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BC Hydro Protection Applications for 500 kV Shunt Reactors

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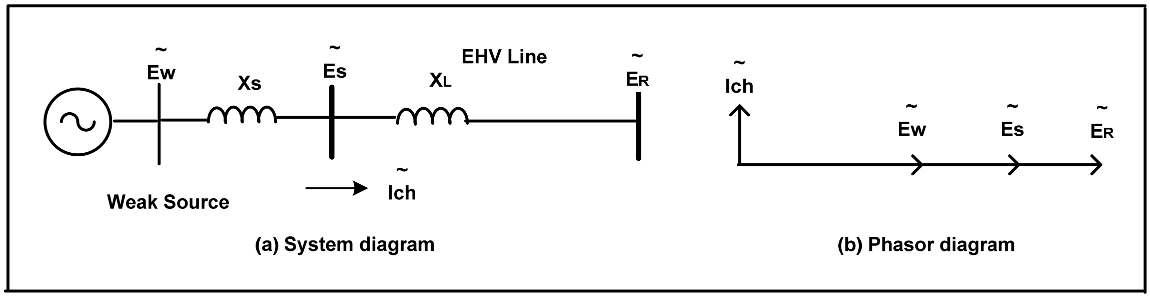
Abstract: This paper summarizes the major BC Hydro 500 kV reactor protection application considerations with an emphasis on turn-to-turn faults and the Inrush Tripping Suppression (ITS) feature that avoids false tripping by sensitive protection elements on reactor energization. It reviews several aspects of 500 kV reactor protection principles, such as criteria for setting ground protection to override magnetizing inrush currents into the reactor and reactor contribution to protection external faults. This paper highlights the implementations of these protection requirements in a multifunction relay, with detailed descriptions and logic diagrams.

I. INTRODUCTION

Shunt reactors are used in power systems to compensate for the effects of high charging currents of long transmission lines and cables. Under light load conditions, these charging currents can result in excessive high voltages. A short transmission line may also require shunt reactors if the line is supplied from a weak source. When the remote end of line is open, the capacitive line-charging current (Ich) flowing through the large source inductive reactance (Xs) causes a rise in voltage (Es) at the sending end of the line [3]. Refer to Fig. 1.1.



(a) System diagram

(b) Phasor diagram

Fig. 1.1 EHV Line connected to a weak system

II. REACTOR FAULTS

The principal hazards to a reactor are similar to that for a transformer: phase or ground faults from insulation failure, bushing failures, turn to turn faults within the reactor winding, loss of oil, and loss of cooling. These failure modes can be grouped into three broad categories:

- Faults resulting in large changes in the magnitudes of phase currents.
- Turn-to-turn faults within the reactor winding, resulting in small changes in the magnitude of phase current, but (possibly) a measurable change in zero sequence current.
- Non-electrical failures such as low oil and loss of forced cooling which result in no immediate change in electrical parameters.

Given the existence of the third category above, it is not possible to provide complete protection to the reactor without the inclusion of non-electrical trip devices. These devices typically include low oil level, high oil temperature, sudden gas pressure and pressure relief. Of these, the sudden pressure device is the most controversial within BC Hydro. An analysis of sudden pressure relay performance on reactive equipment within BC Hydro [2] concluded that of 217 sudden pressure relay operations recorded over a 20 year period, 190 of them (87.6%) were misoperations. While BC Hydro has decided to disconnect sudden gas pressure relays on transformers. A similar decision is not possible for shunt reactors. However, the known insecurity of sudden pressure relaying is still driving us to attempt to obtain complete coverage from electrical protection.

Electrical protection, including differential and overcurent phase and ground protection detects faults resulting in changes in the magnitude of current. Non-electrical protection including gas and temperature detector provides protection for arcing faults and high temperature of the oil or the windings. Both electrical and non-electrical protections are connected for tripping.

For illustration, Fig. 2.1 shows the response of electrical and non-electrical protections for the numbers of reactors faults within the BC Hydro system. [2]

