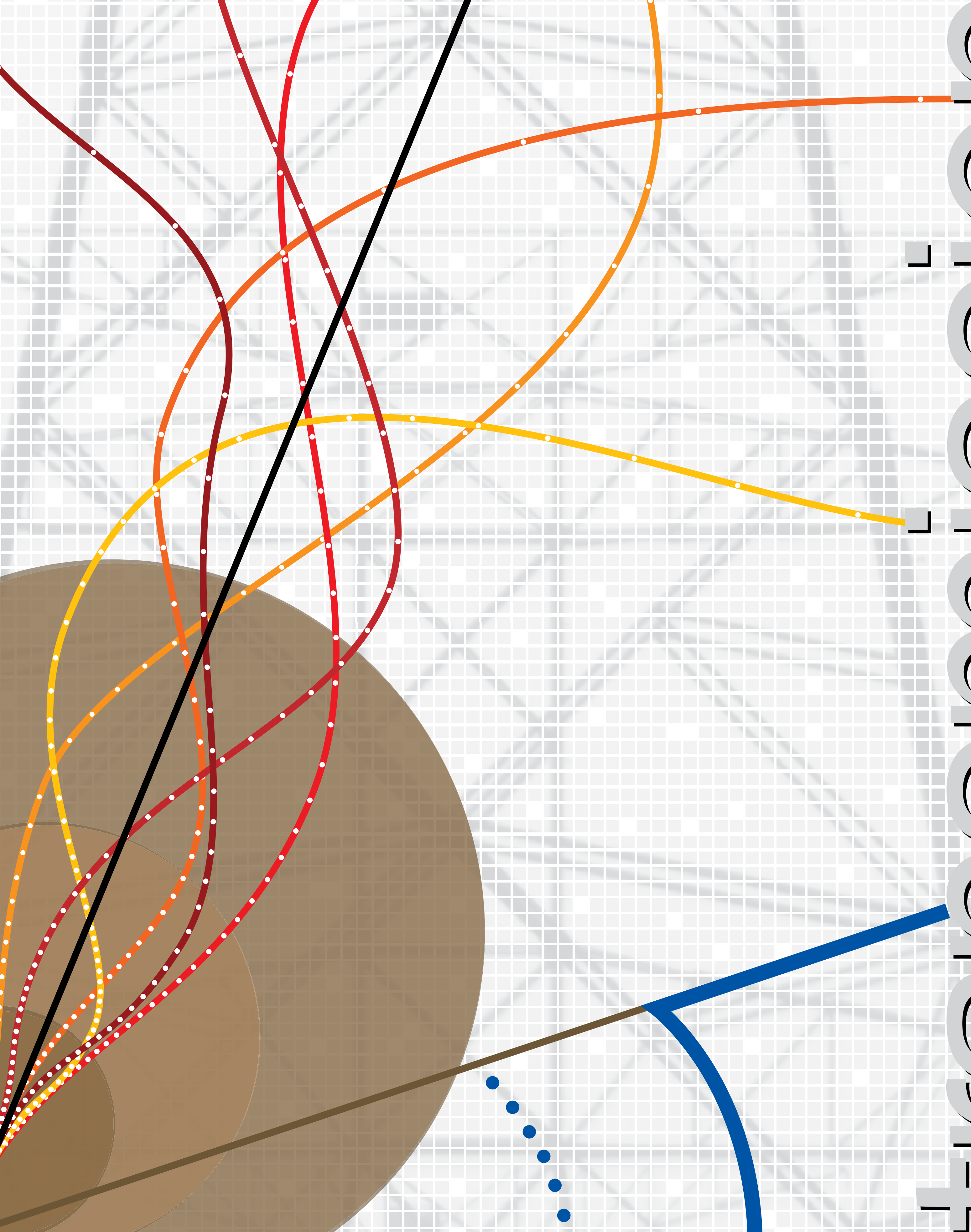


Transmission LINE Protection

doing it right

By Simon Chano, HQT Canada

Hydro-Québec TransÉnergie (HQT) operates the most extensive transmission system in North America. To ensure correct operation of the protection system under many different abnormal conditions, HQT uses redundant sets of protective relaying schemes to improve reliability by increasing the availability of the protection system and follows the NPCC criteria to ensure that protection systems are designed to perform in accordance to high degree of dependability and security.

by Simon Chano, HQT, Quebec, Canada

Each bulk transmission line is equipped with two independent protection systems capable of clearing all faults in the shortest practical time.

