MODERN DEVICES/TECHNIQUES IN THE PROTECTION OF TRANSFORMERS

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Abstract

The development of modern power systems has resulted in the design of wide range of transformers with sizes from a few KVA to several hundred MVA. Very large transformers are used to step up generation voltage of about 25KV to transmission level, such as 330KV. Various sizes and ratings of transformers are employed to step down this 330KV voltage to 132KV and then to distribution level of 33KV, which is further stepped down to 415V for domestic supply. The effects of thermal stress and electro-dynamic forces in transformers must be reduced as much as possible so as to ensure steady electricity supply. Hence the protection package should be able to minimize the duration of a fault within a transformer. The application and size of a transformer determines the protection package to be applied. Until recently, electro-mechanical relays had been in use in protective equipment because of their simplicity and durability. Nevertheless, they have been replaced by solid-state relays. The rapid progress in electronic devices including the introduction of reliable integrated circuits, logic gates and microprocessors has made it possible to produce equivalent relays using both analogue and digital processing. This paper examines the methods of protecting transformers, applying modern equipment.

Keywords: transformer, protection, relay

1. Introduction

Because of their static nature, transformers are normally regarded as very reliable unit. However, there is possibility of failure due to internal faults, which can as well be caused by stresses from external sources. Smaller distribution transformers require only fuse protection or inverse definite minimum time (IDMT) / instantaneous over-current and earth fault relays. This type of protection is economical and effective enough for through faults or external faults. However, coordination with down stream power system protection is necessary, and so this type of protection would lead to time delayed fault clearance for some faults. This is unacceptable for large distribution, transmission and generator transformers, where the effects on system operation and stability must be taken into consideration. Thus high-speed protection is needed to take care of both external and internal faults. Faults in transformers can be classified as:

- Winding and terminal faults.
- Core faults and oil deterioration.
- Abnormal operating conditions like over-voltage, over-fluxing, overload and over-heating.

- Sustained external faults - heavy through current, producing heavy mechanical stresses on windings and insulation.

The protection scheme must be properly designed to take care of these faults individually. Hence factors such as magnetizing inrush current, winding arrangements, winding connections and connection of protection secondary circuits must be considered.

In electro-mechanical relays, movement of armatures or discs is used to operate contacts which in turn cause the tripping of circuit breakers. When the input current exceeds the set value, the disc rotates. The speed of rotation depends on the magnitude of the input current and the eddy-current braking produced by a permanent magnet. Moving contacts are driven by the rotating disc until contact is made with stationary contacts. When this happens, the trip coil of the associated circuit breaker is energized and the breaker will open.

Modern electronic relays use digital circuitry to process incoming signals derived from current and voltage transducers. Analogue to digital converter (A/D) is used to sample and encode the input signals which are then processed to extract relaying information. Any desired time/current characteristic can be produced in the electronic relay as a result of the inherent flexibility of the circuitry involved; sluggishness and overshooting are eliminated. However Reliable power supplies and immunity to electrical interferences from other power equipment in the vicinity must be provided for the modern solid-state relays [2].

2. Protective Devices and Schemes

A typical protection package for a large distribution transformer is shown in figure 1.

The protective devices and schemes are described as follows:

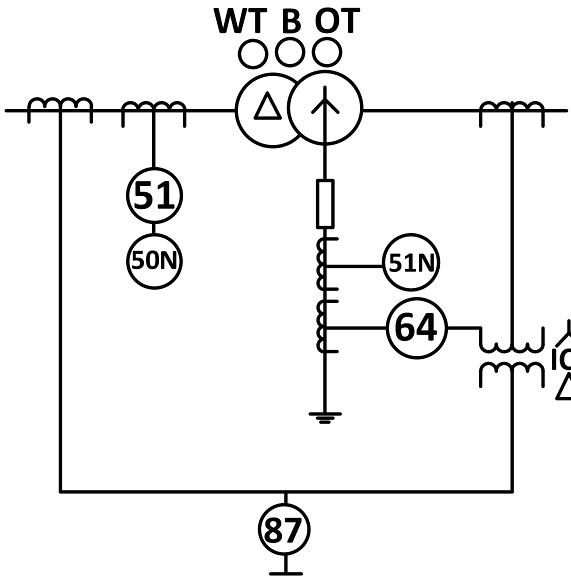


Figure 1: Typical Transformer Protection Package. Legend: WT - Winding temperature, B - Buchholz, OT - Oil temperature, 87 - Biased Differential, 64 Restricted earth fault (REF), 51N - Standby earth fault (SBEF), 50N - Instantaneous earth fault, 51- IDMT over-current, ICT - Interposing Current Transformer.

