Power transformer protection – an outline

What are the main protection types to protect major substation element?

ABSTRACT

Power transformers are used in High Voltage (HV) / Extra High Voltage (EHV) / Ultra High Voltage (UHV) systems as they transfer a huge amount of power to the customers but the volume of vulnerability and damage is also huge and destructive. Therefore, in order to avoid such destruction and loss, protective devices are used with different protection schemes to provide safe and secure power to the customers. These devices not only protect the equipment but also preserve human life and secure the system from impairment.

KEYWORDS

protection, relays, schemes, faults

1. Introduction

The transformers in HV networks are always protected by one main protection device and at least one back-up protection device. Main Intelligent Electronic Device (IED) uses all the protection functions, and the back-up IED has at least an (overcurrent) OC low stage with Inverse Definite Minimum Time (IDMT) curves, an OC high stage and an Earth Fault (EF) protection. In EHV we use two identical main protection devices in a redundant protection system.

In the field of power systems, the role of a power transformer is well known. It is so called backbone of the power transmission systems. High reliability of the transformer is therefore essential to avoid disturbances in transmission of power. When a fault occurs in a transformer, the damage is usually severe. The transformer has to be transported to a workshop and repaired, which

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takes considerable time. To operate a power transmission system with a transformer out of service is always difficult. The impact of a transformer fault is often more serious than a transmission line outage. To prevent faults and to minimise the damage in case of a fault, transformers are equipped with both protective relays and monitors. The choice of protective equipment varies depending on transformer size, voltage level, etc.

2. Failure statistics

Table 1 lists failures for six categories of faults (IEEE C37.90, *Guide for Protective Relay Applications to Power Transformers,* Ref. 1). Winding and tap changers account for 70% of failures. Loose connections are included as the initiating event as well as insulation failures. The miscellaneous category includes CT failure, external faults, overloads, and damage in shipment. An undisclosed number of failures starts as incipient insulation breakdown problems.These failures can be detected by sophisticated online monitoring devices (e.g. gas-in-oilanalyser) before a serious incident occurs [1].

3. Transformer protection

When a fault occurs in a transformer, the damage is proportional to the dissipated fault energy which relates to the fault time. The transformer should therefore be disconnected from the network as soon as possible. Fast reliable protective relays are therefore used for detection of faults. Monitors can also detect faults and sense abnormal conditions which may develop into a fault. The size of the transformer and the voltage level has an influence on the extent and choice of protective equipment. Monitors prevent faults and protective relays limit the damage in case of a fault. The cost for the protective equipment is marginal compared to the total cost and the cost

Table 1: Failure rates

	1955-1965		1975-1982		1983-1988	
	Number	Percent of total	Number	Percent of total	Number	Percent of total
Winding failures	134	51	615	55	144	37
Tap changer failures	49	19	231	21	85	22
Bushing failures	41	15	114	10	42	11
Terminal board failures	19	7	71	6	13	3
Core failures	7	3	24	2	4	1
Miscellaneous failures	12	5	72	6	101	26
Total	262	100	1127	100	389	100

involved in case of a transformer fault. There are often different opinions about the extent of transformer protection. However, it is more or less normal that transformers with an

