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Protection System Lab Experiments with Overcurrent and Differential Relays

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Protection System Lab Experiments with Overcurrent and Differential Relays

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Abstract

Protection System Lab Experiments with Overcurrent and Differential Relays

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This report presents the theory and application of two ubiquitous protection schemes, overcurrent protection and differential current protection, with the design of experiments and exercises for electrical engineering students. The objective of this undertaking is educational, so that students can learn, understand, and execute various operations pertaining to basic functions of relays. The result is a set of instructions for laboratory practices and exercises (lab manuals) which introduces relays in the context of the greater power system protection, and uses equipment modules to present relay functions.

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Chapter 1

Chapter 1 discusses the challenges of the education-driven and class-specific nature of the report. The decisions, adjustments, and outcomes regarding the creation of the report materials are discussed. Section 1.2 particularly addresses considerations of scope for the presented materials from the perspective of the stated objective.

An overview of system protection and electrical concepts are presented in Chapter 2. Specifically, the operation of relays, related devices, and protection technology used in making this lab report are discussed. Although much of this information is not in the finished product of the reports, a thorough background on relays is necessary to identify learning objectives for students.

The scope, discussed in Section 1.2, is then applied to the information in Chapter 2, to create the lab experiments and exercises of Chapter 3. Additionally, Chapter 3 considers the equipment available for the student exercises, and provides details specific to the manufacturer and make of the equipment in regards to the lab experiments. After the lab exercise formulation is discussed, the lab manuals for the overcurrent and differential relay experiments are presented.

Chapter 4 offers concluding remarks and suggestions for future experiments and topics.

In the appendices, the report solutions are attached.

APPROACH

The purpose of this report is to provide an educational introduction to two different types of relays. The approach to meet the objective of this report navigates the challenges and limitations presented by the targeted academic setting. The significance of

the approach to creating this document is comparable to the importance of the objective itself. The approach section covers the planning and the process of the report's creation. After choosing a topic, the approach modified the scope of all deliverables in almost every way. Many factors shaped the approach, and thus shaped the final deliverables. Decisions had to be made as to what materials were to be provided, the scope of the materials, the manner in which the materials were presented, and the format of the materials. Many considerations were tailored to a specific course on power systems. Since the deliverables were to be read not only by instructors, but by students, all materials were to be evaluated not only by standards of theoretical correctness, but in the merit, and sometimes efficiency, of their educational value.

As is unremarkable in pedagogy, two audiences needed to be satisfied. Since this report creates an educational exercise, the resulting lab manual would need to address the needs of an educator as well as the needs of the educated. The needs of the educator are typically straightforward. For example, an educator determines which topics must be included in a class syllabus. However, the needs of the student may require a nuanced approach and subtle skills to best present new materials in a clear and concise manner to students, especially within the restrictions of class time. Taking an educator's perspective, there were some topics that were necessary to mention. Class time is limited, so topics need to be presented to students within a given timeframe. The new materials preferably build on previous topics and similar concepts of the course, and match in difficulty with the other materials of the course. For a seamless transition, it is important that the materials fit the format of the course.

The format of the course resulted in the creation of a lab manual which was formatted based on the precedent set by the other lab manuals of the class. These lab manuals consisted of a pre-lab reading material, a lab exercise, and post-lab questions. It

was assumed that the professor would not spend much lecture time on relays, and so the pre-lab section gives all information the student needs to conduct the experiment. The lab exercise was focused on the lab equipment that was available (not only available, but available for four groups of two). Lab exercises were typically about fifteen pages in length and about two labs were conducted per three-hour session. The post-lab questions were formed in order to emphasize the important take-away concepts about relays.

The primary concern for educating students, was to give a thorough introduction to relays without overburdening them. A good method of teaching is the building of knowledge upon the gradual layering of previously established concepts. For example, while a student may never have heard of a differential relay before, they surely know Kirchoff's Current Law. Thus, a relay may be explained through its basic elements for a student to understand its overall operation. Students targeted by this lab manual are at a beginner to moderate level of power system knowledge. The target class consists of a mix of electrical engineering undergraduate and graduate students. While the materials were intended to be stand-alone, in practice, the lab reports were to be presented to students in-person, accompanied by a teaching assistant who could help with the experiments and answer any questions.

The pre-lab manuals are written using a top-down approach, so that students are able to associate relays with their foundational knowledge of power systems. The labs are organized so that the protection schemes are introduced first, then the general purpose of the relays and related equipment, and then the basic operations of the relays. Although the manual is written as an introduction to protection systems overall, it was important to present the information with the appropriate emphasis. Since the focus of this report was protective relays, relay operations are explained at a detailed, theoretical level. Other equipment that is used in coordination with relays are mentioned but not explained to the

same extent. Surrounding equipment, as well as the strategy behind equipment placement, is included in order to frame the context of relay use. However, the targeted students, at their level, were not expected to learn in-depth protection schemes.

The activities required of students was curated to maximize student engagement and to assess the knowledge retained from the pre-lab manual. Throughout the experiment, students would be asked to make calculations, critically think, and answer questions about equipment setup, as well as set up the equipment correctly themselves through the appropriate settings. This first-hand experience would expose the students to real-world relay operation, and give them a frame of reference for their theoretical introduction. The activities followed the format of past labs and were constrained by time limitations and the equipment available.

In accordance with the course's typical lab format, there are two manuals per lab session, and so one manual was written for each relay type. Since there is an overlap of background materials, this poses questions on the division of material between lab manuals. The overcurrent relay is introduced first. It is paired with basic power system protection concepts. Overcurrent is a familiar idea to the students; hence time-delay operation was a new concept that was the focus for exercises. The differential relay was explained in the second lab manual. Its operation is slightly more complex than an overcurrent relay. Event reporting is present in both labs, but has a larger presence in the second lab where students are taught about fault report analysis and relay operation verification processes. In the second lab, differences between the relays are highlighted, and any similarities are used to more easily introduce the differential relay.

Materials used to guide this report include: previous lab reports as a guide to format, numerous books on relays, technical manuals to the SEL equipment, and previous experience in the lab as a teaching assistant for guidance on the presentation of the lab. A

previous draft of a relay lab manual had been written by a colleague, and I used this as a guide for the scope of material. The necessary technological equipment used to research and develop the lab experiments were used from Dr. Santoso's laboratory. The lab had received a donation from Schweitzer Engineering Laboratories (SEL) in the form of relay modules and supporting equipment. This donation became the base of the experiment exercises.

Besides the scope mentioned in approaching the objective of this report, the greatest constraint was the equipment that was available. The consideration of equipment and use is closely related to the approach of educating students. It is a more practical consideration that involves safety and technical feasibility, but must also provide a straightforward illustration of the discussed concepts. The development of the experiment is further addressed in Chapter 3 of this report.

RESULTS

The report aimed to produce two laboratory manuals and experiences for undergraduate and graduate students. Working closely with SEL equipment resulted in experiments that leveraged simulation modules, relays, and software for understanding overcurrent and differential relays. Due to COVID-19, these exercises expanded into a video lecture as well.

The COVID-19 pandemic posed many challenges and constraints to thoroughly testing the lab manual procedures. In March 2020, the teaching lab was shut down. Since access to equipment was severed, procedures were not fully finalized, especially for the Differential Relay lab manual. Thus, this lab manual is a product of remote work from preliminary results. The pandemic drastically altered the process of teaching students for the remainder of the semester. The first lab manual on overcurrent protection relays

underwent limited testing by students. Due to time constraints from a shortened semester, and difficulty in finalizing the exercises, the second lab manual procedures were not tested by students.

Students worked remotely, and so all information and experiment results were explained and presented through video. The altered lab removed the majority of the software work and focused on analyzing results from relay simulations. Although the SEL software can be downloaded, there are no meaningful results without the relay modules. Since the purpose of the software is to create settings for the relays, and this was no longer possible for students, the majority of software work became lectured material. Event report files and pictures were shared when students did not have access to the relay equipment to create event reports. Questions were asked to analyze the results of simulations that the students would have found in their own experiments.

SUMMARY

Two lab manuals, two sets of lab experiments, two question documents, an introductory video, and a transcript were made for university students studying power system engineering. The materials introduced power system protection strategies and equipment, namely overcurrent and differential relays. Current transformers, time-delay settings, time characteristic curves, event recording and reporting, and their respective software were discussed. Students were assessed through required calculations and problem-solving, and they were further engaged through preparing equipment settings and connections.

Chapter 2

This chapter discusses the theory and technology surrounding protective relays. In the following, there is a breadth and depth of information that could not be presented to students due to limited teaching time. In fact, the amount of information available on protection equipment draws attention to the difficulty of creating a concise and clear manual. The chapter presents information about the available protection system and relay theory and technology without strict limitations. Such a presentation allows for easier assessment of an attempt to curate relay information for a teaching setting.

POWER SYSTEM PROTECTION

Electricity is a fundamental support, and often seen as a fundamental right, for a functioning society and the many other systems that a society depends on. The residential, industrial, and commercial customers of electricity expect reliable service, and so it is important that the power system is protected. System protection has been developed hand-in-hand with the electrical system. Since the development of the power system, power system protection has been an important feature overseeing many devices and their coordination. The method of protection is specific to the architecture and components of the power system.

In general, a protection system takes into consideration reliability, selectivity, speed, economy, and simplicity [1]. Reliability refers to the power system, and its resistance to outages, and is directly related to the reliability of the protective devices themselves. Selectivity of protection refers to the impact of protective devices within and without their protective zones [2]. Speed of sensing and signaling of a device is very important for operation time, and hence the time it takes for a fault to be located and

cleared. Economy refers to the allocation of capital and operation of the protection system, which dictates the implementation of devices throughout the power system and aims to minimize overall costs. Finally, simplicity of the technology and its method of execution are preferred for system efficacy, efficiency, and reliability.

Relays are a fundamental component of power system protection. The protective relay circuit is usually composed of a potential transformer, a relay, and a circuit breaker. Unlike the transformer and circuit breaker, the relay is an intelligent tool that can process inputs and make decisions based on its programmed logic. Early relays were electromechanical [3]. Physically, an electromechanical time-delay overcurrent relay is set with a spiral spring and a conducting aluminum disc. A coil with current produces a magnetic field that interacts with the disc. The spiral spring constrains the disc from rotating. When there is enough current to produce a torque on the disc – which is when the input current exceeds the pickup current – then the disc rotates to close the relay contacts. The torque of the disc, and its speed of closing, increases with the strength of current. The spring resets the disc when the current falls below the pickup current [1]. Relays have developed over time from electromechanical devices to digital devices. With the evolution of microprocessors, relays have become what they are today – with settings dictated by computer logic groups, and software for event reporting.

