A Real-time Simulation-based Practical on Overcurrent Protection for Undergraduate Electrical Engineering Students

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ABSTRACT From prior studies, it is evident that computer-aided education can be beneficial in various ways. It has also been observed that class sizes are becoming larger in engineering disciplines as the importance of engineering education is realized more by the communities. Concurrently, in an outcome-based learning environment, practical classes have become more important to better facilitate student learning, preparing them to the relevant requirements of real-life tasks. This study aimed at developing a simulation-based practical for electrical engineering students with an improved educational process while addressing issues of large class sizes vis-à-vis expansion of physical laboratories and noted that it can be as effective as a traditional practical and accommodating large class sizes efficiently. In this tutorial paper, an industry-standard software is used to educate students on distribution system protection through a practical together with a standard assessment method with a model of feedback for evaluation. The paper contributes with an improved educational process through the practical in providing the students with experiences similar to industry work to meet the requirements of professional bodies and industries considering primary teaching and learning outcomes as the focus of outcome-based education system. Also, it delivers as a better platform for the students connecting lectures and practical sessions more effectively with the adopted methodology and approach. Further, it can provide the students exciting opportunity to best practice on systems that are highly related to industry applications in addition to encouraging them for advancing their education in the related niche areas of power systems protection.

INDEX TERMS Simulation, protection, best practices, overcurrent protection, relays, electrical engineering, laboratories

I. INTRODUCTION Practical laboratory sessions are in general integral parts of teaching and learning that provide hands-on experiences to stimulate interest, amalgamate theoretical aspects and opportunities for investigations and experimentations [1]. An engineering curriculum without practical sessions would not possibly be able to deliver the fundamental aspects of the aims and objectives of the same. The sessions at the laboratories promote objectives such as interaction with technical equipment, understanding methods of scientific enquiry, develop observational skills, analyzing experimental data with accuracy [1]. Like others, undergraduate engineering students too go through a certain amount of laboratory experience where they get engaged with demonstrations of various theories taught in the class including the procedure of training for scientific investigations [1]. Hence, laboratory activities in engineering degree programmes follow processes such as direct instructions to the students [2] who are required to follow the provided instructions using instructional methods to arrive at the answers in various forms such as plots, tables, and explanations. There are different categories of established laboratory instructions e.g. expository, inquiry, discovery and problem-based. The mostly used one is the traditional (expository) type due to its advantages such as minimal involvement of instructor, low cost and time-efficient [2], [3]. However, acquiring practical experiences in the laboratory through traditional bench-work is not the only way and neither necessarily the best way [1]. At the age of
availability of so many different ways of doing a practical laboratory, especially, with the advent of educational and commercial software being made available to the schools for teaching and learning purposes bringing academic staffs and students close to new horizons of teaching and learning.

On the other hand, one of the recent concerns in engineering education is that it needs to be more design oriented and exciting to the students. A survey report shows that undergraduate electrical and control laboratory experiences need to improve [4]. The reason might be, in general, in most of the engineering faculties the same type of laboratory experiments are repeated that were designed long ago provided with necessary instructions [5]. The instructions are mostly technical directing the students to go through the steps and obtain the expected results. Apart from technical instructions, some of the practical instruction-sheets also contain the aspects of precautionary measures and safety that need to be observed during the practical session to avoid any harm or injury to any of the personnel or equipment involved. Another important concern raised indicates that practical works in the laboratories lack of relevance to the job requirements of graduates as they are old stereotype experimentations [5]. In fact, as some of the traditional practical were developed long ago and using very old equipment, they do not necessarily excite the students much apart from very few exceptional students who rightfully take the opportunity to inquire beyond expectations. Further, the real-life industries have been equipped with the most modern and sophisticated technologies in terms of both hardware and software. Certainly, the existing gap between what is being used in the laboratories and what is being used in industries needs to be bridged rationally.

Additionally, one of the most important requirements of electrical engineering students of these days is that they must be equipped with software skills to solve engineering problems using computer algorithms as it saves time, money and can provide the efficient predictions of a similar physical system. According to Engineering Council of South Africa (ECSA) that sets and monitors standards to international norms to ensure the quality of engineering education in South Africa [6], the engineering students should demonstrate competence to use computer software packages for computation, modelling, simulation and information handling [7]. These requirements should be helping the students in the process of enhancing their personal productivity and teamwork as a whole which is one of the most important requirements in industry as every single employee works as a part of a team and contributes to the end-product or outcome in many different forms. According to [8], acquiring skills in industry-standard software should be mandatory within accredited engineering degrees as demanded by The Institution of Engineering and Technology amongst other professional engineering institutes.

Therefore, it is imperative that new approaches have to be explored. This can include but not limited to wide range of new teaching and laboratory material, computer simulation, software assisted instructions, software tools to demonstrate both theory and real-life problems [4] [9]. At present, many universities are using alternative approaches for traditional laboratory for undergraduate courses [1], [2], [9] [10]. This in turn helps to motivate the students as they come across these new approaches that provide them with experiences and the flavor of their future workplaces. Nonetheless, the laboratory activities are being reformed due to the fact that education process itself is going through evolution with the advent of new technology resources [2] made available to the academic institutions, especially in outcome-based educational approach [2], [10], [11]. The curriculums are being improved almost in every academic institute at regular intervals as and when there is a need to introduce new specialist areas of teaching and practical. However, it needs to be considered that it is almost impossible to convert all the traditional practical to other forms that have more advantages [2]. It would be irrational too not to have any traditional experimentation which would simply deprive the students from having experiences of the same although the students might gain a lot of knowledge and experiences from other forms of practical experiments.

