CERTIFICATION OF PROTECTION RELAY MODELS FOR ESKOM USING REAL TIME DIGITAL SIMULATION

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ABSTRACT

This paper describes methods that have been developed to validate relay models within the EMT simulation program used by Eskom. The paper describes how, with a combination of carefully-designed study-system models, and real-time simulator testing, the models used day-to-day by protection engineers in the utility can be validated against actual relay performance under controlled, but representative conditions, and any shortcomings in these models rectified accordingly. Confidence established in these models is essential for system operation investigations, where a key part of the process is injecting these relay models with fault recordings of incidents being investigated by protection engineers on 24-hour standby for the utility's National Control Centre.

INTRODUCTION

Over the years the Eskom transmission network has seen continued growth in the use of series capacitor compensation to strengthen the existing network, as well as the use of series capacitors on new parts of the network as they are being built. However, it is well-known that the characteristics of series compensating capacitors can compromise the reliability of impedance protection on the transmission system, and the introduction of non-linear metal oxide varistors (MOVs) to protect the series capacitors themselves under fault conditions adds further complexity and uncertainty [1]. Thus, while in many parts of Eskom's network the traditional approach to setting protection relays via steady-state fault studies may suffice, it has been recognised that in the vicinity of series capacitors this approach results in unacceptable inaccuracies [2,3].

However, with the emergence of powerful electromagnetic transients (EMT) simulation tools [4,5] it is possible for protection engineers to take into account the complex dynamics of series capacitors and their own protective devices in their analyses. To improve the settings, and thereby the performance, of protection systems Eskom has therefore introduced the use of EMT studies and modelling of protection relays to verify and optimize protection settings based on results of time domain simulations. Reference [2] described the introduction, some years ago, of the DIgSILENT PowerFactory software within Eskom as an integrated simulation tool for power system modelling, fault calculations, protection settings, and incident investigations. Reference [2] also describes the availability within PowerFactory of simulation models of protection relays that, potentially, could closely replicate the behaviour of the actual devices used by Eskom in the field in dynamic (i.e. EMT) simulations.

Although models of the most common relays are provided in the PowerFactory library, the quality of these models depends on the level of detail and precision of the information supplied by the relay manufacturers; the relay models therefore have to be carefully validated before being approved for final use in practical applications (settings optimisation studies) [2]. This is particularly true of modern, numerical protection relays which are in themselves extremely complex devices with a number of interacting elements and possible settings options.

Because of the complexity of modern protection relays, an alternative method of studying relay performance that has emerged in recent years is the use of real-time digital simulators, to which the actual relay can be connected in a hardware-in-the-loop arrangement for detailed testing and analysis. This testing approach has the advantage that it does not rely on third party simulation models of the relay that may suffer from over-simplifying assumptions, lack of available information on proprietary algorithms, modelling errors etc. Rather, the actual relay hardware and settings are studied in a highly-detailed, closed-loop test regime. However, this approach is more cumbersome and expensive for day to day settings optimisation studies, and has usually been seen as more suited for factory acceptance testing of relays, final testing of settings before field commissioning of new protection schemes, or for post-incident analysis to determine the causes of unusual or unexpected protection events on the network.

However, as a result of growing experience in the use of real-time simulators for testing protection relays in South Africa, it has been recognised that the hardware-in-loop testing capabilities of a real-time simulator could in fact be used to complement DIgSILENT PowerFactory EMT studies (rather than as an alternative form of analysis) by providing a detailed verification and certification platform for the relay models that are used in PowerFactory for day to day settings optimisation and fault investigation studies. This paper describes the background to, and need for verification of relay models and the methodology that has been developed for comparative tests of PowerFactory relay models against actual relay hardware using a real-time simulator.

BACKGROUND

Challenges Protecting Series Compensated Networks

Despite its economic advantages, series compensation in the transmission system introduces complex dynamic phenomena that have to be considered when setting impedance protection relays, including voltage and current reversals, subsynchronous oscillations in the relay's measurement variables during faults, and negative infeed effects. At the simplest, steady-state analysis level, the negative reactance of series capacitors means that the instantaneous zone 1 elements of impedance relays protecting the line have to be significantly reduced in reach, or even turned off in some instances. The presence of subsynchronous oscillations during fault conditions further complicates the situation by causing a dynamic spiralling characteristic in the locus of the impedance seen by the relay when plotted on the R-X plane. Because this impedance locus can move alternately into and back out of a relay's protective zones several times during a fault, a further reduction in reach of its instantaneous (zone 1) elements (over and above that dictated by steady state analysis) and an *increase* in the reach of its over-reaching (zone 2) elements is required to ensure security and dependability of these respective elements [1].