The protective system combats numerous abnormal conditions. There are many different types of faults: line-to-ground or line-to-line faults, single-phase, 2-phase or 3-phase, bolted faults, and temporary or permanent faults. There are sub-transient, transient, and steady-state time frames that are considered, as well as sequence analysis. Different types of fault scenarios can create overcurrents, undercurrents, overvoltage, undervoltages, or voltage sags [4]. This report will not enter into these topics in detail, although nuanced relay operations require knowledge of fault analysis.

For example, in the case of a bolted single line-to-ground (SLG) fault, a phase of a line is shorted to ground. Using an infinite bus assumption, the voltage of the line keeps steady. The energized line is shorted to ground with no resistance in between, hence, according to Ohm's law, the line will experience a sudden and significant increase in current. In this scenario, any load downstream will no longer be served. Upstream, the line on the faulted phase experiences an overcurrent, which may damage equipment. To handle this case and other fault scenarios, devices have been invented so that faults are isolated and abnormal currents or voltages can be prevented. The devices are placed strategically throughout a system to minimize power loss to customers. The devices can be relays, and their strategic placement is a part of the power system protection system.

Many systems operate protective devices in strategic sequences and in coordination with other devices. Radial systems can orchestrate time-delay overcurrent relays to isolate events and disrupt the least amount of loads during a fault. Overcurrent relays and differential relays provide necessary protection for power system equipment.

Devices used in grid protection include circuit breakers, relays, fuses, and reclosers. A circuit breaker, like its name implies, is an electromechanical switch that can make and break a circuit. It is a switch to disrupt and sometimes reclose a line. A device that can open the line, but cannot close it again, is a fuse. Fuses are used because they are relatively inexpensive, but they require replacement after every use. A recloser can open and close a line. Although relatively more expensive, reclosers can be configured to address temporary faults and save the fuses in the system.

In the previous SLG example, the use of a mid-line circuit breaker on the faulted phase could open the line to isolate the fault. A downstream load would lose power, but the equipment upstream would be protected from the overcurrent effects of the fault. A device too upstream will disconnect power from more load than necessary. A device too

downstream will not isolate the fault. The more devices placed in a system give more protection for the line to operate normally, and it is the line operator's responsibility to decide on the trade-off between the cost of protection devices and reliability.

The areas of impact around a protective device are referred to as its protection zone. Zones are established for power equipment such as generators, transformers, buses, transmission and distribution lines, motors [1]. Within the zone, each circuit breaker that provides service is associated with two sets of instrument transformers and the respective relays [1]. Power systems are divided into zones so that when a protection system identifies a fault, the abnormal zone can be isolated, and the fault can be cleared with minimal disruption to the other zones. Zones overlap to give the best protection through redundancy. When properly arranged, a fault anywhere in the zone results in all circuit breakers in the zone and overlap regions to open in order to isolate the fault [5]. By defining zones, an operator can ensure that every aspect of the electric system is protected.

Coordination

Coordination of different devices, often through time-delays on protection equipment, is used so that a circuit breaker is not tripped unnecessarily or to save fuses. For reasons such as animals, trees, wind, and lightning, more than 80% of faults on overhead distribution circuits are temporary [1]. If a fault is temporary, or if there is a very short increase in measurements for some other reason than a fault, a time-delay can avoid a false signal, and thus avoid shutting down part of the line.

The coordination time interval is the time between the primary protection device operation and a secondary protective device [1]. Time-delay overcurrent relays coordinate with reclosers and fuses [1]. Relay-controlled substation circuit breakers are

typically upstream from relay-controlled reclosers. Fuses are typically downstream by the loads. Since fuses are cheap, more of them can be placed in the distribution network and are suitable for downstream operation since they will isolate their protected zones with manual resets required after. Reclosers operate midstream between the substation breaker and the fuses. Relay settings are programmed so that reclosers operate first, then fuses or a delayed recloser operates, and then substation breakers. Reclosers are managed to protect the fuses that are in the protection system. Reclosers are convenient, but relatively expensive. A common sequence for reclosers is two fast operations, followed by two slow [1]. Fast operations of the recloser will open the circuit faster than the fuse will melt, clearing temporary faults. Slow operations allow the fuse to operate and clear permanent faults.

RELAYS

Basic Operation

A relay can be viewed as the brain behind a circuit breaker. It is the device that is monitoring equipment (e.g., a line) and if the measurements are abnormal, a relay will send a signal to a circuit breaker to open. Within a protective relay circuit, current is stepped down by a current transformer. The relay then takes measurements at the transformer secondary and calculates the current phasor for the line. If this value exceeds a set threshold, called the pickup current, then the relay will send a signal to the circuit breaker to trip [3].

Relays use multiple components to ensure that the power system is protected from faults and other abnormal conditions. These components include current transformers, circuit breakers, relay operational coils, and restraining coils. Digital relays offer many setting options as well as event recording and report settings.

Relays operate in coordination with other protective equipment. The three components that are most important for relay operation are an instrumental transformer, the relay itself, and a circuit breaker. These three components work together in order to provide protection. An instrument transformer steps down either current or voltage, from which the relay makes measurements. If the relay senses a fault depending on its measurements and the set "pickup" value, then the relay signals to a circuit breaker [3].

Instrument Transformers

An instrument transformer is a device that steps down current or voltage to a desired amount [1]. Instrument transformers, such as current transformers (CTs) and voltage transformers (VTs), insulate the relay circuit from abnormal conditions, and allows protective equipment to be smaller, simpler, and more accurate [1]. It is advantageous to isolate the relay from the higher-current system, since this results in more accurate sensing and measurements, and the measurement equipment does not have to be built to handle large amounts of current. This is important since this equipment must operate during fault conditions, such as overcurrent. Primary currents and voltages may experience fluctuations over a large range during fault conditions, temporarily or permanently, which may damage sensitive measurement equipment. The input is standardized due to convenience and convention.

CT operations must coordinate with the relay operations, and their operations require accuracy and durability in order to provide accurate inputs to the relay under abnormal conditions. CT performance is rated on the ability to recreate an accurate waveshape of the AC waveform, and the ability to preserve the magnitude of the DC component. ANSI/IEEE standards provide accuracy standards (IEEE Std C57.13.6), which relate to satisfactory relay performance [6]. The settings for CTs are chosen for

compatibility with the high and low systems, so that the CT ratio will match the high-side with a ratio to provide 5 A on the low-side. Phase angle errors are not typically crucial for CT operation [6].

CTs are typically set so that the secondary is 5 A, since there is a historical practice of standardizing instruments to 5 A. This has proved convenient for standardizing relay design [6]. Often, the CT is set so that the secondary current is slightly less than 5 A at full load. This is to protect the other sensors and measuring instruments in the relay circuit. Even if instruments do not share the circuit, the standardization of 5 A is typically kept. The exciting current must be negligible in order for the current ratio to accurately step-down the current to 5 A. Analysis of the exciting current can be done using modeling, manufacture specifications, or comparing the CT with its appropriate ANSI/IEEE accuracy class for relaying [6]. A problem with relay measurements may arise if the exciting current of the CT is too high, and the CT is saturated. In this case, the transformer has reached a current where it cannot accurately recreate the AC waveform on the secondary.

Circuit Breakers

A circuit breaker is a device that isolates the fault on the power system. A circuit breaker can be used to manually break the circuit, or is triggered from the relay contacts which activates the breaker coil [1]. A relay is required to detect the fault for the circuit breaker to automatically open the line.

A circuit breaker refers to a circuit opening device for single-pole, or multi-pole, operation. Each pole is associated with a phase of the power system. A trip coil of a circuit breaker initiates the opening of a breaker pole. The trip coil is connected to a mechanism that can open each pole independently, or simultaneously for all phases.

Typically, there is a trip coil and opening mechanism per pole. Trip coils can be connected in parallel or in series to open the three phases simultaneously. Series configuration is preferred for its simplicity and requires less trip current [6].

In the United States, all three phases are typically opened for any type of fault [6]. Connecting a multi-pole circuit breaker so that the malfunction of one pole does not affect the successful tripping of the other poles, is known as independent pole tripping. Independent pole tripping increases protection reliability and does not require a back-up circuit breaker elsewhere in the system. However, there are conditions where single-pole tripping is favorable. In the case of temporary single line-to-ground faults, single-pole trip-reclose systems can clear the fault while reducing the impact to the remaining phases [6]. These techniques are more complex and are more frequently used in Europe than in the United States [6].

TYPES OF RELAYS

Types of relays include: instantaneous, time-delay, directional, overvoltage, overcurrent, undervoltage (or combined voltage/current), power, differential, temperature, and distance.

The SEL 551 and SEL 421 relays will be used to explore overcurrent relays and differential relays, respectively, and so their operation is used as exemplary relays.

Overcurrent Relays

Overcurrent relays are protection devices that are used to monitor transmission and distribution equipment for overcurrent conditions. Overcurrent relays operate by comparing system current to a pre-set current magnitude. When the comparison exceeds

this setting, called the pickup current, then the relay sends a signal to a circuit breaker to trip.

In an electromechanical (EM) relays, there are coils and contact components, which, although are old designs, are still in use in many power systems. The power system is in the process of technological evolution, solid-state electronics, and digital models are now offered. Even after seventy years, the basic principles are the same. The following EM explanations help illustrate the operation of relays. The following explanation of the induction disk model is applicable for overcurrent, overvoltage, undervoltage, power, and other combinations and designs of relays [6]. Similarly, the solid-state version of the induction-disk has a wide application and shares the basic principles of the EM model.

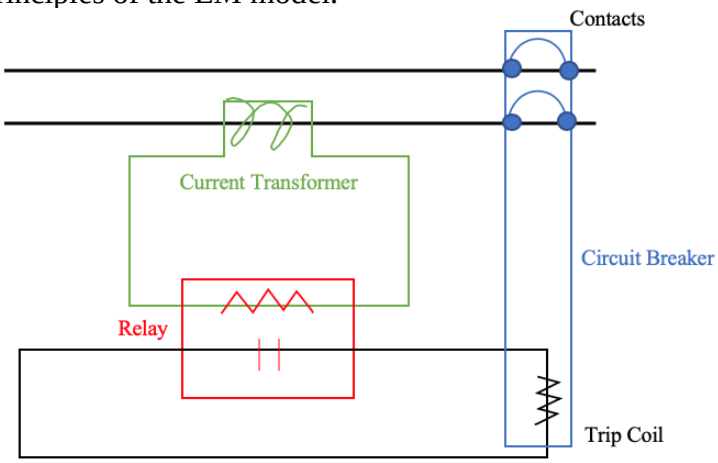

Figure 1: Overcurrent relay circuit with current transformer and circuit breaker

For an EM overcurrent relay, the pickup current is the current at which the relay contacts close. Closing the contacts closes a circuit to the circuit breaker, which exposes the circuit breaker to the trip current, i.e. the current that causes contacts to be opened. If

the magnitude of the secondary current is less than the pickup current, then the relay contacts remain open, blocking the signal to the trip coil.