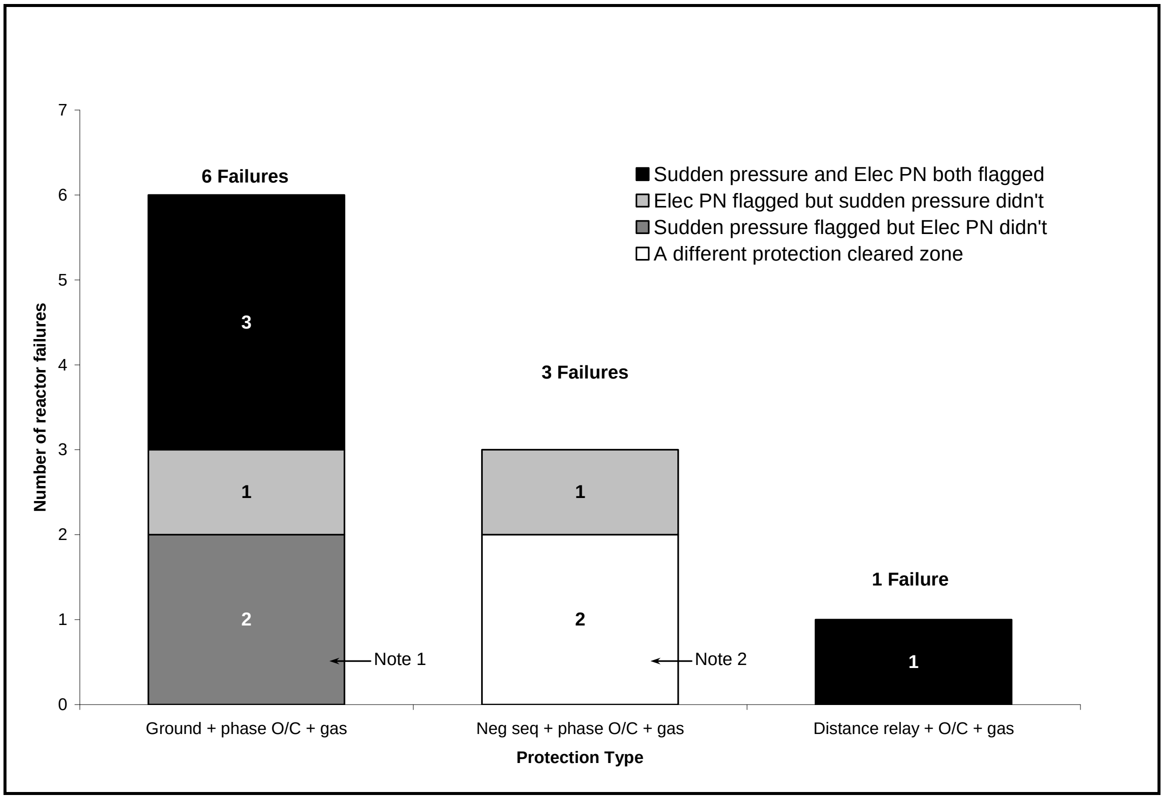


Fig. 2.1 Reactor dependability analysis

Notes:

1. The reactor failure for which only the sudden pressure relay flagged involved a winding fault on a 230 kV shunt reactor.
2. The two reactor failures for which neither the sudden pressure relay nor the electrical protection flagged involved core grounds which were detected by a gas accumulation relay.

The above statistics indicate that both, non-electrical and electrical protections are needed to provide a dependable protection scheme for reactors. Even though the sudden pressure relay is the only sensitive relay element that trips instantaneously, BC Hydro believes it should be supplemented with an electrical protection scheme that is secure, sensitive and dependable. Security problems with the electrical protection proved to be a challenge. As a result, BC Hydro protection engineers have had to apply a carefully crafted combination of delayed tripping and inrush trip blocking to the sensitive directional overcurrent ground protection.

III. SHUNT REACTOR CONNECTION TO 500 kV BC HYDRO SYSTEM

Most shunt reactors in the BC Hydro system are permanently connected through a switching device (a disconnect switch or a circuit breaker) at the ends of 500 kV transmission lines to limit fundamental-frequency temporary overvoltages and energization overvoltages (switching transients). Refer to Fig. 3.1.

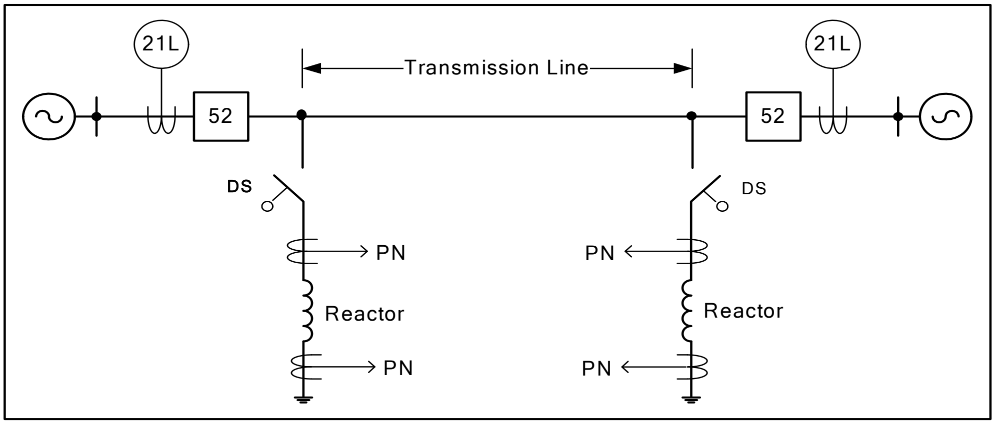


Fig. 3.1 Shunt Reactor connected to EHV Line

In some circumstances, additional reactors connected to the 500 kV bus or the tertiary windings of adjacent transformers are used to maintain nominal voltage under light loads. These reactors are switched on/off automatically via local control schemes and remedial action schemes (RAS). Usually, the switching devices applied to shunt reactors do not have fault current interrupting capability due to extreme TRV requirements needed to successfully clear certain winding to ground faults.

In addition, the neutral of all 500 kV reactors in BC Hydro system are connected to ground – either directly, or using a neutral reactor (possibly with surge arrestors). Refer to Fig. 3.2. Neutral reactors aid in secondary arc extinction on single pole tripping (SPT) lines by compensating for the interphase capacitance between the open phase and the two live phases. The impedance and voltage rating of the neutral reactor are based on the shunt capacitance of transmission line and are determined by EMTP studies.

The neutral reactor is only exposed to significant potential for brief periods during single pole tripping. In addition the available fault current for a neutral reactor fault is limited by the impedance of the main reactor. Therefore, the neutral reactor protection only generates an alarm.

Due to 500 kV shunt reactor being line connected without a dedicated fault current interrupting device, operation of the reactor protection trips the associated line and blocks auto-reclosing.

