SUB-CYCLE OVERCURRENT PROTECTION FOR SELF-CLEARING FAULTS DUE TO INSULATION BREAKDOWN

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INTRODUCTION

This paper presents an innovative method for sub-cycle overcurrent protection for self-clearing faults which occur in cables due to insulation breakdown.

Self-clearing faults have the following characteristics:

1. Faults are self-cleared within a quarter cycle,
2. They always occur near a voltage peak, and
3. Their frequency of occurrence increases over time.

During these types of faults, because of their short duration, conventional overcurrent protection does not operate. The protection scheme presented in this paper is fast enough to operate and has logic to differentiate them from other types of faults, such as through faults or faults cleared by circuit breakers.

The first section of this paper discusses the self-clearing fault phenomena. The second section describes a universal protective relay architecture in which the sub-cycle overcurrent protection scheme has been implemented. The third section describes the protection scheme algorithm and implementation in the relay scheme[1]. The fourth section covers testing of this scheme. An overall universal distribution protection scheme is discussed in section five. Conclusions are given at the end.

1. SELF-CLEARING FAULT PHENOMENA

Florida Power Corporation (FPC) reported a number of cable failures due to insulation breakdown from water penetrating into splices. When water accumulates in a cable splice, it leads to an insulation breakdown followed by an arc. Arcing causes rapid water evaporation and develops high pressures inside the splice which extinguishes the arc and interrupts the current within a quarter cycle. Because the fault current is interrupted by water vapor pressure developed from fault current, these types of faults are called self-clearing. Their frequency of occurrence increases over time. At first, they occur infrequently, once a month, then several times a week, then several times a day, and finally several times an hour until the splice fails, damaging the cable. All self-clearing faults have very similar voltage and current waveforms as shown in Figures 1 and 2, which display measurements of two subsequent faults. Insulation breakdown occurs near a voltage peak and the fault lasts a quarter cycle.

Figures 1 and 2 show self-clearing faults already in a progressed stage. A fault in Figure 1 occurred on August 06, 1995 at 09:38:33 a.m. An essentially identical fault shown in Figure 2 occurred on August 06, 1995 at 09:41:12 a.m., less than three minutes after the previous fault.

Events Leading to Detection of Self-Clearing Faults. Complaints were first received from a customer in a large office park that a UPS system was frequently alarming and switching to battery source. To find causes for these

[1] Patent pending

events, a power quality (PQ) monitoring instrument was installed in the substation on the 12 kV bus with three feeders serving the office park. Soon, first voltage and current waveforms were recorded, very similar to those shown in Figures 1 and 2. The faults did not target or trip breakers. Each time the fault occurred, very similar waveforms were recorded. The faults always occurred on the same phase and were initiated near voltage peaks. This raised suspicions of possible insulation breakdown. Faults caused by outside contacts were ruled out since they would be initiated at random incipient angles. Waveforms looked like current-limiting fuse operation, but there were no current-limiting fuses in this area. Additional portable monitoring equipment was then installed to identify which of three circuits served from the bus was experiencing the fault. The circuit identified as having the fault was all underground cable except for one overhead span crossing an interstate highway. Fault distances were estimated from recorded current peak magnitudes and system X/R ratios. This indicated that faults were close to the substation on a cable (type XLPE) which was three miles long. The exact fault location was not possible to determine since the cable had a low zero sequence impedance. The nature of the fault was a mystery since temporary faults were not thought to be a normal occurrence on underground cables with solid dielectric insulation. Waveforms similar to before were recorded again, three times one day and twelve times the next. The following day, a 600 A molded rubber splice failure occurred in a pullbox just outside the substation fence. This was finally the answer to the “mystery” current waveforms and the fault location.

The splice was replaced with a new one and circuit was returned to service, thinking the problem was solved. One week later a check of the PQ data file showed the waveform occurring again on the same phase as before (four times during one day and eight times the next). A crew was dispatched to investigate the same splice. They could hear a “thumping” while standing near the splice box. The splice box was opened and inspection showed signs of insulation burning. Since the splice box had no “slack” cable remaining for another splice a replacement cable was run from the substation pilaster terminal to the splice box and another splice installed. This event obviously prevented progression to a permanent fault and another outage to the office park. The assumption was the splice or the installation was faulty, and the reoccurrence was an anomaly.

The PQ data file was closely monitored after this incident. Imagine the surprise when three days later the same, identical waveform appeared again. The frequency of occurrence began rapidly increasing over a three-day period. The splice box was checked and again found to be failing. The cable run from the splice box to the overhead crossing was replaced and a new splice installed. This represented the second feeder outage that was prevented by monitoring the PQ data and taking preemptive action.

Cable samples showed that the cable, from the splice to the overhead riser, was filled with water. Inspection of the overhead termination showed the terminator was defective and allowed rainwater to run directly down the cable strands. This water reacted with the aluminum conductor and formed a gas, which forced water out the end of the splice to the concentric neutral. The water caused an insulation flashover, which resealed the splice allowing more water to accumulate.

Since these events, two more splice failures occurred on the distribution system having installed PQ monitoring equipment. On one cable 23 characteristic waveforms were recorded during the week prior to failure of the splice. Again, no relays targeted and no breakers operated until the fault became permanent.

