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Operation and Design of a Protection Relay for Transformer Condition Monitoring

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1 INTRODUCTION

Power transformers are a critical link in the ac transportation of electricity from the generating stations to end users. In terms of total investment, electric power utilities invest at least as much in transformers as they do in generating stations. Transformers are expected to last 20 to 30 years, and in many cases, even longer.

The application of monitoring systems to transformers offers benefits in more cost-effective utilization by detecting faults that can be fixed before causing irreparable damage or in diagnosing faults and determining if they can be repaired, lived with, or require transformer replacement.

Overloading power transformers beyond the nameplate rating can cause a rise in temperature of both transformer oil and windings. If the winding temperature rise exceeds the transformer limits, the insulation will deteriorate and may fail prematurely. Prolonged thermal heating weakens the insulation over time, resulting in accelerated transformer loss-of-life. Through-fault currents create forces within the transformer that can eventually weaken the winding integrity. Transformer overexcitation causes transformer heating and increases exciting current, noise, and vibration.

A comprehensive transformer protection scheme needs to include protection against transformer overload, through-fault and overexcitation, as well as protection for internal faults.

Measurable indicators of transformer serviceability include electrical load; top-oil, hottest-spot and ambient temperatures; fault history; and measured excitation. Utilities that use these indicators can make intelligent profit/risk decisions and plan optimal transformer loading and maintenance. Also smart IEDs with standard flexible communications can ease integration of these devices into the customer control system.

Although transformer monitoring systems have been on the market for some years and have achieved success in detecting and diagnosing problems, their adoption is far from universal. The perceived barriers to the more general application of transformer monitoring include high costs of installation and maintenance, incompatibility between systems and transformers of different manufacture and the difficulty of collecting and assimilating the output of diverse systems across a network.

Including many of the transformer monitoring features in a standard protection relay reduces the cost barriers. Also, the flexibility and standardization of the protection relay communications allows data easier collection and interfacing to the customers existing SCADA systems.

This paper discusses the operation and design of a transformer protection relay that includes many of the common transformer condition monitoring features required making condition monitoring a more economical option.

2 TRANSFORMER RELAY DESIGN FOR CONDITION MONITORING

A comprehensive transformer protection relay for protecting two and three winding transformers (including autotransformers), with up to 5 sets of three-phase CT inputs and 4 voltage inputs has been designed. The relay includes protection against transformer overload, through-fault and overexcitation, as well as standard protection functions such as differential, overcurrent and earth fault etc for internal faults.

The relay includes a number of measurable indicators of transformer serviceability monitoring the electrical load; top-oil, hottest-spot and ambient temperatures; fault history; and measured excitation. Utilities that use these indicators can make intelligent profit/risk decisions and plan optimal transformer loading and maintenance.

The protection relay includes many of the common transformer condition monitoring features required, as listed below and described in more detail later in the paper:

- Transformer top oil and hot spot temperature calculation taking into account the ambient temperature, load variations and oil thermal parameters, based on IEEE Standard C57.91-1995 [2]
- Transformer loss of life calculation, based on IEEE Standard C57.91-1995 [2], providing data on accumulated loss of life, rate of loss of life, aging acceleration factor and residual life hours
- Transformer through fault monitoring based on I^2t calculation of the maximum fault current and fault duration per phase
- Temperature monitoring for example of top oil, bottom oil, cooler inlet/outlet oil, tap changer compartment oil and winding hotspot temperature via the relays ten RTD inputs or four current loop inputs (CLIO - current loop inputs and outputs)
- Monitoring and alarming of other sensor quantities, such as tap changer position, oil level, bushing oil pressure via the relay current loop inputs
- Load and short circuit current and system voltages monitoring via the protection relay current and voltage transformer inputs. The relay can also provide CT and VT supervision of these inputs.

The relay includes flexible industry standard communication options to interface the relay protection and condition monitoring functions to the customers SCADA system. For example the relay supports a number of standard protocols such as MODBUS, IEC60870-5-103, DNP 3.0 and IEC61850 and rear port communication port options such as RS485, fibre optic, Ethernet or redundant Ethernet plus a front communications port for local access.