2.1. The biased differential relay (87)

This is a high-speed protection scheme which is used to clear faults on the LV winding as well as the HV winding, using the basic differential principle that HV and LV CT secondary currents entering and leaving the zone of protection should be equal under load and through fault conditions, but unequal under internal fault conditions, and a differential current will cause the relay to operate. Current transformer locations define the zone of protection. In many cases the HV and LV CT primary ratings will not exactly match the transformer winding rated currents and winding connections in the transformer lead to phase shift in the secondary voltage. As an illustration, a 15MVA, 33/11KV, Dyn1 transformer has 262.4A as the primary winding rated current, and there is no current transformer with the ratio 262.4/1 to match. Similarly there is no current transformer with the ratio 787.3/1 to match the secondary current rating of the power transformer. The Dyn1 connection symbol of the transformer shows that the secondary voltage is phase-shifted 30° behind the primary voltage. The application of the well established principles of differential protection to transformers demands that factors, such as phase shift across the transformer, imbalance of current transformer signals on either side of windings have to be considered. Interposing current transformers (ICT) [3] are usually provided to correct the phase shift, correct the ratio error of the main CT signals and trap LV zero sequence current, otherwise the relay will erroneously operate for external LV earth faults. Also during inrush conditions or during transient overfluxing, high level magnetizing current can cause mal-operation of the relay. Therefore, the differential element must be blocked for these conditions.

Traditionally, phase and ratio corrections as well as zero sequence current filtering were achieved by the application of external interposing current transformers (ICT), as a secondary replica of the main transformer winding arrangement. However, modern differential relays have inbuilt software ICTs. This feature gives the relay the flexibility to cater for line CTs connected in either star or delta [4].

2.1.1. Ratio correction

For example, let us consider a two-winding 15MVA, 33/11KV, Dyn1 transformer:

33KV full load current $= \frac{15000}{\sqrt{3}\times 33} = 262.4A$

HV CT ratio = 300/1

Secondary current of CT $= 262.4 \times \frac{1}{300} = 0.875A$

11KV full load current $= \frac{15000}{\sqrt{3}\times 11} = 787.3A$

LV CT ratio = 800/1

Secondary current of CT $= 787.3 \times \frac{1}{800} = 0.984A$

The traditional method of applying an external ICT is shown in figure 2. The ICT turns ratio is determined as follows:

Relay current = 0.875A

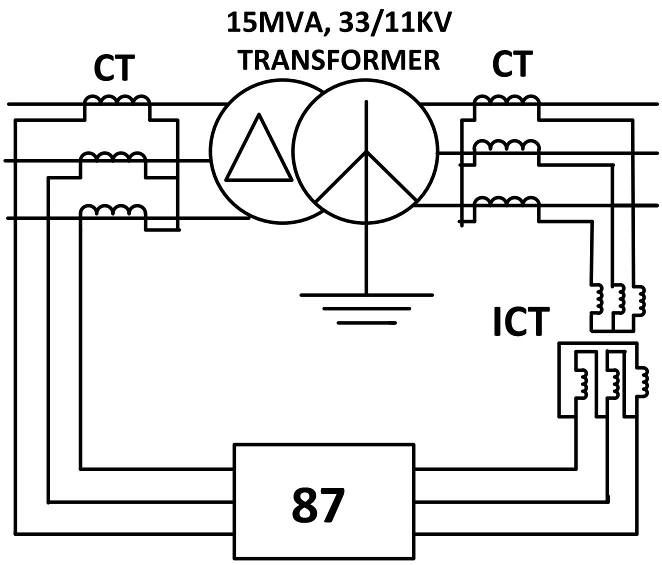


Figure 2: Differential protection circuit.