Simon R. Chano began his career at Hydro Québec as a protection and automation engineer in 1979. His primary focus has been in the areas of protection settings and relay coordination of EHV, HV, MV and LV networks. He is Senior Member of IEEE and Member of CIGRÉ B5 committee. He served as Chair in many IEEE PSRC working groups and was Chair of the "K" Substation Protection Subcommittee of PSRC.
He is the Secretary and Convenor of several CIGRÉ B5 working groups. He has lectured graduate and undergraduate electrical engineers on various programs with several Canadian universities.

The Hydro Québec Transmision Grid

Hydro-Québec TranÉnergie (HQT) operates the most extensive transmission system in North America. The system comprises 32,826 km of lines at different voltages ranging from 765 kV to 69 kV or less that deliver reliable power from 508 transmission substations and 18 interconnections to customers in Québec, other parts of Canada and the United States. Extreme long 735 kV transmission lines of more than 1,000 km from James Bay and the Manic-Outardes complex deliver a winter peak load of 36,251MW in 2007 mainly from 54 hydroelectric generating stations. Almost 96% of the installed system capacity is from hydroelectric generation serving customers throughout a territory of 850,000 sq. km. To offset the effects of distance between generating facilities and load centers, and maintain in the mean time a reliable and secure system, HQT has installed series compensation on many strategic 735 kV lines to enhance the system robustness . Today, HQT uses different modes of reactive power compensation to control the voltage and employs a multi-terminal direct current link from northern Québec to NEPOOL over a distance of 1,200 km.

Hydro-Québec TransÉnergie within a regulatory context

For the bulk system, HQT must meet all regulatory requirements as per the North American Electric Reliability Council (NERC) and the Northeast Power Coordinating Council (NPCC). NERC sets operating and planning criteria to ensure reliable power system operation. On the other hand, NPCC of which Hydro Quebec is a member, establishes reliability criteria for all power systems in the Northeast. HQT coordinates its activities with the "Régie de l'énergie du Québec" (RÉQ) which has the role to establish or adjust transmission rates and conditions, authorize the acquisition, construction or disposal of transmission assets and study customer complaints regarding application of transmission tariff.

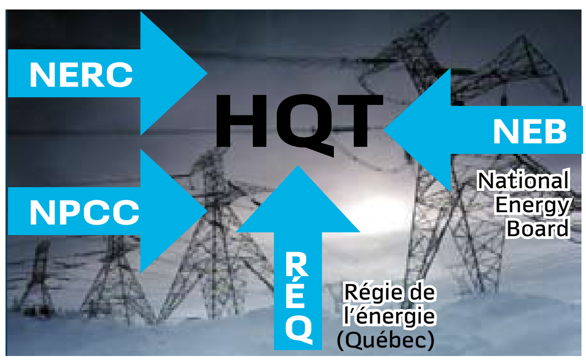
HQT Approach to Bulk Transmission Line Protection

HQT uses redundant sets of protective relaying schemes to improve reliability by increasing the availability of the protection system and follows the NPCC criteria to ensure that protection systems are designed to perform in accordance to high degree of dependability and security. In this regard, dependability is related to the degree of certainty that a protection system will operate correctly when required to operate. Security relates to the degree of certainty that a protection system will not operate when not required to operate. Redundancy at HQT is considered with a special focus on simplicity, operational and maintenance flexibility . Operational flexibility is desirable for maintenance considerations by allowing the transmission line to remain in service with one set of redundant protection out of service.