As the education has become one of the most important prerequisites for all the stakeholders in the society, it is obvious that there are large numbers of students in many classes in many academic institutions across the globe including undergraduate engineering programmes. It is challenging and unreasonable at the same time to expand some of the laboratories with increased number of students. Also, some laboratories are very expensive in terms of specialist equipment, and specialist technicians, and large areas of floor space required to maintain those [1]. As advancement of software development has been playing a great role in educating students of traditional engineering subjects such as electrical, mechanical, or civil engineering, it would be wiser and impactful to bring computer software support to experience an attitudinal change among the students because appropriate use of software permits the students to gather knowledge with the opportunity to explore the equipment to be used beforehand in a safe manner and real-life machinery way [12].

As the faculties in electrical power systems are challenged with problems in providing the students of large class-size with true nature of power systems, a feasible route is to allow them to utilize the modeling and simulation tools [13]. So, a perception to develop a simulation-based practical where students can utilize the existing computer laboratories was conceptualized. It was also felt that the practical studies should be more relevant to the best practices in industries. This motivated the development of a practical on distribution system protection using overcurrent relays which is one of the most fundamental types of protection in electrical power systems. The reason for choosing a practical on protection system is that protection is essential all power systems networks and equipment [14], [15], [16], [17], [18], [19] and every electrical engineering student needs to assimilate its significance and implementation appropriately. The offered practical is similar to the real industry-problem, employs
necessary teaching approach and utilizes RSCAD, which is a proprietary software suit of RTDS Technologies so as to impart the experiences of real-world problem in more meaningful ways.

In [20], the author presented a simulation study of overcurrent protection coordination of a distribution system which is useful in education and training of future power systems engineers. Emphasizing on this particular focus of education, instilling knowledge and skill-sets, the author aimed to improve the process of learning in a step-by-step manner; the author has also included some of the fundamental but important aspects such as inclusion of instantaneous overcurrent relay and a system configuration where there is a parallel feeder in between buses which accommodates an additional and significant learning that both feeders (in parallel) must be tripped for a fault at the downstream bus. Further, verification of time of operation (including grading margin) of the relays with their types and inverse characteristics that can be chosen from the configuration has been one of the focal points of this proposed practical. Further, in this paper, a teaching and learning methodology has been accommodated including a simple but useful model of assessment method and evaluation of module feedback. The practical includes operation of instantaneous, and phase time overcurrent relays with standard characteristics, simulation of fault conditions, calculations and verifications of time multiplier settings (TMS), operating times of relays and coordination of relays including grading margins. Hence, the students gain technical skills in setting protective relays, verifying their operations and also in technical communication as they produce a technical report based on this practical.

Further, the approach undertaken ensures that the learning outcomes of the new approach remains the same compared to the traditional ones and health and safety of the students [1] are accounted for, in fact improved as the students would only be using computers in the computer laboratories or their own computers at remote locations and there would be no electrical hazards present from the practical itself.

The paper is organized in the following manner: Section II depicts the adopted methodology focussing on teaching and learning outcomes, while Section III illustrates the selection of software and practical considering the overview of the software used, selection of practical area and practical undertaken while Section IV provides an executive summary of the practical undertaken with reasoning, teaching and learning approach, teaching and learning outcomes, and the results the students are expected to achieve in a step-by-step method. Section V considers the assessment method adopted while Section VI shows the evaluation and assessment adopted considering the feedback from students. Section VII presents achievements, impacts and future aspirations. Finally, section VIII concludes the work presented in the paper.

II. ADOPTED METHODOLOGY

This work being a part of outcome-based education, utilizes the most commonly used Bloom’s taxonomy in determining the teaching strategies to support and improve the process of learning in such a way that the students progress in terms of cognitive levels [21], [22], [23], [24]. Similar to the typical aspects of any traditional educational program, aim(s), teaching process and evaluation are included in this proposed work in line with cognitive levels of knowledge, comprehension, application, analysis, synthesis and evaluation of Bloom’s taxonomy as shown in Figure 1 [21], [22], [23], [24]. The main concept of the adopted methodology following cognitive learning process is that the academic instructor design the educational aims according to educational objectives related to the subject matter and choose appropriate teaching process ensuring that the students get through successfully from one cognitive level to the other. The students are provided with the necessary information and knowledge on the subject matter on overcurrent protection in the classroom lecture and training on the software before they engage themselves with the practical. in the very next step, they are also taught on the methodology for efficient analyses to ensure that the comprehension level is achieved. In the very next step, the students apply the acquired knowledge and skill onto the assigned practical and achieve the desired results and they should be able to analyse the results they obtain followed by synthesis where they integrate some planned ideas for the last sections of the practical where they would have to demonstrate the competence in protection coordination. In this process, the students should be critically evaluating the relevant decisions with necessary supports and evidences. They prepare (create) an exclusive technical report based on the practical exercise demonstrating their acquired knowledge, skills (related to psychomotor domain), understanding of the subject matter including communication skill in terms writing from the perspectives of exit level outcomes. The effectiveness of the process is primarily determined by the process, steps followed by the educator and the students [21], [22], [23], [24]. Based on all this fundamental principles, the adopted mythology was formulated and utilized in this work for the proposed practical including assessments which are demonstrated in the following sections of the article.

