Managing Transformer Overload - Smart Relays

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Abstract

This article provides an overview of a smart relay for transformer protection, monitoring and overload control based on the IEEE C57.91-1995 standard. Application of this IEEE standard with a suitable relay enables adaptive overload, automated load shedding and predictive overload early warning system functions to be integrated into the protective relay. The standard is introduced and the related functions and their applications are then described.

Sommaire

Cet article fournit une vue d'ensemble à propos d'un relais intelligent servant à la protection, la surveillance et au contrôle des surcharges des transformateurs, le tout selon la norme C57.91-1995 de l'IEEE. L'application de cette norme dans un relais approprié permet d'intégrer, dans le relais protecteur, des fonctions de surcharge adaptée, de délestage automatisé et de prédiction préventive de la surcharge du système par une alerte. Après avoir discuté de la norme et des fonctions qui en découlent, cet article décrit les applications reliées au relais intelligent.

1.0 Smart Relays - what they do

Power utilities have for along time relied on protection relays (electromagnetic and first-generation digital relays) to perform only a single isolated task - fault protection. This was for a number of reasons but mainly due to limited processing power. With the advent of second-generation digital relays using powerful high-speed digital signal processors (e.g. DSPs), the protective relay is able to process the usual protection functions safely and effectively with processing overhead to spare. This additional processing capacity permits the relay to do more than just provide standard protection. These digital relays combined with a Windows-driven relay setting environment provides increased input/output capability, digital fault recording and asset management functionality in powerful yet simplified solution. Such asset management functionality allows protection relays, for example, to provide transformer temperature and overload monitoring. This article discusses the use of a “smart” relay that provides both fault and overload protection of a power transformer.

Transformers are one of the more costly pieces of equipment found in a utility's inventory (see cover photo). De-regulation and on-going business dynamics continuously pressure utilities to do more with less. This creates a growing need for tools to assist in not only transformer protection but the intelligent monitoring of their activities, status and history - smart relays fit the bill. Sometimes overcurrent relays are set to provide fault protection and also provide some level of overload protection. In many cases, the overload aspect of transformer operation is handled by Control Center load dispatchers as this function is too complex for most simple overcurrent relays to effectively handle.

2.0 Basis for Overload Detection

The smart transformer relay framework for overload management is already defined by the IEEE C57.91-1995 transformer load standard. This transformer standard presents the terms that define the transformer “hot-spot” calculation. With information from the top-oil, ambient temperature, current and voltage transducers inputs, the smart transformer relay is able to provide a unique asset management functionality. This functionality includes overload tracking with the temperature (adaptive overload), automated load shedding based on temperature and/or current levels and predictive overload early warning. Combined with loss of life estimation, the smart transformer relay provides protection, monitoring and control for the transformer in one integrated box.

The cornerstone of the smart transformer relay is the ability to model the transformer behavior by an acceptable method. The 'hot spot' temperature - indicated by the 'winding temperature' gauge - is a value that warns of insulation deterioration at some point in a transformer. It is recognized as the single best indicator that a transformer is in an overload state. The calculation method is the subject of a recent IEEE Standard (Guide): C57.91-1995 [1].

$$\frac{dL}{dt} = e^{(39.164 - 15000/(T_{hs} + 273))} \qquad (1)$$

where L is the accumulated loss of life of the cellulose insulation, in per unit and T_{hs} is the hot-spot rise temperature. If T_{hs} = 110°C then dL/dt is 1.00. As a rule of thumb, the rate doubles for every 7^{o}C rise in T_{hs}.

The IEEE standard [1] indicates 180,000 hours or 20.6 years is the normal life (meaning normal solid insulation life) based on a continuous operation at the design hot-spot temperature of 110°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). The above nonlinear formula relates the rate of loss of life to other values of hot spot temperature as in Table 1.

Note that operation at the 'oil bubbles' condition is thought to be acceptable for a short time, because the bubbles will re-dissolve when the oil cools. Taking this basic model and implementing it in a smart transformer relay creates a wide range of unique protection, monitoring and control devices in one integrated platform (Figure 1).