Recently, also some other utilities reported the same phenomenon and the recorded waveforms are very similar to those shown in Figures 1 and 2.

Another documented phenomenon is “elbow backoff” which is the burping of loadbreak elbow connectors caused by increased gas pressure. Gas is also generated by water penetrating into elbow and reacting with the aluminum. Many elbow failures were reported because of the wet cables, but this is the first evidence of splice failures caused by this mechanism.

The above examples show that having advance warning can prevent permanent failures for these types of cable faults. The existence of molded rubber splices and wet cable in distribution systems is a fairly common condition. Early detection may be accomplished by a relay that can respond fast enough (fault duration does not exceed a half cycle) to signature voltage and current conditions. The relay should not respond to faults cleared by reclosers or breakers, faults which are not initiated near a voltage peak, and faults that are not repetitive over some time period such as current-limiting fuse operations. When set parameters are exceeded, the relay can automatically alarm the dispatcher using communication.

Early detection of the breakdown is required to allow time to locate and repair the failing item before a permanent fault occurs. It is possible to estimate the fault location from the current peak value and the X/R ratio of the circuit. There is no guarantee that this will work in all cases, but it was effective in locating faults described here. Field location of the failing device can be difficult and time consuming otherwise.

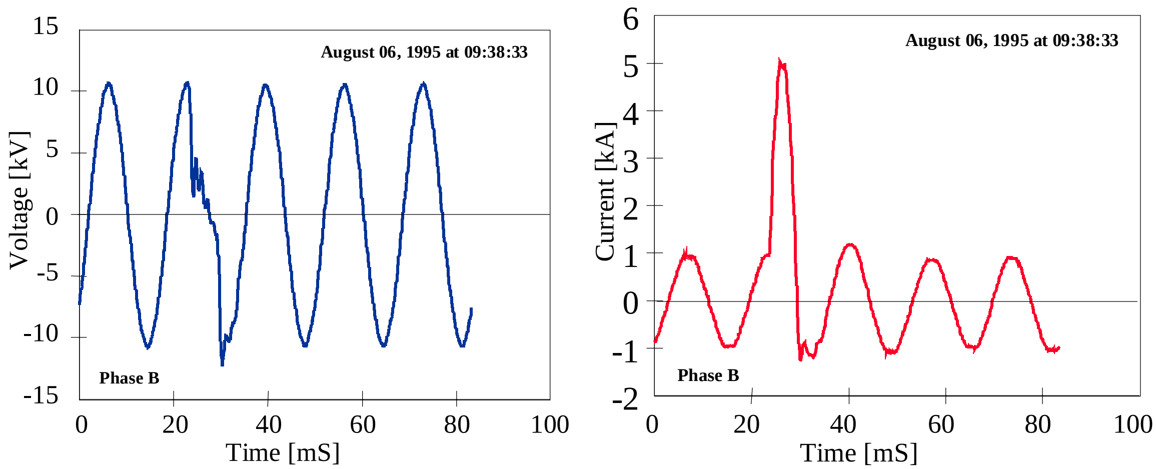


Figure 1. Voltage and Current Waveforms During a Self-Clearing Cable Splice Fault (example #1)

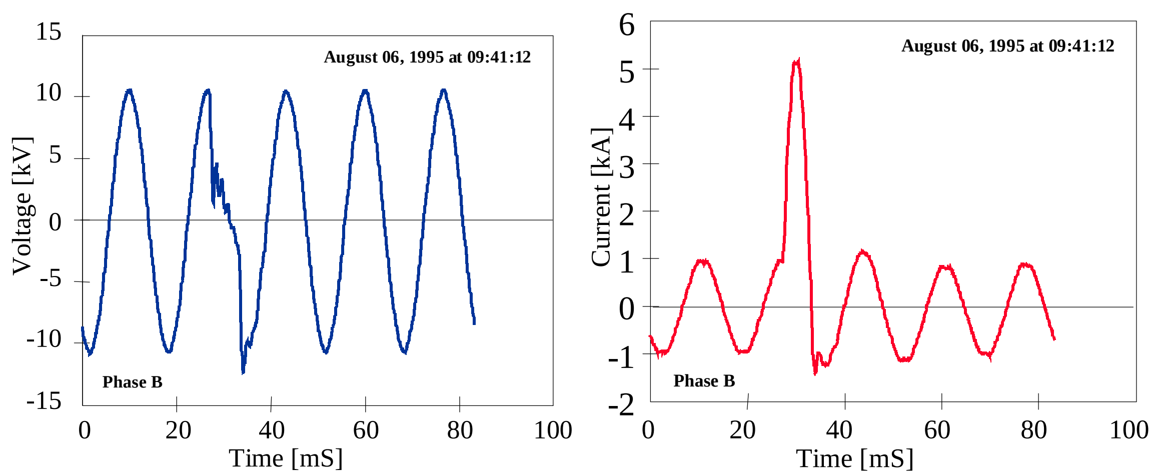


Figure 2. Voltage and Current Waveforms During a Self-Clearing Cable Splice Fault (example #2)