Implementing the Rules

- Each bulk transmission line is equipped with two independent line protection system capable of clearing all faults in the shortest practical time with due regard to selectivity, dependability and security. The total clearing time of every protection system is coordinated with the stability margins of the network.
- Every protection system should not constitute a loading limitation nor should it be affected by any stable system swings.
- Every protection component including control cables and wiring has physical separation to minimize the risk of disabling both protection systems by fire or accidents.
- Both protection systems " Main 1 and Main 2" are provided in separate panels. They are supplied from separate voltage and current secondary windings.
- Communication channels and equipments associated to both protection systems have physical separation to minimize the risk of disabling both protection systems by a single event or condition. In the early 90's, two different communication paths were used on analog microwave - direct end-to-end path between two substations and a loop path through different substations before arriving to final destination. At the present time, HQT has migrated the majority of its microwave analog communication means to digital microwave radio and implemented optical fiber in order to make better use of these technologies. Physical path separation of telecommunication for both protection systems is possible with optical fibre. However, should the microwave radio tower collapse, a common failure mode will not be avoided.

1 Hydro-Québec within a regulatory context



■ Two station service ac supplies are provided in each substation capable of carrying all critical loads associated with the protection systems.

■ Every protection system is supplied from separate direct current (dc) supply and charger in order to ensure proper operation despite the loss of a single dc source.

■ All circuit breakers for Extra High Voltage (EHV) and Ultra High Voltage (UHV) systems are provided with two trip coils and each independent system protection initiate tripping to both of the breaker's trip coils.

Back-up Protection issues

The term "Back-up" is normally looked at from the point of view of dependability but at the expense of security in the advent of incorrect operation of the primary protection. In normal life, events may cause circuit breakers and associated equipment not to always operate correctly and as a general practice, it is necessary to take some remedial measures to successfully isolate the fault on the system. Back-up is considered as a device that operates independently within a certain coordinated time delay with the associated primary protection functions.

The main protection and the back-up protection may sometimes be provided in a different substation (Remote Back-up) or in the same substation (Local Back-up). In case of Local Back-up, a special consideration is given between substation Local Back-up and Circuit Local Back-up.

Remote Back-up

Remote back-up protection is completely independent of the main local protection devices including their associated current and voltage transformers, auxiliary D.C. supply system and breakers. In general, remote back-up has a certain degree of limitation and requires special considerations regarding the operational strategy of the system. Protection selectivity, sensitivity and speed are some additional factors that need to be considered if remote Back-up is envisioned.

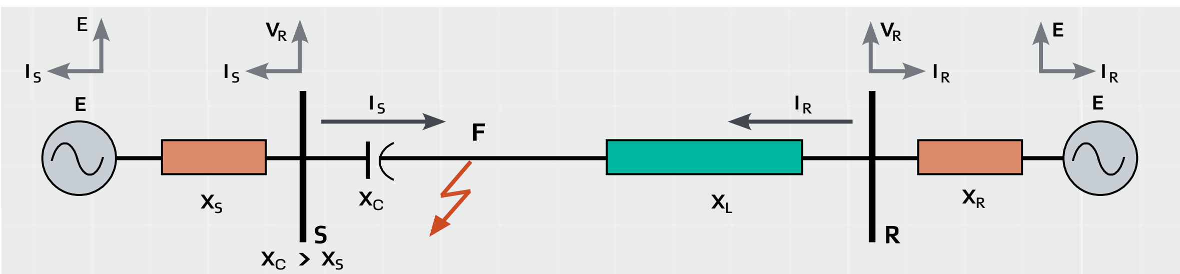
Local Back-up

Local back-up is applied at the local Station to trip local breakers in case the primary protection fail to operate. If the primary relays fail, Local back-up relays will trip the local breakers. Local Back-up offers faster clearing time than remote Back-up and limit CB tripping to one location. Breaker failure protection is initiated locally if CB fail to trip. Local back-up can be subdivided into two groups: Substation local back-up and Circuit local back-up.

