Practical EHV Reactor Protection

Faridul Katha Basha and Michael Thompson
Schweitzer Engineering Laboratories, Inc.

This paper was presented at the 66th Annual Conference for Protective Relay Engineers and can be accessed at: http://dx.doi.org/10.1109/CPRE.2013.6822055.

For the complete history of this paper, refer to the next page.

Presented at the
40th Annual Western Protective Relay Conference
Spokane, Washington
October 15–17, 2013

Previously presented at the
67th Annual Georgia Tech Protective Relaying Conference, May 2013

Originally presented at the
66th Annual Conference for Protective Relay Engineers, April 2013

Practical EHV Reactor Protection

Faridul Katha Basha and Michael Thompson, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Shunt reactors are applied to long, high-voltage transmission lines to offset the impact of line charging capacitance to prevent high voltage during lightly loaded conditions. Shunt reactors are becoming more prevalent associated with the construction of long transmission lines to connect remote wind energy sources to load centers. During conditions when wind generation is at a minimum, the system is more likely to need reactive compensation to control high voltage on the transmission system. It can be difficult to design a protection system that provides adequate sensitivity to the extremely low levels of fault current for in-zone reactor faults, especially turn-to-turn faults, while remaining dependable for high-level terminal faults that are not limited by the impedance of the reactor. Current transformer (CT) selection criteria must balance sensitivity with performance during switching and internal faults. Often, standard equipment ratings put further restrictions on CT sizing selection. This paper discusses the different reactor types currently used, their characteristics, CT selection and performance issues, and different types of reactor faults. The paper also provides guidelines to practicing engineers to evaluate reactor protection design and determine protection elements and relay settings for a high-voltage transmission line shunt reactor. The discussion of various factors that affect the sensitivity and dependability of the protection elements helps in understanding the challenges encountered while determining relay settings. Detailed examples of CT performance calculations and guidelines are provided for protection element settings calculations.**

I. Introduction

Reactors are used on overhead transmission lines to reduce the overvoltage generated under lightly loaded conditions by absorbing excess reactive power produced by the line charging capacitance and therefore facilitating voltage regulation. They are connected either to the substation bus or directly to the transmission line and are often installed at both ends due to the possibility of the line being energized from either end [1].

Shunt reactors are important assets and demand a robust protection scheme to safeguard them from abnormal operating conditions. In-depth discussions of the guidelines available for reactor protection are very limited. Most references consider dry-type reactors to be limited in voltage rating and applied to the tertiary of a transformer, and the resources focus on oil-immersed reactors for high-voltage applications. Hence, the discussion of types of faults and relaying practices for dry-type reactors is oriented towards transformer tertiary applications. But, there are cases where utilities use dry-type air-core reactors for high-voltage applications. The recommended protection practices describe only traditional relaying methods and not advancements in modern microprocessor technology and the implementation of this technology for reactor protection. These factors form the basis of the motivation for this paper.

Shunt reactor faults, such as turn-to-turn faults and ground faults near the neutral, present a formidable challenge to protection engineers because the faults can have very little influence on the phase currents and voltages. Designing a protection scheme that is sensitive to these faults yet secure against normal system unbalances and current transformer (CT) performance issues can be a challenge. Reactors are highly inductive devices with low inherent resistance ($R \ll X_L$) and a high X/R ratio. These characteristics can drive the CTs into saturation due to long dc time constants during energization. The difficulty arises in selecting a CT ratio that can perform without significant saturation during high-magnitude faults and on inrush and also be able to meet the minimum sensitivity requirements of the relay in detecting the low-magnitude internal reactor faults.

This paper provides background information on various types of shunt reactors applied on high-voltage transmission systems. It discusses the characteristics that are relevant to protection. Further, the paper discusses various factors concerned with the sensitivity and security of protection, with a detailed discussion of CT performance issues. The paper proposes a redundant protection design and provides recommendations for settings. The discussion in this paper is to line- or bus-connected shunt reactors with solid grounding and does not specifically address four-legged reactors (although many of the recommendations are useful for this configuration also). This paper also does not address transformer tertiary-connected reactors.

II. Background Information

A. *Why Use a Shunt Reactor on Long Transmission Lines?*

High-voltage and extra-high-voltage (EHV) levels are preferred for transmitting electric power over long transmission lines to reduce the I^2R power loss generated by the line resistance over longer distances. Such long, high-voltage transmission lines have large, inherent shunt capacitances between individual phases and between the phases and ground.

The VARs generated by a line are a function of the sending-end voltage (V_S) and the line susceptance (B) and are relatively constant [2]. On the other hand, the reactive power consumed is equal to $(I_L^2) \cdot X$. The line reactance (X) is fixed, whereas the line current is variable and depends on the load profile of the system, which means that the reactive power consumed by the line is a square function of the load current I_L.

Under light load, the load current and reactive power consumption are lower. The excessive reactive power thus produced can increase the receiving-end voltage of the line above the nominal rated value, resulting in equipment damage [2]. To overcome this, shunt reactors are connected to consume the excess VARs generated during light loads.

B. Reactor Types for Transmission Line Applications

Shunt reactors used for transmission line applications are classified based on two attributes: dry-type or oil-filled construction and the type of core used. The type of core employed determines if the reactor is affected by inrush on energization, as discussed later in this paper.

The following types of shunt reactors are employed for high-voltage transmission line applications and are of relevance for discussion in this paper:

- Dry-type air-core reactor.
- Oil-immersed air-core reactor.
- Oil-immersed gapped iron-core reactor.

1) Dry-Type Air-Core Reactor

Dry-type air-core reactors are air cooled and constructed as single-phase units mounted on insulating support structures and sufficiently spaced to prevent the magnetic fields from individual units from interacting with each other. Due to the absence of an iron core, they are not affected by saturation and inrush.

2) Oil-Immersed Air-Core Reactor

The oil-immersed air-core reactor is analogous to a transformer, but the iron core is absent and replaced by supporting insulators. This results in an inductor that is linear with voltage. Similar to a dry-type reactor, the absence of an iron core eliminates inrush. This type of reactor has a magnetically shielded construction to contain the flux produced within the tank while the reactor is in an energized state [3].

3) Oil-Immersed Gapped Iron-Core Reactor

The oil-immersed gapped iron-core reactor is constructed similar to a power transformer, except that the core has small air gaps, about 2 millimeters, distributed along the core [3] [4]. Due to this arrangement of air gaps along the iron core, a high-energy density is achieved by oil-immersed gapped iron-core reactors, especially for EHV applications.

The presence of air gaps in the core facilitates a longer range of linear operation before core saturation occurs [1] [4] relative to a power transformer. This makes it possible to achieve a relatively higher knee-point voltage of around 1.25 to 1.35 pu for a reactor, whereas a transformer with no air gaps in its core has a saturation knee-point voltage of around 1.1 pu [2]. Also, the air gaps in the reactor core facilitate very little remanence in contrast to a transformer [4]. This results in a gapped iron-core reactor experiencing less severe inrush compared with a transformer.

Gapped iron-core reactors can be used as three single-phase units or three-phase units with a three- or five-legged core construction. The five core legs result in a zero-sequence impedance that is equal to the positive-sequence impedance. The zero-sequence reactance is nonlinear and lower than the normal reactance in three-legged units, resulting in a relatively higher zero-sequence current during ground faults. More information on three- and five-legged core reactor units is available in [4].

Reactors, in general, have inherently low losses compared with inductive reactance. Due to this property, the resistive component is very small compared with the inductive reactance ($R \ll X_L$), resulting in a high X/R ratio and a long dc time constant during energization. This information is of significant importance in analyzing CT performance for reactor protection.

