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TESTING AND OPERATIONAL EXPERIENCES WITH HIGH SPEED DISTANCE RELAY IN BPA 500 KV SERIES COMPENSATED NETWORK

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1. INTRODUCTION

Distance protection is one of the most important components of protection systems available to protection engineers. They can benefit from ideas in the newly developed field of adaptive protection, and can offer an even more selective and sensitive form of protection, under a variety of system configurations.

The benefits of installing series capacitors in the power system are well known. They, however, introduce challenges to protection systems with regards to both the series compensated line(s) as well as adjacent lines [1,2].

Series compensation is a method used to allow transmission of heavy load over long distances. Short fault clearing time is the most important factor to maintain system stability. This is especially true for close in faults with high fault currents. Both fixed series capacitors and thyristor-controlled devices introduce harmonics and non-linearity, which may adversely impact the protection function. To take full advantage of the series capacitor installation in a utility network, it is necessary to explore the impact of series capacitors on protection operation and implement appropriate schemes [3]. In systems with series compensation, low frequency transients, large phase shifts, as well as current and voltage inversions will influence the measured quantities. In addition, protective gaps and MOV's will influence significantly the voltages and currents used by the protection system.

Based on the principle of superimposed transient signals, as outlined in [4,5], the first "travelling wave" relay was developed for commercial use. This relay satisfied the ultra high-speed requirements for one-cycle fault clearances and has been in service for many years. The drawback, however, is that it is not based on a continuous measuring algorithm, and thereby requires combined operation with an impedance measuring device.

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It is not possible to use only one algorithm but rather a hybrid solution with parallel and adaptive algorithms must necessarily be implemented.

A fast tripping hybrid scheme, combining fast tripping algorithms and a full scheme distance protection for single line to ground faults and multi phase faults for EHV (Extra High Voltage) transmission lines has been developed by ABB, Sweden. Verification of the fast measuring algorithms is done by using EMTP/ATP [6], as well as by real time simulation with a power system simulator [7] and with a real time Digital Transient Network Analyzer [8].

The newly developed protection was installed in 500 kV series-compensated networks at Bonneville Power Administration (BPA) already in 1999. Before it was applied the protection system underwent extensive general testing as well as special, project oriented tests for each protected circuit separately. BPA has good experiences with existing protection schemes and wanted to continue to utilize this experience using the most modern numerical protection available. The configuration flexibility, inherent to this new protection device made it possible to continue with established practice, with very little additional effort.

This paper describes some of the most important characteristics of the protection system applied with special emphasis on operation of fast measuring algorithms and their independence on application of series capacitors on protected power lines.

The basic approach towards testing different line protection relays to be used within the BPA's 500kV network is presented in detail. Special attention has been paid to specific, project oriented tests, which have been performed on a complete protection system (not a protection relay only) before it has been installed and commissioned on a particular power line.

The applied testing technology and test results are presented with some interesting and, for series compensated networks, specific practical results; some of which were subsequently confirmed by operation for real faults, which occurred during normal system operation.

2. BPA 500 KV NETWORK AND THE REQUIREMENT FOR SPEED

The BPA EHV main grid transmission system is a 500kV system. This system covers the northwest states of Oregon and Washington with lines in northern Idaho and in western Montana. The 500 kV system also interconnects with California and British Columbia, see Figure 1. Many of the transmission lines are in excess of 100 miles in length.

In order to increase load on the system and maintain reliability, high-speed protection is used, and most of the lines are operated with single pole tripping. Additionally, series compensation is needed in some of the transmission paths to allow for an increase in system loading.

The series capacitors that are installed on the BPA system use metal oxide varistors MOVs [9] to protect the capacitors when, due to fault current or heavy load, the voltage across them exceeds the protective level (usually 2.0 to 2.5 pu). Energy is absorbed by the MOVs during the bypass operation. In the newer installations, a triggered gap and a bypass breaker protect the MOVs when the accumulated energy or MOV current exceeds pre-set thresholds. If the bypass operation occurs due to a single-phase fault operation, only the faulted phase capacitor group will be bypassed. The bypass breaker will remain closed during the single pole fault trip and reclose operation (approximately 1.4 to 1.7 seconds). The series capacitors on the un-faulted phases will remain in service with their bypass breakers open. This will cause a load current unbalance for a short time after the fault operation when both line terminals have reclosed. The line relays must not trip during this time before the bypass breaker on the faulted phase is opened to re-insert the capacitors.