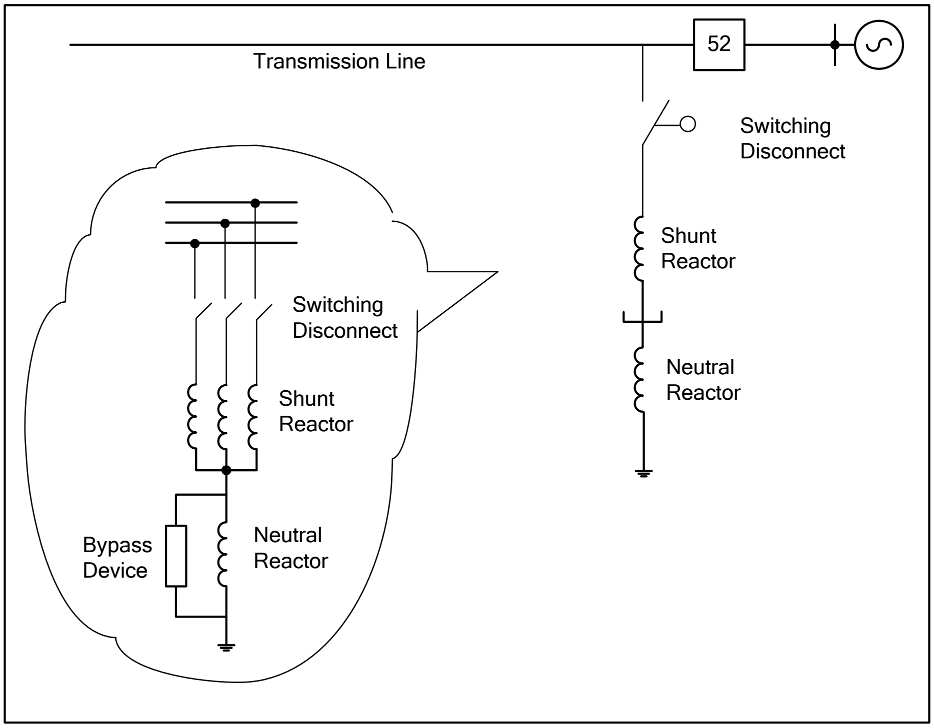


Fig. 3.2 Shunt Reactor connected to ground via Neutral Reactor

IV. CHALLENGES IN SHUNT REACTOR PROTECTION

The protection of shunt reactors presents a number of challenges to the protection engineer.

1. Turn to turn faults in shunt reactors may result in very small operating quantities to the relaying. In addition, shunt reactor differential relays can not detect a turn to turn fault. Therefore a different technique is needed to detect turn to turn faults.
2. Shunt reactors typically have gapped cores to reduce inductance and therefore increase VAR absorption. This manifests itself as very mild saturation and relatively low inrush levels. The inrush levels have very low 2nd harmonic levels, which precludes the use of harmonic restraint to block sensitive elements during inrush conditions.
3. The inrush waveform for shunt reactors tends to have a high X/R ratio, which causes eventual (and not necessarily symmetrical) saturation of the phase CTs. The problems this causes will be listed later.
4. Shunt reactors are often line connected. When the line is deenergized, the stored energy in the line shunt capacitance and the reactor inductance oscillates at a frequency which can be calculated as $60 \cdot \sqrt{\frac{\mathrm{Re\,actorVARS}}{\mathrm{LineVARS}}}$. In most cases, the line shunt capacitance is not fully compensated, which results in the line ringing at a frequency < 60 Hz. This will often result in reactor current increasing (due to the reduced impedance of the bank at the lower frequency) after the line trips. This oscillation may have a zero sequence component. In cases where the line has single pole tripping, the open phase will oscillate (with coupled 60 Hz from the other two phases).

V. LEGACY BC HYDRO PROTECTION SCHEME FOR SHUNT REACTOR

In the absence of references that deal in detail with the dependability and security of turn-to-turn fault detection methods, BC Hydro engineers spent considerable time analyzing reasons for protection misoperations and developing ways to avoid them.

The basic protection philosophy for EHV reactors in the BC Hydro system is to provide protection for all possible faults using electrical and non-electrical devices. For illustration, Fig. 5.1 presents a typical EHV reactor protection one line diagram.

The most challenging aspect has been the development of a turn-to-turn detection scheme that is sensitive enough, yet secure against misoperation due to switching transients and external faults.