III. Reactor Characteristics

A. Linearity

Fig. 1, a reproduction of Fig. 11 from [4], shows the magnetizing characteristics of both gapped iron-core and air-core shunt reactor designs.

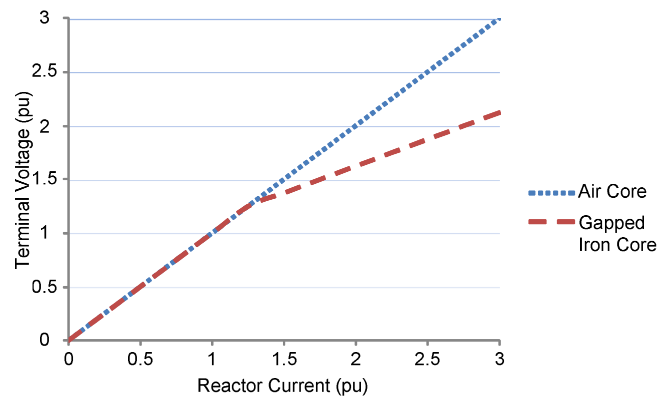

Fig. 1. Magnetizing characteristic of air-core and gapped iron-core reactors [4]

For a gapped iron-core reactor, the current displays a linear relationship with the applied system voltage until a knee-point voltage is reached. Beyond the saturation point, which is determined by the knee-point voltage, the gapped iron core becomes saturated and the current is nonlinear with the operating voltage [4].

On the other hand, for an air-core reactor of either dry-type or oil-immersed construction, no saturation of the core occurs due to the absence of an iron core, and the current increases linearly with voltage, as seen in Fig. 1.

B. Shunt Reactor Switching

1) Reactor Energization

The response of a reactor to its energization depends on the switching instant and the type of core employed.

When a reactor is energized, the three phase windings do not experience symmetrical excitation currents. When the breaker is closed, the individual phases of a reactor are energized at different angles of the applied system voltage. This results in the individual phases experiencing different degrees of dc offset, with the worst experienced by the phase that is energized at the zero crossing of the voltage waveform [1] [4]. Also, the time taken to dampen the dc offsets and reach a symmetrical steady-state operation is long because of the high X/R ratio of a reactor. The dc time constant for a reactor ranges in the order of seconds, whereas it is typically in the order of milliseconds for a transformer [4].

For an air-core reactor, the current is linear with the voltage on energization [4]. Because the core does not saturate, inrush and harmonics are not a concern. When energized, the individual phase currents have a sinusoidal component and a dc offset, depending on the switching instant.

On energization, gapped iron-core reactors give rise to inrush currents and harmonics, similar to transformers. The current increases proportionally to the applied voltage until the saturation knee-point voltage is reached, as seen in Fig. 1. Beyond this point, the reactor core becomes saturated, and the current increases nonlinearly with the applied voltage, giving rise to inrush currents and harmonics. The combination of the three-phase unsymmetrical currents results in a natural unbalance current at the neutral of the reactor. Peak values of the inrush current range from 3 to 5.5 times the rated current [1] [4]. This is much less than for an iron-core transformer. Also, due to the relatively lower zero-sequence impedance in a three-legged core reactor, the unsymmetrical inrush current results in a relatively higher unbalance current at its neutral point compared with the five-legged core construction.

Microprocessor-based relays use digital filtering techniques to eliminate the dc offset and harmonics of the actual switching current.

2) Reactor Disconnection

Shunt reactor disconnections can produce transient overvoltage due to current chopping and circuit breaker restrikes that can stress the reactor and the breaker [6]. Breaker restrikes are produced by a high transient recovery voltage (TRV) across the breaker contacts and result in a high-frequency overvoltage. The high-frequency re-ignition overvoltage thus produced is distributed unevenly across the turns of the reactor windings, with the highest transient overvoltage experienced by the turns closer to the supply-side terminals of the reactor. This can cause failure of the turn-to-turn insulation [4]. Some utilities overcome this transient phenomenon by using circuit switchers that are rated to have higher TRV withstand capabilities [7] [8] or by employing surge arresters [3] [4].

C. Shunt Reactor CT Performance on Energization

One of the difficulties relay engineers encounter while evaluating a protection scheme for a shunt reactor is designing a scheme that is tolerant of CT performance issues. Though the switching current in a reactor is less dramatic than in a transformer, the high X/R of the reactor can drive the CT into saturation. Analysis of the effect of X/R on CT performance is discussed in detail in Section V. Depending on the switching instant, the individual phases and CTs can experience different degrees of dc offset. The long dc decay time in reactors can cause the flux in the CT to accumulate in one direction, and by the time the dc decays and the reactor reaches steady-state operation, the CT may be left with significant remnant flux. On a consecutive switching operation, depending on the switching instant, the flux can either accumulate in the same direction and saturate the CT or cause flux accumulation in the opposite direction and reduce the net remnant flux. This phenomenon experienced by CTs connected to individual phases is uneven, resulting in unsymmetrical saturation of one or more phase CTs. This can cause the following security issues:

- False residual. The unsymmetrical saturation of the terminal CTs results in a false residual current that does not reflect the actual 3I0 current. This can cause the misoperation of zero-sequence elements.
- False differential. CTs connected to a phase differential zone can saturate unevenly, resulting in a false differential current that can cause misoperation of differential elements. This is discussed further in Section IV.

IV. Proposed Protection

The previous sections discussed the purpose and use of a reactor, types of high-voltage reactors, and reactor characteristics. Now we discuss the types of faults that impact the normal operation of a shunt reactor, suggested protection to detect the various faults, and factors that affect the sensitivity and security of the scheme.

A. Types of Shunt Reactor Faults

The types of faults within a reactor zone can be classified based on the location of faults. As indicated in Fig. 2, a reactor can experience phase and phase-to-ground faults on the external connection between the breaker and the high-voltage terminals of the reactor bank (labeled 1 and 2 in Fig. 2), phase-to-phase faults inside the reactor (4 in Fig. 2), high-voltage bushing-to-ground faults (similar to 2 in Fig. 2), winding-to-ground faults (3 and 5 in Fig. 2), and turn-to-turn faults on individual phase windings (6 in Fig. 2).

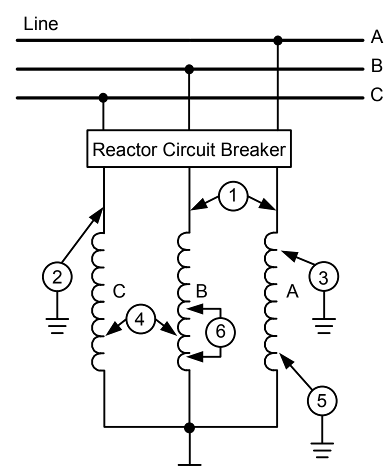

Fig. 2. Types of faults in a shunt reactor

1) Phase Faults

Phase-to-phase faults generate high-magnitude fault currents, especially in the external connection between the reactor bushings and the high-voltage breaker. Internal phase-to-phase faults may not be a concern in dry-type air-core reactors because the individual units are sufficiently spaced apart from each other.

2) Ground Faults

Due to sufficient insulation to ground in a dry-type air-core reactor, the probability of a winding-to-ground fault is very low, unless the ground insulator is bridged by a conducting medium. In oil-immersed reactors, winding-to-ground faults can occur due to proximity to the core and tank [4] [9].

The magnitude of phase-to-ground faults for reactors in general depends on the location of the fault on the winding. The current is higher for ground faults near the supply side (2 and 3 in Fig. 2) because the fault currents are limited only by the source impedance and result in large unbalance currents. For ground faults near the neutral end of the reactor (5 in Fig. 2), the magnitude of the fault is limited by the impedance of the reactor. For a ground fault near the neutral, the faulted phase current remains nearly the same as the prefault current and results in a low unbalance current.

