27

Selection of power reactors

Contents

27.1 Introduction

Maintaining quality of power in terms of voltage and current waveforms (having low harmonic distortions and a stable voltage) is not only obligatory on the part of utility companies to provide quality power to their users, it is also mandatory on the part of utility companies as well as the users to meet the norms of EMC/EMI as discussed in Section 23.18. Power reactor is a simple and a handy tool to tackle these problems as discussed at different places in this book. Like for electronic circuits in Section 6.13 by way of smoothing current and voltage over-shoots ($\mathrm{d}i/\mathrm{d}t$ and $\mathrm{d}v/\mathrm{d}t$ controls respectively), suppressing harmonics at source using harmonic filters (Section 23.9) or providing reactive support to a power network (Section 24.8) etc.

Power reactors are similar to transformers. However, they have only one winding per phase and can be represented as shown in Figure 27.1. They are employed to perform a number of functions, primarily to control and regulate the reactive power of a power system by supplying the inductive and absorbing the capacitive power. Control can be achieved in different ways as noted later. The reactors, depending upon their design and I-ϕ characteristics, can be classified as follows:

1 **Single- or three-phase** Single-phase reactors are used in the neutral circuit either to limit the ground fault currents or as arc-suppression coils (Section 20.5). Similarly, three-phase reactors are used for three-phase applications.
2 **Air-cooled dry type and oil-immersed type** This will depend upon the size of the reactor and the design of the manufacturer. The latest practice is to use air-cooled dry type, which calls for lesser maintenance and is free from any fire hazards.
3 **Indoor or outdoor types** These may be designed indoor or outdoor depending upon the application.
4 **Tap-changing facility** Where necessary such as in reactive power management, the reactance of the coil can be varied by providing an on- or off-load tap changing gear with the reactor, similar to a power transformer.

27.2a Selection of power reactors

When it is required to limit the inrush current a fixed reactance (linear) reactor is more suitable. A variable type reactor will be necessary when it is to be used for voltage regulation or load sharing. In circuits where harmonics may be present, saturated type reactors may be preferred.

The harmonic content may be measured through harmonic analysers and expressed as a percentage of the fundamental component. The current and voltage ratings of the reactors will depend upon their application. A series reactor connected permanently in the circuit, for instance, will be rated continuously and for full system voltage, whereas a reactor used in the ground circuit may be short-time rated and rated for the likely maximum ground fault current and its duration.

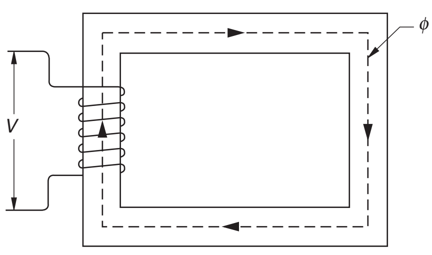


Figure 27.1 General representation of a reactor

27.2b Magnetic characteristics

The magnetic characteristics of an inductor coil will vary with the type of its configuration as discussed below. It can have one of the following shapes:

- Linear (Figure 27.2(a))
- Non-linear (Figures 27.2(b1) and (b2))
- Saturated (Figure 27.2(c))

A reactor can be designed to provide any of these characteristics to meet the different reactive power needs.

27.3 Design criterion and I-ϕ characteristics of different types of reactors

27.3.1 Air-cored or coreless type reactors

These reactors can be made of copper or aluminium winding without any core, similar to an air-cored solenoid, as shown in Figure 27.3. They are merely coils of wire wrapped around a non-metallic core. The cores usually employed are of ceramics, concrete, fibre glass or glass polyester. In the absence of an iron core it causes a large amount of leakage flux (stray magnetic field) in the space, which may also infringe with the metallic tank housing of the reactor, and affect the reactance of the coil, in addition to heating the tank itself. It is therefore important to provide some kind of shielding between the winding of the reactor and the tank. The shielding can be magnetic or non-magnetic as discussed later. With shielding, the characteristics of an air core reactor can be altered according to its application. When no shielding is provided such reactors provide linear I-ϕ characteristics in their operating range, as shown in Figure 27.2(a). In the absence of an iron core, there is no saturation of the core. These reactors are more useful when they are required to be used as current limiting devices as for limiting the inrush currents during switching of large capacitor banks (Section 23.11.2). But they reduce the steady-state power transfer capability (V_1^2/Z) of the system, as discussed in Section 24.8.

