APPLICATION OF NUMERICAL RELAYS FOR HV SHUNT REACTOR PROTECTION

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ABSTRACT

Viewed in the substation yard, an HV, oil immersed, shunt reactor does not differ much from a power transformer, but in reality it is not that simple. There are distinct differences between construction and operating characteristics of these two devices.
In order to explain the properties of shunt reactors numerous current and voltage waveforms either captured as disturbance recordings in the field or simulated by ATP [8] will be presented. On all these figures the nomenclature for current and voltage signals, as shown in Figure 1 below, will always be used.

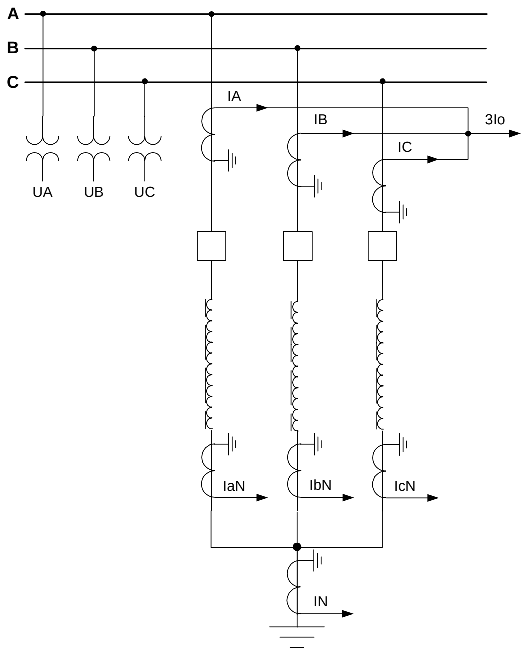

FIGURE 1: Shunt Reactor I & U Signal Definitions

INTRODUCTION

HV, oil immersed, shunt reactors are the most compact and cost-efficient means to compensate reactive power generation of long-distance, high-voltage power transmission lines, or extended cable systems during light load conditions. Two main application of the reactor can be identified as:

- Shunt reactors that are continuously in service, generally used for EHV and long HV lines/cables
- Switched shunt reactors are applied in the underlying system and near load centers

It is common for shunt reactors to be installed at both ends of EHV lines, and sized to prevent the line voltage from exceeding design value when energized from one end. Since there is usually some uncertainty as to which end of a line may be energized (or de-energized) first, shunt reactors are usually installed at both line ends.

Shunt reactor design principles

Two different ways are used in building reactors, commonly referred to as "gapped core" and "coreless" [1] & [2]. The gapped core reactor has a subdivided limb of core steel with airgaps inside the winding – and no limb at all for the coreless concept.
It is easy to verify that the gapped core concept becomes more advantageous as the loss evaluation rate increases and particularly at higher system voltages. This is due to the higher energy density that can be achieved in a gapped core reactor compared to a coreless reactor.

SHUNT REACTOR OPERATING CHARACTERISTICS

Linearity

For normal operating voltages there is a linear relationship between applied voltage and reactor current (i.e. a small increase in voltage will result in a proportional increase in current). The deviation from a true sinusoidal shape in line voltage is in general negligible for normal operating voltages.
As the magnetic flux to a great extent has its path in magnetic core steel the core steel will get saturated for flux densities above a certain level, the saturation point. Once above the saturation point big excitation current is needed to further increase the flux density.

Harmonic content

Steady state harmonics in reactor current arise from partial saturation in the magnetic circuit. These effects are in fact very small, and without practical importance for relaying. Of all harmonics the third harmonic will be the most dominant. In the reactor neutral the third harmonics in the three phases add together and act like a zero sequence current.

Asymmetry between phases

The tolerances on asymmetry between phases of a three-phase reactor or between single-phase units forming a three-phase bank can be judged by the amount of residual harmonics. The result is a zero sequence current in the neutral connection. Standards are realistic, but better tolerances are possible to achieve. A usual figure is 0.5 %.

HV SHUNT REACTOR SWITCHING

The switching in of a shunt reactor gives rise to inrush current – a transient phenomenon related to saturation in the shunt reactor magnetic circuit. In principle, it is the same story as inrush current of a transformer, but there are differences. A reactor core keeps no remanence, because of the air gaps, which makes the whole thing easier. However, the damping of the asymmetric condition –"the dc component" – is slow, due to the inherent low losses in a shunt reactor. It is therefore necessary to keep this phenomenon in mind when designing the relay protection system for HV shunt reactors.