On the other hand, any conduction of the MOVs protecting a series capacitor during through flow of fault current tends to introduce a certain amount of resistance into the fault loop which not only damps the aforementioned subsynchronous oscillations but also tends to move the seen impedance away from the relay tripping characteristics [2]. A further complicating issue when setting the reach of an impedance relay is the increase in the average resistance of single-phase to ground faults experienced in Eskom's network in recent years and a substantial number of incorrect protection operations due to high fault resistance [2]. Hence the coverage of the relays' tripping characteristics in the resistive direction of the impedance plane under dynamic conditions also requires careful consideration.

Settings Optimisation Using Relay Models

In the context of these and other practical challenges, Eskom introduced the use of simulations in PowerFactory, together with dynamic models of protection relays, in the protection settings discipline as a means of verifying and optimising protection settings [2]. In order to illustrate the manner in which EMT studies are used to optimise relay settings and performance, and hence to highlight the critical importance of valid models of the relays themselves in this process, a brief overview of the applications reported in [1] and [2] is provided here.

Current Supervised Zone 1. In general EMT simulations can be used to determine more precisely, for the range of conditions at a particular relay location in a series compensated network, the extent to which the zone 1 element reaches need to be reduced, or if necessary whether such elements have to be turned off completely. However, in some cases the damping effect and added resistance due to MOV conduction for faults on a particular line can be sufficient to prevent the negative reactance of the capacitors in that line from encroaching into the zone 1 impedance characteristics of neighbouring lines. If this is found to be the case, it may be possible to enable the zone 1 elements in the relays protecting the neighbouring lines conditionally, based on measurement of the fault current magnitude seen by these relays, so-called current supervised zone 1 operation [1].

Where such special conditions are thought to exist, a range of careful EMT studies are needed in the first instance in order to confirm whether or not this is in fact the case: simulations are carried out to verify that for any faults behind the electrically-closest capacitor on adjacent lines, and behind the capacitor with the highest protective level in adjacent lines, the impedance seen by the relay will not enter zone 1 when the MOVs on these capacitors conduct, taking into account subsynchronous oscillations and MOV damping. If these conditions are found to exist, further EMT studies are then required to determine whether it is possible to take advantage of them when setting the zone 1 elements of the relay: simulations are used to verify whether simple current supervision by the relay can indeed be used to discriminate between impedances that appear in its zone 1 characteristics as a result of genuine close up faults, and those that do so because of faults behind the series capacitors in the neighbouring lines for the special cases when those capacitors' MOVs fail to operate or are not in service.

From the above descriptions, it can be seen that whilst EMT simulation tools and careful analysis can be used for sophisticated settings optimisation of individual relays in complex network scenarios, this, in turn, relies on accurate modelling of the network itself and, critically, the use of relay models whose characteristics will faithfully reflect the behaviour of the algorithms in the real relays under these complex dynamic conditions.

Zone 2 Over Reach. Because of the need to expand the reach of zone 2 elements in the presence of subsynchronous frequencies in series compensated networks, substantial over-reaching of these zones, and their over-tripping in response to faults in the underlying distribution system can result. Several possibilities for dealing with this issue have been considered [1], that make use of reverse-looking zone 3 elements together with an adapted form of the weak-end infeed logic provided on impedance relays in order to coordinate the over-reaching elements of the affected distance relays with other protection relays that should operate first for external faults. Once again, these solution options require careful simulation of case-specific conditions, with settings decisions made based on the response of a model of the relay under the studied conditions.

High Resistance Faults. Resistive coverage of relay tripping characteristics receives a lot of careful attention when optimising settings in order to improve system performance. This typically involves studying the response of the relays to high resistance faults, taking into account the impact of infeed from the remote end and heavy load transfer conditions. In these EMT studies the objectives are to optimise the reactive and resistive reach settings of the relay under complex practical conditions in which the fault resistance is amplified due to infeed from the remote end, and the tripping characteristic may be shifted as a result of load transfer, as well as to verify the impact, if any, of load encroachment cut-outs in the tripping characteristic on the ability to detect high resistance faults.

Here again, it is evident that the model of the relays used in this kind of analysis must be a good reflection of the characteristics of the actual relays that will be used in practice.

While the above examples have shown the clear value of using EMT simulations and dynamic relay models for settings optimisation, they also highlight the fact that the whole approach relies on sufficiently detailed and accurate models of the real relays deployed on the Eskom network being available within the EMT simulation software package being used. To ensure that performance of the relay models in the EMT simulation program being used by Eskom is acceptable and comparable with that of the real relays, these relay models have to be thoroughly tested, in a manner similar to acceptance testing of the hardware relays themselves [2,3].

HIL Testing of Relays Using the RTDS

An alternative approach to testing protection relays, that does not rely on the use of mathematical models of the relays, is the use of hardware-in-loop (HIL) connection of the actual relay equipment to a real-time simulation model of the power system. Fig. 1 shows a conceptual overview of how HIL testing of relays on a real-time simulator is typically carried out. At the centre of the test facilities is a 19” rack that contains specialised, multi-processor computing and I/O hardware. A detailed EMT-type simulation model of the power system to be studied is developed on a separate personal computer host; this includes representations of all the relevant power system plant and components including instrument transformers, circuit breakers and controllable faults. The model is then compiled and downloaded to run continuously, and in real time, on the RTDS simulator hardware (rack).