With magnetic shielding

A magnetic circuit develops a stray magnetic field around it. A reactor, which is a magnetic circuit, at higher currents

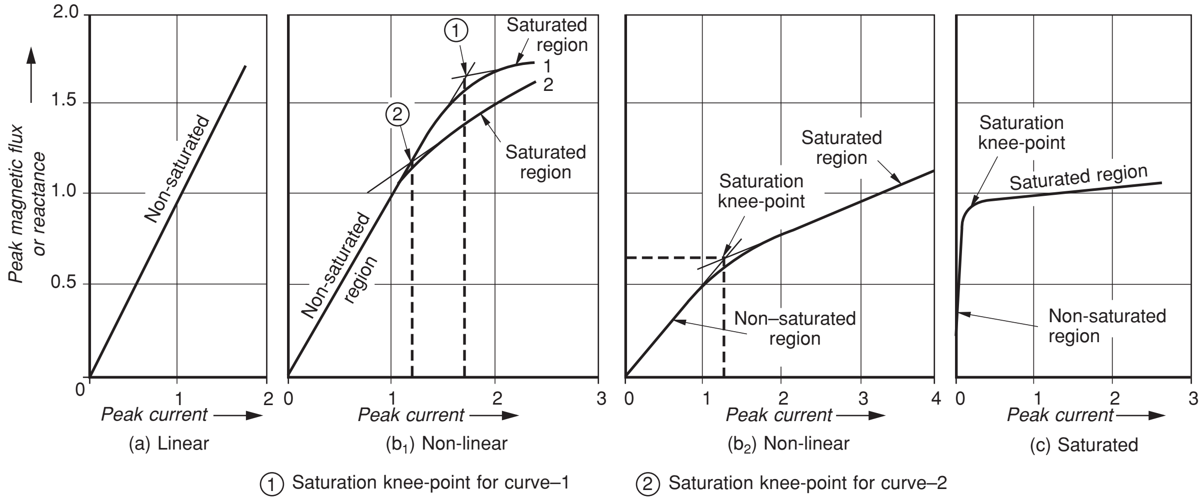


Figure 27.2 Magnetic characteristics of a reactor

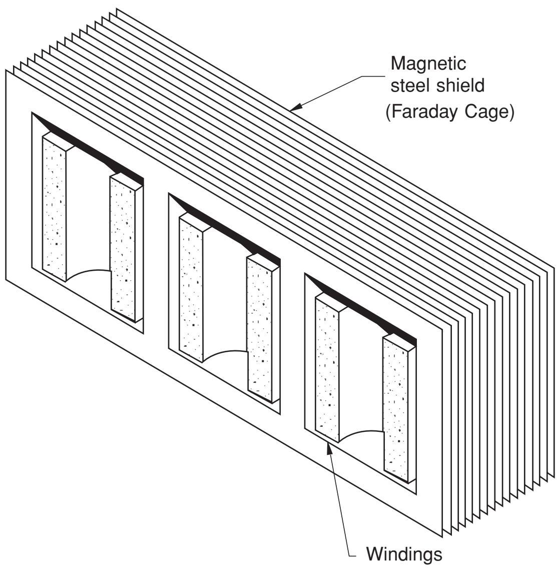


Figure 27.3 Three-phase 'air-cored' magnetically shielded reactor

such as during switching operations or on faults develops high magnitudes of stray fields around it that may link magnetic objects in the vicinity and cause high induced e.m.fs. in them, as in nearby metallic structures and electrical apparatus. All this may result in high circulating currents and consequent heating. In addition, it may also affects the working and performance of the measuring and indicating instruments connected on the system. To reduce such effects a magnetic frame performing a Faraday Cage (Section 23.18) made of steel laminations and rigidly clamped to suppress vibrations and noise (magnetostriction effect) is provided around the inductor coil, as illustrated in Figure 27.4. This frame arrests most of the space magnetic field within the close vicinity of the reactor. The balance field will link the iron frame and would be almost used up in magnetizing it. The steel frame is called the magnetic shield. The self-inductance of the coil, L, is now much less affected. The flux density of the core is designed so that it does not saturate up to 150% of the rated current.

Any increase in the fundamental value of the current beyond 150%, or a voltage drop across the coil of more than 150% of the reactor voltage (this may occur in the presence of harmonics) may, however, saturate the core and reduce the reactance of the coil. Magnetically shielded reactors therefore have limitations when the system harmonics are high or when linear *V-I* characteristics are desirable beyond 150% of the rated fundamental current.

The need for a magnetic shielding is greater in high current reactors than in smaller ratings. For more details on magnetic shielding see Section 28.2.2 on segregated phase bus systems.