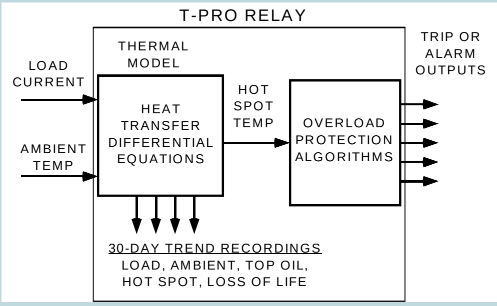

Figure 1: Smart Transformer Relay Model

Table 1: Rate of loss of life to other values of hot spot temperature

Hot Spot Temp. (^{o}C)	Rate of Loss of Life relative to normal
110 (design value)	1
117	2
124	4
131	8
139 (oil bubbles?)	16
147	32

3.0 Adaptive Overload

With the IEEE standard, smart transformer relays are able to detect overload conditions based on calculated hot spot temperature and react in an intelligent manner. By their nature, utilities tend to be conservative so transformer loading is often setup to utilize the transformer at a moderate loading level (e.g. 70% to 120% of nameplate load set as overload limit). There are, however, large savings to be realized by increasing transformer load in a controlled low risk manner thus improving utilization of these transformer assets.

If you have a known overload threshold at ambient temperature, then you can adjust the overload setting based on three approaches: summer/winter setting, ambient temperature and loss of life.

3.1 Approach 1: Summer/Winter Settings

Referring to Figure 2, 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.

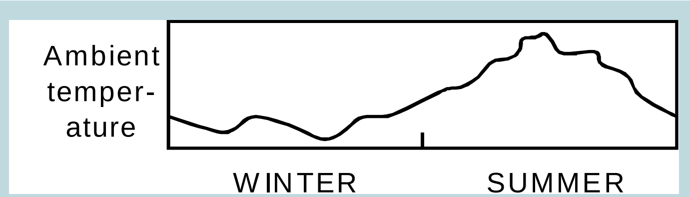

Figure 2: Summer/Winter Settings

3.2 Approach 2: Ambient Temperature

The 'coarse' summer/winter approach above can be made automatic by using a relay and an ambient temperature probe (Figure 3) to sense ambient temperature information. The adaptive pickup levels are defined by the curves of Figure 4. For example, if

- Ambient temperature is 30^{o}C, and
- Rate of loss of life is to be limited to 'normal' or 1 times, i.e. a hot spot temperature of 110^{o}C,

then the pickup is automatically set to 1.0 per unit current. 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.

Figure 3: Ambient Temperature Probe

3.3 Approach 3: Loss of Life

In this approach, the overloading condition is sensed as overtemperature rather than as overcurrent (Figure 5). This idea is closely related to the 'emergency overloading' guidelines of the Standard [1]. In other words, the principle is that a transformer can be loaded beyond its rating if one pays close attention to the effect of hot spot temperature on the loss of life. Inverse-time over-current can still be used beyond 2 per unit current, for fault protection.

