



IEEE Guide for the Protection of Shunt Reactors

STANDARDS

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

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IEEE Guide for the Protection of Shunt Reactors

Developed by the
Power System Relaying and Control Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

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Abstract: A guide to the methods and configurations for the protection of power system shunt reactors is provided in this guide. The protection of oil-immersed reactors equipped with auxiliary power windings, improved turn-to-turn fault protection, and use of digital (microprocessor-based) protection for shunt reactors are included.

Keywords: air-core, auxiliary power winding, circuit switcher, dry-type, dry-type reactors, IEEE C37.109™, iron-core, microprocessor-based relays, neutral reactor, oil-immersed, pole disagreement, protection, protective relay, reactance, resonance, series-compensated, shunt reactors, turn-to-turn, voltage-unbalance relaying

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Introduction

This introduction is not part of IEEE Std C37.109-2023, IEEE Guide for the Protection of Shunt Reactors.

This document is a revision of IEEE Std C37.109-2006, IEEE Guide for Protection of Shunt Reactors. This guide is intended to provide aid in the effective application of relays and other devices for the protection of shunt reactors.

In this revision, the following notable changes have been made.

- Updated general information of shunt reactor selection, including types of reactors (variable shunt reactors), application of dry-type air-core reactors for extra-high-voltage applications and others.
- Added details describing current and voltage transients during switching and clearing of faults on shunt compensated transmission lines and reactors.
- Added line protection coordination considerations for line/bus reactor protection and transformer protection coordination considerations for tertiary reactor protection.
- Updated the reactor protection using latest technologies and protection methods, i.e., Turn to Turn protection using latest development.
- Added informative annexes with examples of line/bus reactor and tertiary reactor application and settings calculations.

Acknowledgments

Figure F.1 reprinted with permission from Schweitzer Engineering Laboratories, Inc., A Fresh Look at Practical Shunt Reactor Protection [B8], © 2022.

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IEEE Guide for the Protection of Shunt Reactors

1. Overview

1.1 Scope

This guide includes descriptions ~~description~~ of acceptable protective relay practices applied to power system shunt reactors. The guide covers protection for dry-type ~~(air-core)~~ and oil-immersed-type reactors connected to ~~used on~~ power system buses and lines. Also included in this guide is ~~are~~ the protection of oil-immersed reactors equipped with auxiliary power windings, ~~improved turn-to-turn fault protection, and use of digital (microprocessor-based) relays for shunt reactor protection.~~

1.2 Purpose

The purpose of this guide is to provide users of shunt reactors acceptable methods and configurations for the protection of power system shunt reactors.

1.3 Word Usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

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IEEE Std C37.015™-~~2017~~ ~~1993~~, IEEE Guide for the Application of Shunt Reactor Switching. ^{8.2} ~~1.2~~

IEEE Std C57.21™-2021, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.

~~IEEE Std C62.22™, IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating Current Systems.~~

3 Definition, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online*¹⁰ and IEEE Std C37.100™ 1992, IEEE Standards Definitions for Power Switchgear [B22],¹¹ should be consulted for terms not defined in this clause.

air-core reactor: A reactor that does not include a magnetic core or magnetic shield.

liquid-immersed shunt reactor: A shunt reactor in which the core and coils are immersed in an insulating liquid.

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¹⁰ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

^{11.3} The numbers in brackets correspond to those of the bibliography in Annex ~~G~~ ~~A~~.

neutral reactor (fourth-leg reactor): A single reactor connected between the neutral of a three-phase shunt reactor and ground, applied in a transmission line for single-phase trip and auto-reclose applications for the purpose of secondary arc extinction and successful single-phase reclose operation.

oil-immersed shunt reactor: A shunt reactor in which the core and coils are immersed in transformer oil.

shunt reactor magnetizing inrush current: The transient magnetizing current that can flow in an iron-core reactor winding during either energization or voltage restoration after fault clearance. Magnetizing inrush current does not exist in an air-core reactor.

split-phase shunt reactor: A shunt reactor where each phase winding is constructed as two parallel half-windings with a common terminal at one end and two separate terminals at the other end.

variable shunt reactor (VSR): A shunt reactor where the inductive reactance is dynamically variable. Typically insulating liquid-immersed with an on-load tap changer (OLTC).

~~For definitions of terms used in this guide, see *The Authoritative Dictionary of IEEE Standards Terms* [B8]³ and IEEE Std C37.100™-1992 [B10].~~

3.2 Acronyms and abbreviations

BFI breaker failure initiate

CLR current limiting reactor

EHV extra high voltage

HV high voltage

MCSR magnetically controlled shunt reactor

OC overcurrent

OLTC on-load tap changer

SIL surge impedance loading

SPT single-phase tripping

SVC static var compensator

TRV transient recovery voltage

VSR variable shunt reactor

4. Use of shunt reactors

The main functions of shunt reactors in transmission and distribution systems are as follows:

- Control of operating voltages to stay within the permissible operating range
- Support of reactive power compensation
- Reduction of switching transients on transmission lines

Shunt reactors can ~~be used to~~ provide inductive reactance to compensate for the effects of high charging current ~~on~~ ~~of~~ long overhead transmission lines and underground/undersea ~~pipe-type~~ cables. Shunt reactors are applied to keep the system voltage within operating limits on open-ended long transmission line and during ~~For~~ light load conditions. In addition to fixed shunt reactors, variable shunt reactor (VSR) designs are now available to meet more frequent variable system conditions because of an increase in renewable generation ~~, this charging current can produce more leading reactive power than the system can absorb with the consequent risk of instability or excessive high voltages at the line terminals (Ferranti effect).~~

4.1 Installation considerations

When planning the installation of shunt reactors, consideration is usually given to the type, rated reactive power, environment, and other factors. For air-core units, because there is no iron core to constrain the magnetic field, the field is broadcast through and around the reactor. This stray field can lead to circulating currents in closed conducting loops which link the reactor stray flux as well as eddy current heating in nearby metallic parts, including any foundation reinforcing rebar. Sufficient clearance to closed electrical loops and nearby metallic parts is observed, and care taken also in the routing of control cables and CT secondary cables. Guidance as to the required magnetic clearances is provided on the manufacturer's drawings. A further consideration which arises due to the stray field is that the magnetic coupling and therefore mutual inductance between phases is somewhat dependent on the phase-to-phase spacing and whether the phases are arranged in a straight line or equilateral triangle. Typically, the manufacturer's recommended clearances keep phase-to-phase coupling within 1% to 2%. For additional information and guidance, refer to Annex F of this standard and Caverly et al. [B6].

From the protection perspective, oil-immersed reactor CT locations external or internal to a reactor can impact protection sensitivity because of stray flux. For internal reactor CTs, magnetic shield or flux equalizing windings are among the methods to reduce effect of stray flux as suggested in CIGRE TB 655:2016, Annex H [B11]. For dry-type air-core units, the reactor stray flux can also have an effect on CT accuracy. This can be addressed through equalizing windings in the CT as described above, or by positioning the CTs sufficiently far away from the reactor.

Refer to IEEE Std C57.21-2021,¹² IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA, CIGRE TB 655:2016 [B11], Caverly et al. [B6], and CIGRE TB 693 [B12] for details of both dry-type and oil-immersed shunt reactors. Some significant factors affecting installation are temperature, altitude, humidity, seismic conditions, contamination, voltage conditions, presence of magnetic field shielding, and spacing between reactors.

¹² For Information on references can be found in ~~see~~ Clause 2.