With non-magnetic shielding

In non-magnetically shielded reactors a cylindrical shield of non-magnetic material, such as aluminium or copper, is provided around the inductor coil instead of a magnetic material (Figure 27.5). Since there is no iron path for the magnetic field, the coil now may not maintain a constant inductive reactance, as in the case of magnetic shielding. Instead, it may become reduced with an increase in the current due to a counter-field generated in the coil by the non-magnetic shielding.

For the theory of neutralization of the magnetic effect on the conductor in a non-magnetic shielding, refer to the continuous enclosures for isolated phase bus systems discussed in Section 31.2.2. As a result of non-magnetic shielding there will be no saturation of the non-magnetic core (inductor coil) and the *V-I* characteristic of the reactor will remain almost linear.

These types of reactors can now be used as current

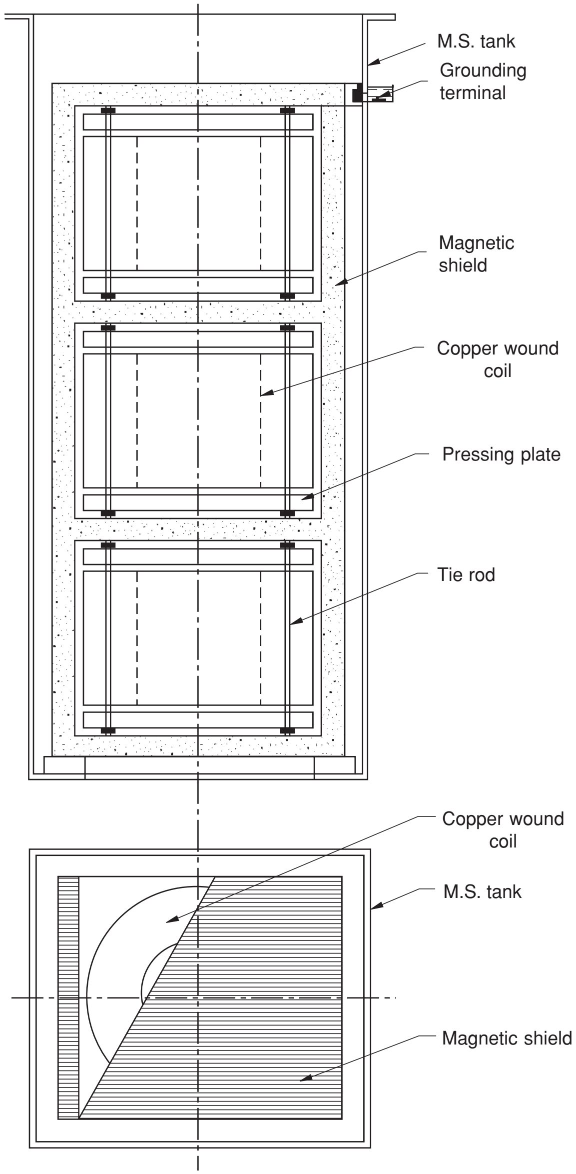


Figure 27.4 Sectional view of a magnetically shielded reactor

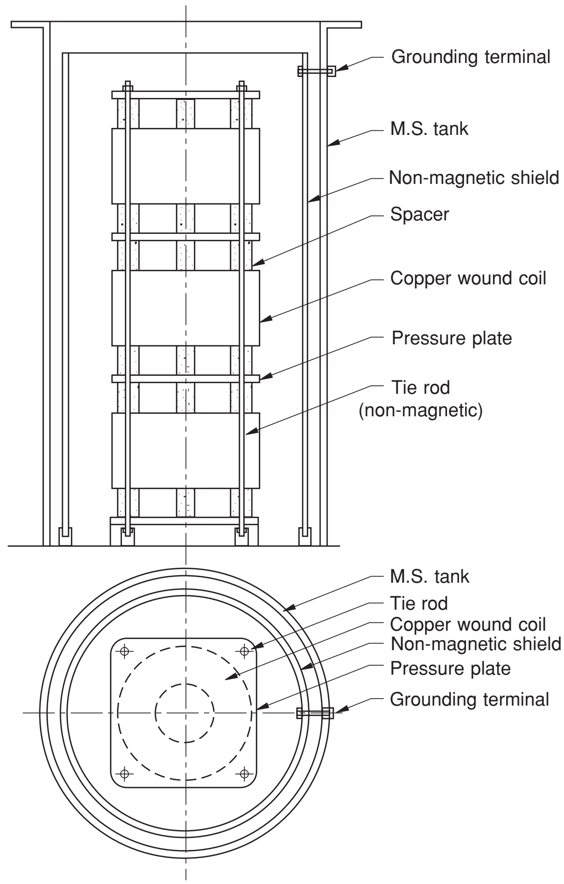
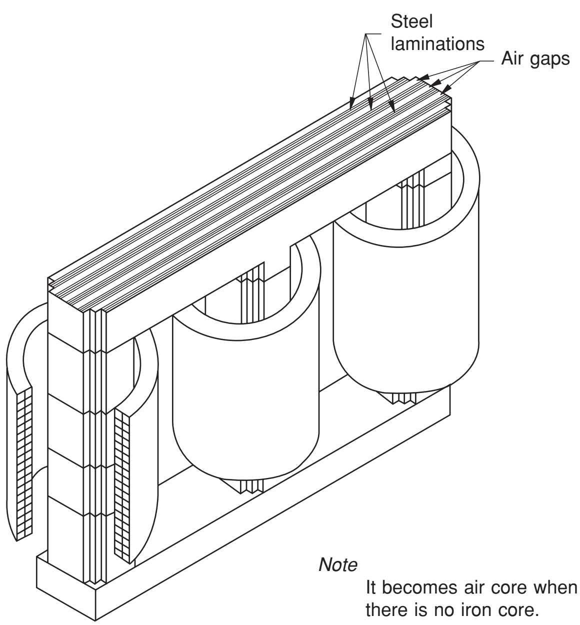


