SHUNT REACTORS

١ DESCRIPTION OF SHUNT REACTORS

General statement

Shunt reactors are inductive loads that are used to absorb reactive power to reduce the over voltages generated by line capacitance.

An inductive load consumes reactive power versus a capacitive load generates reactive power.
A transformer, a shunt reactor, a heavy loaded power line, and an under magnetized synchronous machine are examples of inductive loads. Examples on a capacitive load are a capacitor bank, an open power line and an over magnetized synchronous machine.

Although shunt reactors are inductive loads similar to transformers but they are different than transformers in terms of construction and some electrical characteristics.

To describe the shunt reactors better, we need to look at the different designs of shunt reactors and their electrical characteristics.

١.١ *Design of shunt reactors*

Design and operation
Shunt reactors are mainly used in transmission networks. Their function is to consume the excess reactive power generated by overhead lines under low-load conditions, and thereby stabilize the system voltage. They are quite often switched in and out on daily basis, following the load situation in the system. Shunt reactors are normally connected to substation busbar, but also quite often directly to the overhead lines. Alternatively, they may also be connected to tertiary windings of power transformers. The shunt reactors may have grounded, or reactor grounded neutral.
Shunt reactors normally have iron cores with integrated air gaps. Due to the air gaps, the iron cores cannot be significantly saturated, and the reactors therefore will have a reasonably linear behavior during energizing events, for example.
Three-phase shunt reactors may consist of three separate single-phase cores, or they could be of three-leg or five-leg design (alternatively shell type), see Figure ١ and Figure ٢.
For transmission voltages the Five-leg core type or shell type are mainly used. They make the three phases magnetically independent, while three-leg cores lead to magnetic coupling between phases.
Any significant period of one or two phase excitation necessitates the provision of a clearly defined return path for the zero-sequence flux created by the asymmetrical excitation. Where single phase operation is likely to occur, e.g. in power systems

employing single pole auto-reclosing, there are two optional ways to achieve such a return path for the zero-sequence flux. These are:

١. To use a three phase ٥-limb core (or shell type core).
٢. To use single phase units.

One major advantage with a five leg reactor (or shell type) compared with a three leg reactor is that the construction to reduce vibrations and the long term use is much more stable and stronger.

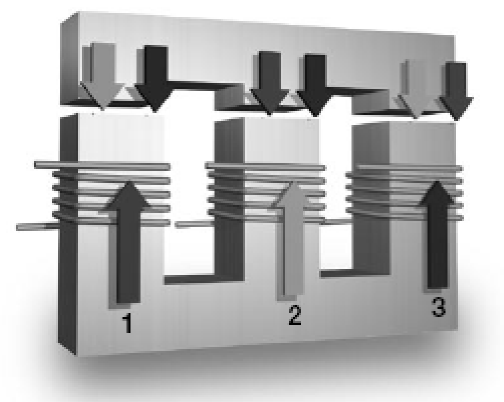


Figure ١ Three-leg shunt reactor core

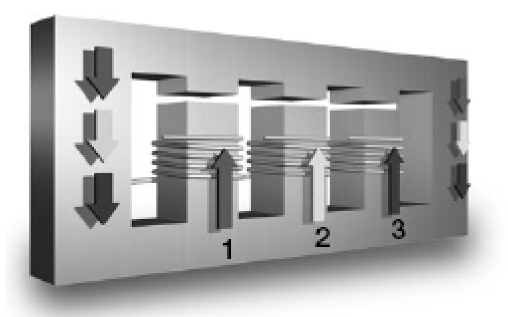


Figure ٢ Five-leg shunt reactor core with three wound limbs

Medium voltage reactors, connected to tertiary windings of transformers, in most cases have air-insulated windings without iron cores.

Oil or Dry type shunt reactors
There are two types of shunt reactor groups one is the oil immersed type similar to transformers the other type is the air core or core-less reactor.
The dry type of reactors are normally used up to ٣٤.٥ kV and often installed on the tertiary of a transformer **Error! Reference source not found.**].

The design is divided in gapped core and core-less reactors. The gapped core has a subdivided limb of core steel with air gaps inside the winding and no limb at all for the core less concept. The gapped core gives compact design with low losses and low total mass, low sounds and low vibrations.
Higher energy density can be achieved in a gapped core compared to an air core.
The slope of the permeability is greater in a gapped core versus an air core reactor.

The primary advantages of dry-type air-core reactor, compared to oil-immersed types, are lower initial and operating costs, lower weight, lower losses, and the absence of insulating oil and its maintenance. The main disadvantages of dry-type reactors are limitations on voltage and kVA rating and the high-intensity magnetic field. There is no magnetizing inrush current when the reactor is energized.

Unit ratings for existing single phase or three phase shunt reactors are:

Three phase up to: ٢٥٠ Mvar
Single phase up to: ١٣٠ Mvar
System voltages up to: ٨٠٠ kV

Single Phase reactors
Single phase reactors are used when the power is above the limits for a three phase shunt reactor.

Three phase (٣-leg or ٥-leg shunt reactors)
Most three phase shunt reactors are designed with five limbs, because of a more robust construction and to reduce vibrations over time, since shunt reactors should last ٤٠-٥٠ years.
The unwound side limbs results in that the zero sequence impedance is equal to the positive sequence impedance.

In a high voltage star connected shunt reactor the zero sequence reactance is dependent on the core arrangement.

The physics are the same as the case with a star/star connected transformer. Under symmetrical excitation the sum of momentary flux values in the three phases is zero. But under earth fault conditions this is not the case and the resulting flux must find a way back external to the three phase coils. In three limb reactors, this resulting flux would go through the air from yoke to yoke; it means that the zero sequence reactance is lower than the normal reactance and also non-linear, leads to higher zeros sequence current.

In some applications it is a distinct advantage if the reactor has high and constant zero sequence reactance. This is the case when single pole reclosing is either required from the beginning, causing zero sequence flux each time a single pole is opened, or considered for future development of the system to limit the zero sequence flux. In certain cases (e.g.

line connected shunt reactors) it is also recommended that the zero sequence reactance be tuned to a fixed, high value by the addition of an auxiliary neutral reactor.

As for transformers, a high zero sequence reactance requires a low reluctance unwound return path in the magnetic circuit, leads to smaller zero sequence current – which is achieved with a five-limb core. In a reactor this will result in a next to absolute decoupling of the phase limbs from each other because the wound limbs are gapped and the outer limbs are not. This is easily verified by measuring non-induced voltage on the other phases when one phase is energized **Error! Reference source not found.**].

Split winding

The split winding is used when the current have exceeded the maximum of mechanical reasons in the construction, then two windings per phase will be parallel in the reactor.