The challenge for the line relays is to provide secure, high-speed, single pole tripping on both long and short lines with both weak and strong sources. The relays must be secure from incorrect operation for heavy loading, system swings, mutual coupling from parallel lines, faults on parallel lines, resistive faults, very weak sources, very strong sources, and when series capacitors are in the vicinity of the relay location.

Figure 1: Indication of BPA 500kV Network in Western United States of America

The BPA reliability criterion for protective relays requires high speed tripping for protective relays that are applied on the 500kv system. Two redundant sets of relays with redundant communications are also required. System stability must be maintained in the event that a breaker fails to clear a fault and the breaker failure protection is required to clear the failed breaker. The protective relays should output a trip in 1 cycle or less for close-in, high magnitude faults. An additional cycle is allowed for communications when tripping is communications aided.

BPA is upgrading its communications systems from analog microwave to digital communications via optical fiber and digital radio. There is still quite a lot of analog equipment in service. The communications aided tripping schemes in the line relays must, therefore, be capable of operating with audio transfer trip equipment as well as with the newer digital equipment. BPA currently uses two-tone and four-tone FSK audio transfer trip equipment to communicate between line relays when only audio channels are available for the line protection equipment.

3. DESCRIPTION OF THE APPLIED MAIN PROTECTION SCHEME

The applied protective device is a multifunctional microprocessor based numerical IED with hybrid combination of a full-scheme high-speed (HS) function and a full-scheme multi-zone distance protection. The HS function operates on the basis of superimposed quantities and makes the decision on fault position faster than the series capacitor can seriously influence the shape of measured voltages and currents. Its advantage is also its independence from faults in voltage measuring circuits and out-of-step conditions in protected networks.

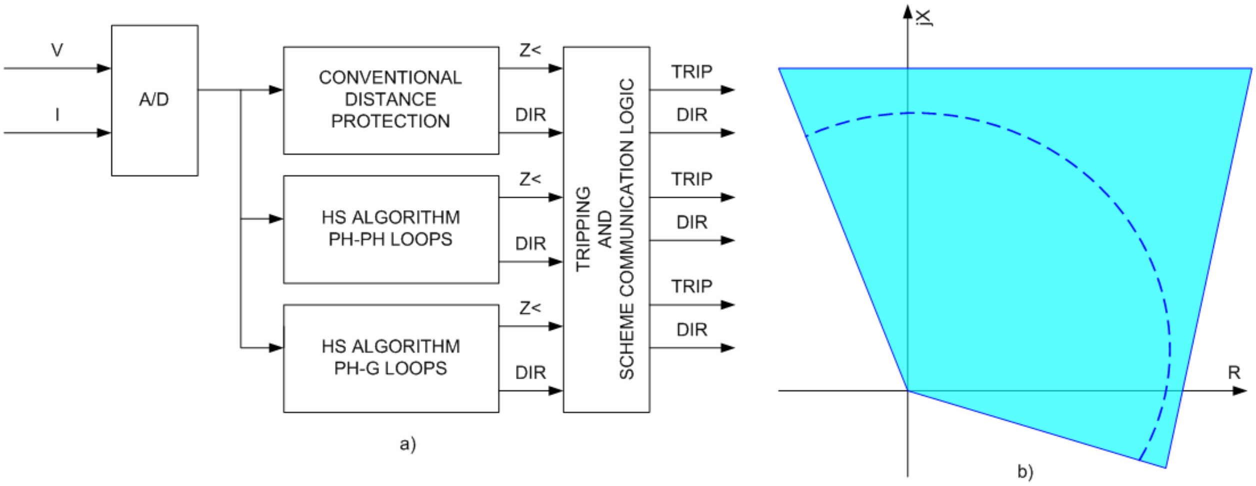

Figure 2: Block diagram of the new protection scheme (a) and the composite operate characteristic (b)

Figure 2a shows the schematic diagram of the hybrid protection that consists of the conventional distance protection, a HS tripping algorithm for multi-phase faults, and a HS tripping algorithm for single phase to ground faults. The binary outputs “Trip” and “Direction” are the phase selective tripping and the directional information, respectively, to be used in the phase segregated pilot scheme.