The neutral point of the bank is in the fault loop and can experience a high current due to the autotransformer effect [1]. The autotransformer effect is caused by the voltage in the unfaulted turns being magnetically coupled into the faulted turns, driving current in the fault loop.

High-magnitude bushing-to-ground faults can occur due to lightning impulses and reactor switching transients that create significant stress on the reactor bushings and eventually damage the bushing insulation.

3) Turn-to-Turn Faults

Turn-to-turn faults (6 in Fig. 2) within the reactor result in small changes in the magnitudes of the faulted phase current. This type of fault reduces the impedance of the faulted winding and causes a corresponding increase in the phase current. This disrupts the three-phase symmetry of the terminal currents, resulting in zero-sequence unbalance currents flowing through the neutral to ground. Although the change in phase current can be very small, the current in the faulted turns increases the operating temperature and pressure inside the tank. This effect can be detected by nonelectrical protection devices such as the sudden pressure relay [9].

These faults are more likely near the high-voltage terminals of the windings. As discussed previously, breaker restrikes produce higher overvoltages near the supply-side turns. When such transient overvoltage exceeds the dielectric withstand capacity of the insulating material between turns, it can deteriorate, damage the insulation, and eventually result in a turn-to-turn fault [4]. A turn-to-turn fault, if not detected and interrupted quickly, can evolve into a fault between windings or a winding-to-ground fault.

B. Line Reactor Tripping Zone

Fig. 2 (and Fig. 3 in Section IV, Subsection C) show a reactor circuit breaker. This breaker is used for both daily switching and fault clearing. In many cases, a reactor switcher (circuit switcher) may be employed. This device is optimized for frequent load switching of the reactor without current chopping and restrikes but is not intended to interrupt fault current and should not be tripped to clear significant faults such as 1, 2, or 3 in Fig. 2. In this case, the reactor protection zone boundary is at the reactor bushing CTs or at a set of high-voltage, free-standing CTs for dry-type air-core reactors. The reactor tripping zone is the local and remote line breakers.

These significant faults may or may not be in the line zone. In some cases, selectivity is desired to prevent tripping of an important line for a reactor zone fault. In this case, the reactor currents are subtracted from the line zone. Subtracting the reactor currents from the line zone is also important if the line protection uses line current differential (87L) with line charging current compensation.

If the reactor currents are not subtracted from the line zone, Faults 1, 2, or 3 will be cleared as line faults. Dependable detection of these faults by the reactor protection is still important so that the faulted reactor can be isolated during the open interval and the line can be automatically reclosed.

Using a reactor circuit breaker introduces a design dilemma. If the CTs for the reactor zone protection are inside the circuit breaker, it may limit the freedom to select the CT ratings for the reactor zone. Very low ratios are required to provide adequate sensitivity for reactor zone faults. However, it may be undesirable to purchase a circuit breaker with standard capacity ratings (2,000 A, for example) with extremely low-ratio CTs (200 A primary, for example). This would limit the ability to have spares or repurpose the breaker for line or bus applications. This paper provides tools for the protection engineer to evaluate high-ratio CTs as available in a standard breaker for reactor zone protection.

C. Single-Line Diagram of Proposed Protection Scheme

Fig. 3 shows the single-line diagram of the proposed protection scheme and is used throughout this paper to discuss the various protection elements. It illustrates a protection scheme for a three-phase solidly grounded shunt reactor bank. Two relay systems, 87Rx and 67Rx, are used. To ensure redundancy, it is suggested that the two relays be supplied by separate dc sources, CTs, and voltage transformer (VT) inputs, as shown in Fig. 3. Table I provides a legend of the protection elements used in Fig. 3.

TABLE I
REACTOR PROTECTION SINGLE-LINE DIAGRAM LEGEND

Element	Description
49	Reactor thermal overload protection
63	Fault pressure protection
71G	Gas accumulator protection (Buchholz)
71Q	Low oil level
80Q	Oil flow indicator
87P	Phase differential protection
REF	Restricted earth fault (REF) protection
50P	Phase instantaneous overcurrent protection
51P	Phase time-overcurrent protection
50N	Neutral instantaneous overcurrent protection
51N	Neutral time-overcurrent protection
67G	Zero-sequence voltage-polarized ground directional overcurrent

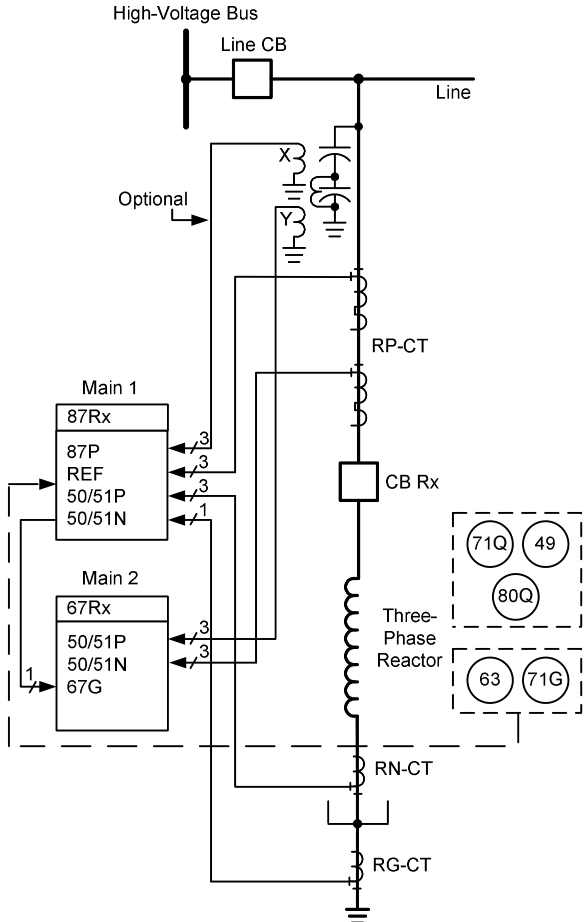

Fig. 3. Single-line diagram of a solidly grounded shunt reactor protection scheme

1) CTs and VTs

The supply-side terminal current information is supplied by three-phase CTs at the high-voltage terminals of the breaker, as shown in Fig. 3, or at the reactor tank discussed in Section IV, Subsection B. These CTs are termed RP-CT throughout this paper. RN-CT provides primary current information from the neutral end of the individual phase windings. RG-CT is a single-phase CT connected between the neutral point and ground. It provides the 3I0 current information flowing at the neutral point of the reactor bank.

The use of RG-CT is critical for reactor protection because it directly measures the 3I0 current from the reactor neutral point. It is highly recommended to use this CT to measure the ground current rather than the summation of currents from RN-CT because it prevents misoperation caused by false 3I0 current resulting from uneven saturation of phase CTs during energization [5]. This CT is critical in schemes used to detect low-grade faults, such as turn-to-turn faults. We see in Section VI that some sensitive schemes that respond to unbalance current may still require supervision during inrush.

In Fig. 3, the number of input signals derived from each instrument transformer unit is indicated by a number marked above the arrowhead in the CT and VT circuit.

2) Mechanical Protection Devices

Fig. 3 also indicates the mechanical protection and monitoring devices available for shunt reactor protection. These devices are usually provided as a built-in option in oil-immersed reactors. From a protection point of view, the mechanical protection devices are a good supplement to the electrical protection elements. For instance, fault pressure relays (63) and gas accumulation relays (71G Buchholz relays) provide sensitive detection of low-grade internal faults, especially turn-to-turn faults. The mechanical trip outputs can be connected to relay inputs and then added to the trip equation and event recorder. This helps indicate the particular device that tripped the breaker and further helps in event analysis. Thermal overload (49) can be used to monitor the oil and winding temperature. 71Q can be applied to indicate if the oil level falls below a predetermined minimum level. 80Q indicates a failure of oil circulation to cooling circuits. Reference [4] provides a detailed explanation of the operating principles and application of these mechanical devices.