The physical elements of the EM overcurrent relay are worthwhile to mention to illustrate inverse time-delay characteristics. Induction-disk relays consist of a disk that experiences electromagnetic force through induction. Current through the relay coil (received from the secondary of the instrument transformer) produces magnetic flux, which is rendered into the rotation of the disk with the help of a lag coil. (The lag coil creates a phase shift of the flux on one side of the disk.) A permanent magnet dampens the rotation, and when the disk is fully rotated, the moving contact on the disk connects with the fixed contact of the relay. The disk rotates slowly for low levels of current, and quickly for high levels of current [1,6].

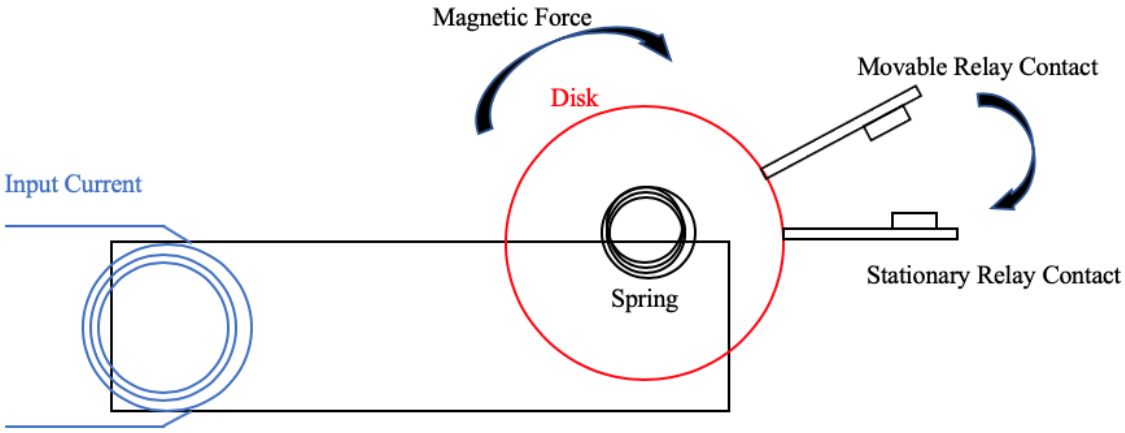

Figure 2: View of induction-disk, time-delay overcurrent relay from above.

Time-characteristic curves are formed for different models and are dictated by the different manufacturers. Time-delay overcurrent relays can be set with a time dial setting and a current tap setting. Relay operating time depends on both settings, and the relay operating time can be determined by referring to the characteristic curves of the relay. The current tap setting is the minimum current at which the relay will operate [6]. Each

manufacturer has different specifications for accuracy. Lower currents are typically less accurate since their operations are at slower speeds and are more susceptible to change with an impure current signal, also the ability to check precise operation is lessened [6]. Lower tap settings are not offered for these reasons. The time dial is related to the placement of the contacts. Time-dials can shift the contacts of the relay so that there is a longer or shorter distance to travel. The EM reset time is closely related to the time dial. An EM relay is reset by a spring. Obviously, this may take different amounts of time with the distance that it needs to reset (dependent on the time dial setting). The time it takes for a relay to reset is important in the case of coordination with reclosers and fast reoccurring faults, however, depending on the equipment the relay coordinates with, reset time is not as important [6].

Directional relays are relays that are based on the direction of the current. For example, an EM induction-disk relay can practice directional torque control by utilizing an external lag coil circuit. Depending on the direction of the current, the lag coil is engaged as a part of the relay circuit. The disk will not turn without the phase shift from the lag coil, and so the relay only operates when the current is in a certain direction and passes through the lag coil.

With the advent of solid-state electronics, the designs of relays have changed, but the basic principles have not. The new versions of these relays duplicate the manufactured time-inverse and characteristic curves, and provide various improvements and more opportunities (wider ranges) for adjustment [6].

Differential Relays

The fundamental operation of a differential relay is based on Kirchoff's Current Law (KCL). Current is conserved so that the summation of current flowing into and out

of a node is zero. Or, alternately arranged, the summation of the input currents equal the summation of the output currents. The summation of two currents of the same magnitude and opposing phase angles is zero. KCL is satisfied so that in a circuit with these currents brought together with a third wire, the result is $I_{wire1} + I_{wire2} + I_{wire3} = 0$, with $I_{wire3} = 0$.

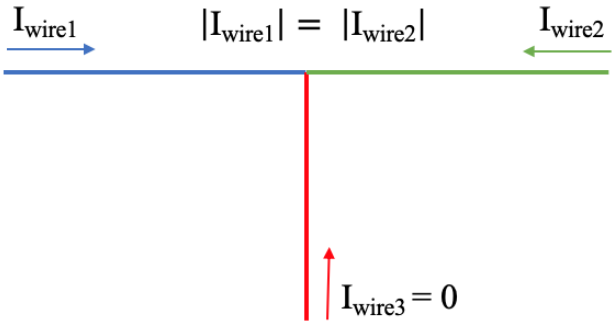

Figure 3: Kirchoff's Current Law

Differential relays involve comparing currents on either side of a power element such as generator windings or a transformer. A differential relay senses current at two locations, often measuring the current before a piece of equipment and after a piece of equipment on a line. According to KCL, the current under normal conditions is preserved and the two currents are equal, $I_1 = I_2$. The differential relay compares the first current with the second current, 180 degrees out of phase with each other. The summation of these two currents, equal in magnitude and opposite in phase, is then zero. However, if there is a fault within the piece of equipment the relay senses (or calculates) the residual current. When a fault occurs within the element, the incoming current and the outgoing current are not equal, and the relay operating coil is activated. Differential relays are especially sensitive to internal faults with currents in opposing directions or one current equal to zero [6]. The sensitivity of differential relays is based on the type of differential

relay, the tap setting (if available) and its application for power system protection, with typical pickup currents between 0.14-3.0 A [6].

In reality, even without a fault, the secondaries of the CT never sum exactly zero. Furthermore, a relay must be able to withstand external faults, and be sensitive to internal faults. Restraint windings inhibit relay operation from poor CT performance [6]. The restraint windings feed into the operation winding, which activates the trip signal from the relay to the circuit breaker. In the case of a fault outside of the relay's protection zone, the current between the two points of sensing would change relatively. In theory, this would not create a current differential, however transients from such a fault case could trigger operation from the relay [7]. Differential protection is often applied to high-voltage devices such as transformers, large motors, and generators due to its ability to selectively respond to internal faults and ignore faults outside of the protection zone [2].

Restraint windings reduce the number of false trips. False trips can occur with CT saturation, which is exacerbated when a large number of circuits are connected to the same bus [1]. For differential transformer protection, there may be an issue with the mismatch of standard CT ratios. Solutions include auxiliary CTs, which may increase errors [7], or adjusting tap settings within the relay. Another issue is a false trip due to large "inrush" current through the primary winding when the transformer is initially energized. A filter can be applied to block harmonic components, while large DC elements can be addressed by using a time-delay setting on the relay [1].

Most differential relays use percentages [6]. Percentages are fixed, which may have adjustable tap settings, or variable which have no taps. Fixed percentage relays operate between 10% and 50% [6]. The percentage specifies the amount of current, compared to the through-current, that is needed to operate the relay. Variable percentage differential relays operate so that relays operate at a low percentage for low through-

currents, and high percentages at high through-currents. This is the relationship that is desired between sensitivity and restraint [6]. For an internal fault, it is desirable to have high sensitivity, and thus low restraint on the restraint windings. For an internal fault, it is desirable to have low sensitivity, and thus high restraint on the restraint windings. This is based on CT performance, which worsens with larger current as in the case during an external fault [6].

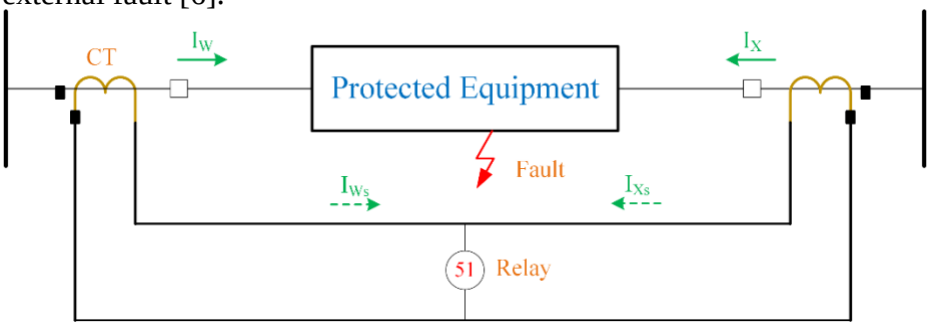

Figure 4: Diagram of a differential relay

A balance beam is a type of EM differential relay. It is a device that closes the relay contacts when an electromechanical force becomes uneven [1]. Transformers with ratings larger 10 MVA typically use differential relays, otherwise fuses are employed [1].

EVENT REPORTING

Event reporting has become an essential feature with the advent of relay modernization. Numerical relays are able to create reports to track and archive abnormal conditions. While it varies widely from software to software, basic aspects of digital reports and storage have common characteristics.

Event reporting has introduced key benefits to fault analysis. A historical record is required to reveal the causes and effects of abnormal power phenomena. The power system is large, geographically disperse, with a massive amount of equipment to run and

monitor. Transients and fault phenomena can happen within cycles, and event reporting stores data to enable analysis of small time frames. The data rate must sustain the granularity of the power events, yet more data points require more storage. Data rate capabilities vary by the manufacturer, which is limited by equipment accuracy and the amount of storage available allotted to these devices.

Data from protection equipment delivers insight on grid operation, as well as information to resolve and prevent future faults. Numerical relays can automatically create reports for engineers to later view and analyze. Reporting must consider data type, data storage, data file types, and user interface. Reports include voltage and current phase information. From this data, engineers can find fault locations, verify relay operation, and verify grid characteristics [8].

Once measurements are taken, and the data has been compiled, data is sent to event report visualization software for a variety of data representation options. User interfaces transform the data into a readable format, which increases the efficiency of engineers. Finally, downloadable reports for larger audience distribution are available. The length and complexity of reports differ based on function, from summaries to in-depth analysis.

Chapter 3

EXPERIMENT DESIGN

The experiment design followed the format of previous labs from the course, which were comprised of a lab manual and a lab exercise per topic. The lab manual was written for a class on power system apparatuses at The University of Texas at Austin which included participation in laboratory exercises. The class had a mixed composition of undergraduate and graduate students with basic knowledge of power systems, who work in pairs during lab sessions. Lab manuals in this course are supplementary to lectures. The material is first explained and then the theory is demonstrated through exercises in a laboratory using power system equipment and simulations. The exercises are often limited by the available equipment and the available time in a lab session. Although the approach is specific to the audience and equipment available for EE394L/EE368L, the documentation and educational exercises created are suitable for teachers and teaching assistants for similar class subjects and teaching environments.