Shunt reactors equipped with auxiliary power windings

Because shunt reactors are used to control voltage at the receiving ends of long Extra High-Voltage and Very High-Voltage transmission lines, these reactors often are located 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 high-voltage reactor application usually calls for oil-immersed reactors that look very similar in appearance to power transformers. When designed with an air-gapped iron core, these reactors can be equipped with a secondary core and winding such that a low-voltage can be extracted from the high-voltage line, see **Error! Reference source not found.**] and **Error! Reference source not found.**].

Shunt reactor in the neutral

For line connected shunt reactors, an additional single-phase reactor (neutral reactor) is sometimes connected between neutral and ground. The purpose of this reactor is to increase the overall zero sequence reactance of the overhead line. In this way, the fault current is kept small in the event of single-phase line faults cleared by single-pole opening of the line breakers. As a result, there will be a high probability that the arc at the fault location is extinguished and that the reclosing operation is successful.

Variable shunt reactor (VSR), with tap-changer

Shunt Reactors are used in high voltage energy transmission systems to stabilize the voltage during load variations. A traditional shunt reactor has a fixed rating and is either connected to the power line all the time or switched in and out depending on the load. Recently Variable Shunt Reactors (VSR) have been developed and introduced on the market. The rating of a VSR can be changed in steps, The maximum regulation range typically is a factor of two, e.g. from ١٠٠-٢٠٠ Mvar. The regulation speed is normally in the order seconds per step and around a minute from max to min rating. VSRs are today available for voltages up to ٥٥٠ kV.

The variability brings several benefits compared to traditional fixed shunt reactors. The VSR can continuously compensate reactive power as the load varies and thereby securing voltage stability. Other important benefits are: - reduced voltage jumps resulting from switching in and out of traditional fixed reactors, - flexibility for future (today unknown) load and generation patterns, - improved interaction with other transmission equipment and/or systems such as coarse tuning of SVC (Static Var Compensation) equipment, - limiting the foot print of a substation if parallel fixed shunt reactors can be replaced with one VSR, - a VSR can be used as flexible spare unit and be moved to other locations in the power grid if needed.

Shell type core

The reactor design is said to follow either a core or shell type concept **Error! Reference source not found.**].The difference in the two concepts was originally attributed to the arrangement of the core. In the core type transformers the coils appear to surround the core and in the shell type the core appear to surround the windings, see Figure ٣.

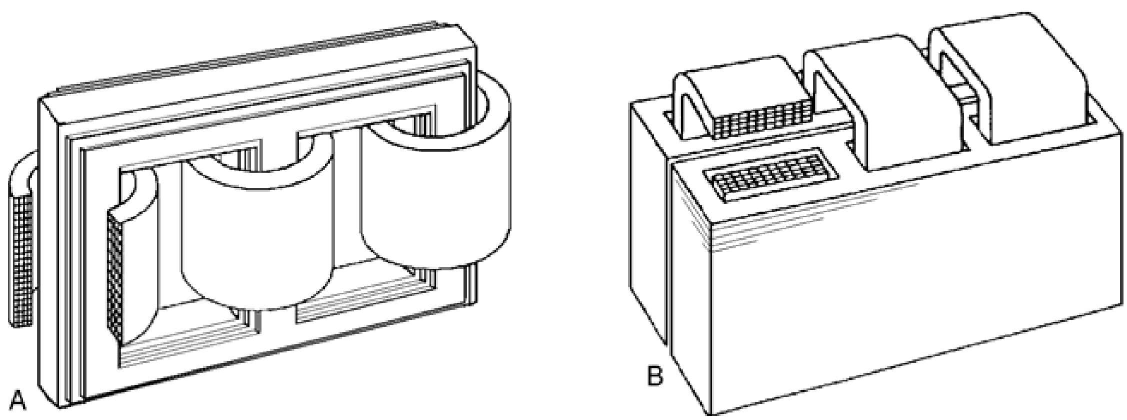


Figure ٣ Reactor construction, Core type (A), Shell type (B).

This simple definition does not always hold. The way reactors are built today; a description as follows would be more adequate:

- In a core type reactor the core limb has a shape of a cylinder around which the coils are arranged. For normal core type power reactors the coils too are cylindrical and arranged concentrically. Each terminal is connected to one coil or several coils in series. Further the coils are slid down around a pre-made core limb to which yokes are connected after the windings are in position. Most often the core limbs and yokes are in vertical position.
- In the shell type reactor the separate coils have rectangular cross section and they are wound in one plane. After the winding work the coils for one terminal are stacked up on each other and connected together. The groups of coils are then in turn, stacked together to form a winding packet for the complete circuit. The packets for each phase are then raised to the upright and adjusted position it has in the reactor. In and around these packets the core is now built up.

A five leg shunt reactor of core type has similar characteristics as a three leg shell type reactor (to have a low vibration and noise level, low zero sequence current), so the reason for a manufacturer to keep to a certain concept may today be historical.

١.٢ *Electrical characteristics*

The electrical characteristics of a shunt reactor that needs to be studied are:

- Air-gap of the shunt reactor core.
- Switching in a shunt reactor
- Disconnection of the shunt reactor
- Dominating harmonics
- Hysteresis
- Losses in shunt reactors

١.٢.١ Air-gap of the shunt reactor core

To avoid saturation of the iron-core of the shunt reactor, small air gaps are distributed along the core. The distribution of the magnetic flux intensity from the iron to the air-gap can in that way handle larger H-field (magnetic flux intensity [A/m]). The air-gap is seldom larger than a couple of millimeter. The magnetic flux intensity is much larger in air than in iron approximately ١٠٠٠ times.
In a transformer the aim is not to have any air-gap, therefore the slope in the B-H curve is very steep with large hysteresis and remanence compared to a shunt reactor, however for a reactor with air-gap the B-H curve becomes flatter and the hysteresis is very small with practically no remanence. This leads to that there are small inrush currents and long DC constants for the shunt reactor, compared to the transformer.
Air core reactors (no iron core), have small inductance L, high losses and high current in the windings.
Oil immersed iron core reactors with air-gap, have higher inductance, smaller losses and less current in the windings.
By introducing iron in the winding a higher inductance can easily be achieved without increasing massively the number of turns as in air-core.

١.٢.٢ Inrush

When switching in air core or iron core reactors, long DC components up to ١ second can occur, some differences distinguishes between inrush in air respective iron core reactors.