In the case of an impedance relay test, the instantaneous currents and voltages from the current and voltage transformers in the real-time model are sent to six channels of a high-precision analogue output card on the rack, converted to power-level secondary currents and voltages using a high-bandwidth amplifier, and injected into the appropriate measurement inputs of the relay. The trip outputs of the protection relay are then fed back into the real-time simulator via a digital input port on the rack and can be used to operate the poles of the circuit breaker in the real-time model. In this way, the relay under test is fed with instantaneous power-level inputs that respond continuously to whatever conditions and contingencies (faults, breaker operations etc.) are occurring in the on-going real-time simulation of the protected plant, and the relay’s trip outputs affect the system it is connected to in the same manner as would be the case in the field.

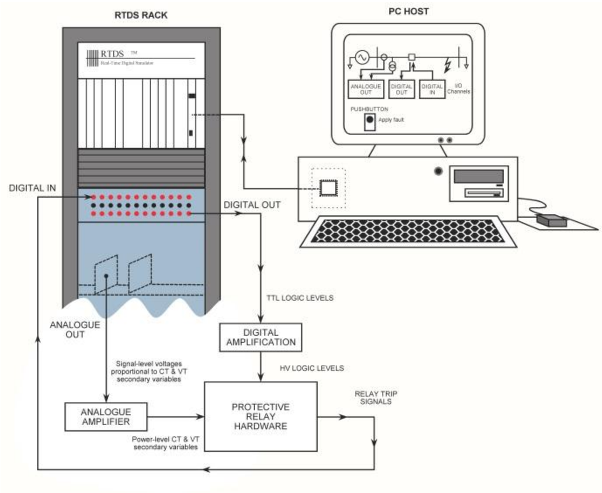

Fig. 1 – Hardware-in-loop testing of protection relays using a real-time digital simulator.

As mentioned previously, whilst the HIL RTDS testing method is often considered as an alternative that allows one to avoid having to study protection schemes using simulation models of the relays, it has been recognised within Eskom that both methods have value. Furthermore, the unique capability that a real-time simulator provides for HIL testing can be used in a complementary manner to provide the means for careful and thorough validation of the relay models that will be used in day-to-day, all-simulation analysis of protection systems in DIgSILENT PowerFactory. The next section explains the methods and procedures that have been developed to exploit these capabilities in the relay model validation process.

VALIDATION TEST METHODOLOGY

For some years, Eskom has helped to establish and fund a specialist real-time simulator facility [6] at a university in South Africa. As part of the on-going research collaboration at this facility, detailed models of virtually all of the generation and transmission plant of South Africa’s main grid (275 kV and above) have been developed for the real-time simulators, and the capacity of the simulators currently available allows significant sections of this detailed transmission grid model to be run at any one time if required for particular studies. However, from experience gained in conducting hardware-in-loop protection studies on the real-time simulators, it has been found best to adapt the scope (size) and level of detail in the models of the protected plant according to the particular focus of the study. In particular, when conducting studies to validate dynamic models of relays used by other EMT simulation tools using the real-time simulators, a two-tiered study-system model approach is deliberately adopted, with small-scale models used wherever careful validation is the focus (referred to here as primary-phase validation) and large-scale models used for more open-ended study (secondary-phase validation).

Primary-Phase Relay Model Validation

In the primary phase of validating dynamic simulation models of protective relays against actual relay hardware using a real-time simulator, the focus is on ensuring that the protected plant chosen to make up the study system is sufficiently representative to reproduce all the fundamental aspects known to critically affect the performance of the relay under study, but sufficiently small in size so that the study system can be represented on both the real-time simulator and in the PowerFactory EMT modelling environment, using exactly the same types of models and simplifying assumptions (e.g. source and transmission line representations) in each case. With this approach, the study system is chosen so as to be sufficiently detailed to represent the principal phenomena being tested, but sufficiently simple to ensure (to the extent possible) that the only difference between the two systems being compared is the relay representation in each case (dynamic model of the relay being evaluated on one hand, and actual relay hardware in closed-loop with the real-time simulator on the other hand). This approach also ensures that the fault events being considered during the tests can be controlled and repeated in exactly the same way on both simulation platforms.

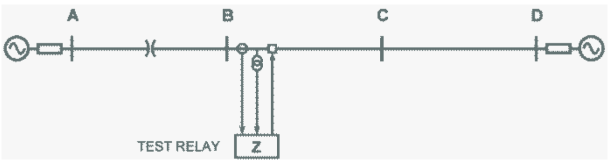

Fig. 2 – Topology of the power system network used for primary-phase distance relay model validation.