In the course considered, protection systems were relatively new to the students. Materials presented about relays and protection systems need to cover basic topics and build understanding from basic electrical engineering concepts. Considering the format of previous labs in the course, the lab manual performs the function of introducing the topic. To allow for more information and depth of information, the material was split into two labs: Introduction to Relays and Differential Relays. By creating two sets of lab manuals and exercises, the first lab manual could be written with more basic theory, while the second manual could be written assuming students have mastered the information from the first.

The core of the lab is stated in the objectives at the beginning of the lab manuals. For example, in the Introduction to Relays Lab, the objectives are:

- To understand the basic functions of relays and transmission system protection schemes
- To calculate the relay parameters for overcurrent protection
- To familiarize with relay settings in the operation of a SEL 551 relay and SEL software
- To learn about event report analysis and verify relay operation

The lab is formulated to enforce the objectives through hands-on learning, calculations, and post-lab questions. The objectives of the first lab are chosen to cover general topics of power system protection and familiarize the students with relay equipment. The objectives of the second lab are similar, but the following exercises assume students are familiar with navigating software and relay equipment. Relatively less guidance in basic instruction is provided in the second lab. This was intentionally written so as to encourage students towards critical and independent thinking.

Students meet the objectives through the experiment exercises and questions. The lab activities were made so that the theory is demonstrated and solidified in the minds of the students. The lab procedures feature calculations throughout to predict experimental results by the application of theoretical relay understanding. Besides for the intention of teaching, the difficulty and quantity of exercises accommodate the necessity of grading. Enough material was produced so that the students can be assigned a grade commensurate to the student's effort and understanding. After the lab exercises, post-lab questions further test the students and allow the students to demonstrate his or her grasp of the material.

THEORY TO EXPERIMENT

From the theory and information discussed in Chapter 2, specific points were chosen for the lab manuals and exercises. All information could not be covered. Since the lab class provides a unique opportunity to work with the equipment, exercises center on simple equipment operation.

After basic power system protection, simple equipment operation for time-delay overcurrent relays requires knowledge of time delay curves, overcurrent, coordination between relays and CTs and circuit breakers. Working with a differential relay model requires similar knowledge of settings, but also introduces the differential principle. Event reporting is a topic that connects power system protection and relay operation. The data required by relay equipment operation, as well as the data produced to analyze and locate faults, are viewed and discussed through event reporting.

The exercises included in the lab manuals represent relay operation in theory and in practice. In practice, the theory translates to reading relay displays and interacting with relay settings. A simulation was created so that relays operation could be viewed, and verified. Scenarios were created to reinforce calculations from the theory. Viewing relay operation was done through the physical display of the relay, as well as through the relay software. The software was an essential tool to change settings, create group settings, and create event reports.

RELAY AND SOFTWARE FEATURES

After considering various options, it was decided that a waveform generator would be best suited to simulate what the relay monitors. Furthermore, a generic waveform generator emphasizes the range of equipment that a relay is able to monitor.

The lab materials will use the 551 SEL relay, a computer, the SEL software, and a SEL adaptive multichannel source, or AMS.

Relays in actual use are hooked up to power equipment. However, since testing a full power system was infeasible, signals sent to the relay for the lab are coordinated through an Adaptive Multichannel Source (AMS) module from SEL. The AMS is a module that simulates power equipment measurements to the relay by generating waveforms. It is frequently used to test simulations with relays for relay operation verification. As it senses and measures a simulated signal, the relay can be observed by the physical interface of the relay, as well as through software. The AcSELerator Quickset Software is the Schweitzer Engineering Laboratories (SEL) software that is compatible with the equipment used in the experiments. This software is used to observe opportunities for relay adjustment as well as even reporting. The AMS and relay are connected through the computer, and the controls for the set-up can be managed by the SEL software.

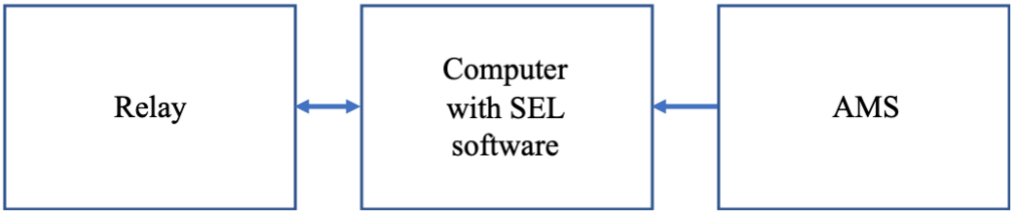

Figure 5: Laboratory exercise set-up with relay, computer, AMS, and connections

In the AcSELerator Quickset software, the relay settings are labeled by logic groups (50P1P and 51P1P or C or R, etc.). The AcSELerator Quickset software provides an interface to create logics, and groups of logics, that can be applied to the relay. The logics are organized into “bits.” These bits represent binary settings that can be coordinated depending on the needs of the relay operator. Examples of constraints or

settings include pickup settings and trip settings. The pickup setting can be set per phase, per element, and specified for the negative sequence. There are options to specify other settings such as the Current Transformer Ratio (CTR), Minimum Trip Duration Time (TDURD), and reclosing intervals, in the Group Logic tab. As mentioned previously, CTR is the current transformer ratio, and is set to match the system. TDURD is the minimum trip duration time, meaning the minimum time a trip signal is sustained. Both settings are necessary for relay operation, and are included in lab instructions for students to set.

A relay operates on parameters set by the relay operator. While the settings differ by manufacturer and model, there are typical settings that must be determined for similar types of relays. Relay settings such as Pickup Current and Time Delay are essential for configuring the overcurrent relay to send a trip signal according to the desired specifications. Students use the current tap setting, the pickup current, and the time-dial setting for time delay operation.

Since relay operation can be specified by phase, by sequence, instantaneous elements, or time-delayed elements, and by many other inputs, it was necessary to simplify instructions for basic understanding. The lab manual uses only three inputs, which are the currents for A, B, and C phases, in order to simplify relay operation. Other settings, one introduced, and are kept steady for the remainder of the experiment. Settings can be configured through the front panel of the relay or the software. Although the students are not instructed to change the relay settings through the front panel (since software is widely used nowadays), there are instructions in the lab to navigate through the panel to familiarize students with the capabilities of such an interface.

The students initially read the relay measurements from the front panel of the relay. Using the front-panel pushbuttons, the meter button shows what the relay is

presently reading. The front panel of the relay displays real-time measurements of the input currents, I_A, I_B, I_C and a neutral current. Students' basic knowledge of faults, current in balanced systems, and CT ratios is tested here. Students need to know that the relay displays actual measurements on the primary of the current transformer. In a balanced system, I_A, I_B and I_C are equal in magnitude but their phases are shifted by 120 degrees. I_N is the summation of I_A, I_B and I_C, and in a perfectly balanced scenario I_N equals zero. During a fault, the faulted phase current will experience a sudden increase while the non-faulted phase currents may increase, although not as drastically as the faulted phase. In an un-balanced fault, I_N is non-zero. The lab experiment provides a comparison for students between normal meter readings, and the readings from abnormal conditions – specifically a single-phase fault.

Alternatively, the relay can be monitored using the HMI (Human-Machine Interface). This interface allows operators to view faults and equipment measurements in a user-friendly environment. The students are instructed to read the results of the simulation from the relay display panel, but to configure the settings through the Quickset software. In the software, there are settings with pulldown menus or text entry options to set parameters.

One setting that is chosen from a pull-down menu is the setting for the SEL relay characteristic curve. Different brands and models of relays have differing characteristic curves. In the labs, the characteristic curves for the SEL relays are introduced. For the SEL 551 relay for example, in the settings is the option to choose a response curve. This curve is called a time-current characteristic curve. The different curves vary in steepness, which changes the speed of the relay's response, called operating time, dependent on the time-dial setting and the variable M, where $M = I_{fault} / I_{pickup}$. The relay response is not only based on if there is abnormal current (if the fault current is greater than the pickup

current), but also based on how much the abnormal current exceeds the current threshold setting, I_{pickup}. The variable M captures the relative value of fault current. Through these calculations, students learn how quick a relay responds to an abnormal measurement depends on its settings and measurements. Students are instructed to calculate relay operating time based on a given time-delay characteristic curve, and then are later tested on such a curve in post-lab questions.

Challenges in the format arose during the COVID-19 crisis. All assumptions made about time limitation, pre-lab/lab/post-lab work, in-class v. take-home environments, and partner dynamics drastically changed. To adapt to the new format, a video took students through the experiment remotely. Measurements from the equipment were given with detailed descriptions of the testing scenarios. Furthermore, TAs hosted virtual office hours for student guidance and to answer any questions from students.

LAB MANUAL PRESENTATION

Introduction to Overcurrent Relays

OBJECTIVES

- To understand the operation of basic functions of relays and transmission system protection schemes
- To calculate the relay parameters for overcurrent protection
- To familiarize with relay settings in the operation of a SEL 551 relay and SEL software
- To learn about event report analysis and verify relay operation

PRE-DISCUSSION

1. Create an account at https://selinc.com/myaccount/
2. Follow the link, https://selinc.com/products/5030/#tab-downloads , and download the latest version of the SEL acSELerator QuickSet SEL-5030 Software on your computer.
3. Follow the link, https://selinc.com/products/5601-2/#tab-downloads , and download the latest version of the SEL synchroWAVe Event Relay Event Visualization and Analysis Software on your computer.
4. Follow the link, https://selinc.com/products/usb-serial/#tab-downloads , and download the latest version of the SEL USB Driver Software on your computer.

Power System Protection Introduction

Power system protection has been in place since the development of the power system. Power systems are expected to be reliable and resilient. Reliability relates to the amount and duration of interrupted service, while resiliency refers to the grid's ability to

recuperate from a disruption event. The North American Electric Reliability Corporation (NERC) is a regulatory authority that develops and enforces reliability standards for the bulk power system of North America. Grid operation must adhere to NERC reliability and resilience standards and assessments to reduce the frequency and severity of outage events.

Grid protection depends on system-specific constraints and goals. For example, mesh systems face different challenges than radial systems. Many systems use strategic combinations and sequences of protection devices. For example, time-delay overcurrent relays can be used with other instantaneous or time-delay protection devices to isolate events and disrupt the least amount of people during a fault.

There are many types of relays, including overcurrent relays and differential relays, which provide necessary protection for power system equipment. Transmission lines, generators, motors, transformers, buses, and indeed all power system equipment are monitored for faulty conditions. While cost and practicality may limit the extent of monitoring the power system, grid operators continually seek new protection technologies and solutions to ensure the reliability, resiliency and security of the electric system.

Overcurrent Relay Introduction

Relays use multiple components to ensure that the power system is protected from faults and other abnormal conditions. These components include current transformers and circuit breakers. Electromechanical (EM) relays used operational coils, and many digital settings may reference an EM quantity. Nowadays, digital relays offer many protective settings, logics, and features to report and record events.

