CIGRE WG A2.48 on Technology and Utilisation of Shunt Reactors

Tutorial

Outline for This Tutorial

Part 1 – Applications, Specification, Design, and Construction

- Applications
- Specifications
- Linearity
- Components
- Design Review
- Design and Construction
- Noise and Vibration

Outline for This Tutorial

Part 2 – Testing
- Works Testing
- Field Testing

Part 3 – Operation and Life Management
- Switching
- Protection
- Control
- Monitoring
- Health Index

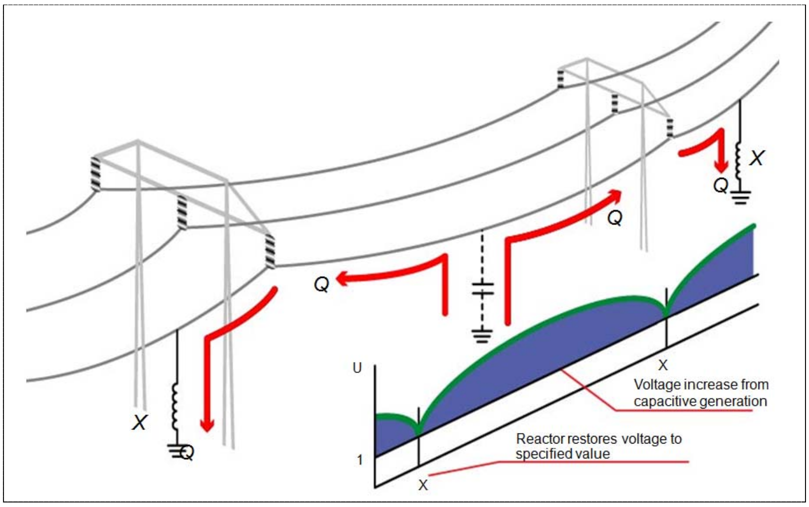
Applications

The voltage on any overhead line or underground cable depends on the balance between reactive power generation by the line or cable capacitance and reactive power consumption by the line or cable inductance.

Maintaining the correct voltage requires reactive power generation and consumption to be in balance. This is more challenging at higher voltages and especially for underground cables, owing to higher capacitance.

Shunt reactors are used to consume reactive power and maintain system voltage.

Applications



Applications

In recent years, there have been major advances in shunt reactor technology leading to the development of variable and controllable shunt reactors:

Variable shunt reactors use a tap-changer to vary the number of turns in the reactor winding. They use proven technology, which is also used in power transformers.

Magnetically controllable shunt reactors use a dc current to control the core reluctance and hence the reactive power output. They are more complex than other types, with a control system and a semiconductor rectifier.

Applications

The range of power absorption for **variable shunt reactors** depends mainly on the capabilities of the tap-changer, which depends on the voltage class. For 420 kV class typical designs have an output range from 40-50% to 100%. The time to vary the output across the full range is typically a few minutes.

The range of power absorption for **magnetically controllable shunt reactors** is from 0% to 100%, or perhaps higher if an overload rating has been specified. The time to vary the output across the full range is a few cycles, i.e. much less than one second.

Applications

Applications	**Fixed SHR**	**Variable SHR**	**Controllable SHR**
Compensation of reactive power in overhead lines	XXX	XXX	XXX
Compensation of slow variation in reactive power		XXX	XXX
Compensation of fast variation of reactive power, e.g. load rejection			XXX
Compensation of reactive power in underground cables	XXX	XXX	XXX
Avoidance of "missing zero" in switching of cables	X	XXX	XXX
Complexity	X	XX	XXX

Specifications

CIGRE working group A2.36 produced brochure 528 covering all aspects of transformer specifications.

This brochure is mostly applicable to shunt reactors, with the following main exceptions:

- System technical requirements (section 5)
- Environmental considerations (section 8)
- Technical requirements (section 11)
- Testing (chapter 13)

Covered later in this tutorial.