The presented distance protection with fast tripping algorithms has been designed with specific requirements on protection of series compensated and adjacent transmission lines. In order to maintain correct directional discrimination in case of voltage inversion a polarization function is added to the main distance protection. The polarization voltage is based on healthy phase and memorized voltage. The separate directional determination for high-speed ground fault detection utilizes superimposed currents and polarizing voltages during a short interval after the fault inception. This makes it possible to extend the reach of the HS tripping zone regardless of the capacitor presence in the fault loop, since its apparent reactance changes slowly.

The comparison of the current level with the voltage level gives impedance circles (Figure 2b) for faults with high fault current. During this condition the effective compensation is reduced due to the influence of the over-voltage (MOV) protection. This enables the protection to be set to cover a larger portion of the protected line.

The full scheme distance protection with three impedance measuring zones has a quadrilateral operating characteristic [10], as shown in Figure 2b.

Ultra high-speed operation is achieved by the characteristic represented by the circle segments in Figure 2b. The filter used for this function [10] gives initially an underestimation of the current, which increases security of the scheme. The comparison of the currents and voltages gives an impedance circular characteristic, within which the operating time is shorter. The apparent characteristic will increase when the filter factors are dynamically adjusted towards a narrower bandwidth and as the estimate of the fault current grows.

A number of additional protection functions, such as directional ground overcurrent protection, are available within the multifunctional IED as complements to the main protection. A set of logical gates, timers and similar functions makes it possible, together with user friendly graphical tools, to design practically any logical scheme. This capability has been used to reproduce the established and proven protection scheme, which BPA has implemented for many years with older generations of protective devices. The complete protection scheme has been further enhanced by complementing it with built-in autoreclosing and synchro-check functionality, phase segregated scheme communication logic (pilot schemes), and direct connection to teleprotection equipment without the need for any communication interfaces.

Development and evaluation of the new protection scheme has been done within an interactive software environment. To fully evaluate operation of the protection scheme, several network configurations have been simulated [11].

4. RELAY PERFORMANCE PRESENTS ANSWERS FOR BPA REQUIREMENTS

For primary protection in the new relay schemes, BPA uses phase distance and ground distance elements plus an additional directional ground over current element as backup. Each relay system has several levels of protection. Primary protection is via the phase and ground distance elements. Single pole tripping is provided by the ground distance elements. The under reaching zone 1 elements operate on a per phase basis and are communications independent. The over reaching zone 2 elements operate on a per phase basis and provide single phase tripping via the permissive tripping logic. The permissive over reaching transfer trip logic POTT is the communications scheme that is used in the protection scheme. This scheme also includes weak end in feed tripping logic (WEI) with permissive echo and local trip. The WEI logic operates when a permissive signal is received from the remote terminal, but the source behind the relay is too weak to provide proper operating quantities to the distance elements. The WEI logic will echo the permissive signal back to the sending terminal allowing its permissive logic to trip. It also trips locally on under voltage. The WEI logic operates on a per phase basis and trips single pole. Reverse zone 3 elements are set to coordinate with the remote zone 2. Their function is to enable the transient blocking logic for faults on parallel lines and to block the WEI logic for external faults. Backup protection trips all three poles. Backup tripping is provided by the time delayed tripping in the distance elements, by the time delayed directional over current ground relay, by multi-phase faults, by evolving faults, and when a breaker is reclosed into a made up fault (switch onto fault). A backup trip is a local three-phase trip, it blocks reclosing, and it sends a backup three-pole direct trip signal to the remote terminal. This trips the remote terminal and blocks the remote recloser.

