TRANSFORMERS - ELECTRICAL DEVICES, INSTRUMENTATION AND CONTROLS

INTRODUCTION

Protective devices, instrumentation and controls can prevent or limit electrical damage to transformers. The protective equipment warns of unsafe or abnormal conditions, or automatically reacts to such conditions.

Where “immediate” action is required, current-limiting fuses or circuit breakers may be provided. They can limit fault energy by interrupting power to the fault. In an ac circuit, this can be in as little as one quarter of a cycle following the report of an unsafe condition. Where immediate action is not required, gauges and metering devices can report conditions that can lead to a fault, and allow operator intervention to prevent faults by correcting those conditions.

OVERVIEW, the management program that lays the foundation for all loss control activities and responsibilities, identifies three elements that are directly involved with instrumentation, protective devices and controls: Employee Training; Maintenance; and Hazard Identification and Evaluation. Employee training requires no introductory comments. Maintenance involves not only equipment servicing, tests and analysis, but also periodic reviews and updates of coordination analyses. Hazard Identification and Evaluation requires a basic knowledge of engineering practices in order to evaluate and select electrical protective devices.

Instrumentation and switchgear requirements may be dictated by the *National Electrical Code*® (NEC). Also, Federal regulations may dictate minimum protection and arrangement requirements for transformers containing regulated gasses or fluids such as polychlorinated biphenyls (PCBs). Such requirements form the basis for “minimum” levels of protection. Beyond those requirements, transformer manufacturers may recommend additional devices, instruments and controls for the units they supply.

This guideline supplements the recommendations and requirements of manufacturers, the NEC and regulatory authorities. It specifically addresses electrical devices, instrumentation and controls for transformers rated over 75 kVA. However, judgment may suggest a recommendation is not practical, or that even higher levels of protection are necessary, based on an evaluation of the importance of the unit. PRC.5.9.0.1 provides guidance in evaluating the importance of a transformer.

POSITION

Provide overcurrent protection for all transformers.

TABLE 1
Minimum Instrumentation And Controls

Device/Control	Transformer Type Dry > 100 kVA	Non-flammable > 10 MVA	Askarel	Oil < 10 MVA	Oil $\geq$ 10 MVA	LFLI
Ambient Temp	I	I or A	I or A	I or A	I or A	I or A
Load Voltage	I	I or A	I or A	I or A	I or A	I or A
Load Current	I	I or A	I or A	I or A	I or A	I or A
Power Factor	I	I or A	I or A	I or A	I or A	I or A
Coil/Winding/Operating Temperature	I					
SF^6 Gas Pressure (if applicable)	I					
Top Oil Temperature		I or A	I or A	I or A	I or A	I or A
Winding Temperature		I or A	I or A	I or A	I or A	I or A
Liquid Level		I or A	I or A	I or A	I or A	I or A
Tank Pressure		I or A	I or A	I or A	I or A	I or A
Current-Limiting Fuses in the power supply (primary) lines - OR - Differential Relays having zones of protection that include primary side fuses, and the circuit breakers necessary for isolation			P		P	P
Sudden Pressure Relay				P if > 20,000 V	P	
Gas Accumulator Relay				A if > 20,000 V	I or A	

NOTES

I = Instrumentation.

A = Alarm to constantly attended control room for all critical units and units having high importance or high value. An alarm is not required for slowly developing conditions where a fast response is not necessary, and where control room instrumentation and written procedures provide for frequent operator review.

P = Protective Device for disconnect.

Ensure at least one member of the Hazard Identification and Evaluation committee has the expertise needed to evaluate electrical protection for transformers.

Protect transformers from direct lightning strikes and from lightning, switching and other surges in accordance with PRC.5.2.1.

Keep an up-to-date coordination analysis in the department responsible for the maintenance of electrical devices. Document the required settings for protective relays and the required specifications for fuses, particularly, the size and type as described in PRC.5.6.7.

Supervise and protect transformers using gauges, metering, alarms and electrical protective devices. Provide a level of protection no less than that described in Table 1. Higher levels of protection, including specialized transformer monitoring systems, may be appropriate for highly important units.

Educate supervisors, equipment operators and maintenance personnel in the hazards involved in their jobs and in the functions of the safety control equipment. Where operating procedures require human intervention to correct an unsafe condition, write procedures and keep them where they are readily accessible to the involved employees. Emphasize the importance of correctly responding to instrumentation and alarms in comprehensive employee training.

Include the testing of protective devices, instrumentation and controls in transformer maintenance programs. PRC.5.9.1 provides additional information.

DISCUSSION

Electrical protection for power transformers is accomplished with surge arresters, grounding, bonding, instrumentation and switchgear. Fuses, switches, vacuum fault interrupters, circuit breakers, relays, meters, control power systems and instrument transformers are commonly used. Many of the devices are available in different classes, designs and constructions; some more reliable than others, faster than others, or safer than others. Table 1 identifies instrumentation, alarms and protective devices used to supervise and protect transformers.