III. SELECTION OF SOFTWARE AND PRACTICAL

The demand of skills required is ever growing in the field of electrical engineering. Especially, the power systems area
demands a lot of study through simulation, as it is practically impossible to have and study a large and real power system network connected with numerous controllers, and with obvious dynamic nature of the power system itself associated with continuously variable power generation, transmission and distribution with various types of connected consumers. Although there are a number of electromagnetic transient simulation software available for power system studies such as Matlab, PSCAD, Electrical Transient Analyzer Programme (ETAP), DigSilent PowerFactory, Power World, OPAL-RT, most of the software used for power system studies are non-real-time in which the users study a certain phenomenon on a given power system model for the time period of interest. Also, some of them do not have the necessary components such as protective relays for simulation of a power system protection case studies in a realistic manner. For example, Matlab and PowerWorld provide library blocks for standard power systems studies but do not support protection aspects. Features for protection studies are available in DigSilent PowerFactory, PSCAD, and ETAP and allow range of protection concepts including overcurrent protection, however, these are of non-real-time type. Although OPAL-RT provides a real-time scenario, RTDS/RSCAD outperforms in many aspects such as the protective relays, protection transformers, circuit breaker, faults, dial, slider, push button blocks in the library resemble the real-life commercial ones with necessary settings and controls making it much easier for implementation and simulation of protection studies together with fault analyses simply using the existing library blocks providing the essential experience equivalent of a practical using real equipment. Further, RTDS/RSCAD is very popular as it is the world’s benchmark for real-time power system simulation and popular in many countries such as United States of America, China, India, South Africa to name a few across the world. RTDS/RSCAD provides technical supports and solutions to the users as and when necessary both locally and from the central support system including training material and resources, especially, it provides immense supports to the academic institutions in terms of licencing and discounts. The software can be installed on a number of desktop/laptop computer with Windows Operating System and simulation studies can be performed from remote locations. Further, real-time digital simulator (RTDS) and RSCAD make it possible to have a real-time study, in a manner similar to a real power system operates, enabling analytical studies to be performed much faster than off-line simulation programs [25]. In such a real-time simulation platform, a user can interact with the system, dynamically to observe any changes in quantities of interest in real-time. Further, RTDS and RSCAD allow the users to physically connect hardware such as protective relays, controllers where inputs signals are taken out of software simulation connecting the physical equipment and output signals from the physical equipment are sent back to the simulation through RTDS hardware. Therefore, learning simulation studies and mastering skills provide the electrical engineering students experiences of real-world power network scenarios.

A. OVERVIEW OF THE SOFTWARE USED

The RTDS was originally developed at the Manitoba HVDC Research Centre in Canada in the 1980s with the first commercial installation of the RTDS took place in 1993 which is now owned by RTDS Technologies. RTDS is the world’s benchmark for performing real-time digital power system simulation [25] consisting of custom hardware and all-in-one software RSCAD designed to carry out real-time electromagnetic transient simulations which continuously operates in real-time to provide accurate results. The software suit RSCAD is used to prepare and run simulation, and to view and analyze results.

The RSCAD suit includes a number of modules such as Draft, Runtime, CBuilder, Multiplot, Cable, T-Line that are used for simulation study of power systems models together with physical hardware such as controllers, protective relays interacting with the simulation model during simulation runtime [25], [26]. For a power system circuit to be studied using RTDS, the Draft module is used together with the Runtime module. The Draft module has a drawing canvas which is used to develop the power system models that consist of various power systems components such as generator, motor, transformer, transmission line, voltage source, resistance, inductance, capacitance, dynamic load together with controls components such as mathematical functions, logical functions, signal generation, signal processing, data conversion, metering and protection. To run a simulation case, RunTime software module is used where the users set up the interface with the power system that is built in the Draft programme using various components such as meter, plot, switch, push-button, slider, light etc. [26].

B. SELECTION OF SIMULATION-BASED PRACTICAL AREA – REASONING

The students attending the practical would be from electrical engineering undergraduate degree programme where they study fundamental subjects such as natural sciences, mathematics and electrical engineering principles before entering into core subjects such as electrical machines, power systems, power electronics, control systems, high voltage engineering. The students attend a certain number of practical hours as per the subject credits and guidelines in line with requirement of learning outcomes. In general, as for the number of laboratory hands on is one for each subject area whereas the number of students may vary in the range of 50–70 over the years in an established programme. The associated students study power systems as one of the core subjects starting from fundamentals of power systems to theoretical aspects of protection of power systems are encompassed. Naturally, the power systems subject aims to provide appropriate hands-on and simulation experiences to stimulate interest, amalgamate theoretical aspects and opportunities for experimentations and investigations. In this paper, the area of power systems protection is chosen for the practical as it is one of the fundamental types of protections in electrical engineering [14], [15], [16], [17], [18], [19].

To prepare and stimulate the minds of future electrical engineering students experiences of real-world power network scenarios.
enginners, it is vital that laboratory experiences complement the theoretical aspects taught in the class as well to demonstrate engineering from the first principles but not forgetting electric utility practicalities because that is where graduate students would apply the knowledge they acquire. Use of simulation-based practical for electrical engineering is ergonomically advantageous compared to traditional practical where a set of practical equipment are available to a group of students. For the simulation of a practical, a student would need a computer system with the simulation software installed in it [4]. This eliminates the need for actual practical equipment and laboratory space as well because the students would use the existing computer laboratories. This also reduces the involvement of technical staffs associated with traditional practical [4].