2. A UNIVERSAL PROTECTIVE RELAY ARCHITECTURE

A sub-cycle overcurrent protection scheme has been implemented in a universal protective relay that uses modular hardware and software components [1-4]. This universal protective relay integrates different functions such as metering, control, PLC, and communication into a single device (Figure 3). Its platform makes it possible to manipulate input voltage and current samples through different algorithms to obtain quantities such as phasors, symmetrical components, and frequency, which combined make faster and more accurate decisions about faults in the system. This platform can be used as a single model intelligent electronic device (IED) throughout a utility for any type of protection, control, or metering. The PC-based software comprises both an intuitive graphical interface for the relay functions and a Computer-Aided Engineering (CAE) program for designing and testing protection, control, and monitoring schemes. The graphical CAE program runs on IBM-compatible personal computers under the Microsoft Windows operating system and serves to develop protective relay schematic diagrams. The software automatically translates the schematic into a form readable by the hardware platform. Any changes to the protection scheme are self-documenting, since the relay cannot perform a function not visually drawn in the CAE package. Relay and control systems can be rapidly developed for specific applications.

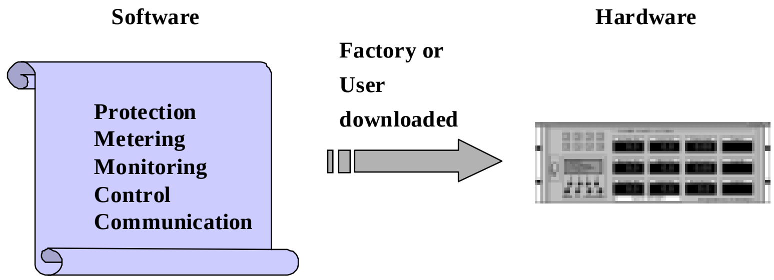


Figure 3. Integrated Functions of the Universal Protective Relay

The highest-level functional blocks for this relay are shown in Figure 4. The scheme is modular and can be pre-configured explicitly for a given application, for example distribution protection. Also, since the scheme is an open, user-programmable universal relay platform, it can be easily modified for the user's particular application.

The schematic is composed of blocks, representing various operations to be performed on voltage and current signals. Several blocks can be easily bound together into a compound block or module which embodies the processing required to implement a more complicated function. Such compound function blocks can then be connected into the schematic. Compound blocks can be further nested and bound together with other simple and compound blocks to compose yet more sophisticated functions. The created schematic diagrams are thus termed hierarchical. The most sophisticated function blocks are usually hierarchical modules containing layers of simple and yet more simple function blocks. The great advantage of modularity in software is that modules can be built, tested, and maintained separately from the whole software. That is, it is not necessary for all the many pieces to be fully functioning together before they can each perform their individual function. Any functions that are constructed graphically and packaged together in a single container can be saved to a file for future use. Thus, the effort expended in developing and qualifying a given module need not be duplicated. Figure 4 shows a high-level scheme that includes four main blocks: application diagram, protection settings, oscillography, and scheme structure.

The Application diagram includes a single-line diagram, measurements, and the recloser/breaker status for intuitive online viewing. The application block can be opened by clicking the mouse (Figure 5). The online view mode displays ongoing real-time values. This mode can be activated whenever the user's PC is in communication with the relay. This is a valuable benefit during relay commissioning and testing, since it is possible to monitor the actual operational state of all internal elements as input conditions are applied or adjusted. During normal operation, the application diagram can be used to determine the status of a protection scheme under load conditions. For example, the degree to which load level or load imbalance affect protection characteristics can be determined. This can be directly observed using the online view, by simply examining the inputs and outputs of the internal protective relay elements. All elements whose status has been changed turn colors from green to red and from "0" to "1".

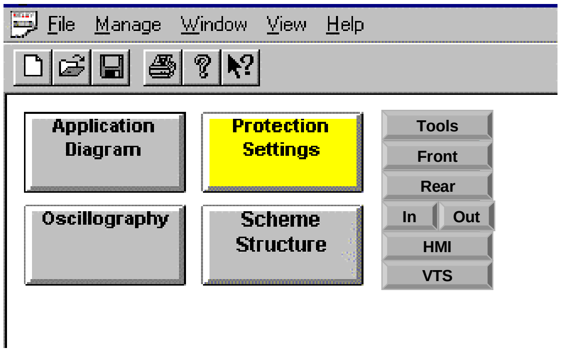


Figure 4. The Relay High-Level Functional Blocks

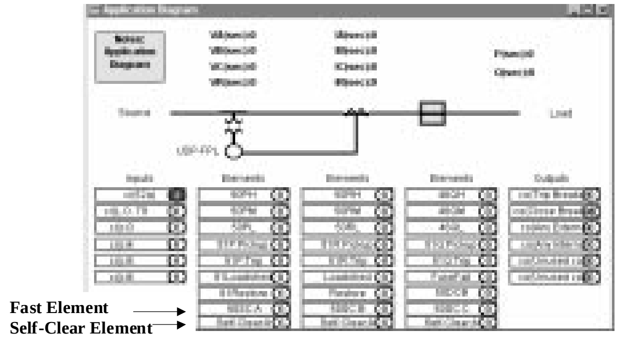


Figure 5. Application Diagram and On-Line View

Setting the relay is performed by opening the Protection Setting block (Figure 4) and typing appropriate values in the window.