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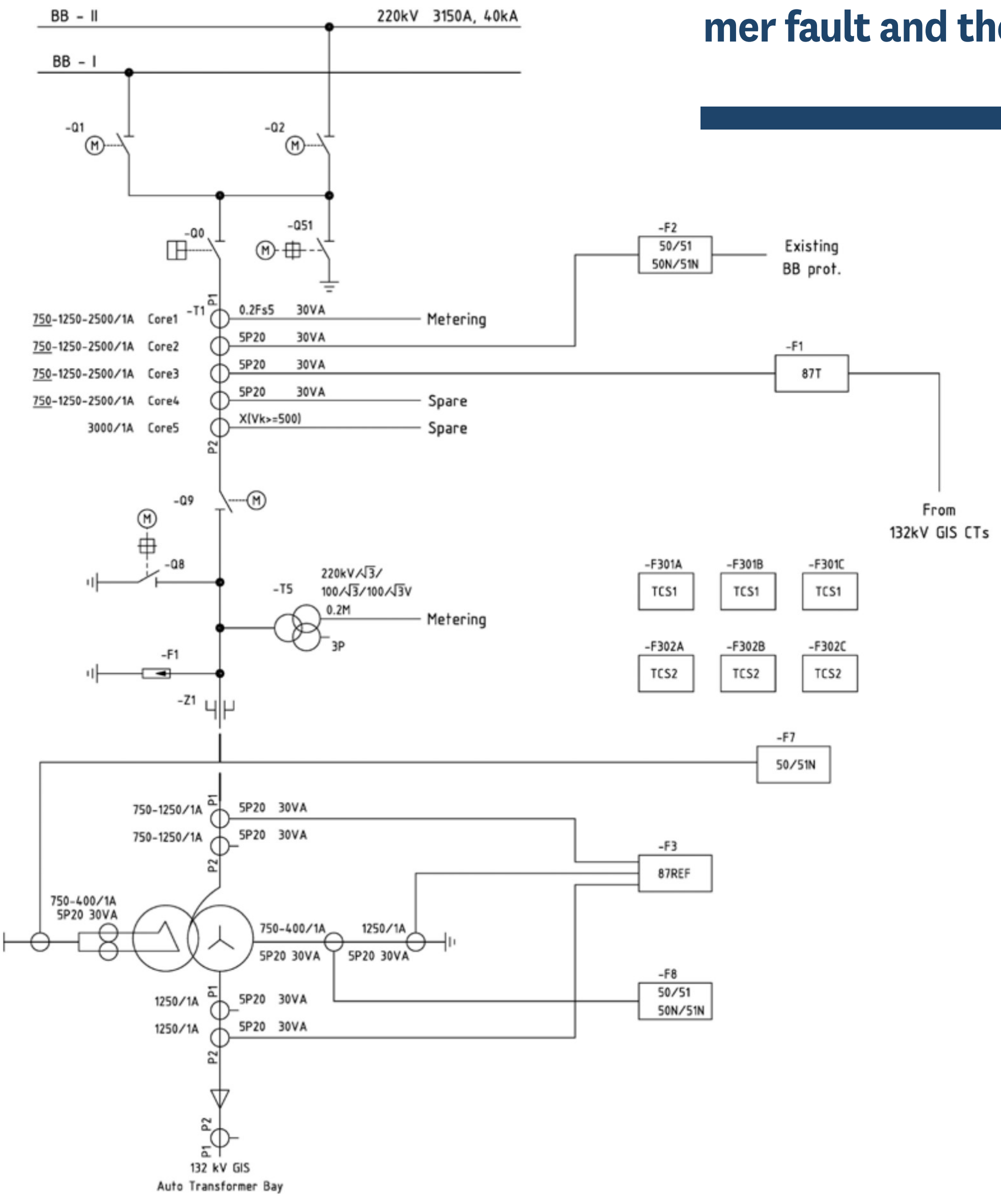

Figure 1: Typical single line diagram of a 220 kV transformer bay with protection

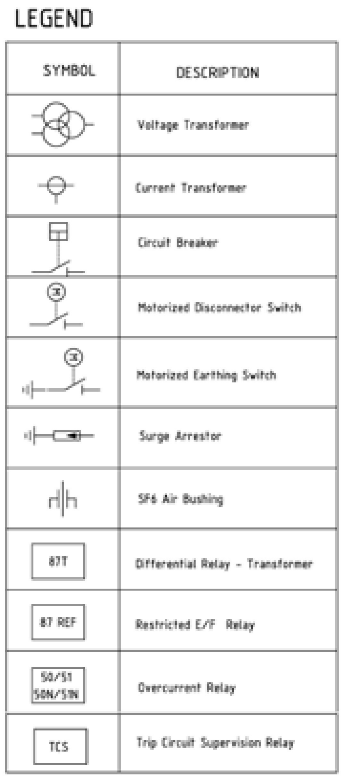

Figure 2: Description of symbols used in Figure 1.

oil conservator are equipped with the equipment showed in Table 2 [2].