LV CT secondary current = ICT primary current = 0.984A

ICT secondary current $= \frac{0.875}{\sqrt{3}} = 0.505$

ICT turns ratio $= \frac{N_1}{N_2} = \frac{I_2}{I_1} = \frac{0.505}{0.984} = \frac{1}{2}$

The phase correction and zero sequence current filtering is achieved by the star-delta connection of the ICT.

But application of a relay with software ICT will result in the setting of the relay as follows. Each of these secondary currents is corrected to 1A (relay rated current).

HV ratio correction factor is $\frac{1}{0.875} = 1.14$ setting applied to relay)

LV ratio correction factor is $\frac{1}{0.984} = 1.02$ setting applied to relay)

Thus, adjustable ratio correction factor ranging from 0.05 to 2, in steps of 0.01, is provided in the relay. This application is illustrated in figures 3a and 3b.

2.1.2. Phase correction and zero sequence current filtering

If a transformer can pass zero sequence current to an external earth fault, it is necessary that zero sequence current filtering is employed in order to prevent the relay from mal-operation due to out of zone earth faults. Obviously, zero sequence current will flow in the current transformers associated with the star winding of Dyn11 transformer if an external earth fault occurs. However, there will be no zero sequence current in the current transformers on the delta winding. So the LV zero sequence current has to be removed otherwise it becomes a differential current and cause the relay to operate. Phase shift of the protected transformer and zero sequence current are catered for by software ICTs for each transformer winding, instead of the scheme in figure 2. The phase correction settings available are Yy0 (0deg), Yd1 (-30deg), Yd2 (-60deg), Yd11 (+30deg), etc. The selection of any of these will depend on the phase shift across the transformer and zero sequence filtering requirements. The phase correction is applied either side of the relay element as shown in figures3a and 3b.

2.1.3.

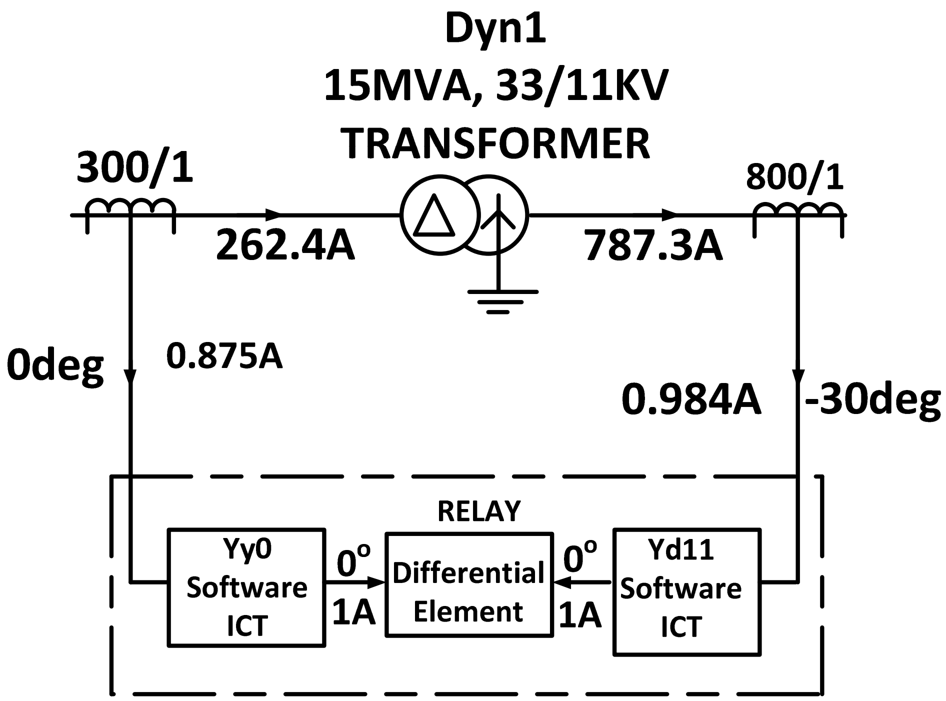
Magnetizing inrush current is associated with a transformer winding being energized with no balancing current present in the other winding or when a load is suddenly disconnected from the transformer raising the voltage at the input terminals of the transformer by 10-20% of the rated value - causing an appreciable increase in transformer steady state excitation current. The magnitude and duration of the current depend on the transformer design, size, system fault level etc. Under normal steady state conditions, the magnetizing current associated with the operating flux level is less than one percent of rated current. But if a transformer winding is energized at a voltage zero, with no residual flux, the flux level during the first voltage cycle is two times normal maximum flux. Consequently, core saturation and high non-sinusoidal current waveform occur. This current is known as magnetizing inrush current and may persist for many cycles, appearing as a large operating signal for the differential protection; and so the relay operates erroneously during inrush. In the past, the operation of the relay under inrush conditions is prevented by a time delay. When a time delay cannot be tolerated, the second harmonic component of the current is used to restrain operation. But if the line current transformer becomes saturated relay operation could be slow [5]. Modern electronic relays overcome this by a technique which recognizes magnetizing inrush current. A Fourier technique is used to measure the level of fifth harmonic in the differential current. The ratio of fifth harmonic to fundamental component is compared with a setting. If the ratio exceeds the setting, the differential protection is inhibited [6].