Fig. 2 shows a single-line diagram of the simple power system topology that has been arrived at for use in primary-phase validation of EMT models of distance protection relays. The system is a simple radial topology with three transmission lines (two in front and one behind the tested relay) fed from controllable AC voltage sources at each end, and with a series capacitor (and optional MOV / spark gap protection) included in the line behind the relay. This simple test system is capable of reproducing all the critical phenomena affecting distance relay performance in series compensated networks at a fundamental level suitable for comparative testing, namely the effects of load transfer in either direction, fault impedance, subsynchronous oscillations, voltage and current reversals, switching transients, offset frequency and evolving faults.

The diagram in Fig. 3 provides a schematic overview of the testing approach used to compare the performance of any specific type of impedance relay hardware against the PowerFactory model of that particular relay using EMT models of this same simple study system running on both simulator platforms (RTDS and DIgSILENT). The left-hand side of Fig. 3 illustrates that on the RTDS platform, as explained earlier, the protected plant in the test system (and its PTs and CTs) is modelled on the real-time simulator, and the voltages and currents from the real-time model are fed to the physical piece of relay hardware whose PowerFactory model is to be validated. However Fig. 3 illustrates that for this particular type of HIL testing, in addition to the relay's trip outputs, an extensive set of additional logic variables of interest from within the relay hardware is read back into the real-time simulator for recording (the number of logic signals is in practice limited only by the available number of binary outputs on the relay hardware, but typically between 20 and 30 channels are recorded, including information such as phase selection, zone starter and trip signals for each phase, as well as other global signals such as forward and reverse fault detection, swing detection and blocking signals).

The right-hand side of Fig. 3 illustrates that on the DIgSILENT platform the entire test system (including PTs, CTs and relay) is represented in the simulation environment. The range of logic variables being monitored in the actual hardware relay is also, as a matter of course, available within the PowerFactory EMT simulation for analysis and comparison if needed. The model validation approach used can then be summarised as follows.

Faults are placed at various positions along the lines B-C and C-D in Fig. 3 (in both the real-time simulator and in DIgSILENT) to determine the shapes of the various elements' characteristics within the relay. These shapes are determined under three different conditions of load transfer (typically zero, medium and heavy load) in both forward and reverse directions, as well as for different values of fault resistance. Once the dynamic characteristics of the relay have been evaluated and documented in this way, both the actual relay and the relay model are subjected to voltage and current reversals to cross-check their performance on series compensated networks; in these tests, the polarisation and memory action of both devices (hardware relay and relay model) are verified.

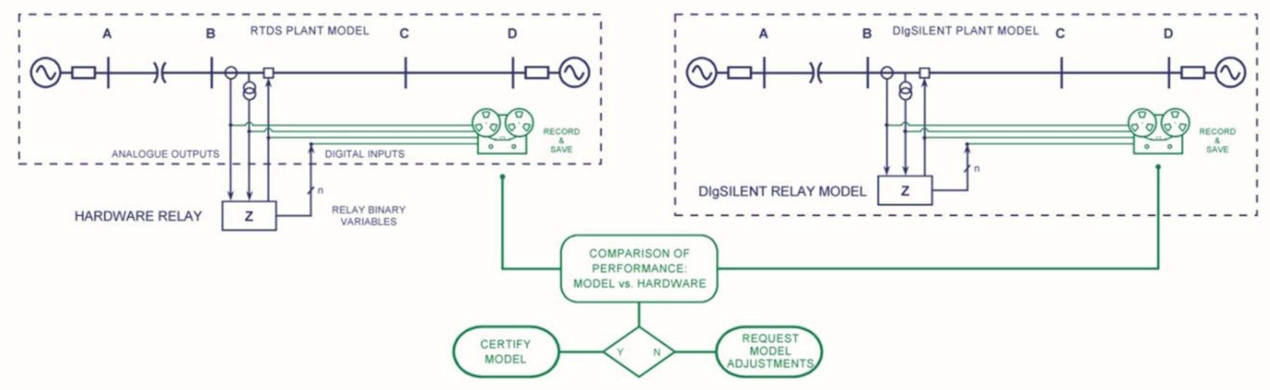

Fig. 3 – Schematic overview of testing approach for validation of relay models on a common test plant.

In an intentionally-simple test model such as that shown in Fig. 2, voltage and current reversals are easily simulated by placing faults behind the reverse series capacitor and simply adjusting the ratio between the magnitudes of the reactive component of the source impedance and the reactance of the series capacitor as required.

Usually this part of the verification process is limited to security tests which are performed to ensure that the relay model correctly replicates the polarisation of the actual device. Faults in the reverse direction, behind the series capacitor, are simulated in such a position that the measured impedance would fall within the relay's static characteristic, simulating voltage reversal as illustrated in Fig. 4 below. Only the performance of zone 1 is observed as all other zones are directionalised by the same relay element.

