

Summary Paper for IEEE C37.109-2023 Guide for Protection of Shunt Reactors

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Abstract—This paper summarizes the protective relaying practices for power system shunt reactors based on the recently published IEEE Std C37.109-2023, “Guide for the Protection of Shunt Reactors,” including the latest protection techniques for turn-to-turn faults. In addition to protection, the paper also points out significant improvements in the latest revision of the Guide including discussions on various reactor construction and configuration, connection and application including the use of dry-type reactors in the EHV systems at and above 345 kV, resonance issues, switching transients, fault clearing, and tripping coordination of line-connected reactors with line protection. The paper also discusses setting examples with discussions on utility events covered in the Guide.

Index Terms—air-core reactor, neutral reactor (fourth-leg reactor), liquid-immersed shunt reactor, oil-immersed shunt reactor, variable shunt reactor (VSR), split-phase shunt reactor, shunt reactor magnetizing inrush current.

I. INTRODUCTION

IEEE Power System Relaying and Control (PSRC) Committee Working Group K26 revised the C37.109-2006 “IEEE Guide for Protection of Shunt Reactors.” This summary paper highlights updates in the Guide IEEE C37.109-2023 [1] to the industry and is referred to as the Guide in the remainder of the paper. Shunt reactors are often required for maintaining system voltage within acceptable limits during light load conditions. They can be installed either on transmission lines or on buses, or on tertiaries of transformers connected to the transmission system.

Two basic shunt reactor configurations are discussed in this paper:

1. Line and bus reactors: Dry-type or oil-immersed, wye-connected, directly grounded, or grounded through a neutral reactor.
2. Tertiary reactors: Dry-type ungrounded wye, connected to the tertiary of a power transformer.

The Guide discusses reactor protection details and various examples in Section 6. Annex A of the Guide summarizes the various protection schemes and settings selection. In addition, some field examples with settings calculations are discussed in Annex B and Annex C.

The Guide is intended for engineers who are familiar with power system protection. This is an application Guide and may

only cover the considerations for some scenarios. Additional reading material is suggested in the Bibliography.

II. REACTOR CONNECTION AND CONSTRUCTION

The Guide provides an overview of the basic construction of oil-immersed iron-core and dry-type air-core units. Shunt reactor construction and configurations can be classified as:

- Dry-type or oil-immersed
- Single-phase or three-phase
- Air-core or gapped iron-core
- Indoor or outdoor installation
- Fixed or variable reactance

Annex F of the Guide expands on various construction arrangements and related protection practices.

The Guide outlines arrangements for connecting shunt reactors to the system: transmission voltage connected (solidly grounded or grounded through a neutral reactor), or tertiary connected (typically ungrounded) and switched either on the bus or neutral sides.

The Guide also introduces variable shunt reactors with tap changers and oil-immersed, iron-core shunt reactors with auxiliary windings to provide station service in remote areas.

III. LINE AND BUS REACTORS

The shunt reactors can either be connected to the substation bus or to the line, but protection concepts are similar. Historically, oil-immersed reactors were almost exclusively used for line and bus applications; however, today dry-type reactors are available through 550 kV.

A. Application and Connection

Reactors are often connected at either one or both ends of a long transmission line, as shown in Figure 1 (a), and are usually wye-connected with a solidly grounded neutral. Reactors are sometimes installed in the middle of long lines to limit the voltage to within the design limits of the line during light load conditions. These reactor banks can be switched using a circuit switcher or circuit breaker or directly connected to the line. In some applications, only one reactor has a breaker allowing it to be switched in or out depending on the need for reactive power and voltage regulation, whereas a second reactor remains directly connected to the line to avoid excessive voltage rise after unexpected load rejections.

In line protection applications where single-phase trip and automatic reclose is used, a fourth reactor is sometimes connected between three phase reactors' neutral point and ground, as shown in Figure 1 (b). The fourth (or neutral) reactor helps suppress the secondary arc current in a faulted and disconnected phase conductor during the auto-reclose dead time.

Reactors can also be connected to the substation bus, solidly grounded, and can be switched. Protection for bus-connected reactors is basically the same as that used for line-connected reactors, except for the resonance consideration discussed in Section III subsection C.

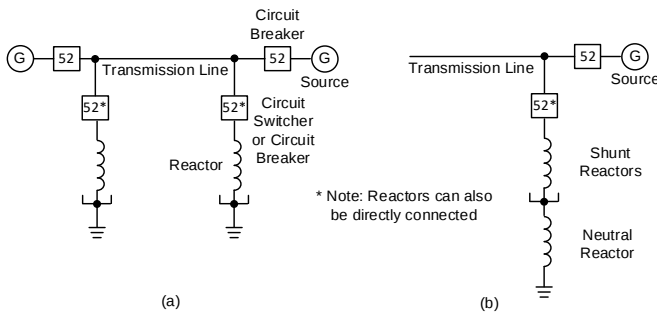


Figure 1. (a) Line-connected, switched shunt reactors without neutral reactor; (b) line-connected shunt reactor with neutral reactor (four-reactor arrangement) connected via circuit breakers to the line

B. System Consideration and Switching

The availability of the switching device between the reactor and the line and the capability of this device to interrupt reactor fault current have a major impact on the protection scheme: See Figure 2 and Figure 3 for line- and bus-connected reactors, respectively.

