Transformer Thermal Overload Protection -

What's It All About?

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Summary: It is possible to design transformer protection relays that detect overload conditions based on calculated hot spot temperatures, and react in an intelligent way. Some such relays are in use now. This paper describes some of the principles and misconceptions.

Introduction: Why are protection engineers interested?

It has been common practice in the past to be conservative in loading power transformers, that is, to seldom load them beyond their full load rating. However, there are large savings to be realized by overloading transformers in a careful way. Special protective relays can help.

The 'hot spot' temperature - indicated by the 'winding temperature' gauge - is a value that flags insulation deterioration at some point in a transformer. It is the single best indicator that a transformer is 'overloaded.' The calculation method is the subject of a recent IEEE Standard(Guide): C57.91-1995[1].

Traditionally, inverse-time overcurrent relays have been used for overload protection, but a difficulty is that transformers are usually outdoors where ambient temperature affects their loadability, and hence the optimum pickup settings of such relays. See Fig. 1, based on the Standard[1].

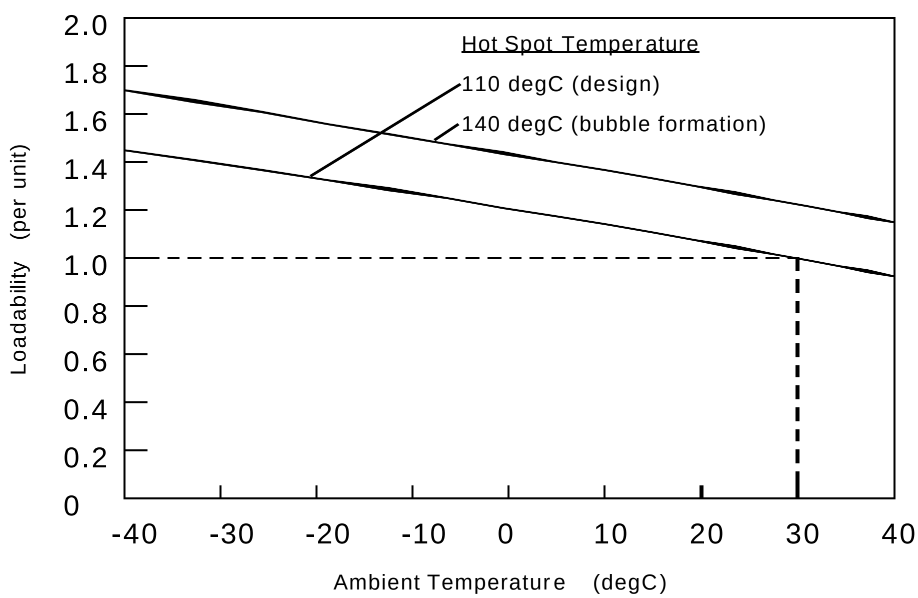

Fig. 1. Transformer loadability versus ambient temperature

(Parameters used: R=10, n=0.8, m=0.9. where R = ratio of no-load to load losses, and 'n' and 'm' are exponents in the heating equations, dependent on the cooling method.)

The intersection of 110^{o}C ambient temperature with one per unit loadability represents the *design condition*, that is, the condition under which continuous loading would result in a steady-state hot spot temperature of 110^{o}C.

Relation between Hot Spot Temperature and Loss of Life

The IEEE Standard[1] suggests normal life (meaning normal solid insulation life) as 180,000 hours or 20.6 years. This is the life corresponding to continuous operation at the design hot spot temperature of 110^{o}C. It is related to the *loss of tensile strength* or *degree of polymerization retention* of the solid winding insulation (page 10 of the Standard). A nonlinear formula relates the rate of loss of life to other values of hot spot temperature as follows:

Hot Spot Temperature degrees Celsius	Rate of Loss of Life relative to **normal**
110 (design value)	1
117	2
124	4
131	8
139 (oil bubbles?)	16
147	32

Note that operation at the 'oil bubbles' condition is thought to be OK, for a short time, because the bubbles will re-dissolve when the oil cools.

Approach Number One: Summer/Winter Settings

Referring to Fig. 1, one can assume a worst-case summer temperature and a worst-case winter temperature, and manually change the relay pickup settings accordingly. Of course, the ability to do this through a communication link is very convenient.