2.1.4. Stability Requirements

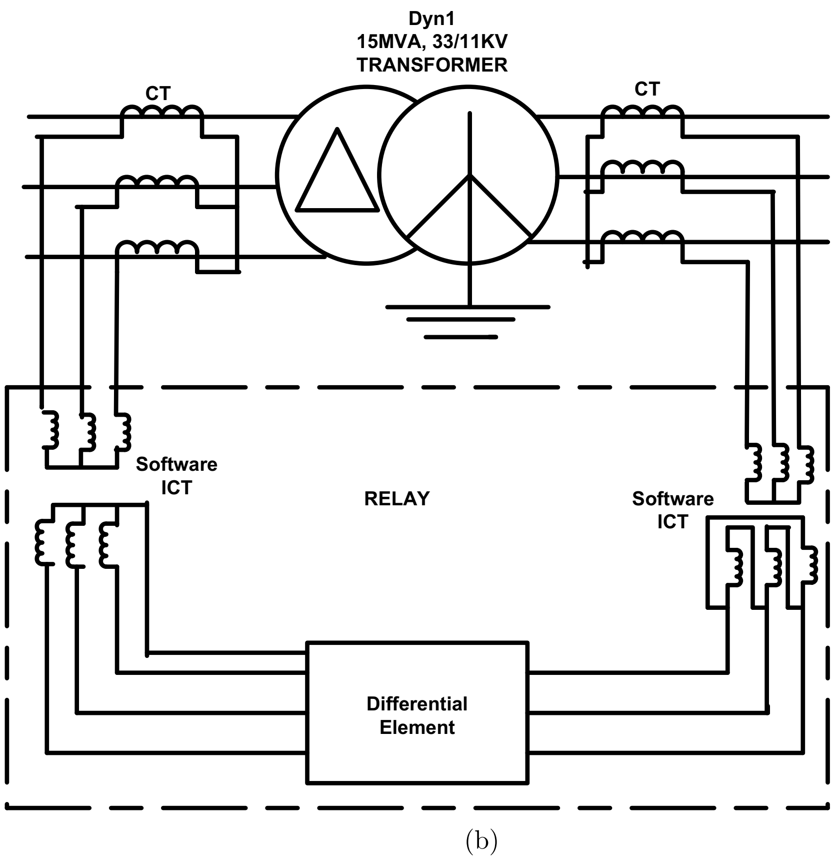
When saturation occurs in one of the main CTs, the output from the saturated CT reduces, resulting in a differential current flowing through the relay and causing maloperation. To overcome this problem, principles of high and low impedance protection are employed [7].

In the case of high impedance protection, the impedance of the relay circuit is made higher than the saturated CT by the addition of a stabilizing resistor R_s. So the spill current resulting from asymmetric saturation of the line CTs will be forced to flow through the saturated CT rather than through the relay circuit.