- For reactors connected to the line via a full-rated circuit breaker, the reactor protection relay will trip only the reactor breaker. However, depending on the failure mode and fault current, a line protection relay can sense the reactor fault and trip the line. More details are discussed in the Guide.
- Typical utility practice is to not trip the reactor breaker due to line protection operation for a line fault and consequent line breakers opening.
- When the reactor breaker is not rated to interrupt reactor short-circuit currents, the reactor protection may be configured to trip the associated line breakers and then open the reactor breaker.
- Line breaker currents on lines with more than 50% shunt compensation may experience delayed current zero-crossings if tripped immediately after energization of the line.

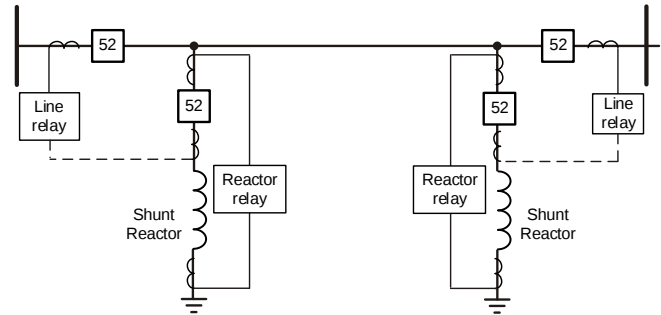


Figure 2. Reactor connected via circuit breakers to the line

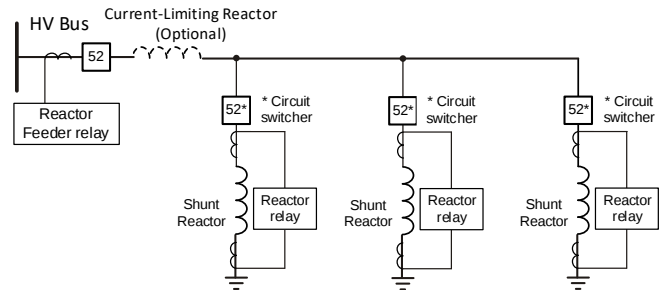


Figure 3. Bus-connected reactors

C. Resonance Consideration for Line Reactors

The presence of a shunt reactor on a line, either in series or in parallel with a capacitance, can result in resonant conditions and oscillations after a disturbance. The shunt capacitance of the line forms a parallel resonance circuit with the shunt reactor. The shunt reactor can also form a series resonance circuit with series capacitance installed on a line. The capacitive coupling from an energized line can cause severe resonant overvoltage into an adjacent de-energized shunt-compensated line (see Figure 4).

For off-nominal resonance frequencies, sensitive protection functions relying on a sequence quantity derived from system nominal frequency (f_s), such as zero- or negative-sequence elements and ratio comparison methods, may cause false operation. These are due to errors after the line is disconnected either during normal de-energization or fault clearance. The off-nominal frequency will also result in errors in impedance measurement in distance elements used for shunt reactor protection. This issue is mitigated by either line breaker status or off-nominal frequency supervision to help prevent nuisance operation of the shunt reactor protection on a de-energized line.

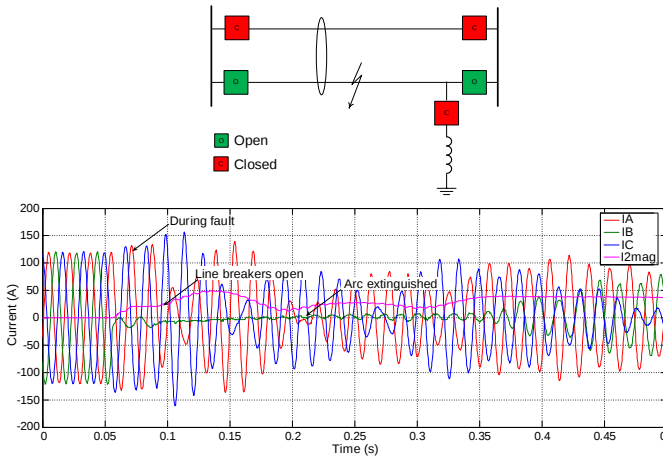


Figure 4. Reactor currents on the 345 kV de-energized line due to mutual coupling

A de-energized shunt-compensated line with an energized parallel line also exhibits oscillatory behavior, as shown in Figure 4 from a field event. The line protection tripped three-phase at both line terminals for a B-phase-to-ground fault. After the secondary arc was extinguished, the B-phase voltage and the B-phase current in the reactor rebuilt due to capacitive coupling with the energized line. Magnetic coupling of three-phase shunt reactors also contributed to rebuilding of the current and voltage in the open phase.