Substation Local Back-up Protection

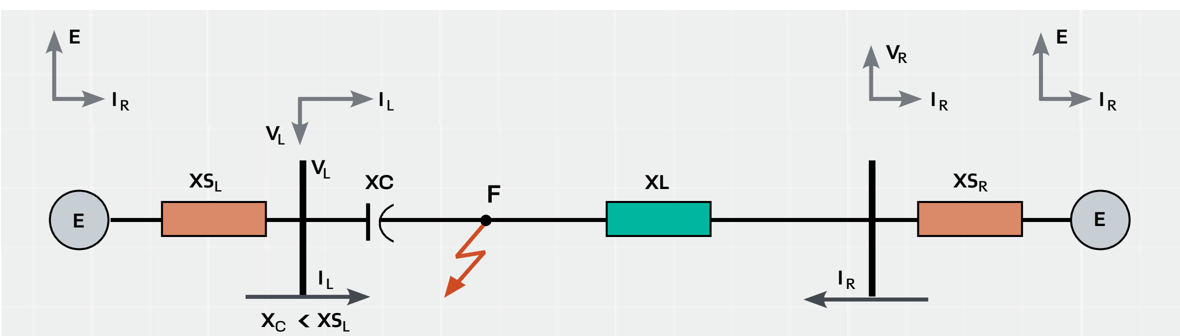
Although powered by the same DC supply of the substation, this form of local back-up protection is similar to remote back-up as it is independent of the primary protection devices including CTs, VTs and other auxiliary trip devices. Substation local back-up offers protection to faults in outgoing transmission lines with certain limitation in meshed networks which constitute short, medium and long lines.

2 Series compensated transmission line - Current Reversal



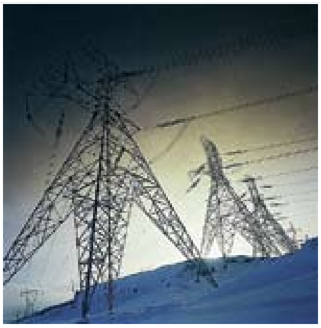
Main 1 Superimposed directional principle | **Main 2** Current differential principle | **Back-up** Impedance measurement

3 Series compensated transmission line - Voltage Reversal



Main 1 Impedance measurement | **Main 2** Phase comparison | **Back-up** Modified impedance

4
Microwave Tower



Circuit Local Back-up Protection

Due to limitations in remote back-up, Circuit local back-up protection operating on different principles or not subjected to the same conditions as the primary protection devices can play a favorable role in the protection of transmission lines. For example, the HQT 735 kV series compensation transmission lines have communication dependent schemes in both main1 and main2 protection devices. In this case, it is important to assume a communication independent Circuit local back-up scheme of a different principal. An impedance based measurement protection scheme is an ideal Circuit local back-up protection in this case.

Breaker Failure Protection

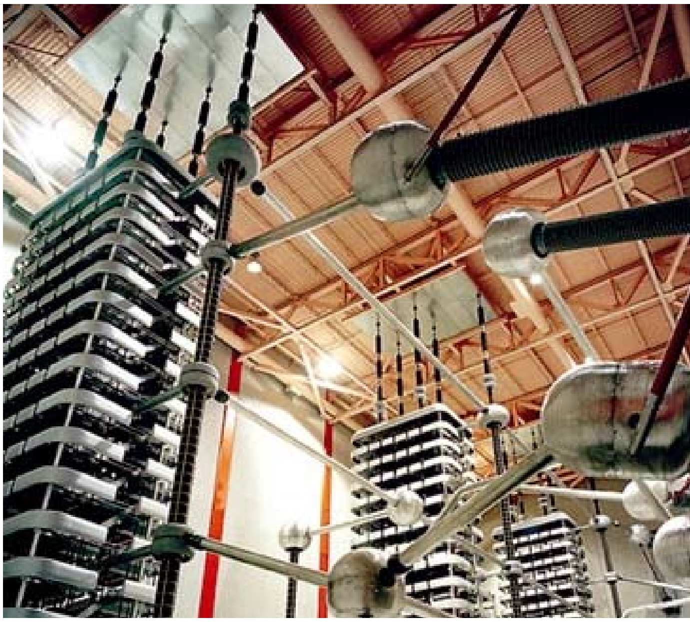
At present, HQT uses one set of independent Breaker Failure protection scheme. This is viewed as part of the Local Back-up protection scheme. The Breaker Failure protection trip the adjacent breakers when the main breaker does not interrupt the fault current. Each of the redundant relaying systems independently initiate the breaker failure function as needed. In general, breaker failure logic based on overcurrent detection is commonly used but in some cases, this function is also achieved by breaker auxiliary switches.

HQT Series Compensated Transmission Lines

Since the early 90's, HQT has implemented series capacitors on the 735 kV EHV transmission system mainly to increase the power transfer capability and improve the system stability. The transmission grid which carries high power over long distances play a key role in areas with bulk power transmission, where power generation plants are more than 1000 km away from load centers.

