Perfecting Performance of Distance Protective Relays and It's Associated Pilot Protection Schemes in Extra High Voltage (EHV) Transmission Line Applications

MLC Gabino, RC Oliveira D Erwin JC Theron M. Thakur
CEMIG PG&E GE Multilin AEP

Abstract

The fundamentals of protective relaying of EHV transmission lines such as 345kV is to ensure secure protection for all line's internal faults, and stable operation for all foresee-able external faults during system contingencies. This paper provides an overview of how utilities have traditionally applied distance protection relays and its associated pilot protection schemes for protecting EHV Transmission Lines. These traditional methods cover most aspects of the protection and control of EHV lines, however these methods lack in performance when they are subjected to actual power system and fault conditions.
This paper highlights the needs in perfecting distance protection relays and its associated pilot protection schemes for EHV transmission lines ensuring reliable performance during all foresee-able system load and fault conditions.

This paper also compares the findings of a real time closed loop study against with traditional methods of protecting and controlling a 345 kV EHV transmission line, and provides guidelines to ensure dependable performance of distance protective relays during dynamic system conditions.

Keywords: Power System Protection, Distance Protection, Pilot Communications Aided Protection, Real-time Digital Simulation, EHV Transmission Line Protection

1. Introduction

Modern economies are becoming increasingly dependent on reliable and secure electricity services. The substantial supply disruptions that struck North America and Europe during 2003 clearly demonstrated the fundamental importance of secure and reliable transmission networks. This requirement enforces protection engineers to look into investigating new tools and techniques above traditional ways of performing EHV Transmission Line Protection.

The art and science of the protective relaying of EHV Transmission lines has evolved over many years. There are many textbooks and technical documents which describe [2], [5], [8] and [9] various EHV Transmission line protection schemes used for different conditions and situations, and assists relay engineers in selecting the most appropriate EHV Protection scheme for a particular installation, however Protective relaying is both "Art and Science". The proper relaying scheme for EHV Transmission Lines can be influenced by a number of factors such as transmission line voltage level, length, proximity to generation sources, load flows, stabilities studies etc. Performing setting calculations of Transmission Line protection relays always offers a challenging opportunity to protection and control engineers who examine many fundamental relaying considerations that apply, in one degree or another, to the protection of other types of power system equipment. To assist their P&C engineers, every utility has more or less come up with EHV Transmission Line Protective Relay Setting Guidelines based on their protection and control philosophies which typically are in alignment with IEEE standard C37.113-1999.

Although different utilities have their unique protection and control philosophies for EHV lines, there seem to be an underline commonality in their P&C philosophies, which are as follows:

- Redundant Protection Systems/Schemes with complete Non-Pilot Backup within each should be provided for EHV Transmission Lines.
- Separate Redundant Isolated Batteries for System #1 and System #2 Protective Relays should be considered.
- Impedance based Phase and Ground Distance Protective Relays/Elements must be used to protect EHV Transmission Lines. This may not be applicable to Short Line Applications.
- High-speed Pilot Protection Schemes much be provided for all EHV Transmission Lines
- Dual Pilot Protection Schemes over physically independent channels should be utilized at 345Kv Line, and shall always be utilized at 765kV Lines.
- Single Pole Tripping, and High Speed and Supervised Reclosing of Circuit Breaker should be provided to maintain the integrity of overall Transmission Network and it’s Stability.
- Load Encroachment Element/Function should be used to over come effects of Load on EHV Lines
- Power Swing and Out-of-Step Blocking/Tripping must be considered on EHV Lines
- EHV Transmission Line Backup Ground Protection shall be set to sense and clear faults on Lines associated with the Remote End Station in the event of a Station Battery Failure at the Remote End Station. This is commonly referred to as “Measured Station Battery Failure”
- EHV Transmission Line Backup Phase Protection shall be set to sense and clear faults during Breaker Failures from the Remote End Stations unless a Direct Transfer Trip (DTT) protects for this condition enhanced breaker failure scheme. This is commonly referred to as “Measured Breaker Failure”.
- Backup EHV transmission Line Protection should be set to clear line faults in less than 60 cycles.
- All Phase and Ground Distance Zone Settings must comply with proposed NERC Task Force requirement to permit loading of the line without trip to 150% of emergency line ampere rating, with 0.85 per unit bus voltage and a load angle of 30 degrees.

In line with above-mentioned Protection and Control Philosophies and IEEE standards for Protection of EHV Lines, Utilities have developed their own specific Relay Setting Guidelines for EHV Lines. In the following paragraphs, this paper will describe Distance Protection Element/functions setting guidelines common amongst the various North American Utilities

1.1 Phase Distance Elements/Functions Setting Guidelines:

- Zone 1 Reach:
  Zone 1 reach is set to obtain instantaneous tripping for as much of the protected zone as possible. The zone 1 setting might not be applicable if the line is too short (less than 10 miles) because short lines do not have enough impedance for a relay to adequately

distinguish between a Zone 1 fault and a fault that overreaches the remote bus. Generally Zone 1 for Two-Terminal Lines is set between 80% - 90% of the line impedance, $Z_{L.}$

q Zone 2 Reach:
Zone 2 reach is set to protect the remainder of the line left unprotected by the zone 1 setting and provide an adequate margin. To coordinate with the relays at the remote bus, time delays of 20-30 cycles are typically added to zone 2 settings, though times may vary depending on the circumstances. This time delay should be set longer than backup clearing time for a remote breaker failure condition by a margin of a few cycles. Generally Zone 2 is typically set between 125%-150% of line impedance, Z_L (150% may be required for short lines with low impedance and large percentage reach errors). Zone 2 may be the same element as for Overreaching Pilot Trip in POTT, DCB, DCUB, or Trip Supervision in permissive underreaching (PUTT) schemes [6]. This setting is checked to ensure that it does not reach beyond the zone 1 setting of the next line section.

q Zone 3 Reach:
Even though the transmission line is fully protected with Zone 1 and Zone 2 relays, a third forward-reaching zone is often employed. This Zone 3 is applied as backup for Zone 2 and may be applied as remote backup for relay or station failures at the remote terminal [2] . Generally Zone 3 reach is set to 200% of the line impedance, Z_L with a 60-cycle time delay, provided it does not reach beyond any zone 2 of the remote station’s line sections. Zone3 setting needs to be verified that each zone 3 relay is not set to trip on load under extreme conditions [7], [8]

1.2 Ground Distance Elements/Functions Setting Guidelines:

q Zone 1 Reach:
In determining the ground distance reach, mutual coupling and cross feed need to be considered. Mutual coupling could cause overreach on the part of the ground distance elements unless the reach is pulled back. For this reason, Zone 1 ground distance is generally set between 50% and 80% of the positive sequence line impedance, Z_L. The reach should be closer toward the low end of this range with the more mutual coupling that exists on an EHV Line, unless measuring of the parallel line zero sequence current will dynamically reduce Zone 1 reach.

q Zone 2 Reach:
For the ground distance zone 2 reach, the following two calculations needed to be done:

- Calculate 110% of line impedance, Z_L.
- Add 50% of the shortest remote line impedance to line impedance, Z_L.

Generally we set the zone 2 reach between the results of 1 and 2 above, with a time delay of 20-40 cycles. Reaches should be checked in fault study software such as ASPEN with both mutual impedances and cross feed being considered since both have significant effects on ground distance reaches.

- Zone 3 Reach:
  The same principles of Zone 3 Phase Distance rules follow setting up a ground distance Zone 3 reach.

1.3 Load Encroachment

As per NERC Task Force requirements [7], [8], Phase distance settings and other applicable phase and ground distance zone settings must permit loading of the line without trip to 150% of emergency line ampere rating, with 0.85 per unit bus voltage and a load angle of 30 degrees.