The relay also includes programmable leds for user friendly local indication and programmable scheme logic for easy scheme customization. Sequence of event and disturbance recording features are also included that can help diagnosing faults and alarms.

As described above the relay includes four transducer (current loop) inputs with flexible ranges of 0-1mA, 0-10mA, 0-20mA or 4-20mA which can be used with a number of external monitoring sensors to indicate temperature, oil level etc. Associated with each input there are two time delayed protection stages, one for alarm and one for trip. Each stage can be set for 'Over' or 'Under' operation. Four current loop outputs are also provided with ranges of 0-1mA, 0-10mA, 0-20mA or 4-20mA which can alleviate the need for separate transducers. These may be used to feed standard moving coil ammeters for analog indication of certain measured quantities or for input to SCADA using an existing analog RTU. Up to 24 digital inputs are available to provide status information from external devices such as CBs or external sensors and up to 24 output contacts are available to provide alarm and trip outputs.

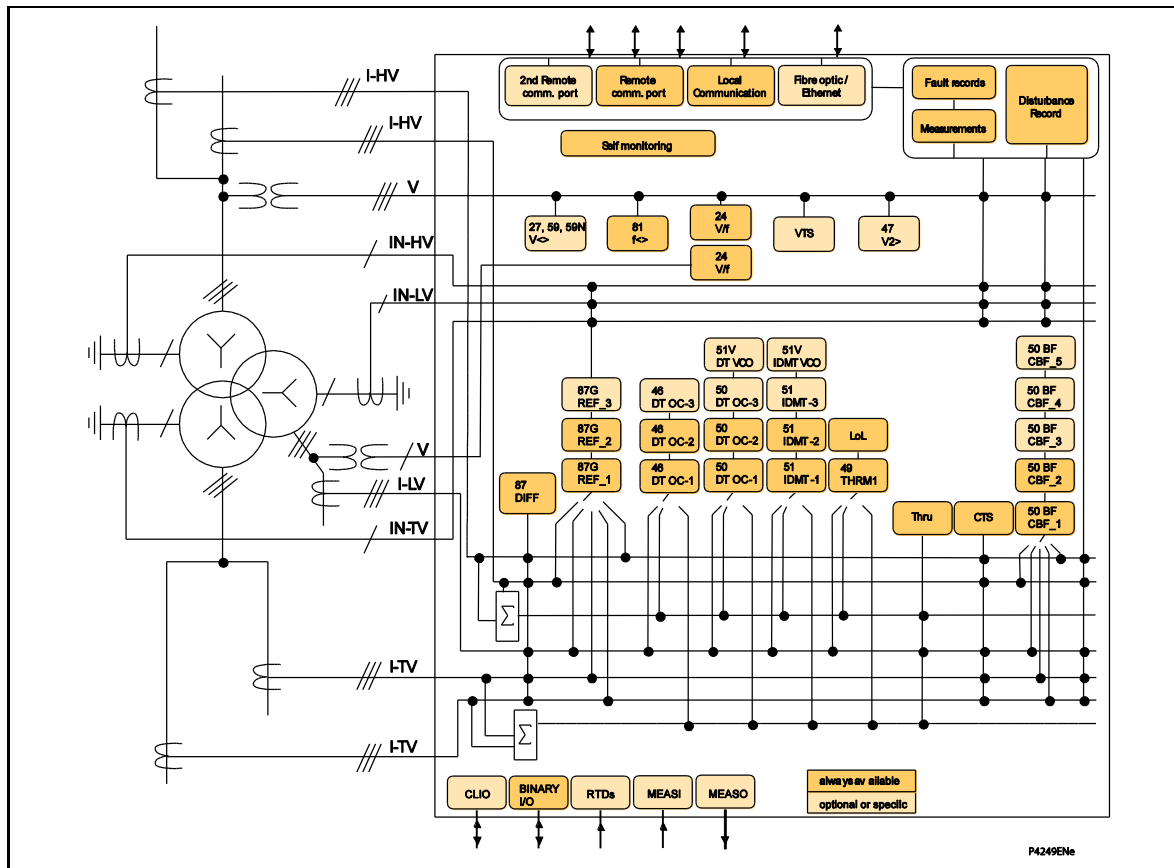
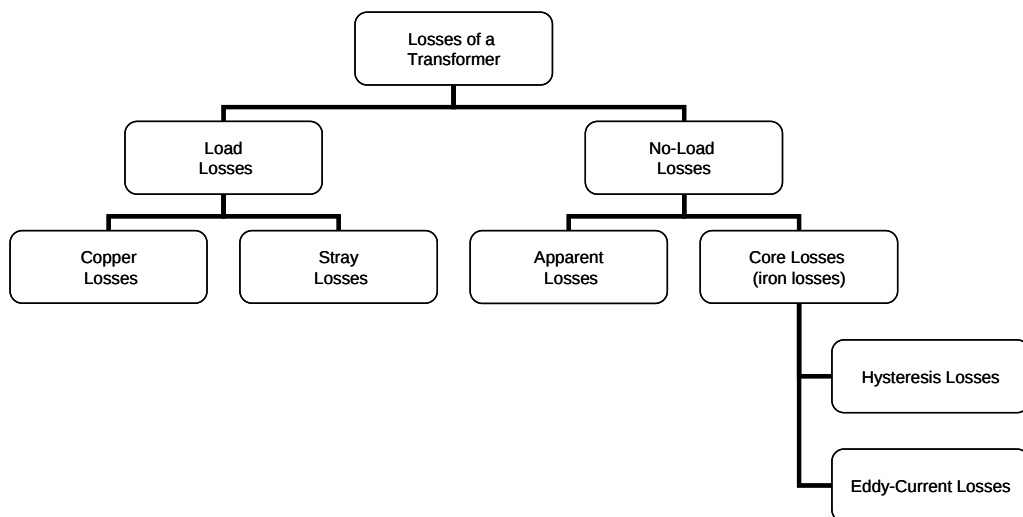