5. LABORATORY TESTING AT BPA AND SOME INTERESTING RESULTS

Prior to installing relays on the 500kv system, BPA evaluates the relays, the proposed settings, and the internal operational logic in their laboratories using a digital line model. Portions of the system that are of interest are modeled using the Electromagnetic Transients Program EMTP [6]. Various fault conditions are studied and data files for the model line are created. The fault data is played into the relays and the operational data is collected and analyzed. The relay performance for various fault types, fault locations, and system conditions are studied. Single-phase faults and multi-phase faults at various locations along the line are generally studied. The relay performances for external faults are also analyzed. Tests with fault resistance, heavy line load, parallel lines, and system swings are included where appropriate. The advantage in doing this is that special operational problems can be analyzed prior to installing the relays in the system. This has allowed BPA to correct relay element problems, setting problems, and operational logic problems prior to installation.

As an example, consider the case when a single-phase fault occurs on a heavily loaded parallel line. The relays on both the faulted line and on the un-faulted line need to operate correctly during the fault despite considerable zero sequence mutual coupling. They are also subjected to load unbalance during the time that the faulted phase is open. Additionally, one phase of a series capacitor can be bypassed for a short period of time after the line terminals are reclosed. These types of faults are studied with the EMTP program [6] and played into the relays.

An interesting problem was discovered during model line testing for relays that were to be installed on two parallel, series compensated lines. The series capacitors on the lines are located at the line terminal in one of the substations. The potentials for the relays are from the line side of the series capacitors. At the terminal where the series capacitors are located, a close-in single line to ground fault was applied to one of the lines. The remote zone 2 on the parallel un-faulted line correctly detected the fault and sent the permissive signal to the local terminal. The corresponding reverse reaching zone 3 elements at the local terminal, however, did not operate and the permissive echo back logic was not blocked. This resulted in an incorrect permissive echo to the remote terminal. The zone 3 settings were proper and the element should have operated (see Figure 3 left). Further testing revealed that the directional element was not operating. The measured direction was plotted (see Figure 3 right) and it was discovered that due to the series capacitors at the line terminals, the angle of the fault impedance phasor was just outside of one of the directional blinders, which was set originally to 285 deg. The angle setting was changed to 315 deg and the element operated correctly. The direction of load current was close to –15 deg.

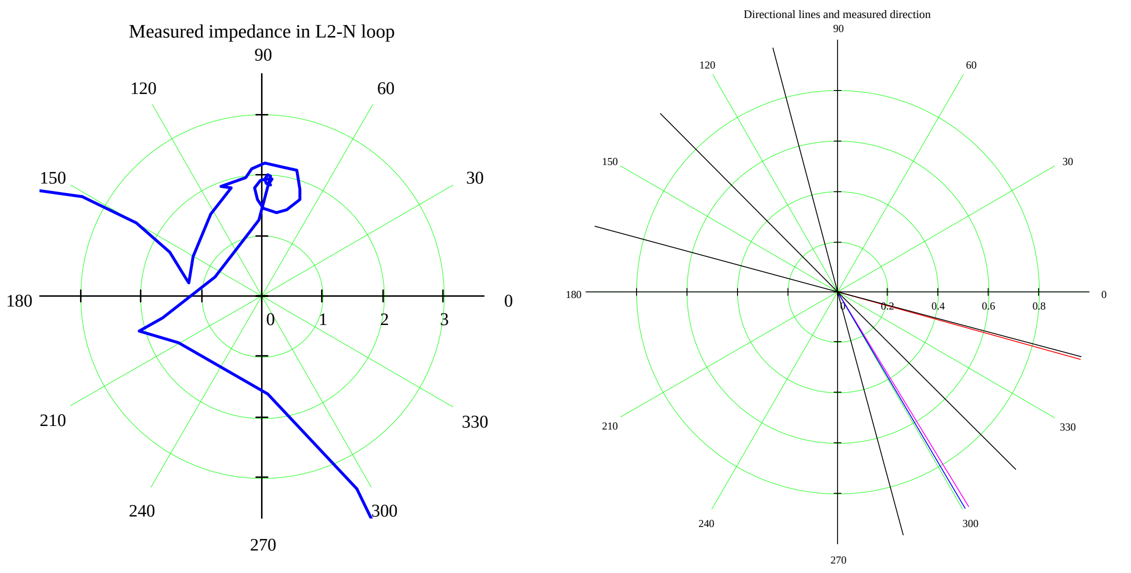

Figure 3: Impedance measurement by Zone 3 L2-N element (left) and reverse directional measurement for L2-N element