Resonance issues are also encountered on the shunt and series-compensated lines during single-phase tripping and reclosing for single line-to-ground faults. The typical practice is to bypass a series capacitor for single-phase tripping before reclosing. The disconnected phase starts oscillating due to the capacitive coupling from the energized healthy phases, resulting in nuisance reactor protection operation. Such a nuisance operation will block the line from auto-reclosing. To avoid this, sensitive protection elements may need to be blocked.

IV. TERTIARY REACTOR

Dry-type reactor banks are often connected to the delta-connected tertiary of a transformer bank, as shown in Figure 5. Each wye-connected, ungrounded reactor bank can be switched with a bus-side breaker or neutral-side breaker of the reactor bank.

A. Application and Connection

Reactors connected in ungrounded wye on a transformer delta tertiary offer an economical option for providing reactive power to the transmission system. Phase-to-ground faults on only one phase of the ungrounded wye reactor have no immediate effect on the reactor. Often this condition is alarmed to allow operators to disconnect the reactor and take appropriate action. More details and considerations are discussed in the Guide.

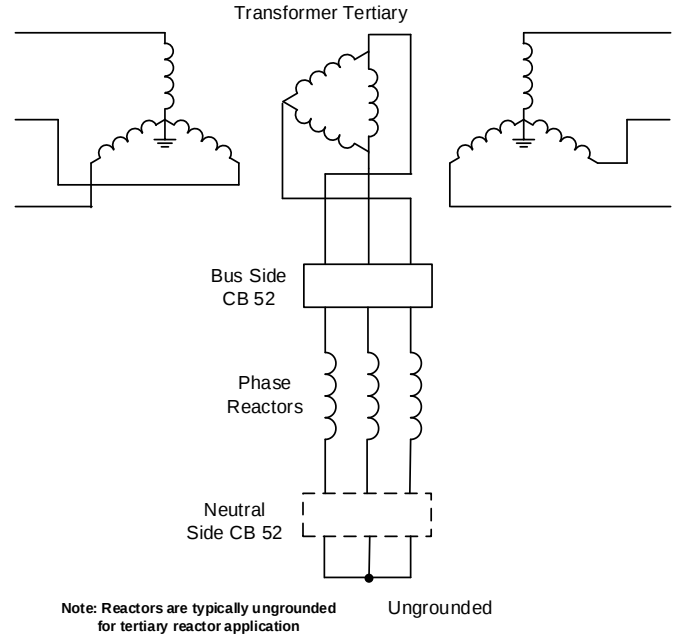


Figure 5. Typical dry-type shunt reactor connection with three-pole reactor with bus-side switching or neutral-side switching

B. System Consideration and Overall Protection Scheme

It is advantageous to provide discrete protection for the tertiary bus and reactor, separate from the main transformer differential protection, as shown in Figure 6 (b) and 6 (c). The Guide details the various protection zones and advantages of schemes, as shown in Figure 6.

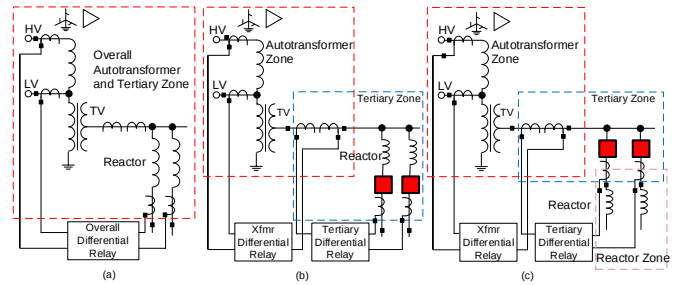


Figure 6. (a) Overall autotransformer and tertiary zone; (b) separate autotransformer and tertiary zone with neutral-side breakers and (c) separate tertiary zone with bus-connected breakers

V. LINE AND BUS REACTOR PROTECTION

This section discusses protection elements for line reactor protection.

A. Protection Elements and Details

Two or more protective relays are used to provide either the same protection and control functionality or reduced functionality in the second relay serving as a backup function.

Typical functions used for the line/bus reactor protection are illustrated in Figure 7.