١.٢.٢.١ Switching in air core reactors

For an air core reactor where L is practically constant (i.e. permeability $\mu = \frac{\Delta B}{\Delta H} = k$, is constant) a simple model with a breaker switched in can describe the electrical principles, see Figure ٤ below **Error! Reference source not found.**]:

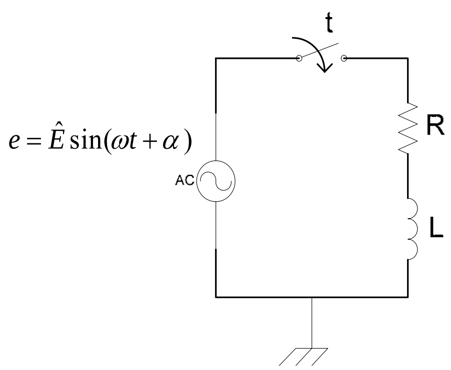


Figure ٤ Simple shunt reactor model

$$\frac{e-u_L}{R}=i_L \qquad \textbf{eq. ١}$$

$$u_L = L\frac{di_L}{dt} \qquad \textbf{eq. ٢}$$

$$\frac{e-L\frac{di_L}{dt}}{R}=i_L \qquad \textbf{eq. ٣}$$

$$i'_L+\frac{R}{L}i_L-\frac{e}{L}=٠ \qquad \textbf{eq. ٤}$$

The instantaneous voltage value when the breaker is closed.

$$e=\hat{E}\sin(\omega t+\alpha) \qquad \textbf{eq. ٥}$$

The derived short current obtained through the limiting values

$$\begin{cases} i_L = i_{AC}+i_{DC}=٠ \\ t=٠ \end{cases} \text{and} \begin{cases} i_L = i_{AC} \\ t=\infty \end{cases} \qquad \textbf{eq. ٦}$$

$$i_L = i_{AC}+i_{DC}=\frac{\hat{E}}{|Z|}\left(\sin(\omega t+\alpha-\varphi)-\sin(\alpha-\varphi)\cdot e^{-\frac{R}{L}t}\right) \qquad \textbf{eq. ٧}$$

Where the impedance is

$$|Z|=\sqrt{R^{٢}+(\omega L)^{٢}} \qquad \textbf{eq. ٨}$$

The first term in eq. ٧ states the time function for the steady state condition which is an AC current and the second term indicates the transient condition which is a damped DC current.

The time constant of the damping is $\tau=\frac{L}{R}$.

The time constants for shunt reactors are longer than transformers and can be up to ١ second. Transformers have DC constants up to a couple of hundred milliseconds.

The inrush can therefore easily saturate a CT measurement of the current.

As can see from eq. ٧ the size of the short circuit current is depending on the voltage phase angle at the instantaneous moment when the breaker is closed. If $\alpha = \varphi$ then the elapsed curving inward oscillation disappears (transient part) and the short circuit current only consists of the steady state part.
With regard to the instantaneous phase angle of the voltage α there is two cases of special interests:

Case ١ $\alpha = ٠$
The short circuit is here done when the voltage run-through zero. In this case the current reaches its absolute maximal instantaneous value, which is realized analytically when the derivative of i_k with regard to α and t shall be zero in the maximum moment, i.e.

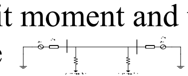
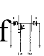
$$\frac{\partial i_k}{\partial \alpha} = \sqrt{٢}\, I_k \left[\cos(\omega t + \alpha - \varphi) - \cos(\alpha - \varphi) \cdot e^{-\frac{R}{L}t} \right] = ٠ \qquad \textbf{eq. ٩}$$

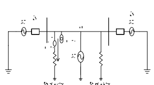
$$\frac{\partial i_k}{\partial t} = \sqrt{٢}\, I_k \left[\omega \cdot \cos(\omega t + \alpha - \varphi) - \frac{R}{L} \sin(\alpha - \varphi) \cdot e^{-\frac{R}{L}t} \right] = ٠ \qquad \textbf{eq. ١٠}$$

$$\tan(\alpha - \varphi) = \tan(-\varphi) = -\frac{\omega L}{R} \qquad \{\alpha = ٠, \alpha = \pi, \alpha = ٢\pi, \ldots\} \qquad \textbf{eq. ١١}$$

The maximum inrush current $i_{k\max}$ appears when using realistic power system impedances, approximately at the same time when the steady state current reaches its first peak value, i.e. $t \approx \dfrac{\left(\varphi + \frac{\pi}{٢}\right)}{\omega}$, see eq. ١٢ below:

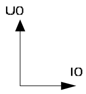
$$i_k = \sqrt{٢}\, I_k \left[١ + \sin(\varphi) \cdot e^{-\frac{R}{\omega L}\left(\varphi + \frac{\pi}{٢}\right)} \right] \qquad \textbf{eq. ١٢}$$

We observe that the current time derivative is zero in the short circuit moment and that the DC component initial value is not the maximal imaginable, since  in the expression of .

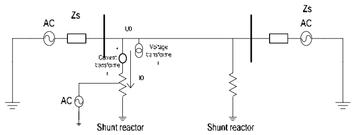
Case ٢ 

In this case has the steady state short circuit current the (negative) top value in the short circuit moment and the DC component has in consequence hereby largest possible value. Installed in eq. ٧ the short circuit current can be derived:

$$i_k = \sqrt{٢}\, I_k \left[e^{-\frac{R}{L}t} - \cos(\omega t) \right]$$ **eq. ١٣**

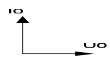
Maximum instantaneous value occurs likewise approximately in the AC components first top value at time 

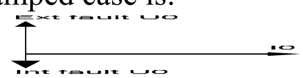
and is:



eq. ١٤

Because the asymmetry in a certain (some) degree here is largest it is close to expect that this maximum value not is much less then the theoretic correct value that can be derived in the case $\alpha = ٠$. This is also correct for a power network characteristic data and one can with good approximation use this simple expression when deriving the inrush current.

Observe the ideal case with  when both cases lead to the same result. In this un-damped case is:



eq. ١٥

Figure ٥ Aircore reactor

A short circuit current with DC component is often called unsymmetrical short circuit current, and speaks about greater or less degree of asymmetry that is dependent on the instantaneous time of the short circuit. With maximum asymmetry it is meant a current which DC component has the same value as the AC components un-damped top value. Observe that the word symmetry and asymmetry here is used in another meaning then three phase symmetry and three phase asymmetry.

١.٢.٢.٢ Switching in oil immersed iron core reactors

For an iron core reactor where L is not constant, the permeability is depending on the magnetic field intensity H [A/m] and magnetic flux density B [Vs/$m^{٢}$] (i.e. permeability $\mu = \frac{\Delta B}{\Delta H}$) a simple model with a breaker switched in can describe the electrical principles see Figure ٤, Figure ٨ and Figure ٩.

The magnetizing characteristic of a shunt reactor
The relation between voltage and current can be described with two lines one for the unsaturated part and one for the saturated part. The intersection between is called knee point and is usually located at ١٢٥ – ١٣٥ % of the voltage amplitude. The saturated region has a slope of ٢٠ – ٤٠ % of the unsaturated region. Typical HV shunt reactor magnetizing characteristic is shown in Figure ٦ **Error! Reference source not found.**].