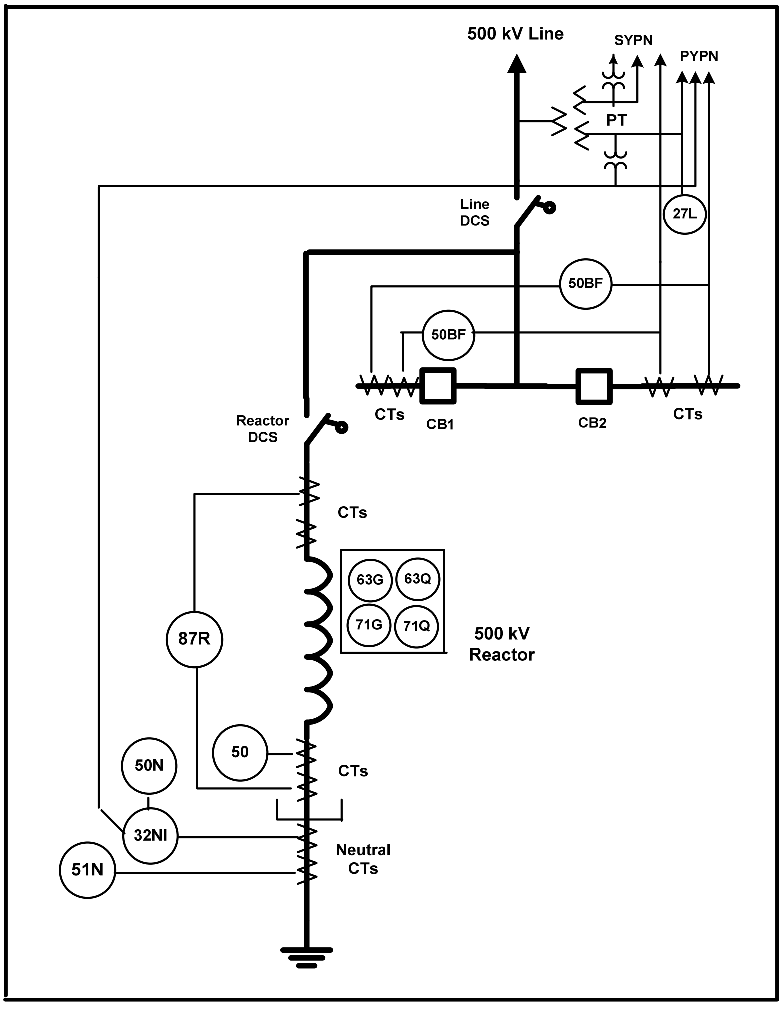
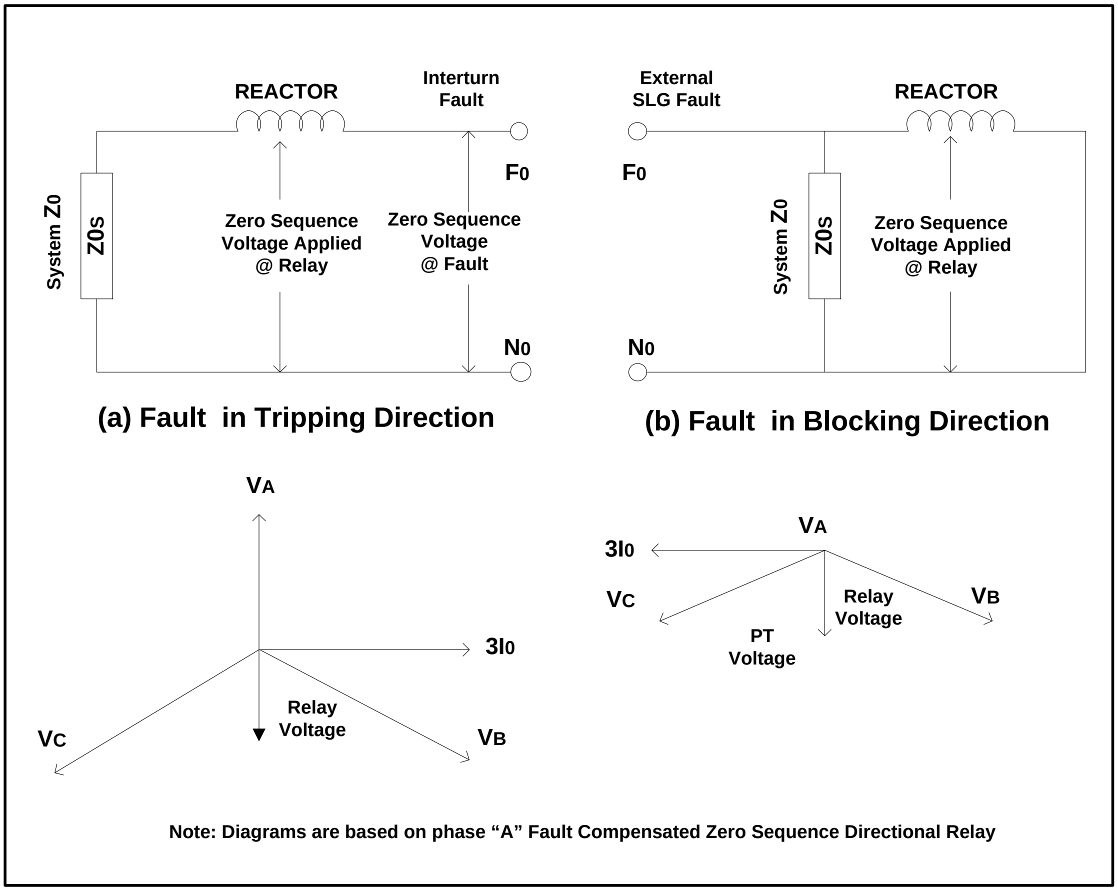


Fig. 5.1 EHV Reactor Line Connected Protection One Line Diagram

Differential protection connected to reactor supply-side and neutral-end CTs has been applied as a primary protection for faults between windings of different phases, winding-to-core or winding-to-tank faults.

Turn-to-turn faults result in through fault currents that can not be detected by differential protection. These faults result in both a reduction of impedance of the phase involved and a circulating fault current which adds to the phase current through transformer action. If the reactor neutral is solidly grounded, this reduction in impedance causes an increase in current magnitude in the affected phase, resulting in a zero-sequence current flowing through the neutral to ground. Based on this, measurement of phase impedance or zero-sequence current has been used for detection of turn-to-turn faults in grounded reactors.

BC Hydro’s preference is to detect turn-to-turn faults using a directional neutral current relay (Device 32N). The basic operation of this scheme is shown in Fig. 5.2.



Note: Diagrams are based on phase “A” Fault Compensated Zero Sequence Directional Relay

Fig. 5.2 Compensated Zero Sequence Directional Relay for turn-to-turn faults

Device 32N is directionalized to detect zero-sequence current flow into the reactor for turn-to-turn faults. This device will not operate for external ground faults (e.g. bus or line). A setting of about 5-10 % of reactor rating is applied. Tripping is slightly delayed by the tripping timer, and further supervised by Inrush Tripping Suppression (ITS) logic. ITS will block the ground overcurrent tripping on deenergization of the reactor and will retain the blocking function for a few seconds after energization.

The relay is connected to a neutral CT to avoid the risk of undesirable operation due to unequal saturation of the three phase CTs during reactor energization.

Inverse time neutral overcurrent relay 51NT is utilized as a backup protection in addition to non-electrical protection.