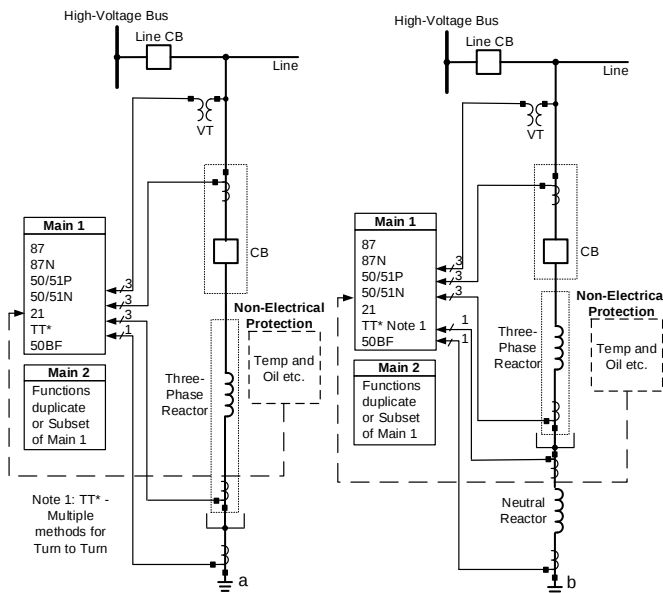


Figure 7. Typical reactor protection

Protection for faults resulting in significant increase of phase currents can be detected by the combination of overcurrent (50/51), differential (87), and distance (21) relays. Protection for faults resulting in a minor increase in current is achieved by sensitive protection schemes including restricted earth fault (REF), turn-to-turn fault protection, sensitive ground fault protection (50N/51N), and non-electrical protection, as shown in Figure 7.

Settings of threshold for the overcurrent protection also depends on the type and configuration of the reactor. As an example, extra-high voltage (EHV) dry-type reactors may have multiple series coils per phase, and shorting of one coil may not increase the phase current as much as the case in an oil-immersed reactor. The Guide discusses in detail the thresholds used in diverse designs of shunt reactors including gapped iron-core and air-core designs. The Guide further discusses the impact of inrush currents in the gapped iron-core on instantaneous overcurrent settings (50N/50G).

Differential protection (87) provides reliable protection for faults within the reactor involving ground or multiple phases in gapped iron-core reactor configurations but is not very useful in air-core dry-type reactors where the probability of multiphase or phase-to-ground faults is low.

Differential protection could either be low-impedance percentage differential protection or high-impedance protection. Settings thresholds of differential relay applications are discussed in detail in the Guide. The settings thresholds are selected to be biased more toward security as such faults in gapped-iron-core designs tend to generate currents that do not require pickup settings below 20% of the rated current. Sensitive settings may require added security measures provided by the manufacturers, such as dc-level detectors, dynamic slopes, and directional supervision. In addition to these supervisions, there are applications which set harmonic restraint features to provide more security, but they may not be effective in all applications. The use of instantaneous (high set or unrestrained) differential settings are also mentioned in the

Guide where harmonic blocking or restraint is used to add security. If harmonic blocking or restraint is not used, unrestrained settings do not provide an added advantage.

REF protection, sometimes called ground current differential, is to detect winding faults involving ground (phase-to-ground faults) in grounded reactor configurations of gapped-iron-core designs. In contrast to phase differential schemes, the scheme compares the neutral current (I_N) with the terminal-side residual ground current (I_G), which is the sum of three-phase currents. With sensitive settings provided, REF is blocked during energization due to uneven response of CTs.

Distance protection (21) is used as a backup protection to detect phase-to-phase, phase-to-ground, and to some extent, turn-to-turn faults. A single zone distance function set to less than the reactor reactance with a margin is applied. Additional considerations are needed for a four-legged reactor configuration, non-linearity of the reactor during overvoltage conditions, and the potential misoperation after line de-energization during ring-down oscillations.

B. Sensitive Protection for Turn-to-Turn Faults

Differential protection cannot detect turn-to-turn faults within the reactor winding as the currents measured at the phase terminals (I_T) and neutral (I_N) terminals will be the same, as shown in Figure 8.

Current circulates in the shorted turns, resulting in localized heating and insulation failure. In an oil-immersed reactor, it is important to detect such a fault and isolate the unit quickly, preventing severe winding damage and possible tank rupture from oil combustion due to arcing. Turn-to-turn faults in dry-type air-core reactors result in flashover of the coil and may be detected by overcurrent relays without catastrophic failure due to the absence of oil.

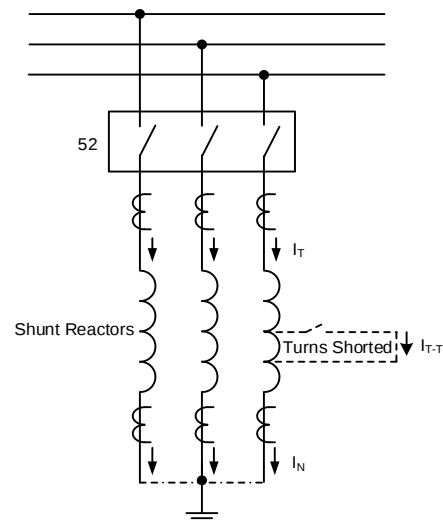


Figure 8. Turn-to-turn fault in one phase of a shunt reactor

The negative- and zero-sequence directional method (67Q/67N) uses phase relationship between negative- and zero-sequence voltage and negative- and zero-sequence current to detect turn-to turn-faults, as shown in Figure 9.