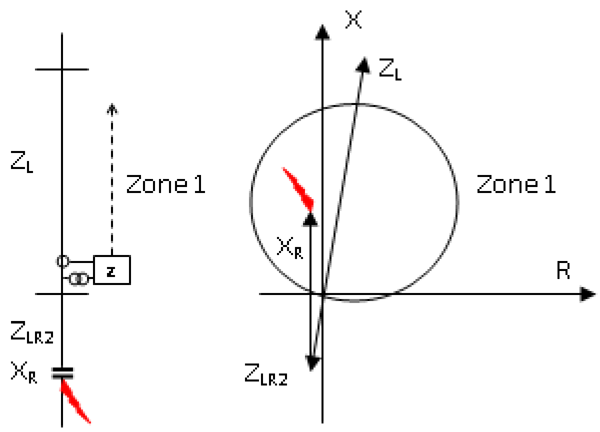

Fig. 4 – Example of fault position for voltage reversal to test dynamic directionality.

During this phase of the study the approach taken is to conduct the tests on the real-time simulator, and on the DIgSILENT PowerFactory model, in parallel, and to document only the main outcomes (e.g. location of trip vs. no-trip boundaries) and pertinent characteristics of the actual relay's response versus that of the relay model for later reporting. However, as the tests are being done, wherever interesting or unexpected responses are encountered, more-detailed results are saved from the real-time simulator for that particular test case, including recording COMTRADE files of the currents and voltages injected into the relay, and of the binary outputs obtained from the relay, for later in-depth analysis and investigation. After these tests are completed the PowerFactory model of the particular make and model of relay being validated is either certified as accepted for use in the settings optimisation process within Eskom, or referred back to the supplier of the simulation program for relevant adjustments.

Once the formalised, procedural documentation and validation of the relay model's characteristics has been carried out as described above, further, more open-ended real-time simulator tests are typically performed in order to gain more familiarity with the details (and limitations) of both the hardware relay and its simulation model in the PowerFactory program. As an example, the simple radial power system topology of Fig. 2 may then be used to examine the responses of both the hardware relay and the relay model's phase selector to evolving faults. However, in some cases, this more open-ended phase of the testing may also involve the use of more complex test-case topologies on the real-time simulator, as outlined in the next subsection.

Secondary-Phase Relay Model Validation

During the more open-ended phase of the testing, the focus is on using the real-time simulator environment to gain a better understanding of both the relay hardware itself and of its EMT simulation model in more-complex scenarios, with less emphasis being placed on ensuring exact replication of the studied system on the RTDS and DIgSILENT simulation platforms. Such studies may still consider relatively simple test systems, but with the inclusion of one or more synchronous generators to allow the responses of the relay's power swing detection and blocking elements to be studied. However, this phase of the testing may also include attempts to reproduce, using more-complex, larger-scale system models on the real-time simulator, difficult fault conditions that are known to have occurred on the real transmission system, and for which a better understanding of the actual response of the relays in the field is desired. The response of the hardware relay and the relay model in PowerFactory to these more-complex events, as reproduced on the simulator, can then be analysed for possible settings improvements. In this secondary phase of the testing, or in cases of interesting or unexpected results in the primary phase that are saved for later analysis, the logic variables recorded from within the actual relay hardware are particularly important since they allow one to analyse the time sequence in which pertinent elements and logic variables picked up within the relay following application of a fault, but prior to the final issuing (or failure to issue) of a trip signal.

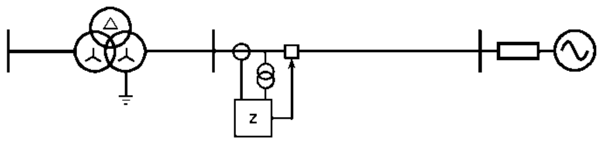

Fig.5 – Single-line diagram of the network developed to verify the ground loop impedance calculation method used in one particular relay under test.

As an example of the kind of additional study that has been carried out during the secondary-phase testing, in the case of one particular relay whose PowerFactory model was being validated, the documentation available at the time from the manufacturer of the relay itself was insufficient for Eskom to determine some critical aspects about the way in which ground loop impedance is calculated in the relaying algorithms. As a result, after completion of the primary-phase validation studies already described, for this particular relay the network of Fig. 5 was then used to establish, via experimental testing on the real-time simulator, exactly what equations are used within the relay in question when calculating ground loop impedance.

It was known that the relay in question could implement one of the following two equations when measuring ground impedance:

$$Z_A = \frac{V_A}{I_A} \qquad (1)$$

$$Z_A^+ = \frac{V_A}{I_A + 3I_0 K_0} \qquad (2)$$

The objectives of the tests were to establish whether the relay uses eqn (1) or eqn (2) above, and if eqn (2) is in fact used, to determine the scaling factor the relay uses when converting measured positive sequence impedance into a loop impedance.