- Inrush Tripping Suppression Logic

Inrush current is associated with energizing of reactors. Transient currents larger than the reactor rated current can flow when a reactor is first energized. The reactor protection should remain stable, i.e. not operate, during the inrush transient conditions. Thus, BC Hydro developed the so called Inrush Tripping Suppression (ITS) logic. ITS is intended to block tripping from the most sensitive ground overcurrent protection when the reactor is switched in and for a short period thereafter in order to allow for inrush to subsidize. Tripping for this sensitive element should also be blocked when the associated line is deenergized.

VI. PRESENT BC HYDRO PROTECTION SCHEME for EHV REACTORS Using MULTIFUNCTIONAL PROTECTIVE DEVICES

BC Hydro presently uses multifunctional devices for shunt reactor electrical protection. These devices include phase, ground and neutral overcurrent elements. Neutral overcurrent elements are connected to CTs in the neutral of the reactor, while ground overcurrent elements derive their zero sequence quantity from phase CTs on the source side of the reactor. Fig. 6.1 presents a recent BC Hydro protection one line for a 500 kV shunt reactor. Even though the basic philosophy of shunt reactor protection in the new scheme is the same as used in the legacy scheme, using multifunctional relays offers more flexibility by virtue of the inclusion of several elements with different operating principles and the ability to program them to achieve a specific function. Fault records are an additional advantage of using modern multifunctional relays.

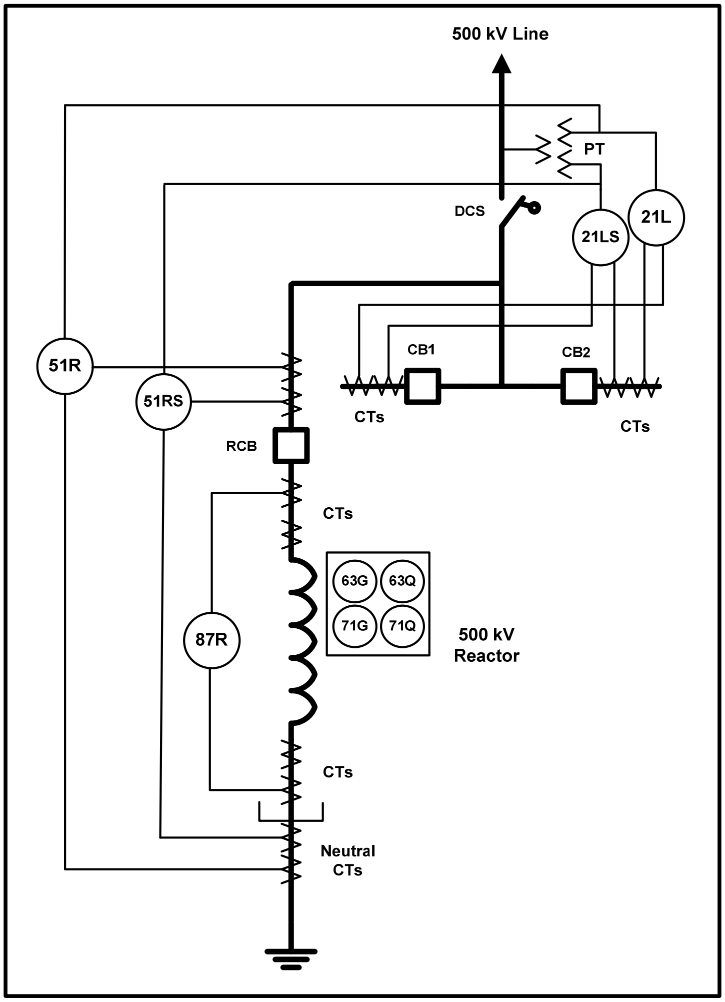


Fig. 6.1 Present BC Hydro Protection One Line for 500 kV Shunt Reactor

Differential protection provides the primary protection for multiphase faults. It also provides sensitive protection for winding-to-core and winding-to-tank faults.

Phase overcurrent protection is used for large magnitude multi-phase internal faults. Pickup of the inverse time phase overcurrent is set to start at 120% of reactor rated current. It is assumed that the voltage applied would never be more than 120% of nominal voltage for long enough to allow the overcurrent element to time out. BC Hydro applies overvoltage protection on the 500 kV system set at just less then 120% of nominal voltage with a short time delay that will trip before 51P protection. The very inverse time characteristic curve is selected to provide at least 1.6 second delay at 1.5 x pick up (i.e. 1.8 times reactor rating).

Instantaneous phase overcurrent element to provide fast protection for high magnitude faults. This instantaneous element is set above the maximum current than can flow in the reactor during transient conditions (usually set at two times reactor rated current).

Medium set- Instantaneous phase overcurrent element (50P) is used in Inrush Tripping Suppression (ITS) logic and is set at 80% of reactor rated current.

Instantaneous Neutral ground overcurrent element (50N)

The directional neutral ground scheme in a multifunctional relay is provided by the 50N element connected to reactor neutral current transformer (CT) and controlled by a zero sequence voltage polarized directional element connected to the source side of the reactor looking into the reactor. The relay is directionalized to see zero sequence current flow into the reactor. Its main purpose is to detect turn-to-turn faults. This device will not operate for external faults (faults out of reactor zone) such as line to ground faults. Again, refer to Fig. 5.2. The setting of this element is about 5-10 % of reactor rating. This setting could be slightly desensitized because of the directional element's sensitivity. 50N is connected to a separate neutral CT to avoid the risk of undesirable operation due to unequal saturation of three phase CTs during reactor energization.

Tripping from the 50N element is time delayed by 15 cycles and supervised by ITS. Time delay of 50N is necessary to avoid race between reset of ITS logic and transient pick up of the 67N element.

Fig. 6.2.and Fig. 6.3 shows the current flow into reactor during reactor switch in and line deenergizing respectively.