3) Fault Coverage by 87Rx and 67Rx

The proposed scheme uses the 87Rx relay as the Main 1 protection system and the 67Rx relay as the Main 2 protection system. They are applied simultaneously for a redundant design.

The 87Rx relay uses 87P to detect internal phase and ground faults. It provides sensitive detection of high-grade faults (1, 2, and 3 in Fig. 2) and internal winding faults (4 in Fig. 2). The REF element provides sensitive detection of ground faults, especially low-grade winding-to-ground faults near the neutral (5 in Fig. 2). The 87Rx relay uses trip signals from 63 and 71G mechanical relays to cover turn-to-turn faults (6 in Fig. 2), but this option is available only for oil-immersed reactors. The overcurrent elements (50/51) back up the 87P and REF protection.

The 67Rx relay employs the 67G (directional ground overcurrent element) as the primary and only electrical protection for detecting turn-to-turn faults (6 in Fig. 2), regardless of the reactor type. The 67Rx relay also uses 50/51 phase and neutral overcurrent elements to provide redundant protection for both phase and ground internal faults. Both the relay systems together cover all possible faults, as indicated in Fig. 2.

D. Factors That Affect Sensitivity and Security

The high X/R ratio and the different degrees of dc offset experienced per phase on switching result in unsymmetrical three-phase currents on energization in reactors, causing the following security issues:

- An unbalance current at the neutral point is generated with harmonics in gapped iron-core reactors. This can cause misoperation of sensitively set protection elements that use the 3I0 current for detecting faults, especially turn-to-turn faults.
- One or more phases of the terminal CTs (i.e., RP-CT and RN-CT) are driven into saturation, misleading the relay with false differential currents, as discussed previously.

A turn-to-turn fault results in through-fault currents that cannot be detected by either of the phase (87P), ground (87N/REF), or negative-sequence (87Q) differentials, but it generates an unbalance current (3I0) that flows through to the ground. Section VI discusses a suitable method that uses the unbalance 3I0 from RG-CT to detect turn-to-turn faults. The magnitude of this 3I0 current depends on the number of turns involved and the reactor zero-sequence impedance. Because the magnitude of the faulted phase current has a small increase in its value, the unbalance 3I0 generated can be very small. This leaves protection engineers with the challenge of developing a scheme that is sensitive to this unbalance fault current yet secure against misoperations due to unbalance currents produced by switching transients, normal power system unbalances, and external faults.

Phase differential protection provides high-speed tripping for high-magnitude internal faults. A sensitively set phase differential can be susceptible to false differential currents due to uneven CT saturation of the boundary CTs. To avoid uneven CT saturation, utilities may employ CTs of identical ratings and identical excitation characteristics at the zone boundaries such that they suffer the same degree of saturation and prevent false differential currents. However, the proposed scheme is set to be tolerant of dissimilar CTs at the boundary of the differential zone. It is important that the operating pickup for the differential elements be chosen carefully so that a good balance between sensitivity and security is achieved. Section VI discusses evaluating the pickup under such conditions.

Because the phase currents are summed in a phase differential circuit, the inrush currents and harmonics generated during switching cancel out in the differential element, especially in saturated iron-core reactors. If the pickup is set securely to avoid misoperation on uneven CT saturation, the harmonic restraint elements can be disabled.

When the transmission line is de-energized with the reactor in service, it forms a parallel resonant circuit with the line capacitance, resulting in frequency ringdown [9]. Because the reactor impedance is proportional to the frequency of the system voltage, frequency ringdown can cause the impedance of the reactor to decrease when a line is de-energized. This condition can cause subharmonic currents and voltages to be measured by the relay. The protection elements must be set securely so that they do not respond to such subharmonic signals [5].

V. Selecting Suitable CT Ratings

Selecting CT ratings for reactor protection applications can be a challenge. The full load current of the reactor may be two orders of magnitude smaller than the rating of the line that the reactor is connected to and possibly three orders of magnitude less than the maximum fault current levels in the zone of protection.

A high ratio and accuracy class are desirable to provide adequate performance during high-grade short circuits in the zone (1, 2, and 3 in Fig. 2). Yet a low ratio is desirable to provide adequate sensitivity to low-grade short circuits in the zone (4, 5, and 6 in Fig. 2). Further, as previously stated, standard equipment ratings may limit users to high-ratio CTs in a reactor breaker—tempting the users to tap the CTs down to obtain adequate sensitivity. Using fewer turns in a high-ratio CT reduces the effective accuracy class, which can introduce performance issues.

We show in subsequent sections that the target sensitivity to detect turn-to-turn faults is 10 to 15 percent of the reactor rating. In the following discussion, we use a 345 kV, 20 MVA three-phase reactor as an example. The rated current of this reactor is 33.5 A primary. The target sensitivity of the elements used for turn-to-turn fault detection is therefore 3.35 A to 5.03 A primary. The example system has a maximum fault current level of 6,800 A. So, the ratio of minimum to maximum fault that the protection system must cover is around 2000:1. This is indeed a challenge.

The CT selection criteria that we propose are as follows:

- Provide adequate sensitivity to detect 10 to 15 percent of reactor rated current.
- Size the CT accuracy class voltage rating to prevent asymmetrical saturation on switching. This is a low current, but with a long dc time constant.
- Size the CT accuracy class voltage rating to limit saturation for the maximum internal fault current condition to a reasonable level. Otherwise, this problem can result in insufficient current to pick up high-set elements.

A. Criterion 1 – Provide Adequate Sensitivity

Using our 345 kV, 20 MVA reactor as an example, we determined that the protection must be able to detect currents in the range of 3.35 A to 5.03 A primary. The minimum pickup setting of protection elements is 0.25 A secondary for a 5 A nominal relay and 0.05 A secondary for a 1 A nominal relay. The use of a 1 A nominal relay in an otherwise 5 A nominal system for reactor protection was proposed in [5]. Table II gives the sensitivities that would be available from various ratios that could be specified. Only CT ratios that can provide the specified sensitivity range of 10 to 15 percent of rated current are listed.

TABLE II
POSSIBLE CT RATIOS FOR 345 KV, 20 MVA REACTOR

CT Ratio	Minimum Sensitivity in Percent of Reactor Rating	
	5 A Relay, 0.25 A	**1 A Relay, 0.05 A**
10T	7.5	NA
13.4T*	10	NA
20T	15	NA
60T	NA	9
67T*	NA	10
80T	NA	12
100T	NA	15

* Target CT ratio to obtain 10 percent sensitivity.

B. Criterion 2 – Prevent Asymmetrical Saturation on Switching

Reference [10] derives an equation to evaluate if a CT can be driven into saturation when subjected to a sinusoidal current with an exponentially decaying dc offset. The function solves for where the volt-time area, which is proportional to the magnetic flux density in the iron core, reaches the accuracy class limit for the boundary condition of a fully offset waveform. Equation (1) states that if V_S is less than 20, the CT does not go into saturation.

$$20 \geq V_S = \left(1 + \frac{X}{R}\right) \bullet I_S \bullet Z_B \quad (1)$$

where:

I_S is the current in per unit of the tapped CT primary rating.

Z_B is the CT burden in per unit of tapped standard burden.

X/R is the X/R ratio of the circuit driving the current I_S.

V_S is the per-unit saturation voltage.

The main factors that affect the evaluation of V_S are I_S multiplied by Z_B, which is the voltage developed by the CT to drive ratio current through the connected burden circuit, and the X/R ratio, which affects how quickly the dc offset decays and the current becomes symmetrical.