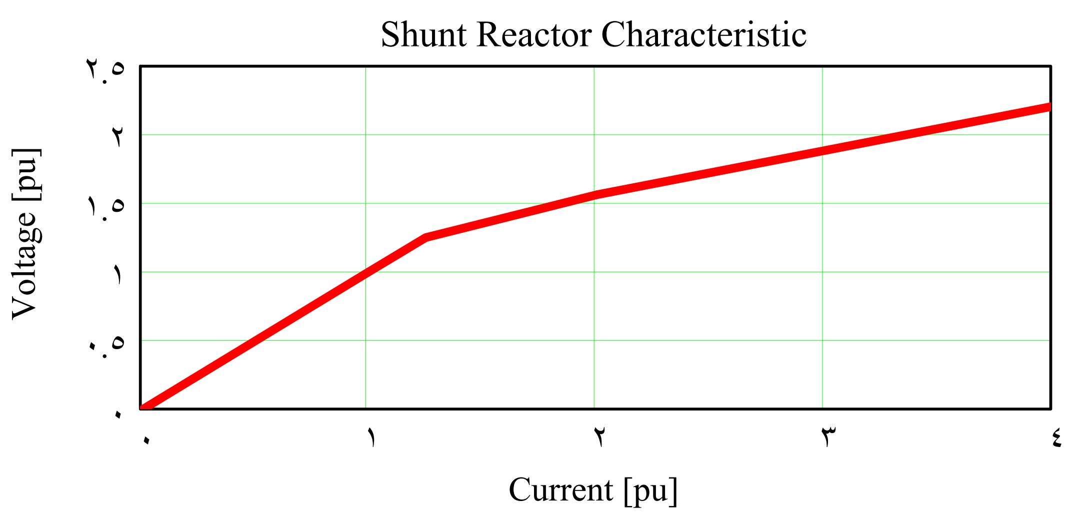


Figure ٦ Typical magnetizing characteristic of a gapped core shunt reactor

Description of parameters
L = inductance [H]
N = number of windings
l_{FE} = length of flux in iron yoke and limb [m]
$\mu_{.} = ٤\pi ١٠^{-٧}$ permeability in air [Vs/Am]
μ_r = permeability constant iron
μ = total permeability [Vs/Am]
B = magnetic flux density [Vs/$m^{٢}$]
H = magnetic flux intensity [A/m]

Φ = total flux [Vs]
A_{FE} = iron area in limb [m^{٢}]

Switching in a shunt reactor

The inductance L and permeability μ of the shunt reactor can be derived **Error! Reference source not found.**]

$$L = N^{٢}\frac{\mu.\,\mu_r A_{FE}}{l_{FE}} = N^{٢}\frac{\mu A_{FE}}{l_{FE}} \qquad \textbf{eq. ١٦}$$

$$\mu = \frac{\Delta B}{\Delta H} \qquad \textbf{eq. ١٧}$$

The differential equation when a shunt reactor is switched in follows

$$\frac{di}{dt} = \frac{١}{L}(\tilde{e} - Ri) \qquad \textbf{eq. ١٨}$$

By using the flux Φ [Vs] eq. ١٩ and flux intensity H [A/m] in eq. ٢٠ into the eq. ١٧ and eq. ١٦ the inductance L can be derived see eq. ٢١

$$\Phi = B \cdot A_{FE} \cdot N \qquad \textbf{eq. ١٩}$$

$$i = \frac{H \cdot l_{FE}}{N} \qquad \textbf{eq. ٢٠}$$

$$L = \frac{d\Phi}{di} \qquad \textbf{eq. ٢١}$$

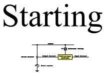
By introducing the inductance in eq. ٢١ the magnetic flux over the inductance follows in eq. ٢٣:

$$\frac{di}{dt} = \frac{di}{d\Phi}(\tilde{e} - Ri) \qquad \textbf{eq. ٢٢}$$

$$\frac{d\Phi}{dt} = (\tilde{e} - Ri) = u_L \qquad \textbf{eq. ٢٣}$$

To derive the magnetizing voltage and the total magnetic flux the recursive equations (Euler equations **Error! Reference source not found.**]) are used in eq. ٢٤ and eq. ٢٥:

Starting conditions:

 , $B[١] = B_R$, $\Phi[١] = B_R \cdot A_{FE} \cdot N$

$$u_L[k] = \tilde{e}[k] - R\,i_L[k] \qquad \textbf{eq. ٢٤}$$

$$\Phi[k+١] = \Phi[k] + \Delta t \cdot u_L[k] \qquad \textbf{eq. ٢٥}$$

The magnetic field intensity (H) can be derived from the graph in **Error! Reference source not found.**] after calculating of the magnetic flux density (B):

$$B[k+١] = \frac{\Phi[k+١]}{A_{FE} \cdot N} \rightarrow H[k+١]$$ **eq. ٢٦**

Calculate the magnetizing current i_L :