The types of protection in Table 2 are used with different schemes depending upon the ratings of the transformer and fault levels. In order to plot the protection schemes, we have different codes for different type of protection called ANSI device numbers or ANSI codes, Figure 1.

Figure 1 shows typical single line diagram for the 220 kV substations in which the transformer is protected by differential protection along with overcurrent and restricted earth fault protection.

Figure 2 shows the description of symbols and codes used in Figure 1, types of protection devices / IED's and other switching / measuring devices.

Description of codes

A. Current protection functions

ANSI 50/51 – phase overcurrent

Three-phase protection against overloads and phase-to-phase short-circuits.

ANSI 50N/51N or 50G/51G – earth fault

Earth fault protection based on measured or calculated residual current values:

- ANSI 50N/51N: residual current calculated or measured by 3-phase current sensors
- ANSI 50G/51G: residual current measured directly by a specific sensor.

Table 2: Protection used for ratings above 5 MVA

List of protection types used for transformers of rating above 5 MVA
Gas detector relay (Buchholz relay)
Overload protection (thermal relays or temperature monitoring systems)
Overcurrent protection
Ground fault protection
Differential protection
Pressure relay for tap-changer compartment
Pressure relief device

B. Differential protection ANSI 87T – Differential

Three-phase differential protection has a task to protect particular zone from difference in current which is entering and leaving from one side to another in a particular zone. The differential protection function protects the zone between the main and additional current sensors inside the protected zone between the two sets of current transformers (CT) [5].

4. Transformer protection types

OVERCURRENT PROTECTION

Basic principle

Fault impedance is no greater than the load impedance, therefore fault current is greater than load current. Over current relays sense fault current and also overload current. When the fault current is above a certain level called the pickup level, relays pick up and disconnect the circuit.

Types of over current include:

- overload current
- short circuit current

Overload current

We exercise different characteristic curves to cover possible overloads during shorter periods of time, e.g. during through faults.

Three-phase differential protection has a task to protect particular zone from difference in current which is entering and leaving from one side to another in a particular zone

Short circuit current is 5 to 20 times the full load current

Because of high currents, these stress the equipment thermally and high thermal power is dissipated. On the other hand they cannot be detected by thermal relays because there is no time for a temperature rise.

While the high stage overcurrent operates as a back-up protection and the differential protection is the main protection, the low stage with its characteristic curve protects from possible overloads during through faults and is not a back-up protection. If there is a through fault just behind the transformer, the differential protection would not trip. Yet, the transformer would be overloaded and if the circuit breaker behind the transformer does not trip, then the whole transformer must be disconnected.

Short circuit current

This includes phase faults, winding faults and earth faults. Usually short circuit current is 5 to 20 times the full load current, therefore fault clearance is desirable.

Characteristic curves

IEC 60255 defines a number of standard characteristics as follows, Table 3:

- Standard Inverse (SI)
- Very Inverse (VI)
- Extremely Inverse (EI)
- Definite Time (DT)

Table 3: IEC Inverse Characteristic Equations

IEC Inverse Characteristic Equations		
IEC SI (Standard Inverse)	IEC VI (Very Inverse)	IEC EI (Extremely Inverse)
$t = TMS\,x \frac{0.14}{\left(I/_{Is}\right)^{0.02} - 1}$	$t = TMS\,x \frac{013.5}{\left(I/_{Is}\right)^{1} - 1}$	$t = TMS\,x \frac{80}{\left(I/_{Is}\right)^{3} - 1}$

In protecting power transformer, overcurrent relay is typically used as a backup protection following Inverse Definite Minimum Time (IDMT) curve with coordination of other relays.

Where,

TMS = time multiplier setting (relay operating time can be varied by varying the TMS setting)
Is = set current value
I = measured current value
t = operating time (sec)

A Earth fault protection

Earth fault is the most frequent occurring fault in the power system. In HV/EHV networks an earth fault manifests as a flow of current through neutral/return conductor of the grounded system. Although phase fault relay responds to earth faults, such protection lacks sensitivity. To overcome this, separate earth fault

Earth fault is the most frequent occurring fault in the power system

relays are used which respond to residual component of current and thus are unaffected by the unbalanced load conditions. Since neutral earthing resistance is generally used, low settings are required.