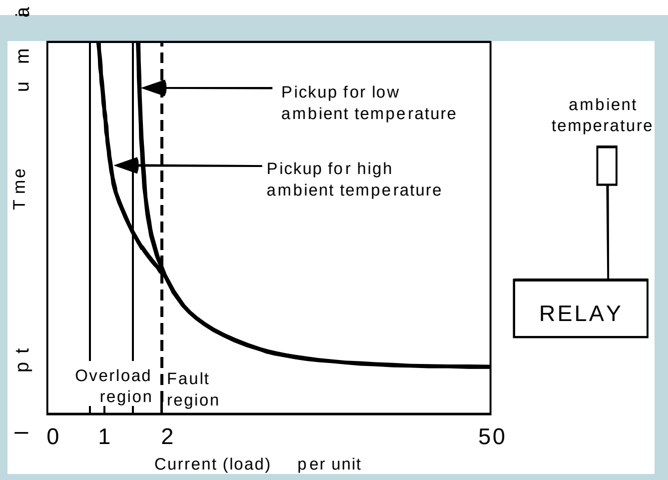

Figure 4: Adaptive pickup level for an inverse-time overcurrent relay

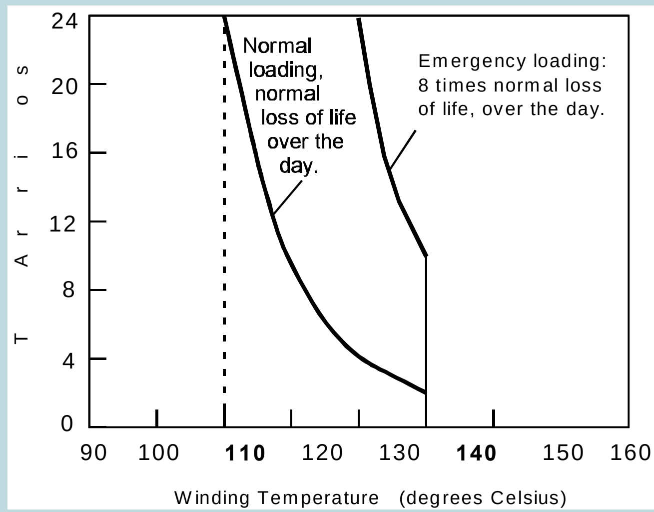

Figure 5: The inverse-time overtemperature relay characteristic

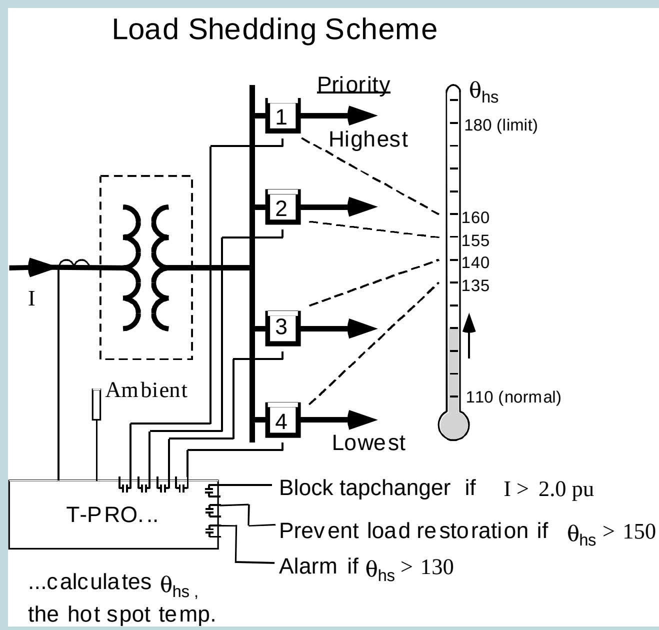

Figure 6: Transformer Relay - Load Shedding Model

4.0 Priority-Based Automatic Load Shedding

Yet another application of the IEEE transformer loading standard with a "smart" relay is the ability to monitor both the transformer's current and/or temperature and set multiple prioritized overload levels for alarm or trip. This gives the utility the ability to provide preferential service to customers and avoid unnecessary full-load transformer trips. In addition, the tapchanger can be blocked if current is above a user-defined setting and prevent load restoration if hot-spot temperature is greater than a user-defined level (Figure 6).

4.1 Transformer Load Management - BC Hydro Example

BC Hydro's Northfield Substation Project (located on Vancouver Island) has two identical 30/40/50//56 MVA, 138/25 kV Canadian General Electric transformers. In conjunction with these transformers they are using two T-PRO relays from APT Power Technologies with ambient and top-oil temperature probes. One T-PRO is used for transformer protection and hot spot temperature monitoring and the other T-PRO is used for transformer hot spot temperature monitoring only. The purpose is to detect a transformer overload condition that might occur under rare contingencies, then initiate an alarm and staged load shedding of feeders.

In the first T-PRO application, the relay is used for differential protection and load shedding with top-oil and ambient temperature inputs. The purpose is to detect when the transformer overload condition occurs and then initiate an alarm back to the Control Center and to subsequently shed feeders sequentially if the overload condition persists. Additionally, T-PRO's overload level detectors blocks tap changer control. Load restoration is blocked until load drops to a certain level then is restored manually by the operators.

The second T-PRO application duplicates the overload protection function of the first.