$$i_L[k+١] = \frac{H[k+١]}{N} \cdot l_{FE}$$ **eq. ٢٧**

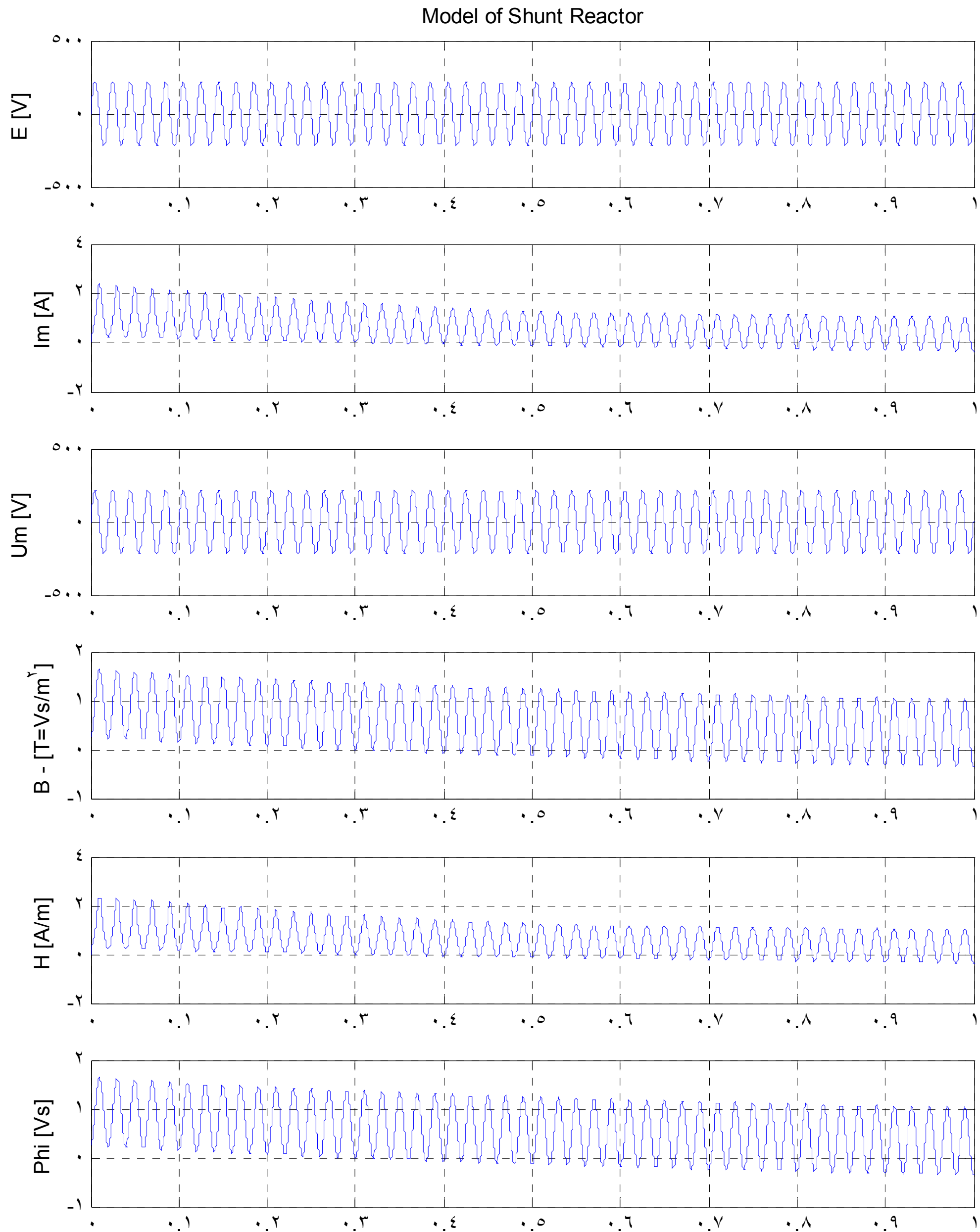


Figure ٧ Test result of inrush

E = Voltage over shunt reactor model [V]
I_m = Magnetizing current trough shunt reactor [A]
U_m = Magnetizing voltage over inductive part [V]
B = Magnetic flux density [T=Vs/m^٢]
H = Magnetic field intensity [A/m]
Phi = Magnetic flux over the shunt reactor [Vs]

During inrush the permeability can move up over the threshold knee and cause a transient current greater than ٢$\sqrt{٢}I_k$ (٣ to ٥ I_k) and after several seconds reaching steady state current, see Figure ٦ and Figure ٧.

As the shunt reactor is moving from saturation region to steady state region, the permeability increases towards the constant value (μ) and the current decreases to steady state value. The damping time τ also increases with less saturation as the permeability of the shunt reactor moves towards steady state.
Both above statements can be seen from the following equations:

$$i \cdot N = \frac{\phi l_j}{\mu_{.} \mu_r A}$$ **eq. ٢٨**

$$\tau = \frac{L}{R}$$ **eq. ٢٩**

Figure ٨ Bus connected, ٣٠٠kV, ١٥٠MVAr, oil immersed shunt reactor

Figure ٩ Bus connected, ٤٢٠kV, ٢٠٠MVAr, oil immersed shunt reactor

١.٢.٣ Shunt reactor disconnection

Disconnection of small reactive current was at one time regarded as a dangerous operation because of the risk of current chopping and resulting switching overvoltage. Modern surge arresters are fully capable of handling this condition, and besides, the tendency of the circuit breaker to chop reactor current is not so pronounced for typical HV shunt reactor rated current values **Error! Reference source not found.**].

However, the primary current chopping causes a transient, an exponentially decaying dc current component in the CT secondary circuit (see Figure ١٠ for a similar example). This secondary dc current has no corresponding primary current in the power system; it is caused by a discharge of the magnetic energy stored in the magnetic core of the current transformer. However these discharge secondary currents are typically very small for shunt reactors and pose no effect on the reactor protection schemes with numerical relays **Error! Reference source not found.**]

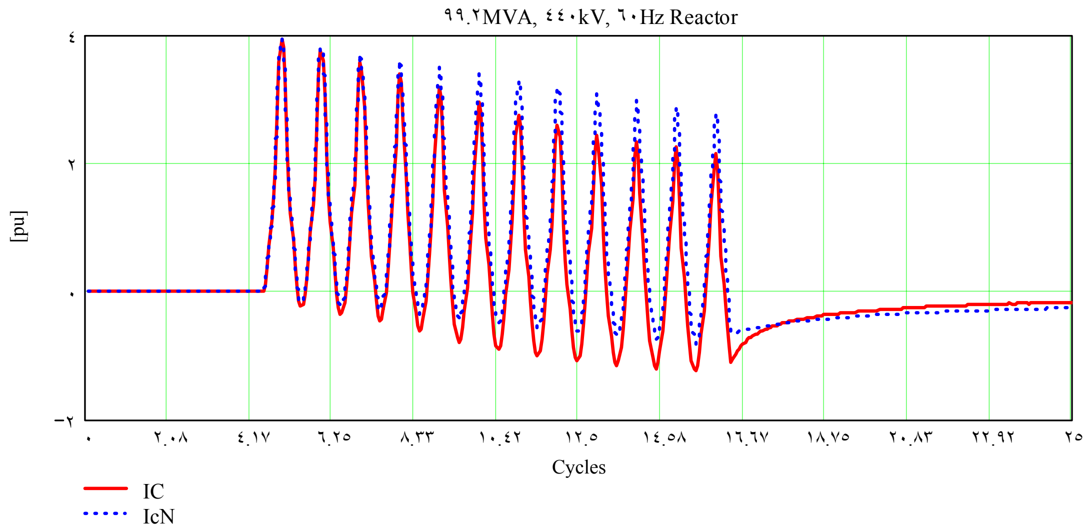


Figure ١٠ Phase C winding currents during shunt reactor switching in and tripping out

١.٢.٤ Harmonics

The zero, ٢nd and ٣rd harmonics in a shunt reactor are described below.

١.٢.٤.١ Zero Harmonic (DC)

The zero harmonic current (DC component, offset) appears at connection and disconnection of the shunt reactor, with a time constant up to ١ second for shunt reactors, due to inherent low losses in a shunt reactor (small resistance compared to inductance).

١.٢.٤.٢ ٢nd Harmonic

Inrush current in a shunt reactor doesn’t appear as a differential current like that which appears in a transformer, unless the CT saturates after some time due to long DC time constant. The level of ٢nd harmonic is small in shunt reactors compared to transformers.

١.٢.٤.٣ ٣rd Harmonic

The ٣rd harmonic is the dominant harmonic in shunt reactors during normal operating condition, due to asymmetries in the reactor windings.
The ٣rd harmonic can be seen in the neutral point of the shunt reactor or as residual using all phases **Error! Reference source not found.**].

١.٢.٥ Hysteresis

There is practically no remanence in a shunt reactor compared to a transformer. The small air gaps along the reactor winding create a thin hysteresis in the B-H curve for the reactor and therefore very small remanence.