Figure 27.5 Sectional view of non-magnetically shielded reactor



Note
It becomes air core when there is no iron core.

Figure 27.6 A gapped iron three-phase reactor

limiting reactors and also as harmonic suppressors. They are also recommended for capacitor application due to their linear characteristic which will not disturb the tuning of the filter circuit.

27.3.2 Gapped iron core or saturated type reactors

Reactors of this type, as shown in Figure 27.6, tend to saturate at lower currents (Figure 27.2(c)). The current drawn by them is too low, even up to the saturation level, due to high leakage reactance which can increase to 100%. They therefore provide a high inductive impedance initially which becomes stabilized with saturation of the core. After saturation, the I-ϕ characteristic

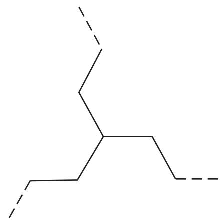


Figure 27.7 Six- or nine-limb zig-zag arrangement of windings to limit the harmonics

becomes almost constant or flat. Such reactors thus have non-linear magnetizing characteristics and the current drawn by them contains many odd harmonics. When the reactor is to be connected on a power system these harmonics must be suppressed as much as possible through filter circuits or by using a multi-limb core arrangement, such as the six- or nine-limb zig-zag arrangement illustrated in Figure 27.7. Beyond the point of saturation, the rise in current is rather fast compared to a small rise in the magnetization or the voltage.

Unlike an air core, the inductor coil now has an iron core that may be provided with air gaps or non-magnetic separators in between to reduce the iron content and hence the induced magnetic field. The I-ϕ characteristic can thus be varied as required by altering the gap, i.e. the iron content in the core. They are suitable as current limiters, and can also limit the occurrence of over-voltages. Where required, they can be provided with a tap-changing facility to regulate their reactances. Likely applications are:

- Voltage stabilization and control of temporary over-voltages.
- Flicker control in industrial supplies through $V = L\,(di/dt)$ (Section 6.9.4).

27.4 Applications

Some of the applications where a power reactor can be used to provide a reactive support or compensation to improve the quality of a power system are noted below.

27.4.1 Shunt reactors or compensating reactors

These are meant for parallel connections to absorb the reactive power (capacitive power) of the system and are generally used on transmission and large distribution networks, as shown in Figure 27.8 and usually connected to the tertiary winding of the main transformer. They may have a fixed or variable reactance, rated continuously, and any of the magnetic characteristics as illustrated in Figure 27.2. Broadly speaking, they can perform the following functions:

1. Limit the switching surges as discussed in Section 23.5.1. But they may affect the steady-state power transfer capability of the system (V_1^2/Z). Refer to reactive power control (Equation (24.10)).
2. Adjust the steady-state voltage control by supplying reactive power and compensating the capacitive content.
3. Suppress the harmonic contents.