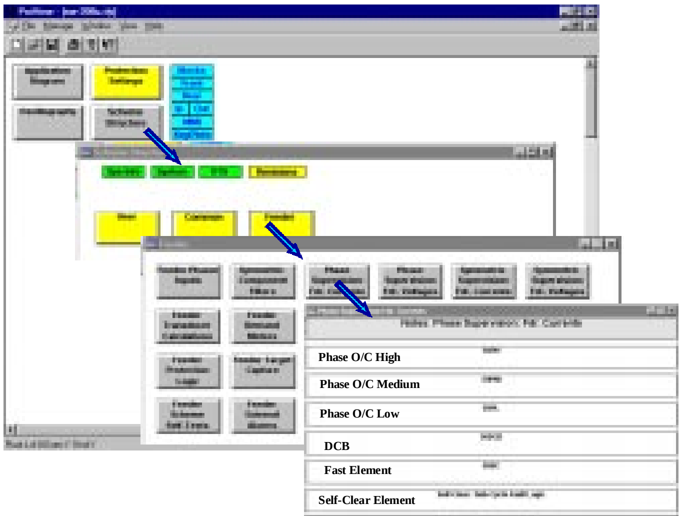
The Scheme Structure block contains the relay scheme that can be secured against unauthorized changes by implementing the access levels. The seven smaller blocks in Figure 4 are supporting tools in the scheme design.

A scheme can be built by selecting, clicking and dragging pre-designed elements located in the “Blocks” block (Figure 4). Figure 6 shows a portion of the hierarchical scheme structure. All protection functions are implemented in the “Feeder” block. To access fast and self-clear element modules, where the sub-cycle overcurrent protection scheme has been implemented, first it is necessary to open the “Phase Supervision: Feeder Currents” block, and then the “50SC” block or “Self-Clear/Sub-Cycle Fault Logic” block. Description of the sub-cycle overcurrent protection scheme is given in Section 3.

“Front” and “Rear” blocks (Figure 4) include virtual views of the relay front and rear panels. The Rear panel view displays which terminal and contacts are used. Another contact can be added by clicking and dragging a contact icon from the Rear block.

The Virtual Test Set (VTS) model is programmed in the relay software. It models the simplified system shown in Figure 7, including a voltage source, source impedance, and line impedance. Various faults, system parameters, and fault incidence angles can be modeled. It provides the ability to conveniently verify that the software design has the intended functional characteristics. VTS capabilities are encapsulated within each and every input module. Therefore, the relay automatically has built-in test capabilities with as many independent and matched signal sources as there are relay inputs, analog or contact. The VTS is used in the sub-cycle overcurrent protection scheme development and verification. Waveforms generated by the VTS simulating a self-clearing fault is shown in Figure 8, which represents the relay’s oscillography. Virtual testing is convenient for initial verification of logical components, or the entire scheme, prior to live testing.

Multiple Function-Specific Oscillography. The scheme includes multiple function-specific oscillographic view for overview or focused analyses of event records such as phasor input vectors, waveforms, and magnitudes; contact inputs and outputs; breaker/recloser inputs and outputs; phase and residual current protection; and under-frequency load shedding. Oscillographic report formats provide an intuitive visual overview of system conditions and relay responses. Figure 8 shows an opened oscillographic window displaying waveforms representing simulation of a self-clearing fault using the VTS. The relay response to the fault is also shown.



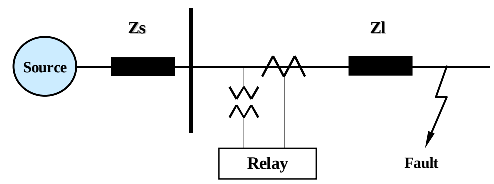


Figure 6. Scheme Structure Block showing Location of Fast Element and Self-Clear Element

Figure 7. Virtual Test Set Representing System Model

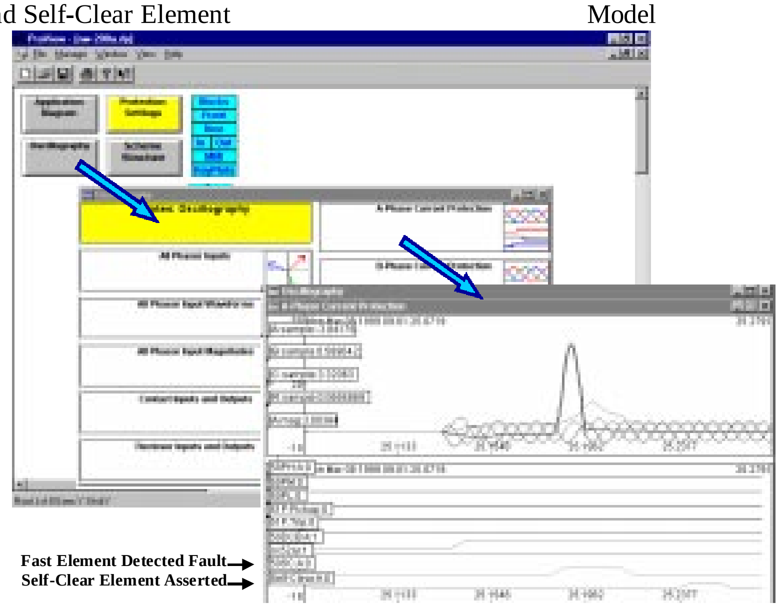


Figure 8. Multiple Function-Specific Oscillography showing Self-Clearing Waveforms and the Relay Response

The Human-Machine-Interface (HMI) is the LCD display and pushbutton interaction on the relay front panel which can be programmed according to the users' exact needs. Typical functions include breaker/recloser status, target outputs, external alarms, breaker/recloser control (closing and opening), and measurement.