In most protection application cases, we use this equation to evaluate the performance of the CT for high-current faults. In the reactor application case, the current of interest is the reactor rated current, so it is relatively low. The burden loops can be quite large given the distances that can exist between the relay panel and a line reactor located on the far side of a large EHV substation, and as we have already established, the X/R ratio of the reactor is very high.

Using more turns improves the evaluation of V_S in the two following ways:

- More turns reduce the current through the burden loop and, therefore, the voltage that the CT must develop.
- More turns increase the volt-time area available before the CT saturates. The volts per turn of a given CT is a function of the iron in the core of that CT.

We return to our 345 kV, 20 MVA reactor example. Reference [11] provides detailed instructions on how to use (1). The reader is encouraged to use the information in [11] to reproduce the results presented here.

The reactor rated current is 33.5 A. This is a balanced current, so we use the one-way CT lead resistance to calculate Z_B. For this example, the distance from the relay to the reactor is 1,326 feet using # 10AWG cable—giving a lead resistance of 1.326 ohms. The CT internal resistance is 0.00225 ohms per turn. The X/R ratio of the reactor is 53.75.

Table III gives the results for several low-ratio CTs. Notice that low-ratio CTs are typically not available in high accuracy class ratings. With few turns, the amount of iron required to obtain the necessary volts per turn for a high C rating becomes prohibitive. Table IV gives the results for several high-ratio CTs. Both 1200:5 and 2000:5 multiratio C800 CTs are evaluated.

Table III
SATURATION EVALUATION FOR LOW-RATIO CTS

Current Rating	Accuracy Class	Full Turns	Tapped Turns	V_S
50:5	C100	10T	10T	48
100:5	C100	20T	20T	24
300:5	C200	60T	60T	4
400:5	C200	80T	80T	3

TABLE IV
SATURATION EVALUATION FOR HIGH-RATIO CTS

Current Rating	Accuracy Class	Full Turns	Tapped Turns	V_S
1200:5	C800	240T	60T	4.2
1200:5	C800	240T	80T	2.4
1200:5	C800	240T	100T	1.6
2000:5	C800	400T	60T	6.7
2000:5	C800	400T	80T	3.9
2000:5	C800	400T	100T	2.6

The results of the V_S calculation need to be interpreted within the context of the application. As stated earlier, a V_S greater than 20 indicates that the CT can saturate. However, (1) assumes that the CT has no remanence, which is unlikely given the high X/R ratio of the switching current. Equation (1) is only valid for a sinusoidal current with a dc offset. If a gapped iron-core reactor experiences inrush with high harmonics, the total current is higher and the time constant of interest is the magnetic circuit time constant—not the reactor X/R ratio. Finally, the protection elements reading the currents from the CTs may have tolerance for CT saturation or can be set to have tolerance for some level of CT saturation.

From this, we see that 10T and 20T CTs should only be used with caution. The tapped multiratio CTs are all relatively immune to CT saturation on switching. If the reactor in the zone has a gapped iron core, use a more conservative selection to tolerate the inrush than with an air-core reactor.

C. Criterion 3 – Limit Saturation for a Maximum Fault to a Reasonable Level

Reference [12] discusses the effect of high fault currents on low-ratio CTs. CT saturation can be so severe that a high-set overcurrent element—especially one that responds to the fundamental component of the signal—may not pick up.

Transient CT saturation can only be studied using time domain simulation techniques. Several programs are available to perform this analysis. General purpose transient simulation programs such as Electromagnetic Transients Program (EMTP) or Alternative Transients Program (ATP) include CT models. The IEEE PES Power System Relay Committee (PSRC) has developed a Microsoft® Excel® spreadsheet for simulating CT transient performance [13]. This spreadsheet uses a Fourier filter to extract the fundamental component of the CT waveform to evaluate the response of a digital relay.

Reference [14] describes a CT performance simulation program that was originally written in Beginner's All-Purpose Symbolic Instruction Code (BASIC) programming language. The simulation program was later implemented in MATLAB® and compiled in an executable program. The authors used this program to evaluate the transient performance of the CTs for this application. The program outputs an ASCII data file. We developed an Excel spreadsheet that samples the data file at 16 samples per cycle and extracts the fundamental component of the CT waveform using a cosine (COS) filter to better emulate the response of the relays used.

Considering the first two criteria, we evaluated the performance of two CTs for transient performance. The first is the C100, 20T CT applied with a 5 A relay. While there are concerns about this CT saturating during switching because V_S is greater than 20, it provides the desired 15 percent sensitivity per Table II. Fig. 4 and Fig. 5 show the raw and filtered currents from the simulation.

This CT experiences extreme saturation for this maximum fault. The filtered value eventually reaches 80 A after several cycles. Examination of these data provides guidance on the upper setting limit for any instantaneous elements used to detect this fault.

The second CT evaluated is a C800, 400T CT tapped to 100T applied with a 1 A relay. This CT provides the desired 15 percent sensitivity per Table II, and there are no concerns about saturation on reactor switching currents. Fig. 6 and Fig. 7 show the raw and filtered currents from the simulation.

This CT performs much better. As long as instantaneous overcurrent elements are set below approximately 30 A secondary, they will be dependable and fast.

The final concern with applying a 1 A nominal relay in this application is the I^2t withstand capability of the relay. Will a maximum fault damage the relay? The relay is rated for 100 A for 1 second. This equates to an I^2t of 10,000.

If we neglect any CT saturation and assume that the full ratio current is applied to the relay for a breaker failure clearing time of 0.25 seconds, we get $(68A)^2 \cdot 0.25$ seconds = 1,156, so there is no concern about damaging the relay in this application.