5.0 Predictive Overload System

Moving one step ahead of standard relay trip and alarm actions is the ability to predict when overload will occur and provide a 30 and 15 minute warning back to the Control Center where preventive load adjustment may be possible.

There are two approaches to monitoring the transformer overload using:

- Excessive hot spot temperature
- Excessive loss of life

The first approach, hot spot temperature early warning, has the hot spot temperature being calculated into the future every time step (e.g. five seconds) under the assumption that the load current and ambient temperatures do not change (Figure 7). If this calculation indicates that the hot spot temperature exceeds its TRIP setting (user-defined), then a 30 and/or 15 minute warning alarm is activated. Further implementation has a time-to-trip option over a SCADA communication channel (e.g. Modbus or DNP 3).

The second predictive overload monitoring approach uses an excessive loss of life warning. This overcomes a difficulty with simple over-temperature as an indication of overload. As an example, suppose the hot-spot temperature trip setting is 140°C. If the temperature hovers at values just below that level, then there will eventually be unacceptable damage to the cellulose insulation, but no trip will occur (Figure 8). Also, if the temperature briefly exceeds the setting but then falls back to normal levels, a trip should not occur, but will (Figure 9).

These reliability and security issues can be overcome by using the "loss of life" concept. By providing a predictive warning (e.g. 30 and 15 minutes warning) back to a utilities control center for load dispatch where corrective action can be taken.

5.1 Predictive Overload - Manitoba Hydro Whiteshell Example

Manitoba Hydro's application of predictive overload involves a Westinghouse step-up 115kV to 230kV transformer with a series phase shifting unit. A previous disturbance in the Whiteshell area of Manitoba resulted in the overcurrent relay pick-up and trip of the main transformer. If the overcurrent relay had a higher trip setting and more time before tripping, then Manitoba Hydro load dispatchers may have been able to change the load and prevent the overcurrent trip.

Using a T-PRO relay, Manitoba Hydro is able to send an alarm through their Modbus SCADA system indicating the time left before tripping. This provides the operators with an early warning indictor that allows them to respond to overload condition 30 and 15 minutes in advance. The overcurrent relay can still be set to trip in fault overcurrent conditions, typically about 200% of nameplate capacity, while allowing the T-PRO's TOEWS© (transformer overload early warning system) application to provide protection against overloads. The predictive overload system gives the operators an opportunity to adjust the system prior to damaging transformer overload conditions.