The network in Fig. 5 was used to create specific ground fault current distributions from the three-winding transformer behind the relay, and the remote source in front of the relay. The ground fault was applied progressively further down the line from the relay until the relay stopped tripping in order to ascertain which of the above two equations is actually used by the relay. Once this study was completed, a simple radial network was simulated with no shunt charging reactance in the line and no source at the remote end. Once again, a ground fault was applied progressively further down the line from the relay until it stopped tripping in order to ascertain the value of the scale factor used in the actual relay.

These real time simulator tests, together with post-testing analysis, were able to show that the practical relay being tested used eqn (2) to calculate ground impedance and a scale factor of $(1 + K_0)$ to scale the calculated positive sequence impedance to obtain a loop impedance. Since the documentation of the relay itself was not clear in this regard, the PowerFactory model of the relay implemented based on that documentation also had to be adjusted to replicate precisely the real relay's performance.

EXAMPLE RESULTS

Tripping Characteristics

During the primary-phase of model validation the most fundamental issue is the comparison of the dynamic characteristics of the actual relay and those of its PowerFactory model under different loading conditions. The results are presented graphically on the well-established R-X plane in order to assess the fitness of the relay model. Figs. 6 and 7 show two examples of such results from the relay model validation process in which the zone 2 characteristics of a particular make and model of impedance relay used by Eskom were compared against those of its PowerFactory model.

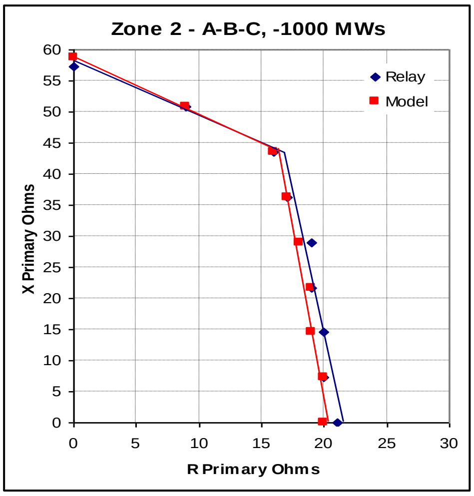

Fig. 6 – Comparison of zone 2 phase to phase characteristics for large power importation: hardware relay versus PowerFactory model.

Fig. 6 shows that for conditions of large negative active power transfer (relative to the forward direction of the relay being tested) the zone 2 phase-phase characteristics were found to be very close to each other, indicating very good replication of the actual relay's algorithms by the PowerFactory model. By contrast, the results in Fig. 7 clearly identified that the load encroachment module of the PowerFactory model did not perform well for phase to ground faults, which then had to be corrected.

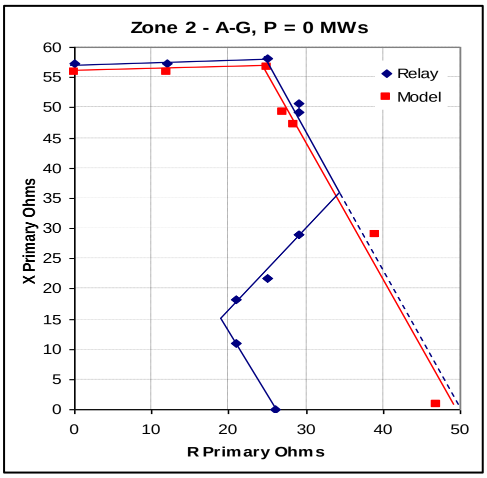

Fig. 7 – Comparison of zone 2 characteristics for zero active power transfer: hardware relay versus PowerFactory model.

The following additional example results illustrate the importance of testing the relay models using the proposed comparative method, as small discrepancies in modelling approach or a misunderstanding of the relay description in the manufacturer's manual may lead to serious errors in model measurements.

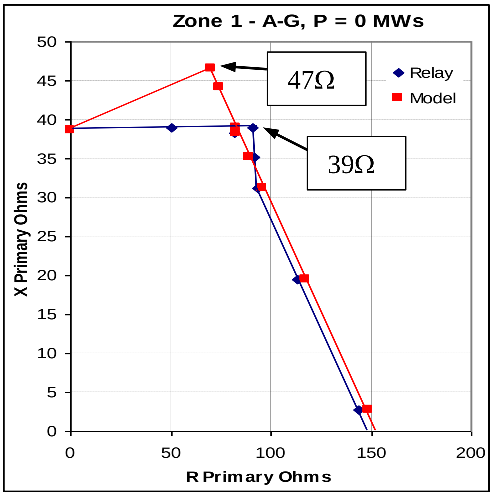

Fig. 8 – Comparison of zone 1 ground characteristics for zero active power transfer: hardware relay versus PowerFactory model.