4.2 Applications of shunt reactors – Line, bus, and/or transformer tertiary

Shunt reactors required for maintaining system voltage within acceptable limits can be installed either on transmission lines or on buses, or on tertiaries of transformers connected to the transmission system. At system voltages below 230 kV where the primary purpose is to maintain the system voltage, shunt reactors are installed on buses. On extra high-voltage (EHV) systems at 345 kV and higher, shunt reactors are also installed on the lines to limit switching transients and to limit steady-state open-end voltages within permissible limits. Sizing of the reactor is generally determined by planning studies such as power flow and transient studies. Shunt reactors on lines can either be directly connected or connected through a switching device as determined by the studies. In addition, these switching devices may incorporate a controlled switching feature. In many bus-connected shunt reactor applications, reactors are operated in stages. For example, breakers or reactor switchers can be used to operate the selected shunt reactors to provide a more precise voltage control. System operators can take advantage of this additional fine control to meet specific system operating requirements. In addition to switched reactors, some utilities presently use VSRs with tap changer (see Variable shunt reactor in 5.5). For additional information, refer to Annex F of this guide and CIGRE TB 693:2017, Section 3 [B12].

5. Reactor connection and construction ~~and characteristics~~

Shunt reactor construction and configurations can be classified as follows:

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

The two general types of construction predominantly used in power systems ~~for shunt reactors~~ are dry-type air-core and oil-immersed gapped iron-core reactors. The basic construction features of each type, ~~along with variations in design~~, are discussed in 5.1 and 5.2. Additional details are provided in Annex F.

5.1 Dry-type air-core reactors

Modern dry-type air-core reactors are constructed as single-phase units which are typically mounted side by side on base support insulators and, optionally, on support pedestals. They consist of one or more concentric helical windings which are electrically connected in parallel and separated by cooling ducts to facilitate their natural convective cooling. The windings are typically constructed of aluminum conductors which are insulated with a type of insulating tapes or films and then encapsulated, typically in an epoxy fiberglass composite, to provide mechanical strength and support, and protection of the winding and insulation material from the environment. They may be designed for either indoor or outdoor application.

In some cases, a so-called “three-phase stacked unit” is constructed by mounting the three single-phase units, one on top of the other, separated by interphase support insulators. Dry-type air-core tertiary shunt reactors normally consist of a single coil per phase, whereas at voltages of 115 kV and above, two or more series connected coils, depending on the voltage, are normally used. The multiple series coils may be arranged one on top of the other in a single column or as multiple series connected columns supported by suitably rated base insulators. The specific physical arrangement is of some importance from a protection perspective because it in part determines what type of faults may occur and therefore what protection methods are effective. Further construction details are addressed in Annex F. The differences in construction between dry-type air-core and oil-immersed gapped iron-core units also lead to important differences from a protection perspective. These differences are also addressed in further detail in Annex F.

~~Dry type shunt reactors generally are limited to voltages through 138 kV and can be directly connected to a transmission line or applied on the tertiary of a transformer that is connected to the transmission line being compensated. The reactors are of the air core (coreless) type, open to the atmosphere, suitable for indoor or outdoor application. Natural convection of ambient air is generally used for cooling the unit by arranging the windings so as to permit free circulation of air between layers and turns.~~

~~The layers and turns are supported mechanically by bracing members or supports made from materials such as ceramics, glass polyester, and concrete. The reactors are constructed as single-phase units and are mounted on base insulators or insulating pedestals that provide the insulation to ground and the support for the reactor.~~

~~Since the dry-type shunt reactor has no housing or shielding, a high-intensity external magnetic field is produced when the reactor is energized. Care is thus required in specifying the clearances and arrangement of the reactor units, mounting pad, station structure, and any metal enclosure around the reactor or in the proximity of the reactor. A closed metallic loop in the vicinity of the reactor can produce losses, heating, and arcing at poor joints; therefore, it is important to avoid these loops or to maintain sufficient separation distances. The magnitude of current induced in the loop, which is responsible for extra losses and heating, is dependent on the orientation of the loop with respect to the reactor, impedance of the loop, size of the loop, and distance of the loop from the reactor. Another consideration is the effect of the magnetic fields on the impedance deviation between phases. Methods of minimizing the deviations include adequate separation or arranging the reactors in an equilateral triangle physical configuration. Deviation from impedance values for reactors will result in a deviation from the actual rating in megavars. The deviation issue as it applies to relaying is discussed in 7.4.3. The reactor manufacturer can provide guidance regarding appropriate clearances or recommendations to minimize stray heating, losses, and impedance deviations.~~

~~For the same range of applications,~~ The primary advantages of dry-type air-core reactors, compared to oil-immersed iron-core types, include being environmentally friendly requiring lower maintenance, elimination of site initial and operating costs related to oil containment and fire deluge, lower weight, ~~lower losses~~, and the absence of insulating oil and its maintenance. Because ~~The main limitation for the application of dry-type air-core reactors is that of connection voltage where the reactor size becomes prohibitive for higher transmission system voltages. Since~~ these reactors do not have an iron core, the impedance is linear with respect to voltage and there is no transient energization magnetizing inrush current or harmonics when the reactor is energized or voltage changes instantaneously at its terminals. The absence of insulating oil also eliminates the possibility of consequential failures involving oil fires spreading to other equipment. The main disadvantage of dry-type air-core units is that they typically require more space in the station than oil-immersed gapped iron-core units for the same MVA rating.

5.2 Oil-immersed reactors

The two design configurations of oil-immersed shunt reactors are coreless type and gapped iron-core type. ~~Both designs are subject to low-frequency long time constant currents during de-energizing, determined by the parallel combination of the inductance of the reactor and the line capacitance. However,~~ The gapped iron-core design is subject to more severe ~~energizing inrush~~ energization current than the coreless type. Most coreless shunt reactor designs have a magnetic circuit (magnetic shield) that surrounds the coil to contain the flux within the reactor tank. The ~~iron-steel~~ core-leg that normally provides a magnetic flux path through the coil of a power transformer is replaced (when constructing coreless reactors) by insulating support structures. This type of construction results in an inductor that is linear with respect to voltage.

The magnetic circuit of a gapped iron-core reactor is constructed in a manner ~~very~~ similar to that used for power transformers with the exception that small gaps are introduced in the iron core to improve the linearity of inductance of the reactor and to reduce residual or remnant ~~remanent~~ flux ~~when compared to a reactor without a gapped core.~~

Oil-immersed shunt reactors can be constructed as single-phase or three-phase units and are very similar in external appearance to that of conventional power transformers. They are designed for either self-cooling or forced-cooling.

5.3 Connection to the system

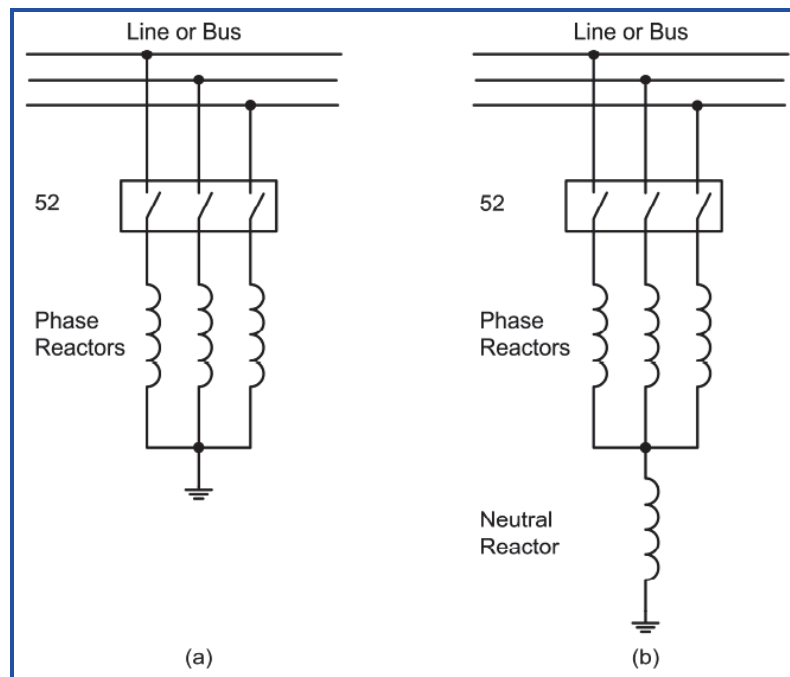
Line-connected reactors can be connected either at one end of the line or at both ends of the line. Reactors can be directly connected to reduce overvoltages on long lines or can be switched to control voltage and reactive power. These reactors are normally directly grounded as shown in Figure 1(a) or grounded through the neutral reactor as shown in Figure 1(b).