Approach Number Two: Adaptive Pickup

The 'coarse' approach above can be made automatic by using a relay that can sense ambient temperature information. See Fig. 2. The pickup levels are defined by the curves of Fig. 1. For example, if

1) the ambient temperature is 30^{o}C, and
2) the rate of loss of life is to be limited to 'normal,' that is, a hot spot temperature of 110^{o}C,

then the pickup is automatically set to one per unit current (plus a margin if desired). If the ambient temperature is -10^{o}C then the pickup adjusts to about 1.3 per unit.

If one allows higher rate of loss of life, for a short time, then higher loads can be tolerated, that is, the inverse-time curve moves upward.

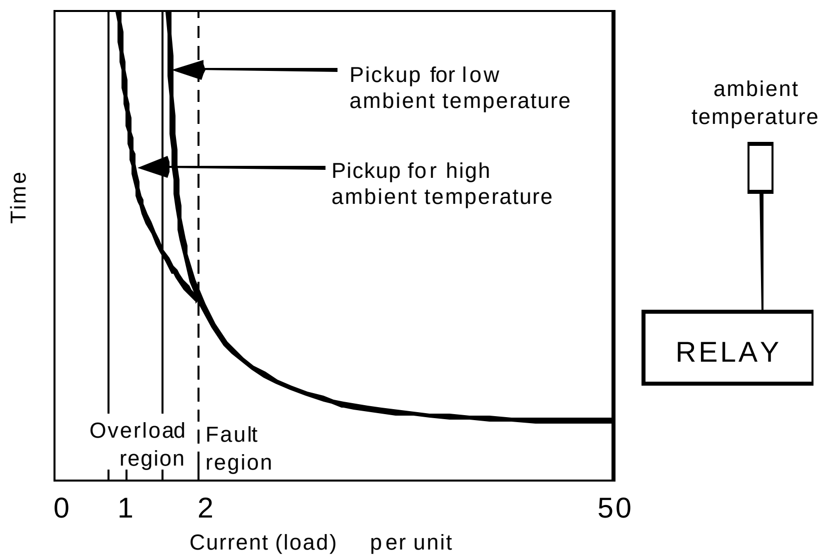

Fig. 2 Adaptive pickup level for an inverse-time overcurrent relay.

Approach Number Three: Overload = Overtemperature

In this approach, the overloading condition is sensed as overtemperature rather than as overcurrent. See Fig. 3. This idea is closely related to the 'emergency overloading' guidelines of the Standard[1]. In words, the principle is that a transformer can be loaded beyond its rating if one pays close attention to hot spot temperature. Inverse-time over-*current* is still used beyond two per unit current, for through fault protection.

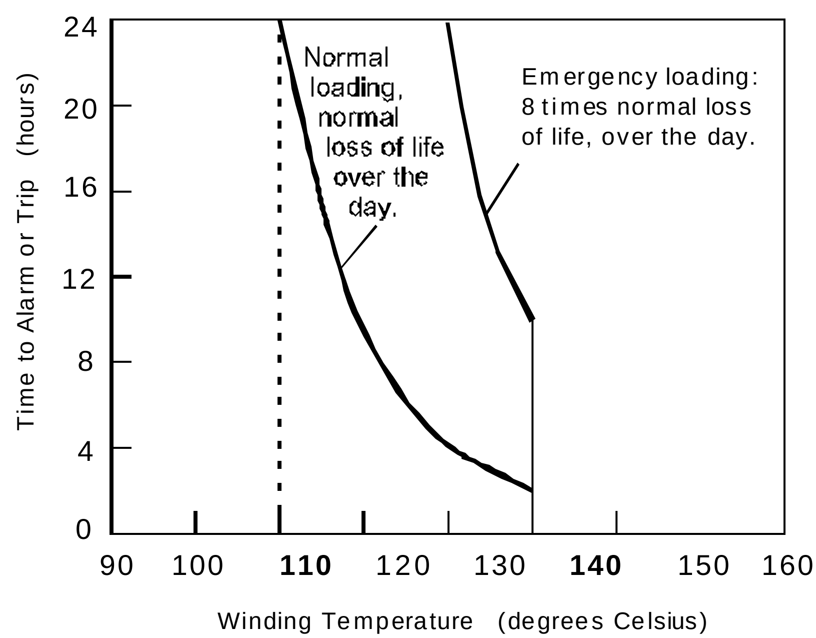

Fig. 3. The inverse-time overtemperature relay characteristic.