As practical laboratory experience is extremely important in engineering to develop skills and competencies required by industries [5], this simulation-based practical has been purposefully and carefully designed considering teaching and learning outcomes as well as industry needs such as the future power engineers should be capable of designing a protection scheme for a distribution system using all the necessary protective gears that include selection of protection transformer ratios, selection of types of relays required, setting of overcurrent relays, consideration of overcurrent and fault conditions at various locations, selection of pick-up currents and time multiplier settings, selection of inverse characteristics, operating time calculation of a relay in various operating/fault conditions including a circuit breaker failure, grading margin and protection coordination. The main reason is that if a student is introduced to a real-life industry-problem, the experiences can become manifold as it can motivate and stimulate the students to a great extent. As a matter of fact, this can be benefitting the academic and technical staffs involved in the process as well. Although this is not the first real-time simulation-based practical in the world, the endeavour is to introduce the students to the power systems protection area to exploit the advantages of the RTDS/RSCAD that can simulate power system protection aspects in a similar manner to real-life scenario. Finally, the narrowed down area arrived at was simulation of distribution system protection using RTDS/RSCAD. The configuration of the distribution system was adopted from [27]. The distribution system, the relay settings, breakers, sources, fault locations, etc. are based on an example case developed in [27] by using actual data taken from a modern numerical relay of the very own manufacturer. However, the same teaching and learning objectives can be achieved using other network configurations such as an IEEE bus system with respective protective gears of similar features and careful design of the protection scheme. It would be possible develop all types of overcurrent protection circuits using all the necessary components and run/test as real-life projects.

The students could be provided with lectures sessions on overcurrent conditions in electrical distribution systems, and the use of protective devices such as fuses and overcurrent relays together with different characteristics of overcurrent relays, their application areas. Further, they could be tutored with examples of calculations of fault currents at various locations of the system and reasons of failure of a relay and/or circuit breaker to isolate the faulty part of a power system although there is a persisting fault in it. They also need to be taught on grading margin required if a relay fails to detect a fault or to pick-up or a circuit breaker fails to open in the event of a fault detected by the relay, the relay in the upstream of the system must detect the same fault condition and ensure the opening the associated breaker after certain time delay so as to protect the system and the equipment connected to it from any possible thermal and mechanical damage as consequences.

C. SIMULATION-BASED PRACTICAL UNDERTAKEN – COGNITIVE THINKING

Prior to the practical, the students be provided with practical-sheets to prepare themselves for the practical and write-up a pre-practical report which be assessed and taken into consideration as a part of examination. The students do the practical with the guidance of the associated lecturer and on completion submit a post-practical report which would also be assessed. With this traditional approach, the students are having limited approach apart from they are being helped out by the academic staff and obviously none of the students would try to repeat even a part of the experiments to verify the previously obtained results which could in turn develop a very good observational skill in them. Therefore, the main aim of this simulation-based practical is to provide the students with the followings:

- Use of industry-standard software and acquire skill in solving power systems problems quickly and efficiently, and meeting ECSA Exit Level Outcomes (ELOs) or graduate attributes (GAs) requirements.
- Help the students to observe similarities/dissimilarities for the quantities of interest which in turn can instil thoughtfulness in the students’ mind.
- Avoiding errors in results due to metering imperfections (due to wrong scale choice, wrong choice of meter (e.g. low power factor watt-meter), vertical/horizontal orientation unless all meters used are digital, or calibration of the meter).
- Production of end-results from the software (snap-shot or continuous) which are much more accurate as compared to plotting a graph or preparing a table with some selected data values. This also serves a saving in student-time to prepare their post-practical report.
- Making the practical hundred per cent safe (from any electrocution).

With simulation-based practical, it is very easy to change the system, as compared to traditional ones where actual equipment is required for any change in practical set-up. This allows the academic staff to create a number of practical cases for different students and they would be doing the same practical but with different sets of software equipment which is almost impractical in a traditional practical. Also, the
academic staff can help the students during the practical being outside of the laboratory using remote-desktop functionality of computer operating systems. In addition, this approach serves a saving in technicians-time generally involved in practical that can be utilized for helping the students for many other useful purposes.

Apart from the design of a simulation based practical for final year electrical engineering students using industry-standard software this work also examined the specific content of the practical as it would be related to final year module where ECSA ELOs or GAs are assessed on the basis of experimentation, data analysis and investigation [7]. This was ensured through a combination of the teaching and industry experience of the academic staff involved and by knowledge of educational theories to warrant the teaching and learning interesting, and meeting industry needs at the same time.

IV. DESCRIPTION OF PRACTICAL UNDERTAKEN

Utilizing the adopted methodology and from the perspectives of the learning outcomes of the practical exercise, the students have to conduct simulation studies and investigations on a given system designed by the academic instructor in the field of power systems protection and prepare a written technical report upon completion of the task presenting the expected results and analyses for assessment purposes. The more focused area and aim of the practical are to familiarize the students with the working of overcurrent relays, especially, phase instantaneous, time overcurrent relays with inverse time characteristics e.g. IEC standard inverse, very inverse characteristics. The students would be acquainted with the coordination of relays with their applications for protection of a distribution system using real-time digital simulation software RSCAD.

FIGURE 2. Distribution system [27]

1. Understanding working of phase instantaneous overcurrent relay (RELAY F1)
2. Understanding phase time overcurrent relay (RELAY F2)
3. Calculation and verification of operating time of phase time overcurrent relay (RELAY F2)
4. Understanding and setting of phase time overcurrent relays (RELAY 1-4) for protection coordination with fault conditions

FIGURE 3. Diagrammatic representation of the practical exercise

The students need to have prior knowledge in the area of overcurrent protection which they are taught in the lecture sessions with examples using overcurrent relays and the procedure for protection coordination for a given power distribution system. Special instructions alongside the conventional instruction-sheet on how to use RTDS and RSCAD efficiently need to be provided. The students should also be informed with the use of RTDS racks on their availability and effective utilization of time to get their system ready for simulation.