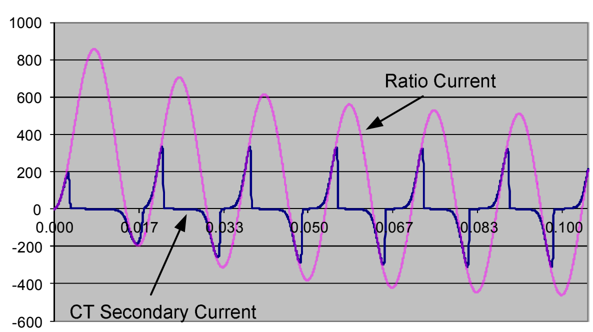

Fig. 4. C100, 20T CT with 6,800 A fault—raw sample data

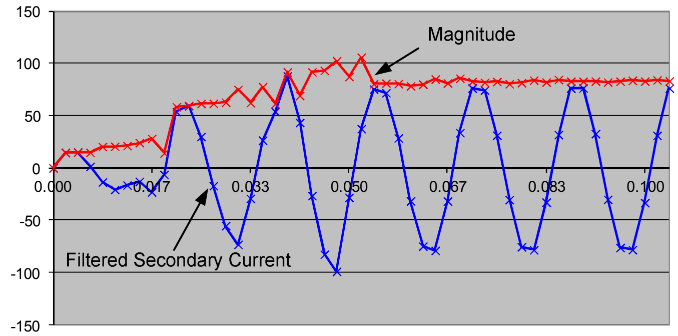

Fig. 5. C100, 20T CT with 6,800 A fault—filtered data

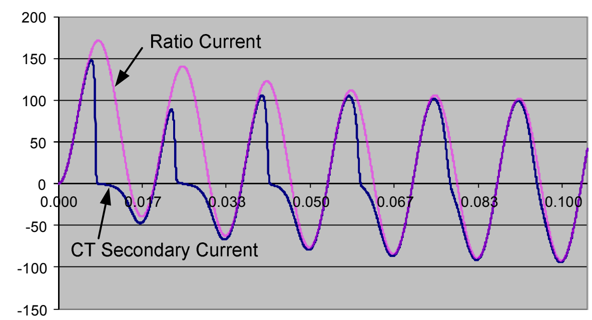

Fig. 6. C800, 400T CT tapped at 100T with 6,800 A fault—raw sample data

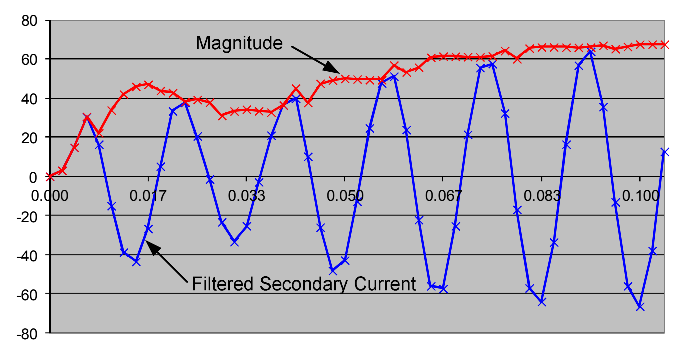

Fig. 7. C800, 400T CT tapped at 100T CT with 6,800 A fault—filtered data

D. CT Evaluation Conclusions

Based on the previous analysis, we determine that either 2000:5 or 1200:5 C800 CTs can be applied with 1 A nominal relays to meet all three selection criteria. There is no CT available that can meet all selection criteria if a 5 A nominal relay is specified. If a 5 A nominal relay is specified anyway, the engineer can either sacrifice sensitivity by using a higher ratio or sacrifice security by making CT saturation during reactor switching more likely.

VI. Shunt Reactor Protection Guidelines

Unlike transformers, there is no dedicated microprocessor-based relay built to protect a shunt reactor. Because most of the protection elements used in shunt reactor protection are readily available in a transformer protection relay, it can be used as the Main 1 protection device for a shunt reactor. The guidelines discussed in this section apply to all the shunt reactor types discussed in this paper.

A. Phase Differential Protection (87P)

The proposed scheme uses a low-impedance percentage differential relay. The zone of protection of the differential element is defined by RP-CT and RN-CT, as shown in Fig. 3. This element operates on a slope characteristic based on the ratio of the operate current to restraint current [11].

The high X/R of the reactor can cause prolonged CT saturation during switching such that the CT might be completely saturated by the time the reactor reaches steady-state load operation [1]. This, combined with the possibility of uneven saturation of the boundary CTs where one CT experiences severe saturation and the other boundary CT does not saturate at all, can cause the differential to misoperate on a false differential current that is almost equal to the load current. To ensure security under such conditions, the pickup can be set at reactor rated load current such that it is above the false differential current seen by the relay.

On the other hand, a sensitively set differential element can be responsive to the minimum internal fault conditions, especially near the neutral end of the winding, because the current seen by one boundary CT is almost equal to the rated current, resulting in a differential current that is above pickup.

While considering the pickup setting, it is necessary to balance sensitivity with security. We recommend setting the pickup in the range of 0.5 to 1.0 pu of rated current. A setting closer to the lower limit of the proposed range drives the differential scheme towards higher sensitivity, and a setting closer to the upper limit increases security.

1) Slope Setting

The general purpose of a slope setting is to prevent misoperation due to false differential currents on CT saturation during high-grade through faults and during normal operation. A reactor does not experience a high-grade through-fault current because a fault on the line causes voltage depression and the current through the reactor is relatively less than the rated current. So, the slope setting is not as significant as it is in transformers or bus differential applications, and the Slope 1 and Slope 2 settings can be left at the relay default values.

2) Unrestrained Pickup (U87P)

Because high-speed operation can be achieved by the high-set overcurrent elements (50), the unrestrained differential element can be disabled.

B. Overcurrent Protection (50/51)

The overcurrent elements supplement the differential protection to detect internal faults.

1) Instantaneous Overcurrent Elements (50P/50N)

The instantaneous elements should be set above the maximum magnitude of the filtered switching or inrush current seen by the relay. Due to the possibility of CT saturation during high-magnitude faults, the pickup for the overcurrent elements should be set below the minimum saturated CT current, per the discussion in Section V. A typical pickup setting for a 50P element is based on a phase-to-phase internal fault on the high-voltage terminal side (equal to a close-in, line-to-line fault on the transmission line) under *N – 1* source conditions with a 50 percent margin. 50N can be set similarly based on a phase-to-ground internal fault.

2) Phase Time Overcurrent Element (51P)

The pickup setting of the time-delayed overcurrent element must allow for a certain degree of current above the reactor rated current to account for the overcurrents produced by the system overvoltages because it is under these conditions that the reactor is put to use. It should also be secure to the overcurrent produced as a result of a temporary rise in voltage in unfaulted phases during a single-line-to-ground fault in the power system. Such temporary overvoltage never exceeds 1.3 pu of system nominal voltage [4] [9]. Because the reactor current is linear with applied voltage until the saturation knee-point voltage, as shown in Fig. 2, the rise in current for such temporary overvoltage is also linear with that of the applied voltage. Hence, we recommend using a pickup setting of 1.5 pu of reactor rated current for time-delayed overcurrent elements. The time-delay setting can be set based on the reactor thermal overload rating, expressed in terms of primary current versus time and obtained from the specification sheet.

3) Ground Time-Overcurrent Element (51N)

The ground time-overcurrent element operates on residual 3I0 of RP-CT currents and is set similar to the phase time-overcurrent element with a pickup setting of 1.5 times the reactor rating. Because the unbalance current for an external fault seen at the reactor terminals is less than 1 pu of reactor current [1], the pickup is tolerant to external ground faults. The time-delay setting can be set similar to 51P.

C. REF Protection

The REF element can provide sensitive protection for faults involving ground, especially near the neutral, in the reactor zone. An REF element typically works on a current-polarized directional principle of operation. Fig. 8 shows the operating region of the phase angle comparator.

The phase angle of the 3I0 current at the terminals of the reactor measured by the residual of the RP-CTs (labeled "reference current" in Fig. 8) is compared with the phase angle of the 3I0 current at the ground connection of the reactor measured by the RG-CT (labeled "operating current" in Fig. 8). The directional element measures the torque generated by multiplying the two complex numbers representing the currents. If the two currents are both into the zone of protection, the torque is positive and the element trips. If the two currents are out of phase, the torque is negative and the element restrains.

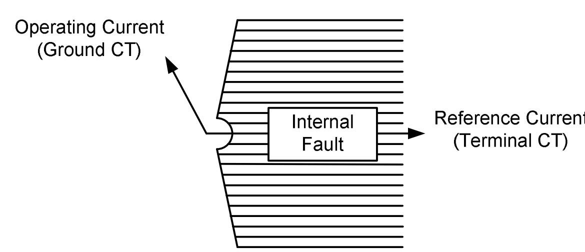

Fig. 8. REF directional element tripping and restraint region

This element is very tolerant of unequal performance of the three RP-CTs for several reasons. The operate region of the directional element allows for a phase angle error of almost ±90 degrees before an incorrect decision can be made. In addition, because the RG-CT directly measures the unbalance current, it is not possible for it to see a false 3I0. Thus, for a fault not involving ground and with false 3I0 in the RP-CTs, the element does not operate due to the fact that the 3I0 magnitude from RG-CT in the torque equation is zero. Finally, the tripping decision for REF is made on the magnitude of the current in the RG-CT, which is immune to false 3I0.

