Implementation of Time Domain Simulations and Relay Modeling
Settings of protection relays on the Transmission system require number of fault studies to calculate relevant impedances that the relay will be measuring during faults on the network. Steady state fault calculations and analysis used to be sufficient to obtain required fault quantities. Increased series compensation on the ESKOM network and introduction of non-linear metal oxide varistors (MOV)s protection on series capacitors resulted in significant inaccuracies of steady state fault calculations.

For this reason ESKOM introduced electromagnetic transient (EMT) simulations and modelling of protection relays to verify and optimize protection settings based on results of time domain simulations. Steady state fault calculations were also improved by introduction of iterative fault calculation process to approximate MOV impact on fault quantities. In this paper the implementation process is described with few simulation examples. Possible improvements in protection reliability and benefits in understanding of complex system phenomena are highlighted.
In recent years ESKOM commissioned a number of series capacitors in order to increase transfer capability of existing network with level of compensation reaching 65% in some instances. Most of the series capacitors (SC) are protected by non-linear MOVs conducting during fault conditions to limit voltage produced across series capacitor. The current that MOVs conduct depends on voltage drop across the capacitor which varies not only with system configuration (fault level and position) or fault resistance but varies over the cycle of fault current due to non linear characteristic of MOV.

In steady state fault calculations the effect of MOVs on magnitude and angle of fault currents can not be taken into consideration and the results become inaccurate due to substantial amount of resistance introduced by MOVs (10 – 30 ohms) into the fault loop.

While in most other places on the ESKOM transmission system the steady state calculations are sufficient, in the vicinity of SCs time domain EMT simulations are required. The results of EMT simulations are not easy to use for calculations of the values of fault currents and voltages as they change in time substantially due to sub-synchronous resonance induced by SCs and non- linearity of MOVs (Figure 1).

To achieve adequate balance between dependability and security of protection systems on series compensated networks some compromises have to be made. In many places the instantaneous zone 1 has to be either switched off or reduced to a fraction of standard 80% increasing dependence of instantaneous operation on telecommunication systems. Large Zone 2 settings necessary to cover the line during adverse sub-synchronous oscillations, substantial resistance of MOVs and possibility of series capacitor being by-passed result often in overreaching of step-down transformers supplying distribution networks and possibility of overtripping for not cleared lower voltage faults. On the other hand requirements for high reliability of protection systems are constantly increasing due to depleted stability margins and higher possibility of overload particularly during serious network disturbances.

At the same time the average fault resistance on the ESKOM Transmission system increased in recent years and we have also experienced multiple line failures due to common reasons such as fires under transmission corridors and simultaneous failures of tele-protection systems.

To ensure that protection settings can be tested against the above conditions an additional setting verification process has been introduced where protection relays are modelled on a simulator and tested using EMT time domain simulations. In this way protection settings can be optimized to achieve the best performance at a particular location.

**Integrated Simulation Tool**

Over the last two years the System Operations and Planning Division of ESKOM has been introducing an integrated power system simulation tool for power system modelling, studies and analysis including fault calculations, protection settings and incident investigations.

The model of the ESKOM Transmission and Sub-transmission networks has been compiled based on previous simulator data. The model includes 2762 lines with total length of 55704 km and 2295 transformers with total transformation power of 217033 MVA.

One of the software features is the ability to model protection relays that very well replicate the performance of real devices in both static and dynamic (phasor and
EMT) simulations. During the run of a simulation the relay models are supplied via modelled CTs and VTs and operate associated circuit breakers once tripping or closing conditions are established. The models of protection relays consist of blocks that perform dedicated functions such as measurement blocks, where magnitudes and angles of phasors are calculated based on selected type of filter and sampling rate, polarizing blocks, directional blocks, zone measuring blocks, power swing blocking, associated timers etc, in line with the relay’s original design. Fragment of the relay is illustrated on figure 2.

Models of most common relays are provided in the software library. In many cases, however, modifications to existing models are required to match particular order or specific configuration of the relay. Adjustments that do not require changes of the software code can be done by the user, while other changes must be provided as part of a maintenance contract. Some older electronic relays are difficult to model due to a variety of comparators simultaneously used with many adjustments to the relay characteristics to improve performance in certain situations.

The quality of models entirely depends on the precision of information provided by the manufacturers. It is therefore critical for the protection engineer in a power utility to have access to detailed information about the relay algorithms.