Sizing, location, and number of shunt reactors are dictated by line parameters and system conditions. Refer to Annex E for details and additional analysis.

Shunt reactors can be connected to the transformer tertiary winding for the same purpose of controlling voltages, reactive power support, and reducing switching transients.

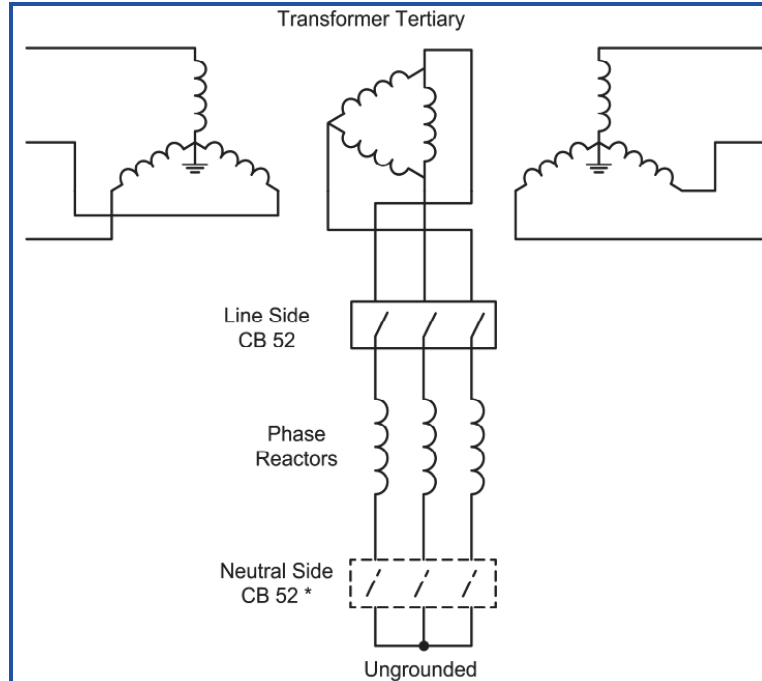
Typically, reactors connected to the tertiary bus are ungrounded. Tertiary reactors may have breakers located on the tertiary bus or neutral side of the reactor, depending upon the breaker fault current interruption capability. A neutral-side breaker results in additional issues and protection challenges, which are discussed in 6.2.

Figure 2 shows the tertiary reactor connection with line- and neutral-side breakers.



(New)

Figure 1 — (a) Three-phase reactor connected to the line or bus; (b) phase reactor grounded through neutral reactor connected to the line or bus



(New)

Notes:

1. Reactors are typically ungrounded for tertiary reactor application
2. Breaker can be on line side (shown with solid lines) or neutral side.
(shown with dashed lines)

Figure 2—Three-phase reactor connected to the transformer
tertiary winding

5.4 Reactors grounded through a neutral reactor

For HV transmission line shunt reactors, an additional single-phase reactor (neutral reactor) is sometimes connected between the three-phase shunt reactor's neutral and ground as shown in Figure 1(b). Reactors grounded through a neutral reactor (fourth-leg reactor) are used to enable fast and successful single-phase reclosing on the main transmission lines. During the autoreclosure dead time, after a single-line-to-ground fault is cleared, the faulted phase remains capacitively and inductively coupled to the remaining two healthy phases, resulting in continuation of the fault current known as a secondary arc current. The presence of a secondary arc prevents deionization of the air around the fault location, resulting in an unsuccessful reclose attempt. Use of a properly rated neutral reactor helps in ensuring faster secondary arc extinction and successful single-phase reclose operation. Neutral reactor sizing for a single-phase tripping (SPT) application is determined via system studies [B27]. For short lines based upon system studies, some SPT applications may not need neutral or line reactors.

Excessive overvoltages can occur on the open phase during the single-pole open deadtime if the shunt compensation level is very high (e.g., more than 70% of the line charging). The neutral reactor can be used to reduce the resonance to lower the open-phase voltage to acceptable levels. Neutral reactors are also installed on the line reactors to reduce voltages higher than permissible on de-energized shunt-compensated lines in parallel with an energized line due to resonance conditions. The neutral reactor is sized to limit the voltage across the phase reactor to an allowable level and also to limit the voltage from the reactor neutral to ground compatible with the reactor insulation characteristics [B35], [B10].

5.5 Variable shunt reactor (VSR) with tap-changer (for oil-immersed only)

VSRs integrate an on-load tap changer (OLTC) that adjusts reactive power compensation to maintain acceptable bus voltages under variable load profile and network configuration. The OLTC is typically controlled by an automatic voltage regulator (AVR) or a power management system (PMS) that allows VSR rating to be changed in discrete steps. The typical regulation range starts as low as 20%, and goes to 100%, and is available for systems up to 550 kV. The regulation speed is normally in the order of seconds per step and approximately a minute from maximum to minimum rating.

VSR can be bus- or line-connected depending on line or cable length and compensation requirements. The flexible reactive compensation ranges achieved by recent VSR technologies have enabled newer facility designs to deploy a line connected VSR through either disconnect switches, which saves space and cost, or through circuit breakers.

5.6 Auxiliary windings (for oil-immersed only)

Because shunt reactors are used to control voltage on long HV transmission lines, reactors often are in remote regions that may not have an extensive or reliable distribution grid. Obtaining reliable station power for the reactor switching station can be a problem. The HV reactor application usually calls for oil-immersed reactors that look similar in appearance to power transformers. When designed with a gapped iron core, these reactors can be equipped with a secondary core and an auxiliary winding such that a low voltage can be extracted from the HV line.

6. ~~Typical~~ Reactor protection

~~The following~~ Two basic shunt reactor configurations are considered:

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

~~b) Oil immersed, wye connected, with a solidly grounded or impedance grounded neutral, connected to the transmission system~~

Major fault protection for line and bus reactors can be achieved through overcurrent (OC) relaying, differential relaying, distance, or a combination of these methods. Protection for turn-to-turn faults can be provided by negative- or zero sequence directional or normalized negative sequence ratio method, negative or zero-sequence OC, thermal, gas-accumulator (oil-immersed only), sudden-pressure relays (SPRs) (oil-immersed only), or by a combination of these relays. See 6.1.4.

Major fault protection for tertiary ~~dry-type~~ reactors can be achieved through OC, ~~overcurrent~~ differential, or negative-sequence relaying schemes, or by a combination of these relaying schemes. Protection for ~~low-level~~ turn-to-turn faults can be provided by negative-sequence directional OC method, normalized negative-sequence ratio method, or a zero-sequence overvoltage ~~a voltage-unbalance-relay~~ scheme connected at the neutral with compensation for inherent unbalance of system voltages and the tolerances of the reactor. See 6.2.4.

~~Major fault protection for oil immersed reactors can be achieved through overcurrent relaying, differential relaying, or a combination of both. Protection for low-level turn-to-turn faults can be provided by impedance, negative or zero sequence overcurrent, thermal, gas-accumulator, sudden-pressure relays, or by a combination of these relays.~~

6.1 High-voltage ~~Dry-type~~ reactors (bus/line) – Application and protection

Historically, oil-immersed reactors were almost exclusively used for line and bus applications; however, today dry-type reactors are available through 550 kV.