Overcurrent relays are protection devices that are used to monitor transmission and distribution equipment. Overcurrent relays operate by comparing system current to a pre-set current magnitude. When the comparison exceeds this setting, called the pickup current, then the relay sends a trip signal to the circuit breaker, which then opens. The current sensed by the relay and compared to the pickup setting is the current on the secondary of a current transformer. This improves accuracy and safety for relay operation. The current transformer ratio is a setting that is selected by the relay operator and determined by the CT in the system.

Time delays are used to clear temporary faults conditions. Time-delay overcurrent relays can be set with a time dial setting and a current tap setting. Relay operating time depends on both settings and can be determined by referring to the time-current characteristic curves (TCC curves) of the relay. The curves, discussed in following sections, have various steepness, which change the time delay of the fault and thus the time when the relay's circuit breaker is tripped. Time delay and reset time calculations using time-delay curves are necessary for understanding relay devices and determining their optimal settings and operations in varying fault conditions.

Recommended Reading

1. Read Section 10.3 of the Glover Sarma textbook for further introduction to Overcurrent Relays.
2. Read Section 10.10 of the Glover Sarma textbook for further introduction to Differential Relays.
3. Read Chapter 10 of the textbook for a better understanding of power system protection.

Experiment

To acquaint students with relays, the experiment necessitates equipment set-up, navigating relay settings and software, and calculations.

To observe the operation of relays, these experiments are formed using a simulated signal. Signals are sent to the relay from an Adaptive Multichannel Source (AMS) module from Schweitzer Engineering Laboratories (SEL). The relay can be observed by the physical interface of the relay, as well as through software. We use the AcSELerator Quickset Software which relates to the SEL equipment used in the experiment. This software is used to set the relay, view relay measurements using its HMI, and download event reports recorded by the relay.

The AMS SEL-4000 and software is necessary for creating relay simulations. The AMS is used to test relays by simulating the waveforms of the current transformer. By setting the relay, connecting the relay with the AMS, and then monitoring the relay through its software, the performance of the relay can be assessed. The waveform, magnitude, and time duration of the secondary of the current transformer will be set by the TA using the AMS. Students will be able to observe relay behavior and determine fault conditions from the results of the relay tests.

The SEL 551 relay will be used to explore an overcurrent protection elements, a different unit, such as the SEL 421 relay, can be used to explore differential protection elements.

AcSELerator Quickset Software

The AcSELerator Quickset software provides an interface to create logics, and groups of logics, that can be applied the relay. The logics are organized into “bits.” These bits represent binary settings that can be coordinated depending on the needs of the relay

operator. Examples of constraints/settings include pickup settings and trip settings. The pickup setting can be set per phase, per element, and specified for the negative sequence.

There are options to specify other settings such as the Current Transformer Ratio (CTR), Minimum Trip Duration Time (TDURD), and reclosing intervals, in the Group Logic tab.

The relay can be monitored using the HMI (Human Machine Interface). This interface allows operators to view equipment measurements in a user-friendly environment.

OVERCURRENT RELAYS

The time of operation of a time-overcurrent relays is given as:

$$t(I) = TD * \left(\frac{A}{M^p - 1} + B\right) + \mathrm{K}$$

where

TD is relay time-dial setting

M is the relay pickup current ratio (I_{fault}/I_{pickup})

A, B, p, K are the constants to provide selected curve characteristics

The reset time for a time overcurrent relay is given as:

$$t(I) = \left(\frac{t_r}{M^2 - 1}\right)$$

where

t_r is the reset time for (M=0)

Though these are standard definitions provided by IEEE, different relay manufacturer provides standard curves inbuilt in their relays. The list of standard available curves can be found in the relay's instruction manual.

The set of curves available in the SEL 551 and SEL 421 relay are:

Curve Type	Operating Time	Reset Time
U1 (Moderately Inverse)	$T_p = TD \bullet \left(0.0226 + \frac{0.0104}{M^{0.02} - 1}\right)$	$T_r = TD \bullet \left(\frac{1.08}{1 - M^2}\right)$
U2 (Inverse)	$T_p = TD \bullet \left(0.180 + \frac{5.95}{M^2 - 1}\right)$	$T_r = TD \bullet \left(\frac{5.95}{1 - M^2}\right)$
U3 (Very Inverse)	$T_p = TD \bullet \left(0.0963 + \frac{3.88}{M^2 - 1}\right)$	$T_r = TD \bullet \left(\frac{3.88}{1 - M^2}\right)$
U4 (Extremely Inverse)	$T_p = TD \bullet \left(0.02434 + \frac{5.64}{M^2 - 1}\right)$	$T_r = TD \bullet \left(\frac{5.64}{1 - M^2}\right)$
U5 (Short-Time Inverse)	$T_p = TD \bullet \left(0.00262 + \frac{0.00342}{M^{0.02} - 1}\right)$	$T_r = TD \bullet \left(\frac{0.323}{1 - M^2}\right)$

Figure 5: Experiment 1 Figure 1, SEL operating times and reset time equations for U curve types

Curve Type	Operating Time	Reset Time
C1 (Standard Inverse)	$T_p = TD \bullet \left(\frac{0.14}{M^{0.02} - 1}\right)$	$T_r = TD \bullet \left(\frac{13.5}{1 - M^2}\right)$
C2 (Very Inverse)	$T_p = TD \bullet \left(\frac{13.5}{M - 1}\right)$	$T_r = TD \bullet \left(\frac{47.3}{1 - M^2}\right)$
C3 (Extremely Inverse)	$T_p = TD \bullet \left(\frac{80}{M^2 - 1}\right)$	$T_r = TD \bullet \left(\frac{80}{1 - M^2}\right)$
C4 (Long-Time Inverse)	$T_p = TD \bullet \left(\frac{120}{M - 1}\right)$	$T_r = TD \bullet \left(\frac{120}{1 - M}\right)$
C5 (Short-Time Inverse)	$T_p = TD \bullet \left(\frac{0.05}{M^{0.04} - 1}\right)$	$T_r = TD \bullet \left(\frac{4.85}{1 - M^2}\right)$

Figure 6: Experiment 1 Figure 2, SEL operating times and reset time equations for C curve types

SEL 551 Relay

Figure 7: Experiment 1 Figure 3, front and back panels of the SEL 551 relay

Caution!
Do not change any relay settings which are not mentioned in the lab instruction manual. Also notify TA before saving any modified setting.

1. There are many ways to communicate with a relay. The most common ways are through the front panel screen and by using the SEL acSELerator QuickSet software. The AcSELerator QuickSet Software should be installed, and in the following steps this software will be used to access relay settings. Before using the software, however, it is important to familiarize oneself with the physical interface of the relay. Notably, the relay must be properly connected to a computer (steps 2, 5, and 6), and the front-panel pushbuttons can be used to read the settings and measurements of the relay from the LCD display (steps 3, 4, and 5). Step 5 instructs how to coordinate the speed setting of the relay with the Quickset software for proper computer connection.

2. Connect the SEL 551 Relay to your computer using the USB 662/663 cable. Use the serial port at the back of the SEL 551 Relay as shown in Figure 1.

3. Using the front panel, navigate and identify the initial currents measured by the relay.

4. List the different menus available that can be accessed using the front panel.

5. Navigating through the settings, using the left/right arrows and “Select” button, find the SPEED settings of the relay module:

→ “Set” → “Port” → Select the correct port (the connection port is labeled by the connecting cord) using the “Select” button →”Show” → Use the up and down arrows to find the speed of the relay communications. Report the speed of the relay:

6. SEL acSELerator QuickSet SEL-5030 Software is a software developed by SEL to communicate and configure SEL relays.

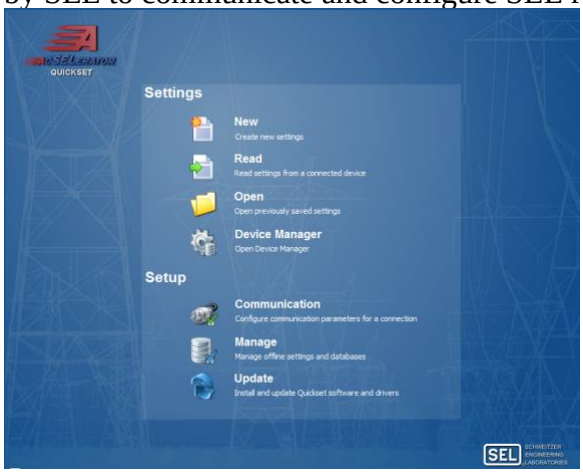

Figure 8: Experiment 1 Figure 4, AcSELerator Quickset Software screenshot

To begin communication with the relay through your computer, the communication settings need to be updated to match that of the relay.

Open acSELerator QuickSet SEL-5030.

Go to Communications (below Setup) → Set Active Connection Type to Serial

→Under “Device” dropdown menu select the connection between the relay and computer to “COM4”

→ Change the baud rate to the speed found in part 5. Do not change any other setting. Click “Apply”.

The status bar at the bottom of the screen should say “Connected” after around 10 seconds.

1. Calculate the following :

   a. For a very inverse U3 curve, the pickup current is set at 60 A (at the primary of the CT). The CT ratio is 600/5. An SLG fault occurs and the resulting fault current in phase A is 600 A. The settings of the relay are such that the time dial settings is 0.8. What is the operation time in cycles?

   b. Calculate the pickup current in terms of the secondary current of the CT.

2. The following steps aim to program the relay according to the required settings for the previous examples.

   a. In the Quickset software, click Read (present below Settings)

   This reads the existing setting file present in the relay. It may take several minutes.

   b. Most modern digital relays provide the option of putting in different groups of settings and using one particular group at a time. However, SEL 551 has only one group of settings.

   c. Set the following:

      i. CTR Phase – 120

      ii. TDURD – 2 cycles

      iii. 50P1P through 50P6P – Off

      iv. 50ABCP – Off

      (50 corresponds to Instantaneous Overcurrent Element)

We are interested in 51 Element which is Time-Overcurrent

v. Set 51P1P to the calculated pickup current in Step 7

vi. Set 51P1C and 51P1TD similar to that of Step 7

vii. Set 51P1RS – N

viii. Set 51P2P – Off

Do not change any other settings in other settings tabs.

d. Now that the settings file has been created, it needs to be sent to the relay.

Send the settings file to the relay by File → Send. The Quickset software will identify which part of the settings file has been changed and selects only that part of settings file to be sent to the relay. Select OK.

e. The various information processed by the relay can be viewed on the relay display or on your computer using HMI in Quickset. To access HMI, navigate to Tools → HMI → HMI

3. In this step you will interact with the relay during a current simulation. The TA will program the AMS to send a digital current signal to the relay long enough for the results to be shown on the relay LCD. The relay will measure the signals and report the phase currents of the CT primary. The A, B, C phase LEDs will light if a trip occurs.

a. Observe the fault currents displayed by the Relay

b. What is the secondary CT current during the fault?

c. Verify the currents displayed by the relay by calculation

d. Why has the relay not tripped?