The relay models have to be carefully validated before being approved for practical applications, similarly to the relay acceptance tests. Usually comparison of model performance to the relay manual description is sufficient. In cases of relays for compensated networks where dynamic performance of polarizing elements is critical, more complicated EMT simulations are required. Some relays use additional starting and phase selection algorithms that measure electrical parameters in a different manner than measuring zones (e.g. loop vs. positive sequence impedances). Coordination of such elements can not be easily observed on the same X/R plane making evaluation more complicated. In some cases where relay manuals are not specific enough and information not easily available, relay injection tests are necessary during model validation at substantial expense.

Preferably every new relay purchased by ESKOM should be supplied with a relay model. In this way many costly misunderstandings during the introduction of new technology could be avoided.

The introduction of new methodology in the protection field required concerted training effort. Traditionally protection engineers were little involved in dynamic or EMT studies relying on results from “specialised units” in power utilities such as operations planning. To understand fundamentals of time domain analysis and successfully run simulations for protection modelling, protection personnel had to go through specialized training courses for time domain simulations and protection modelling.
model. In the case of relay not operating for a certain fault all input signals required for operation of a functional block can be identified from the relay frame and displayed on a time axis to analyze their pick-up and drop-off during fault conditions. The relay function that does not perform according to expectations can be easily identified and reasons for incorrect performance analyzed further, often leading to setting adjustments. Figure 3 illustrates an example for A-G fault where fault voltage and current, measured impedance and zone 1 block input and output signals are displayed on the time axis.

From the above graphs it is clear that all necessary supervising signals (directional element, phase selector – starting and loop selection) picked up to effect zone 1 operation and power swing blocking did not operate so the zone 1 issued correct trip command.

The relays modelled in the software can be injected with externally generated or recorded waveforms of fault currents and voltages. To achieve this, the original CTs and VTs associated with the relay during modelling must be disconnected and the relay must be connected to a separately modelled CTs and VTs that are reading COMTRADE data from the record instead of a simulation. This feature is extensively used in ESKOM to analyze the performance of relays during regular fault investigations. For many years ESKOM engineers used to calculate positive sequence or loop impedances from disturbance records and graphically compare them with relay characteristics to evaluate whether tripping conditions were met. In most cases this method provided very good results. However, in situations where polarization and dynamic response of the relay would play a significant role, the results could be incorrect.

Another advantage of using relay models is that the impedances plotted on the X/R plane are actual, modified impedances measured by the relevant zones in exactly the same way as the relay in the field. This way the dynamic behavior of the relay as well as relay specific measuring algorithms are being evaluated, which is a significant improvement in the quality of available tools in both areas of settings and performance analysis. Moreover, all elements in the tripping sequence including directionality elements, fault detectors, impedance starters, power swing blocking, phase selectors, load corrections etc. are being evaluated.

In the area of fault investigations model injections are particularly important in ESKOM due to our specific structure of fault investigations where 24/7 stand-by protection engineers are analyzing protection performance based on remote access to a network of stand alone digital fault recorders (DFRs) immediately after the incident. They provide feedback to the National Control and initiate immediate actions in case of incorrect operations. On the ESKOM transmission system the relay recordings are not accessible remotely and have to be downloaded on site. Moreover, only a fraction of relay population has recording capabilities.

**Verifications of relay settings**

To ensure effective and non-disruptive implementation of relay modelling for protection settings, the settings calculation process remained unchanged - based on well established setting philosophies and manufacturers’ recommendations. Relay modelling requirement has been introduced as an additional verification process once the preliminary settings have been calculated.

During settings verification the relay modelled in the software with its preliminary settings is tested against a variety of faults and situations in the time domain to evaluate its performance in extreme conditions and establish realistic operating boundaries at its particular conditions.
location. EMT simulations are required for relays close to series capacitors to precisely evaluate the impact of non-linear MOVs and analyze the performance of relay specific algorithms e.g. memory polarization during sub-synchronous resonance and voltage reversals. If necessary, adjustments to the relay settings are made to achieve required performance. At the same time any possible errors or omissions can be effectively eliminated to make sure that the settings issued for commissioning are of the highest quality.

Relays modelled in the software during the setting phase remain on the system model for subsequent injections of disturbance records during investigations.