Considering the above guidelines, the Load Encroachment element/function is set to prevent tripping of Distance Protection Elements on load.

1.4 Pilot Protection Schemes

Pilot Protection Schemes are used to improve tripping speed and/or coordination of EHV transmission Lines. When selecting a pilot protection scheme, following important criteria's should be considered;

- Dependability: the ability of a relay system to trip for <u>internal faults</u>
- Security: ability of a relay system not to trip for <u>external faults</u>
- Physical and electrical limitations and cost.

The following Pilot schemes are being used by most North American Utilities:

<u>Directional Comparison Blocking (DCB)</u>
The most common pilot scheme on EHV Transmission Lines is Directional Comparison Carrier Blocking (DCB). It normally uses phase directional distance relays for phase faults, and ground directional overcurrent and/or ground directional distance relays for ground faults. At each terminal, the phase and ground tripping elements must be forward directional and set to overreach the remote terminal. The reverse blocking elements should be reverse directional, with the exception of the ground overcurrent-blocking element, which can be non-directional. The blocking elements must reach farther, or be set more sensitively, than the corresponding tripping elements at the remote terminal.

This scheme provides dependability but not necessarily security.
<u>Permissive Overreaching Transfer Trip (POTT)</u>
POTT schemes use overreaching zones at each end of the protected line that work with a communication system to determine if the fault is between the two terminals. Phase distance relays detect multiphase faults, whereas ground distance or directional ground overcurrent relays are used to detect ground faults. Communication between terminals is by means of Power Line Carrier, Fiber Optic cable, Microwave Transmission or Radio Communication. The one most commonly used is Power line Carrier. It uses a Frequency Shift Keying (FSK) channel in which the transmitters continuously send a GUARD frequency during non-fault conditions, and are keyed to the TRIP frequency by an output from any one of the overreaching elements during a fault. In order for the relay to trip, there must be no GUARD received and there must be a TRIP received. This scheme provides security but not necessarily dependability.

Permissive Underreaching Transfer Trip (PUTT)

PUTT schemes use underreaching 1st zone relays. A communication path between the relays to communicates a direct transfer trip signal to the remote terminal. Phase distance relays detect multiphase faults, whereas ground distance functions or directional ground overcurrent functions detect ground faults. Communication between terminals is by means of Power Line Carrier, Fiber Optic cable, Microwave Transmission or Radio Communication. The one most commonly used is Power Line Carrier. It uses a Frequency Shift (FSK) channel in which the transmitters continuously send a GUARD frequency during non-fault conditions, and are keyed to the TRIP frequency by an output from any one of the underreaching elements during a fault. In order for the relay to trip, there must be no GUARD received and there must be a TRIP received. This scheme provides security but not necessarily dependability.

Pilot Wire

A cable, either copper or fiber optic, is strung on poles to create a "hard wire" path between two stations. Pilot wire protective relays are at each end. The cable is connected so that for external faults, the current in the cable circulates in a loop and no current flows in the protective relay. During internal faults, the currents in the cable oppose each other, so current is forced through the protective relay. This scheme provides security and dependability but it has physical limits and is expensive.

By following above Relay Setting Guidelines, P&C philosophies, P&C Engineer first collects and Reviews an EHV Line Data Sources such as network configuration, circuit parameters (circuit length, conductor size, impedance, thermal capability, mutual characteristics, etc.), maximum (emergency) load flow, CT and VT ratio, polarizing source, relay wiring designs etc., and then perform fault studies to verify EHV line Relay Settings. This methodology covers most aspects of the protection and control of EHV lines, however these methods lack in performance when they are subjected to actual power system and fault conditions.

To address those performance issues, the following parts of the paper will discuss P&C philosophies of a Brazilian Utility, CEMIG, on its 345kV Transmission Lines and then perform real time power system simulations to verify dependable performance of Montes Carlos to Irapé 345kV Line relay settings during dynamic power system conditions.

1.5 Background on CEMIG Montes Carlos to Irapé 345kV Line

Companhia Energética de Minas Gerais – CEMIG is one of the largest and most important electric energy utilities in Brazil due to its strategic location, its technical expertise and its market. CEMIG’s concession area extends throughout nearly 96.7% of the State of Minas Gerais, whose territory is situated in the Southeastern region of Brazil and covers an area of 567,478 thousand square kilometers.

The Irapé plant is the largest of Cemig’s current projects. It is noteworthy due to both the size of the investment and its location in the Jequitinhonha Valley, considered to be the least developed region in the State. In the waters of the Jequitinhonha river, just between the municipalities of Berilo and Grão Mogol, the Irapé plant is located and will have a generation capacity of 360 MW delivered by 3 Francis 120 MW generating units. At 208 meters, the dam is the highest in Brazil.

To transmit the energy generated at the Irapé power plant to the electric system is being built a 345 kV transmission line (TL) Irapé-Montes Claros 2 with 140 km of extension. That TL was projected with redundant protection systems that consist of two protection systems implemented in each line end. Also, there is a pilot scheme to provide a protection system what covers 100% of the line with fast tripping. The pilot scheme applied is Hybrid POTT (hybrid permissive over-reaching transfer trip), including the complementary weak-infeed and echo functions.

There are independent pilot channels for each protection systems. Therefore, we have two transmitters and two receivers in each end of the line for each protection system, segregated by phase, once the single-phase autorecloser is used. The main protection uses carrier channels and the supplementary protection uses digital radio. The maximum fault clearance time allowed to 345 kV transmission lines, including the circuit breaker operating time is 100 ms for all type kind of faults,

Phase and ground distance functions were set with quadrilateral characteristics. They provide better resistance coverage and arc compensation than the Mho characteristic.

The settings of distance zones were done according to the following grading criteria:

- The first zone is an under-reaching fast tripping zone (non-delayed), set to 80% of the line-length.
- The second zone is a time delayed overreaching zone and it is applied to a permissive pilot scheme. Ground directional overcurrent function is used in conjunction with zone 2 in the pilot scheme. This increases the coverage for high-resistance faults. The time delay was set to 500ms.
- The third zone is a time delayed overreaching zone that reaches the next remote busbar and is used as back-up protection. The settings of back-up zones present some difficulties, as the reach is dependant on the switching state of the network and the infeed conditions. The time delay was set to 1s.

Based on above-mentioned guidelines, CEMIG's P&C engineers calculated relay settings for Montes Carlos to Irapé 345kV EHV Line. Since Montes Carlos to Irapé 345kV Line was very important, CEMIG decided to conduct closed loop power system studies for this transmission line. The primary intension in conducting this study was to verify the accuracy of Line Protection Settings.

2. Closed Loop Power System Studies

As per CEMIG's requirements, a real time power system simulation case was built in Real Time Digital Simulator [4]. The Distance protection relays were connected to this simulator model that included the Irapé to Montes Claros (MCLD) line, with two communications channel that were connected back-to-back to ensure a complete distance with pilot protection scheme is formed. The protection scheme was then exposed to various internal and external faults at fault locations as indicated in figure 3.1.