Fig. 1: Transformer protection and condition monitoring functional diagram

3 TRANSFORMER THERMAL MODEL FUNDAMENTALS

Factors that influence the transformer thermal characteristic and generate heat, which causes a rise of temperature are mainly Core losses and Conductor resistance loss (usually referred to as Copper loss i.e. I^2R loss). The losses in a transformer are shown in the following diagram.



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Fig. 2: Transformer Losses

The rating of a transformer usually depends upon the *maximum permitted working temperature* of the transformer insulation [1]. The steady-state temperature rise is reached when these losses are

balanced by the transformer cooling due to radiation, convection and conduction of heat. The losses increase with output and the maximum output or *transformer rating* is based on the losses that give the maximum permitted temperature T_p . The permitted temperature rise θ_p also depends upon the ambient temperature of the surrounding air T_a :

$$\text{Maximum temperature rise } \theta_p = T_p - T_a$$

During energization, the transformer inrush current causes the transformer to be overloaded for a short duration until its temperature reaches T_p . The inrush current is well in excess of the full-load current (perhaps up to 10 times) but the transient time is sufficiently short to ensure that θ_p is not exceeded.

4 THERMAL MONITORING AND PROTECTION

The relay thermal overload monitoring and protection is based on IEEE Standard C57.91-1995 [2]. The thermal overload trip is based on the hot spot temperature Θ_H or top oil temperature Θ_{TO} , each with its own exclusive time constant setting. The top oil temperature can be calculated or can be measured directly by one of the current loop or RTD inputs. The hot spot temperature can only be calculated. The ambient temperature Θ_A can be measured directly or an average value can be set by the user (average ambient temperatures covers 24 hour time periods). Since transformer loads are becoming increasingly non-linear, RMS current values are used to replicate the winding hotspot temperature. The winding, the temperature of which is under supervision, can be selected as either HV or LV or TV or biased current. It is recommended to select the biased current option so that an overall thermal condition monitoring of the transformer is carried out.

The biased current used by the thermal protection element is not the same as the biased current used by the differential protection. To calculate the bias current, the thermal element considers the maximum rms phase current of each transformer winding. The thermal bias current calculation is as follows.

$$I_{bias} = \frac{MaxHVI_{rms} + MaxLVI_{rms} + MaxTVI_{rms}}{2}$$

The relay has up to three hot spot stages and up to three top oil stages. The Top Oil tripping signal is asserted when the top oil (measured or calculated) temperature is above the setting and the time delay has elapsed. Also, the Hot Spot tripping signal is asserted when the hottest-spot (calculated only) temperature is above the setting and the time delay has elapsed.