The instantaneous current values during shunt reactor switching in can be visualized from Figures 2 & 3. Input data for all figures in this chapter are obtained from actual disturbance recordings in the field. Depending on the switching instant the currents might have a long lasting dc component. The worst condition is when the reactor phase is closed in at zero voltage. The flux will increase with the voltage-time-area during the first voltage half-cycle to a value twice the maximum flux in normal operation. The current is proportional to the flux density, until reactor core saturation occurs. Above the point of saturation the current will increase faster than the flux. Without saturation, the first peak of the current with full dc offset would be 2,82 times rated current. The actual current peaks might rise to a value in between 3 and 5,5 times depending on the particular shunt reactor design details. Such time intervals, when reactor core goes into saturation, are clearly visible in current IB in Figure 2. The time to more or less fully balanced operation around zero flux in the core may be fairly long often in order of seconds, but such condition is of no harm for the shunt reactor itself.

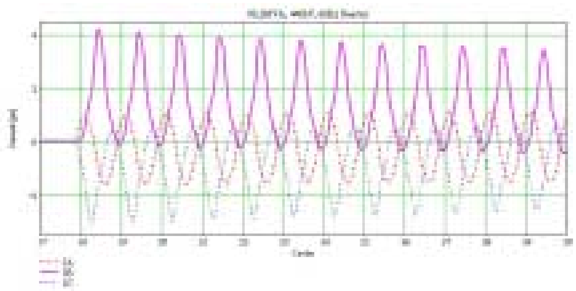

FIGURE 2: Shunt Reactor Phase Inrush Currents

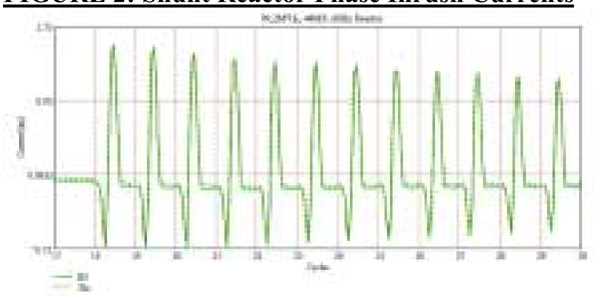

FIGURE 3: Shunt Reactor Neutral Inrush Current

For a three-phase reactor the different phases will experience different degrees of dc offset. The combination of the individual phase current offsets will give a neutral current rich in harmonics and also with possibly dc offset from the zero line as shown in Fig. 3

In recent years, so-called point-on-wave closing relays are available from switchgear manufacturers. By using these relays switching of different power system devices, including shunt reactors can be performed without a disturbance to the rest of the power system (see Figures 4 & 5).

NUMERICAL PROTECTION RELAY RESPONSE DURING SHUNT REACTOR SWITCHING

All numerical relays utilize so-called sampling technique of the input current and voltage signals. Typically 12 to 32 samples per fundamental power system cycle are used depending on the particular relay design. From these samples numerical relays calculates root-mean-square values of the input quantities by using different type of digital filters. These RMS values are then typically processed by different protective functions (i.e. phase and ground overcurrent).

In order to apply correct relay settings for shunt reactor protection application, it is of outmost importance to understand the relay digital filter response to typical input current waveforms, which can be encountered.

Response of two different types of digital filters will be investigated.

- TRMS (i.e. True RMS filter), which extracts equivalent RMS value from the input signal. Therefore this filter includes the dc component and higher harmonic components from the input quantity into its output result

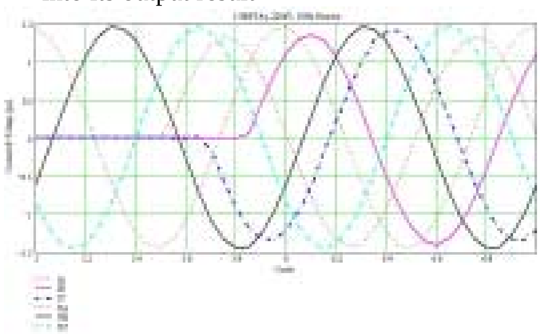

FIGURE 4: Phase Currents with point on wave closing relay

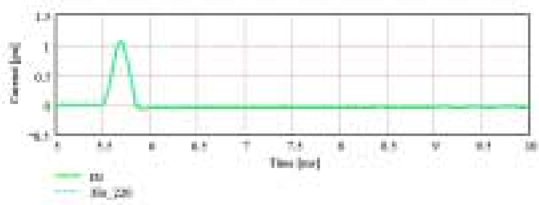

FIGURE 5: Neutral Current with point on wave closing relay

- DFF (i.e. Digital Fourier Filter), which extracts only RMS value of the fundamental component from the input signal. This filter effectively suppresses the dc component and higher harmonic components in the input quantity.