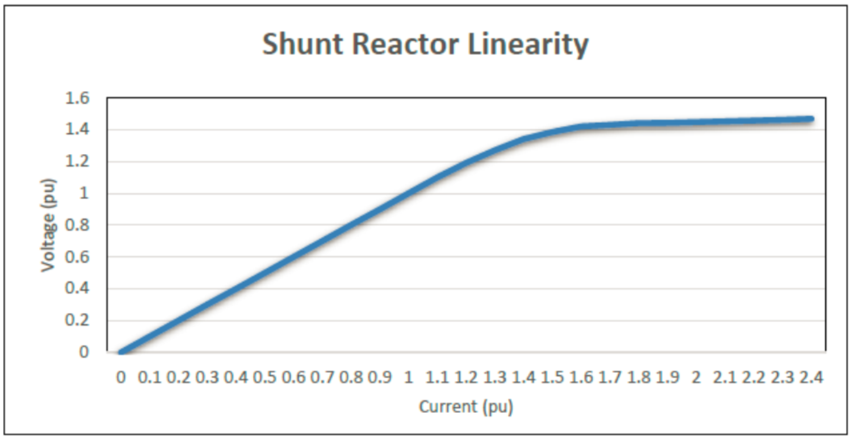
Linearity

In normal operation, a shunt reactor is operating in the so-called linear region. The reactance does not change with voltage and the behaviour of the shunt reactor is predictable.

Once a physical limit is reached the reactance changes (decreases) with voltage, and the shunt reactor is no longer operating in the linear region. The behaviour of the shunt reactor becomes difficult to predict.

Typically there is a requirement for shunt reactors to remain linear up to and slightly beyond the maximum system voltage. For strong networks, users would typically specify linearity up to $1.1U_{max}$.

Linearity



Components

Evidence suggests a high prevalence of bushing problems with shunt reactors. These seem to be caused by two main problems:

•Vibration

Avoid bushings with spring-loaded components

Consider dry bushings with silicone insulators

•Voltage transients (from switching)

Specify bushings with a higher insulation level than the winding

Switching is covered later in this tutorial

Design and Construction

Main types of oil-immersed shunt reactor are as follows:

- Core-form, gapped core
- Core-form, magnetically shielded (“air core”)
- Shell-form, magnetically shielded (“air core”)

Some other types were manufactured in the past, and may be found in service.

Design and Construction

With all designs:

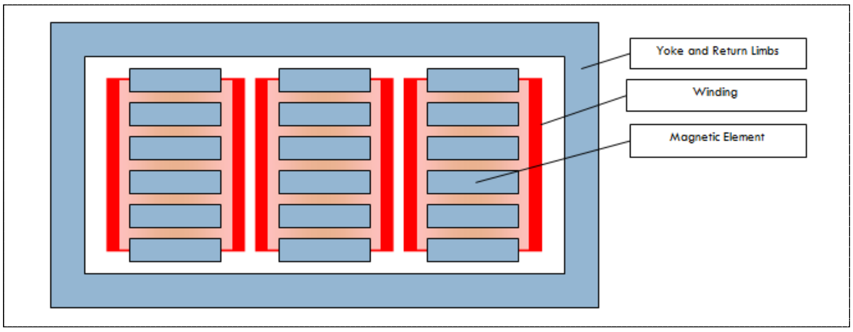
- Winding designs are essentially similar to power transformers
- Clamping for both core and windings requires special consideration, owing to higher levels of vibration compared with power transformers
- Except for special designs with auxiliary windings, external short-circuits are not a design consideration

Design and Construction

Main features of core-form gapped core shunt reactors:
- Wound core limb comprises magnetic elements, separated by insulation (usually ceramic) blocks
- Yokes and in some cases outer limbs form complete magnetic circuit, wholly or partly surrounding windings

Most common arrangement for three-phase designs is with the three phases in-line, but trefoil designs (three phases arranged in a triangle) are also possible.

Design and Construction



Example design – gapped core with five limbs

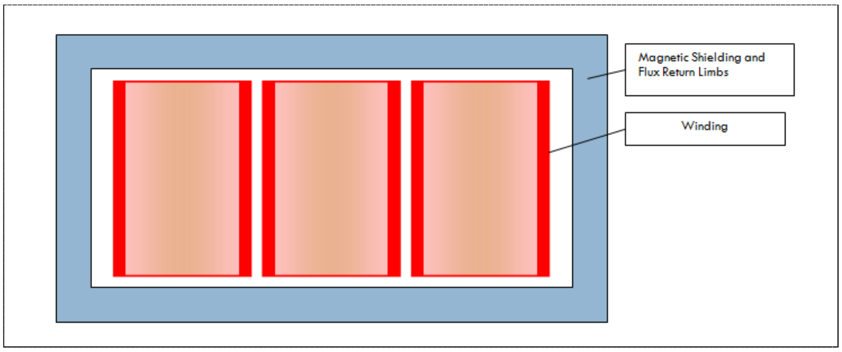
Design and Construction

Main features of core-form magnetically shielded (“air core”) shunt reactors:

- No magnetic core limb. Some designs use support structure (made of insulating material) inside windings
- In most designs magnetic shield comprises horizontal yokes above and below windings. Some designs also include outer limbs

Magnetically shielded shunt reactor designs are often similar to magnetically shielded series reactor designs.

Design and Construction



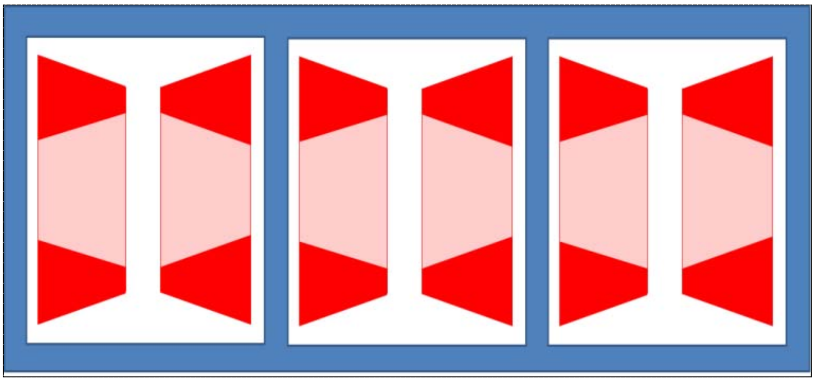
Example design – core-form magnetically shielded (air core), with top and bottom yokes and also outer limbs

Design and Construction

Main features of shell-form magnetically shielded ("air core") shunt reactors:

- Core design broadly similar to core design for shell-form power transformer, but without central magnetic limb through winding
- Core completely surrounds winding

Design and Construction



Example design – three-phase shell-form magnetically shielded ("air core")

Design and Construction

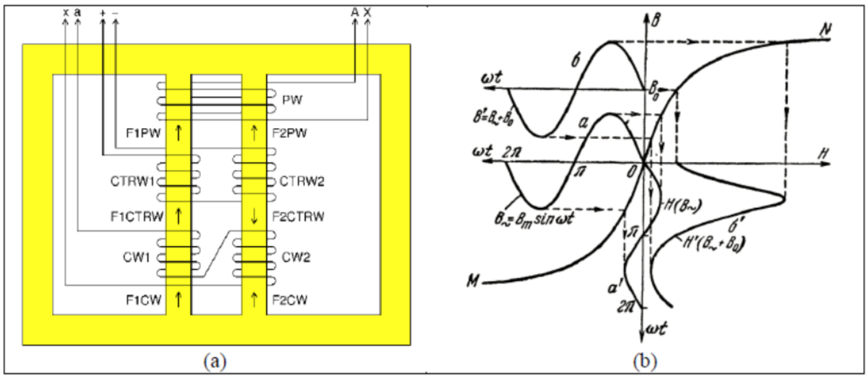
Feature	Core-form, gapped core	Shell-form, magnetically shielded	Core-form, magnetically shielded
Core design	Gapped core	Magnetically shielded	Magnetically shielded
Phase	1-ph or 3-ph	1-ph or 3-ph	1-ph or 3-ph
Magnetic characteristic	Non-linear	Non-linear	Non-linear
Linearity range	Moderate	High	Very high
Damping effect in non-linear region	High	Low	Very low
Reactance path	Via gapped core and magnetic shield	Via winding and magnetic shield	Via winding and magnetic shield
Regulation	With OLTC	With OLTC	With OLTC
Zero-sequence impedance	100% for five-limb core designs	100%	100% for designs with full magnetic shield
Size and weight	Lower	Lower size	Higher
Noise sources - main	Gapped core	Magnetic shield	Windings
Noise sources - others	Windings	Windings	Magnetic shield

Design and Construction -Controllable SHRs

Controllable shunt reactors have a special core design, to allow magnetisation by a dc current injected from an auxiliary winding. In most cases this is similar to a transformer core, but with the limbs split vertically.