There are two types of earth fault protection:
1. Restricted
2. Unrestricted

Restricted earth fault (REF)

Under normal conditions and by application of Kirchhoff's laws the sum of currents in both current transformers (CTs) equals zero. If there is an earth fault between the CTs then some current will bypass the CT's and the sum of currents will not be zero. By measuring this current imbalance, faults between the CTs can easily be identified and quickly cleared.

Fault detection is confined to the zone between the two CTs hence the name 'restricted earth fault'.

A restricted earth fault (REF) is an earth fault from a restricted/localised zone of a circuit. The term 'REF protection method', means that earth faults outside this restricted zone are not sensed. REF is a type of 'unit protection' applied to transformers or generators and is a more sensitive differential protection.

REF protection is fast and can isolate winding faults extremely quickly, thereby limiting damage and consequent repair costs. If CTs are located on the transformer terminals only the winding is protected. However, quite often the secondary CT is placed in the distribution switchboard, thereby extending the protection zone to include the main cable.

Without REF, faults in the transformer star secondary winding need to be detected on the primary of the transformer by the reflected current. As the winding fault position moves towards the neutral, the magnitude of the current seen on the primary rapidly decreases and could potentially not be detected (limiting the amount of winding which can be protected). As the magnitude of the currents remain relatively large on the secondary (particularly if solidly earthed), nearly the entire winding can be protected using REF. As it is essential that the current in the CTs is balanced during normal conditions (and through faults), historically REF has been implemented using high impedance relays. CT's have also been specified as matched pairs and the impedance of leads/wires and interconnecting cables has had a large influence on the functioning of the relay. Measurement errors associated with these issues have been responsible for nuisance tripping and the system can be difficult to commission. This may be the reason some people avoid the use of REF. Recent advances in numerical relay technology have all but eliminated these issues, making the implementation of REF relatively easy, ensuring no nuisance tripping and simplifying commissioning [6].

During normal condition, the current with no interruption flows through the protected equipment and the net current through the relay is zero

Unrestricted earth fault

It responds to earth fault from any point in network. This protection is used to sense earth fault at any point in the system.

In the absence of earth fault the sum of three line currents is zero hence the vector sum of three secondary currents is also zero:

$I_{as} + I_{bs} + I_{cs} = 0$
$I_{rs} = 0$,

Where,
I_{rs} = residual current
$I_{as} + I_{bs} + I_{cs}$ = per phase currents (red, yellow, blue)

In case of a fault, residual current is not zero. The earth fault relay is connected in such a way that residual current flows through it if the relay operates above pickup level, as in Figure 3.

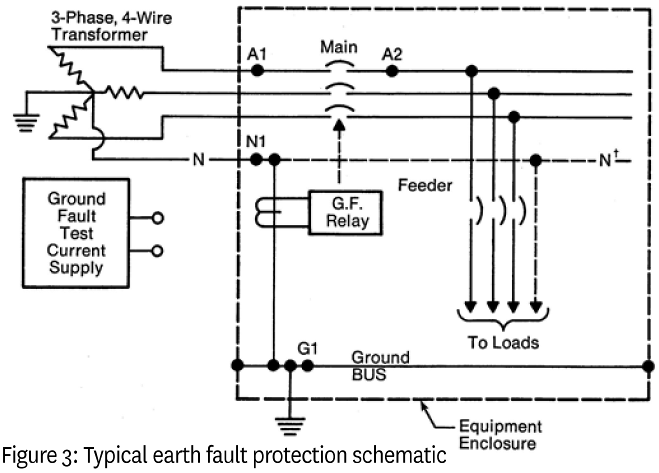

Figure 3: Typical earth fault protection schematic

B Differential protection

Basic principal

It is based on the principle of Kirchhoff's current law, i.e. by comparing the secondary current of the current transformers located at each end of the protected equipment. During normal condition, the current with no interruption flows through the protected equipment, and the net current I_n through the relay is zero. The figure shows a scheme of differential protection. Let us assume I_1, I_2 and I_3 are the three respective secondary currents of the relay in case of normal operation. If any fault occurs outside the boundary defined by current transformers, the relay would not operate. But if it occurs in the region bounded by the two current transformers, the relay will give the signal to the circuit breaker to trip the circuit.