From Figure 8 it is obvious that the overcurrent relays, which use DFF filtering technique, can be set more sensitive than the relays that use TRMS filter for its operation. Similar results can be obtained if similar analysis is performed for the neutral point current as well. All setting recommendation in this document will be given for relays, which utilize DFF filtering technique (i.e. relays which effectively suppress the dc component and higher harmonic components in the input quantity).

CURRENT TRANSFORMER PERFORMANCE DURING SWITCHING IN OF SHUNT REACTOR

It is well known fact that one of the principal difficulties with shunt reactor protection scheme is false operation during reactor energizing and de-energizing [3], [4]. As explained previously, during this period relatively high and long lasting dc current component typically causes most problems for protective relays. If the protection relays maloperate this typically happen some hundreds of millisecond or even 1 to 2 seconds after circuit breaker closing. What is most difficult to understand is why this problem often happens randomly and not with every reactor switching attempt. Most problems are typically encountered with restricted ground fault protection, differential protection, distance protection and ground fault protection during switching.

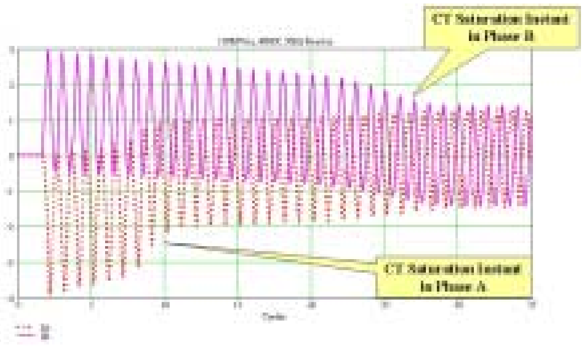

FIGURE 6: Reactor phase current saturation

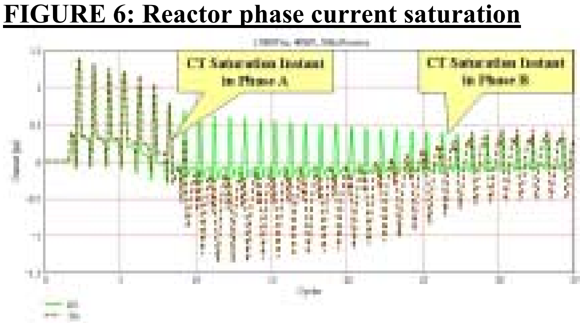

FIGURE 7: Reactor neutral current saturation

Therefore performance of these three relays during switching in of the shunt reactor will be explained here in more details. It should be noted that HV shunt reactors are typically switched in and out at least once per day or even more often depending on the power system loading patterns. As shown in Figure 2 during unsynchronized switching in of shunt reactor relatively high and long lasting dc current component might appear in one or more phases. This current waveform moves the operating point of CT magnetic core on the hysteresis curve in one direction and when the dc component diminish it leaves the main CT with certain level of residual (i.e. remanent) flux. During normal operation reactor current is always around 1pu and therefore of a relatively low magnitude, which is never big enough to move the operating point towards the origin. Therefore when next switching attempt comes, depending on the moment of switching, residual flux in the CT core can increase or decrease. Thus this mechanism will sooner or later cause CT saturation during reactor switch in operation. This CT saturation then causes problems for protective relays, which lose the correct information about the primary current and therefore can maloperate. Such CT saturation event is captured by numerical relay disturbance recorder and it is shown in Figures 6 & 7.

This type of CT saturation is reflected in the CT secondary side as:

- Loss of information about primary dc component
- Reduced current magnitude

Figure 8 represents the DFF & TRMS filter output value for the IA current waveform shown in Figure 6.