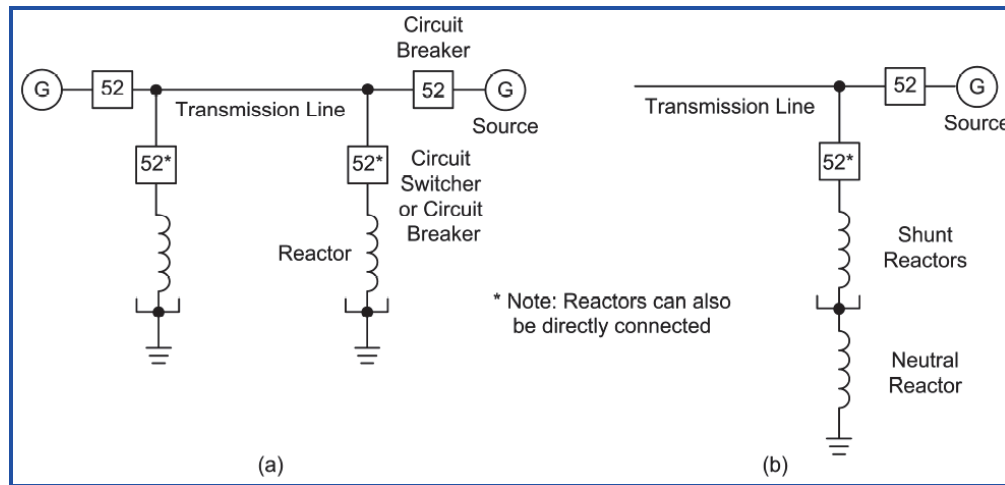
~~8. Oil-immersed reactors—application and protection~~

6.1.1 Reactor connections

~~Oil-immersed~~ Reactors are often connected ~~either at to~~ one or ~~at~~ both ends of a long transmission line, as shown in Figure ~~3 6~~ (a), and ~~they~~ 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 by means of the 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 the reactive power and voltage regulation, where a second reactor typically remains directly connected to the line to avoid excessive voltage rise after unexpected load rejections ~~permanently~~.

~~Another reactor bank arrangement for single-phase tripping and reclosing of circuit breakers is the four-reactor scheme (Edwards *et al.* [B5]) shown in Figure 6(b).~~ In-line protection applications where single-phase trip and automatic reclose is used ~~this application~~, a fourth reactor is sometimes connected between three reactors' ~~the reactor bank~~ neutral point and ground, as shown in Figure 3(b). The fourth (or neutral) reactor aids in suppressing ~~to suppress the~~ secondary arc current in a faulted and disconnected phase conductor during reclose dead time ~~single-phase fault interruption~~.

~~Oil-immersed~~ Reactors can also be connected to the substation bus, ~~and as with line-connected reactors, are generally~~ solidly grounded and can be ~~either~~ switched ~~or permanently connected~~. Relaying protection for bus-connected reactors ~~and for four-reactor configured banks~~ is basically the same as that used for line-connected, ~~solidly grounded, oil-immersed~~ reactors (~~Kimbark [B13]~~).



(New)

Figure 3 — (a) Line-connected, switched shunt reactors without neutral reactor; (b) line-connected shunt reactor with neutral reactor (four-reactor arrangement)

6.1.2 System considerations

6.1.2.1 Clearing of reactor faults

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:

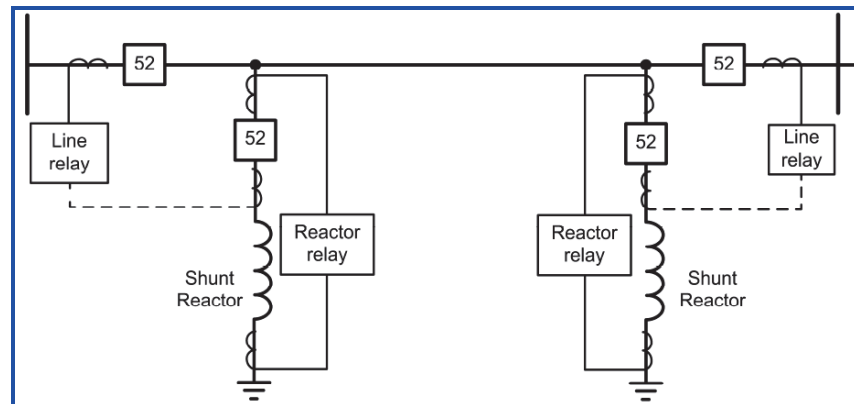
- For reactors connected to the line via full-rated circuit breaker, the reactor protection relay will trip only the reactor breaker. However, depending on the failure mode and fault current, a line protection relay can sense the reactor fault and trip the line. Hence to prevent line relay operation for the reactor fault, the reactor CT can be wired to the line relay to exclude shunt reactor current from the line protection zone as shown in Figure 4 with dashed lines. This may also be beneficial for the line differential relay to compensate for the full line charging current rather than dealing with a variable amount of charging current, depending on whether the reactor is switched in or out [B26]. However, such CT connection does affect the operation and settings for the line relays.

- See 6.1.2.2. A typical utility practice is not to trip the reactor breaker due to line protection operation for the line fault and consequent line breakers opening. This can cause resonance phenomenon, leading to undesirable operation of the reactor protection and subsequent blocking of the line reclose attempt.
- When the reactor breaker is not rated to interrupt reactor short-circuit currents, 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 compensations may experience delayed zero crossings if tripped immediately after energization of the line [B33], [B30].
- Directly connected line reactors: A typical relaying practice for a line with directly-connected reactors is to trip the local line breaker and transfer trip the remote_line breaker. ~~A dual channel is recommended for extra security (The Art of Protective Relaying EHV Systems [B19]).~~ For a reactor fault in a ~~direct~~ line-connected reactor, line breakers at both terminals are usually locked out ~~so as~~ to block reclosing of the line.

~~For a fault in a switched line reactor, on a line where rapid reclosing is desired, both line breakers can be tripped, the reactor bank switching device opened, and then the line breakers can be automatically reclosed if system conditions permit.~~

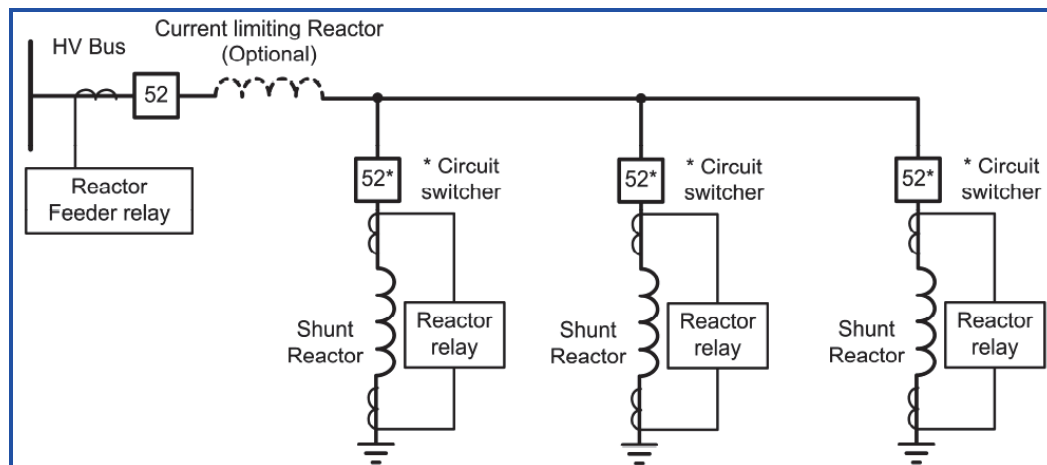
- Switched reactors connected via circuit switcher: When a circuit switcher or circuit breaker with lower interrupting rating is used ~~is utilized~~ as the reactor bank switching device, a blocking or coordinated tripping scheme can be applied. In this scheme, the circuit switcher interrupts reactor faults within its rating, and the line/bus ~~terminal~~ breaker operates only on higher_level faults beyond the rating of the circuit switcher. Other users, with concern for reliability of trip blocking, may choose to operate the higher capacity line ~~terminal~~ breaker directly for faults beyond the rating of the circuit switcher without blocking trip of the circuit switcher and depend on the faster circuit breaker to clear the fault. However, use of a full-rated circuit breaker for reactor switching eliminates the need for a coordinated tripping scheme.

- Another approach is to use a current-limiting reactor installed Figure 5 (shown dashed) on the high side of the reactor switching device to reduce the available current fault level to that which can be handled by the reactor switching device. This may allow the use of reactor switching devices designed specifically for reactor switching that also have limited fault interrupting ratings, and in addition reduce the need to trip the line/bus breaker in the event of reactor faults. Additional transient studies may be required.



