POSSIBLE USES OF ONLINE CONDITION MONITORING FOR REAL-TIME RATING OF SUBSTATION EQUIPMENT

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Abstract

With the demand for electricity increasing worldwide, electricity utilities are finding themselves in situations where existing equipment may be more fully utilised in order to meet demand, as an alternative to or in conjunction with major augmentations to the electricity network. While this is not at the stage of universal necessity, there are areas in which an improved method of rating existing switchyard equipment may allow utilities to better meet the expectations of those connected to the network. At this time, little work has been done worldwide on the use of dynamically determined ratings on substation equipment. This paper reviews some pre-proposed methods for rating substation equipment, considers practical limitations of the implementation of such methods and considers how real-time, continuous online monitoring of the equipment may assist in the provision of dynamic rating capabilities.

1. INTRODUCTION

Traditionally in the electricity industry, high voltage substation equipment has been operated below a rated load current. This rating is a value provided by equipment manufacturers based on a particular set of conditions (commonly an ambient temperature of 40°C and altitude below 1000m).

However, this can result in two situations for electricity utilities. Often ambient conditions are not as severe as the "worst case". In these situations equipment can handle higher load currents while remaining within its design parameters.

The converse situation is also sometimes the case, in which ambient conditions exceed the nominal "worst case" criteria. In such situations, high voltage equipment should be de-rated. This is particularly the case in summer months in Australia when ambient temperatures are high. However, it can also be due to other factors.

Dynamic loading seeks to exploit the above situations while managing the potential risks to ensure that network stability and safety are retained. It should be noted that dynamic loading is not an overload of equipment, rather, it is the ability to operate equipment acceptably within its design parameters, while responding to the imposed environmental (external) conditions at the time [1].

Dynamic loading techniques are of most use in situations where normal loads have grown to the extent that they approach the rated load of one or more pieces of high voltage equipment in a substation.

2. BACKGROUND

To date, little research has been done into the practical application of dynamic loading to substation equipment.

Some research has been done into the dynamic loading of transmission lines and cables, both internationally and within Australia, and there are a number instances of commercial quality installations that have been used successfully by utilities to dynamically rate their transmission lines [2]. However, there is very little literature on dynamic loading of substation equipment,

and few instances worldwide where dynamic loading of substation equipment is utilised.

A Conseil International des Grande Réseaux Électrique (CIGRE) task force has been set up to review the current status of dynamic loading of transmission equipment in the electricity industry and establish future requirements. The task force is in the early stages of its research, and has published some initial observations and findings [1].

Also, some work has been done by the Mid Atlantic Area Council (MAAC), a member council of the North American Electric Reliability Council (NERC), in developing mathematical models and equations that can be used to perform dynamic loading calculations for substation equipment [3].

3. DYNAMIC LOADING PRINCIPLES

Dynamic loading is considered to be any condition where the nameplate rating of equipment is exceeded while managing the consequent risks. It can be considered in a number of timescales [1].

In short term scenarios, for periods of up to approximately twenty minutes, safe ratings are likely to be pre-determined and based upon predictive models taking in to account ambient temperature and pre-fault loading. Real-time data is of little benefit in short term loading.

In medium term scenarios, of several hours, real-time models may be used to determine ratings based on actual values of quantities such as temperature and loading. In these situations, real-time online monitoring is of value because it provides data that can be used in conjunction with equipment models to determine loading limits applicable at the time. If real-time data is not available, ratings can be determined using assumed ambient temperatures and loads.

In long term situations, such as extended increased requirements after failure of another piece of equipment or changing environmental conditions, the goal is to establish an acceptable level of continuous power transfer for time periods greater than the equipment thermal time constants.

Dynamic loading is most appropriately considered at the level of a group of substation equipment associated with a transmission circuit. Because there are several individual items of plant involved, consideration must be given to all items of equipment associated with the circuit being considered. These include, as a minimum, switchgear (circuit breakers and disconnectors), current transformers (both primary and secondary circuits), protection systems, electrical conductors, power transformers, power cables and any other series connected equipment.

In some instances one item of equipment will determine the limiting rating for the circuit; in others, equipment capability will be closely matched and a number of limitations may become significant [1].

4. DYNAMIC LOADING THEORY

The work published by the CIGRE task force has considered, for each component of a transmission circuit in turn, rating principles, risk considerations and real-time ratings [1].