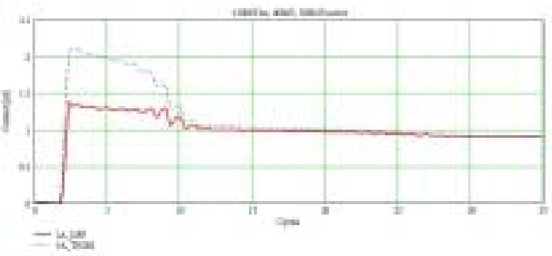

FIGURE 8: Reactor phase current DFF & TRMS

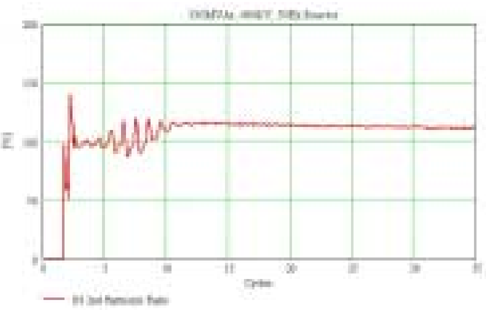

FIGURE 9: Reactor neutral current 2nd harmonic

RESTRICTED GROUND FAULT RELAY PERFORMANCE DURING SWITCHING IN OF REACTOR

Modern numerical relays typically offer restricted ground fault protection of a low impedance type. This gives the following benefits to the end user:

- This relay can be applied with different type of CTs at the reactor bushing and at reactor neutral point (i.e. CTs doesn't need to be identical)
- Main CTs can be shared with other relays
- No galvanic connection is necessary between CTs at the reactor bushing and at reactor neutral point
- In case of an internal fault no high voltages will appear in the CT secondary wiring

Typically these restricted ground fault relays of a low impedance type calculate the differential current as a difference between zero-sequence currents at the reactor bushings and the reactor neutral point. As additional operating criteria they often use directional principle (i.e. product type relays). However for shunt reactor protection these sometimes might not be enough to prevent maloperations. Let's have a look into the disturbance-recording file captured by numerical relay, which is shown in Figures 6 & 7.
The problem is that when one or more phase CTs saturate false 3Io current appears at the reactor bushings.
Unfortunately this very often manifests as the current of opposite polarity in comparison with the neutral point current, which then causes the directional restricted ground fault relay (i.e. product type relay) to maloperate during reactor switching in.
Calculated phase angle difference between neutral point current and zero-sequence current at the reactor bushing for the above event is shown in Figure 10.
Obviously it is necessary to have some additional means to restrain low impedance, restricted ground fault relay from maloperations during shunt reactor switching in.

One very effective method is to check the amount of second harmonic component in the shunt reactor neutral point current and adaptively prevent relay operation if the preset limit is exceeded (see Figure 9).

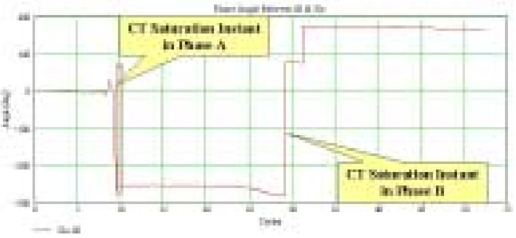

FIGURE 10: Phase angle difference between 3Io & IN during reactor switching

DIFFERENTIAL RELAY PERFORMANCE DURING SWITCHING IN OF REACTOR

Modern numerical relays typically offer differential protection of a low impedance type. This gives the following benefits to the end user:

- This relay can be applied with different type of CTs at the reactor bushing and at reactor star point (i.e. CTs doesn't need to be identical)
- Main CTs can be shared with other relays
- No galvanic connection is necessary between CTs at the reactor bushing and at reactor star point
- In case of an internal fault no high voltages will appear in the CT secondary wiring

Here the situation is little bit easier because the relay measures essentially the same current on both ends of the protected winding. However again the long lasting dc component can cause uneven saturation of the two CTs and cause the relay maloperations. Let's have a look into the disturbance-recording file captured by numerical relay, which is shown in Figure 11.
As it can be seen in Figure 11 due to uneven CT saturation on the two winding ends differential protection had unwanted operation and it has disconnected the shunt reactor from the power system. Thus if sensitive setting is required for the differential protection (i.e. 10-15% of the reactor rated current) it might be necessary to have some additional means to restrain low impedance differential protection relay from maloperations during shunt reactor switching in.
One effective method is to enable second harmonic blocking feature commonly readily available in numerical transformer differential relay. Second possibility is to delay the restraint differential protection operation only during reactor switching.

In the same time in order to have secure operation for heavier internal fault, the unrestrained differential level can be typically set down to 200% of shunt reactor rated current and without any time delay.

