent in purchasing a PC configuration for regular digital design courses. The cost of dedicated software is also fairly low since EMTP packages are usually distributed to universities for a minimal fee. Even though there are a number of other less obvious constraints that need to be resolved in order to implement such an approach to teaching protective relaying, it is felt that it is worth the effort. The main reason is the difference in student interest and motivation experienced by teaching such an advanced course versus the classical power system fault analysis and protection course.

8 CONCLUSIONS

An advanced approach to teaching protective relaying requires interdisciplinary knowledge and extensive experimental methodology. This means that various developments in theory and technology from diverse areas such as control, signal processing, computer engineering and communications have to be presented in such a way that their impact on the protective relaying fields is clearly understood. The main emphasis should be on the new protective relaying device and system designs and new concepts for relaying proposed based on these designs. By implementing this approach, it is felt that the students will get better understanding of the new trends in protective relaying. This may bring a fresh appeal to this classical power engineering field by emphasizing that it is now more than ever an exciting mixture of the art and the science.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support from Texas A&M University and Washington State University expressed by offering the advanced protective relaying courses in their curricula and enabling the author to implement some ideas of the new approach to teaching as described in this paper.

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ABSTRACTS–ENGLISH, FRENCH, GERMAN, SPANISH

An advanced approach to teaching protective relaying courses
This paper introduces interdisciplinary treatment and experimental method for teaching protective relaying courses. The main goal of this approach is to teach students how the latest developments in the theory and the technology have affected the field of protective relaying. A computer relaying course is discussed as an example.

Une approche de l'enseignement de cours de relais de protection
Cet article introduit un traitement interdisciplinaire et une méthode expérémentale dans l'enseignement des cours de relais de protection. Le but principal de cette approche est d'enseigner aux étudiants la façon dont les derniers développements dans la theorie et la technologie ont affecté le domaine de la protection. Un cours de protection numérique est discuté en exemple.

Hochfortschrittliche Lehrmethode für Schutzsignalübertragungskurse
Dieser Artikel beschreibt interdisziplinäre Behandlungs- und Experimentalmethoden für die Durchführung von Kursen über Schutzsignalübertragung. Bei dieser Vorgangsweise kommt es in der Hauptsache darauf an, Studenten mitzuteilen, wie die neuesten Entwicklungen in der Theorie und Technologie den Bereich der Schutzsignalübertragung beeinflußt haben. Ein Computerschutzsignalkursus wird als Beispiel erörtert.

Método avanzado de enseñanza en cursos de relés de protección
Este artículo introduce tratamientos interdisciplinares y métodos experimentales para la ensenanza en cursos de relés protección. El objetivo principal de este método consiste en enseñar a los estudiantes cómo los últimos avances en la teoria y en la tecnología han infuído en el campo de los relés protección. Como ejemplo, se analiza un curso sobre relés de protección.