4.1 Power Transformers

According to the standard IEC354, it is possible to calculate the relative ageing of a transformer from temperature and load information over time.

When transformers are designed, manufacturers provide an estimate of the life of the transformer based on constant operation at a particular temperature (usually 98°C) [4]. According to the standard, operation at higher temperatures will decrease the expected life of the transformer and at lower temperatures will increase the expected life of the transformer (halve or double the expected life for every 6°C difference).

The standard also provides a means of calculating the relative "used life" of the transformer, which can be calculated based on actual temperatures where online monitoring is provided. It is also possible to calculate the length of time an operator can safely run the transformer into overload for, based on the thermal characteristics of the transformer as measured at time of manufacture.

A major source of information on the loading behaviour is Australian Standard 2374.7, *Loading guide for oil-immersed power transformers* [4], which is very similar to the popular IEC Standard 354. The standard identifies a number of stressors which impact on the life assessment of a transformer, and therefore must be taken into account when considering overload of a transformer:

- the occurrence of unusual events such as overvoltages, surges and through faults;

- the transformer design (which cannot be readily modified);
- the temperatures of the various parts of the transformer;
- the concentration of moisture in the insulation and in the oil;
- the concentration of oxygen and other gases in the insulation and in the oil; and
- the number, size and type of impurity particles [4].

The standard also proposes a set of equations for calculating the steady-state temperature under different conditions, transient temperature and loss of life of equipment under given input conditions. These can be summarised as follows.

4.1.1 Short term overload

The short or medium term overload capability of a transformer can be calculated using the following equation. This assumes a change in load of a step function [4].

$$\Delta\theta_t = \Delta\theta_i + (\Delta\theta_u - \Delta\theta_i)(1 - e^{-t/\tau_0}) \qquad (1)$$

where:
$\Delta\theta_t$ – Oil temperature rise above ambient after time t
$\Delta\theta_i$ – Initial oil temperature rise above ambient
$\Delta\theta_u$ – Ultimate (steady state) oil temperature rise above ambient for load applied during the overload time t
t – Overload time interval
τ_0 – Oil time constant (hours)

Parameters such as the oil time constant can be obtained from manufacturing heat run tests. Other parameters can be either assumed depending on seasonal conditions, or measured in real time.

Note that equation (1) can be solved for either the temperature rise after a set time period ($\Delta\theta_t$), or the time period that will produce a set temperature rise (t), if the other is known. Also, oil temperatures will vary with location (particularly height) within the transformer tank, therefore given and calculated values will differ depending on whether the analysis is based on top oil, bottom oil or average oil temperature.

4.1.2 Long term overload

The model for the long term overload capability is dependent on the cooling method of the oil.

For oil natural cooling, the relevant equation is [4]:

$$\theta_h = \theta_a + \Delta\theta_{or}\left[\frac{1 + RK^2}{1 + R}\right]^x + Hg_r K^y \qquad (2)$$

For oil forced cooling, the equation is [4]:

$$\theta_h = \theta_a + \Delta\theta_{br}\left[\frac{1 + RK^2}{1 + R}\right]^x + 2[\Delta\theta_{imr} - \Delta\theta_{br}] + K^y + Hg_r K^y \qquad (3)$$

where:
θ_h – Hot spot calculated temperature
θ_a – Ambient temperature
$\Delta\theta_{br}$ – Bottom oil temperature rise above ambient
$\Delta\theta_{imr}$ – Average oil temperature rise above ambient
$\Delta\theta_{or}$ – Top oil temperature rise above ambient
R – Ratio of load losses to no-load losses at rated current
K – Load applied during steady state overload
Hg_r – Hot spot to top oil gradient
x – Oil temperature exponent
y – Winding temperature exponent

For oil directed cooling, the equation is [4]:

$$\theta'_h = \theta_h + 0.15(\theta_h - \theta_{hr}) \text{ (for } K > 1) \qquad (4)$$

where:
θ_h' – Hot spot calculated temperature
θ_h – Hot spot calculated temperature from equation (3)
θ_{hr} – Hot spot temperature at rated conditions

Most of these parameters can be obtained from typical values given in Australian Standard 2374.7, or given by equipment manufacturers.

Overload calculations have traditionally been done as a table of figures calculated from ambient conditions and loadings. However, the use of real-time online monitoring can enable overload capability to be calculated based on real-time temperature and loading information. This can provide a truer indication of the transformer's capabilities than is otherwise possible, and can be used to assist operators in their decision making in real-time.