The distribution system considered for the practical is as shown in Figure 2 [27] with the diagrammatic representation of the exercise in Figure 3 where there is a phase instantaneous relay (Relay F1) and phase time overcurrent relays (Relay F2, and Relays 1–4). All the relays require the user to set the pick-up value of the relay on the software system. However, for the Relays 1–4, time multiplier setting is also a requirement. The phase time overcurrent relays can be set to the desired characteristics, e.g. IEC standard inverse or very inverse as shown in Table 1 where TD is time dial options which is also known as time multiplier setting and M is multiples of pick-up current. Modern numerical relays allow the use of user-defined tripping characteristics, besides IEC and ANSI standard characteristics. [14], [19]. Many other relevant and useful characteristics can be found in [19]. It is intended that the primary protection (the main/dedicated protection) is to clear the fault as fast as possible to reduce any damage to the system while the backup protection must operate should there be a
failure in primary protection scheme. However, the operation of backup protection causes isolation of larger part of a network as compared to the primary protection. Therefore, to reduce undesired disconnection of any part of a network, appropriate coordination is necessary [15], [17], [28]. Overcurrent protection schemes are much more economical and can be employed without any expensive accessories to provide faster, reliable and selective fault clearing as compared to other types such as distance and differential protection systems [14], [19].

In terms of proper protection coordination, incorporated grading margin is chosen typically and it depends on the circuit breaker operating time, dropout time, and safety margins. Using overcurrent relays, selectivity can be achieved through time grading although it might cause high tripping time in some applications depending on the grading path. The issue of higher tripping time with heavier faults due to grading margins can be overcome by the application of inverse definite minimum time relays which can clear heavier faults at the upstream with decreased operating time. However, grading time should also be considered carefully to ensure selectivity [14].

| IEC Characteristic curve type | Operating time equation |
|------------------------------|-------------------------|
| Standard inverse             | $T_D \left( \frac{0.14}{M^{0.02} - 1} \right)$ |
| Very inverse                 | $T_D \left( \frac{13.5}{M - 1} \right)$ |
| Extremely inverse            | $T_D \left( \frac{80.0}{M^{2.0} - 1} \right)$ |
| Long time back-up            | $T_D \left( \frac{120.0}{M - 1} \right)$ |

As shown in Figure 3, for the practical exercise, students are required to understand and demonstrate working of phase instantaneous and phase time overcurrent relays. Once the students acquire sufficient knowledge and confidence on the operational aspects of these relays, they should be able to set phase time overcurrent relays and achieve proper protection coordination considering grading margin for fault conditions at different buses.

**A. TEACHING AND LEARNING APPROACH**

Apart from previous teaching session in the class room lectures on the overcurrent protection aspects, at the beginning of each practical session, the academic staff involved should provide a short introduction and training to the students on RTDS/RSCAD including power systems components, and protection devices including their controls and necessary measurements. The session would also cover few small example cases on how to develop a power system network on the Draft module of RSCAD, wise selection of component blocks from various sections of library.

One such snap-shot is shown in Figure 4 where a voltage divider circuit has been developed from RSCAD example [26] using a three-phase voltage source, bus connectors, resistances, and ground connection. It also shows the use of a three-phase root mean square (r.m.s.) block to illustrate how to measure r.m.s. voltage of three-phase nodes. The students would be introduced to the RunTime module after error free compilation of the Draft circuit. On the RunTime canvas, the students would learn how to use control components such as slider to control voltage, frequency or phase angle of the voltage and how to display them e.g. using meters, plots. A snap-shot the RunTime is shown in Figure 5. It also depicts different plots that show the real-time results for the simulation.

**TABLE 1. IEC inverse characteristics [19]**

**FIGURE 4. A snap-shot of draft module**

**FIGURE 5. A snap-shot of runtime**

Therefore, the teaching and learning approach undertaken can be summarized as follows:

- Teaching and learning of overcurrent and fault conditions in the lecture sessions.
- Teaching and learning of power systems and equipment protection due to overcurrent using fuses and overcurrent relays.
- Teaching and learning of practical examples of fault current calculations.

**B. TEACHING AND LEARNING OUTCOMES**

In the process of developing the practical, the broad technical objectives are listed as follows:

- To understand the working of a phase instantaneous relay (Relay F1) and phase time overcurrent relay (Relay F2).
• Setting Relays 1–4 for three-phase fault conditions at Buses B and C and ensuring proper protection coordination of relays.

From the broad objectives and perspectives of ECSA ELOs or GAs, the following learning outcomes are structured:

• Students are required to conduct the simulation study using the specified software to determine or predict the specific outputs of the study.

• Students are required search related literatures and evaluate them as to how the knowledge gathered helped them in the related simulation study.

• Students are tasked to obtain specific results based on simulation study and analyse them technically.

• Students are supposed to ensure appropriate selection of equipment or tools for the simulation study.

• Students should be interpreting the results obtained and conclude with proper reasoning.

• Students should be able to communicate technically on the simulation practical.