١.٢.٦ Losses

The fundamental losses in a shunt reactor are winding resistance and magnetization losses, eddy current losses are also present but small in comparison.
The resistance loss is proportional to the weight of the winding material and to the square of the current density. The magnetization loss in the core steel also rises by approximately the square of the flux density.
The total loss is generally ٠.٢% active power (W) of the total reactive power of the shunt reactor distributed as follows **Error! Reference source not found.**]:

- Resistance losses in winding, $P = RI^{٢}$ ٦٠-٧٠%
- Core steel loss ٢٠-٣٠%
- Eddy current losses, winding and mechanical parts ٥-١٥%

٢ APPLICATION OF SHUNT REACTORS

Shunt reactors are used to compensate for large line charging capacitance of long high voltage power transmission lines and cables.

Their major applications are:

- Preventing over voltages that occur when the line is lightly loaded (Ferranti Effect).
- Providing voltage control.
- Compensating for line charging reactive power demand of the open-circuit line.
- Suppressing the secondary arc current for successful single pole reclosing.

٢.١ *Connection to the Power System and Grounding Methods*

The reactors are normally connected to power system in three locations. They can be connected to Line, Bus or Tertiary winding of the power transformer or auto-transformer.

٢.١.١ Line and Bus connected reactors

The line connected reactors are normally connected at both ends of the line as each end can be energized or de-energized independently.
The shunt reactors can be connected directly to HV lines (see Figure ١١) or via circuit switcher or circuit breaker to HV lines or buses depends on the application (see Figure ١٢).

The permanently connected reactors are used to prevent overvoltages appear on long lines due to lightly loading or open circuit. The switched reactors are used for voltage control.

These reactors are normally grounded, solidly or via a neutral reactor (see Figure ١١ and Figure ١٢). The neutral reactor is used where single pole auto-reclose is applied, to suppress the secondary arc current.

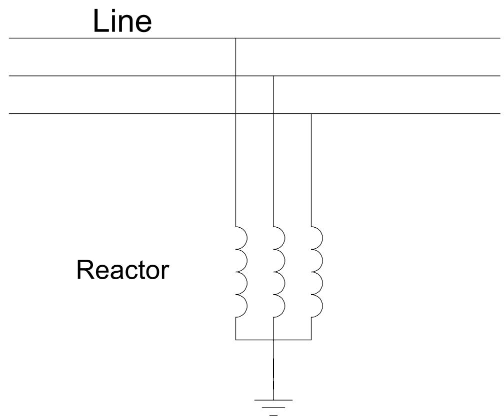


Figure ١١ Solidly grounded three phase reactor directly connected to line

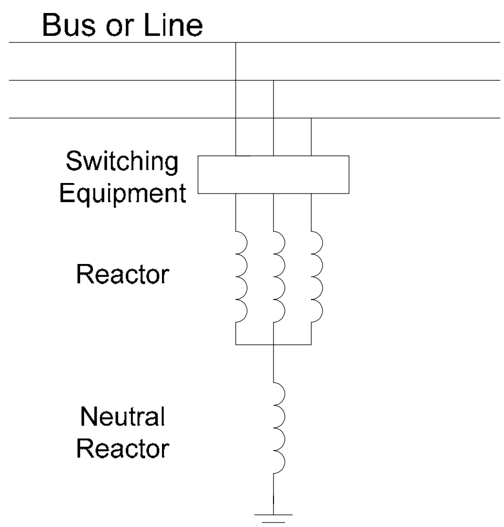


Figure ١٢ Three phase and neutral reactor connected to bus or line via circuit switcher or circuit breaker

٢.١.٢ Tertiary winding connected reactors

These reactors are normally ungrounded and can be switched via circuit switcher or circuit breaker. These switching devices can be on supply side or neutral side of the reactor (see Figure ١٣ and Figure ١٤).
Some utilities have used grounded reactors to reduce TRV (Transient Recovery Voltage) duty of the switching breaker.

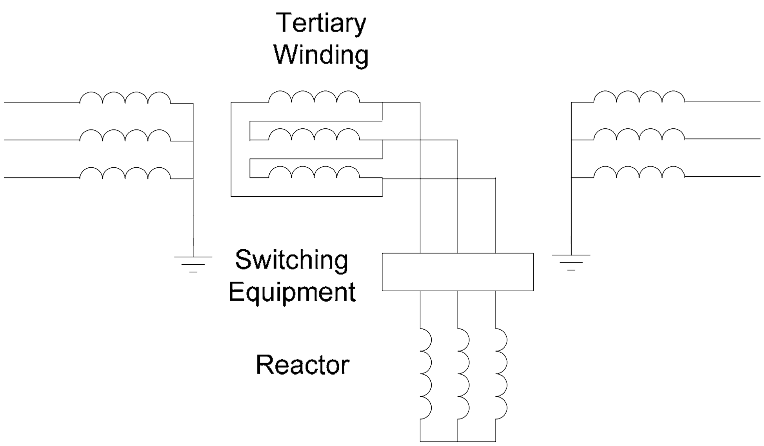


Figure ١٣ Shunt reactor connected to transformer tertiary winding switching via circuit switcher or circuit breaker on supply side

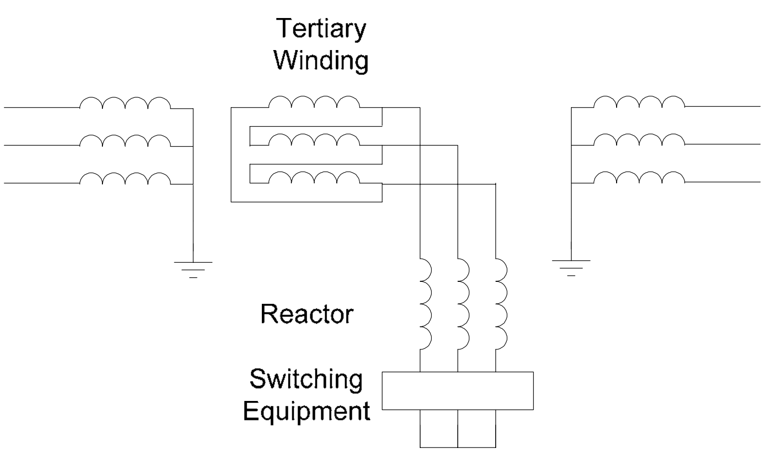


Figure ١٤ Shunt reactor connected to transformer tertiary winding switching via circuit switcher or circuit breaker on neutral side

٢.٢ *Effects of Shunt Reactors on Transmission Line Voltage*

To better understand the effects of the shunt reactors, we can use the nominal-π circuit of a transmission line and compare the receiving-end voltage of a lightly loaded line with and without shunt reactors.