4. Now an SLG fault on phase A is created similar to that of Step 7.

a. Observe the fault currents displayed by the Relay

b. Based on the fault current, the relay identifies the type of fault. This is shown by glowing LEDs on the front panel. What is the type of fault recognized by the relay?

c. Based on the current measurement displayed by the relay, what would have been the CT secondary current that was the input to the relay?

d. With the same fault current, if the CT ratio had been set at 200, what current would the relay sense for phase A?

5. The relay and meter read circuit data in real time. When a fault occurs, the relay usually trips in a few cycles (based on its settings), and so the resulting trip signals are not observable to the human eye. Furthermore, it is highly unlikely that a protection engineer is observing the meters on the relay at the time the fault occurs. For these reasons, the relay provides recording functions, and software like Quickset records and creates event reports for abnormal circuit behavior. The following step demonstrates how to access the recordings of these fault events.

The event files can be obtained using Quickset. Tools → Events → Get Event Files. This may take a minute to load. The event file on the top is the most recent event file.

a. What is the highest rate the report can support (samples/cycle)?

b. Why would you want a lower rate than the highest possible rate? Why would you want the highest possible rate?

c. Select the lower rate for the report and select the most recent event file. Click “Get Selected Events”. Select your preferred location for saving the file and click Save.

d. Open the saved event file using Synchrowave Event Software

e. Observe that the phase A current magnitude is 600 A.

f. On the following image, please identify the pickup current, the fault current on phase A, the time delay, and the actual trip.

Figure 9: Experiment 1 Figure 5, Synchrowave Event Software screenshot

g. What happens to the magnitudes of the currents on phase B and C?

h. Move the cursors such that one cursor is at the pickup current and the other cursor is at the beginning of the trip signal. What was the time taken for the relay to trip? Does it match with the value calculated for this scenario in Step 7?

6. Reset the relay by selecting the Target Reset button on the Relay. Disconnect the communication between the Relay and the Computer: Communications → Disconnect.Disconnect the C-662 cable from the back of SEL 551 Relay.

REVIEW QUESTIONS

1. What are the benefits of a time-delay overcurrent relay over a fuse?

2. List at least 2 equipment elements associated with a relay that helps protect a circuit.

3. What is the purpose of including a current transformer between a power system device and a relay?

4. What setting would be changed if the relay were designed to trip after a longer amount of time?

5. List different uses or benefits of performing fault analysis using event reports downloaded from the relay.

6. The U3 very inverse time-overcurrent relay curve is shown below. Draw an approximate curve for a .8 time dial and identify the operating time corresponding with the relay settings used in step 7.

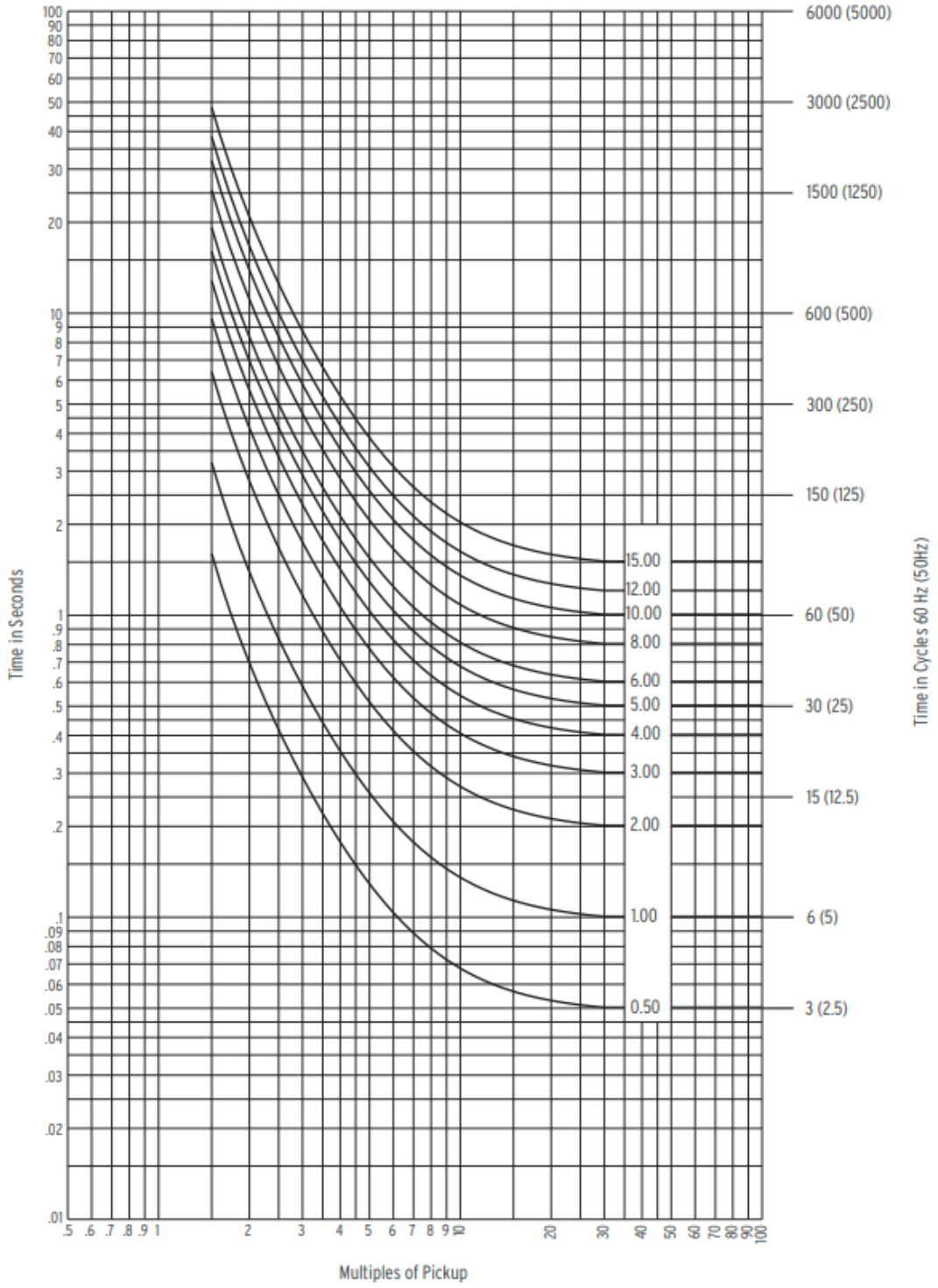

Figure 10: Experiment 1 Figure 6, Very Inverse Time Current Characteristic Curve

Introduction to Differential Relays and Event Reporting

OBJECTIVES

- To understand the operation and basic functions of differential relays
- To learn about event report analysis and to verify relay operation
- To become familiar with relay settings and decisions involving relays and protection schemes.

DIFFERENTIAL RELAY INTRODUCTION

A relay is a part of the protective layer of a power system. The responsibility of a relay is to determine whether there is an abnormal condition on the system or equipment it monitors. The abnormality, such as a fault or an unbalanced condition, may occur within the monitored equipment, or on a connecting line to the monitored equipment. The operations of a relay may be triggered by a current or voltage phasor that exceeds a threshold. There are many categories of relays, and this lab will focus on a type of relay called a differential relay.

A differential relay bases its operation on the principle of Kirchoff's Current Law (KCL), where the magnitude of current entering a node must equal the magnitude of current leaving the node. In terms of the power system, this node can take the form of equipment such as a bus or a transformer or a line. In normal operation, current enters and exits power equipment through terminals. A relay monitors these terminals to see if KCL is satisfied as expected. During an abnormal event, such as a fault, the current may flow in an alternative path (from the fault location to ground, for example), other than the expected terminals of the power equipment. In such situations, KCL is not satisfied as expected; the relay identifies a current mismatch and signals to a circuit breaker to trip, isolating the fault.

In order to detect abnormal conditions, a differential relay takes phasor measurements from two or more locations (as required) in the monitored zone. Current transformers (CT) scale down the current before being sensed by the relay. Current differential relays combine the secondary currents from these CTs, to compare the magnitude and phase of current entering the zone and current exiting the zone. Comparison is implemented by measuring current exiting the zone 180 degrees out of phase with current entering the zone. Thus, the summation of the two currents equal zero under normal operating conditions since the currents entering and exiting are actually equal in magnitude and phase. If the summation results in a value that exceeds a set threshold, then the relay senses a fault.

Consider Figure 1. In this illustration the two currents being compared are IW and IX. By way of two CTs, the secondary currents, IWs and IXs, are fed into the relay for comparison. In normal operations IWs and IXs are equal in magnitude but are in opposite directions, meaning the phasors are 180 degrees out of phase. The sum of such phasors is zero. The combination of IWs and IXs should result in no current at the relay if there is no abnormal condition present across the protected equipment. In the case of a current mismatch, there will be current through the relay, which will trigger relay operation when the current exceeds a certain threshold. The relay then sends a signal to trip a circuit breaker. Differential relays are placed on each phase for a three-phase circuit, and typically one differential breaks all three phases.

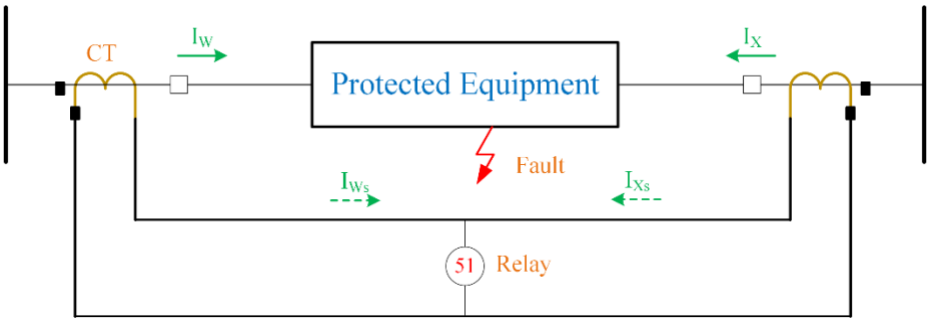

Figure 11: Experiment 2 Figure 1, Diagram of a differential relay

There are advantages and disadvantages of a differential relay. A differential relay creates a relative mechanism to examine the operating conditions within its protective zone. In this way, this protected sphere will not be triggered by neighboring systems that experience overload or faults – this reduces false triggers. On the other hand, to avoid misoperation, inputs for differential relays need to be accurate and time-synchronized. Differential relays may be a more expensive option compared to other relay types due to their strict input requirements.

Recommended Reading

1. Read Section 10.10 of the Glover & Sarma textbook for further introduction to Differential Relays.
2. Read Chapter 10 of the textbook for a better understanding of power system protection.
3. Introduction to Overcurrent Relay Lab report for more directions on SEL equipment and software.