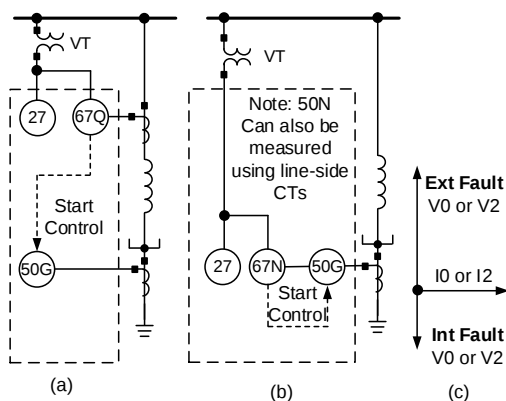


Figure 9. (a) Turn-to-turn fault protection for grounded reactor using negative-sequence directional control; (b) turn-to-turn fault protection for grounded reactor using zero-sequence directional control; and (c) phase relation for external and internal fault

The normalized negative-sequence ratio method (60R) monitors vectorial difference ($V2/V1-I2/I1$) and operates if the set threshold is exceeded, providing a very sensitive turn-to-turn fault detection.

The directional (67Q/67N) and negative-sequence ratio (60R) schemes are set with time delay and disabled during energization. The Guide provides detailed discussions to improve security and sensitivity of turn-to-turn protection performance.

In oil-immersed reactors, turn-to-turn faults are also detected by non-electrical protection devices such as sudden pressure and gas accumulation devices.

C. Neutral (Fourth-Leg) Reactor Protection

The Guide discusses neutral reactor sizing and protection of the fourth-legged shunt reactors, which are applied for single-phase trip application. Figure 10 shows the example of a neutral reactor with bypass breaker.

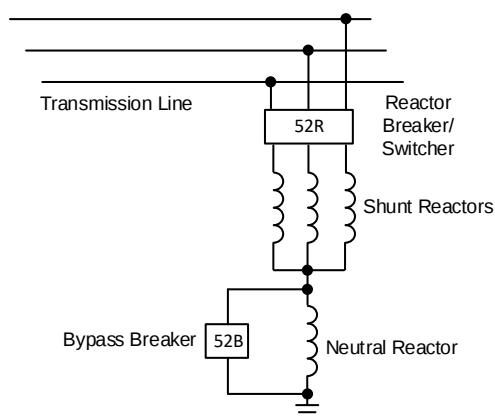


Figure 10. Neutral reactor with bypass device

VI. TERTIARY REACTOR PROTECTION

This section discusses protection elements for the shunt reactor connected to the tertiary winding of the system transformer.

For ungrounded tertiary reactors, neutral overcurrent protection is ineffective and thus unnecessary.

A. Phase-Overcurrent Protection

Typical functions used for the tertiary reactor protection are illustrated in Figure 11.

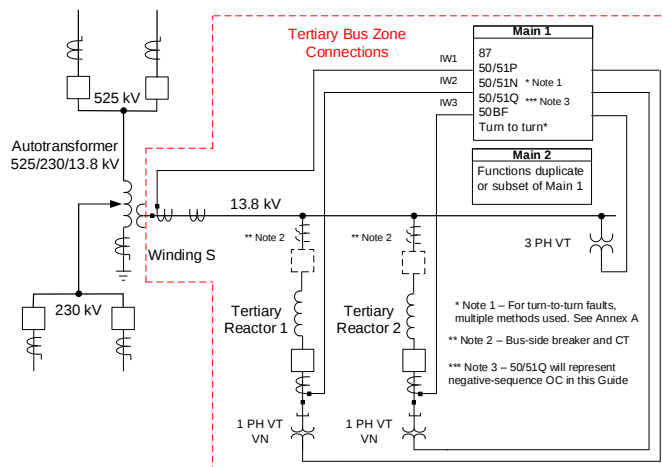


Figure 11. Example of combined tertiary and reactor protection using microprocessor-based relay

Phase overcurrent elements (50/51) detect a completely shorted phase (Figure 12). During this condition, the faulted phase current is three times the rated phase current, with unfaulted phase currents at 1.73 times the rated. For electromechanical relays, the significant dc offset during energization is considered when setting the phase overcurrent pickup; however, microprocessor relays typically filter out dc.

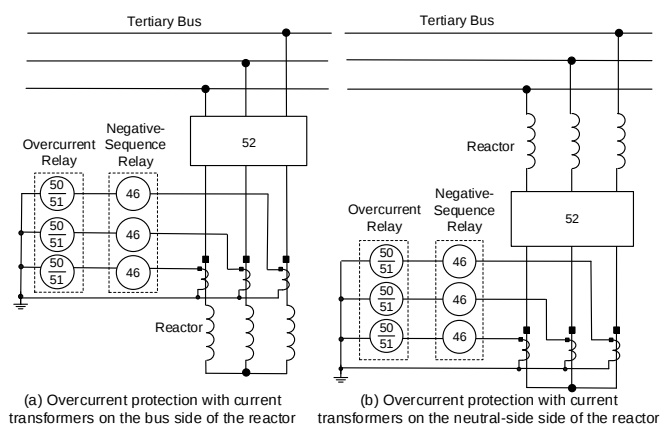


Figure 12. Example of combined tertiary and reactor protection using microprocessor-based relay

Phase-overcurrent protection can also provide backup protection for multiphase faults on the source side of the reactors, including the transformer tertiary bus if the CTs are on the transformer tertiary bushings. When the CTs are inside the transformer delta tertiary connection, the phase-overcurrent elements may require blocking from operating on circulating zero-sequence current resulting from system ground faults. The

Guide discusses blocking methods for both electromechanical and microprocessor relays. See Figure 13.