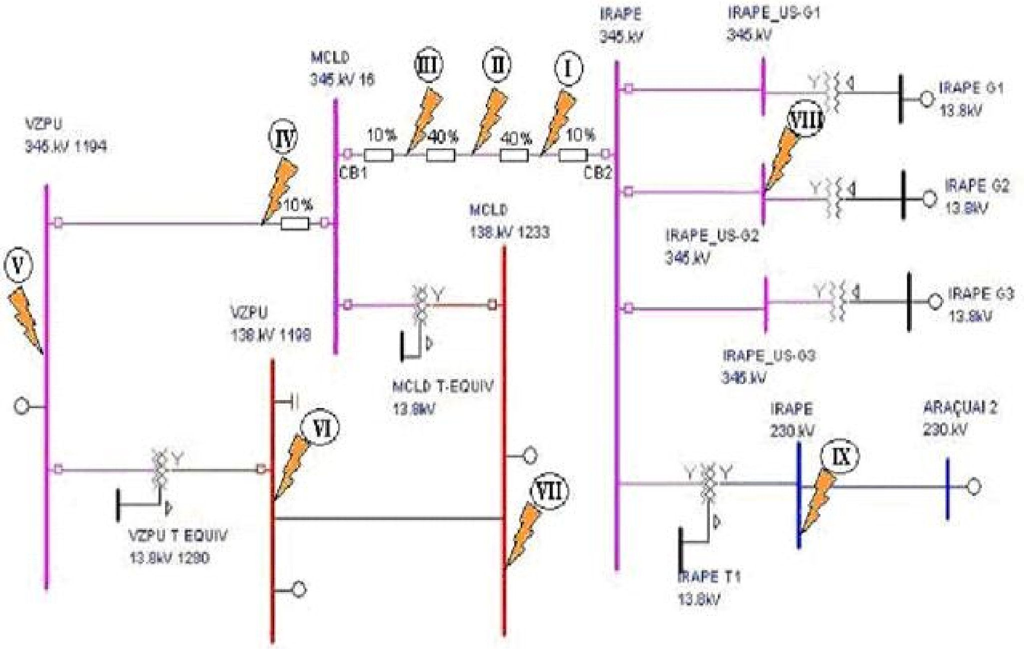

Figure 3.1: System layout indicating line under investigation and Fault Locations

The simulator monitored all tripping and reclosure signals, indicating the protection scheme's performance, and operated all associated circuit breakers (with simulated opening time of 3 cycles) on this line based on the scheme performance, in a single-pole-tripping application. The model also included all necessary fault logic to apply any fault type (including evolving faults) of any given resistance at any specified point on voltage wave at all the fault locations as highlighted in figure 3.1. This was thus a full closed-loop test setup. The maximum expected pre-fault load on the line was 360.8 MVA from Irapé to Montes Claros.

During the first stages of applying the calculated Protection Settings to internal faults on the model power system (as indicated in figure 3.1), it was apparent that the Irapé source was much weaker than the Montes Claros (MCLD) source, which was also anticipated. What was interesting to note, was that the zero sequence impedance of the Irapé source was very high, and that the whole scheme would need special attention due to this.

There were many significantly interesting results of this closed loop power system studies. The findings of these studies forced us to re visit our line protection relay settings, which were calculated based on traditional methodology. The following section of the paper will give us an insight into those interesting findings and corrective actions taken to fix them.

2.1 Phase Distance Elements

- Phase Distance Zone 1:

  During single-phase to ground faults at location 1 (90% of the line length as indicated in figure 3.1, thus 10% from Irapé) it was noted that the phase impedances started to enter the Zone 1 phase impedance characteristic at the Irapé end. For a Phase A to ground fault, the AB (blue) and CA (red) impedance trajectories did enter the associated Zone 1 Phase distance element as can be seen in figure 3.2. This occurred within half a cycle from when the A-to-ground trajectory entered Zone 1 Ground characteristic, and would normally, in systems with stronger sources, occur much slower and then would Phase distance Zone 1 AB and CA be shut down for this A to ground fault. This had the undesirable effect that the protection tripped the line three-phase, where a single-pole trip is expected. An attempt was made to keep the Zone 1 Phase distance characteristic as was originally set, by blocking the zone with the Load Encroachment feature. For this particular case, it is clear that the positive sequence impedance trajectory (the solid magenta Z1 trajectory of figure 3.2) is well outside of zone 1 phase distance element, thus can't this resolve the operation of the phase distance Zone 1. The only alternative was to change the Zone 1 Phase distance characteristic to a more conservative quadrilateral shape as in figure 3.3. This ensured that Phase distance zone 1 was stable for all single-phase to ground faults but still provided the expected performance for phase faults. This wasn't encountered at the Montes Claros (MCLD) end. The operating time for Zone 1 phase was always less than 25 ms.

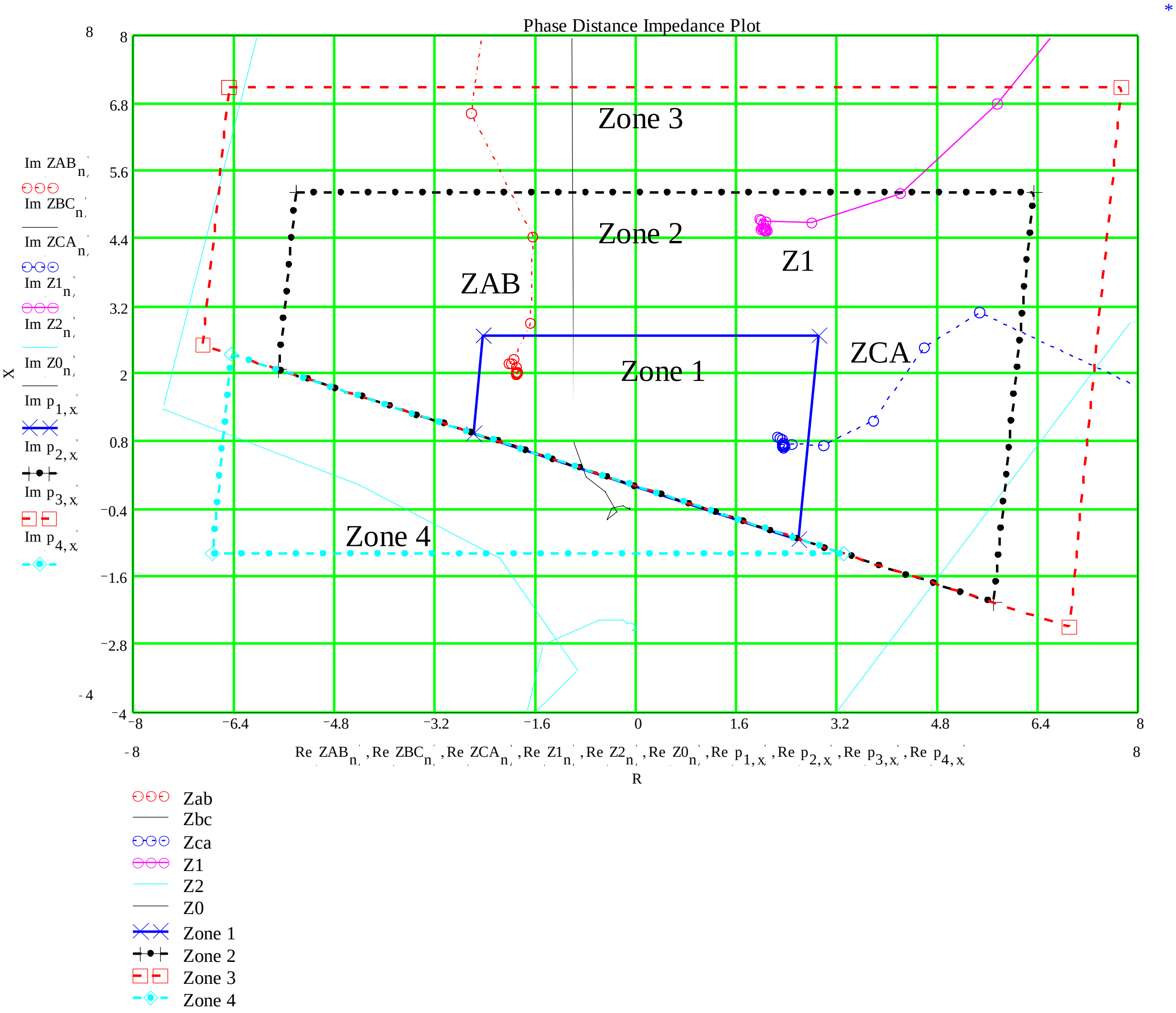

Figure 3.2: Original Phase Distance characteristics with Z1, ZAB and ZCA impedance plot for A-to-ground fault at Location 1 (10% from Irapé) as seen from Irapé