Based on extensive system studies, series capacitors were mainly installed at one end of the line and in some locations, in the middle of the transmission line. The level of compensation varied between 20 to 44% of the transmission line impedance. Common and crucial issues that need to be considered are in terms of correct relay selection, logic, setting and testing yielding to adequate protection performance. Transient simulator testing was determined to be the most effective approach to study all complex issues in relation to weak in-feed, harmonic and sub-harmonic components, superimposed on fault current waveforms, low frequency current oscillation, the effect of zero sequence mutual impedance of parallel lines, voltage and current reversals, shunt reactor switching and line reclosing are also issues that need to be considered.

Short-circuit currents are also influenced by series capacitors. To protect the capacitor during high levels of short-circuit currents, the series capacitor is protected with air-gaps, metal oxide varistors (MOVs), current limiting devices, and bypass switches. Operation of air-gaps and conduction of MOVs introduce transients and unbalances that must be taken into consideration to ensure that the integrity of the line protection scheme is not adversely affected.



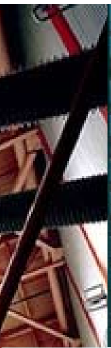
Issues Related to Series-compensated Lines

The effect of series compensation on transmission line distance protection depends on the location of the series capacitors, the degree of compensation, network configuration, and line parameters. The most common effect of series capacitors is voltage reversal. For this reason it is absolutely essential that the line protection use the polarized or the memorized voltage for the determination of the fault direction on series compensated lines.

Figure 3 shows a typical voltage inversion at Bus L assuming a three phase fault with $X_C < X_{SL}$. Current inversion could also take place in a series-compensated network. This takes place when the reactance from the fault point to and including the source reactance is net capacitive. Figure 2 illustrates the condition for current reversal. However, during the TNA simulation studies at the research institute of Hydro-Québec (IREQ), current inversion was not observed due to the level of series compensation together with the ZnO protective arrestors across the series capacitors.

HQT Series Compensated Transmission System Criteria

A strict total fault clearing time is imposed on the HQT series compensated transmission system. All circuit breakers provided for these lines have isolation capability between 33 to 42 ms. All circuit breakers tripping orders are three phase initiation. Reclosing is only permitted on single phase faults. Priority to reclose first on line ends away from series capacitors. All protection and control schemes block reclosing at the remote end of the line when reclosed on permanent faults.



Communication channels & equipment associated to both protection systems should have physical separation.

Series capacitors on the 735 kV EHV transmission system increase power transfer and improve system stability.

Relay Selection

Many relays were put on extensive TNA testing program at IREQ but only two types of Main protections have passed all tests according to the HQT criteria within the timeframe of the testing period. The non-communication based Impedance relays were also carefully evaluated according to the real topology of the series compensated network. For all relays, settings were evaluated in real time testing according to various philosophies and relay characteristics. It was noted that the modified starting unit characteristics of those relays gave good results and restrained from false operations during all type of faults and during normal system switching. See Figures 7, 8.

Superimposed Directional Detection Principle

This principle is based on voltage and current deviation where the incremental impedance ΔZ is computed based on the phasor difference between the voltage during the fault V D and the voltage immediately prior to the fault V A divided by the phasor difference between the current during the fault and the current immediately prior to the fault. The use of superimposed components allows the relay to determine the direction of a fault very quickly, typically in 4 ms. This type of protection is totally communication dependent with the remote terminal of the line and provide ultra high speed tripping if no blocking signal is received from the remote end of the line. The transient change of ΔV and ΔI for a forward line fault initiated on the positive cycle of the voltage waveform will be located in the II and IV quadrant as illustrated in the figure 5. Settings fix the boundaries for the relay to emit a trip signal in the dependent mode to the remote end and to block for normal line and shunt reactor switching. See Figures 5, 6.