C. EXPECTED SIMULATION RESULTS FROM THE STUDENTS

As mentioned earlier, the students would have to demonstrate competence in understanding overcurrent protection for the distribution system considered, they would have to study the following cases and produce expected results as follows:

1) WORKING OF PHASE INSTANTANEOUS OVERCURRENT RELAY (F1)

Relay F1 is a phase instantaneous overcurrent relay which compares the actual value of current with the pick-up value set by the user and generates a trip signal for the associated circuit breaker to open and isolate the faulty part of the system once the actual value of current exceeds the pick-up value without any intentional time delay. In this case study, the students would be expected to understand how the pick-up value of a phase instantaneous relay can be set in realistic manner and increase the circuit current and hence the current seen by the relay for it to generate the trip signal upon exceeding the pick-up value.

![Figure 6: Increased load on the feeder](image)

![Figure 7: Increased load – Relay F1 to pickup](image)

In this regard, the students would run the simulation first and then increase the electrical load (using the slider) to a certain value (e.g. 3.6 MW as shown in Figure 6) so that the current seen by the relay (4.963 A) is less than the pick-up value (5.5 A) of the relay. Therefore, they should observe that the relay would not trip and load current still be supplied as shown in Figure 6. Hence, the TRIPF1 remains at ‘0’ indicating that the relay has not generated the trip signal and the BRKF1 remains at ‘1’ indicating that the Breaker 1 remains in closed condition. The students should be observing the pick-up value of the relay and current seen by the relay during the operation. In the next step, the load is increased to value (e.g. 4.1 MW) that will cause the current through the relay coil from the previous value of 4.963 A to exceed the pick-up value (5.5 A) causing the relay to trip instantaneously which is shown in Figure 7. The students also need to understand and explain that there is no time delay between the occurrence of overcurrent, generation of the trip signal and opening of the circuit breaker as the relay is of instantaneous type.

2) WORKING OF PHASE TIME OVERCURRENT RELAY (F2)

Relay F2 is a phase time overcurrent relay which compares the actual value of current with the pick-up value set by the user and generates a trip signal for the associated circuit breaker to open and isolate the faulty part of the system once the actual value of current exceeds the pick-up value with an intentional time delay determined magnitude of the current seen by the relay, pick-up value, time multiplier setting and the chosen inverse characteristic e.g. standard inverse, very inverse of the relay. In this case study, the students would be expected to understand how a phase time overcurrent relay can be set in a realistic manner and increase the circuit current and hence the current seen by the relay for it to generate the trip signal upon exceeding the pick-up value and verify the operating time of the relay. To work with the Relay F2, the students need to open the relay box RelayF2 and follow the instructions. BrkF2 is the switch for blocking/de-blocking the relay, CLOSEF2 is to close the CB after tripping. LoadF2 is to change the load on the feeder, IBURF2 shows the r.m.s.
value of CT secondary current, curve type dial shows the selection of characteristic curve (e.g. very inverse) for the relay, IpF2 and TmF2 are the pick-up value and time multiplier settings of the relay. The settings completed by the students are observed in Figure 8.

In the next step, the students should be instructed to change the LoadF2 to 3.0 MW from its initial value of 2.3 MW, observe the phenomenon and explain it. Verification of the operating time of the relay showing both the values obtained from calculations and simulations should be completed at this stage. The simulation results shown in Figure 9 for the change of LoadF2 to 3.0 MW where IBURF2A, IBURF2B, IBURF2C are the instantaneous values of currents in the associated Relay F2 and IRF2rms is the r.m.s. value of the current seen by the relay. It also shows that the BRKF2 is initially at ‘1’ indicating that it is in ‘closed’ condition and goes to ‘open’ condition due to the initiated overcurrent condition. The trip signal TRIPF2 generated by the Relay F2 is shown in the Figure 9. Figure 10 illustrates determination of operating time of the Relay F2 which would be compared with the calculated value for verification purposes.

Using the formula of the chosen inverse characteristic, in this case the very inverse characteristic (the equation is shown in Table 1) the student would verify the operating time of the relay calculated from the current (5.52 A) and for a pick-up value of 5.0 A (found to be 1.298 seconds) and that obtained from simulation results as shown in Figure 10 (found to be 1.2926 seconds).

In the following step, the students are supposed to understand the significance of time multiplier setting (TMS) which would be increased to 0.02 from the initial value of 0.01. The results are shown in Figure 11 and the operating times (which is now larger than the previous one) are found to be very close to each other; calculated value using very inverse characteristic equation as shown in Table 1 being 2.596 second whereas simulation results showed it to be 2.511 seconds as shown in Figure 11. This clearly demonstrates how the students would effectively achieve the results and understand significance of the TMS and its impact on the operating time of the relay with constant load current of the system.

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The verifications through observing the simulation results as shown in Figures 12 and 13 respectively for the operation of the Relay F2 and determination of the operating time of the same (found to be exactly 2 seconds) should be done by the students as they should be instructed to understand the effect of load current on the operating time as well. Therefore, they would have to demonstrate it with another value of load and same TMS. Furthermore, the students are supposed to set the Relay F2 to operate at 2 seconds with of 3 MW load on the feeder. Therefore, the students need to calculate the TMS (using the equation shown in Table 1) for this relay and demonstrate that the relay takes time to operate which is close to 2 seconds.

3) DEMONSTRATION OF SETTING RELAYS 1–4 FOR FAULTS AT BUSES (B AND C) AND ACHIEVING PROPER PROTECTION COORDINATION BETWEEN THEM

Relays 1–4 are phase time overcurrent relay for which all the necessary setting are required to be set by the user as was explained for the Relay F2. This case study is for the students to understand the requirements, implementation and achievement of proper coordination of the associated relays.