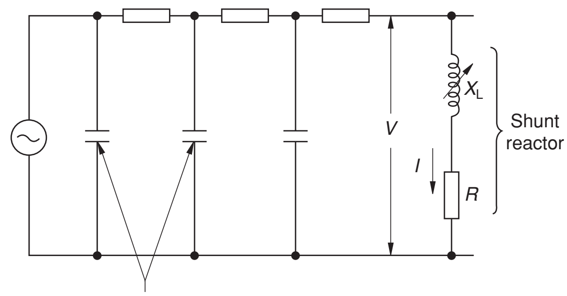


Figure 27.8 Use of a shunt reactor to compensate for the reactive power

Their ratings can be calculated by

$$R = \frac{V^2}{W}$$

$$X_L = \frac{V^2}{VAr}$$

$$VAr = I^2 \cdot X_L \text{(neglecting } R\text{)}$$

where

R = reactor resistance – Ω/phase
X_L = reactor reactance – Ω/phase
V = rated voltage of reactor – volts
W = reactor loss – watts/phase
VAr = rated output – VAr/phase
I = rated current of reactor – A

Note
See also Example 28.10 for the application of a saturable air core type reactor to make up deficient reactance in one phase in a 3ϕ unbalanced current carrying system.

27.4.2 Current limiting or series reactors

These are connected in series in a circuit, as shown in Figure 27.9 and are meant to limit the high inrush current, such as during switching of HV capacitor banks (Section 23.10).

They may also be used to limit the currents under fault conditions by adding to the circuit impedance to

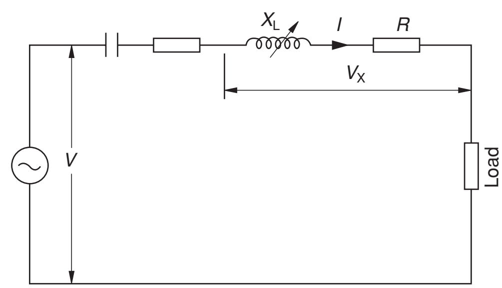


Figure 27.9 Use of current limiting reactor, (1) to limit the fault current, or (2) to limit inrush current during a capacitor switching

match with the breaking capacity of the interrupting device when the fault level of the system may exceed the breaking capacity of the interrupting and protective devices. Such a situation may arise due to ever growing power demands and consequent additions of new generating units or power stations on the existing transmission and distribution networks, raising the fault level of the system. Sometimes it may even exceed the rupturing capacity of the existing switching and protective devices. This feature is becoming a usual phenomenon with the existing power transmission and distribution power networks the world over.

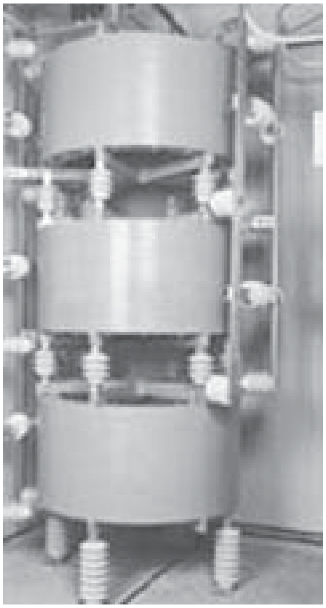
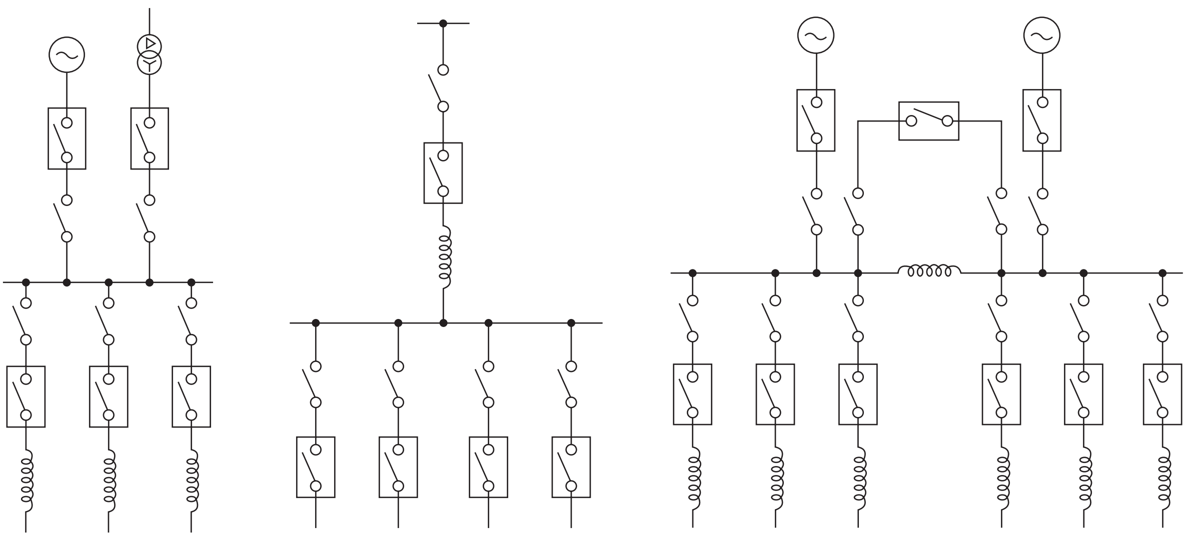