Experiment

The Schweitzer Engineering Laboratories (SEL) 421 Relay will be used to explore differential relays. Throughout this lab, students will become acquainted with

differential relays, the equipment and software necessary to test a relay, relay settings, and relay calculations. The experiment necessitates equipment set-up, setting navigation, and the interpretation of event report software.

To observe the operation of the relay, a simulated current input signal is created by an Adaptive Multichannel Source (AMS) module and sent to the relay. Once the signal is read by the relay, the physical interface of the relay can display the relay's measurements and operations. Relay measurements and operations can also be observed through the AcSELerator Quickset Software HMI. This software can display and change the relay settings, as well as create groups of logic patterns.

Event reporting is critical to determine necessary actions for a faulted area, and to conduct analysis for a fault scenario. The Quickset software offers options to record and download events, which then can be read by an event report processing software such as the SEL SynchroWAVe Event Relay Event Visualization and Analysis Software.

Software

1. An account at https://selinc.com/myaccount/
2. The latest version of the SEL acSELerator QuickSet SEL-5030 Software. Follow the link: https://selinc.com/products/5030/#tab-downloads
3. The latest version of the SEL synchroWAVe Event Relay Event Visualization and Analysis Software. Follow the link: https://selinc.com/products/5601-2/#tab-downloads
4. The latest version of the SEL USB Driver Software. Follow the link: https://selinc.com/products/usb-serial/#tab-downloads

DIFFERENTIAL RELAYS PART A

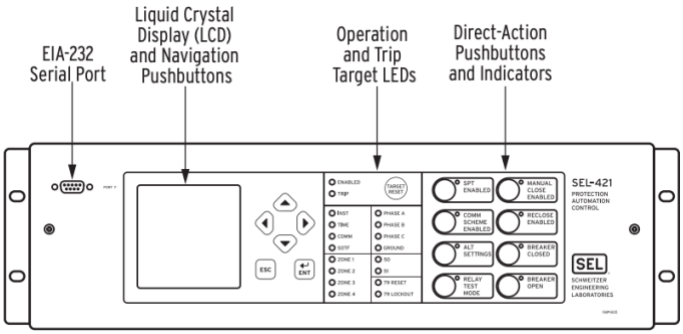

Figure 12: Experiment 2 Figure 2, Example of a SEL 421 relay front panel

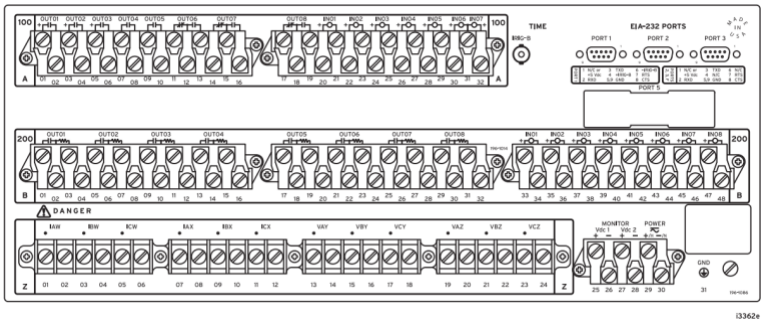

Figure 13: Experiment 2 Figure 3, Example of a SEL 421 relay rear panel. Note connection ports, power source, phase current inputs, phase voltage inputs, optional outputs and inputs.

Caution!
Do not change any relay settings which are not mentioned in the lab instruction manual. Also notify TA before saving any modified setting.

1. Connect the C-662 cable to the serial port 1 (PORT 1) on the back of SEL 421 Relay.

2. Press “Esc” to reach the Main Menu, then “Set/Show” □ Port □ 1 □ Communications Settings

3. What is the communications speed of the SEL 421?

4. In AcSELerator Quickset Go to Communications (below Setup) → Set Active Connection Type to Serial → Change the baud rate to the speed found in step 2. Do not change any other setting. Click “Apply”.

a. Read the settings file after connecting to the relay.

b. Meanwhile, on the front panel display of the relay, go to Meter and view the RMS measurements.

c. Observe that there are several settings groups. Furthermore, there are several setting options for a variety of protection schemes in each group.

d. Open HMI and observe the different quantities that can be monitored and measured by the relay.

5. The relay is configured to perform differential protection of a line. It is programmed such that it sees currents from both ends of the line and calculates the difference in current.

a. Group 1 → Set 1 → Relay Configuration → Phase Inst O/C → E50P = 1→ 50P1P = 100 A

Send to active settings to Relay. The relay is now configured such that the pickup current is 100 A. This pickup current is different from a pickup current setting in an overcurrent relay. For an overcurrent relay the pickup current represents a set limit for current flowing through one point that the relay monitors on a circuit. For a differential relay, the pickup current is the set limit for the difference between two points that the relay monitors on a circuit.

Consider a line which suffered an overload condition for a short duration and has a load current of 200 A flowing through it.

b. Observe the sending and receiving currents seen by the relay using HMI.

c. Explain what the current measurements represent in terms of the current flowing through the simulated line or equipment. Reference Figure 1.

d. Why has the relay not tripped when the current flowing through the line is greater than the set pickup current?

e. Calculate the following:

The relay has the following settings. For a very inverse U3 curve, the pick-up current is set at 100 A. The CT ratio is 200/1. The time dial setting is 1.0. An SLG fault occurs and the resulting fault current in phase A flowing into the fault is 600 A at one end of the line. At the other end of the line, the current flowing into the fault at phase A is 200 A.

Current of 100 A is flowing through the line from one end to the other in B and C phases.

Calculate the expected time for the relay to issue the trip signal based on differential protection.

EVENT REPORTING PART B

6. Download the event report corresponding to the fault. Notice that the SEL 421 can record more events and records at the rate of 8 samples/cycle as well as 4 samples/cycle. Download the event report at 8 samples/cycle for higher resolution.

a. Observe that the phase A current magnitude is 800 A.

b. Move the cursors such that one cursor is at the pickup current and the other cursor is at the beginning of the trip signal.

Identify the time taken for the relay to trip. Does it match with the calculated value in Step 13?

7. Reset the relay by selecting the Target Reset button on the Relay. Disconnect the communication between the Relay and the Computer: Communications → Disconnect.

8. Disconnect the C-662 cable from the back of SEL 421 Relay.

REVIEW QUESTIONS

1. How does an operator prevent a line or equipment from burning out or overheating from an external fault while employing differential protection?

2. What is the ANSI Code for Differential Protection?

3. What are the benefits of using differential protection over simple overcurrent protection?

4. List some equipment (at least 3) that are typically protected using differential protection.

5. Why do we need to regularly check for event reports present in the relays and download them?

6. List different uses or benefits of performing fault analysis using event reports downloaded from the relay.

Chapter 4

Conclusion

From the execution of this report, materials for educational purposes have been created and implemented in a class setting. The materials include: two lab manuals, two sets of lab experiments, two question documents, an introductory video, and a transcript. Although created for a specific university course in mind, these experiments could be used in industry to provide a basic and introductory understanding of relay operation. Power system protection theory as well as protection equipment application for overcurrent and differential relays were discussed. Related equipment surrounding relays, as well as generic relay settings were introduced. Event reporting and software applications were addressed, and software, amongst other relay materials, is included in lab manuals through which students are assessed and engaged. Lab manuals and exercises are presented for future work, and can be complemented with further topics of study.

Further Topics of Study

This report offers a beginner's guide to studying protective systems and relays. Through the study of the report's manuals and exercises, students may lay a foundational grasp of protection systems and relays. Teachers may wish to expand upon this foundation with further study. Besides examining other types of relays, further topics of study include, but are not limited to, transformers in relay circuits, relay communications, numerical relays, network optimization, the inclusion of distributed generation (DG) in protected systems, and fault-finding procedures. These topics have not been previously

mentioned in this report, but a brief reference to them in this section may recommend them for inclusion in future educational scenarios.

It may be of interest to model transformers in relay circuits. The phase shifts of protected transformer equipment and the phase shifts of CTs must be connected to correctly compensate for the 30-degree phase shifts allotted to transformers [1]. This is achieved by connecting a transformer's delta side in wye for the CT, and a transformer's wye side in delta for the CT [1]. Further exercises and modeling on this topic highlights details of forming a relay circuit, and the importance of correct correction for what a relay senses, measures and compares in its circuit.

Depending on the size of the protective zone, there may be considerable distances between the CT secondaries of a zone. When this is the case, the use of differential relays is not as practical. However, with recent changes in communications, there are more opportunities to compare information between long-distance terminals [6]. Communication plays a large role in coordination between devices, as well as the ability to transport and sharing data between substations and service areas. Relatively new technologies are being implemented for communications, such as fiber-optic cables, which enable differential relay protection [6].

Relays have developed from electromechanical models to numerical models with the evolution of steady-state and digital technologies. While the EM models are appropriate for basic relay explanations, numerical relays are the modern form of relay and should be understood. By pairing the foundational concepts of relays with computer science principles such as digital signals and data processing, topics on numerical relays is the natural sequel to an introduction to relays.

For further study beyond the apparatus level, there are studies in network. Network optimization dives deeper into the protective strategy of power systems, and

looks closer at the coordination of devices by zone. Research, such as that in [9], attempts to find optimization between relay and other device coordination to minimize the disturbance of the system during faults. Other research, such as in [10], focuses on a technique to determine relay settings to achieve optimization. Intrazonal and interzonal coordination amongst system protection devices can become complicated, and different algorithms and optimization strategies have arisen in conjunction with communication and digital advances.

Changes to the greater power system are placing new strains on protection devices. Relay settings need to be reconfigured with the introduction of DG and other distributed energy resources (DERs) in the power system. Fault currents may behave differently with the introduction of DG [11]. There is a risk of "backflow" which is a problem larger than just the protection system, but will have important consequences in making modifications to the existing protection system. Reference [12] examines this question in relation to switches, fuses, reclosers, and relays, while [13] examines problems with directional relays with DG interaction.

While this report covers the basic relay operation, the next phase of system protection is addressing faults through line maintenance. Fault finding is a major aspect of protection analysis and power system maintenance. Algorithms for fault finding based on information from protection devices can greatly decrease the time it takes for maintenance workers to identify faults on the extensive distribution system, and therefore decrease maintenance time and outage time for customers. Fault finding applies knowledge of events and reporting, as introduced in this manual. [14] presents the theory and application of several impedance-based fault techniques. New techniques that limit inputs, such as in [15], or techniques for new automation, such as in [16], are progressing fault-locating abilities. [17] examines fault location with increased DG in a system.

Algorithm development can be studied further in papers such as [18,19,21]. These topics emphasize and enhance the presented lab exercises herein, and build upon knowledge of relays, which reinforces previous learning points.