4.2 Switchgear

Transmission substation switchgear (circuit breakers and disconnectors) is typically designed for applications

where the load current does not exceed the rated normal current under specific conditions. These are:

- that the ambient temperature does not exceed 40°C and the average temperature, measured over a period of 24 hours, does not exceed 35°C; and
- that the altitude above sea level at which the switchgear is located is 1000m or less [1].

The rated normal current is based on the maximum permissible total temperature limit of the component parts of the switchgear, determined under the above conditions. The actual temperature of these parts in service depends on both the actual load current and the actual conditions.

It is possible to operate at a higher current than the rated normal current, provided that acceptable temperature limits of component parts of the equipment are not exceeded. This is possible under several situations:

- when actual conditions are more favourable than those outlined in relevant standards;
- when equipment has been designed with increased capability beyond the standard; or
- when the duration of overload is less than the thermal time constant of the equipment.

Similarly, the load current must be reduced to less than the rated normal current when actual conditions are not as favourable as those in the standard, to retain the temperatures of components within relevant limits.

4.2.1 Short term overload

When switchgear has been operating at a current level below its allowable continuous load current I_a, it is possible to increase the load current for a short time to a value greater than the allowable current without exceeding the permissible temperature limitations. There are different factors which influence the length of time period t_s of the overcurrent I_s. These are:

- the magnitude of the current I_s;
- the magnitude of the initial current I_i carried prior to the application of I_s;
- the thermal time constant of each component of the switchgear; and
- the ambient temperature prior to and during application of overcurrent I_s [1].

MAAC [3] propose rating methods for transient circuit breaker loading primarily based on:

- ambient temperature;
- temperature rise as a function of the 1.8 power of current (circuit breakers) or 2.0 (disconnectors);
- maximum temperature determined to be acceptable for various switchgear components under normal and emergency conditions; and
- acceptable accelerated deterioration of some switchgear parts under emergency conditions.

The equation MAAC proposes to model the switchgear transient response is [3]:

$$I_{eat} = I\left(\frac{\theta_{\max et} - \theta_a}{\theta_r}\right)^{\frac{1}{n}} \qquad (5)$$

where:
I_{eat} – Emergency rating for time t duration
I – Adjusted rated continuous current under specific conditions, given by equation (7)
$\theta_{\max et}$ – Allowable emergency maximum temperature for time t duration
θ_a – Ambient temperature
θ_r – Limit of observable temperature rise at rated continuous current
n – Taken as 1.8 (circuit breakers) or 2 (disconnectors)

Equation (5) can be solved for either the temperature rise ($\theta_{\max et}$) produced by a given short time emergency current (I_{eat}) after a set time period (t), or the emergency current that will produce a given temperature rise after a set time period, if the other is known.

4.2.2 Long term overload

The main limiting factors of long term overload capability of switchgear are the ambient temperature and design capability of the equipment beyond the requirements of the relevant standards. A long time emergency loading with temperature rise exceeding the design limits is not recommended, since equipment safety cannot be ensured. In general, insulating materials in contact with current carrying components set the limits for the maximum allowable temperature rise [1].

The equation proposed by MAAC for the long term (steady state) overload capability of switchgear is similar to that for short term emergency capability [3]:

$$I_a = I\left(\frac{\theta_{\max} - \theta_a}{\theta_r}\right)^{\frac{1}{n}} \qquad (6)$$

where:
I_d – Long term current rating
I – Adjusted rated continuous current under specific conditions, given by equation (7)
θ_{max} – Allowable max. temperature ($\theta_{max}=\theta_r+40^\circ C$)
θ_a – Ambient temperature
θ_r – Limit of observable temperature rise at rated continuous current
n – Taken as 1.8 (circuit breakers) or 2 (disconnectors)

In equations (5) and (6), the adjusted rated continuous current is given by:

$$I = I_r \left(\frac{\theta_r}{\theta} \right)^{\frac{1}{n}} \qquad (7)$$

where:
I – Adjusted rated continuous current under specific conditions
I_r – Nameplate rated continuous current
θ_r – Limit of observable temperature rise at rated continuous current
θ – Test observable temperature rise at rated continuous current
n – Taken as 1.8 (circuit breakers) or 2 (disconnectors)

Equations (5), (6) and (7) represent the models of switchgear adopted by MAAC [3].