As described previously, all tests were done with remote end infeed present, which explains the very different shapes of the relay characteristics shown in the measured results in the figures in this paper compared with those found in the relay manuals. The tripping characteristics shown in relay manuals are provided for a radial feeder as an illustration only, and they do not include the influences of line loading, remote end infeed and line charging current (important for longer lines). The performance of relays on the real network is much better visualised by studying their characteristics under conditions of remote end infeed, where load transfer and the additional voltage drop across the fault resistance itself modify the effective relay characteristics substantially. The remote source also provides a path for the circulation of sequence components which further impacts on the relationships between measured voltages and currents (magnitudes and angles).

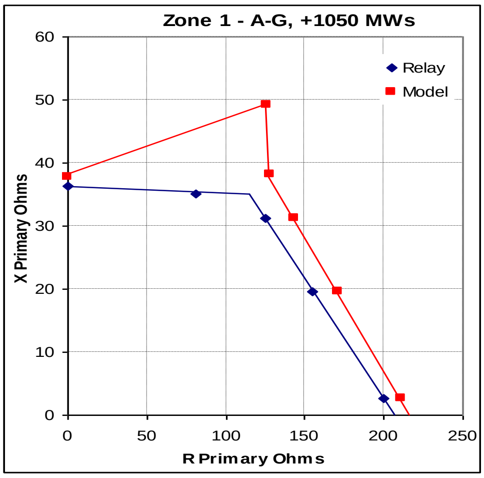

Fig.9 – Comparison of zone 1 ground characteristics for high exporting active power transfer.

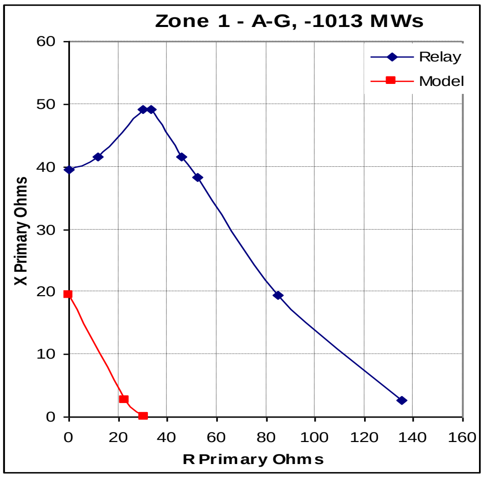

Fig.10 – Comparison of zone 1 ground characteristics for high importing active power transfer.

Fig. 8 shows a comparison of an actual relay and its model's zone 1 phase to ground characteristics tested without any load on the line; Fig. 9 shows the same comparison with 1050 MW of exporting load and Fig. 10 with 1013 MW of importing load.

The no load comparison already indicates that the model equations do not work well particularly for faults further away from the relay location. The zone 1 characteristic in the model overreaches the remote busbars well into the second line (note the 47 primary-ohm reach of the relay model characteristic which was actually set to 30.6 primary ohms). The measured reach of the real relay (39 primary ohms) likewise does not correspond to the actual setting value of 30.6 ohms which is alarming as the real relay will itself overreach significantly in such conditions. This had to be factored into the setting calculation process to prevent unnecessary tripping for busbar faults and faults on adjacent lines.

Similarly, excessive overreaching of the model is also clear on the second comparison, shown in Fig. 9, for exporting load on the line. The discrepancy between the actual relay and model characteristics here was very high and had to be corrected before the relay model could have been accepted for professional use in Eskom.

In Fig. 10 the characteristics of zone 1 of the actual relay and that of the model under conditions of importing load did not compare at all, but the reason for the very small effective zone 1 characteristic in the model was not a problem with the model of the zone characteristic itself but rather with one of supervising elements that incorrectly limited the zone 1 reach. This was also identified during RTDS testing and corrected.

It was very interesting to note the excellent resistive coverage of both the relay and the model in this test. With a zone 1 resistive setting of 63 primary ohms the relay was tripping comfortably for up to 200 ohms primary fault resistance with exporting load. Again the relay setting procedure had to be adjusted to ensure good stability of the relay in high load conditions and for external faults.

Once the measuring algorithms are validated in various dynamic conditions, including verification of the power swing detection elements, the performance of the directional elements during voltage reversals is tested as well as overall performance for selected evolving faults.

Directionality

On series compensated networks the most important parameter to ensure stability of the relay is its ability to detect correct directionality in voltage reversal conditions by use of voltage memory and polarisation.

To make sure that the relay model performed as expected a series of simple faults were simulated behind the reverse series capacitor as indicated in Fig. 11 below and the performance of relay and model were compared.

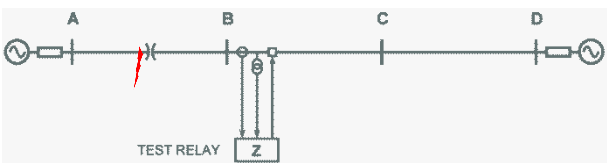

Fig. 11 – Fault position for relay directionality tests.

The results for different types of faults simulated under conditions of no load, high importing and high exporting load are shown in Table 1 with an indication of tripping or not (NT – no trip). For all simulated faults both the relay and the model should remain stable.