Figure 27.9(a) A typical 3-phase current limiting reactor (Source: Nokian Capacitors)

These reactors consist of three phase coils usually stacked one above the other with support insulators between them as shown in Figure 27.9(a). The gap between the two coils is maintained (>300 mm) such that each of them would fall nearly out of the inductive interference of each other. The foundation of the inductor coil must also be ensured to have no closed loops in the reinforcement concrete steel (RCC). The reactor coil may be introduced in the outgoing feeders, incoming feeders or between the bus couplers as shown in Figure 27.10.

Some of such connections are illustrated in Figure 27.10. They are also used for load sharing of two power systems. They are connected in the circuit permanently and may have a fixed or variable reactance, rated continuously and can be made to have linear (fixed reactance) or nonlinear magnetic characteristics as required. When they are required to limit the inrush currents, fixed reactance, linear reactors should be preferred. During a fault condition, the reactance of the reactor should not diminish due to the saturation effect. This is an essential requirement to limit the short-time fault currents. Ideally, current limiting reactors must have no-iron circuit and must be of air core or coreless type. The iron core type provide non-linear saturating type characteristics, and at over-currents have a tendency to diminish their reactance due to the saturation effect, while the reactors are required to offer high impedances to limit the fault currents. The coreless type will provide a near-constant reactance at all currents due to the absence of an iron core and hence, their preference over other types for such applications.

Similarly, gapped iron core reactors as shown in Figure 27.6, in which the iron core content is reduced by providing an air gap or non-magnetic material between the core laminations, also raise the saturation level (the core



(a) Feeder connections

(b) Tee-off connections

(c) Busbar sectionalizer connections

Figure 27.10 Series reactor connections

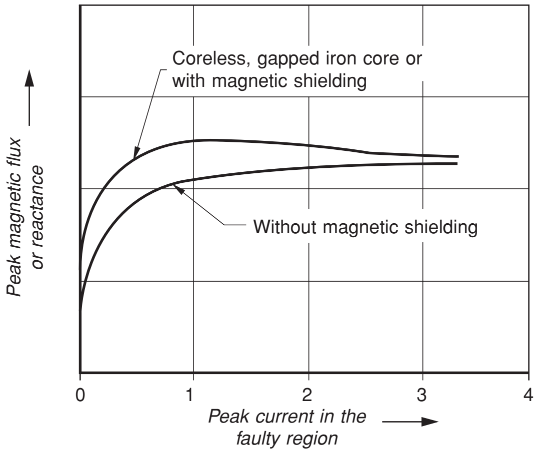


Figure 27.11 Typical characteristics of a current limiting reactor (coreless, gapped iron core or magnetically shielded core type)

remaining unsaturated, Figure 27.11) to help provide an adequate impedance on fault. They may also be employed as a current limiter, such as shown in Figure 27.9. It must, however, be ensured that the voltage available across the load does not fall below the permissible level as a result of the voltage drop across the reactors. The reactors for such applications should be continuously rated.

For Figure 27.9 the rating of the series reactor can be determined by

$$\text{VAr} = \sqrt{3} \cdot V_x \cdot I$$

$$X_L = \frac{V_x}{\sqrt{3} \cdot I}\ \Omega/\text{phase}$$

where

VAr = rating of the series reactor (Volt.Amp)

V_x = rated voltage drop of the reactor phase to phase in volts

= voltage induced in the reactor when operating at rated current and rated reactance

I = rated current of the reactor (A)

R = resistance of the reactor

$\because$ $R << X_L$ (less than 2–3% of X_L) may be ignored

Example 27.1

Consider a distribution system as illustrated in Figure 27.12(a) being fed by two power sources in tandem:

- A transformer 5000 kVA, 33/11 kV, having p.u. reactance of 7.15% and connected to a power grid.
- A generator 2500 kVA, 11 kV, having a steady-state p.u. reactance, x_d of 25%.

A three-phase fault somewhere in the bus system, without reactive compensation and ignoring the line impedance, can reach a level of

$$\text{Fault MVA} = \frac{\text{base MVA}}{z_{eq}} \qquad \text{(Equation (13.6))}$$

where z_{eq} = equivalent p.u. impedance of the combined power system at the point of fault.