Often, instrumentation is installed to permit human action. Operators decide on and initiate protection. This obviously results in a relatively slow response time, but certain applications, such as load management, can tolerate the time needed for human intervention and reaction. Knowledge of the equipment and its history is important in the decision process.

Relays are switching devices that respond to electrical, mechanical and thermal inputs. Response levels of the relays may be adjusted by changing relay settings. Proper settings are documented in the coordination analysis. Following maintenance and repairs, relays should be reset to provide the proper tripping characteristics for effective protection.

A special type of instrument transformer is a bushing-type or window-type current transformer (CT). This CT is doughnut shaped. Typically, it has a high transformer turns ratio. Its secondary winding provides power to relays and instruments. Its primary winding is not truly a part of the unit. The line conductor or central bushing conductor around which the CT is placed becomes the primary "winding."

Thermal relays and "hot spot" (hottest spot in the windings of a fluid-insulated power transformer) thermometers generally depend on bushing-type CTs to **simulate** the hot spot temperature in a power transformer. The indicator shows the theoretical hot spot temperature. The hot spot temperature is not read directly, but instead, the CT provides electric power establishing current through a circuit containing a heating coil. In the relay and thermometer, this operating current flowing through the heating coil is directly proportional to the current flowing through the bushing on the transformer. Higher current through the bushing results in higher current flowing through the coil, and in a higher temperature in the device. The reference temperature produced by the heating coil is used to calibrate and set the indicator.

Alternately, thermocouples imbedded in transformer windings provide for a direct reading of winding temperature. These are normally installed at locations that a transformer manufacturer calculates will develop the highest winding temperature under normal operating conditions. While generally more accurate than indirect reading devices, imbedded thermocouples may not actually be located at the hottest spot in the windings. Some thermocouple temperature indicators have two pointers, one indicating the fluid temperature and the other indicating hot spot winding temperature.

Differential relays use CTs to measure current flow through primary and secondary transformer bushings, or primary and secondary circuits encompassing the desired zone of protection. Any fault occurring in the transformer or in transformer and protected distribution circuitry (between the CTs) is sensed by the differential relay which responds to the changes in the relationship between incoming and outgoing flows. Details of such designs and specific relaying schemes are beyond the scope of this guide.

An overcurrent relay operates when a CT senses excessive current. These relays may be timed or instantaneous, solid state or electromagnetic, and they may have single or double circuit closing contacts.

Many protective devices react to transformer fluid and tank conditions. Each has a protective function, although some react slowly to problems and have limited loss control value. The following list describes the uses of some protective devices:

- Liquid level gauges/indicators require periodic checks to determine that the liquid level is acceptable, and may have low level alarm contacts. A low level alarm indicates loss of insulating fluid, and represents a dangerous operating condition that could lead to internal flashovers and overheating. The normal fluid level is typically marked on the device as the 25°C (77°F) level. This is the reference temperature of the fluid, transformer tank and core, when filling the unit to the 25°C mark. Filling adjustments are made if the ambient (and fluid) temperature differs.