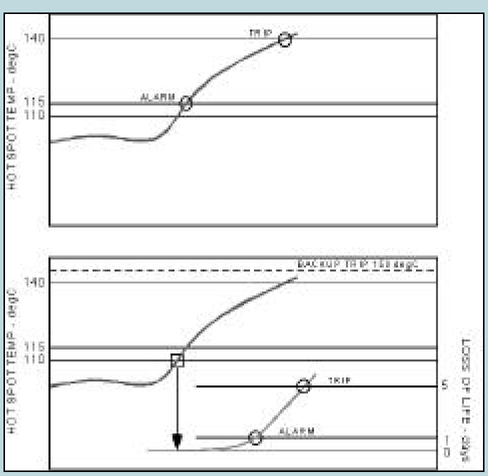

Figure 7: Simple Overload

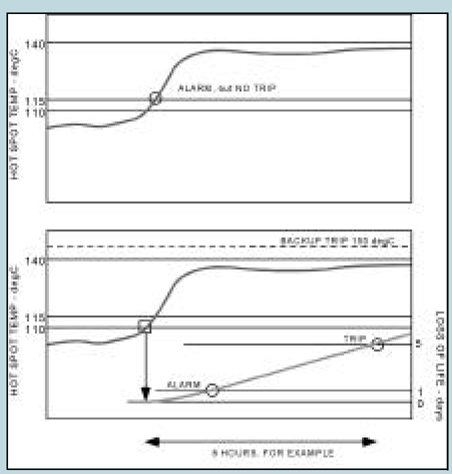

Figure 8: Sustained Moderate Overload

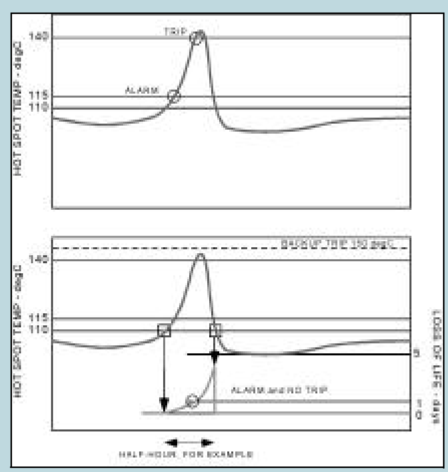

Figure 9: Short-Time Severe Overload

6.0 Conclusion

The ability to protect, monitor and control utility transformer assets in one integrated platform is now possible with improved processing power and simplified Windows-driven interfaces. IEEE transformer loading standards provide the framework by which smart relays can include adaptive overload based on temperature, automated load shedding and predictive overload early warning. Transformer overload issues are becoming more critical as market demands change and utility systems are pushed harder. In the end, utilities are able to provide a secure reliable protection system that also incorporates overload monitoring and control. This ensures minimal impact on the end-user and manages transformer-loading risk on the transformer with the potential for introducing economic benefits by improving transformers utilization.

7.0 Acknowledgments

Special acknowledgment to Manitoba Hydro and BC Hydro for their contribution to the examples. Also, acknowledgment to Dr. Glenn Swift for his insightful comments during the preparation of this article.

8.0 References

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

[2]. Swift, G and Zhang, Z, "A Different Approach to Transformer Thermal Modeling," 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.

About APT Power Technologies: APT Power Technologies (APT) has been supplying advanced technology products to power utilities for 15 years. Its products are used in the power industry for protection, monitoring and control solutions. For further information, visit the website at:

www.aptpower.com

About the Authors

Dave Fedirchuk received his B.Sc. degree in electrical engineering from the University of Manitoba in 1972.

Since graduating, Dave has spent 22 years with Manitoba Hydro in the System Performance group performing relay settings and disturbance analysis. For the last 5 years Dave has been working with APT Power Technologies as a Product Manager.

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Power Team Manitoba

Imagine that you work for a local engineering firm, and you need a left-handed monkey wrench for completion of a rush project. Where would you look for this uncommon, esoteric tool: the yellow pages? The Web? Canadian Tire? Well, in Winnipeg it would make sense to run through your mental list of other engineering organizations that might have this tool. The chances are you could arrange to borrow such a device by making a few phone calls.

There's just something about the Winnipeg milieu that seems to foster cooperation - a lot to do with both population size and the diversity of activities here. Winnipeg has a population of about 600,000 which is just about optimum in the sense that there are perhaps a hundred or so working electrical power engineers, and the city is small enough that regular **IEEE Power Engineering Society** luncheon meetings are well-attended.

What about 'diversity'? Of course a larger centre, like Chicago, has lots of diversity. But Winnipeg is just large enough that there is sufficient diversity. In the electric power area we have a major utility bigger than most American utilities: **Manitoba Hydro**. And a second utility: **Winnipeg Hydro.** And 'heavy equipment' transformer manufacturers: **Pauwels Canada Inc**. and **Carte International Inc.** And a 'light equipment' protection relay and disturbance recorder manufacturer: **APT Power Technologies**. You could call **RTDS Technologies Inc.** a 'medium-weight equipment' manufacturer of digital power system simulators. And an international consulting firm: **Teshmont Consultants Ltd**. And a major research operation: **Manitoba HVDC Research Centre** ('The Centre'). And a generator of engineering graduates and research: the **University of Manitoba** (a 'transformer' of technologically-inclined high-school students into engineers, and into advanced-degree holders).

In an attempt to encourage the Power Team Manitoba idea, a "link" Web site has been started. It's still embryonic (prototypical?), but take a look:

www.aptpower.com/ptm/

IEEE News Flash

Vijay Bhargava Elected Fellow Of The Royal Society Of Canada

Vijay Bhargava has been elected a Fellow of the Royal Society of Canada / La Societe royale du Canada for his substantial theoretical contributions to the field of third generation wireless communications systems. Vijay is a Professor at the University of Victoria and is a Past Director of IEEE Region 7 (Canada).