If a more accurate representation of the thermal state of the transformer is required, the use of temperature monitoring inputs (RTDs or Current Loop Inputs (CLI)) which target specific areas is recommended. Also, for short time overloads, the application of RTDs/CLI and overcurrent protection can provide better protection.

4.1 Top oil temperature

If the top oil temperature is not available as a measured input quantity, it is calculated every cycle by the following equation:

$$\Theta_{TO} = \Theta_A + \Delta\Theta_{TO}$$

Θ_{TO} = Top oil temperature

Θ_A = Ambient temperature

$\Delta\Theta_{TO}$ = Top oil rise over ambient temperature due to a step load change

Θ_A can be acquired by measurement directly or can be set by the user through the user interface.

4.2 Hot spot temperature

The hot spot temperature can only be obtained by calculation. The following equation is used to calculate the hot spot temperature every cycle:

$$\Theta_H = \Theta_{TO} + \Delta\Theta_H$$

where:

Θ_H = Hot spot (winding) temperature

Θ_{TO} = Top oil temperature

$\Delta\Theta_H$ = Hot spot rise above top oil temperature

4.3 Cooling modes

Four cooling modes are available in the relay - **Natural, Forced Air, Forced Oil, Forced Air Oil**. The oil exponent and winding exponent can be set independently for each mode. These exponents are empirically derived and are required to calculate the variation of $\Delta\Theta_H$ and $\Delta\Theta_{TO}$ with load changes. The oil and winding exponent values changes for each mode of cooling to approximately account for changes in the resistance and viscosity with changes in load.

The cooling mode selection can be made in the relay by using digital inputs or can be set to a fixed mode in the setting file. The digital inputs enable the thermal characteristic to be changed to match the different cooling modes as fans and pumps are switched on and off.

5 LOSS OF LIFE STATISTICS

As stated in IEEE Std. C57.91-1995 [2], aging of insulation is a time function of temperature, moisture and oxygen content. The moisture and oxygen contributions to insulation deterioration are minimized due to modern oil preservation systems. Therefore, temperature is the key parameter in insulation ageing. Temperature distribution is not uniform; the part with the highest temperature undergoes the greatest deterioration. Therefore the hottest spot temperature is considered in loss of life calculations.

As indicated in IEEE Std. C57.91-1995 the aging acceleration factor is the rate at which transformer insulation aging for a given hottest spot temperature is accelerated compared with the aging rate at a reference hottest spot temperature. For 65°C average winding rise transformers, the reference hottest spot temperature is 110°C. For 55°C average winding rise transformers, the reference hottest spot temperature is 95°C. For hottest spot temperatures in excess of the reference hottest spot temperature the aging acceleration factor is greater than 1. For hottest spot temperatures lower than the reference hottest spot temperature, the aging acceleration factor is less than 1.

The relay includes a single stage definite time delay alarm based on aging acceleration factor (F_{AA}) and loss of life (LOL). Measurements are also available for Accumulated loss of life (LOL) in hours, Residual life at reference hottest spot temperature, Rate of loss of life (ROLOL) in %, Aging acceleration factor (FAA), Mean aging acceleration factor (FAA,m), and Residual life hours at FAA,m ($L_{res}(FAA,m)$).

The model used for loss of life statistics is based on the equations for *Loss of Life* LOL and *Accelerated Aging Factor* F_{AA} as stated below.

Loss of life is calculated every hour according to the following formula:

$$LOL = L(\Theta_{H,r}) - L_{res}(\Theta_{H,r})$$

where:

$L(\Theta_{H,r})$ = life hours at reference winding hottest-spot temperature. This parameter is set by the user.

$L_{res}(\Theta_{H,r})$ = residual life hours at reference winding hottest-spot temperature.

The insulation aging acceleration factor F_{AA} , for each time interval Δt , is calculated according to the following formula:

$$F_{AA} = \frac{L(\Theta_{H,r})}{L(\Theta_H)} = \frac{e^{\left[A + \frac{B}{\Theta_{H,r} + 273}\right]}}{e^{\left[A + \frac{B}{\Theta_H + 273}\right]}} = e^{\left[\frac{B}{\Theta_{H,r} + 273} - \frac{B}{\Theta_H + 273}\right]}$$

where:

$L(\Theta_H)$ = life hours at winding hottest-spot temperature.