Low impedance protection allows the full spill current to flow through the relay but raises the relay setting in proportion to the level of through fault current. Biasing features, which effectively increase the currents needed to operate the relay when high currents flow are introduced to reduce the degree of matching needed. The increase in setting is therefore normally based on a percentage of the through current and so is usually referred to as percentage biased differential protection. Small amounts of bias are very effective when high currents are flowing to external faults. If, as an illustration, a current of 20p.u. were flowing to an external fault on the LV side of the 15MVA transformer referred to above. Let relay operating current be set at 0.15A. If



(a)



(b)

Figure 3: Differential protection circuits.

2% bias is to be applied, then:

Through fault current on LV side of transformer $= 20 \times 800 = 16000A$.

CT secondary current $\frac{16000}{800} = 20A$

2% bias $= 0.02 \times 20A = 0.4A$

New relay setting = 0.15A + 0.4A = 0.55A.

2.2. Inverse Definite Minimum-Time (IDMT) over-current relay (51)

This is needed to protect the transformer against external faults. It provides protection against three-phase faults, inter-phase faults and overloads. The relay monitors the current supplied by the associated current transformer and triggers a timing system whenever the current exceeds the set value. Operating time decreases as relay current increases, approaching a definite minimum value. This feature allows adequate discriminating time margins to be obtained between relays applied to adjacent sections of networks during short-circuit conditions. The minimum operating current of the relay must exceed the rated current of the transformer. The main CT output is fed to a step-down ICT in the microprocessor-based overcurrent relay. After full-wave rectification, the output of the ICT is fed to a shunt-connected resistors circuitry. This circuit is switched by the user to obtain the desired current setting and associated inverse time/current characteristics.[8]

2.3. Restricted earth fault protection (64)

This is a more sensitive, high speed earth fault protection applied to the LV winding. Its operation is limited to detection of earth faults within the LV winding; hence the name restricted earth fault protection.

2.4. Standby earth fault, SBEF (51N)

This is a back-up protection device to clear any sustained external LV faults.

2.5. The instantaneous earth fault relay (50N)

The instantaneous earth fault relay is an inherently restricted earth fault element associated with the HV over-current. It is installed as an earth fault protection for the HV winding, which is delta-connected and hence does not pass zero sequence current to the upstream HV when LV earth fault occurs. So this relay can be set to operate without any intentional time delay, since there is no need to grade it with other earth fault protection.

Earth fault relays normally have low settings corresponding to 20% or less of the rated current of protected circuit since they are connected in such a way that they are not affected by normal balanced currents.

As mentioned before, all these relays now have solid-state versions which have a number of time/current characteristics not available in the old electro-mechanical relays.

2.6. Winding temperature, oil temperature, Buchholz and pressure relief device

These are protective devices which are connected to directly trip the circuit breaker as well as operate auxiliary relays for flagging purposes. They clear faults that might not be detected by protection devices operating from the line current transformers. Such faults include excessive temperature in the winding or in the oil, winding inter-turn faults or core lamination faults.

2.6.1. Winding temperature device

Any transformer generates a large amount of heat while in operation, due to load current flowing in the windings, inadequate oil circulation arising from faulty pumps or blockages in ducts or pipes. Traditionally, thermostats or bulbs containing volatile liquids were positioned in the oil and within the windings. These operate remote pressure switches connected to them by small-diameter tubes. In recent years, a temperature sensitive bimetal stem is placed near the top of the transformer tank where the oil tends to be hottest. The stem is heated by both the surrounding liquid and a heater element which is fed from a current transformer connected to one of the phase windings The combination of the two temperatures is indicated on a device, known as Dial Hot Spot Thermometer. When an unacceptable over-heating occurs, resistance bridges, comprising of heat-sensitive resistors (sensors) are used to produce imbalance output signals that initiate either alarms or the opening of appropriate circuit breakers [9]

2.6.2. Buchholz relay

Any fault, such as insulation puncture, shorted turns, poor contact, which occurs inside a transformer in operation is generally accompanied by the evolution of gas as a result of the decomposition of oil or solid insulation. This gas bubbles rise to the surface and finally find their way to the conservator. On its way there, the gas is collected in what is known as Buchholz relay installed on a stub pipe between the tank and conservator. The Buchholz relay has an upper and a lower float. As gas collects in the relay housing, it displaces oil out of it. The top float drops, and its mercury switch completes an alarm circuit. In the case of more serious fault, such as an interturn short, and the like, the gas is usually librated in an explosive fashion and a large amount of oil is forced from the tank into the conservator. This causes the lower float to rise and close its mercury switch, thereby activating a tripping circuit which disconnects the transformer from supply line and averts a major breakdown [10]

2.6.3.