(New)

Figure 4—Reactors connected via circuit breakers to the line



(New)

Figure 5—Bus-connected reactors

6.1.2.2 Resonance phenomenon for line reactors

The presence of a shunt reactor either in series or in parallel with a capacitance generates oscillations after a disturbance. 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 the series capacitance installed on the line. The capacitance coupling from an energized line can induce severe resonant overvoltage into the adjacent de-energized shunt-compensated line due to coupling between them [B35], [B10], [B31].

Capacitance associated with a transmission line can be grouped into four categories:

- Phase-to-ground (shunt) capacitance of the line
- Interphase or mutual capacitive coupling between phases of the line
- Capacitive coupling between parallel lines
- Series capacitance of a series-compensated line

Shunt reactors installed on transmission lines interact with the line capacitance especially after the line is disconnected, resulting in a slow ringdown of the trapped energy. These oscillations may contain more than one frequency due to interactions between shunt reactance and various capacitances, either to ground or to other phases or lines. The distributed capacitance of the transmission line forms a parallel resonant circuit with the shunt reactor(s) having a natural off-nominal resonant frequency depending on the degree of shunt compensation, K_{sh} . The K_{sh} is defined as percentage of the total shunt reactance in Mvar to the total line positive-sequence charging Mvar. The dominant resonant frequency can be estimated by Equation (1) as follows:

$$f_R = f_s \times \sqrt{\frac{K_{sh}}{100}} \quad (1)$$

(New)

where

$$K_{sh} = \frac{\text{Total Shunt reactor Mvar}}{\text{Line charging Mvar}} \times 100\% \quad (2)$$

(New)

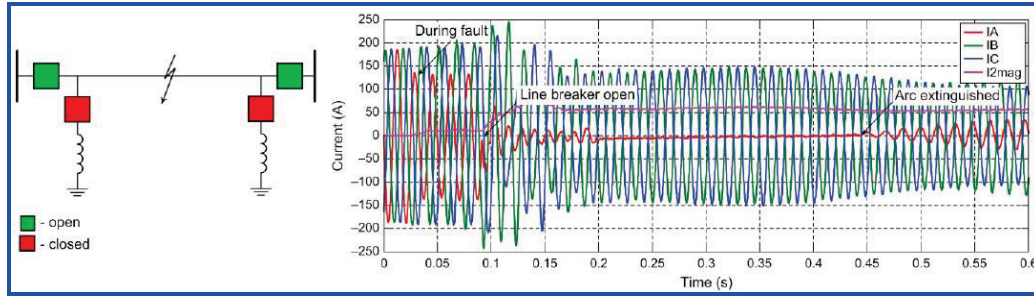
f_s is equal to system nominal frequency

f_R is equal to resonant frequency

For example, if the degree of shunt compensation $K_{sh} = 70\%$, the resonance frequency would be $f_r = (f_s \times \sqrt{0.7}) = f_s \times 0.8366 = 50.2$ Hz in a 60 Hz system. The frequency of oscillation can be above or below the nominal system frequency depending on whether the line is overcompensated or undercompensated.

For off-nominal resonance frequencies, sensitive protection functions relying on a sequence derived from system f_s nominal frequency such as zero- or negative-sequence elements and ratio comparison methods, may result in false operation 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 [B8]. For line de-energization during fault clearance, a reactor three phase current or voltage supervision can also provide security.

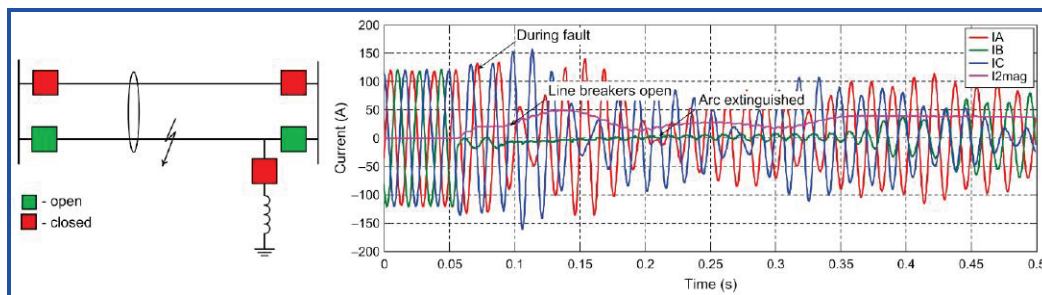
Figure 6 shows a field event on a 256 km (160-mile), 345 kV overcompensated (~110%) line, with 80 Mvar shunt reactors at both ends. The line protection tripped three-phase at both line terminals for a phase-to-ground fault. However, after the line was de-energized, the trapped charge generated currents that led to the operation of a negative- sequence OC relay set in the reactor protection only at one end of the line. The waveforms shown in Figure 6 are currents in the reactor after the line was de-energized. The ringdown current in the two unfaulted phases, after the line was de-energized, approached the rated current of the line reactor, causing the negative-sequence protection to operate and in turn prevented the line from autoreclosing. It is to be noted that the resonant frequency of ringdown current was initially 62.5 Hz after the line trip and then transitioned to 44.45 Hz after one reactor tripped.



(New)

Figure 6—R1 reactor currents on the 345 kV three-phase de-energized line due to single-phase line fault

A de-energized shunt-compensated line with an energized parallel line also exhibits oscillatory behavior, as shown in Figure 7 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 extinguished, the B-phase voltage and hence the B-phase current in the reactor rebuilt due to mutual 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. The dominating resonant frequency in the unfaulted phases is 64.1 Hz.



(New)

Figure 7—Reactor currents on the 345 kV de-energized line due to mutual coupling

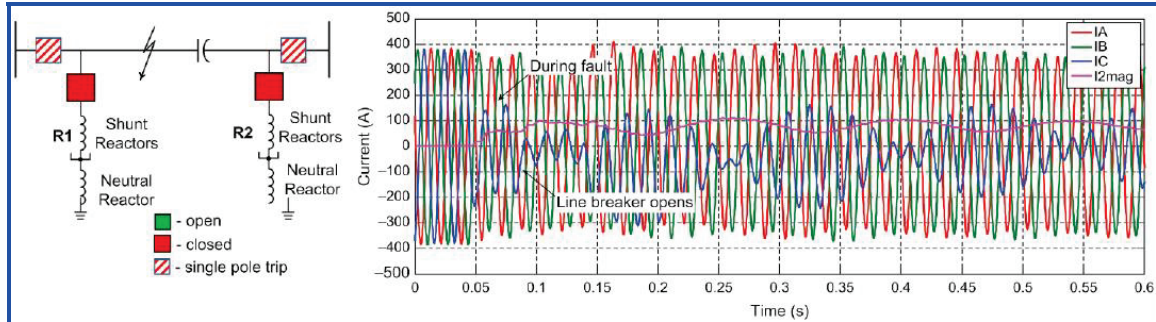
The distributed shunt capacitance of the transmission line can form a parallel resonant circuit with the shunt reactor(s) having a natural frequency close to 60 Hz. This resonant circuit can be troublesome and should be taken into account by the system planner and the relay protection engineer.

~~When a deenergized transmission line with directly connected reactor(s) is physically close enough to another energized line for the two lines to be electrically coupled, it is possible for higher than-rated system voltage to develop across the “deenergized” reactor. This problem can be prevented by isolating the reactor by means of a dedicated reactor switching device at the same time as, or immediately following, the de-energizing of the line (Pickett [B15]).~~

Another phenomenon of concern to ~~a the relay~~ protection engineer occurs when a series- and shunt- compensated transmission line is de-energized without bypassing a series capacitor or with delayed bypassing. ~~If the series capacitor is not bypassed, the shunt reactor and series capacitor~~ -.The parallel-resonant circuit can produce a poorly damped sinusoidal current voltage at a low frequency generally less than 60 Hz, which can last for several seconds, with an initial voltage approaching the ~~that can approach~~ rated voltage. ~~This substantial voltage, at a reduced frequency, can cause misoperation of impedance relays used to protect shunt reactors, unless the impedance relays are specifically designed for the application.~~

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

Figure 8 represents a shunt reactor application on a shunt and series-compensated 500 kV transmission line with SPT. The shunt reactor phase-differential relay (87) scheme is not adversely impacted by line faults or the resonance phenomenon. Figure 8 shows a field event of a C-phase-to-ground fault, subsequently resulting in resonance from the line capacitive and shunt reactance. The resonant frequency in the C-phase voltage and current is around 57 Hz and is decaying during dead time, while A- and B-phase voltage and current are still at 60 Hz.