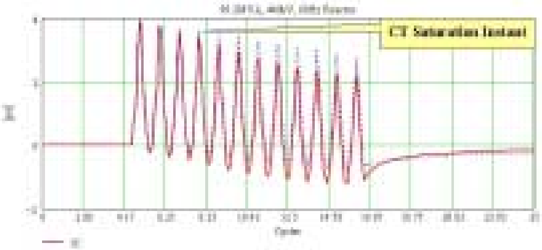

FIGURE 11: Reactor neutral current 2nd harmonic

DISTANCE RELAY PERFORMANCE DURING SWITCHING IN OF REACTOR

Especially in countries influenced by USA protection practice distance or underimpedance relays are used for shunt reactor protection. However these relays are as well affected by CT saturation during shunt reactor switching. Measured impedance by distance relay can be as low as 70% of shunt reactor rated impedance during switching!
Disturbance recording shown in Figures 6 & 7 was used to calculate apparent impedance, which would be seen by distance relay during this switching. Apparent impedances for all three phases are shown in Figure 12.

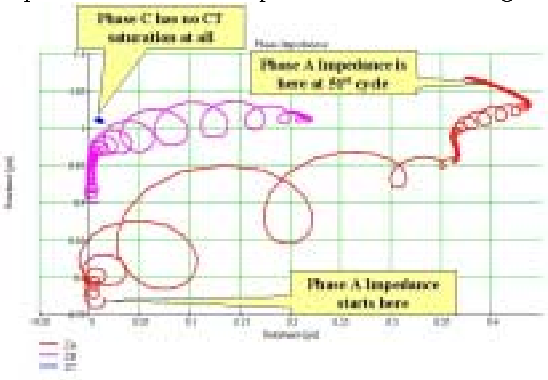

FIGURE 12: Apparent impedance during shunt reactor switching

From Figure 12 is obvious that especially phase A distance element would have problem to remain stable during this switching attempt.

GROUND OVERCURRENT RELAY PERFORMANCE DURING SWITCHING IN OF REACTOR

Numerical ground overcurrent relay might maloperate during reactor switching if it is set too sensitive. Typically in such cases either pickup current value or time delay are increased. However, another very effective method for such type of problem is to enable second harmonic blocking feature for ground overcurrent relay, which is readily available in certain numerical protections. Then the relay will check the second harmonic component level in the measured input current and prevent relay operation if the preset limit is exceeded (see Figure 9).

SHUNT REACTOR BEHAVIOUR DURING EXTERNAL AND INTERNAL FAULTS

Shunt reactor is connected in parallel with the rest of the power network, and it can be treated as a device with the fixed impedance value. Therefore the individual phase current is directly proportional to the applied phase voltage (i.e. I=U/Z), except during reactor core saturation.

Thus during external fault condition, when the faulty phase voltage is lower than the rated voltage, the current in the faulty phase will actually reduce its value from the rated value. Depending on the point on the voltage wave when external fault happens the reduce current might have superimposed dc component. Such behavior is verified by an ATP simulation and it is presented in [7]. As a result, shunt reactor unbalance current will appear in the neutral point. However, this neutral point current will typically be less than 1 pu irrespective of the location and fault resistance of the external fault.

Similarly during an internal fault the value of the individual phase currents and neutral point current will depend very much on the position of the internal fault. Assuming that due to the construction details, internal shunt reactor phase-to-phase faults are not very likely, only two extreme cases of internal phase to ground fault scenarios will be presented here.

In the first case the Phase A winding to ground fault, 1% from the neutral point has been simulated in ATP [7]. As a result the phase currents on the HV side (i.e. in reactor bushings) will be practically the same as before the fault. However phase A current at the shunt reactor star point and common neutral point current will have very big value due to so-called transformer effect. These currents can be so high to even cause CT saturation.
This type of the internal fault shall be easily detected and cleared by the differential, restricted ground fault or neutral point ground overcurrent protection, but not by reactor HV side overcurrent or HV residual ground fault protections.

In the second case the Phase A to ground fault, just between the HV CTs and shunt reactor winding (i.e. shunt reactor bushing failure) has been investigated. In this case the currents have opposite properties. The phase A current on the HV side is very big (limited only by the power system source impedance and fault resistance), while the phase A current in reactor star point will have very small value due to a fact that phase A winding is practically short-circuited.
As a result, shunt reactor unbalance current will appear in the neutral point. However, this neutral point current will typically have a value around 1 pu (i.e. similar value as during external ground fault).
This type of the internal fault (i.e. shunt reactor bushing failure) shall be easily detected and cleared by the differential, restricted ground fault or HV side overcurrent or HV residual ground fault protections. Neutral point ground overcurrent protection can operate with the time delay.