However, in the case of a gapped iron-core reactor, inrush currents can result in a real unbalance current that is rich in harmonics. This current is asymmetrical and can therefore drive the CTs into saturation. Further, the time constant is the magnetic circuit time constant, which is much longer than even the reactor circuit electrical time constant. In this case, because there is little real 3I0 present, the false 3I0 in the terminal CT residual can overwhelm the true signal and result in the phase angle swinging into the operate region, causing misoperation. For this reason, the inrush suppression logic described in Section VI, Subsection D should be used to block this sensitive element for a time period after energization to allow the inrush current to subside.

The sensitivity of the REF element is typically set to 10 to 15 percent of reactor rating with a short inverse- or definite-time delay.

D. Turn-to-Turn Fault Protection (67G)

Detecting turn-to-turn faults in a reactor using electrical measurements is extremely difficult. For oil-filled reactors, the sudden pressure (63) and Buchholz (71G) relays provide mechanical protection for these types of faults. Sensitive electrical protection for these faults is recommended and is necessary for dry-type reactors.

Fig. 9 shows the recommended scheme logic. The proposed protection scheme uses a zero-sequence voltage-polarized directional element responding to the 3V0 and 3I0 (RP-CT) measured at the terminals of the reactor zone to control tripping of a definite-time ground overcurrent element measuring the 3I0 current in the RG-CT. This element is used to indicate whether the 3I0 flowing in the ground CT is caused by a zero-sequence voltage unbalance on the system, which is caused by a fault to ground (external fault), or by an unbalance in the reactor zone, which is caused by shorted turns in a phase of the reactor.

The directional element overcurrent supervision measuring the RP-CT residual current and the ground overcurrent element measuring the RG-CT 3I0 currents should both be set to 10 to 15 percent of reactor rated current. In our example, we chose a 100T CT that allowed the 0.05 A minimum sensitivity of the 1 A nominal relay to achieve 15 percent sensitivity. This is only 5 A primary current at 345 kV. An element this sensitive requires additional supervision to ensure security. Fig. 9 includes a special logic labeled "inrush suppression logic" that is described later in this section.

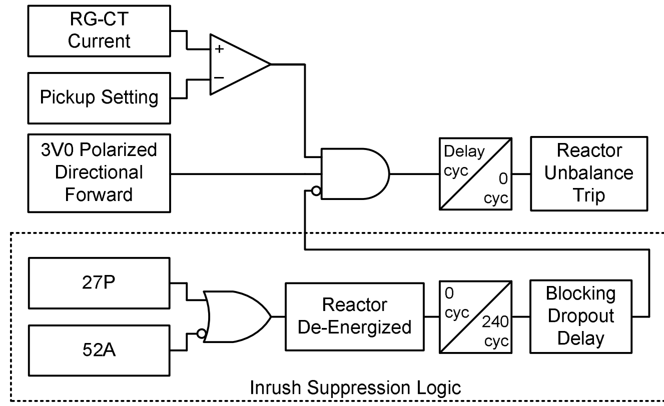

Fig. 9. Voltage-polarized ground overcurrent element with inrush suppression logic to detect turn-to-turn faults

1) Ground Overcurrent Element

The tripping decision uses the RG-CT current because it is immune to operation on false 3I0 caused by unequal CT performance. This element is set to the 10 to 15 percent minimum sensitivity used to rate the CTs and relays, based on the discussion in Section V. A short definite-time delay is included to prevent tripping on unbalances caused by external faults. This delay is typically set to be slightly longer than normal system fault clearing times. If pilot protection is used on the adjacent lines, a delay of 10 to 15 cycles is used.

2) Directional Control

Unbalance current caused by turn-to-turn faults in the reactor typically does not create much unbalance in the system voltages [1] [9]. The reactor impedance is several orders of magnitude greater than the system source impedance. For this reason, a typical torque-based directional element that uses the product of complex numbers 3V0 multiplied by 3I0 is likely not able to make a forward directional decision. On the other hand, unbalance currents in the reactor zone caused by short circuits on the system result in enough significant 3V0 for the directional element to make a reverse directional decision.

The recommended relays use an impedance-based directional element that uses 3V0/3I0 = Z0. The Z0 measured by the relay is the zero-sequence source impedance feeding the fault [15]. For an external fault, the impedance seen by the relay looking into the reactor terminals is the zero-sequence impedance of the reactor. So, setting the forward and reverse impedance thresholds to approximately half the reactor zero-sequence impedance in secondary ohms allows the relay to easily discriminate between internal and external faults.

Consult the reactor test reports to determine the zero-sequence impedance. For dry-type air-core and oil-filled, five-legged gapped iron-core reactors, the zero-sequence and positive-sequence impedances are nearly the same. However, for other types, the zero-sequence and positive-sequence impedances are likely different.

The directional element also includes a check of the ratio of I0/I1. This ratio check is used to prevent operation of the directional element on small system unbalances. The default setting of this ratio check is 10 percent. To detect 10 percent 3I0 unbalance, the ratio setting needs to be lowered to less than 3.3 percent. This low setting is allowable given that the manufacturing tolerances on a reactor should result in well-matched per-phase impedances and low natural unbalance.

The fault detectors supervising the directional element also need to be set to the 10 to 15 percent minimum sensitivity used to rate the CTs and relays, based on Section V. These fault detectors are the reason that the RP-CTs had to be rated for such high sensitivity, even though the tripping element responds to the current in the RG-CT.

3) Inrush Suppression Logic

The main danger for misoperation of this sensitive unbalance element is immediately after energizing the reactor or immediately after clearing a close-in fault that results in a voltage depression and sudden increase after the fault is cleared. Inrush results in real zero-sequence unbalance currents flowing in the reactor zone and RG-CT. This is when the dc offset in the reactor current can drive CTs into saturation. Fig. 9 shows logic that blocks this sensitive element for 4 seconds after either of these conditions are detected to improve security [7].

The logic uses an undervoltage element to detect a close-in fault or when the line is de-energized and monitors the 52A contact of the reactor breaker to detect if the reactor is de-energized while the line remains energized. Either of these conditions blocks the element immediately upon de-energization of the reactor. The dropout delay keeps the sensitive reactor protection out of service for 4 seconds after the reactor is energized. The undervoltage element is set to 0.8 pu of nominal voltage because this can easily detect a close-in line fault or line de-energization condition. Because the turn-to-turn fault currents do not cause a significant voltage depression, the undervoltage pickup of 0.8 pu does not block the protection on turn-to-turn faults. Also, by blocking 67G on line de-energization, the element is prevented from operating on subharmonic signals.

4) Why 87Q and REF Cannot Be Used to Detect Turn-to-Turn Faults

A transformer differential monitors the ampere-turn (AT) balance of a transformer. As long as this AT balance exists, there is not any differential current in the differential circuit. A turn-to-turn fault in a transformer winding creates an AT unbalance, and this is reflected as a differential current in the differential circuit [16]. This functionality is similar for the 87Q element, except that the operating and restraint quantities here are the negative-sequence terminal currents, making the element unresponsive to balanced load current and therefore sensitive.

However, a turn-to-turn fault in the reactor winding marginally increases the faulted phase current and results in an unbalance that is analogous to a power system unbalance. The negative-sequence unbalance current produced by this fault, as measured by the boundary CTs, cancels each other in the differential circuit per Kirchhoff's current law. Similarly, in the REF element, the zero-sequence current flowing in RP-CT and RG-CT flows through the zone and provides a restraining torque, unless the fault evolves to the grounded core or tank.

Fig. 10 shows the oscillographic recording for a turn-to-turn fault that was triggered in the A-phase winding of a test system that was simulated in a Real Time Digital Simulator (RTDS®). Note that the negative-sequence differential (87Q) and REF forward indication never picked up for the turn-to-turn fault. The operating current for the negative-sequence differential function in the relay is the vector sum of the negative-sequence currents seen at the boundary of the differential zone. In Fig. 10, the phasors 3IS2 and 3IT2 are equal and opposite and therefore cancel each other in the negative-sequence differential element. But, for the same event, the voltage-polarized ground directional overcurrent pickup (T-T PICKUP) asserts and the trip bit (T-T TRIP) asserts after a 15-cycle time delay.