- Top oil temperature thermometers/indicators directly measure the fluid temperature at the top of the tank. The term “oil” is used in the name of this equipment, historically, regardless of the dielectric in use. As windings overheat, this heat is transferred to the fluid. Hot fluid rises to the top of the tank where the sensors are located. These devices may be used to initiate forced air cooling as described later. This method of supervision responds slowly to conditions causing overtemperature, but can support preventive maintenance actions.
    - The indicator normally has two pointers, one indicating the temperature of the fluid, and the other a red “drag pointer” to record the highest temperature reached since the device was last reset. The drag pointer is typically reset by sliding a magnet across the dial face.
    - The indicator may have multiple contacts, each adjustable by removing the dial face. Where three adjustable contacts are provided, one may start the first stage of fans required for forced air cooling. The next may start the second stage of fans. The third may provide an overtemperature alarm, or may trip circuit breakers to reduce transformer loading. Contacts should be set to maintain safe temperatures in the unit.
- Pressure-vacuum gauges are used on sealed tank transformers (most fluid insulated units.) Abnormal conditions can lead to tank rupture, deformation or leakage of air into the tank through poor seals. Air/oxygen will accelerate aging of the oil. Alarms may be provided for out-of-limit conditions. Generally, transformers should not be run under a vacuum.
- Pressure relief devices are sometimes available with alarm contacts. Generally, there are two types of devices. Both operate when pressure in the tank exceeds approximately 5 psi – 10 psi (0.35 bar – 0.7 bar). With a diaphragm type relief device, the device ruptures and must be immediately replaced. The valve type opens but reseats itself and reseals the tank once pressure is relieved. With the operation of either type of relief device, the cause of the overpressure should be investigated and the transformer serviced before the unit is placed back in service. Relief devices are not installed for the purpose of relieving fast developing pressures caused by high energy arcing. High energy arcing in a transformer causes the tank to rupture. Relief devices typically protect against pressures caused by overheating upon overloading a unit.
- Rapid pressure rise (sudden-pressure) relays may be arranged to trip transformer power supply circuit breakers. These devices operate on the rate of rise principle and quickly detect high energy arcing in a transformer. Detection is slower for lower energy arcs. Slow pressure increases in a transformer will not be detected by these devices. A thorough inspection of the transformer is warranted when these relays operate. Most units over 5000 kVA should have this protection.
- Gas accumulation detection relays are used in transformers having a piped interconnection between the main tank and an auxiliary (conservator) tank. The conservator tank contains excess transformer fluid and a vented air space, often with a bladder type arrangement to prevent the fluid making direct contact with air. The main tank has no vapor space under normal conditions. Fluid flows freely between the conservator and the main tank due to thermal cycling. A gas accumulating chamber (part of the relay) connects to the top of the main tank to collect bubbles formed as the winding insulation deteriorates. The relay measures the volume of gas accumulated with time. With other than a minimal rate of gas formation, shutdown and repairs are required.
- Combustible gas relays sample gases from the vapor space in sealed tank transformers. Combustible gases are formed upon the decomposition of insulating materials. The relay operates by drawing the sample gas across a “hot” conducting wire. A combustible gas ignites, further heating the wire and reducing the current flowing through the circuit, which sounds an alarm.
- The true Buchholz relay is a dual chambered protective relay that provides both gas accumulator and sudden pressure rise detection functions.

Even a fuse is too slow to reliably protect against certain disturbances. Upon experiencing excessive current flow, a portion of a fuse heats and melts, thereby physically severing a connection automatically and opening the circuit. But the time required depends on the specifications for the fuse. Even after the connection is severed, current may flow for a few cycles through an arc. The ordinary fuse may act too slowly and may allow several cycles of damaging current to flow through an arc before interrupting it. This can be severely destructive to a transformer. The arc can be extinguished more quickly by a current-limiting fuse which can interrupt the flow in the first quarter of the first cycle, or at 60 Hertz, in about 4/1000 sec. This may reduce the severity of damage and is recommended with certain transformer installations even if fire and dielectric breakdown potentials are low. See the requirements for askarel, LFLI and large oil units in Table 1.

A lesser level of protection against high energy faults is that provided by differential relays used with circuit breakers. These are more expensive than current-limiting fuses. Because it is highly dependent on a good maintenance program for its reliability, the differential relay is less reliable than a current-limiting fuse. However, relays can trigger a circuit breaker to open all three phases simultaneously and can thus avoid the problems caused by the loss of one phase, as may occur with fuses. Used together in a circuit, differential relays and circuit breakers and current-limiting fuses provide a highly reliable level of protection.

A coordination analysis determines suitable trip characteristics for the interrupting device (fuse or circuit breaker). The proper rating and speed of operation is selected in order to minimize shutdowns by isolating the faulted circuit without taking circuits out of service unnecessarily, and to minimize property damage. Other information needed to select an interrupting device is the short circuit interrupting kVA rating; this is the capacity needed by the device to safely interrupt any fault current in the circuit being protected.

Assuming that any contribution from the downstream circuit is unimportant, the maximum fault current on the secondary side of a transformer is a “bolted through-fault.” The downstream interrupting device should have the capacity necessary to handle this fault. A quick estimate of the required interrupting rating of a breaker, located immediately downstream of a transformer, may be found using the following “rule of thumb”:

$$\text{Interrupting Rating (kVA)} = \frac{\text{Transformer kVA}}{\text{Transformer Impedance(\%)}}$$

$$\text{Interrupting Rating (amps)} = \frac{\text{Transformer kVA}}{\text{Transformer Impedance(\%) x Voltage(kV) x } \sqrt{3}}$$

“Transformer impedance”, also called “impedance voltage.” is a value expressed as a percentage and is stamped or imprinted on the transformer nameplate.

The values in the right side of the equation are those of the upstream transformer. A definition of the term is beyond the scope of this guide.

If this supply transformer belongs to the public utility company, a more accurate “connection point” capacity may be available from them. Engineers calculate capacities more accurately than the rule of thumb by using more complex formulas and additional information.

Maintenance for electrical equipment should follow manufacturers’, NFPA and AXA XL Risk Consulting’s Property Risk Consulting Guidelines. Refer to PRC.5.6.1, PRC.5.7.4, PRC.5.9.1, and NFPA 70B for more information.