The differential protection designed for the transformer is of a percentage type where restraint coils are employed.

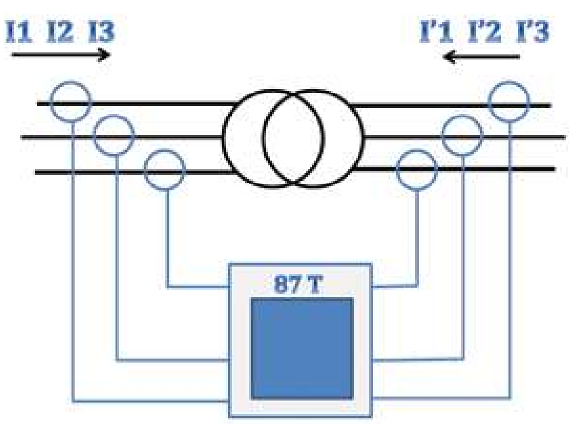

Figure 4: Transformer differential protection schematic

Restraining coils are also called bias coils. Due to the difference in the magnetising currents of the high and low voltage current transformers, the current through the operating coil will not be zero even under normal loading conditions or external fault conditions. Therefore to provide stability on external faults bias coils are provided. To obtain the required amount of biasing, a suitable ratio of the biasing coils with restraining coils needs to be provided.

Following points while designing a differential protection scheme for a transformer must be considered:

- There is always a certain amount of unbalanced current in the operating coil of a transformer differential relay because the current transformers are not ideally matching due to the turns ratio of transformer and also due to the resistance of coil.
- Due to the requirement of magnetising current, some unbalanced current remains in the operating coil as there is no current in the secondary while the current in primary performs excitation.
- Inrush current does exist in transformers. Its magnitude and duration depends on residual field present in the core and the point on the ac cycle where the re-energisation has occurred. Initially its value is 10 to 20 times the full load current in large transformers and becomes negligible in few minutes.
- The presence of tap changer in the transformer also adds complexities [4].

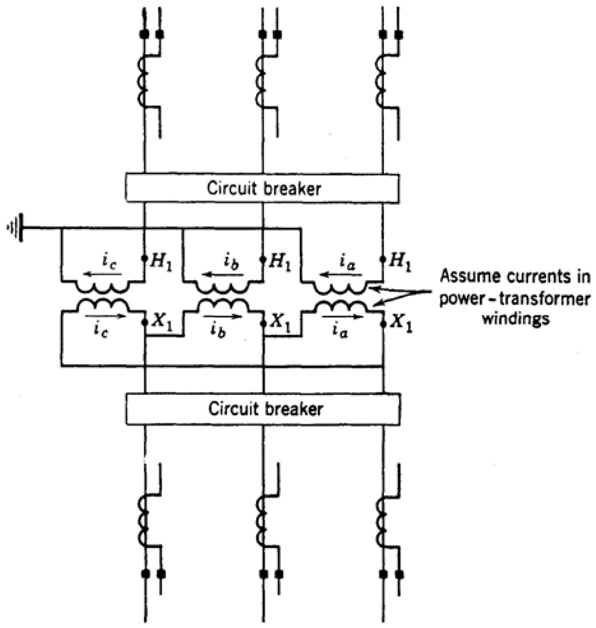

Figure 5: Transformer differential protection - single line diagram

The presence of tap changer in the transformer causes additional complexities in the protection

The scheme on the Figure 5 shows the typical differential protection for a star/delta transformer showing the connection for current transformer and relay coils.