Although the nominal-π circuit do not represent a transmission line exactly and the discrepancy between the nominal-π and the actual line becomes larger as the length of the line increases, it can be shown that the nominal-π may represent long lines sufficiently well if a high degree of accuracy is not required **Error! Reference source not found.**].

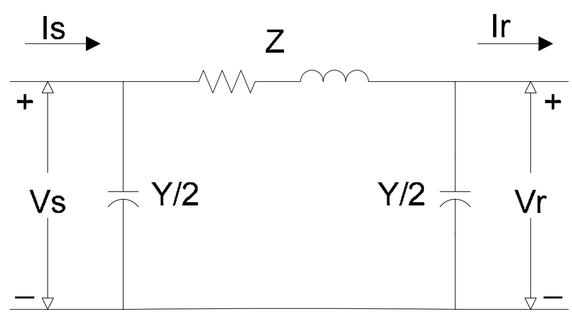


Figure ١٥ Nominal-π circuit of a transmission line

To derive Vs from the above circuit (Figure ١٥), we note that the current in the capacitance at the receiving end is VrY/٢ and the current in the series arm is Ir + VrY/٢, then

$$Vs = (VrY / ٢ + Ir)Z + Vr$$ **eq. ٣٠**

$$Vs = (ZY / ٢ + ١)Vr + ZIr$$ **eq. ٣١**

Is would be the summation of the current in the shunt capacitance at the sending end which is VsY/٢, and the current in the series arm.

$$Is = VsY / ٢ + VrY / ٢ + Ir$$ **eq. ٣٢**

$$Is = VrY(١ + ZY / ٤) + (ZY / ٢ + ١)Ir$$ **eq. ٣٣**

The equations eq. ٣١ and eq. ٣٣ can be expressed in the following form:

$$Vs = AVr + BIr$$ **eq. ٣٤**

$$Is = CVr + DIr$$ **eq. ٣٥**

Where

$$A = D = ZY / ٢ + ١$$ **eq. ٣٦**

$$B = Z$$ **eq. ٣٧**

$$C = Y(١ + ZY / ٤)$$

eq. ٣٨

A and D are dimensionless and B and C are in ohms and mhos, respectively.

Now let us look at an example of a line and using the above equations and compare the no load receiving-end voltage before and after applying the shunt reactors.

Example: A single-circuit ٢١٥ kV, ٢٣٠ mile transmission line has the following series impedance and shunt admittance per mile:

$z = ٠.٨٤٣١\angle ٧٩.٠٤^{\circ}$ Ω/mi

$y = ٥.١٠٥\times ١٠^{-٦}\angle ٩٠^{\circ}$ S/mi

Then

$Z = z\times l = ١٩٣.٩١\angle ٧٩.٠٤^{\circ}$ Ω

$Y = y\times l = ١.١٧٤\times ١٠^{-٣}\angle ٩٠^{\circ}$ S

We can also derive the no load receiving-end voltage (Vr,nl) by substituting Ir =٠ in Vs equation eq. ٣٤.

$$Vs = AVr,nl$$

$$Vr,nl = Vs / A$$

Now we need to calculate Vs and A.

To calculate Vs, we use the Vs equation eq. ٣٤ and assume the load on the line is ١٢٥MW at ٢١٥ kV with ١٠٠% power factor.

$Ir = ١٢٥MW / \left(\sqrt{٣}\times ٢١٥kV\right) = ٣٣٥.٧\angle ٠^{\circ}\ A$

$Vr = ١٢٤.١\angle ٠^{\circ}\ kV$

$A = ٠.٨٩\angle ١.٤٢^{\circ}$

$B = ١٩٣.٩١\angle ٧٩.٤^{\circ}\ \Omega$

Then

$Vs = ١٣٩.٧\angle ٢٨.٥٠^{\circ}\ kV$

and

$$Vr,nl = Vs / A = ١٥٧.٠\ kV$$

Now we calculate the no load receiving-end voltage for the same transmission line when identical shunt reactors are connected at both ends of the line (see Figure ١٦), compensating for ٧٠% of the total shunt admittance of the line.

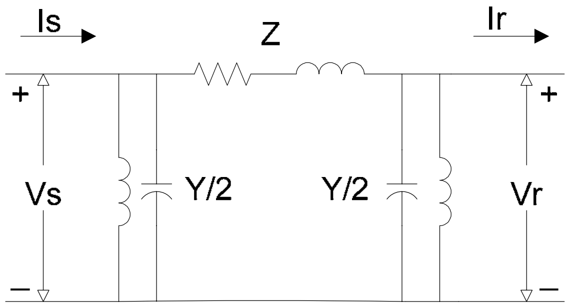


Figure ١٦ Nominal-π circuit with shunt reactors added to both end of the transmission line

Vs would be the same, but A would change since adding shunt reactors changes the value of Y:

$Z = ١٩٣.٩١\angle ٧٩.٠٤° \ \Omega$

$Y = (١ - ٠.٧) \times ١.١٧٤ \times ١٠^{-٣} \angle ٩٠° = ٣.٥٢٢ \times ١٠^{-٤} \angle ٩٠° \ S$

and

$A = ZY/٢ + ١ = ٠.٩٦٧\angle ٠.٣٨°$

Then

$Vr,nl = Vs/A = ١٤٤.٥ \ kV$

This example shows that adding shunt reactors can limit the rise of the no load voltage at the receiving end of the line from ١٥٧.٠ kV to ١٤٤.٥ kV.

٣ SHUNT REACTOR FAULTS AND ABNORMAL CONDITIONS

The modes of failure differ from air-core to oil-immersed designs and this affects their protection requirements and schemes.

٣.١ *Fault types in Dry-type reactors*

Three types of faults occur in dry-type reactor installations **Error! Reference source not found.**]:

١ Phase-to-phase faults on the tertiary busbar, resulting in high magnitude phase current.
٢. Phase-to-ground faults on the tertiary busbar, resulting in a low-magnitude ground current, dependent upon the size of the grounding transformer ground resistor.
٣. Turn-to-turn faults within the reactor bank, resulting in a very small change in phase current.

Phase-to-phase faults are a low probability fault for dry-type reactors because the reactors are single phase units with relatively wide spacing between phases. The main cause of these phase-to-phase faults is when arcing from a failed reactor is not detected soon enough and the fault ionization moves up into the tertiary busbar resulting in a phase to phase fault.

Since dry-type reactors are mounted on insulators which provide standard clearance and insulation to ground, direct winding-to-ground faults are low probability as well and are produced only when this neutral insulation is bridged by, for example, an animal. Damage done by a winding to ground fault is determined by the grounding transformer/resistor impedance.

Turn-to-turn insulation failures in dry-type reactors begin s tracking from insulation deterioration. Once the arc is initiated, these failures, if not detected quickly, cascade to the entire winding because of the arc's interaction with the reactor's magnetic field. If the reactor bank is ungrounded, the current in the healthy phase will increase to ٣ times normal phase current and could thermally damage the un-faulted phases of the reactor bank.