In order to avoid irreparable damage to the tank in the case of a heavy gas evolution, a pressure relief device is installed on a transformer. This is a low steel pipe communicating with the tank at one end and closed by a disc of thin glass at the other. When the pressure inside the tank rises dangerously, the disc bursts, so that excess oil and gas are expelled into the atmosphere before the tank has time to be deformed.

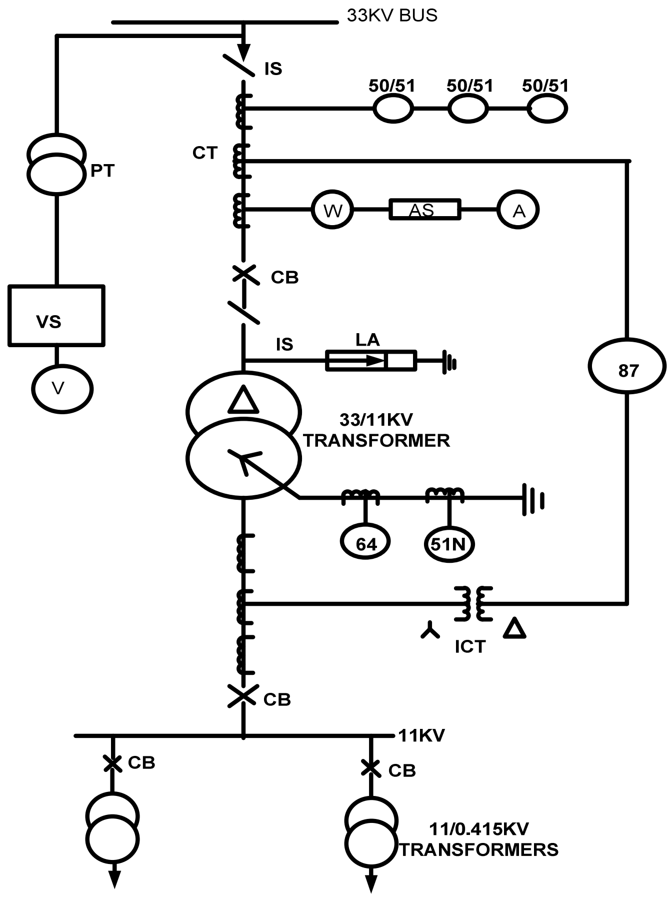


Figure 4: Single line diagram of 33 / 11KV substation. Legend: IS - Isolator, CT - Current transformer, PT - Potential transformer, LA - Lightning Arrester, A - Ammeter, AS - Ammeter switch, V - Voltmeter, VS - Voltmeter switch, W - Wattmeter, CB - Circuit breaker.

Figure 3 is the single line diagram of a 33/11KV substation, showing the associated protective devices.

3. Conclusion

Transformer is one of the most important equipment in the electrical power system. In specifying a protection scheme, the economic effect of the loss of the transformer and the cost to repair a major breakdown should be taken into account. If the transformer HV voltage is above 33KV, high-speed protection can be justified. If the voltage is less, the cost of the protection scheme must be related to the value of the transformer[10]. Thus the importance and ratings of a transformer are the factors that determine the type of protective equipment applied. Transformers rated up to 5MVA and used at voltage levels below 33KV can effectively and economically be protected with fuses. The rating of these fuses must be above the maximum exciting-current surges. As for larger transformers IDMT overcurrent and earth fault relays are used for protection. Current and time settings of these relays must be such that they should not operate when the maximum exciting-current surges flow, and also, correct discrimination with other protective equipment on associated networks must be provided for by the settings. These relays can also serve as back-up protection for all large transformers, where the main protection is the current-differential scheme. This type of protection works on the principle that the current entering a circuit is equal to the current leaving it under healthy conditions. The zone of protection is marked by the positions of current transformers on the primary and secondary sides of the transformer. Transformers are also protected by other protective equipment that do not rely on line current transformers for operation. Modern protection systems are based on electronic devices and circuits.

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