Switchgear in substations has traditionally been operated to its nameplate rating, without emergency rating or de-rating factors applied. The use of real-time online monitoring can provide temperature and current information which are inputs to the above equations, and can be used to apply dynamic loading factors during network operation.

4.3 Other equipment

The allowable temperature rise of other equipment (such as line traps, current transformers and conductors) is dependent on one or more of the following factors:

- the allowable maximum temperature of components (as defined in IEC 60694 table 3), primarily limited by the characteristics of insulating materials in contact with current carrying conductors or the chemical stability of bolted current-carrying joints; and
- the maximum acceptable sag of flexible conductors [1].

In many cases, thermal performance is not the limiting factor in design and equipment may have a greater capability than is implied by the design loading. The extent of this margin can generally only be determined by evaluation of type test evidence, reassessment of design calculations or performance of heat run tests for equipment that is in service [1].

As with switchgear, where equipment is operating at a lower ambient temperature than specified there is an inherent margin that can be utilised for dynamic loading without risk of temperature exceedance. Conversely, where the ambient temperature exceeds that specified, loading capability may be less than design rating. Dynamic loading, where applied, is based on assumed seasonal environmental conditions and the duration of that additional load.

The maximum loading of protection relays is restricted by the thermal limit of input circuits. Current transformer secondary windings and cabling may also impose a thermal limit (particularly where the loading capability of other circuit components has been significantly increased). The loading capability may not be increased at low ambient temperatures since protection relays may be accommodated in temperature-controlled environments [1]. Saturation of metering cores is also a potential limiting factor, as this may result in loss of control of the overload situation.

Whilst substation infrastructure is generally not considered a critical factor in determining dynamic loading capability, it may still give significant risks.

4.3.1 Short term overload

MAAC [3] propose rating methods for short term (transient) loading based primarily on:

- ambient temperature;
- temperature rise as function of the 2.0 power of the current;
- maximum temperature determined to be acceptable for various equipment components under normal and emergency conditions; and
- acceptable loss of life and short circuit withstand capability conditions.

The equations for the models for this equipment are identical to that for switchgear.

Similarly to switchgear, other substation equipment has traditionally been operated to its nameplate rating, without emergency rating or de-rating factors applied.

The use of real-time online monitoring can provide temperature and current information which, as inputs to the above equations, can be used to apply emergency rating or de-rating factors during network operation.

5. DYNAMIC LOADING IN PRACTICE

In practice many of the factors to be applied in the models and equations can be difficult to measure accurately. In some cases, often for more recently manufactured equipment, some information can be made available by manufacturers. However, especially for older equipment, such information is rarely available and must be obtained by methods such as performing heat run tests in the field. In some cases, such tests are not practical for equipment that is in service.

The following sections briefly describe methods that can be used to measure, or approximately measure, factors that are required to enable real-time dynamic loading calculations to be made.

5.1 Power Transformers

Power transformers can be comprehensively monitored, and systems currently exist to perform dynamic loading calculations. Sensors are available to measure factors which are used in the loading calculations, such as top and bottom oil temperatures, as well as factors having an influence on a transformer's capability to handle overload, such as dissolved gas and moisture levels [5,6]. Thus it is currently feasible for transformers to be dynamically loaded in network operation.

5.2 Other equipment

The main factors to be measured for other equipment are ambient and equipment component temperatures. There are three common methods for measuring equipment temperatures, each with advantages and disadvantages:

- the use of optical fibres, which has a high degree of accuracy but presents challenges achieving effective insulation along the fibre between ground and a high voltage conductor;
- thermocouples attached to components such as terminal palms, which transmit measurements via a radio link, but are not particularly common (and present challenges in providing a supply voltage); and
- thermal imaging techniques for external components, which is a readily available technique but not ideal for long term or permanent installation.

Challenges exist where temperatures of internal components are to be measured, and where an item of equipment has components with different time constants. These challenges are particularly the case for circuit breakers and current transformers. However, in such cases, conservative approximations can be made and models simplified to suit.

6. CONCLUSION

The primary aim of this work is to develop a feasible method for common application of dynamic loading in network operation. This outcome will enable greater utilisation of existing network assets and thereby assist in the operation of an electricity network.

In doing so, a secondary aim is to bring dynamic rating measurements together as a system so that all potential limitations in a substation are considered during an overload event, taking into account all necessary aspects of equipment condition.

7. REFERENCES

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