Appendix A: Solution to Overcurrent Relay Manual

OVERCURRENT RELAYS

3) Using the front panel, navigate and identify the initial currents measured by the relay.

Answer:

IA = 0 IB =0 IC =0

4) List the different menus available that can be accessed using the front panel.

Answer:

Meter, events, status, set, control

5) Navigating through the settings, using the left/right arrows and “Select” button, find the speed settings of the relay module.

Answer:

2400

7a) For a very inverse U3 curve, the pickup current is set at 60 A (at the primary of the CT). The CT ratio is 600/5. An SLG fault occurs and the resulting fault current in phase A is 600 A. The settings of the relay are such that the time dial settings is 0.8. What is the operation time in cycles?

Answer:

M = 600/60 = 10

Operation Time = TD * (.0963 + (3.88)/(M^2 – 1))

= 0.108 sec = 6.48 cycles

7b) Calculate the pickup current in terms of the secondary current of the CT.

Answer:

60 * (5/600) = .5 A

9a) Observe the fault currents displayed by the Relay

Answer:

IA = 48 A IB = 0-5A IC = 0-5A

9b) What is the secondary CT current during the fault?

Answer:

IA/CTR = 48/120 = .4 A

9c) Verify the currents displayed by the relay by calculation

Answer:

.4 (Given) *CTR = .4*120 = 48 A

9d) Why has the relay not tripped?

Anwer:

Pickup Current is set to 60 A at the primary of the CT, so 48 A is not enough to trip the relay.

10a) Observe the fault currents displayed by the Relay

Answer:

IA = 600 A IB = 0-5A IC = 0-5A

10b) Based on the fault current, the relay identifies the type of fault. This is shown by glowing LEDs on the front panel. What is the type of fault recognized by the relay?

Answer

Light on “A” of LED panel denotes a single phase fault.

10c) Based on the current measurement displayed by the relay, what would have been the CT secondary current that was the input to the relay?

Answer:

IA/CTR = 600/120 = 5 A

10d) With the same fault current, if the CT ratio had been set at 200, what current would the relay sense for phase A?

Answer:

IA/CTR = 600/200 = 3 A

11a) What is the highest rate the report can support (samples/cycle)?

Answer:

4 Samples per cycle

11b) Why would you want a lower rate than the highest possible rate? Why would you want the highest possible rate?

Answer:

A lower data rate corresponds to less memory needed for data storage. A higher rate corresponds to more data and finer data granularity.

11f) On the following image, please identify the pickup current, the fault current on phase A, the time delay, and the actual trip.

Answer:

Pickup current: “IA: 64 A”

Time delay: 108.33 ms

Fault current: IA mag 598.7 A

The trip occurs at purple vertical line (third panel)

11g) What happens to the magnitudes of the currents on phase B and C?

Answer:

Phases B and C increase from approximately 10 A to about 48 A.

11h) Move the cursors such that one cursor is at the pickup current and the other cursor is at the beginning of the trip signal. What was the time taken for the relay to trip? Does it match with the value calculated for this scenario in Step 7?

Answer:

The time delay shown is 108.3 ms, which corresponds to the calculations from Step 7.

REVIEW QUESTIONS

1. What are the benefits of a time-delay overcurrent relay over a fuse

   Answer: Time-delay settings can save a fuse. A fuse must be manually replaced after use.

2. List at least 2 equipment elements associated with a relay that helps protect a circuit.

   Answer: Current transformers and circuit breakers

3. What is the purpose of including a current transformer between a power system device and a relay?

   Answer: A CT allows for greater precision from measuring devices, and downstream equipment does not need to be fortified to handle large currents.

4. What setting would be changed if the relay were designed to trip after a longer amount of time?

   Answer: The time-delay setting

5. List different uses or benefits of performing fault analysis using event reports downloaded from the relay.

   Answer: Event reports allow for detailed analysis of the system, equipment and potential fault. Analysis can be used for relay performance verification, fault location, and system parameter verification.

6. The U3 very inverse time-overcurrent relay curve is shown below. Draw an approximate curve for a .8 time dial and identify the operating time corresponding with the relay settings used in step 7.

Answer: The curve is drawn between the .5 and 1 time dial curves, following the U3 shape.

Appendix B: Solution to Differential Relay Manual

DIFFERENTIAL RELAYS PART A

3) What is the communications speed of the SEL 421?

Answer:

9600

5b) Observe the sending and receiving current seen by the relay using HMI.

Answer:

I_{AS} = 200 A I_{AR} = -200 A

I_{BS} = 200 A I_{BR} = -200 A

I_{CS} = 200 A I_{CR} = -200 A

5c) Explain what the current measurements represent in terms of the current flowing through the simulated line or equipment. Reference Figure 1.

Answer:

In Figure 1, these currents represent IW and IX , which are the currents that enter the relay.

5d) Why has the relay not tripped when the current flowing through the line is greater than the set pickup current?

Answer:

Although the current flowing through the line is greater than the pickup current, the pickup current is compared with the differential of the current flowing through the line. Since there is no differential current, there is no trip.

5e) Calculate the following:

The relay has the following settings. For a very inverse U3 curve, the pick-up current is set at 100 A. The CT ratio is 200/1. The time dial setting is 1.0. An SLG fault occurs and the resulting fault current in phase A flowing into the fault is 600 A at one end of the line. At the other end of the line, the current flowing into the fault at phase A is 200 A.

Current of 100 A is flowing through the line from one end to the other in B and C phases.

Calculate the expected time for the relay to issue the trip signal based on differential protection.

Answer:

Fault current = Summation of current flowing into the relay = 600+200

M = Fault current/pickup current = 800/100 = 8

Tp=TD∗(0.0963+ 3.88/(M^2−1))

Tp=0.1578 sec=9.47 $cycles$

EVENT REPORTING PART B

6b) Move the cursors such that one cursor is at the pickup current and the other cursor is at the beginning of the trip signal. Identify the time taken for the relay to trip. Does it match with the calculated value in Step 13?

Answer:

The event report shows that the time taken to trip, the time between sensing the pickup current and the trip signal, is 154 ms. This is very close to the calculated value of 158 ms.

REVIEW QUESTIONS

1. How does an operator prevent a line or equipment from burning out or overheating from an external fault while employing differential protection?

   Answer: The operator coordinates differential protection with overcurrent protection devices

2. What is the ANSI Code for Differential Protection?

   Answer: 87

3. What are the benefits of using differential protection over simple overcurrent protection?

   Answer: Differential protection protects only the zone that it is intended for, and it is more robust against false tripping from faults outside of its protection zone.

4. List some equipment (at least 3) that are typically protected using differential protection.

   Answer: Generator, Transformer, Bus Bar, Reactor and Lines

5. Why do we need to regularly check for event reports present in the relays and download them?

   Answer: Older event reports will be overwritten with new event reports by the relay. Therefore, we must check for relay reports periodically and download them to be saved and later analyzed, or else the information will be lost.

6. List different uses or benefits of performing fault analysis using event reports downloaded from the relay.

   Answer: Relay performance verification, fault location, system impedance parameter verification

References

[1] Glover, J. Duncan, Mulukutla S. Sarma, and Thomas Overbye. *Power system analysis & design.* Cengage Learning, 2016.

[2] Thompson, Michael J. "Percentage restrained differential, percentage of what?" 2011 64th Annual Conference for Protective Relay Engineers. IEEE, 2011.

[3] Vittal, Vijay, and A. R. Bergen. *Power systems analysis.* Prentice Hall, 1999.

[4] Santoso, Surya. *Fundamentals of electric power quality.* University of Texas at Austin, 2012.

[5] Stevenson, William D. Elements of power systems analysis. McGraw-Hill, 1982.

[6] Blackburn, J. Lewis, and Thomas J. Domin. *Protective relaying: principles and applications.* CRC Press, 2015.

[7] Horowitz, Stanley H., and Arun G. Phadke. *Power system relaying.* Vol. 22. John Wiley & Sons, 2008.

[8] Ferrer, Héctor J. Altuve, and Edmund O. Schweitzer, eds. "Modern solutions for protection, control, and monitoring of electric power systems." Schweitzer Engineering Laboratories, 2010.

[9] Lwin, Min, et al. "Stochastic optimization for discrete overcurrent relay tripping characteristics and coordination." IEEE Transactions on Smart Grid 10.1, 2017.

[10] Chattopadhyay, Bijoy, M. S. Sachdev, and T. S. Sidhu. "An on-line relay coordination algorithm for adaptive protection using linear programming technique." IEEE Transactions on Power Delivery 11.1, 1996.

[11] Girgis, Adly, and Sukumar Brahma. "Effect of distributed generation on protective device coordination in distribution system." LESCOPE 01. 2001 Large Engineering Systems Conference on Power Engineering. Conference Proceedings. Theme: Powering Beyond 2001 (Cat. No. 01ex490). IEEE, 2001.

[12] Lwin, Min, et al. "Protective device and switch allocation for reliability optimization with distributed generators." IEEE Transactions on Sustainable Energy 10.1, 2018.

[13] El-Khattam, Walid, and Tarlochan S. Sidhu. "Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter." IEEE Transactions on power delivery 23.2, 2008.

[14] Das, Swagata, et al. "Impedance-based fault location in transmission networks: theory and application." IEEE Access 2, 2014.

[15] Das, Swagata, Neeraj Karnik, and Surya Santoso. "Distribution fault-locating algorithms using current only." IEEE transactions on power delivery 27.3, 2012.

[16] Ananthan, Sundaravaradan Navalpakkam, et al. “Model-based approach integrated with fault circuit indicators for fault location in distribution systems.” 2019 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2019.

[17] Min, Kyung Woo, Swagata Das, and Surya Santoso. "Improved method for locating faults upstream from distributed generation." 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D). IEEE, 2016.

[18] Kulkarni, Saurabh, and Surya Santoso. "Time-domain algorithm for locating evolving faults." IEEE Transactions on Smart Grid 3.4, 2012.

[19] Das, Swagata, et al. "Distribution fault location using short-circuit fault current profile approach." 2011 IEEE Power and Energy Society General Meeting. IEEE, 2011.

[20] Santoso, Surya, et al. "Distance estimation technique for single line-to-ground faults in a radial distribution system." 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 00CH37077). Vol. 4. IEEE, 2000.

[21] Santoso, Surya, and Thomas A. Short. "Identification of fuse and recloser operations in a radial distribution system." IEEE transactions on power delivery 22.4, 2007.

[22] ISO-NE. “Requirements For Circuit Breakers Used for Independent Pole Tripping on the New England Transmission System.” ISO New England. https://www.iso-ne.com/static-assets/documents/rules_proceds/isone_plan/othr_docs/requirements_for_circuit_breakers_used_for_independent_pole_tripping.pdf, June 10, 2014.

[23] So, C. W., and K. K. Li. "Time coordination method for power system protection by evolutionary algorithm." IEEE Transactions on Industry Applications 36.5, 2000.