Θ_H = hottest-spot temperature as calculated in thermal overload protection.

$\Theta_{H,r}$ = hottest-spot temperature at rated load.

B = constant B from the life expectancy curve. This parameter is set by the user. IEEE Std. C57.91-1995 [2] recommends a B value of 15000.

The residual life hours at reference hottest-spot temperature is updated every hour as follows:

$$L_{res}(\Theta_{H,r}) = L_{res,p}(\Theta_{H,r}) - \frac{\sum_{i=1}^{3600} F_{AA,i}(\Theta_H)}{3600}$$

where:

$L_{res,p}(\Theta_{H,r})$ = residual life hours at reference temperature one hour ago.

$F_{AA,i}(\Theta_H)$ = mean aging acceleration factor, as calculated above. It is calculated every second.

The accumulated loss of life (LOL) is updated in non-volatile memory once per hour. It is possible to reset and set a new loss of life figure, in the event that a relay is applied in a new location with a pre-aged resident transformer.

Daily rate of loss of life (ROLOL) in percentage per day is given as follows and it is updated every day:

$$ROLOL = \frac{24}{L(\Theta_{H,r})} \cdot F_{AA,m}(\Theta_H) \cdot 100\%$$

The mean aging acceleration factor $F_{AA,m}$ is updated per day and is given by:

$$F_{AA,m} = \frac{\sum_{n=1}^N F_{AA,n} \cdot \Delta t_n}{\sum_{n=1}^N \Delta t_n} = \frac{\sum_{n=1}^N F_{AA,n}}{N}$$

where:

$F_{AA,n}$ is calculated every cycle

$\Delta t_n = 1\text{cycle}$

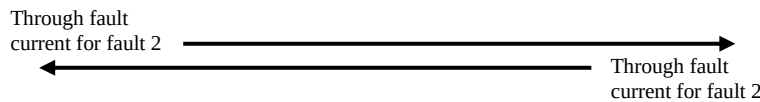
$F_{AA,m}$ states the latest one-day statistics of F_{AA} . When the relay is energized for the first time, $F_{AA,m}$ default value is 1.

The residual life in hours at $F_{AA,m}$ is updated per day and is given by:

$$L_{res}(F_{AA,m}) = \frac{L_{res}(\Theta_{H,r})}{F_{AA,m}}$$

6 THROUGH FAULT MONITORING AND CONTROL

According to statistics [3], through faults is the main culprit in causing transformer failure and according to IEEE Std. C57.109-1993 [4] mechanical effects are more significant than thermal effects for fault-current magnitudes near the design capability of the transformer. However, at fault-current magnitudes close to the overload range, mechanical effects are less important unless the frequency of fault occurrence is high. Figure 3 below depicts an example initiation of a through fault.



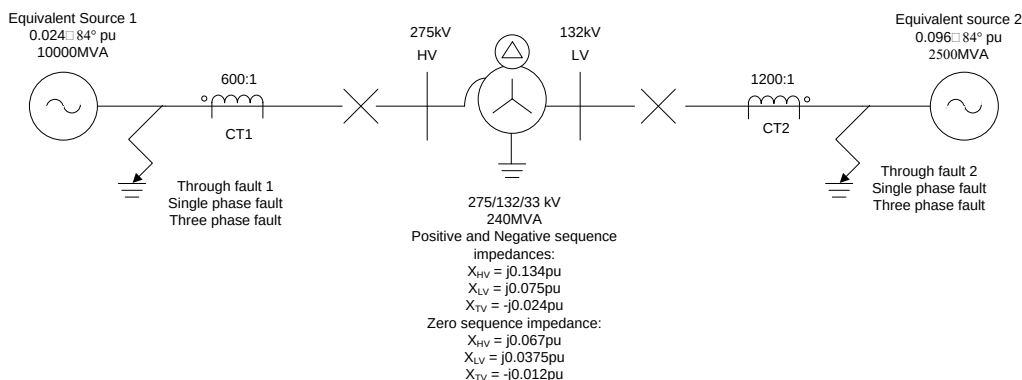


Fig. 3: Through fault monitoring example

As fault duty and feeder exposure increase, the incidence and severity of through faults experienced by a transformer will tend to go up over time. IEEE Std. C57.12 [5] provides construction guidelines for short-circuit withstand for transformers. The standard states that a transformer shall withstand 2 seconds of a bolted fault at the transformer terminals.