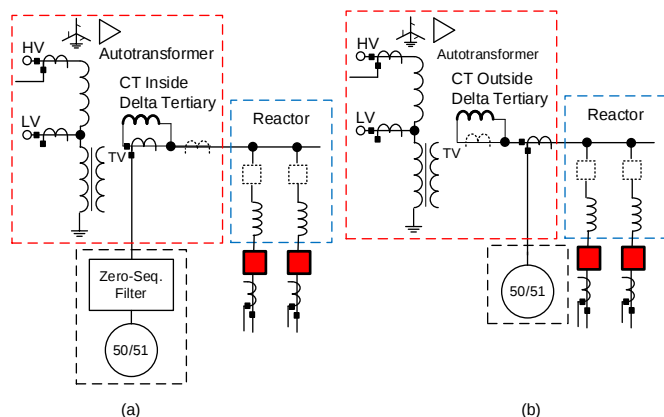


Figure 13. Example of combined tertiary and reactor protection using microprocessor-based relay

B. Differential Protection

Differential protection covers multiphase faults (phase-to-phase and three-phase). As previously stated in Section IV, based on the CT location, the reactors may or may not be included in the transformer differential zone (Figure 6). It may be necessary to prevent misoperation of the differential element on reactor energization; methods are discussed in the Guide.

C. Negative-Sequence Overcurrent Protection

Negative-sequence overcurrent elements may provide protection for unbalanced currents resulting from phase-to-phase faults and possibly limited protection for turn-to-turn faults. The Guide discusses pickup and time delay considerations.

D. Sensitive Turn-to-Turn Protection

Turn-to-turn faults can be difficult to detect by measuring phase currents and voltages due to the slight changes in measured phase current and voltages for this type of fault. The Guide describes several methods including neutral overvoltage (59N), zero-sequence voltage differential (87V), and split-phase overcurrent. Two additional methods are negative-sequence directional overcurrent and normalized voltage and current ratio, which are discussed in the Guide [1].

Neutral overvoltage protection requires a single voltage measurement of the neutral-to-ground voltage with an overvoltage relay 59N (Figure 14). This scheme can detect open-phase and turn-to-turn faults, including complete short-circuit of an entire phase winding. The Guide describes sensitivity and time delay considerations, as well as acceptable types of potential devices.

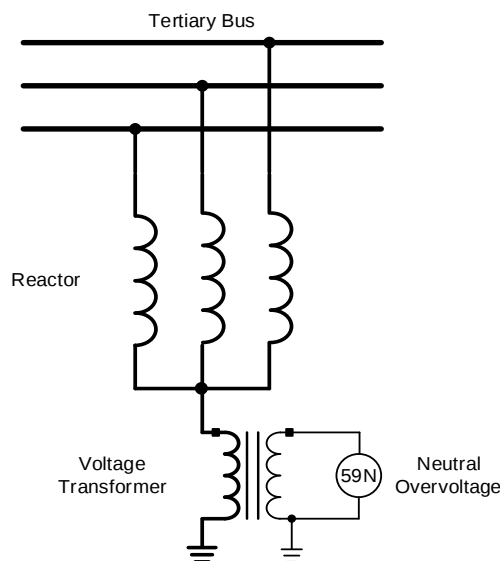


Figure 14. Neutral overvoltage-unbalance scheme

Because the 59N element is sensitive to unbalanced phase voltages resulting from inherent system unbalance and reactor impedance differences between phases, the pickup can either be desensitized or, if three-phase tertiary bus voltages are available, a zero-sequence voltage differential element 87V can be configured (Figure 15). This element compares the neutral voltage with the zero-sequence voltage developed by the three-phase tertiary bus VTs.

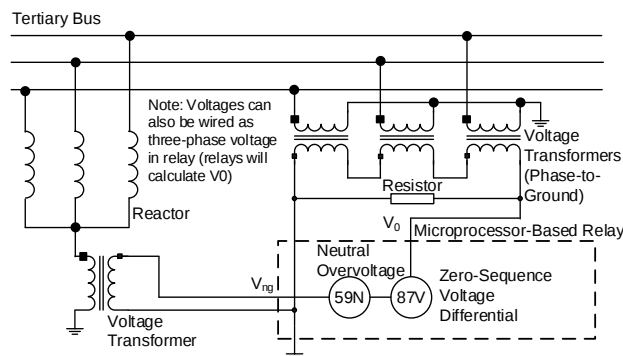


Figure 15. Zero-sequence voltage differential relay for dry-type reactors

The split-phase method is only applicable to reactors constructed from multiple parallel windings per coil (Figure 16). The Guide describes three-phase sensing and single-phase sensing, noting that single-phase sensing is more common. The two neutral-end leads are connected in opposition through a CT whose output is connected to an overcurrent relay 50/51. A turn-to-turn fault in one of the parallel phase windings produces an imbalance between current in the parallel windings, resulting in a difference current measured by the overcurrent relay. The Guide discusses pickup considerations as well as methods of dealing with inherent split-winding current imbalance due to manufacturing tolerances and stray flux induction in the leads.