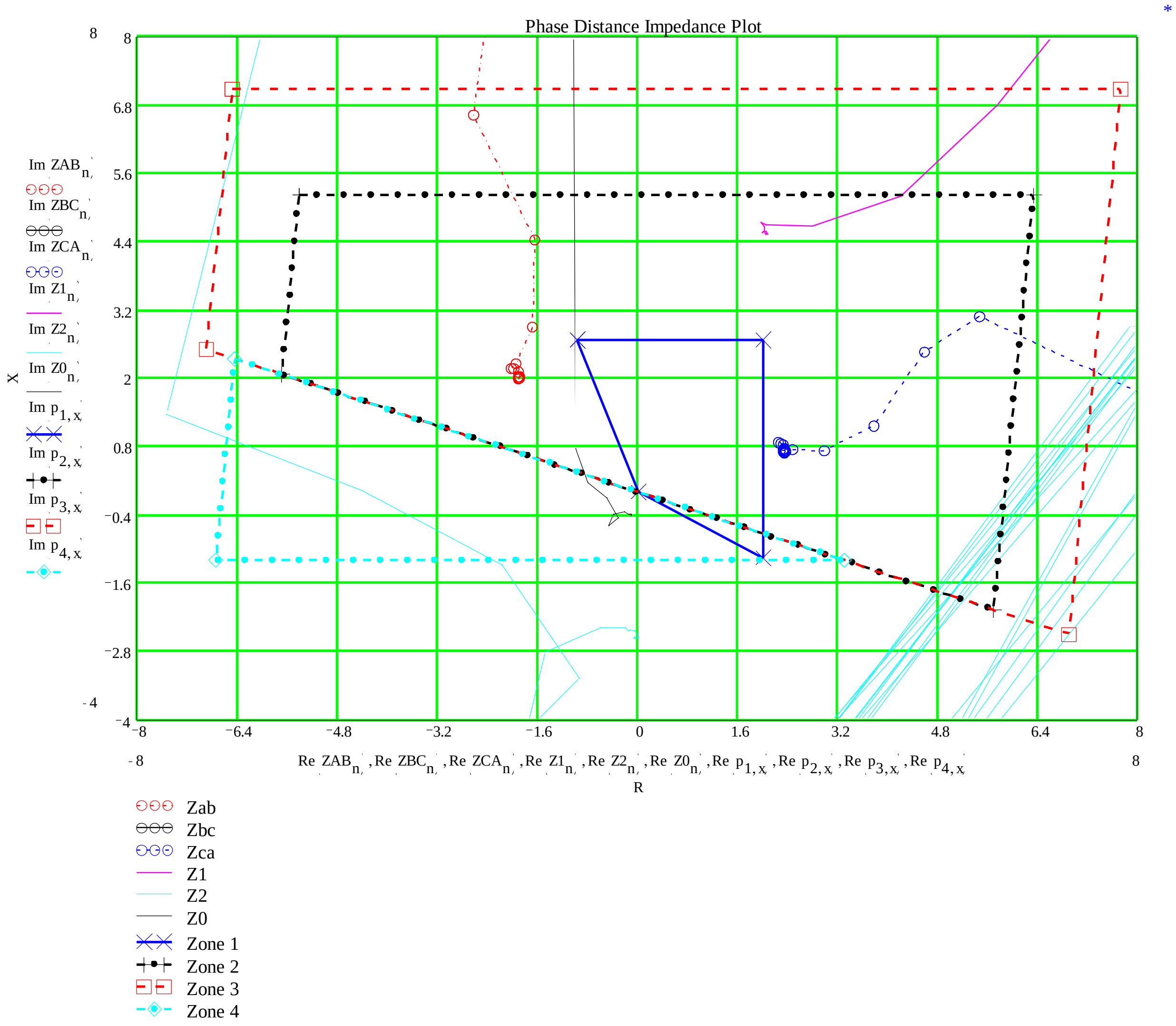

Figure 3.3: New Phase Distance characteristics with Z1, ZAB and ZCA impedance plot for A-to-ground fault at Location 1 (10% from Irapé) as seen from Irapé

- Phase Distance Zone 2:
  Zone 2 is associated with the Hybrid POTT scheme and back-up stepped distance. Zone 2 did cover the remote bus from both ends, including high resistive faults, and from the Irapé when only 1 generator was in service. The overreaching Zone 2 phase tripped always in less than 530ms, for external faults applied longer than the Zone 2 timer setting.

- Phase Distance Zone 3:
  Zone 3 is associated only with the back-up stepped distance scheme, and did cover the remote bus locations 5 and 8 as per figure 3.1. Load encroachment wasn't necessary, since the minimum load impedance of 329.9 Ohms is significantly far from the 7.11 Ohm blinder. This is however an aspect that would need to be re-visited whenever the Irapé system and maximum anticipated load changes. The faults were never applied longer than the Zone 3 timer, however, Zone 3 phase did pick up when anticipated.

- Phase Distance Zone 4:
  Zone 4 is associated only with the Hybrid POTT scheme, operated as expected, and no characteristic changes were required.

The current supervision of all distance elements were necessary to be set more sensitive than expected to ensure coverage of high resistive faults, and to cater for the weak source at Irapé. A setting of 0.1 p.u. for zones 1, 2 and 3 and a setting of 0.05 p.u. for zone 4 were found to provide adequate sensitivity and co-ordination.

2.2 Ground Distance Elements

- Ground Distance Zone 1:

The Ground Distance zones were initially set with similar quadrilateral characteristics as the Phase Distance elements. This did ensure that faults with arcing resistance of 40 Ohms were nicely covered as expected. However, when the load conditions were increased to maximum, from Irapé to Montes Claros and high resistive external single-phase-to-ground faults were applied to the Montes Claros bus, the apparent impedance would enter the Zone 1 Ground Distance characteristic. This is presented in figure 3.4. This phenomena is widely described in [3], where it is clear that the forward load, in combination of the high arcing resistance, caused the apparent impedance to drop into the operating characteristic of Zone 1.

To compensate for this but still keep good high-resistive fault coverage, it was necessary to change the top end of the Ground Distance Zone 1 characteristic to be tent shaped. A Compensation limit setting of 85° was found to be sufficient, which dropped the impedance characteristic by 5°. When the same fault was applied to the changed characteristic, it was safely outside the Ground Distance Zone 1 characteristic, as seen in figure 3.5. Single-phase high resistive faults at 25% of the line, or location 3 (75% from Irapé) as seen from Irapé was still adequately covered by Zone 1 Ground, as can be seen in figure 3.6.

This effect of the load and high arcing fault resistance dropping the impedance characteristic into Zone 1 Phase was seen only at the Irapé end, since the maximum anticipated load would only be from Irapé to Montes Claros. At the Montes Carlos end, this could drop the apparent impedance below the resistive axis for internal faults at Montes Claros. Typically the voltage memory expansion of the quadrilateral or Mho characteristic should compensate for this, though the Mho characteristic might exhibit blind spots, and should be evaluated especially if single-pole-tripping is a requirement.