In the relay design the through fault monitoring element can monitor the HV, the LV or the TV winding. In three winding applications, the winding through which the highest current would flow during an external fault should be monitored. The through fault current monitoring function gives the fault current level, the duration of the faulty condition and the date and time for each through fault. An I^2t calculation based on the recorded time duration and maximum current is performed for each phase. This calculation is only performed when the current is above the provided setting and if the differential protection element has not started. Cumulative stored calculations for each phase can be monitored so that the user may schedule the transformer maintenance based on this data. This may also justify possible system enhancement to reduce through fault level.

A single stage alarm is provided for through-fault monitoring. The alarm is issued if the maximum cumulative I^2t in the three phases exceeds the relevant setting. A through fault event is recorded if any of the phase currents is bigger than a trigger setting. This setting should be greater than the overload capability of the transformer. According to IEEE Std. C57.109-1993 [4], values of 3.5 or less multiples of normal base current may result from overloads rather than faults. IEEE Std. C57.91-1995 [2], states that the suggested limit of load for loading above the nameplate of a distribution transformer with 65°C rise is 300% of rated load during short-time loading (0.5 hours or less). On the other hand, the suggested limit of load for loading above the nameplate of a power transformer with 55°C rise is 200% maximum.

7 OVEREXCITATION MONITORING AND PROTECTION

The magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency. Overvoltage and/or underfrequency conditions can produce flux levels that saturate the transformer core. This could cause stray flux to be induced in unlaminated components that have not been designed to carry the flux. The resulting eddy currents in solid components (core bolts and clamps) and end of core laminations can cause rapid overheating and damage. These abnormal operating conditions can exist in any part of the power system, so any transformer may be exposed to overexcitation. A severely overexcited transformer should be disconnected to avoid transformer damage.

For overfluxing protection and alarming the relay includes three definite time setting stages and one DT/IDMT setting stage plus a single stage alarm setting that can be combined to create a combined multi-stage V/Hz trip operating characteristic using programmable scheme logic. Reference should be made to the manufacturers' withstand characteristics before formulating these settings.

Transient overfluxing conditions can cause unwanted operation of the transformer differential protection if stabilization is not provided. Overexcitation of a power transformer is a typical case of a.c. saturation of the core that produces odd harmonics in the exciting current. The third harmonic is the most suitable for detecting overexcitation conditions, but either the delta connection of the CTs or

the delta connection compensation of the differential relay filters out this harmonic. The fifth harmonic, however, is a reliable quantity for detecting overexcitation conditions.

The relay filters the differential current and determines the fundamental component and the fifth harmonic component. If the ratio (5th harmonic component)/(fundamental component) exceeds the set value in at least one phase in two consecutive calculations, and if the differential current is larger than 0.1 pu, differential tripping is blocked selectively per phase.

The 5th harmonic element can also be used to raise an alarm due to persistent overfluxing that may be caused by geomagnetic disturbances that may not be detected by the conventional a.c. overfluxing protection.

8 CONCLUSION

Power transformers are a critical link in the ac transportation of electricity from the generating stations to end users. The application of monitoring systems to transformers offers benefits in more cost-effective utilization by detecting faults that can be fixed before causing irreparable damage or in diagnosing faults and determining if they can be repaired, lived with, or require transformer replacement. Although transformer monitoring systems have been on the market for some years and have achieved success in detecting and diagnosing problems, their adoption is far from universal. The perceived barriers to the more general application of transformer monitoring include high costs of installation and maintenance, incompatibility between systems and transformers of different manufacture and the difficulty of collecting and assimilating the output of diverse systems across a network.

This paper discusses the operation and design of a transformer protection relay that includes many of the common transformer condition monitoring features required making condition monitoring a more economical option.

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