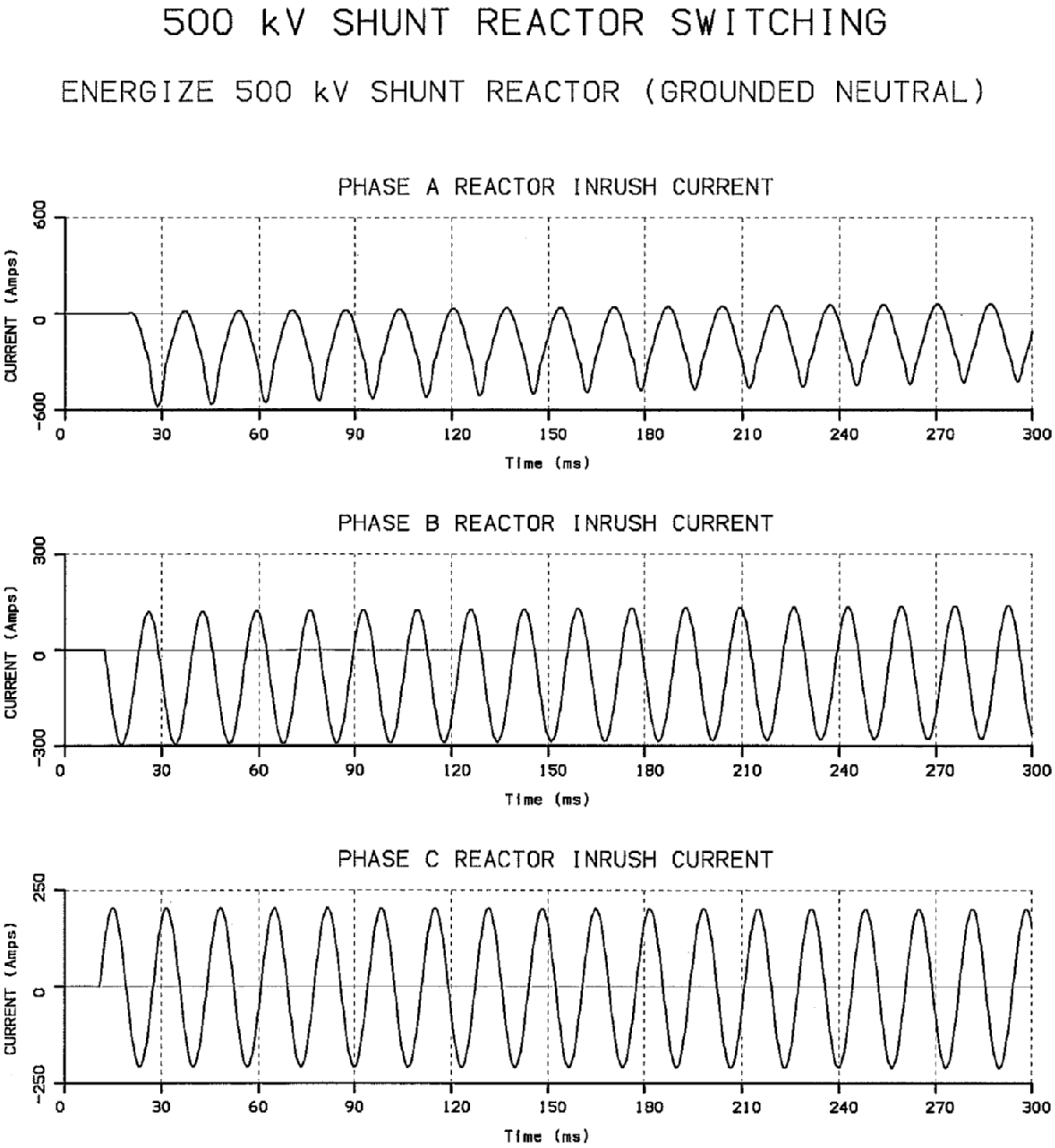


Fig. 6.2 500 kV Shunt Reactor Energization Currents

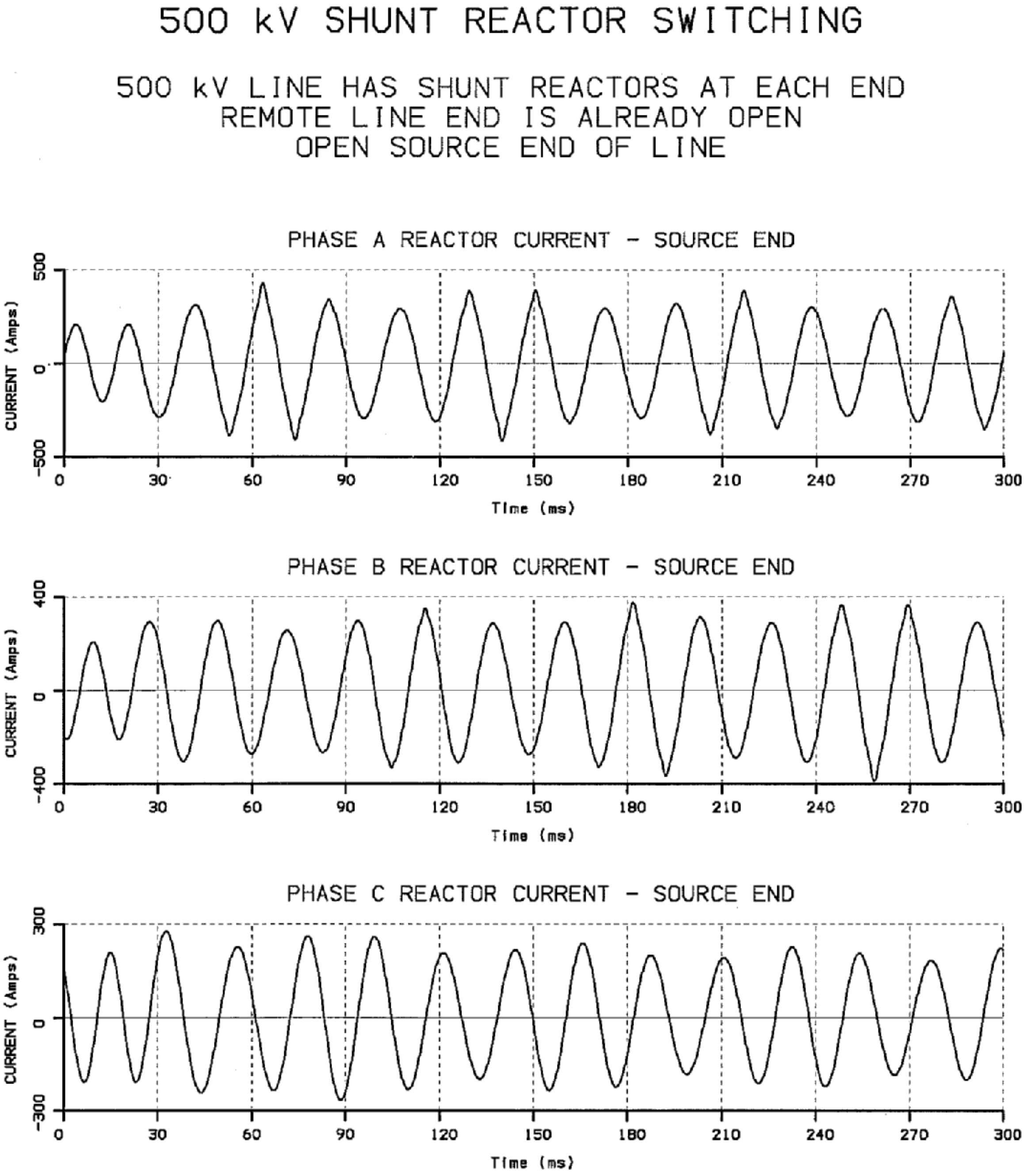


Fig. 6.3 500 kV Shunt Reactor De-energization Currents

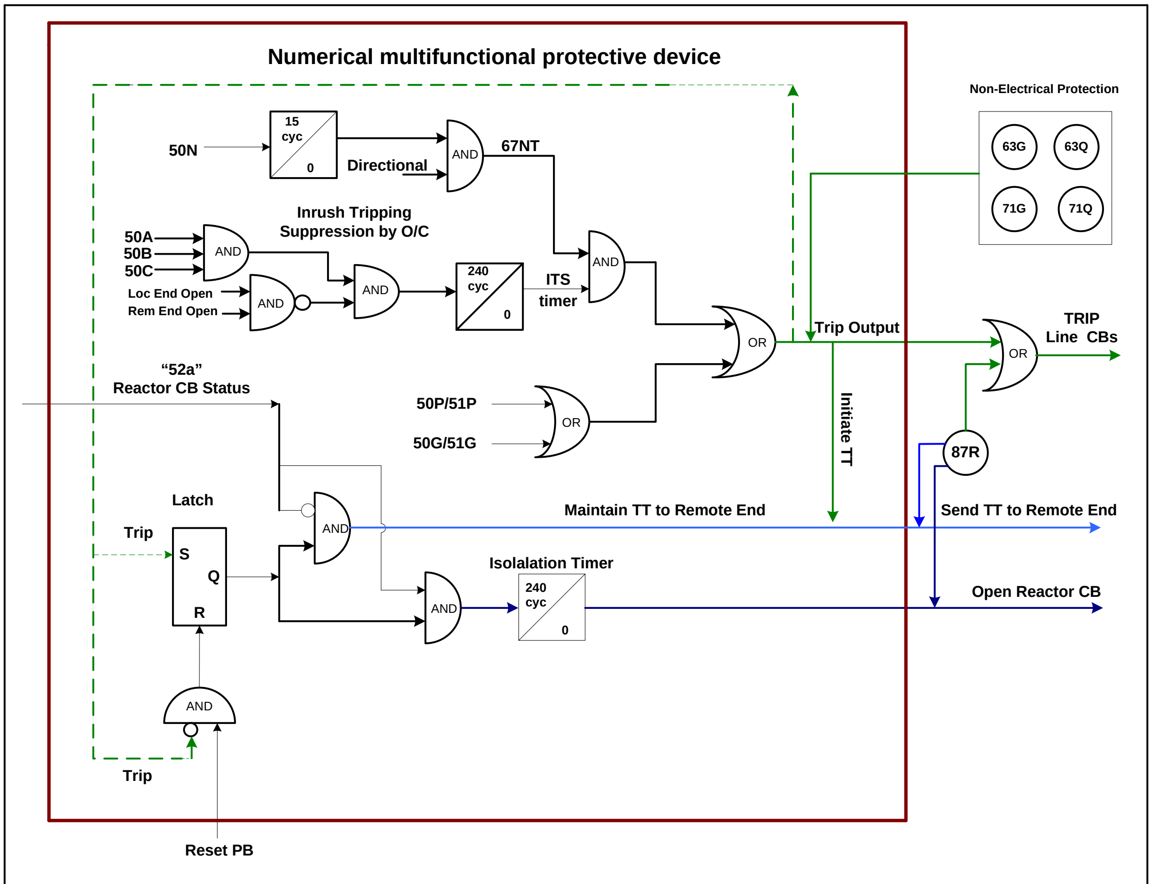
Inrush Tripping Suppression Logic

Inrush current phenomenon is described above in section V. In new protective devices, the logic for inrush tripping suppression to block turn-to-turn fault protection is provided internally in the multifunctional protective device used as a reactor protection.