Consider the base level as 5000 kVA, 11 kV

$\therefore$ Generator reactance at the new base

$$= 25 \times \frac{5000}{2500} \text{ (Equation (13.1))}$$

$$= 50\%$$

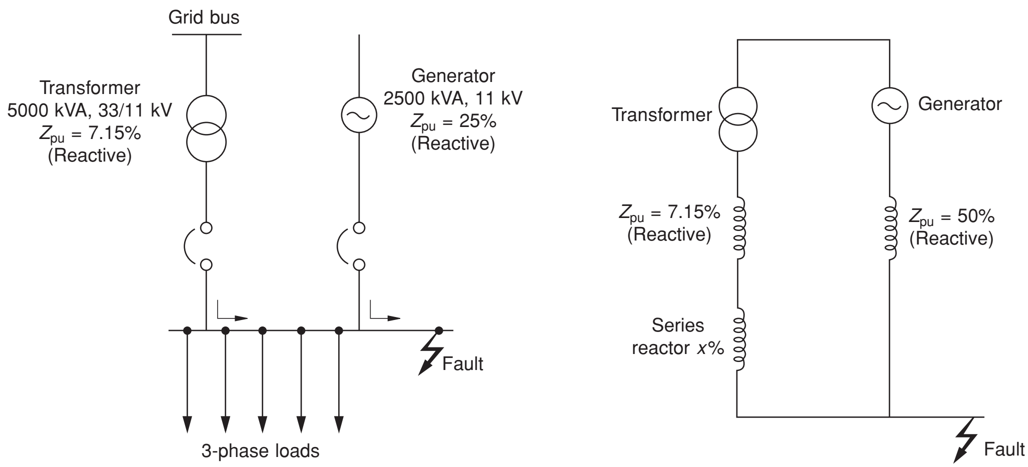
and $$\frac{1}{z_{eq}} = \frac{1}{0.0715} + \frac{1}{0.5}$$

or $$z_{eq} = 0.0625$$

$$\therefore \quad \text{Fault level} = \frac{5000}{0.0625} \qquad \text{(Equation (13.6))}$$

$$= 80 \text{ MVA}$$

If the fault level is required to be limited to 50 MVA, a series reactor of reactance, x% may be introduced into the transformer circuit, as illustrated in Figure 27.12(b),



(a) Location of fault (b) Equivalent circuit

Figure 27.12 Application of a series reactor

The new $z_{eq} = \frac{5000}{50 \times 1000}$

$= 0.1$ p.u.

and the new reactance $\frac{1}{0.1} = \frac{1}{0.0715 + x} + \frac{1}{0.5}$

or $0.1 = \frac{(0.0715 + x)(0.5)}{0.5715 + x}$

or $x = 0.0535$ p.u. or 5.35 %

at 5000 kVA base and 11 kV

∴ A series reactor of reactance 5.35% may be used to limit the fault to the required level.

27.4.3 Damping reactors

These are meant to limit the inrush currents occurring during a switching operation of a capacitor. They are connected in series with the capacitors and may be short-time rated for the values of the inrush currents and continuously rated for normal line currents. They are almost the same as the series reactors with fixed reactance.

27.4.4 Neutral grounding reactors

These are meant to limit the ground fault current to a desired level to protect the generator or the transformer and are used between the neutral of the system and the ground. They are single-phase and may be short-time rated, otherwise they are the same as the current limiting reactors (Figure 27.13). Their ratings can be calculated by

$$X_L = \frac{V_1}{\sqrt{3}} \cdot \frac{1}{I_g}$$

where

X_L = reactance – Ω

V_1 = rated voltage of the system

$\left(\frac{V_1}{\sqrt{3}} - \text{rated voltage of the reactor}\right)$

I_g = current through the ground (rated current of the reactor)

X_o = zero sequence reactance (or impedance) – Ω

$= 3 \cdot X_L$

Example 27.2

Consider a three-phase reactor having the following specifications:

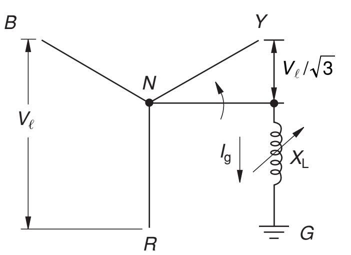


Figure 27.13 Neutral grounding reactor or a Petersen coil

$V_r = 33$ kV

V_x = 3% of the system voltage (phase to phase)

System current, $I_r = 650$ A.