In addition to the auxiliary winding for dc magnetisation, most controllable shunt reactors also include a second auxiliary winding to supply the semiconductor rectifier which provides the dc current.

Design and Construction -Controllable SHRs



(a) (b)

Noise and Vibration

Levels of noise and vibration in shunt reactors are generally higher than for transformers of the same voltage class and rated power. Noise and vibration are thus more important considerations for shunt reactors than for power transformers.

Noise sources differ between different designs (core-form gapped core, core-form magnetically shielded, shell-form magnetically shielded), although typical noise levels are broadly similar.

Noise and Vibration

According to a survey made by the working group:

•For any design concept, changing the design parameters can give a change in noise level of up to **5dB**

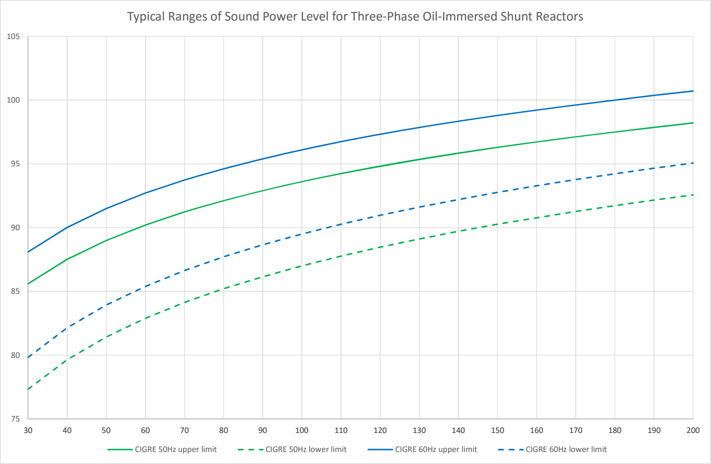
•Resonance in the core or tank can increase noise levels by up to **10dB**

•Noise levels can increase by up to **2dB** between ambient temperature and operating temperature

•Manufacturing tolerances can change the noise level by up to **±2.5dB**

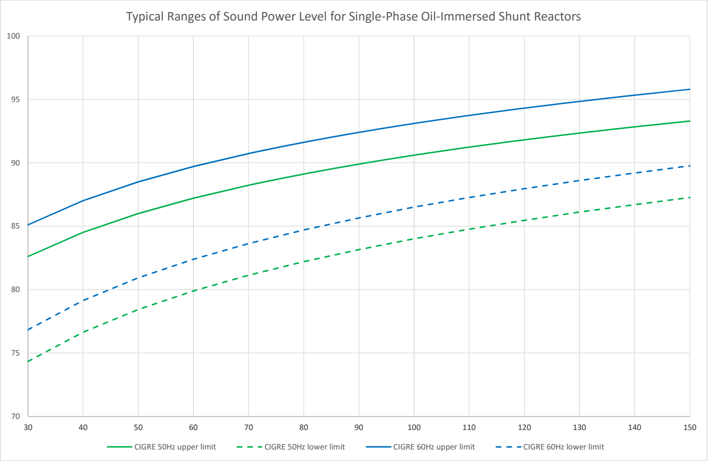
•Measurement uncertainty is assumed to be **±1.5dB**

Noise and Vibration



Typical noise levels for three-phase shunt reactors, from survey made by the working group

Noise and Vibration



Typical noise levels for single-phase shunt reactors, from survey made by the working group

Works Testing

Works testing of shunt reactors is substantially more challenging than works testing of power transformers of the same voltage class and rated power.

Major challenges include:

•There is no LV winding, so all test voltages must be directly applied, if necessary using a test transformer. (The test transformer contributes background noise and partial discharge during certain tests).

•Reactive power demand during certain tests is very large, and may be substantially greater than the rated power of the shunt reactor.

Works Testing

Major challenges (continued):

- The reactance-to-resistance ratio is very high, which complicates accurate measurement of losses.
- It is not possible to separate core losses from losses in the windings and elsewhere. Correction of losses to operating temperature is thus a further complication.
- In some cases it may be difficult to achieve the required impulse waveshapes, especially for switching impulse.