As is clear from Table 1 the real relay behaved correctly during all simulated faults. The model also behaved correctly in almost all faults except AB and CA phase to phase faults for very high load export conditions. This gave us an assurance that memory and polarisation were implemented correctly in the relay model but some adjustments are still necessary to match the model to the actual relay performance perfectly. With a bit lower exporting load the model also performed 100% correctly.

Table 1 – Directionality tests results for different line loading conditions.

Fault Type	Load MWs	Relay	Model
A-B-C	0	NT	NT
A-B	0	NT	NT
B-C	0	NT	NT
C-A	0	NT	NT
A-G	0	NT	NT
B-G	0	NT	NT
C-G	0	NT	NT
A-B-G	0	NT	NT
B-C-G	0	NT	NT
C-A-G	0	NT	NT
A-B-C	+1271	NT	NT
A-B	+1271	NT	**TRIP**
B-C	+1271	NT	NT
C-A	+1271	NT	**TRIP**
A-G	+1271	NT	NT
B-G	+1271	NT	NT
C-G	+1271	NT	NT
A-B-G	+1271	NT	NT
B-C-G	+1271	**NT**	NT
C-A-G	+1271	NT	NT
A-B-C	-1216	NT	NT
A-B	-1216	NT	NT
B-C	-1216	NT	NT
C-A	-1216	NT	NT
A-G	-1216	NT	NT
B-G	-1216	NT	NT
C-G	-1216	NT	NT
A-B-G	-1216	NT	NT
B-C-G	-1216	NT	NT
C-A-G	-1216	NT	NT

The results of these parallel tests serve to correct the design of the PowerFactory model so as to ensure as close as possible replication of the hardware relay operation. Completed tests are concluded with an evaluation report that serves as a certification for a particular model to be used in power system and protection analysis in Eskom.

Well tested and trusted models provide excellent tools for improving relay settings and performance particularly in difficult system conditions, beyond N-1, such as high loading as a result of parallel circuit failures, near voltage collapse sequences following large disturbances, power swings after faults close to power stations etc. Well tested relay models also serve as an immediate reference during day-to-day protection operation investigations that are provided to National Control in 24/7 stand-by mode in Eskom. In cases of incorrect protection operations the protection engineers on stand-by inject recorded fault scenarios into the relay models in order to replicate and evaluate the performance of the relays in question in the field. As a result, focused and immediate recovery actions can be undertaken.

CONCLUSION

The experience gained from the introduction of detailed EMT simulation into the protection environment has been that, with improved modelling and analysis tools the potential for much better understanding of relay and system performance, and hence more-appropriate settings, now exists. However, the actual realisation of this potential in practice depends on the representativeness of the dynamic models of the relays used within the day-to-day EMT simulation tools employed by the settings engineers.

This paper has described an approach that has been developed to make use of real-time simulators, together with actual relay hardware, to validate the dynamic models of protection relays. Using the real-time simulator in this way as a complementary tool to validate relay models, as well as to develop trust in these models and better understand their scope and validity, has allowed for improved design of, and greater confidence in, the settings arrived at for protection schemes. This has proven to be of critical importance in obtaining better performance from the transmission network at a stage when it is simultaneously under stress as a result of growing demand, and significant changes as it is strengthened and expanded to meet this demand growth in ways that are challenging to its protection systems. As a result of more detailed EMT simulation and analysis tools, together with validated models for these tools, protection engineers are able, with greater confidence, to find a balance between settings that provide adequate protection of the system and settings that are over-conservative and may therefore exacerbate problems already being experienced on over-stressed networks.

Relay models currently available in simulation software packages are fully dynamic, with replicas of virtually all components of the actual protection relay hardware. Therefore from an academic perspective, a complete validation of such models would require a much broader scope of testing than that described here. The validation approach presented here, however, has been specifically tailored to achieve the most important goal – the introduction of relay modelling to large-scale development and verification of relay settings, improved quality of protection investigations and a very effective educational platform in the day-to-day duties of protection engineers in the power utility.

In most practical applications, and in the majority of incorrect relay operations related to relay settings, even somewhat imperfect but fully-dynamic relay models already provide an excellent tool for improvement of setting philosophies, elimination of errors and better understanding of increasingly complex relays as well as power system performance, which is particularly important for young engineers that are often intimidated by the protection discipline. With more reliable protection models readily available in power system simulation tools as a result of the validation approach described here, much more analysis can be performed revealing possible weaknesses of protection systems in difficult system conditions. However, it should be borne in mind that in those situations where a higher degree of certainty is considered necessary when studying relay performance, testing the relay hardware itself using a real-time simulator complements the approach of relying on relay models.

Ideally, however, relay models for EMT studies should be provided by the relay manufacturers. The best possible quality of models would be then be available, saving power utilities costly validations of third-party models and eliminating many uncertainties.

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