Another interesting problem was discovered while using a fault simulation program to check relay settings on a series compensated line prior to staged fault tests on a new series capacitor installation. The line is about 50% compensated. This line is running in parallel with three other lines, and one of them is also 50% compensated. As the fault was moved beyond about 50% of the line, the series capacitors remain fully in service during the fault operation. The voltage on the line side of the series capacitors can approach, and even exceed 1 per unit, for faults beyond this point up to about 80% of the line. As the fault location approaches the remote bus, the fault voltage drops as expected. Since the line relays at the terminal with the series capacitors get their relay potential from the line side of the capacitors, EMTP studies were done to confirm the data from the fault study. Fault files for the digital model line were created and played into the relays. The results of the testing indicated that the relays would detect the faults and operate properly.

Another possible issue was discovered during the model line testing for the above line relays. One of the test cases was a single line to ground fault on the line side of one of the series capacitors, and there was a simulated maximum system load prior to the fault. When the data for the relay on the adjacent parallel line, was played into that relay, the sub harmonic impedance oscillation caused the impedance phasor to move from the reverse zone 3 characteristics and cross the forward directional line, momentarily entering the zone 1 region (see Figure 4). This fault was a simulation of one of the actual system faults that were to be applied during the staged fault testing of the series capacitors.

The suspect relay on the adjacent parallel line operated correctly during the staged fault tests so no changes were made to the relay settings or the operational logic at that time. BPA is currently updating its own EMTP model and will re-address this issue with the corrected model. BPA also has the staged fault test data to compare the results of the EMTP model simulations.

Model line testing is a very valuable tool that can resolve many issues and problems before they materialize in the operating system. The real world, however, is not quite so forgiving. There are always faults and operating conditions that occur which were unexpected. Analyzing these unexpected types of events is very educational and allows for the opportunity to update the system models, testing, and setting criteria.

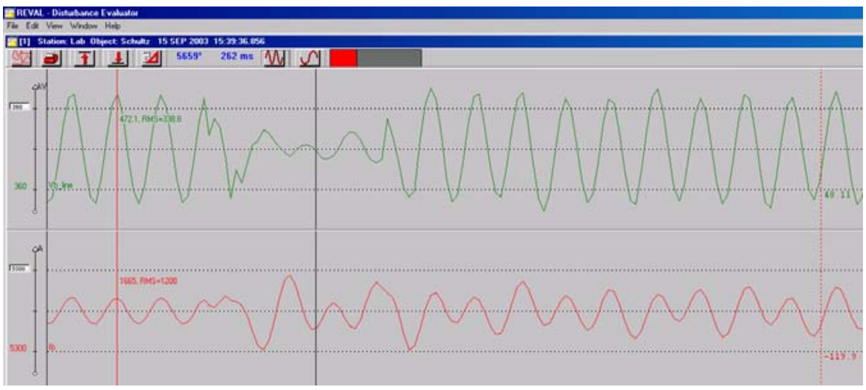

Figure 4: Subharmonic oscillations in phase L1 voltage (upper signal) and current (bottom signal) as recorded during simulation testing

6. OPERATIONAL RESULTS ON REAL CASES AND FIELD TESTS RESULTS

In August of 2003 two single-phase to ground faults occurred about 10 minutes apart on a 159 mile line that passes through a mountainous area. The faults were most likely caused by a tree. The resistance of the first fault was quite high and the ground distance elements in the relay did not initially detect the fault. The other set of relays did detect the fault and opened the faulted phase. The fault resistance in the second fault was less and the ground distance elements properly detected that fault. A week and a half later a forest fire crossed under the line causing three faults in one day and one fault the next day. There were several single-phase to ground faults and one multi-phase fault. The faults were most likely mid-span faults. The fault resistance for the single line to ground faults was quite high and the ground distance elements had problems detecting these faults. The phase distance elements had no problem detecting the multi-phase fault. As a result of these faults BPA reviewed the setting criteria for the resistive blinders in the over reaching ground distance elements.