The first instruction for this cases study for the students is to demonstrate the tripping of the Relays 1 and 2 at ‘t’ seconds with a pick-up value of 1 A and a three-phase fault BUS C (‘t’ is supplied to the students during the practical and different students would have different values of ‘t’). For this, the students are supposed to find the TMS of Relays 1 and 2 first which they should obtain using the fault current, pick-up value and the inverse characteristic formula. For an example, value of t=2 seconds, the fault current should be 10 A (IBUR1) as shown in Figure 14 and the corresponding calculated TMS to be 0.6733 (using the equation shown in Table 1). IBUR3 and IBUR4 are the currents seen by the Relay 3 and Relay 4 respectively.

The results obtained from the simulation as shown in Figures 15 and 16 should be obtained once a fault is applied with the calculated value of the TMS for Relays 1 and 2. Figure 15 shows that the signal FLTB is at ‘0’ while FLTC is at ‘1’ indicating that there is no fault at BUS B but at BUS C. Figure 16 shows the trip signals TRIP1 and TRIP2 from Relay 1 and Relay 2 respectively at the same instant.
It also should be noted by the students that Relays 1 and 2 are in parallel feeders connected to the faulty bus and hence they must operate at the same time to open the respective circuit breakers (BRK1 and BRK2) which is shown in Figure 17.

The students are supposed to observe the operating time of the relays (including the opening of the circuit breakers 1 and 2) from Figures 15, 16 and 17 as the fault is applied at 0.5 seconds and the relay issues the trip signals at 2.5 seconds, hence ensuring the operating time to be 2.0 seconds.

The following step is to achieve protection coordination for the same fault at the same location in case Relays 1 and 2 and/or respective circuit breakers (CB) fail to operate due to various reasons (failure/s in CB, tripping mechanism, tripping voltage, protective relay etc.). In such a case, the Relay 3 has to operate with a grading margin of 0.4 seconds. Hence, the TMS for the Relay had to be calculated (using the formula shown in Table 1 and grading margin) and found to be 0.808.

Figures 18 and 19 show the non-operation of the Relays 1 and 2 and respective breakers while the operation of the Relay 3 and breaker 3 for the same fault at BUS C. The students are also supposed to note the time (do the calculation using the equation shown in Table 1 for verification) when the breaker 3 opens as it includes the grading margin.

Finally, the students are required to grade the Relay 4 for a fault at BUS B with a grading margin of 0.4 seconds. To achieve this, the operating time the Relay 3 is required for a fault (FLTB) at BUS B only with no fault at BUS C as shown in Figure 20. Figure 21 shows the trip signal (TRIP3) from Relay 3 for a fault at=0.5 seconds giving the operating time to be 2.23 seconds.
Hence, the operating time of the Relay 4 should be 2.63 seconds. This assists to determine the TMS (using the equation shown in Table 1) for the Relay 4 which is found to be 0.528. With a fault at BUS B and Relay 3 being made inactive, the obtained simulation results are shown in Figures 22 and 23 respectively.

![FIGURE 22. Relay 4 trip signal](image22)

![FIGURE 23. Breaker status (BUS B)](image23)

They illustrate that there was no trip signal issued from the Relay 3 and hence Relay 4 had to pick-up to cause circuit breaker 4 to open to isolate the fault. Again, the students are required to take note of the operating time of the Relay and grading margin included in it. In this example case, the grading margin obtained from simulation was found to be 0.385 seconds which is very close to 0.4 seconds (an error of +3.75%).

All this case studies implemented on a real-time industry standard application software with components featuring all the practical aspects of real equipment, on the settings and operations of phase instantaneous and phase time overcurrent relays, their testing for operations including operating time, proper coordination of a number of associated relays completed by the students provide them with a great deal of necessary knowledge and skill-sets required of them to work in the practical field as a professional electrical engineer, especially, in the niche area of protection of power systems which is of utmost importance.

**V. MODEL OF ASSESSMENT METHOD**

To ensure that the students tested effectively considering all applied levels of Bloom’s domains by aligning the assessment method with the exercise and techniques the following assessment criterion be considered to evaluate the students on completion of the practical:

- The extent to which the students are able to correctly conduct different sections of the study under carefully-controlled changes in operating condition is assessed via the correctness of the results obtained.
- To the extent on the students’ ability to explain the reasons for the particular findings in each section of the investigation in terms of theoretical material covered in the course.
- To the extent the students are able to analyse data and results, and document them in the post-practical report supported by necessary theoretical background.
- To the extent the students are able to select and use appropriate equipment, meter, and features of the software in use.
- To the extent the students are capable of drawing appropriate conclusion based on obtained evidences or reasonable responses.
- To the extent the students are able to communicate technically in written form the purpose, process and outcomes of the study.

All the above assessments should be internally done by the academic staff involved and externally examined to meet the ELO or GA requirements.