Troubleshooting and Outage Analysis. Relay event records of interest can be uploaded to personal computers. The active schematic permits examination of relay inputs and outputs, operation of every internal relay element in-between, and the complex logic that combines them. If the cause of a relay operation is not known, the active schematic can be examined to determine the cause. Analyses of relay operations and outages can be accomplished by uploading event records and replaying them. It is possible to investigate how relay settings influence relay operation. Settings can be modified with a personal computer and then tested by replaying an actual fault record with the modified settings. With this capability, one can predict how the relay will perform in the field, and how it will perform in the future. The relay in the field can effectively be re-tested with an exact duplication of recorded input conditions.

Outage analysis or relay testing can be performed on an identical scheme on the user's computer without affecting the relay setting or connections. If tests must be performed on the actual relay, then after tests are completed, the relay becomes *automatically* fully functional by downloading the scheme containing all settings, contact outputs, and other programmed parameters. This eliminates the possibility of the user overlooking specific parameters.

3. IMPLEMENTATION IN THE PROTECTION SCHEME

The sub-cycle overcurrent protection scheme for self-clearing faults has been designed for the universal relay presented in this paper. A block diagram of the scheme is shown in Figure 9. Included is fast overcurrent element which responds to faults within a quarter cycle, protection logic to differentiate these type of faults from other faults including let-through faults, a counter to record the number of fault occurrences, and a timer to record frequency of fault occurrences.

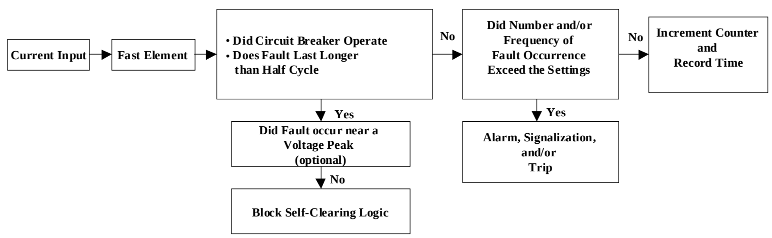


Figure 9. Block Diagram of Sub-Cycle Overcurrent Protection Scheme for Self-Clearing Faults

Figure 10 shows the opened "50SC" and "Self-Clear/Sub-Cycle Fault Logic" blocks from Figure 6. Both these blocks include input signals, blocks with algorithms, and output signals. Figure 10 also shows signal flow in the relay scheme from the "50SC" block to the "Self-Clear/Sub-Cycle Fault Logic" block. Here, the output signals of "50SC" block are at the same time the input signals for the "Self-Clear/Sub-Cycle Fault Logic" block. Then the output signals of the "Self-Clear/Sub-Cycle Fault Logic" block become the input signals for the other blocks to display the number and frequency of fault occurrences, to initiate alarm and/or to trip the breaker.

The simplified scheme protection logic of a self-clearing block from Figure 10 is presented in Figure 11. It operates as follows: when fast element (50SC) detects a fault, it asserts 50SC input to 1. This asserts sR output to 1, and at the same time NOT #1 output to 0. Element AND #1 has output 0. If the fault goes away before any reset element operates, 50SC input will change to 0 and output NOT #1 will change to 1. Output AND #1 changes to 1 and after time set on timer #2 output changes to 1. If event no longer exists, NOT #2 has output 1 and AND #2 output changes to 1, which asserts self-clearing logic and updates the counter. If any reset element operates during this process, the self-clearing logic is blocked. The logic can be programmed to display number of events, frequency of events, and to trip breaker after defined criteria.