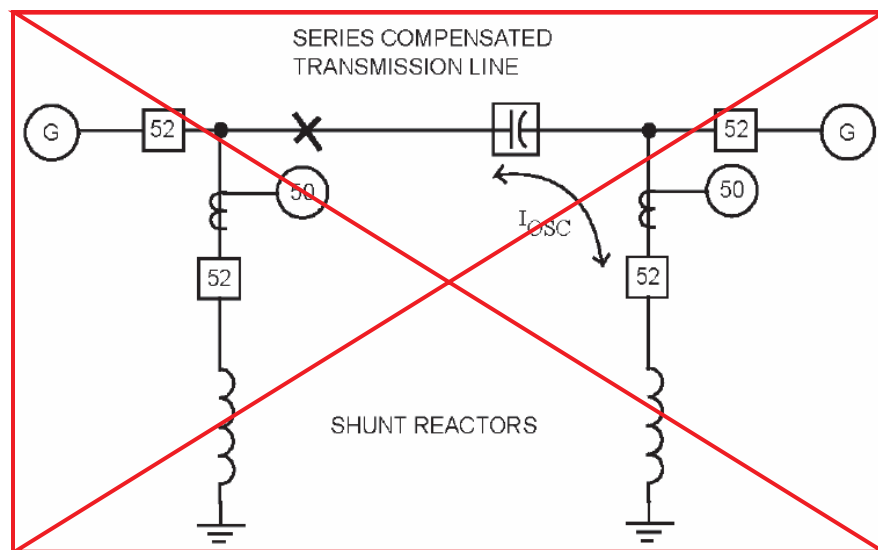
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**Figure 8—R1 Reactor currents during one phase open on 500 kV
series-compensated line**

During the fault, the shunt reactor current in the faulted phase becomes smaller as a result of the depressed fault voltage. Upon opening of the line circuit breaker(s), the line capacitive reactance transiently discharges through the line and shunt reactor (assuming the capacitors are not bypassed for a line fault). Resonant current can become higher than the OC protection threshold and may cause this protection to misoperate.

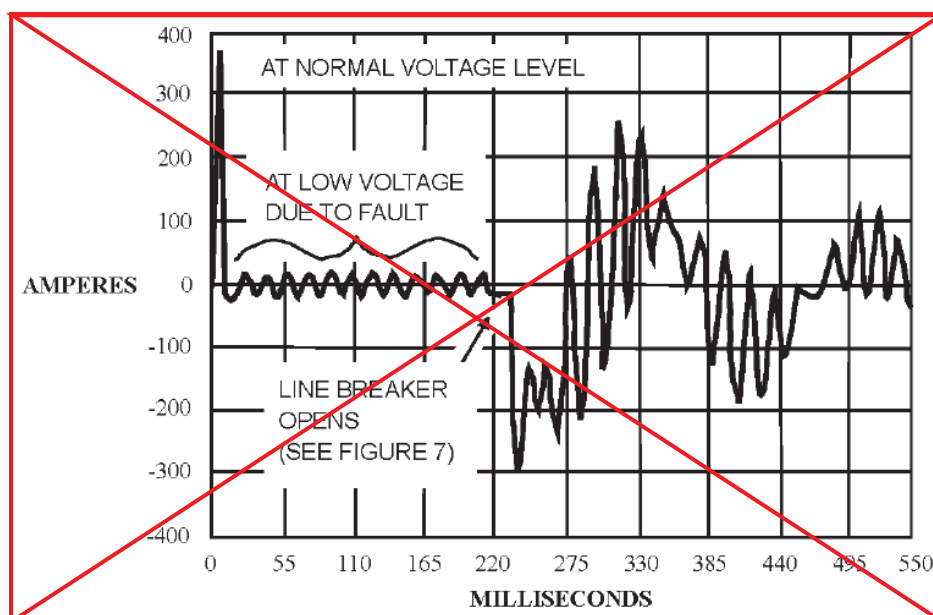
Figure 7 represents a one-line diagram of shunt reactor application on a series capacitors compensated transmission line. If the main shunt reactor winding is protected with a differential relay (87) scheme, then phase and ground faults on the series-compensated line should not have any undesirable impact on the shunt reactor protection.

Figure 7 illustrates a fault applied on the series-compensated line. It is noted that before opening the line circuit breaker, the voltages are severely depressed on the line side and bus side of the shunt reactor installation. As shown from Figure 8, the current in the shunt reactor is small as a result of the depressed fault voltage. Upon opening of the line circuit breaker(s), the series capacitors will transiently discharge (IOSC) through the line and shunt reactor (assuming the capacitors are not bypassed for a line fault). The use of overcurrent protection (50), as shown in Figure 7, is covered in 8.4.1.



(Deleted)

Figure 7— Fault on series-compensated line with shunt reactors



(Deleted)

**Figure 8— TNA study results of series-compensation
and reactor oscillations**

6.1.2.3 Reactor switching

Some utilities use controlled switching for reactor operations. Controlled closing is done typically at voltage peak to reduce dc offset in the currents. Controlled opening is done after a current zero-crossing to help minimize the risk of reignition by ensuring that the circuit breaker contacts have moved sufficiently far apart when the current is interrupted [B18], [B4].

To control the power system voltage, shunt reactors are switched on or off either manually or automatically. One of the most important aspects of switching reactors is current chopping on opening and the reignitions which can result. The reactor load current is small and highly inductive. When the breaker interrupts this small inductive current an unstable arc is formed, leading to current chopping.

The energy of the chopped current is stored in the shunt reactor inductance. It is exchanged in an oscillatory fashion between the reactor inductance and its parallel stray capacitance and results in a high-frequency oscillatory voltage on the reactor terminal. This voltage contributes to the transient recovery voltage (TRV), which is seen by the circuit breaker contacts. If the contacts are not sufficiently far apart immediately following the current chop, the dielectric strength between the contacts will not support the TRV and a reignition occurs. The resulting reignition overvoltage is much more severe than the chopping overvoltage, is very fast—typically several hundreds of kilohertz—and involves a polarity reversal. Such reignitions can damage or fail both the circuit breaker and the reactor. These switching concerns are applicable for both line and bus shunt reactors and tertiary units. Various mitigation methods are discussed in IEEE Std C37.015™ 2017, including opening resistors, surge arrester to ground at reactor, surge arrester across CBs, snubbers, CCVTs/surge capacitors to ground at reactor terminals, and controlled switching. Refer also to Chapter 6 of *Current Interruption Transients Calculation* [B34].