For internal ground fault in some other location in-between these two positions the shunt reactor currents will have values somewhere in the range limited by these two extreme cases.

SHUNT REACTOR TURN-TO-TURN PROTECTION SCHEMES

Turn-to-turn faults in shunt reactor present a formidable challenge to the protection engineer. The current and the voltage changes encountered during such fault are very small and therefore sensitive and reliable protection against turn-to-turn faults is difficult to achieve. At the same time the longitudinal differential protection offers no protection at all for such faults. Hence special protection schemes shall be employed.

One such scheme, often used in certain countries, utilizes a fact that the HV shunt reactor winding is often made of two half-windings connected in parallel (i.e. the HV lead is brought out at the mid point of the winding, and the two neutral leads at the bottom and the top of the winding). This gives the opportunity to install two CTs in the winding star point (i.e. one in each winding part). Then so-called split phase differential protection can be utilized to detect turn-to-turn faults. However this protection scheme have the following drawbacks:

- This special CT arrangement might cause reactor manufacturing problems
- Typically low CT ratio is required, which can cause longitudinal differential protection problems during reactor switching in, if the same CTs are used for both differential protections
- This scheme can be only used if the shunt reactor is specifically ordered with these CTs

Second turn-to-turn protection scheme for shunt reactors, successfully used in some other counties, utilize the following facts:

- HV power system voltages are well balanced during normal load conditions
- Modern HV, oil immersed shunt reactors have very small manufacturing asymmetry between individual phases
- Shunt reactor winding impedance is approximately proportional to the square of the number of active turns
- Short circuit between some number of turns will cause the decrease of the winding impedance only in the faulty phase and corresponding small raise of the shunt reactor neutral point current
- Currents during turn-to-turn fault are of the small magnitude and they will not produce any sufficient unbalance voltage
- Any external cause of neutral point current (i.e. external phase to ground fault) will cause appearance of unbalance voltage which can be used to block the operation of turn-to-turn protection scheme

In case of a bigger winding turn-to-turn fault which might cause the sufficient voltage unbalance, sensitive directional zero sequence relay connected on the shunt reactor HV side and set to look into the reactor shall be capable to detect such fault.

This protection scheme was developed even before multifunctional numerical relays were available. To implement such shunt reactor turn-to-turn protection scheme within multifunctional numerical relay utilizing its graphical configuration facilities, and readily available logical gates, timers etc. shall not be a big problem for a modern protection engineer.

REACTOR MECHANICAL FAULT DETECTION

Similarly to the power transformers, HV oil immersed shunt reactors typically have the following built-in mechanical fault detection devices:

- Gas detection relay (i.e. Buchholz relay) with alarm and trip stage
- Sudden pressure relay
- Winding temperature contact thermometer with alarm and trip stage
- Oil temperature contact thermometer with alarm and trip stage
- Low oil level relay

These mechanical relays are excellent compliment to the electrical measuring relays previously explained. It is recommended to arrange that these mechanical relays trip reactor circuit breaker independently from electrical relays. However signals from mechanical devices shall be connected to binary inputs of numerical relays in order to get time tagging information, disturbance recording and event reporting in case of their operation.

TYPICAL REACTOR CONTROL SCHEMES

The shunt reactors are generally designed for natural cooling with the radiators mounted directly on the tank. However sometimes it is required to have some control action in the cooling circuit depending on the status of the shunt reactor circuit breaker. The control action can be initiated by the circuit breaker auxiliary contact or by operation of an overcurrent relay set to 50% of the reactor rated current. By using overcurrent relay secure control action is obtained when reactor is energized regardless the circuit breaker auxiliary contact status.

In order to improve power system performance, lately it is often required by the electrical utilities to perform automatic shunt reactor in and out switching, by monitoring the busbar voltage level. This functionality is quite easy to integrate into multifunctional, numerical relay. However user must carefully check relay performance regarding the following points:

- Over/under voltage relay with reset ratio or 1% or better is required for such application
- Over/under voltage relay shall be capable to operate only when all three voltages are above/below set operate level or relay must be capable to measure and operate on the value of the positive sequence voltage

TRADITIONAL SHUNT REACTOR PROTECTION AND CONTROL SCHEMES

Usually multifunctional numerical protection relays are used for both power transformer and shunt reactor protection. However, typically old protection schemes for shunt reactor protection, with just a few protection functions are still specified and applied today.