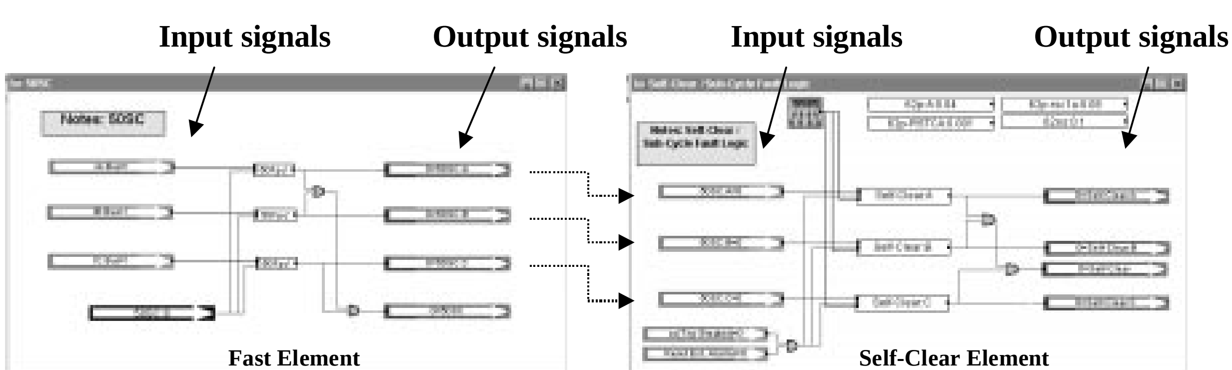


Figure 10. Implementation of the Relay Scheme

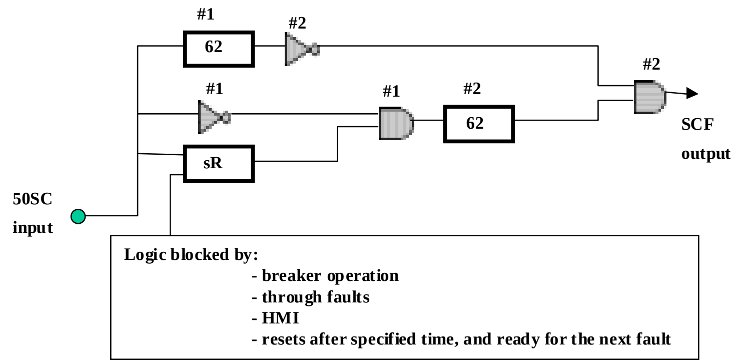


Figure 11. Simplified Sub-Cycle Overcurrent Protection Scheme Logic

4. TESTING

Following virtual testing, the sub-cycle overcurrent protection scheme was tested on a Real-Time Power System Simulator (RTPSS) and in a high power laboratory.

The RTPSS is a computer-controlled, analog-based device employing high fidelity voltage and current amplifiers. It has the ability to simulate a comprehensive set of system configurations and faults. A block diagram of the RTPSS is shown in Figure 12. The test system enables repetitive simulations and can quickly obtain relay response data in a statistical fashion to expedite evaluation. Various system disturbances and faults can be easily simulated. It effectively simulates transients as well as instrument transformer responses. The RTPSS was used to verify the overall operational and logic performance including sensitivity and stability of the sub-cycle overcurrent protection scheme.

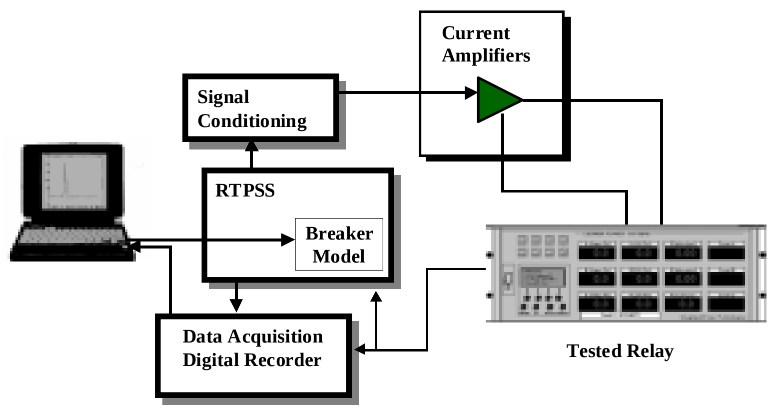


Figure 12. Block Diagram for Testing the Sub-Cycle Overcurrent Protection Scheme on the RTDSS

Relay performance in actual operating conditions and voltage levels was verified in a high power laboratory. A one-line test circuit is shown in Figure 13. Located at the Cooper Power Systems Thomas A. Edison Technical Center, the laboratory includes a 500 MVA three-phase test generator with voltage transformations up to 69 kV and momentary test capacities of 150 kA. Sensitivity and stability of the sub-cycle overcurrent protection scheme were tested. Test parameters included: test voltage 22 kV, load current 500 A, short circuit current 3,000 A. Self-clearing faults were simulated by making ground faults through 18 A current-limiting fuses. Test procedure was as follows:

a) closed circuit breaker to establish load current, b) ground fault initiated by closing a breaker in series with a current-limiting fuse (available fault current was 3,000 A_{RMS}), c) fuse operated, limiting the short-circuit current to

1,800 A peak, simulating a self-clearing fault, and d) load current reestablished representing normal operation. Ratio between let-through short-circuit current and the load current was smaller and duration of faults were shorter than in the recorded waveforms shown in Figures 1 and 2. Both these parameters represent more severe cases and were selected to verify extreme performances of the protection scheme.

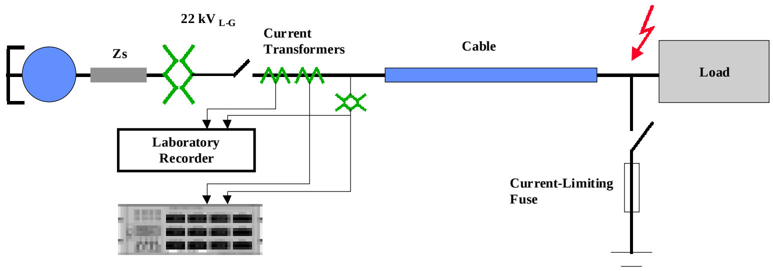


Figure 13. The Single-Line Diagram of the Circuit for Testing the Sub-Cycle Overcurrent Protection Scheme in the High Power Laboratory

Test current waveforms presented in Figures 14 to 17 were obtained during testing by the RTPSS. Sensitivity tests simulated self-clearing faults and verified proper relay responses. Figure 14 shows test current waveforms. The same event captured by the relay's event recorder is given in Figure 15, which shows current waveforms and the relay response. Current waveforms recorded by the relay and laboratory recorder are very similar. The relay response record indicates fast element operation followed by the self-clear element. Stability of the scheme was tested, simulating through-fault currents and faults cleared by the breaker. The self-clear algorithm did not operate for these types of faults. Figure 16 shows test current waveforms. The same event recorded by the relay's event recorder is given in Figure 17. Here again, current waveforms recorded by the relay and laboratory recorder are very similar. The relay response record this time indicates fast element operation while the self-clear element was not asserted since this was not a self-clearing fault.