The consequence of increasing the resistive blinders reach had to be thoroughly studied. One consequence is an unintended operation of ground distance elements under heavy load conditions for external faults on series compensated lines where sub harmonic oscillations can occur. Model line testing indicated that the resistive reach settings of the ground distance elements could be extended more than that initially set on the relays. BPA implemented the setting changes to the test relays in the laboratory. BPA also maintained the strict setting limitations on all phase distance elements and on the instantaneous ground distance elements. The actual data from the faults that was recorded in the relays and in the digital fault recorders was played into test relays with the digital model line. With the new blinder settings the relays detected all of the faults. One needs to wait for another forest fire or wind blown tree to see if the real world will reveal any more surprises.

The lesson that BPA has learned with the August 2003 faults is that higher fault resistances should be used for model line testing. 25 ohms was used as a maximum fault resistance for the initial model line tests. Based on these faults, this value should be increased to at least 100 ohms.

Another actual fault revealed a problem in the fuse failure detection logic and a gap in the weak end in feed logic. The fuse failure logic is based on zero sequence current and voltage measurement. If a zero sequence voltage above a set level is detected, and an associated zero sequence current is not also detected, the fuse failure logic will assert and block the distance elements. The fault was an A phase to C phase fault 26% from the local terminal. The line relays identified the fault and output a trip in 15 milliseconds. Two of the sources to the faulted line were long parallel lines. The remote terminals correctly identified the fault and transmitted the permissive signals to the local terminals. The local terminals on both lines, however, did not detect the reverse fault and block the permissive echo. The permissive signals were echoed back to the remote terminals and both lines tripped. On reviewing the event reports from the local relays it could be seen that the zone 3 elements were blocked by the fuse failure logic. This fault created enough zero sequence voltage to satisfy the 3V0 requirement of the logic, but the zero sequence current was very small, and it was distributed between the two parallel lines, see Figure 5.

Two changes were made to prevent this from happening in the future. The setting for the 3U0 detection level was increased and the setting for the detection level for 3I0 was decreased to its minimum setting. Additionally, the fuse failure logic was modified to include the weak end in feed logic. Any time the fuse failure logic blocks the distance elements, the weak end in feed logic is also blocked. Such modifications in relay operating logic are done easily by using the corresponding graphical engineering tools.

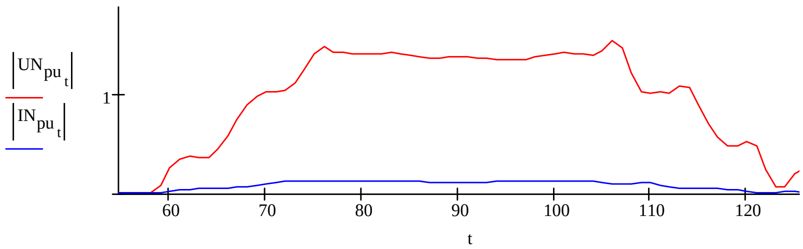

Figure 5: Residual voltage UN and residual current IN (both in pu) forming the positive operating conditions for fuse failure logic

BPA was very fortunate to be installing some of new relays on lines that were also having new series capacitors installed. The capacitor controls and protection were tested using staged system fault tests. This allowed the new relays to be tested on many actual system faults. Relays were installed on the faulted lines as well as on adjacent lines. Over all, the relays performed very well during the fault tests. A couple of problems revealed themselves, which were able to be addressed as a result of the system tests.

One of the more interesting problems that BPA discovered was on a line terminal at a station 159 miles from the location of the fault test. That line terminal was protecting an outbound line so the applied faults were in the reverse direction. There was also some load on the system. When the fault was initially applied, the impedance moved into the zone 3 regions as it should have, but it was just outside of the set reach of the element and so zone 3 did not operate. As the remote fault was cleared, the associated sub harmonic oscillations caused the measured impedance to move toward a directional blinder and momentarily cross into the zone 2 regions. This caused a momentary permissive signal to be sent to the remote terminal. The event was too short to cause an undesirable trip, but still needed to be addressed. The key here is that the zone 3 element did not initially pickup. This operation also pointed out the need for the transient blocking timer in the current reversal logic. If zone 3 would have operated and set the transient blocking timer, the permissive signals would have been blocked when the impedance momentarily entered the zone 2 region.