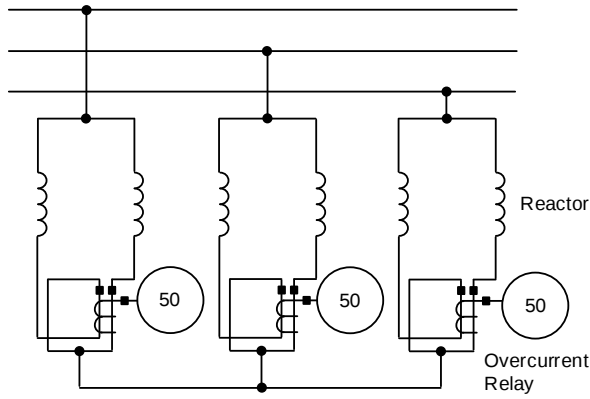


Figure 16. Split-phase protection (single-phase sensing)

E. Reactor Breaker Failure

When the reactor switching device is on the source side of the reactor, breaker failure protection may be applied using breaker failure initiate, current detector and a timer (Figure 17, AND1 gate). However, if current detector sensitivity requirements cannot be achieved, low-current logic may be required.

Special considerations are necessary if the reactor switching device is located on the neutral end of the reactor. The Guide describes example cases where an external fault occurs with the neutral end breaker open. If the protective elements are configured to only trip the reactor breaker, it will not clear the fault (Figure 18 and Figure 19). Additionally, the location of the CTs with neutral end breakers must be considered when determining which, if any, protective elements will operate. The Guide discusses each case in Figure 18 and Figure 19 and evaluates which elements may and may not operate, and where special breaker failure logic may be required.

For example, consider the middle cases in Figure 18 and Figure 19, for a three-phase fault external to the open neutral breaker. In Figure 18 the CTs are located on the source side of the breaker, so the protective elements will operate, and a 50BF element along with breaker 52b contacts may be used to trip the breakers necessary to de-energize the tertiary bus and clear the fault. However, in Figure 19, the CTs are located on the neutral end of the breaker and do not measure any current. Protection for this fault must be provided by a tertiary differential relay (Figure 6).

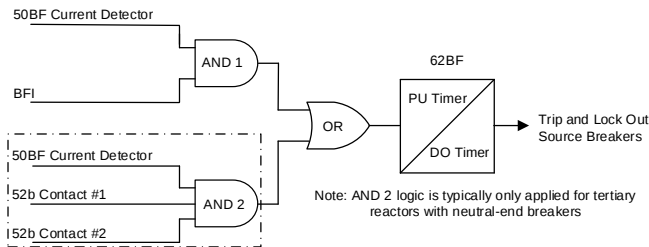


Figure 17. Breaker failure logic for the reactor breaker located at the neutral end of the reactor

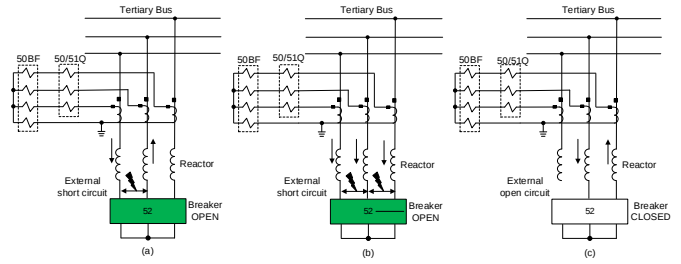


Figure 18. Line-side CT neutral-side breaker open, with external fault and 50BF

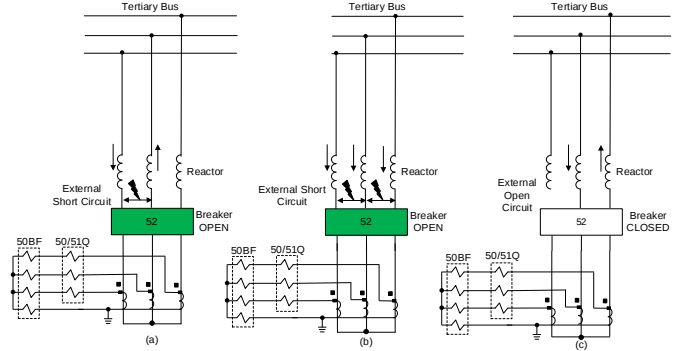


Figure 19. Neutral-side breaker open, CT on breaker neutral with external fault and 50BF

F. Ungrounded Bus Issues

The Guide discusses ground faults on ungrounded tertiary buses. This protection is provided by three-phase VTs connected wye-grounded/broken-delta, with the broken-delta output providing zero-sequence voltage to an overvoltage relay that can be configured for alarming or tripping.