The first protection scheme utilizes restricted ground fault protection (i.e. 87N) as reactor unit protection. This protection shall trip instantaneously for all internal phase to ground faults. For internal phase-to-phase fault detection, overcurrent protection (i.e. 50/51) is utilized. Ground overcurrent protection (i.e. 50G/51G) is used as backup protection for ground faults and as main protection for circuit breaker pole disagreement condition.

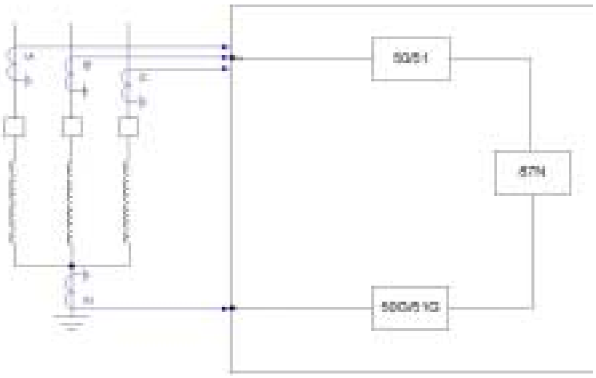

FIGURE 13: First traditional protection scheme

The second protection scheme utilizes differential protection (i.e. 87) as reactor unit protection. This protection shall trip instantaneously for all internal phase to phase and phase to ground faults. Overcurrent protection (i.e. 50/51) is used as backup protection for internal phase-to-phase faults. Residual overcurrent protection (i.e. 50N/51N) is used as backup protection for ground faults and as main protection for circuit breaker pole disagreement condition.

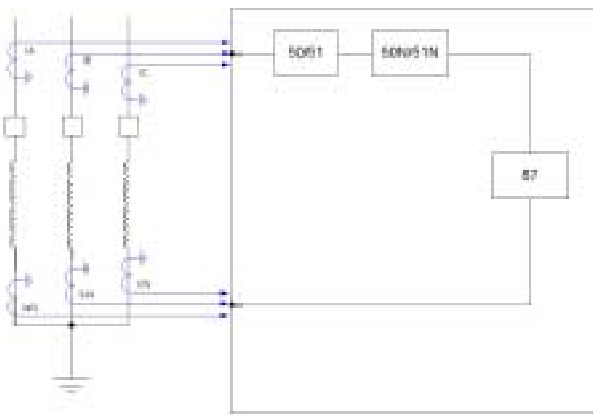

FIGURE 14: Second traditional protection scheme

Actually it shall be noted that the numerical multifunctional relays can offer much more functionality than shown on the previous two figures. Please refer to the following section to see proposed shunt reactor protection scheme with modern, multifunctional numerical protection relay.

CONCLUSIONS

The paper has described a number of details regarding HV shunt reactors and their protection and control schemes. In order to help the end user to properly select and apply multifunctional numerical relays for HV shunt reactor protection and control, an example of possible application of such relay, which utilizes DFF filtering technique, is presented on the next page in Figure 15.

All proposed protection or control functions in Figure 15 are typically readily available in multifunctional numerical transformer protection relays. However suitability of a particular relay to be used for shunt reactor application shall be carefully evaluated.

Table 1 gives the summary about each function from Figure 15 as well as some typical setting values [5], [6]. These settings are proposed for HV shunt reactors with own circuit breaker. In case that the HV shunt reactor is directly connected to the HV line without its own circuit breaker, these settings have to be revised. The proposed settings shall be considered only as guidelines.

It is hoped that this paper will provide some guidance to those seeking assistance in HV shunt reactor protection and control issues.