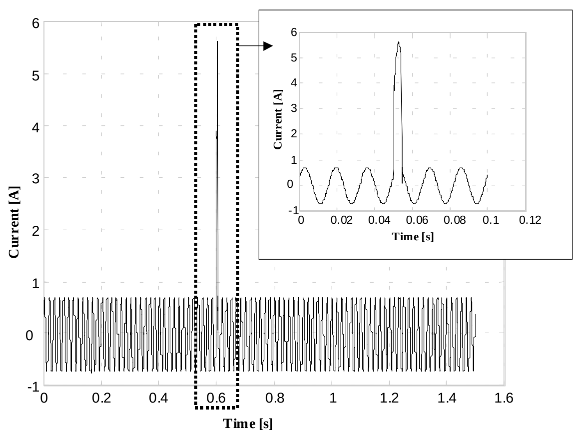


Figure 14. A Current Waveform Representing Self-Clearing Faults (Recorded by the RTPSS Recorder)

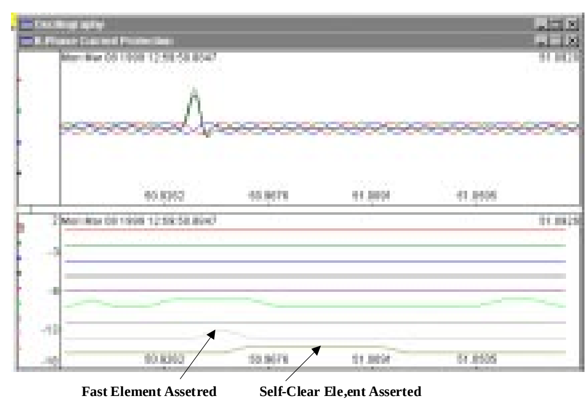


Figure 15. The Same Test as in Figure 14 Recorded by the Relay's Event Recorder

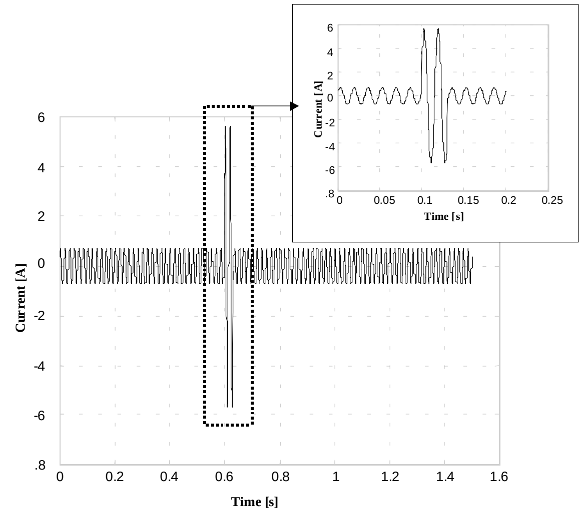


Figure 16. A Current Waveform Representing Let-Through Faults (Recorded by the RTPSS Recorder)

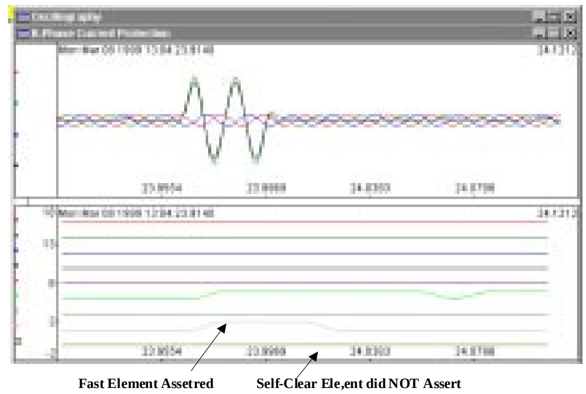


Figure 17. The Same Test as in Figure 16 Recorded by the Relay's Event Recorder

Test current waveforms representing self-clearing faults shown in Figures 18 and 19 were obtained during testing in the high power laboratory. Figure 18 shows test current waveform. The same event recorded by the relay's event recorder is given in Figure 19. The relay response record indicates fast element operation followed by the self-clear element.

Faults cleared by load side connected fuses cannot be differentiated from self-clearing faults. But, fuse operations may be less frequent and can easily be differentiated with logic implemented in the relay scheme.