To determine the size of the reactor

V_x in absolute terms

$= \frac{3}{100} \times 33$

= 0.99 kV, say 1 kV

Size of a three phase reactor	*Size of a single-phase reactor*
$\text{VAr} = \sqrt{3} \times 1.0 \times 650$ = 1125 kVAr	$\text{VAr} = \frac{650 \times 1.0}{\sqrt{3}}$ = 375 kVAr

and $X_L/\text{phase} = \frac{1 \times 1000}{\sqrt{3} \times 650}$

= 0.89 Ω/phase

27.4.5 Grounding transformer or neutral couplers

These are meant to provide a neutral to an ungrounded system.

When the ground transformer neutral is connected to the ground directly or through a current limiting reactor its neutral current may be considered for a short-time duration only, i.e. until the ground fault exists assuming that the ground fault protective scheme will isolate the faulty circuit promptly.

But when the neutral is grounded through an arc-suppression coil (reactor) the current through the grounded neutral may be of a limited amplitude, say, up to its continuous rating (Section 20.5) and it may exist for longer.

These transformers are three-phase and may be connected for zig-zag or star/delta connections (Section 20.9). The delta may also be made open type by inserting a resistor across it to help adjust the zero-sequence impedance, if required.

27.4.6 Arc suppression or Petersen coil (reactor)

These are meant to compensate the ground capacitive current on a ground fault in the system, which may be grounded naturally or artificially (Section 20.5). They are connected between the neutral of the system and the ground and are single-phase and may be short-time or continuously rated, depending upon the system requirement. If it is being used as a ground fault neutralizer it may have to be continuously rated. It may be of variable type to help tuning with the system ground capacitance.

27.4.7 Tuning or filter reactors

These are meant to be used in series with a capacitor to form a series resonant circuit tuned to a frequency below that of the lowest harmonic for reducing and filtering (smoothing) the harmonics or communication frequencies. They also help in meeting EMC/EMI requirements.

They provide a near short-circuit for the required harmonics to filter them out of circuit. They may be single-phase or three-phase and connected in series or parallel of the capacitor circuit and may have a fixed or variable reactance, rated continuously with saturated magnetic characteristics. They may incur heavy losses. A typical three phase harmonic filter is shown in Figure 27.14. Figure 6.22(p3) also shows an SVC substation with shunt reactors.

27.4.8 Smoothing reactors

These are meant to provide high impedance to harmonic currents and block their entry or reduce their amplitudes and are therefore also known as blocking reactors (Section 23.5.2, Equation (23.6)). They may have any of the magnetic characteristics shown in Figure 27.2 and have a fixed reactance, rated continuously.

The above are only some applications where a reactor can be made use of to improve system parameters to a desirable level. There can be numerous similar applications where a power reactor can be gainfully employed to improve the parameters of a power circuit or system.

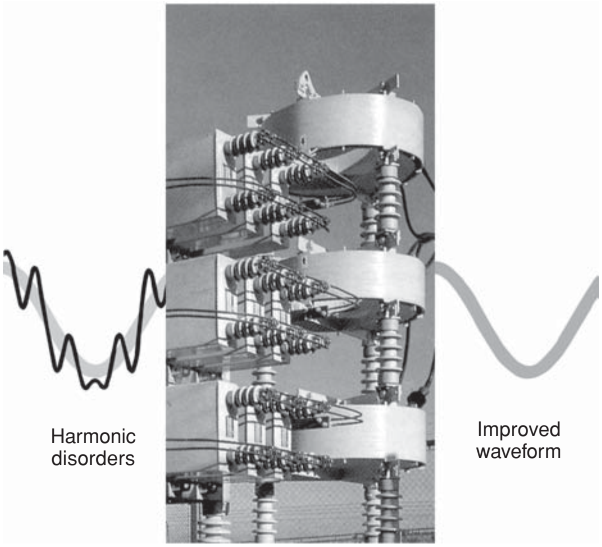


Figure 27.14 A typical three phase tuning or filter reactor (Courtesy: ABB)

Relevant Standards

IEC	*Title*	*IS*	*BS*	
60076–4/2002	Guide to the lightning impulse and switching impulse testing – Power transformers and breakers.	–	–	–
60289/1988	Reactors.	5553 (1 to 8)/1998	BS EN 60289/1995	–

Relevant US Standards ANSI/NEMA and IEEE

IEEE-62/1995	Guide for field testing of electric power apparatus insulation. Part I – oil filled reactors

Notes

1 In the table of Relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.

2 Some of the BS or IS Standards mentioned against IEC may not be identical.

3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.