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[8] ATP is the royalty-free version of the Electromagnetic Transients Program (EMTP). For more info please visit one of the following web site: http://www.ee.mtu.edu/atp/

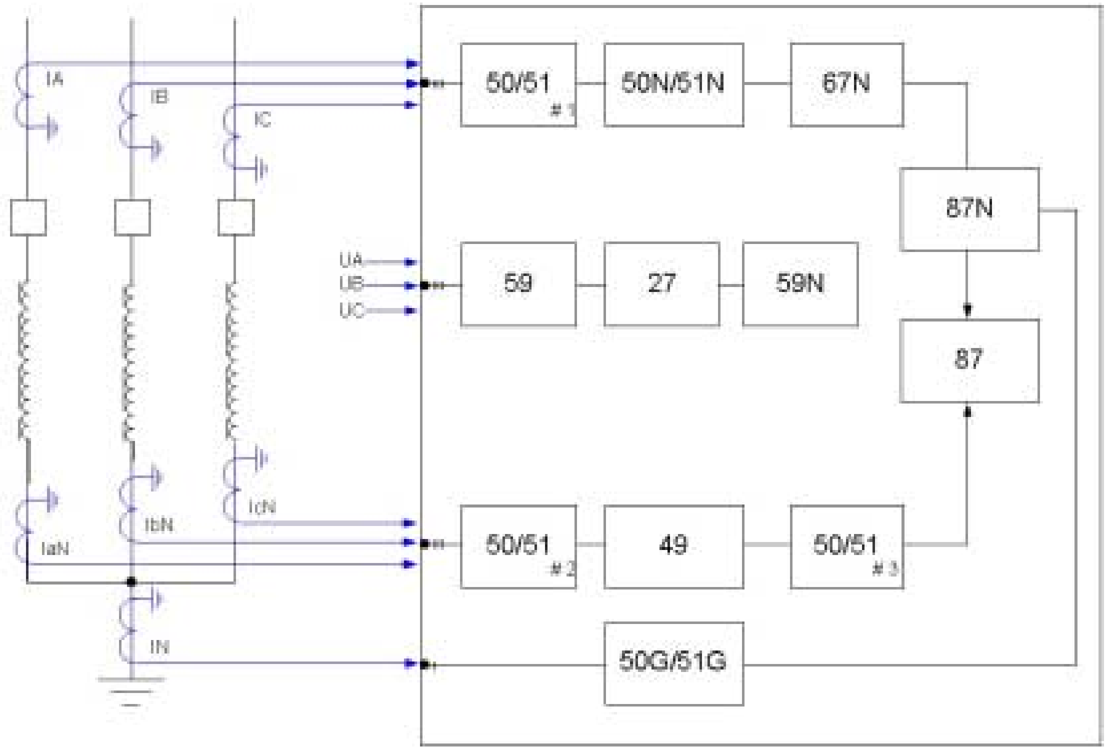

FIGURE 15: complete HV shunt reactor protection and control scheme with modern, multifunctional, numerical relay

TABLE 1: List of functions for complete HV shunt reactor protection and control scheme

Function	**Comment**	**Typical setting shown in percents of the shunt reactor rating**
87=low impedance diff. protection	Check suitability for shunt reactor application with relay manufacturer.	Set restraint differential level to 10-15% with 2nd harmonic restrain set at 10%. Set unrestraint differential level 200%.
87N=low impedance REF protection	Check suitability for shunt reactor application with relay manufacturer.	Set differential level to 10%. Set operate angle for directional criteria to ±65 deg. Relay shall include adaptive 2nd harmonic restrain feature.
#1-50/51=HV overcurrent protection	Backup protection, sensitive for internal faults close to the reactor bushings.	Set low set to 130% with time delay in between 0.6s and 1s. Set high set to 250% with time delay of 0.1s.
#2-50/51=HV overcurrent protection	Backup protection, sensitive for internal fault close to the reactor star point.	Set low set to 130% with time delay in between 0.6s and 1s. Set high set to 200% with time delay of 0.1s.
#3-50/51=HV overcurrent protection	Used as circuit breaker failure protection and indication that reactor is energized for the cooling control logic.	Set low set to 30% with appropriate time delay as CBF protection. Set high set to 50% in order to indicate that shunt reactor is energized.
49=thermal overload protection	Shall be used with great care. Shunt reactor overload can only be caused by overvoltage in a power system	Specific manufacturing data are required in order to properly set this function. Possible to use winding/oil contact thermometer instead.
50G/51G=ground fault protection in reactor neutral point	Backup protection, sensitive for internal fault close to the reactor star point. Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
50N/51N=ground fault overcurrent protection in reactor HV side	Backup protection, sensitive for internal faults close to the reactor bushings.	Set low set to 20% with time delay in between 0.6s and 1s or even longer. Use 2nd harmonic blocking. Set high set to 175% with time delay of 0.1s.
59N=unbalance overvoltage	Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
67N=directional ground fault protection	Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
27&59=under/over voltage	Used for automatic shunt reactor control. Often more than one stage required.	Specific system data are required in order to properly set these functions.