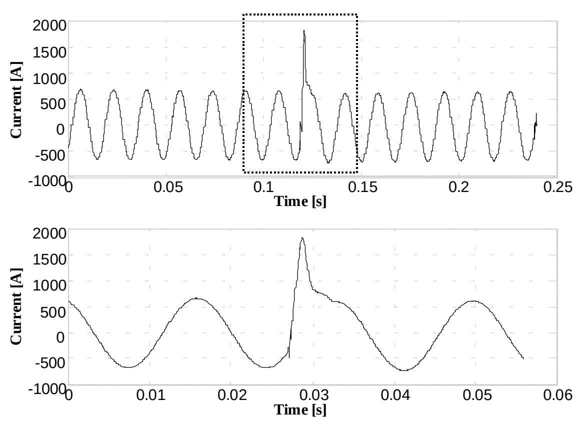


Figure 18. A Current Waveform Representing Self-Clearing Faults (Recorded by the High Power Laboratory Recorder)

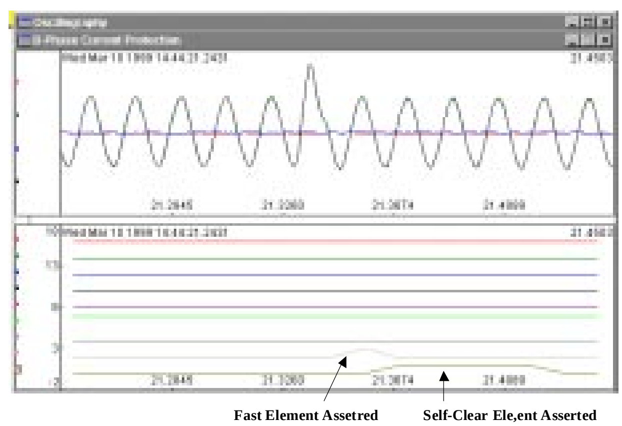


Figure 19. The Same Test as in Figure 18 Recorded by the Relay's Event Recorder

5. PROTECTION OF DISTRIBUTION SYSTEMS

The self-clearing fault detection as described in this paper has been added to a Universal Distribution Protection (UDP) scheme intended for distribution feeder protection. This provides a comprehensive feeder protection relay but and diagnostics for underground circuits that can prevent permanent faults. Other standard protective functions include:

- Inverse time-overcurrent protection for phase, negative-sequence, and zero-sequence current, improving relay sensitivity and reliability for different fault types.
- Instantaneous and time-delayed overcurrent in three levels for all phases and all symmetrical components. The first level provides coordination with high current faults at the beginning of the line; the second level coordinates for low current faults at the end of the line. The third level monitors the protected line for low current events, such as arcing, for reporting back to the operator center.
- Negative-sequence directional element for unbalanced faults, positive-sequence directional element for balanced faults. These can be enabled on a per zone basis for coordination in looped systems or for ungrounded systems. Any time-overcurrent function and any overcurrent zone can be set independently to act as directional forward, directional reverse, or non-directional.
- Programmable reclosing with advanced capabilities for sequence coordination, and shot-dependent and fault-dependent fast-reclosing and fast-tripping.
- Under-frequency load shedding and restoration. This function disconnects load during disturbances to support system stability and closes the load back after the system recovers.

6. CONCLUSIONS

This paper presents an innovative method for sub-cycle overcurrent protection for self-clearing faults that occur in cables due to insulation breakdown. Self-clearing faults have the following characteristics: faults are self-cleared within a quarter cycle, they always occur near a voltage peak, and their occurrence progresses in time. First they occur infrequently, once a month, then several times a week, then several times a day, and finally several times an hour until the splice fails resulting in service outages.

During these types of faults, conventional overcurrent protection does not operate since the fault duration is too short. The sub-cycle overcurrent protection scheme is fast enough to operate and has logic to differentiate these faults from other type of faults such as through faults or faults cleared by reclosers or circuit breakers. The scheme is integrated in a universal relay platform as an additional function of a Universal Distribution Protection scheme intended for distribution feeder protection.

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Biographies

Ljubomir A. Kojovic currently holds the position Chief Power Systems Engineer for Cooper Power Systems at the Thomas A. Edison Technical Center. He has Ph.D. degree in power systems and his specialties include protective relaying, digital modeling, systems analysis, and testing. He is a Senior Member of IEEE Power Engineering Society; is included in the roster of experts for United Nations Development Organization (UNIDO); and is a registered Professional Engineer in the State of Wisconsin. Dr. Kojovic has authored more than 80 technical papers.

Charles W. Williams Jr. graduated from the University of Florida with a B.S.E.E. in EE. Charlie has been employed for the past 27 years in the Distribution Engineering Department at Florida Power Corp. His present title is Staff Engineer. His past responsibilities include Transformers, Lightning Protection, Power Quality, and Special Engineering Studies and Problem Analysis. His current assignment is as Staff Engineer, Distribution Reliability. His primary responsibilities are Reliability Program Development and Analysis. His professional activities include work with the IEEE SPD Committee and the EPRI lightning Research Project. He has participated in research projects at the University of Florida on rocket triggered lightning and the impact of harmonics on revenue metering. He is a past member of the IEEE Transformers Committee and is a Past Chairman of the Overhead Distribution Committee of the Southeastern Electric Exchange. He is a member of the Distribution Subcommittee of the PES and an active member of several working groups. Charlie has been a licensed Professional Engineer in the State of Florida since 1975.