**VI. EVALUATION AND ASSESSMENT – FROM MODULE FEEDBACK**

Examination and evaluation of ELOs or GAs could be conducted using traditional methods. Performance this proposed approach using the software-based simulation practical, could be compared with a similar traditional one.

| Questions/score                                                                 | 1 | 2 | 3 | 4 | 5 | Mean |
|--------------------------------------------------------------------------------|---|---|---|---|---|------|
| Simulation-based practical is helpful to the students                         | - | - | - | - | - | -    |
| Choice of software for the practical was good                                 | - | - | - | - | - | -    |
| Choice of practical area was good                                             | - | - | - | - | - | -    |
| The instructions on the practical were well facilitated                       | - | - | - | - | - | -    |
| You were comfortable on using the software for the practical                 | - | - | - | - | - | -    |
| Teaching and learning approach is appropriate                                 | - | - | - | - | - | -    |
| The practical on distribution system is beneficial                            | - | - | - | - | - | -    |
| You are now used to the features of overcurrent relays                        | - | - | - | - | - | -    |
| Preparing post-practical report was easier than other practical               | - | - | - | - | - | -    |
| The same practical should be run every year                                   | - | - | - | - | - | -    |
| Overall                                                                      | - | - | - | - | - | -    |
Most importantly, comments made on completion-of-course questionnaires by the students would indicate on the design of the practical, and its suitability for final year electrical engineering students. A standard method is used to prepare a feedback form for the students using logically developed structured set of questions on the practical work attended by them as shown in Table 2. The reasons being it is a typical and natural way to reach out to the students as it is easier, simpler, less time consuming and less expensive. Further, the data collected could be stored in a database for necessary expert evaluation in terms of relevant quantitative analyses. Table 2 would show the responses (the numbers in the rows would show the number of students response) corresponding to various aspects to a five-point scale according to standard procedure with credits of 1=strongly disagree, 2=disagree, 3=neutral, 4=agree, and 5=strongly agree. The mean for each aspect would be shown together with overall mean for the practical (a standard: a mean of 4.5–5.0 exceeds expectations, 4.0–4.45 meets expectation, 3.5–3.95 requires monitoring while 0–3.45 requires action). Observing the Table 2, it would be easy to measure the performance if it meets its prospects, and expectations including respective scores.

VII. ACHIEVEMENTS, IMPACTS AND FUTURE ASPIRATIONS

The introduction of the presented practical has achieved immense response and really been an attracting one among the student body, both internally and externally (to the university; a number of relevant industrial organizations came forward in a philanthropic manner to donate a number of various related equipment and imparted state-of-the-art advanced knowledge in the process to further such activities), as a springboard for them to learn on and become specialists in the area of power systems protection. A number of final year electrical engineering capstone projects were formulated based on this practical and students gathered knowledge not only on overcurrent protection, but also on different types of generator protection, transmission line protection, distribution system protection along with distributed energy resources, and batteries. Many of such projects were awarded prizes in the electrical engineering programme. A number of motivated MSc students have graduated in the area of power systems protection. To add to that an inspired candidate has pursued PhD and graduated in the power systems protection area with a number of top-tier journal publications. Also, currently there is a student pursuing PhD after completion of MSc in electrical engineering in this field who initially started with overcurrent protection at the undergraduate level. Therefore, the presented practical has shown its educational benefits and significant impacts on the engineering education including higher degrees as it improves the process of teaching and learning of the very fundamental aspects of power systems protections in electrical engineering along with skill development in the very niche areas.

Based on the experiences, the followings can be considered as future aspirations:

- Development of an MSc degree course in power systems protection encompassing the fundamentals and advanced aspects protection systems in all areas of power generation, transmission and distribution systems.
- Development of MSc research topics with concepts such as optimization of overcurrent protection coordination of a distribution system using various optimization algorithms e.g. genetic algorithm, particle swarm optimization, firefly algorithm; communication assisted protection scheme using overcurrent relays for a distribution system with renewable energy resources focusing on selectivity and speed of the protection system; application of superconductive fault current limiter in a distribution system with appropriate protection coordination ensuring reliability of the protection system; use of directional overcurrent relays for protection of a distribution system with distributed energy resources and in micro grid environment; protection coordination issues on with directional overcurrent relays in various network configurations; protection and control of renewable energy based micro grid with different energy storage devices such as batteries, super capacitors; protection coordination of a distribution system with PV-based generations; reducing miscoordination due to injection of distributed energy resources using adaptive and optimization techniques; arc furnace protection using overcurrent relays; development of protection schemes of a distribution system for charging electric vehicles; distribution management system with sharing information for enhanced operation, control and protection coordination.
- Further, development of undergraduate practical and/or final year capstone projects based on the concepts such as of ring main protection, parallel feeder protection, differential protection of generator and transformer, automatic synchronization of a generator, development of supervisory control, and data acquisition system along with protection of a distribution system, distance protection of transmission lines, motor protections.

VIII. CONCLUSION

The presented work is an illustration of effectiveness of simulation-based practical in electrical engineering whereby the emphasis is on the process of preparing one of such electrical power systems practical. The structure, teaching and learning approach, and assessment method for developed practical are demonstrated and analyzed. The findings of the considered approach of doing practical using real-time software would be very insightful to the students that resembles the hands-on experience on a real power system network. This practical would encourage the academic staffs and students to learn on various other subject matters in electrical engineering practical that are highly related to industry applications. This exercise undoubtedly can improve the process of developing the practical itself including teaching and learning approach and exit level outcomes and meeting the requirements of the professional bodies and institutes. In future, this endeavour would also accommodate the academics to allow the academic staffs and students to develop and implement other practical
sessions in electrical engineering. A number of capstone projects developed in electrical engineering based on similar concepts were found to be very useful and exciting to the student body in terms of gathering knowledge and developing skill-sets. Additionally, a number of final year students were taken to the next levels at MSc/PhD in electrical engineering in the same area of the practical and it would be a continuous process of improvement since they would learn the way to study and gain experiences in niche areas. An MSc in Power Systems Protection degree can also be in the perspectives as a cherry on top. The exercise serves as a true springboard for inspiration for continuous future developments.

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