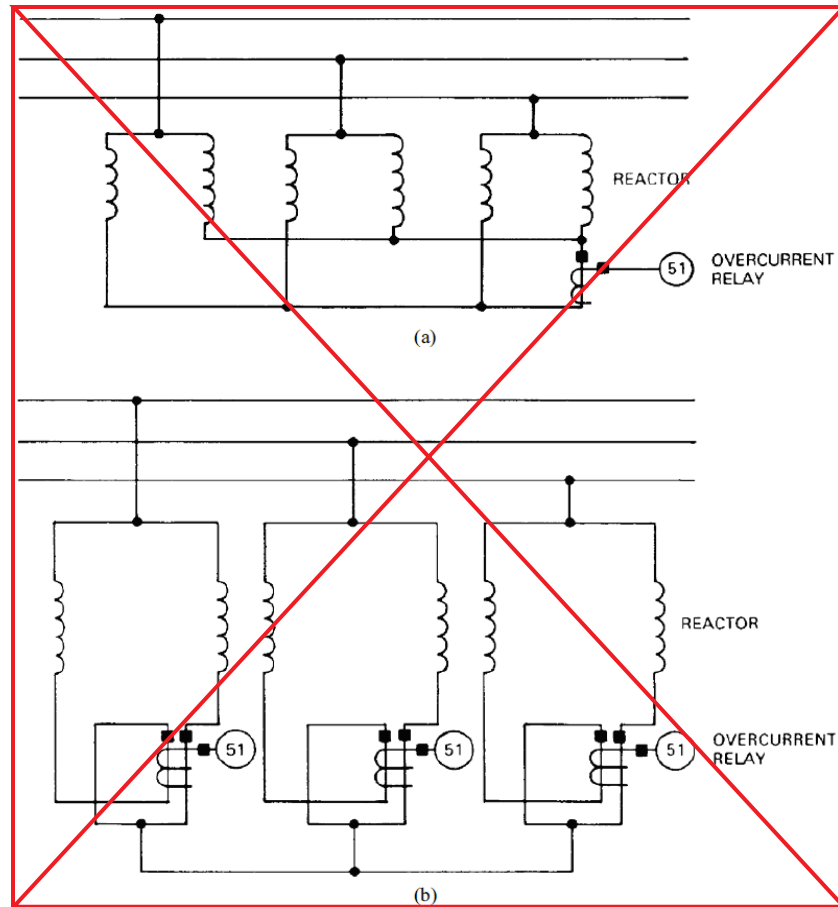
6.1.3 Failure modes and types of faults

6.1.3.1 Oil-immersed reactors

The failures encountered with oil-immersed reactor installations can be categorized as follows:

- Faults resulting in large changes in the magnitude of phase current, such as bushing failures, insulation failures, etc.

- Turn-to-turn faults within the reactor winding, that may result ~~resulting~~ in small changes in the magnitude of phase current
- Miscellaneous failures such as auxiliary power winding faults, overvoltage, low oil, loss of forced-cooling, and pole disagreement



~~(Deleted)~~

~~Figure 5—Split-phase protection: (a) three-phase sensing and (b) single-phase sensing~~

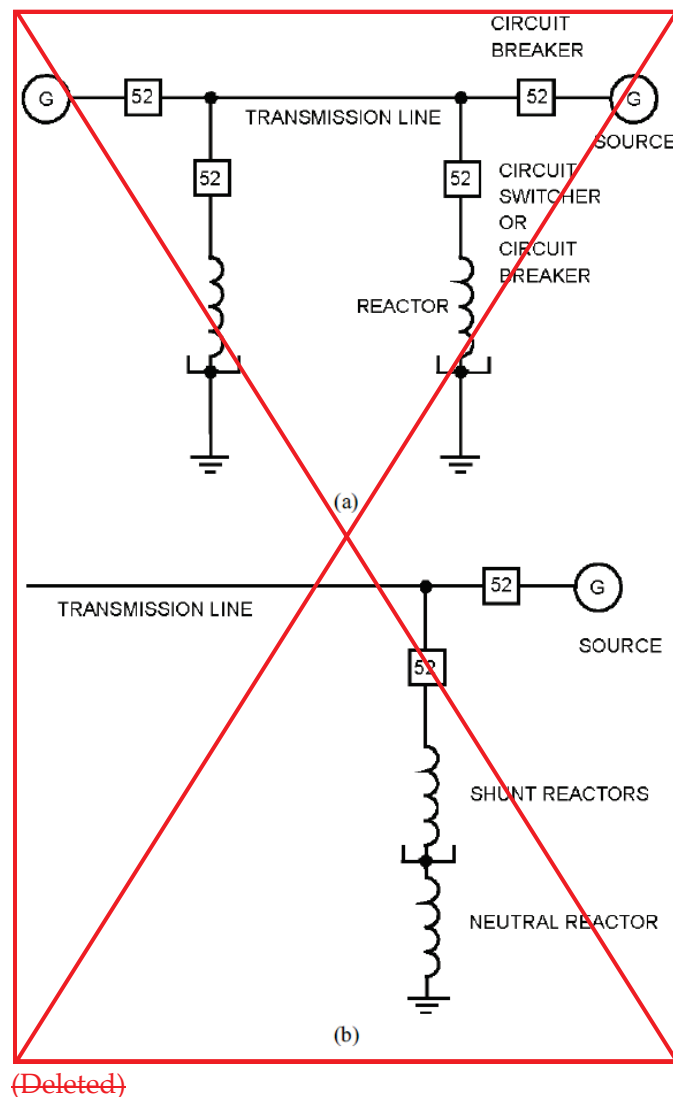


Figure 6 — One-line diagram of (a) Line-connected, switched shunt reactors and (b) line-connected shunt reactor with neutral reactor

Due to the proximity of the winding with the core and tank, [in the oil-immersed reactors](#), winding-to-ground failures can occur. The magnitude of current resulting from this type of fault is dependent upon the location of the winding-to-ground fault with respect to the reactor bushing. The farther the fault is away from the bushing, the lower the [terminal zero-sequence and phase currents](#) ~~fault~~ **current**. Bushing failures within or external to the tank, as well as faults on the connection between the transmission line and the reactor bank, can result in large increases in the magnitude of phase current.

Low-level faults within an oil-immersed reactor will result in a [small](#) change in the reactor impedance, and can [also](#) increase the operating temperature, internal pressure, and accumulation of gas. [They are difficult to detect in the initial stage and](#) if not detected, the turn-to-turn fault is likely to evolve into a major fault.

6.1.3.2 Dry-type reactors

[For dry-type units, by far the most common failure mode is faults along the winding, either due to surface tracking or degradation of turn-to-turn insulation and resulting turn-to-turn faults. As with oil-immersed gapped iron-core units, such faults are difficult to detect in the initial stage. In the case of dry-type units, a turn-to-turn fault, if undetected, may evolve into a flashover of the individual coil or column which can then be easily detected. For dry-type air-core shunt reactors applied at transmission voltages, phase-to-phase faults are exceedingly rare as the insulation between phases is provided by the air space between the adjacent phases. Phase-to-ground or partial winding-to-ground faults are also quite rare as a consequence of the physical arrangement, the exceptions being \(a\) for faults along the winding such as surface tracking or turn-to-turn faults which progress to a phase or partial winding flashover to neutral and then to ground via the neutral to ground connection, or \(b\) flashover of the base insulators in cases where each phase consists of multiple series connected winding columns supported by base insulators. Additional details are provided in Annex F.](#)

6.1.4 Protection ~~Relaying~~ practices

6.1.4.1 Overall protection scheme

Typically, redundant protection relays are provided for reactors. Refer to IEEE Std C37.120-2021, IEEE Guide for Protection System Redundancy [B24] and Annex A of this guide for typical recommendation for redundant protection Main 1 and Main 2 systems. In EHV applications, sometimes a spare single-phase reactor is used to substitute one of three single-phase reactors, when taken out of service for maintenance purposes [B11]. Protection scheme design may accommodate this spare reactor switching. Two or more protective relays may be used for the reactor protection, where both relays can perform the same protection and control functionality (Main 1 and Main 2), or the second relay may be a backup for the main relay with reduced functionality and operate in case the main relay fails.

~~8.4.1—Protection for large-magnitude faults~~

~~Relaying~~ Protection for faults producing large increases in the magnitude of phase current is achieved by the ~~generally a~~ combination of OC ~~overcurrent~~ (50/51), differential (87), and ~~or~~ distance (21); relaying. A typical protection scheme with two reactor protection relays and mechanical protection is ~~Common schemes are~~ illustrated in Figure 9 (Selak et al. [B38], Basha and Thompson [B2]).

Protection for faults producing a small increase in the magnitude of phase current is achieved by sensitive electrical protection including restricted earth fault (REF), turn-to-turn fault protection, sensitive ground-fault protection (50/51N), and non-electrical protection such as temperature, oil, and pressure mechanical devices.