Current Differential Principle

The scheme is based on a percentage bias current differential principle, and respond according to the operating and restraining characteristic. This principle passed all TNA tests which included stable and unstable power swings. The integrity of the communications channel is very important for the operation of this scheme. Analog communication channels if used have to be reliable. Digital fiber-optic communication channels are rapidly replacing the analog channels for high-capacity performance and speed. However, communication interfaces and propagation delays between the sending and receiving end of the line gave conclusive results during the early series compensation on the system . This simple current differential technique can be used for all type of series compensated or uncompensated lines regardless of the length of the lines since it is not affected by voltage reversals for faults near the series capacitors nor it is affected by low fault current contribution from the remote end of the line. Adequate settings, proper CT selection, Channel-delay asymmetry, CT saturation and out-feed current are issues worthwhile the attention for this particular scheme.

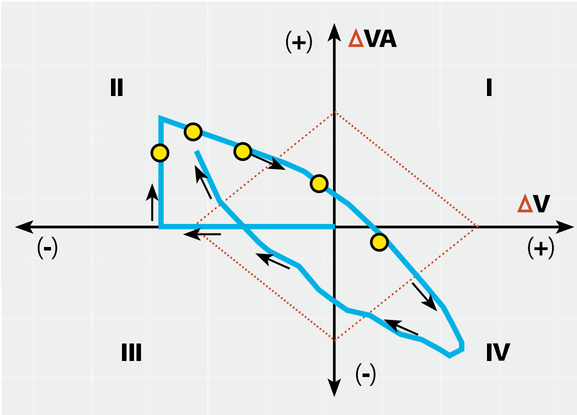
Phase Comparison Principle

The scheme is channels communication dependent. The relay compares the local square wave and the received remote square wave on one half-cycle. A trip permissive signal is asserted only for internal faults. See Figure 9.

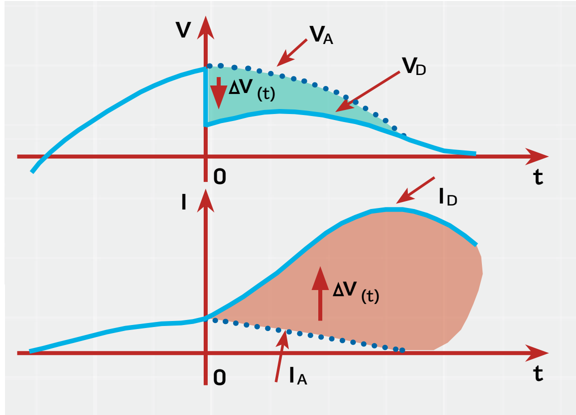
Series compensated lines Back-up Protection

As Main 1 and Main 2 series compensated protection lines are totally dependent on communication channels, an impedance based measurement relay was also selected as a result of TNA testing. The starting element controls the

5 Superimposed directional principle



6 Superimposed voltage and current



measurement elements and has a modified lens characteristic to avoid being sensitive to load and power oscillations. From careful settings, all back-up impedance based measurement relays selected for series compensated lines were stable for all transient conditions and dynamic series compensation issues on the system.

HQT General Guidelines for the 735Kv to 69Kv Transmission Lines

Overhead transmission lines have to be protected against phase and ground faults. Today's HQT practice is to provide two redundant line protection schemes from different manufacturers and in some cases an additional individual back-up scheme. The primary protection schemes are considered as Main 1 and Main 2 or protection "A" and protection "B". The numerical relays are connected to separate CT coils and voltage transformer (VT) coils. Where possible, the tripping signals are sent to separate tripping coils of the circuit breaker (CB). The communication medium is usually by fiber-optic (FO) and digital microwave. There are fewer applications with PLC and analog radio microwaves.

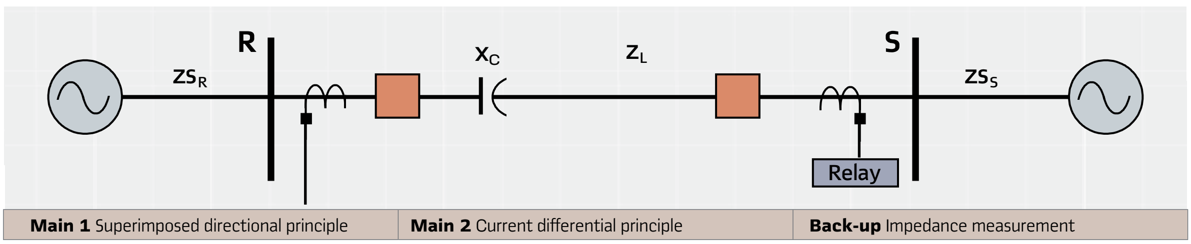
Other multiple adequate schemes could also be envisioned depending on system studies and requirements.