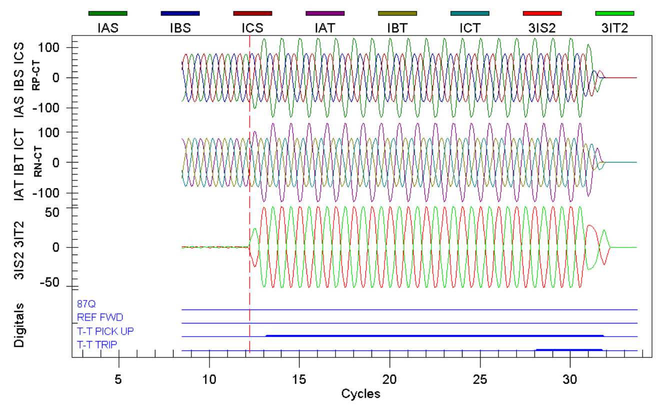

Fig. 10. Turn-to-turn fault at 40 percent of the A-phase winding from neutral, simulated in RTDS

The appendix of this paper provides the protection functions in the proposed scheme and their recommended setting guidelines.

VII. Conclusion

Shunt reactors for high-voltage transmission lines use dry-type air-core reactors in addition to oil-immersed types. The air-core reactors have linear magnetizing characteristics on energization and therefore no inrush effects compared with gapped iron-core reactors. The air gaps in a gapped iron-core reactor facilitate less severe inrush and harmonics compared with a transformer.

Reactors have a higher X/R and longer dc time constants that can cause uneven saturation on energization, resulting in false residual and false differential currents. Operation on the false residual can be avoided by using direct measurement from the ground CT to operate sensitive elements.

Reactors can experience both high-magnitude and low-magnitude internal faults. Recommendations are provided to design redundant protection and evaluate protection settings for all shunt reactor types. The proposed protection scheme involves two relay systems applied simultaneously. In addition to electrical protection, mechanical protection available in oil-immersed reactors is highly sensitive to low-magnitude faults, such as turn-to-turn faults, and is an excellent supplement. A method is proposed to evaluate a suitable CT ratio to ensure sensitivity to low-grade faults and dependability on high-grade faults.

The differential provides high-speed protection for high-grade faults. The pickup setting has to balance both sensitivity and security. A generalized pickup setting is recommended that is secure to false differential current yet sensitive to minimum internal faults and that can be used regardless of the similarity of the boundary CTs.

REF protection offers sensitive protection for minimum internal ground faults.

Turn-to-turn faults cannot be detected by 87P, 87Q, and REF. A highly sensitive method is presented that uses the 3I0 current measured directly from the ground CT to detect turn-to-turn faults. A sensitive zero-sequence impedance-based directional element distinguishes between internal and external faults. The inrush tripping logic prevents operation on switching transients, subharmonic signals, and reactor disconnection.

Overcurrent elements back up the differential elements and provide thermal overload protection. Setting recommendations are provided for sensitive and secure operation.

VIII. Appendix

Table V provides the protection functions in the proposed scheme and their recommended setting guidelines.

Table V
Recommended Settings Summary

Function	Description
87P, phase differential	Pickup = 0.5 to 1.0 pu of reactor rated current Slope 1 and 2 = default values Restraint Slope 1 limit = default value Unrestrained pickup = off
REF	Pickup = 0.1 to 0.15 pu of rated current
67G	Pickup = 0.1 to 0.15 pu of rated current
67G Directional Settings	Forward threshold: $Z0F = \frac{Z_0}{2}$ Reverse threshold: $Z0R = \frac{Z_0}{2} + \frac{1}{2 \bullet I_{Relay\_Nominal}}$ Positive-sequence restraint factor = fault detector setting in pu of reactor rated current divided by 3 Forward and reverse fault detector = 0.1 to 0.15 pu of rated current
50P	Pickup = set at 50% of minimum close-in line-to-line fault on the line under *N – 1* source condition
50N	Pickup = set at 50% of minimum close-in line-to-ground fault on the line under *N – 1* source condition
51P, 51N	Pickup = 1.5 pu of rated current

IX. References

[1] Z. Gajić, B. Hillström, and F. Mekić, "HV Shunt Reactor Secrets for Protective Engineers," proceedings of the 30th Annual Western Protective Relay Conference, Spokane, WA, October 2003.

[2] E. Nashawati, N. Fischer, B. Le, and D. Taylor, "Impacts of Shunt Reactors on Transmission Line Protection," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011.

[3] J. H. Harlow (ed.), *Electric Power Transformer Engineering*. CRC Press LLC, Boca Raton, FL, 2004.

[4] Cigre WG Report B5.37, "Protection, Monitoring and Control of Shunt Reactors," August 2012.

[5] H. Miller, J. Burger, and M. Thompson, "Automatic Reconfiguration of Zones for Three-Phase and Spare Banks," proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[6] IEEE Standard C37.015, IEEE Guide for the Application of Shunt Reactor Switching.

[7] M. B. Selak, R. Barone, and A. Elneweihi, "BC Hydro Protection Applications for 500 kV Shunt Reactor," proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA, October 2008.

[8] Y. Xue and M. Thankur, "CREZ Line Protection Design: Challenges and Solutions," proceedings of the 39th Annual Western Protective Relay Conference, Spokane, WA, October 2012.

[9] IEEE Standard C37.109, IEEE Guide for Protection of Shunt Reactors.

[10] S. E. Zocholl, J. Roberts, and G. Benmouyal, "Selecting CTs to Optimize Relay Performance," proceedings of the 23rd Annual Western Protective Relay Conference, Spokane, WA, October 1996.

[11] M. Thompson, R. Folkers, and A. Sinclair, "Secure Application of Transformer Differential Relays for Bus Protection," proceedings of the 58th Annual Conference for Protective Relay Engineers, College Station, TX, April 2005.

[12] G. Benmouyal and S. E. Zocholl, "The Impact of High Fault Current and CT Rating Limits on Overcurrent Protection," proceedings of the 29th Annual Western Protective Relay Conference, Spokane, WA, October 2002.

[13] IEEE PES Power System Relay Committee, "CT Saturation Theory and Calculator.zip." Available: http://pes-psrc.org.

[14] S. E. Zocholl and D. W. Smaha, "Current Transformer Concepts," proceedings of the 46th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 1992.

[15] K. Zimmerman and D. Costello, "Fundamentals and Improvements for Directional Relays," proceedings of the 63rd Annual Conference for Protective Relay Engineers, College Station, TX, March 2010.

[16] B. Kasztenny, M. Thompson, and N. Fischer, "Fundamentals of Short-Circuit Protection for Transformers," proceedings of the 63rd Annual Conference for Protective Relay Engineers, College Station, TX, March 2010.

X. Biographies

Faridul Katha Basha received his BE in electrical engineering from Anna University, India, in 2008 and an MSEE from the State University of New York at Buffalo in 2011. Since graduation, he has been employed with Schweitzer Engineering Laboratories, Inc. as a protection engineer in the engineering services division.

Michael J. Thompson received his BS, magna cum laude from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now Ameren), where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of a number of numerical protective relays. He is presently a principal engineer in the engineering services division at SEL, a senior member of IEEE, a main committee member of the IEEE PES Power System Relaying Committee, and a registered professional engineer. Michael was a contributor to the reference book *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers, and has a number of patents associated with power system protection and control.

Previously presented at the 2013 Texas A&M
Conference for Protective Relay Engineers.

20130214 • TP6600-01