Incidentally, it is probably desirable to over-ride this function if the current is sufficiently high to exceed the rating of such things as an on-load tap-changer.

Hot Spot Temperature: How is it Determined?

- **Misconception: The installation of fiber optic sensors to measure the 'real' hot spot temperature, is ideal**. The location of hot spots is a guess. Also, the temperature at which insulation deterioration takes place is not a fixed, easily defined level. So the calculation of a value that is 'reasonably accurate' is sufficient. The point is that it is an indication of trouble, whether it is 'dead on' or not.

- **Misconception: A 'more accurate' method of calculation will give a more accurate result.** The IEEE Standard[1] is somewhat confusing in that two different methods of calculating hot spot temperatures are presented. They might be called the older 'long-standing easy-to-use method' and the 'more accurate but complex' newer method. Let us call these the 'old' and 'new' methods for convenience. The 'new' method is only more accurate if the input data is sufficiently accurate, which may not be the case.

The reason for protection engineers to be interested in the following two items is that relay algorithm designs are dependent on the equations presented in the Standard.

- **Misconception: The long-standing method cannot handle continuously changing load: only step changes with exponential responses.** In fact, the differential equations for this method can handle completely general load patterns.

- **Misconception: The long-standing method cannot handle continuously varying ambient temperature.** In fact, it is easily added in a logical way.

A Basic Thermal Model

Fig. 4 shows a thermal model of the situation within a transformer, modeled with lumped thermal capacitance and lumped thermal nonlinear resistance. A detailed discussion of the rationale for this model is given in a paper to be presented next year[2].

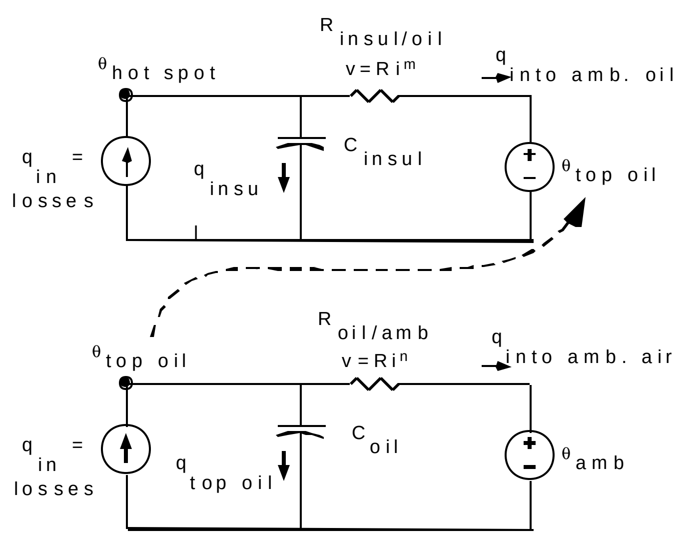

Fig. 4. Electrical circuit analogy for thermal conditions within a power transformer.

The usefulness of this model for electrical engineers is that it relies entirely on circuit theory for a solution. The input losses (an *ideal current source*) q_{in} are due to the copper loss of the windings and the core loss. Completely arbitrary load current and operating voltage are permissible, from which the losses can be calculated at any point in time. Similarly, the ambient temperature (an *ideal 'voltage' source*) can be a completely arbitrary function of time as well.

The present Standard [1] avoids the use of an analogy, relying instead on either pure heat transfer principles, or 'exponential time constant' analogies. One of the problems with the latter is that if "n" or "m" is non-unity, the response to a step change is not truly exponential. Also, it is not necessary to *think* in terms of step changes. For example, for a study, one might assume that the ambient temperature varied sinusoidally throughout a 'standard day,' as is in fact suggested in the IEC Standard[3] for overheating.

Conclusion

Hot spot temperature and **loss of life** are useful concepts that can be incorporated into protective overload relay design.

References

[1] IEEE Std. C57.91-1995 IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

[2] Swift, G and Zhang, Z, "A Different Approach to Transformer Thermal Modeling," to be presented at the IEEE Transmission and Distribution Conference, New Orleans, April 12-16, 1999.

[3] IEC (International Electrotechnical Commission) Standard 354 Second Edition, 1991-09, Loading guide for oil-Immersed power transformers," pp. 143-145.