To avoid incorrect steady state calculations on series compensated networks as a result of the MOV protection impact on fault quantities, ESKOM introduced an iterative script whereby series capacitors protected by MOVs are replaced by series (or parallel) connection of linearized equivalents. Iterative fault calculations are then performed to adjust the values of the equivalent resistance $R_c$ and capacitance $X_c$ according to the changes of calculated fault current.

**Simulation examples used for protection settings**

**Performance During High Resistance Faults**

Over the last few years ESKOM observed increasing average of fault resistance during single phase to ground faults on the Transmission system (note: for every fault on Transmission system apparent fault resistance is measured and recorded in protection performance database). The reasons for this phenomenon have not been definitely established yet but deteriorating earthing conditions, large number of fire related faults, increasing fault levels and even some hydrological impacts such as level of water bed are being considered.

![Fig. 4 a/b](image)

Clearly the relay at substation D (picture 4a) measures fault impedance in zone 1, trips the breaker and sends permissive channel to the remote end. The remote end (end C, picture 4b) cannot trip even in permissive mode due to weaker source impedance and high load transfer and it measures the impedance above its permissive zone.

As a result number of incorrect protection operations due to high fault resistance is substantial. For this reason resistive coverage of relay characteristics receives a lot of attention to improve overall system performance. Limitation of impedance relays in detection of resistive faults is well recognized and with an aid of relay modelling can be easily evaluated at the particular relay location. Detailed analysis of relay performance for high resistance faults in the software often leads to improved settings without compromising relay stability during high load conditions.

In the example below a 35 ohms A-G fault was simulated in time domain on heavy loaded (1500MWs) line C-D with unequal source impedances at both ends of the line (common example from ESKOM Transmission system on long supply corridors to Cape and Natal). Figure 4 a/b illustrates impedances measured by the relay during the first 30 milliseconds of fault when both breakers are still closed. Clearly the relay at substation D (picture 4a) measures fault impedance in zone 1, trips the breaker and sends permissive channel to the remote end. The remote end (end C, picture 4b) cannot trip even in permissive mode due to weaker source impedance and high load transfer and it measures the impedance above its permissive zone.
After the breaker at substation D opened the relay at substation C measures the impedance inside tripping characteristics and can issue a trip command.

This is a classical example of sequential tripping which takes place often at any Transmission system. Application of weak infeed function could prevent sequential operation in this example and trip the breaker faster but only if all security criteria (usually level of voltage depression and current) would be satisfied which is not granted for every situation.

After analysis of position of measured impedance with respect to tripping characteristics it becomes clear that slightly increased reactive (not resistive) reach of the relay permissive zone at substation C would improve performance of this relay for high resistance faults and speed up operation.

Possible adverse impacts of extended permissive zone have to be then evaluated to make sure that none of the security areas were compromised.

**Network model validation**

EMT simulations can not be performed on model of the entire Transmission and Subtransmission network due to its dimensions. Relevant parts of the system with all elements that may play a role in the simulation have to be remodeled. In practice, for settings of protection relays, a copy of relevant system portion can be used with loads lumped just beyond step down transformers (400/132kV or 275/88kV) and carefully selected source impedances to represent parts of the network with insignificant impact on results.

For the purpose of setting verifications on the ESKOM Cape Corridor (high level of series compensation) a separate model of Transmission system was prepared with all relevant details including non linear models of MOVs and dynamic controllers at power stations. The model was then validated for load flow, fault levels and dynamic response where results from analysis performed on the entire network model were compared with results from Cape Corridor model.

As final evaluation step, real incidents recorded on DFRs were simulated on the Cape Corridor model to compare behavior of model with real system.

For each comparison the following, critical parameters had to be adjusted to ensure adequate reflection of real conditions:
- generation pattern
- transmission outages
- load flow
- voltage levels
- faulty phase/s, fault duration and location recorded on separate, very accurate travelling wave fault locators
- point-on-wave fault inception
- fault impedance

For illustration the position of fault relatively far away from relay location was selected to indicate that model of the entire system closely reflects the real system behavior. For faults on a particular line practically only source impedances are being evaluated and comparison is not very challenging.

In a similar way movement of impedances measured by the relay were compared indicating very good correlation.

Good validation results provide assurance that the results of EMT simulations on the Cape Corridor model are sufficiently reliable to evaluate protection performance and to optimize settings in time domain simulations.

For analysis of longer duration events where response of dynamic regulators and load play a significant role, additional validation steps would have to be undertaken.

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**Comparison between simulated and recorded impedance plots**

**Simulated Impedance**

**Recorded Impedance**