Special equipment is required to meet some of these challenges.

Works Testing – Losses and Reactance

There are two main types of shunt reactor loss measurement system in use:

- Using current comparators, standard capacitors, and high precision wattmeters (mainly three-phase systems)
- Using a Schering bridge based on a current comparator technique (single-phase systems)

It is possible to calibrate individual components of each type of measurement system, or the complete system. The latter is more usual for Wattmeter based systems.

Works Testing – Losses and Reactance

Correction of losses to operating temperature is a further challenge. The working group have evaluated three methods in detail:

- Experimental determination of the temperature coefficient of losses
- Assuming that the temperature coefficient of losses is the same as for resistance losses
- Theoretical determination of the temperature coefficient of losses, from design data

The last method typically gives the best results.

Works Testing – Linearity etc

Linearity is usually checked by measuring reactance over a range of voltages, up to and perhaps slightly beyond U_{max}. Note that reactive power demand increases as the square of the test voltage, and may thus be substantially greater than the rated power of the shunt reactor.

An alternative method can be used to determine the knee-point (end of the linear range). This involves dc injection to saturate the core/magnetic shield.

Works Testing – Switching Impulse

For shunt reactors with an inductance of less than 1H (e.g. 75Mvar, 150kV, 50Hz) it is difficult to achieve the required waveshape, esp. the required time above 90% of the specified voltage and the required time to first zero.

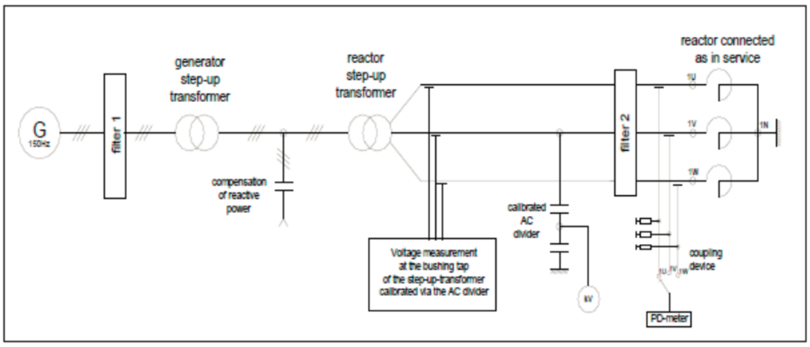
It may be necessary to use an additional loading capacitor (alt. a second impulse generator) in parallel with the shunt reactor under test.

Works Testing – Induced Voltage

The induced voltage test on a shunt reactor usually requires the use of a test transformer to apply the voltage. If partial discharge measurements are required, the test transformer is a source of background noise.

The induced voltage test requires reactive compensation. Depending on the test configuration, this may be considerably more than the rated power of the shunt reactor.

Works Testing – Induced Voltage



Normal test set-up for induced voltage test with partial discharge measurements on a shunt reactor

Works Testing – Induced Voltage

Works Testing – Induced Voltage

Three-phase excitation is preferable for three-phase shunt reactors, but single-phase excitation reduces reactive power demand during the test and may be a useful alternative for larger shunt reactors.

Another alternative for lower voltage three-phase shunt reactors is a special phase-by-phase applied voltage test.

Works Testing – Noise

The noise test on a shunt reactor usually requires the use of a test transformer to apply the voltage. The test transformer is an additional source of noise.

Any test transformer required should be designed or selected to have the lowest possible noise level during the shunt reactor test.

The sound intensity method should be used for noise measurements, as this will better exclude the noise from the test transformer.

Works Testing – Vibration

Excessive levels of vibration may damage the tank and fittings, especially bushings. The aim of vibration measurement should be to identify the point or points on the tank where vibration is highest. This is achieved by finding the point on each tank panel where vibration is highest.

Measurements are best made using accelerometers. Strain gauges are not a particularly useful measurement method, giving poor results.

Works Testing – Special Tests for VSRs

For variable shunt reactors, the note following special recommendations:

- Losses and reactance should be measured on both extreme tap positions, and any intermediate tap positions required.
- Linearity should be checked on the tap position with fewest effective turns (minimum reactance), as this is the worst case for the shunt reactor.
- Switching impulse test should be made on the tap position with fewest effective turns (minimum reactance), as this gives highest volts/turn.