The highly resistive quadrilateral characteristic of Zone 1 Ground paid off during internal resistive evolving faults (from phase-to-ground to Phase-to-phase-to-ground) when the second fault occurred after the Neutral Directional OC and the faulted phase distance elements were shut down, ensuring a single-pole trip would translate into a 3-pole trip. This can be seen in figure 3.7, a B to ground fault evolving to a B to A to ground fault. The operating time for Zone 1 ground was always less than 25 ms.

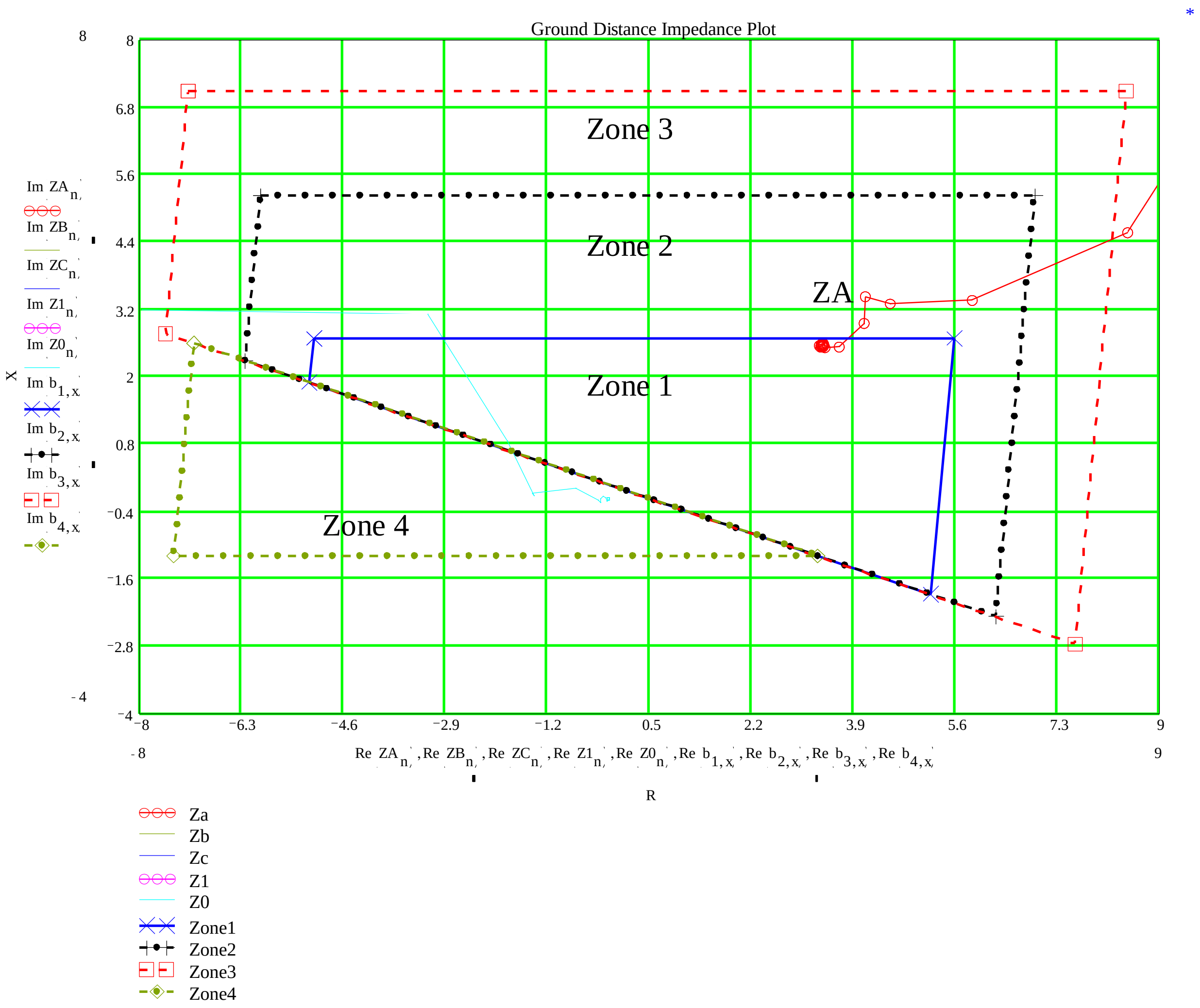

Figure 3.4: Original Ground Distance characteristics with ZA impedance plot for A-to-ground fault at Bus MCLD as seen from Irapé

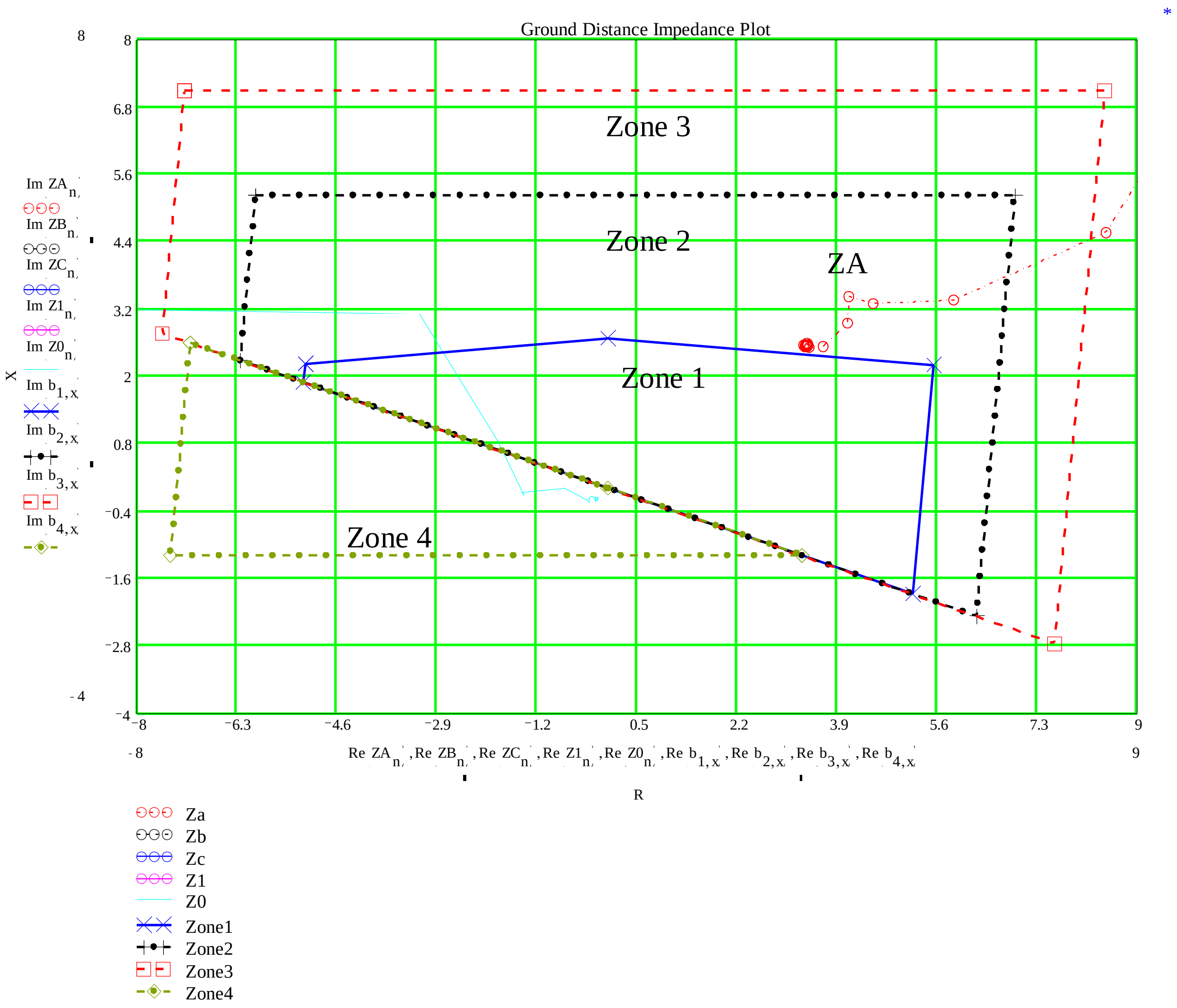

Figure 3.5: New Ground Distance characteristics with ZA impedance plot for A-to-ground fault at Bus MCLD as seen from Irapé