C Bucholz relay

- Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against several types of faults. Named after its inventor Mr. Max Buchholz (1875–1956) in 1921, relay is used to set off an alarm in case of incipient (i.e.slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults, Figure 6. It is usually installed in the

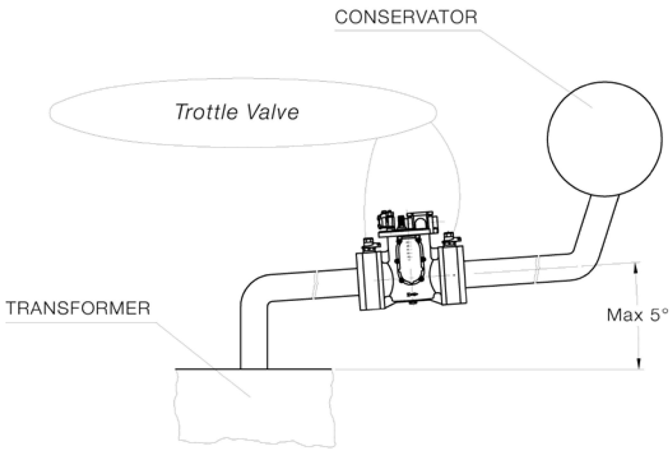

Figure 6: Bucholz relay fitting location

pipe connecting the conservator to the main tank.

- It is a universal practice to use Buchholz relays on all oil immersed transformers having ratings in excess of 750 kVA. The Buchholz relay is a protective relay for equipment immersed in oil for insulating and cooling purpose, Figure 7 and Table 4.

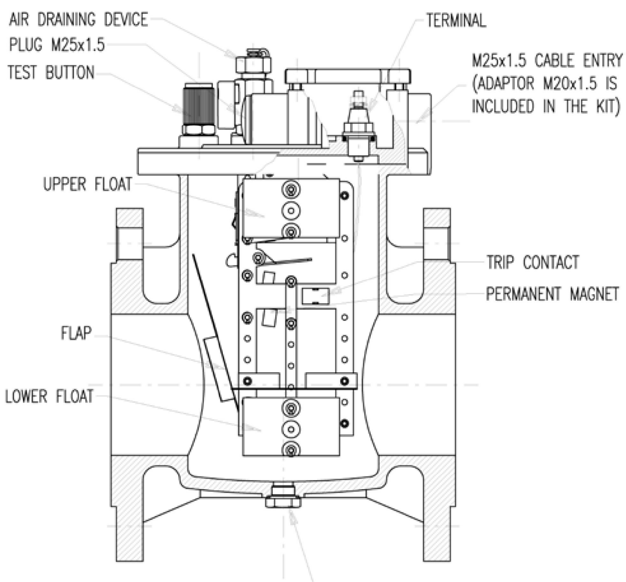

Figure 7: Bucholz relay

5. Monitoring of transformer

A Winding temperature indicator

The winding is the component with the highest temperature within the transformer and is subject to the fastest temperature increase as the load increases. In order to have control of the temperature parameter within the transformer, the temperature of the winding as well as top oil, must be measured. An indirect system is used to measure winding temperature, since it is dangerous to place a sensor close to the winding due to the high voltage. The sensor in the winding temperature indicator directly measures the CT current and uses the algorithms associated with IEC 354 to provide accurate winding temperatures for all cooling gradients via the feedback system, Figure 8.

Figure 8: Winding temperature meter

B Oil temperature indicator

The oil temperature indicator (OTI) measures the top oil temperature. This is a specific measurement location at the top of the transformer. Its temperature is used for the transformer control and protection, Figure 9.

Figure 9: Oil temperature meter

C Oil level indicator

An oil level gauge is required so that the correct oil level can be maintained, Figure 10. There is usually a mark on the gauge that indicates the 25 °C level, which is the proper oil level at that temperature. Maintaining the proper oil level is extremely important because if the oil level falls below the level of the radiator inlet, flow through the radiator will cease and the transformer will overheat [5].

Figure 10: Oil level meter

Conclusion

This article explains the basic information and provides an overview on different types and schemes of transformer protection. The protection schemes so far designed can successfully protect the transformer and mitigate the risk of enormous destruction that can be caused by transformer explosion; protecting major and expensive power system equipment and human life. The engineers and researchers are still working on utilising the new technologies for protecting transformers more successfully and more cost effectively.

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