Works Testing – Special Tests for VSRs

For variable shunt reactors, the note following special recommendations:

- Induced voltage test should be made on the tap position with fewest effective turns (minimum reactance), as this gives highest volts/turn.
- Noise and vibration should be checked on tap position with fewest effective turns (minimum reactance), as this is likely to be the most severe case. Noise should be checked on any other tap positions required.

Works Testing

An over-view of the requirements standards for performance tests:

Test	**A2.48 consensus**	**IEC 60076-7**	**IEEE C57.21**	**Chinese National**	**Indian National**	**GOST R 52719**
Winding Resistance	Routine	Routine	Routine	Routine	Routine	Routine
Reactance	Routine	Routine	Routine	Routine	Routine	Routine
Loss	Routine	Routine	Routine	Routine	Routine	Routine
Ins Res	Routine	Routine			Routine	Routine
Cap and Tan Delta	Routine	Routine	Routine	Routine	No	Routine
Temp Rise	Type	Type	Type	Type	Type	Type
Vibration	Type	Type	Special		Special	Type
Noise	Routine	Type	Routine	Type	Special	Type
ZPS reactance	Special	Special		Special	Special	Type
Mutual Reactance	Special	Special		Special	Special	Special
Harmonics	Special	Special		Special	Special	Type
Loss (operating temp).	Type	Special		Special	Type	Special
Linearity	Special	Special		Type	Special	Special
Magnetic Characteristics	Special	Special	Type	Type		Special
Noise (operating temp).	Type	Special	Type	Type		Special

Consensus within CIGRE working group A2.48 is similar to IEC 60076-7, with some minor changes. Most important change is for noise to become a routine test.

Works Testing

An over-view of the requirements standards for dielectric tests:

Test	A2.48 consensus as per IEC 60076-3	IEC 60076-7	IEEE C57.21	Chinese National	Indian National	GOST R 52719
Applied Voltage		Routine	Routine	Routine	Routine	Routine
Induced Voltage (w/stand)		Routine (≤72.5kV)	Routine (≤54kV)		Routine (<300kV)	Routine
Induced Voltage with PD		Routine (>72.5kV)	Routine (>54kV)		Optional (≥300kV)	Routine
Line Terminal W/stand					Optional (≥300kV)	
Lightning Impulse		Type/Routine	Routine (>123kV)	Routine	Type/Routine	Type
Switching Impulse		Routine (≥170kV)	Routine (≥362kV)	Routine	Optional (≥300kV)	Type

Consensus within CIGRE working group A2.48 is that dielectric testing for shunt reactors should be similar to dielectric testing of power transformers acc. IEC 60076-3, with some additional options for induced voltage testing.

Field Testing

CIGRE working group A2.34 produced brochure 445 covering all aspects of transformer maintenance, including field testing.

This brochure is mostly applicable to shunt reactors, with the following main exceptions:

•Certain tests are not applicable to shunt reactors, as they only have one winding (transformation ratio, impedance)
•Other tests are applicable, but results may be more difficult to interpret or less useful for diagnosis (dielectric frequency response, perhaps also winding cap and PF and winding frequency response)

Switching

CIGRE working group B5.37 produced brochure 546 covering protection, control and monitoring of shunt reactors. This brochure also considers the possible effect of current and voltage transients caused by switching on protection systems.

To minimise current and voltage transients, it is good practice to use point-on-wave switching to connect and disconnect shunt reactors. The optimum point-on-wave for switching is at or near the current zero.

Protection

CIGRE working group B5.37 produced brochure 546 covering protection, control and monitoring of shunt reactors.

Electrical protection schemes may include the following:

- Differential (87R/ΔI)
- Distance/impedance (21/Z<)
- Phase overcurrent (50 and 51/I>> and I>t)
- Restricted earth fault (87N/ΔI)
- Time delayed earth fault overcurrent (51I/NE)

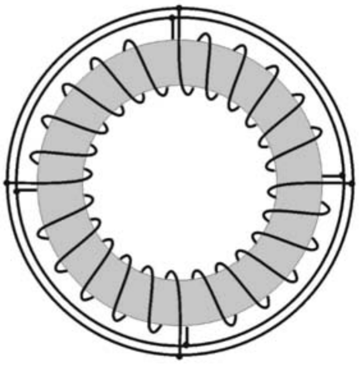
Protection

Additionally, the following non-electrical protection devices may be used with shunt reactors:

- Buchholz (63)
- Pressure relief device
- Thermal overload, usually as part of oil or winding temperature indicator
- Oil level

The Buchholz relay has high sensitivity to internal faults, as do differential and restricted earth fault protection.