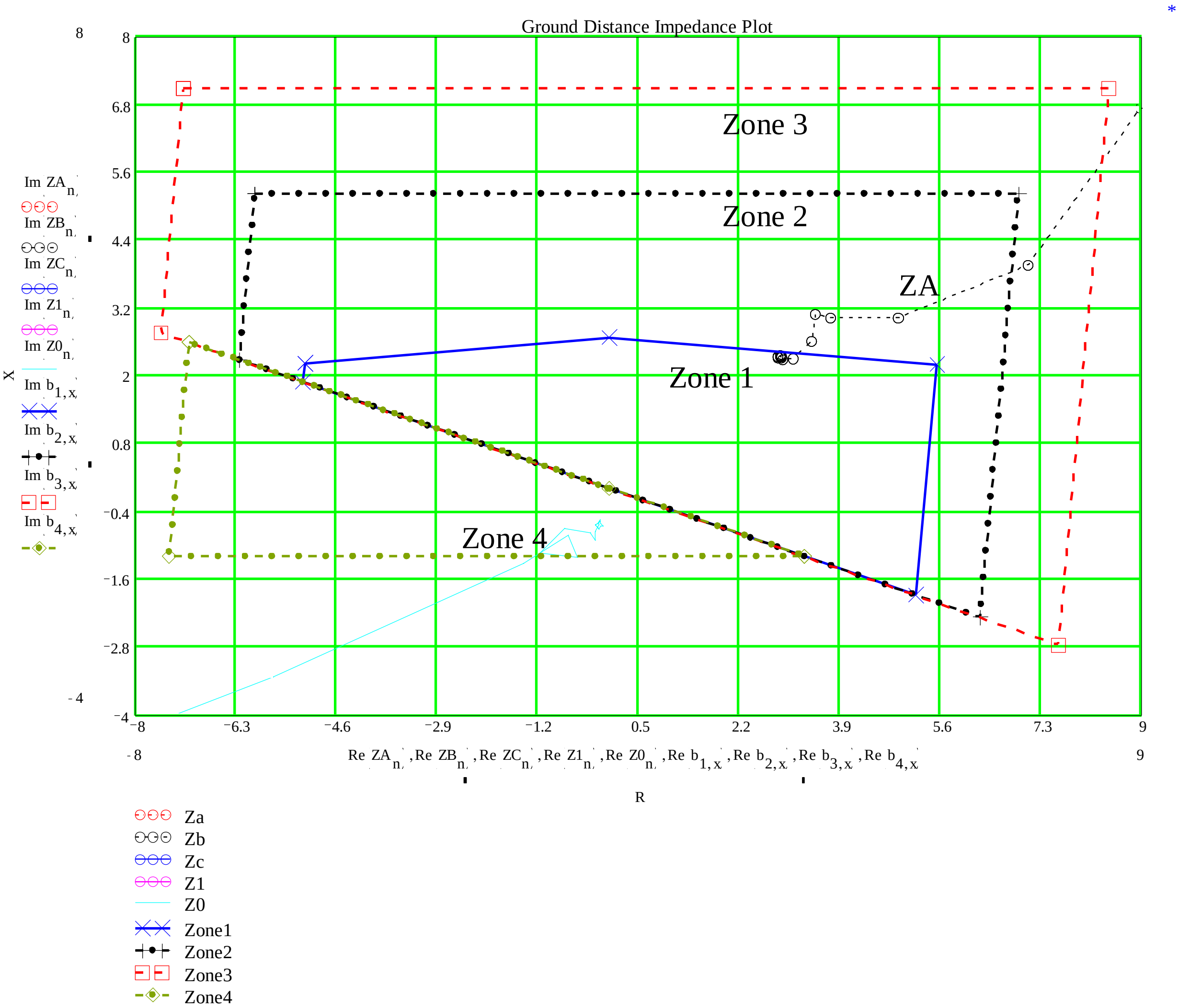

Figure 3.6: New Ground Distance characteristics with ZB impedance plot for B-to-ground fault at position 3 (25% of the line) as seen from Irapé