ITS will block the ground overcurrent tripping on deenergization of the reactor and will retain the blocking function for a few seconds after energization.

The phase overcurrent element used for ITS is set to 80% of reactor rated current, and is used in combination with line status and time delay of 240 cycles. Refer to Fig. 6.4.

Inrush tripping suppression logic can also utilize line voltage measurements to detect energizing and deenergizing of the line. This can be more secure on highly compensated lines, since reactor current may increase on deenergization as the line resonates at below nominal frequency. The additional security may be offset by the requirement to add additional logic to account for the state of switching devices which lie between the VT and the reactor.



Note:

50 elements measure reactor current

See Fig. 6.1 for system one line diagram

Fig. 6.4 Present Logic Diagram for Protection of 500 kV Line Connected Shunt Reactor utilizing multifunctional protective devices

Logic to detect single phase flashover or incomplete close of Reactor Switching Device

Additional logic is developed in the same device to detect single phase flashover or incomplete close of reactor switching device. The intent of this function is to trip the reactor by means of a phase overcurrent function if there is current flowing in any phase (50A OR 50B OR 50C) when the auxiliary contact of the switching device indicates that it is open. This is intended to guard against flashover across the switching device head. Refer to Fig. 6.5.

Fig. 6.5 illustrates the breaker flashover or long pole discrepancy protection applied on 500 kV reactors in BC Hydro. This logic will trip line circuit breakers and isolate the reactor if the protection detects current flow through the reactor during a switching off condition.

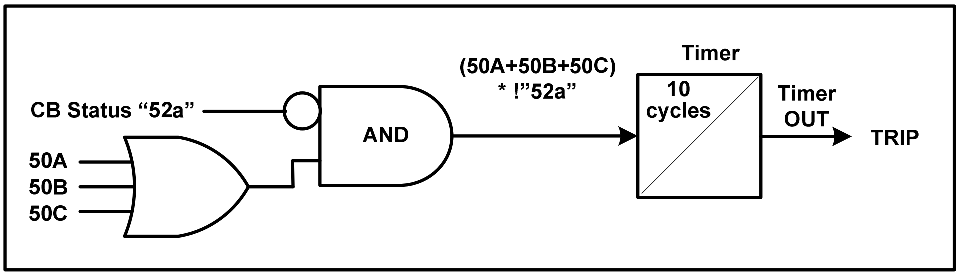


Fig. 6.5 Reactor Breaker Flashover or Incomplete Operation Logic

This logic was easily implemented because of the availability of elements in the multifunctional relay.

VII. REACTOR TRIPPING and ISOLATION SCHEME

If the reactor position is shared with a line, local tripping will no longer be sufficient to clear the fault and a direct transfer trip (DTT) from the reactor terminal will be required to trip the remote terminal of the associated line.

Protection tripping for reactor (similar to transformer) is lock-out tripping, to prevent re-energization of the reactor unless a visual inspection of the reactor takes place and the lock-outs are hand reset (in legacy protection schemes). Lock-out tripping is accomplished by close blocking of all tripped CBs and open MODSs in the reactor isolation zone. For those CB's tripped, which are not part of the isolation zone, block closing is maintained until the associated isolating MODs are open. The DTT is also maintained until the reactor is isolated.

With modern relays, BC Hydro implements the isolation scheme logic redundantly inside both the protection devices.

VIII. NON-ELECTRICAL PROTECTION

Notice that non-electrical protection devices are generally provided as accessories of the reactors. These devices are connected for trip purposes to the inputs of device 51R illustrated in Fig. 6.4.

IX. SUMMARY

BC Hydro is experience with EHV shunt reactor protection indicates that developing a sensitive electrical protection is necessary to complement the non-electrical protection devices supplied with the reactor. The paper describes the challenges encountered in developing the electrical protection schemes and how it was overcome, mainly with the development of the inrush tripping suppression logic. The paper also shows the advantages BC Hydro sees in using modern protective devices because of the flexibility they offer in providing additional protective functionalities.

X. References

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Biographies:

Meliha B. Selak is a Specialist Engineer in the Protection and Control Planning group of BC Hydro. An electrical engineering graduate of Sarajevo University, she joined Energoinvest Corporation in Sarajevo in 1975. She then worked as a research and consulting engineer in the field of power system engineering on a variety of international projects. Prior to joining BC Hydro in 2000, she worked as a research engineer in the Power System Group at the University of British Columbia on Real-Time Power System Simulator (OVNI) in connection with EMTP. Her technical activities include power system protection and control applications, power system analysis, evaluations and interconnection studies for the various plants connecting to the power system, as well as development of protection guidelines. She has authored or co-authored several technical papers on power system protection and EMTP studies. She is active in the IEEE Power & Energy Society.

Ralph P Barone is a Senior Engineer in the Protection and Control Planning group of BC Hydro. He graduated from the Electrical Engineering program of the University of British Columbia in 1988 and joined BC Hydro the same year. During the past 20 years he has been involved in HVDC control maintenance and technical support (including starting a mailing list for HVDC support staff), maintenance and operational support for transmission system protection systems (including analysis of several large scale protection misoperations) and specification and setting creation for new protection systems. He is a senior member of the IEEE.

Ahmed F. Elneweihi is a consultant in the protection applications field. He worked for BC Hydro for 34 years before he took early retirement in 2005 to work as a consultant. The last 30 years of his experience in Hydro has been in the Protection and Control Planning Department where he progressed to the specialist engineer level, then was the manager of the department for the last four years before his retirement. He was active in the Power System Relaying Committee of IEEE where he was a member, vice-chair, and a chair of several Working Groups that produced papers, Special Publications, and Guides in the protection of electrical equipment. He has authored and co-authored several WPRC and IEEE papers in a wide variety of protection applications.

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