VII. ANNEXES

A. Annex A

Annex A of the Guide has three tables.

Table A.1 discusses the various protection elements, i.e., phase differential (87), REF (87N), distance (21), overcurrent (50/51), and various turn-to-turn protection and sensitivity. The Guide provides the details of each protection scheme.

Table A.2 discusses the range for various protection elements for line/bus reactors. For example, percentage phase differential (87) element pickup can be set $(0.2 \text{ to } 0.75) \times I_{\text{RATED}}$ based upon CT analysis and in consultation with the relay manufacturer. These ranges are suggested based on the field experience of utilities.

Table A.3 discusses the range for various protection elements for tertiary reactors.

B. Annexes B, C, and D

Annex B includes a line reactor protection example.

Annex C includes multiple examples of transformer tertiary reactors, and their configuration when being employed in the field.

Annex D includes a discussion on voltage-based schemes for a tertiary reactor. This annex also discusses the details of turn-to-turn fault protection methods.

C. Annexes E and F

Annex E discusses line parameters and shunt reactors for compensation. The annex also briefly discusses reactive power compensation devices and shunt reactor types.

Annex F addresses various topics which were not addressed in the previous version of the Guide:

For oil-immersed, iron-core units:

- Design differences between transformers and reactors
- Impact of reactor high X/R on CT performance
- Different types of iron-core shunt reactor construction
- Magnetically controlled shunt reactors (a brief review)
- Variable shunt reactors (a brief review)

For dry-type, air-core units:

Historically, shunt reactors applied at or above 138 kV were almost exclusively oil-immersed gapped iron-core type. Since in the early 2000s, this began to change, and dry-type air-core units have been applied at successively higher voltages. There is presently a significant installed base for dry-type air-core shunt reactors up to and including 420 kV, and units have been type-tested and are available up to 550 kV.

Due to significant differences in construction compared to oil-immersed iron-core units, dry-type air-core units have very different typical modes of failure. These construction and failure mode differences lead to significant differences in the appropriate protection design, and in some cases relay settings. In addition, even within the dry-type air-core shunt reactor family, there are various configurations, depending on voltage rating, direct connected or tertiary connected, and other factors that lead to significant variations in possible or likely failure modes and the resulting appropriate protection design.

Annex F provides an overview of the various different dry-type air-core physical arrangements and, along with other sections of the Guide, key resulting implications for protection design.

One typical example of 69 kV or below dry-type reactors is shown in Figure 20. For voltages at 115 kV and above, multiple series-connected coils are usually selected. See the Guide [1] for details.

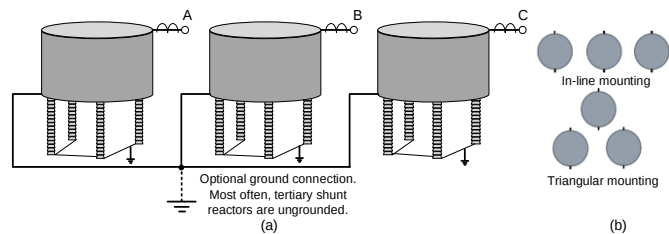


Figure 20. (a) Single coil per phase arrangement; (b) in-line and triangular mounting configurations

VIII. SUMMARY

The 2023 revision of C37.109-2006, “IEEE Guide for the Protection of Shunt Reactors” significantly contributes to the Transmission and Distribution industry. The Guide delves into comprehensive protection practices for power system shunt reactors, emphasizing their crucial roles in voltage control, reactive power compensation, and transient mitigation during switching. The Guide covers various reactor types, from oil-immersed to variable and dry-type air-core reactors designed for EHV scenarios, addressing the complexities associated with shunt reactor applications. Notably, the Guide also briefly highlights the generation of post-disturbance oscillations in shunt reactors coupled with line stray capacitance. Three utility events illustrate resonant overvoltage implications, where the shunt reactor interacts with line capacitance, inducing severe resonant overvoltage in adjacent de-energized shunt-compensated lines.

The Guide meticulously details protection practices, including phase overcurrent (50/51), differential (87), REF (87N), distance (21), sensitive turn-to-turn, and negative- and zero-sequence directional overcurrent functions. Practical examples, settings calculations, and considerations for different reactor types contribute to a comprehensive Guide tailored for power system protection professionals. The Guide enhances the understanding of shunt reactor applications and provides practical insights into protection practices, making it an invaluable resource for protection engineers.

IX. REFERENCE

- [1] IEEE Std C37.109-2023: IEEE Guide for the Protection of Shunt Reactors.