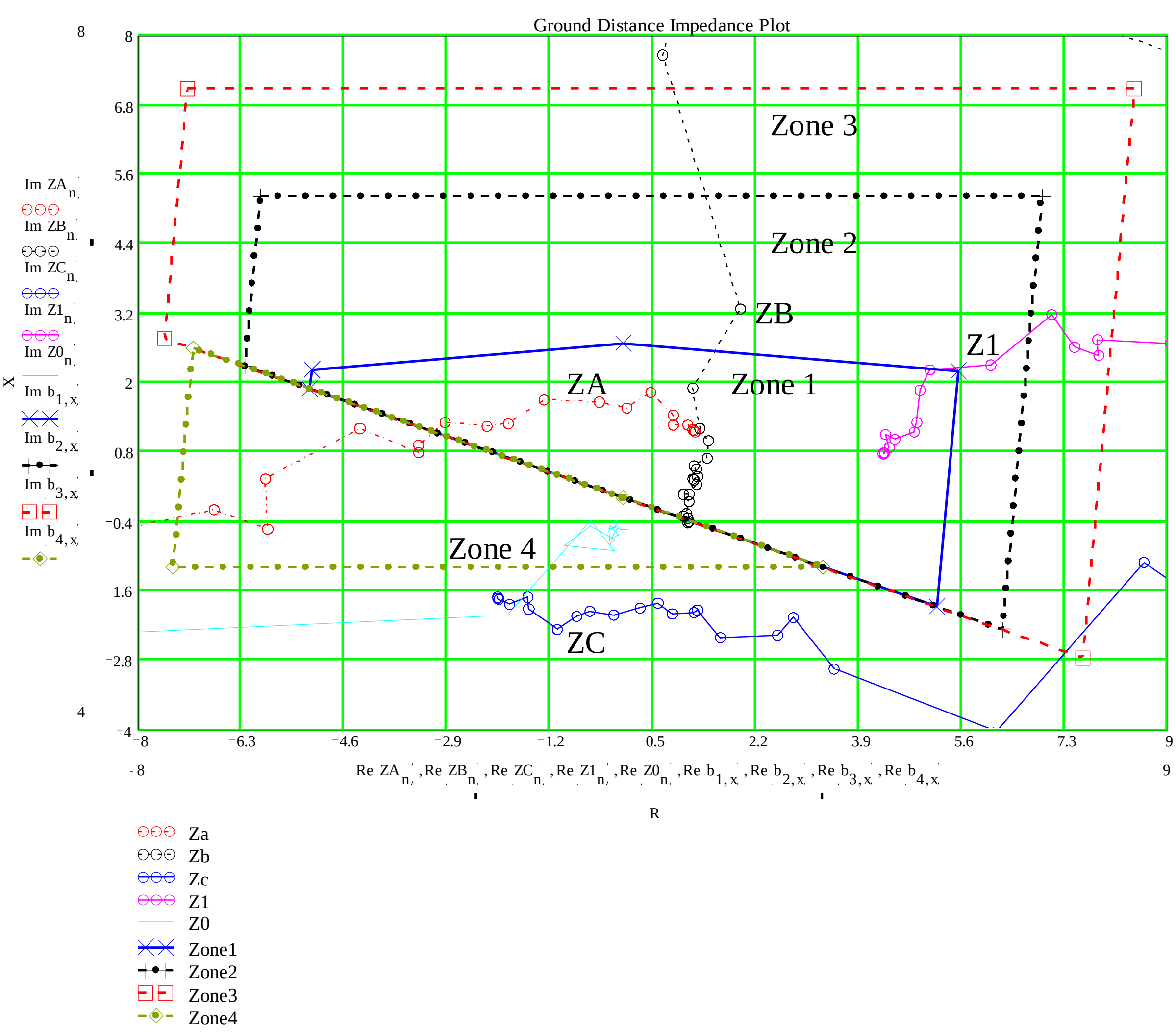

Figure 3.7: New Ground Distance characteristics with Z1, ZA, ZB and ZC impedance plot for B-to-ground evolving to B-to-A-to-ground fault at position 1 as seen from Irapé

- Ground Distance Zone 2:
  Just as phase distance, zone 2 is associated with the Hybrid POTT scheme and back-up stepped distance, and did cover the remote bus in all cases as expected. The overreaching Zone 2 ground tripped always in less than 530ms, for external faults applied longer than the Zone 2 timer setting.

- Ground Distance Zone 3:
  Zone 3 is also associated only with the back-up stepped distance scheme as for ground distance. Due to the large zero sequence impedance at Irapé and infeed effects, single-phase-to ground faults at location 5 didn’t enter ground Zone 3, but did enter phase zone 3. This is acceptable since this is back-up protection, and zone 3 ground was already set to 210% of the line impedance and couldn’t be set beyond this. Load encroachment was again not necessary, since the minimum load impedance of 329.9 Ohms is significantly far from the 7.82 Ohm blinder. Again would this is need to be re-visited whenever the Irapé system and maximum anticipated load changes. The faults were never applied longer than the Zone 3 timer.

- Ground Distance Zone 4:
  Zone 4 is also associated with only the Hybrid POTT scheme, operated as expected, and no characteristic changes were required. Just as for the Phase Distance, the current supervision of all distance elements were necessary to be set more sensitive than expected to ensure coverage of high resistive faults, and to cater for the weak source at Irapé. A setting of 0.1 p.u. for zones 1, 2 and 3 and a setting of 0.05 p.u. for zone 4 were found to provide adequate sensitivity and co-ordination.

2.3 Ground Directional Overcurrent Elements

Since this is a single line and no mutual zero sequence impedances are anticipated on the line (normally seen in parallel lines), the Neutral Directional overcurrent (OC) forward (FWD) and reverse (REV) operands can be used in the Hybrid POTT scheme as extended forward and reverse looking elements. Negative sequence directional OC thus need not be considered, and wasn't used in this application.

Just as for the Distance Supervision, the pickup settings had to be set more sensitive to 0.1 p.u. for Neutral Directional OC FWD and 0.05 p.u. for Neutral Directional OC Rev. This ensured adequate co-ordination and sensitivity ensuring all high resistive faults and infeed conditions will be covered by the Hybrid POTT scheme during all expected load conditions. For security, a positive sequence compensation factor of 0.063 was used and the neutral directional overcurrent function was blocked during open pole and single-pole trip conditions, ensuring the scheme would render reliable performance and stability for this particular single-pole tripping application.

With the aid of the overreaching Zone 2 and Neutral Directional elements, the Hybrid POTT scheme always operated in less than 26ms.

2.4 Weak Infeed Elements

Generally the Neutral Directional OC elements were sensitive enough if at least one generator was in service at the Irapé end. However, since Irapé is a generating plant and can have all three generators out of service and the 345 kV to 230 kV transformer at Irapé (figure 3.1) will be installed later, a weak infeed addition to the scheme should be considered to ensure that the line would be secured for internal faults during this condition. Since single-pole-tripping is not required during this condition, an undervoltage element, supervised by the Neutral Directional OC and Zones 2 and 4 distance elements, was used. A setting of 0.8 p.u. was adequate. The weak infeed part of the Hybrid POTT scheme operated in less than 36ms.

2.5 Echo Elements

Line energization normally would occur from Montes Claros to Irapé. In the event that a remote fault occurs between the closures of CB1 (at MCLD) and CB2 (at Irapé), it is desired that the overreaching Zones 2 and Neutral Directional OC Forward elements at Montes Claros be allowed to trip CB1 under these circumstances. This was accomplished by using the built-in Echo feature of the Hybrid POTT scheme, where the Irapé end would echo all permissive Receive signals back to the Montes Claros end in the event when CB2 (the local breaker) is open. Applying various faults at position 1 in figure 3.1 proved this, including that the sensitivity of Neutral Directional OC Forward and Zone 2 Phase and Ground was adequate. It was however necessary to adjust the Echo duration and lockout to ensure proper co-ordination due to transmission delay. Trip times were less than 36ms during echo conditions.

2.6 Switch Onto Fault Element

Although this is not part of the pilot scheme, it is essential to use a Switch Onto Fault element to ensure that in the event that one of the breakers are closed onto a fault, that the line will be tripped. During this event for faults close to the breaker (which is the most common, when grounding connectors were left on the line), the distance elements are blind to this fault since the polarizing memory voltage would be zero. It is thus essential to determine what is as sensitive overcurrent pickup setting that can be used to ensure these faults would be covered, but still be stable for normal line energization events. An overcurrent setting of 0.83 p.u. was adequate. Trip times were less than 22ms, including for faults at the remote end.

2.7 Synchronizing Check Element

Although this is also not part of the pilot scheme, it is essential to use a Synchronizing Check element to ensure that the Irapé system would be safely reconnected after a transient multi-phase fault and reclosure. The normal sequence for reclosing is to first reclose the line from Montes Claros and then at Irapé with synchronism check for system security. It was found that the maximum voltage setting had to be changed to ensure synchronism check would allow the breaker to close and the recloser dead time at Irapé had to be extended.

3. Summary and Conclusion

In line with above findings, the closed loop power system studies on CEMIG's Montes Carlos to Irapé 345kV Line provided numerous instances where traditional methodology of setting line protection relays failed to ensure dependable performance of distance protective relays during dynamic system conditions

To ensure high level of dependable performance for Montes Carlos to Irapé 345kV Line, the following setting changes were performed:

- Distance Elements:
  Zone 1 Phase characteristic had to be changed to ensure single-pole-tripping would occur, not intervene during single-pole-to-ground faults.
  Zone 1 Ground characteristic had to be changed to ensure no overreaching would occur during high resistive faults in the presence of the maximum anticipated forward load.
  The current supervision of all distance elements had to be sensitized to ensure adequate sensitivity for remote and high resistive faults.
- Neutral Directional Elements had to be sensitized to cover all expected faults and ensure co-ordination.
- Echo Elements (duration and lockout) had to be adjusted to ensure proper communications channel co-ordination.
- Switch Onto Fault elements (Current pickup) had to be adjusted to ensure sensitivity for all line energization faults and stability during all line energization events.
- Synchronizing check maximum voltage and Recloser dead times had to be changed to ensure proper co-ordination between both ends.

From the simulator test results it is clear that not all contingencies were (or could be) taken into account, and compensated for, during the protection settings calculation phase. Most of the distance characteristics and associated settings were found to be adequate, but many other elements had to be changed to ensure a Distance protection scheme, performing as is required to maintain system stability and security during all foreseeable transient and permanent fault conditions. The maximum allowable 100 ms operating time (including circuit breaker time) is thus achievable after above changes were implemented.