Auto-reclosing Function

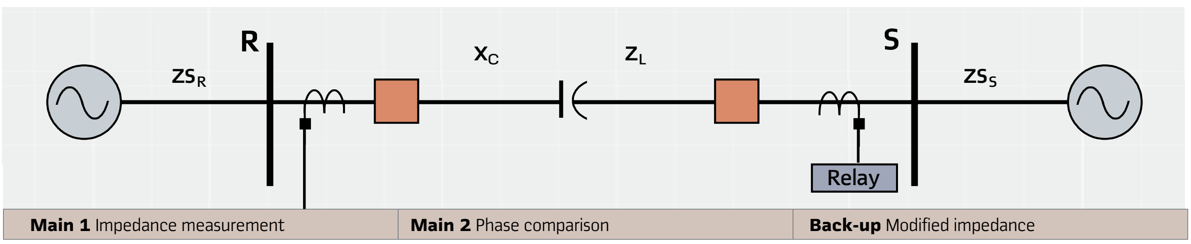
Since the majority of line faults are transient in nature, it is necessary to de-energize the faulted phase and allow for arc de-ionization before initiating a reclose command to circuit breakers. Only three phase automatic reclosing is used on the 735 kV transmission system initiated by single phase fault detection. Depending on certain applications, some principles are used:

The effect of series compensation on transmission line distance protection depends on the location of the series capacitors.

7 Series capacitors installed at the beginning of the line



8 Series capacitors installed at mid section of the line



■ Single phase auto-reclosing is easily achieved by line differential protections, where faulted phase segregation and separate trip outputs are provided.

■ Single phase auto-reclosing is also achieved by permissive under-reach distance protections, provided the use of 4 independent acceleration channels per line protection function. A logic confirming the presence of zero sequence current is conditioned with the acceleration signals.

■ Three phase or single phase auto-reclosing for other high to low voltage transmission system are subjected to system studies. Multi-phase faults could also initiate three phase auto-reclosing in special cases provided that the system is not impacted.

Functional Relay Testing

List of Functional tests for Line protection

The functional testing of protection relays plays a very important role in ensuring their correct operation when installed in the field. The functional tests listed in this article are viewed as specific tests during the process of protection verifications. The inclusion of specific functional tests is typically required in order to verify a specific application on the power system or to verify a specific application based on previous "lesson learned" undesired relay behavior as a result of a disturbance. This functional relay testing list is used by test personnel to define the test program carried on tools such as" Hypersim" transient network simulator and other standard test boxes.

Functional type test implementation strategy

The majority of functional type tests performed on distance relays are based on individual relays. However, certain tests are carried out according to a complete protection scheme to include two distance relays with communications. The latter will be a simulation of a tone unit which includes a certain delay on operation and drop-out. Another method of communication will be to connect a optical fiber between two identical relays using the integrated communication technology within the protection devices.

Functional testing plays an important role in ensuring correct protection operation.

List of functional tests

During the tests for internal and external faults, closing and drop-out contact time are measured for all type of distant position faults. Fault incidence angle is varied (ex. 20 faults/cycle; every 18 deg.) and the tests are performed for: Short Lines; Long lines; Strong or weak sources ; Mutual coupling lines; Series compensated lines; CT and CVT models, etc. Other tests are performed to verify: SOFT; Fuse Supervision; Resistive faults; Evolving faults; Reclosing on permanent faults; reclosing logic functions; "Weak- infeed" logic; Instantaneous overcurrent to verify speed, sensitivity, directionality and hysteresis. Also included in the test program are the following functions: Current reversal; SIR; Load encroachment logic; CT Saturation ; Harmonics; Breaker failure; Phase discrepancy; Power oscillation; Fault Location; Overvoltage/Undervoltage detectors; Current Supervision; Grounding tests, Frequency tests; CVT Modelling; Three terminal lines with outfeed, etc.

9 Phase comparison protection - Internal fault condition