٣.٢ *Fault types in oil immersed reactors*

The oil-immersed reactor faults are broken into three categories:

١. High current phase-to-phase and phase-to-ground faults.
٢ Turn-to-turn faults within the reactor winding.
٣. Miscellaneous failures such as loss of cooling or low oil.

Because of the proximity of the winding with the core and tank winding-to-ground failures can occur. The magnitude of this fault decreases as the fault is located closer to the neutral side of the reactor. Turn-to-turn faults start out as a small change in phase currents but increase operating temperature internal pressure, and accumulation of gas. If these are not quickly detected they will evolve into a major fault.

٣.٣ *Failure rates of shunt reactors*

The definition of failure rates yields;
Failure rate = no of failures / (total population * total unit years)

Actual failure rate data for reactors is not always kept by utilities. Failure rates of shunt reactor may vary large from utility to utility in different countries and is affected by design, quality and workmanship. For example a failure rate between ٠.٥-١.٠% of shunt reactors, may increase to several percent during large expansion of the grid. Yearly maintenance of the shunt reactors and bushings will keep the failure rate down.
Data from Canada and India indicates the distribution of failures can for example be approximately ٣٠-٤٠% bushing related, ٣٠-٤٠% winding related, ١٥-٢٠% magnetic circuit, ١٠-١٥% terminals, and the failure origins may be distributed as ٨٠% dielectric, ١٠% thermal, ١٠% mechanical or others like unknown, chemical, geomagnetic induced currents.

٣.٤ *Turn to turn faults*

Phase to Phase and Phase to Ground faults can be caused by turn-turn faults. The location of the turn-turn fault is most likely in the windings closest to the high voltage part of the shunt reactor, caused by for example an impulse voltage from electrostatic discharge like lightning storms. Each winding on the shunt reactor can be seen as an inductance parallel with a leakage capacitance and capacitance to ground. The inductive part acts stiff on inrush currents, and the capacitive part causes an exponential distribution of voltage over the winding, with max at the top due to high frequency.

The capacitive part consists of the insulation material e.g. paper. If the highest voltage difference between the windings on top of the shunt reactor exceeds the capacitive insulation level, the insulation material deteriorates and causes a turn-turn fault between two windings. A possible way to protect for this is to design the shunt reactor with more insulation in the top and equip the system with a surge arrester, to limit high currents.

Earlier problems with oil containing copper used in shunt reactors and transformers caused turn-turn faults, today with improvements in oil quality, this special problem has disappeared.

Another cause of the turn-turn fault is vibrations. Vibrations create insulation material fatigue which in turn reduces the level of insulation and can cause a turn-turn faults. Samples from oil and material could tell the condition of the shunt reactor insulation.

Turn-turn faults can also be caused by excessive water in insulation paper, which can give raise to water vapor bubbles when temperature increases, thus creating a low dielectric strength region leading to electric arc.
The main risk for short-time failures is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress, which are the windings and leads. These bubbles are likely to occur when the hot-spot temperature exceeds ١٤٠ºC for a reactor

with winding insulation moisture content above ٢%. This critical temperature will decrease as the moisture concentration increases.

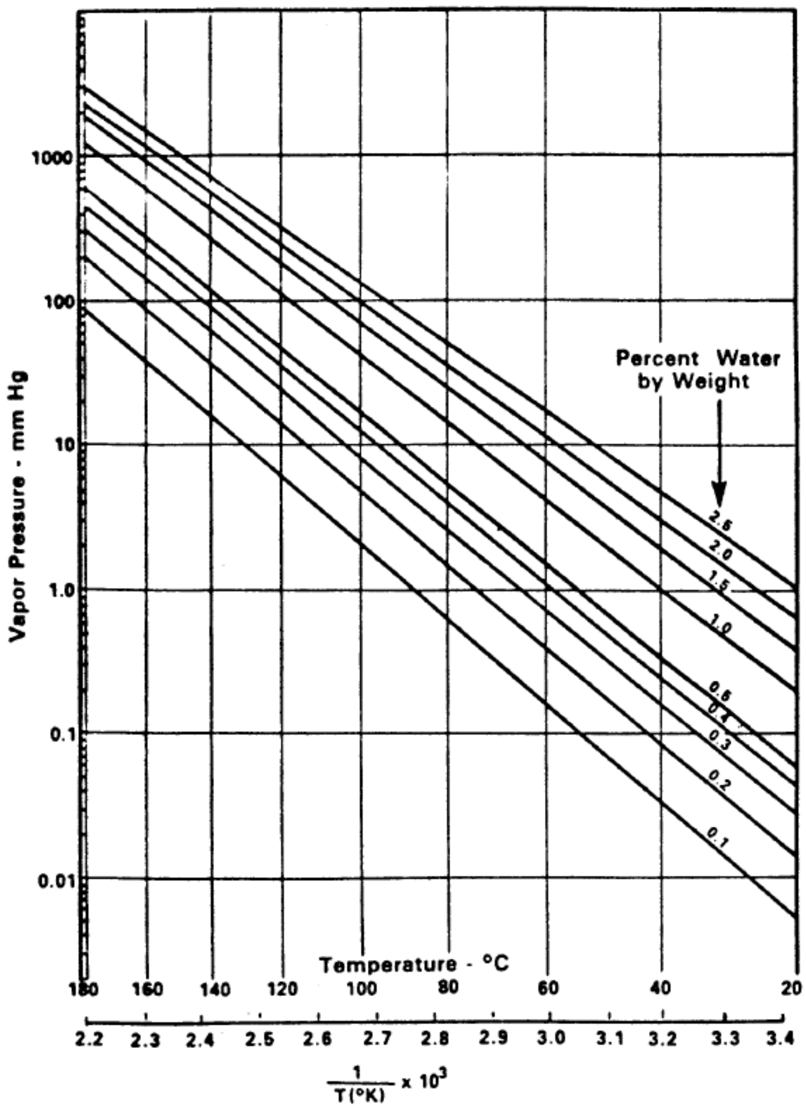


Figure ١٧ Equilibrium chart relating water vapor pressure over oil to water concentration in insulation (kraft) paper vs. temperature.

The risk with excessive water in insulation paper can be mitigated by using an on-line monitoring system with algorithms to determine water content in paper and bubbling temperature, so as to issue warnings when the reactor is close to a dangerous condition, before a turn-turn fault happens.

٣.٥ *Bushing failure*

Overvoltages due to lightning impulses or even due to the reactor switching can bring about very high dielectric stresses to the reactor bushings. Specifically in case of externally generated overvoltages, the bushings will be the first ones to suffer the stress. This fact can lead to bushings insulation deterioration, which ultimately would cause a phase-ground fault with severe damages to the reactor itself or even to neighbor devices due to porcelain shards being thrown. This is a severe risk also to people working close to the equipment.