By plotting the trajectory of the impedance it was found that the changing of one of the directional blinders and increasing the reactive setting of the zone 3 elements was needed. The blinder change is the same change that was discovered during model line testing a couple of years earlier (see Figure 3). The decision at that time was to change the blinder setting on only those relay terminals that are in the vicinity of series capacitors. Because this terminal is not in the close vicinity to series capacitors, the change was not initially made on this terminal. BPA now has better system loading data for own updated EMTP model for that part of the system.

A test relay was setup in the laboratory and the fault records from the event were played into the relay. The relay exhibited the same problem as the in service relay. This problem was repeatable for every test. Then the zone 3 reactive reach was increased, the directional blinder was set according to our earlier test data, and the pickup time of the permissive element was adjusted to be sure that it is less than the period of the sub harmonic oscillations. The faults were re-played into the test relay and the relay operated properly. These changes were then made to the in service relays.

7. CONCLUSIONS

Technical characteristics of modern complex transmission networks require extensive testing of protective devices. The tests must be performed in laboratories as general tests for the specific network as well as the project oriented tests for each particular installation. Bonneville Power Administration (BPA) performs such tests regularly on all protective devices together with staged fault tests, where protective devices are tested live together with corresponding primary equipment. The results of these tests serve further enhancement of relay settings and internal logic. At the same time contribute continuous development of numerical network models.

Network modelling is used together with disturbance records from everyday events within the power system to further study the operation of all protective devices and their performance. It may happen that the results indicate the increased demands on relay performances as the system develops and the operating conditions become more and more stringent.

Application of numerical protection devices meets the requirements better, if they offer an extensive flexibility in settings of the main characteristic parameters as well as in design of internal logical functions. They must of course at the same time continuously develop the quality of the main protection parameters: speed, sensitivity, selectivity, dependability, and security.

8. REFERENCES

[1] F. Andersson and W. Elmore, “Overview of Series-Compensated Line Protection Philosophies”, Western Relay Protective Conference, Washington State University, Spokane, Washington, October 1990.

[2] J. Cheetham, A Newbould, and G. Stranne, “Series-Compensated Line Protection: System Modeling and Test Results”, 15th Annual Western Relay Protective Conference, Washington State University, Spokane, Washington, October 1988.

[3] D. Novosel, A. Padhke, M.M.Saha and S. Lindahl, “ Problems and solutions for microprocessor protection of series compensated lines”, Proceedings of Sixth International conference on Developments in Power System Protection, 25-27 March 1997, Nottingham, UK; Conference Publication No. 434,IEE 1997, pp 18-23.

[4] M. Chamia and S. Liberman, “ Ultra high speed relay for EHV/UHV transmission lines- Development, design and application “, IEEE Transactions on PAS, Vol. PAS-97, No.6, Nov./Dec. 1978.

[5] G. Nimmersjö and M.M. Saha, “A new approach to high speed relaying based on transient phenomena“, IEE-DPSP-89, Edinburgh, UK, April 1989.

[6] Alternative Transients Program (ATP), Rule Book, K.U.Leuven, EMTP Centre, Leuven, Belgium 1987.

[7] G. Nimmersjö, B. Hillström, O. Werner-Erichsen, and G.D. Rockefeller “A digitally controlled real time, analogue power-system simulator for closed loop protective relaying testing“, IEEE Trans. on PWRD, Vol. 3, No. 1, January 1988.

[8] G. Nimmersjö, M.M. Saha, and B. Hillström, “ Protective relay testing using a modern digital real time simulator “, presented at IEEE PES Winter meeting 2000, Singapore, January 23-27, 2000.

[9] G E Lee and D L Goldsworthy , “ BPA´s pacific AC intertie series capacitors : experiences, equipment & protection“, IEEE Trans. on PWRD, Vol. 11, No. 1, January 1996.

[10] A. Engqvist and L. Eriksson, Numerical Distance Protection for Sub-transmission lines, Cigré, 34-04, Aug./Sept. 1988.

[11] C. Öhlen, J. Esztergalyos, G. Nimmersjö, and M.M. Saha, “EMTP used in testing of a protection scheme for series compensated network“, Cigré, Stockholm, June 11-17, 1995.