Protection - CTs



Internally mounted protection CTs in shunt reactors can be affected by stray flux, so it is recommended that they are fitted with flux equalising windings.

Control

CIGRE working group B5.37 produced brochure 546 covering protection, control and monitoring of shunt reactors. According to a survey reported in their brochure, 2/3 of operators who responded control their shunt reactors manually.

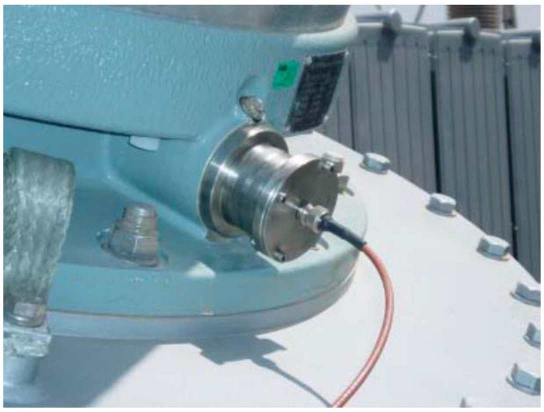
To improve system performance, operators may chose to implement automatic control by monitoring system voltage. This is possible in most multi-functional relays, although some care may be necessary.

Monitoring

CIGRE working group A2.27 produced brochure 343 covering transformer condition monitoring. This brochure is mostly also applicable to shunt reactors.

CIGRE working group B5.37 subsequently produced brochure 546 covering protection, control and monitoring of shunt reactors. This partly updates the earlier brochure.

Monitoring



Given the high prevalence of bushing problems with shunt reactors, consideration should be given to implementing bushing tap monitoring.

Health Index

Health indices are widely used by operators of different types of power equipment, including both power transformers and shunt reactors.

There are two main approaches to health indices as follows:

- Estimation of remaining life
- Determination of current condition and associated risks

In the experience of members of the working group, the latter approach is usually more successful.

Health Index

A guide for power transformer asset health indices is in preparation by CIGRE working group A2.49.

Experience within CIGRE working group A2.48 suggests that broadly similar methods can be used for both power transformers and shunt reactors. Some adjustments may be necessary, e.g. shunt reactors are not normally subject to short-circuit forces but may suffer from excessive levels of vibration.

Reliability Survey

CIGRE working group A2.33 was established to make a reliability survey for power transformers. Their brochure is at an advanced stage of preparation. It does not include any separate reliability data for shunt reactors.

CIGRE working group A2.48 attempted to make a separate reliability survey for shunt reactors, but were not able to obtain sufficient information. Available information was published, in the name of the working group, at the CIGRE A2 colloquium at Shanghai in 2015.

Reliability Survey

Available information suggests:

- Unclear whether failure rate for shunt reactors is comparable with or higher than transmission transformers.
- High prevalence of bushing failures. Other common components where failure originated include winding, core, and tank.
- Unclear what most important failure causes are.
- Most common failure mode is dielectric. Other common failure modes include mechanical and thermal.

Conclusions

There are have been improvements in shunt reactor technology in recent years, leading to widespread availability of variable and also magnetically controllable shunt reactors. These have a wider range of applications than conventional fixed shunt reactors.

Users needs to adapt specifications and also design review procedures for the special requirements of shunt reactors, taking account of the particular technology used.

Works testing of shunt reactors is more challenging compared with power transformers of the same voltage class and rated power.

Conclusions

Levels of noise and vibration in shunt reactors are generally higher than for transformers of the same voltage class and rated power, and thus require special consideration.

Switching, protection, control, and monitoring systems need to be adapted to the special requirements of shunt reactors. CIGRE working group B5.37 have produced a very useful guide on this subject (brochure 546).

Bushing reliability is a challenge for shunt reactors. It can be improved by selection of appropriate bushings and hopefully also by monitoring in operation.