EHV dry-type reactors may need special considerations in setting OC relays due to physical configuration (see 6.1.4.2.1). Differential protection cannot detect the most frequent fault-type, a turn-to-turn fault, within a dry-type reactor. However, differential protection can operate for other types of faults within the differential zone of EHV dry-type reactors.

One of the principal difficulties with shunt reactor protection is false relay operation during iron-core reactor energizing and de-energizing. During these periods, dc offset with long time constants and low frequency components of the reactor energization current cause many of the problems. High impedance differential relays are generally recommended over summation connected ordinary low impedance overcurrent relays for this reason (Englehardt [B6]). Percentage restrained (biased) low impedance differential relays that perform as well as high impedance relays can also be applied. Where ordinary low impedance differential relays are used, it is generally recommended that the relay be sufficiently desensitized to prevent misoperation.

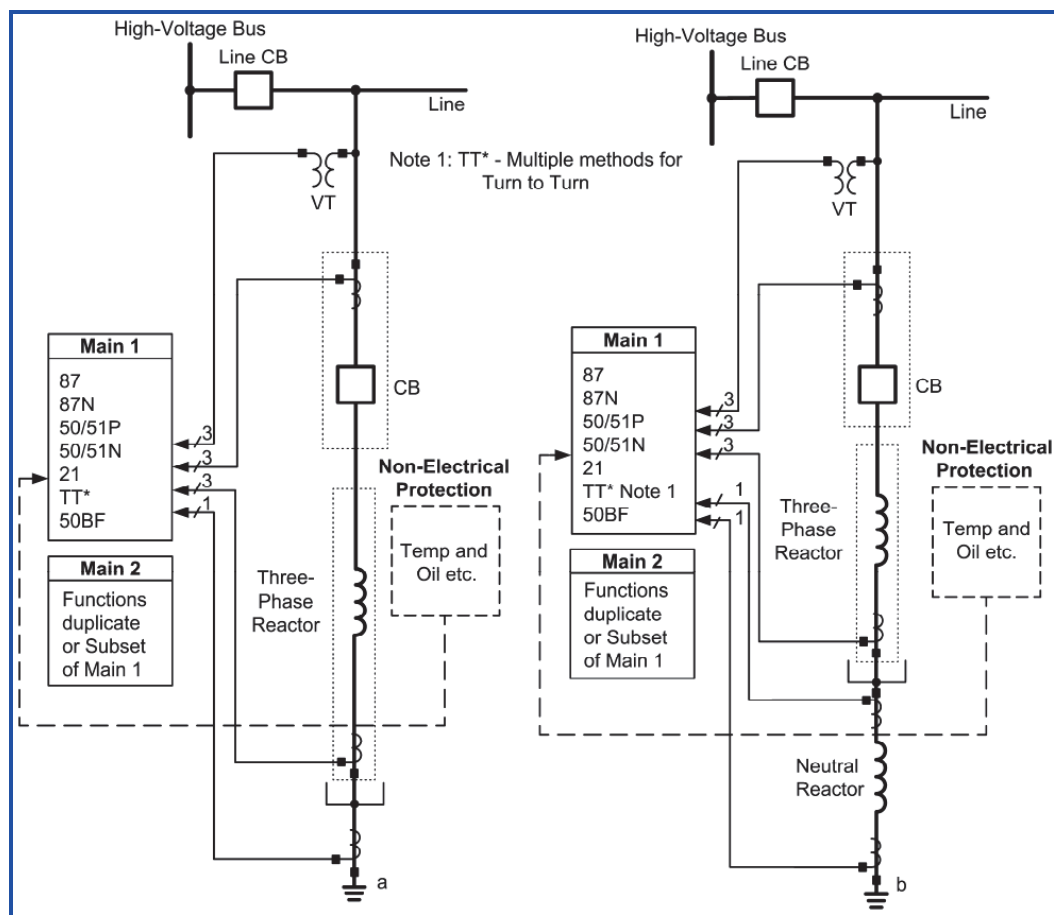
Phase overcurrent protection can be useful for protection for large magnitude internal faults. Phase instantaneous overcurrent protection should be set higher than the maximum current that can flow in the reactor during transient conditions. During energization, transient offset in the current can result in peak currents approaching twice rated levels. Since the reactor impedance is proportional to the frequency of the voltage applied to it, higher than normal currents will also flow during conditions of lower than normal frequency (such as during the de-energization of the line/reactor combination as noted in 8.3.2). Therefore, immunity to the transient offset of current and low frequency current is an important attribute of a reactor instantaneous phase overcurrent relay. That is, the relay should be tuned to respond to fundamental frequency only.

6.1.4.2 Protection functions

This subsection discusses various protection functions for line/bus reactors.

6.1.4.2.1 Phase-overcurrent protection (50/51)

Phase-OC relays are connected to CTs on the line/bus side of the reactor. Phase time-OC (51P) is set above maximum reactor current during ~~If the relay is immune to off nominal frequency current, the likely other source of high phase current is~~ temporary overvoltage. Considering maximum temporary overvoltage ~~high voltage on unfaulted phases~~ during ~~single line to~~ ground-fault conditions ~~faults~~ on the power system, it is generally acceptable to select a setting of 1.5 times rated reactor current. ~~High voltage (HV) and extra high voltage (EHV) systems are usually effectively grounded, and the rise in voltage on an unfaulted phase rarely exceeds 1.3 per unit (pu) during a single line-to-ground fault [B9]. However, it is important to determine the maximum expected temporary overvoltage for each application of a phase OC relay to determine if the relay settings remain secure (see the standard definition of "ground fault factor" in IEEE 100 [B8]). Therefore, a setting of 150% of reactor current at rated voltage is normally sufficient to override temporary overvoltages. However, the maximum temporary overvoltage should be determined for each application of an instantaneous phase overcurrent relay.~~



(New)

Figure 9—Typical reactor protection

When energizing a gapped iron-core shunt reactor, the actual peak value of the current has been documented to be between 3 and 5.5 times the nominal rms current [B9]. For dry-type air-core reactors, peak value can be up to $2.82 (2 \times \sqrt{2})$ times the rms current. The reactor energization currents in the three-phases experience different degrees of dc offset (without controlled closing). Due to the long time constant of the shunt reactor, the time to reach steady-state condition is very long and in the order of several seconds. Depending on the relay design and how it effectively removes the dc component from the phase currents, sufficient time delay may be needed to overcome reactor energization currents.

Instantaneous OC protection (50P) based on fundamental frequency phasor is typically set to 2 to 2.5 times the nominal current for iron-core reactors. Some utilities may select higher settings, depending upon the reactor design, relay design, and minimum available fault current at the reactor location. Use of the fundamental frequency phasor, rather than rms, is recommended for the 50P function, because it provides better accuracy and security during transients. A small delay of 0.1 s is typically applied for this function [B17].

Alternate protection considerations are required for HV dry-type air-core reactors for OC protection. For dry-type air-core units consisting of multiple series coils per phase, consideration is given to the possibility of flashing over a single coil when deriving the OC setting. For example, if the design includes three series coils per phase, shorting one coil results in a current increase of at least 50% of nominal current (ignoring the fault impedance). Current increase may be higher due to mutual coupling between the coils in the same phase (consult reactor manufacturer about mutual coupling between coils). The 50P element needs to be set below the increased phase current to sense this fault condition. Hence, dry-air-core type reactors' design and the number of series coils determine the selection of the 50P/51P settings. See F.6 for additional information regarding EHV dry-type air-core reactors.

~~Differential schemes have been applied as primary protection for the detection of winding-to-core or winding-to-tank faults. The ground differential (87G) or restricted ground fault schemes are useful when the shunt reactors are a single phase per tank design. Figure 10 shows a high-impedance ground differential (87G) scheme; however, a low-impedance scheme can also be implemented. Where a reactor differential relaying scheme is used that is sensitive to mismatch in current transformer performance during a fault, it is recommended that the current transformers on both sides of the reactor have similar excitation characteristics. Ground fault back-up protection can be provided by a neutral overcurrent relay.~~