4. Recommendations

During the process of applying a Distance protection, with communications aided scheme to an EHV transmission line, the following guidelines can be used to ensure the scheme will operate as expected:

- Follow the guidelines as stipulated in the IEEE standard C37.113-1999 when calculating all distance impedance characteristics, timers and pilot protection scheme operands.
- Ensure all the Distance elements conform to the latest NERC criteria for Distance elements and pilot protection schemes.
- Ensure that all overreaching distance elements coordinate with the remote relay's reverse elements and no blind spots are present in terms of characteristics and sensitivity.
- Ensure that the calculated distance element characteristics, supervising currents and pilot protection elements (normally ground directional overcurrent elements) exhibit the required expectations during all foreseeable system loads (both directions if anticipated); fault conditions, including transient, high resistive, permanent and evolving faults and stability during all reclose events (if a recloser is used) as follows:
    - Distance Zone 1 reach up to setting, and never overreaches for faults at the end of the line. The current supervision has to be adjusted and coordinated with VT fuse fail, if required.
    - Distance Zone 2 always covers the end terminal; reach up to expected reach and trips for permanent faults after expected time delay. The current supervision should allow zone 2 performance as expected.
    - Distance Zone 3 (if used and set forward) always covers up to the neighboring line end terminal and trips for permanent faults after expected time delay. The current supervision should also allow zone 3 performance as expected. The blocking of Zone 3 by Load Encroachment occurs as expected.
    - Distance Zone 4 (if used and set reverse) always covers all reverse faults. The current supervision should be more sensitive than the current supervision of zone 2 of the remote relay, to ensure coordination.
    - Ground directional elements (if used by the pilot scheme) consisting of either Neutral directional OC elements or Negative sequence directional OC elements, or both, exhibit the expected sensitivity and security for all internal and external faults as is expected.
    - Weak infeed elements (if used) perform as is expected, with adequate sensitivity and no operations during any other transient events.
    - Echo elements are properly set and coordinate with the communications channel.
- The Out-of-step blocking element never picks up during any load condition and Out-of-step tripping (if used) operates for the expected impedance swing characteristics.
- Switch onto fault elements exhibit the necessary sensitivity for all line faults and security during all expected line (or system) energization events.
- In Single-pole-tripping applications, the anticipated tripping and reclosing occur as expected, all elements initiating single-pole-tripping exhibit the anticipated sensitivity and security.
- In Parallel lines, Zone 1 doesn't overreach and is properly compensated, including for remote faults when the parallel line is de-energized and grounded at both ends.

- In Series compensated lines, Zone 1 also doesn't overreach, Zone 4 always operate for only reverse faults and the Ground directional OC elements exhibit the necessary directional security and sensitivity to ensure a secure pilot protection scheme.
- Breaker failure protection gets initiated and operates as expected (if used in the same device).
- The recloser (if used) operates as expected and, if used with Synchronism check, has the proper coordination with the remote recloser. The expected transients during reclosing are a very good generic check of overall system security.
- All other back-up current or voltage elements, is used (eg. Phase OC, Neutral OC, Negative sequence OC, Undervoltage, Overvoltage or Frequency elements) operate as expected and don't exhibit any unexpected performances.
- All local programmed logic (eg. Direct transfer tripping or special protection schemes) perform as expected.

A large part of the abovementioned recommended testing can be performed with any local test equipment, but when a scheme involves single-pole-tripping with a recloser, or reclosing using synchronism check, or consists of a parallel line, or has a series capacitor and all foreseeable system transients should be monitored for scheme sensitivity and security, a closed-loop real-time system is recommended. This normally depends on the economic, reliability and security expectations of the associated line to determine what testing and simulation measures should be followed to ensure expected protection scheme operation.

5. References

[1] M. G. Adamiak, G. E. Alexander, Dr. W. Premerlani, "Advancements in Adaptive Algorithms for Secure High Speed Distance Protection, GE Publications GER-3962

[2] Power Systems Relaying Committee (PSRC) of the IEEE C37.113-1999, IEEE Guide for Protective Relay Applications to Transmission Lines

[3] G.E. Alexander, J.G. Andrichak, W.Z. Tyska, S.B. Wilkinson, 1986, Effects of Load Flow on Relay Performance, 39th Texas A&M Relay Conference

[4] A Real Time Digital Simulator for Testing Relays IEEE Transactions on Power Delivery, Jan. 1992, Vol. 7, No.1, pp. 207-213.

[5] Applied Protective Relaying, Westinghouse Electric Corp., Relay Instrument Division, 1976.

[6] Art & Science of Protective Relaying By C. Russell Mason

[7] ERC Final Recommendations – Blackout of August 14, 2003

[8] NERC Planning Standards, North American Electric Reliability Council, September 1997 and updates on specific sections through July 2004, http://www.nerc.com/standards/

[9] Alexander, G. E., and Andrichak, J. G., "Distance Relay Fundamentals," Twenty-third Annual Western Protective Relay Conference, October 1996.

6. Biographies

Reginaldo Cezari de Oliveira, received his BSEE degree from Pontifícia Universidade Católica de Minas Gerais, Brazil, in 1980. He joined Furnas Centrais Elétricas SA in 1981 as a Protection and Control Maintenance Engineer.

In 1986 Reginaldo joined CEMIG (Companhia Energética de Minas Gerais SA) as a Senior Engineer where he is involved in the protection and automation maintenance engineering.

Maria Lúcia de Carvalho Gabino obtained her bachelor's degree in electrical engineering from Pontifícia Universidade Católica de Minas Gerais, Brazil, in 1988. She has been with CEMIG (Companhia Energética de Minas Gerais SA) since 1989, where she has worked as Protection's Engineer in the Operation's Planning Department of Transmission.

Davis Erwin received the B.Sc and M.Sc degrees from New Mexico State University in 1996 and 1998, respectively. Since 1999, Mr. Erwin has been working for Pacific Gas and Electric as a system protection engineer. Mr. Erwin's responsibilities include 500kV EHV Transmission Lines protection and remedial protection schemes. He is also a Registered Professional Engineer in the state of California, USA.

Manish Thakur received the B.E (Hons.) degree from Regional Engineering College Nagpur, India in 1996 and the M.Sc. degree from the University of Manitoba, Canada in 2001.From 1996-1999, Mr. Thakur worked for ABB Network Control & Protection Business Area as a protective relays testing and commissioning engineer. From 2001-2005, Mr. Thakur worked for GE Multilin as a relay application engineer. Mr. Thakur is currently working with American Electric Power as a protection and control engineer in station projects engineering department. Mr. Thakur's areas of interest are Automatic Motor Bus Transfer Schemes, High-Impedance and Ungrounded fault detection schemes, Distribution and Transmission System protection, and Special Protection Schemes. He is also a Registered Professional Engineer in the province of Ontario, Canada and a member of IEEE.

JC (Jacobus) Theron received the degree of Electrical and Electronic Engineer from the University of Johannesburg, South Africa in 1991. Mr. Theron's engineering working experience include from 1992 to 1997 for Eskom (South Africa) as Protection, Control and Metering Engineer, from 1999 to 2002 for GE Multilin (Canada) as Protective Relaying Consultant, from 2002 to 2003 for Alstom T&D (USA) as Senior Systems Engineer and since 2003 for GE Multilin (Canada) as Protection and Systems Engineer, leading the Project and Consulting Engineering team. He specializes in transmission, distribution and rotating machines protection applications support, system designs and transient system testing.