

Optimal Utilization of Power Transformers Through Virtual Sensing

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Abstract—Power transformers are the most critical and expensive assets for utility companies and are expected to last for at-least 30-40 years. Unfortunately, many of them have failed before reaching their rated life. In order to prevent such premature failures, utility companies usually deploy real time asset management system by installing thermal sensors (e.g. fiber-optical sensor) inside the tank of large transformers (~500MVA). However, being expensive, sensor deployment may not be commercially viable for small and medium size (<=250MVA) transformers. This paper proposes an asset management scheme of such power transformers through virtual (sensor-less) sensing. It simulates transformer internal heating phenomena (like hot-spot temperature, insulation aging, loss of life, etc.) using easily available SCADA measurements, ambient temperature from on-line weather forecast, and transformer assets data. It predicts future load and incentive and optimizes transformer operation by analyzing the economic incentive for carrying power and payoff for the loss of life calculated from virtual sensing. Proposed scheme is evaluated and implemented in Fortum's transformers in Finland and experimental results are presented.

Index Terms-- Power Transformer, Condition Analysis, Real-time, Economic Analysis

I. INTRODUCTION

Transformer failure statistics exhibit that most of the failures have occurred before reaching their rated life due to lack of proper maintenance or unplanned usage [1,2]. In order to prevent such premature failures, utility companies have started to focus on optimal asset management through real time monitoring of internal phenomena like winding hot-spot temperature rise, temperature of cooling fluid, ambient temperature, etc. Accurate knowledge of these parameters is further used to calculate insulation aging, assessment of the risk of bubble evolution, short term forecasting of the overload capability, efficient control of the cooling banks, etc.

In past, many methods have been proposed for condition monitoring of power transformers. Wang et al. [3] provides an excellent review of these methods for condition

assessment of transformers in practice. For example, Bhandari et al [4] proposed a knowledge base method for an effective life cycle assessment of the power transformer which aims at maximizing its utilization during its life cycle. Stirl et al. [5] proposed an on-line overload monitoring system for power transformers. Bajracharya et al. [6] proposed a model-based predictive optimization framework for the optimizing the loading of a transformer by recommending load changes when required and by keeping the temperature within the safe limits.

Above mentioned methods are mainly focused on monitoring the health, life-cycle, and overloading of the transformers in real time. Unfortunately, these methods fail to capture the economic advantage of overloading a transformer with real time pricing. Since in the real-time market, the price for carrying electricity fluctuates a lot, it might be profitable to overload the transformer for certain period over the day which can compensate the loss of life of the transformer. Recently, there is a growing trend to deploy fiber optic sensors (e.g. [7]) for analyzing the economics of overloading, unfortunately, most of these methods are not commercially viable for small and medium size transformers due to higher investment cost. Hence, there is a growing demand for low cost asset management system for small and medium size transformers.

In this paper, we proposed a low cost optimal asset management system through virtual sensing. Transformer internal heating phenomena like hot-spot temperature, insulation aging, loss of life, etc. are calculated based on easily available SCADA measurements, ambient temperature forecast, and transformer assets data following the IEEE loading guide [8-11]. Transformer operation is then optimized by analyzing the economic incentive for carrying power and payoff for the loss of life of the transformer. Since in the real-time market, the price for carrying electricity fluctuates a lot, it might be profitable to overload the transformer for certain period over the day which can compensate the loss of life of the transformer.

Proposed scheme is implemented as a pilot project in Finland and initial case studies are made on 5 selected transformers. This pilot validated the technical and economical feasibility of transformer operation/maintenance through virtual sensing.

II. HOTSPOT TEMPERAURE ESTIMATION

Accurate knowledge of the winding hotspot temperature is a critical input for calculation of the insulation aging, assessment of the risk of bubble evolution and short term forecasting of the overload capability. Hotspot temperature depends on top oil, bottom oil, duct oil and wind temperatures as shown in Figure1. These temperatures depend on fluid flow condition within the transformers as shown in Figure2.

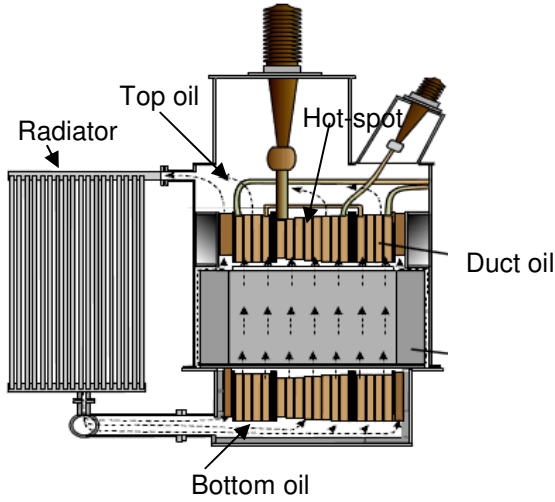


Figure1: Schematic diagram of a power transformer

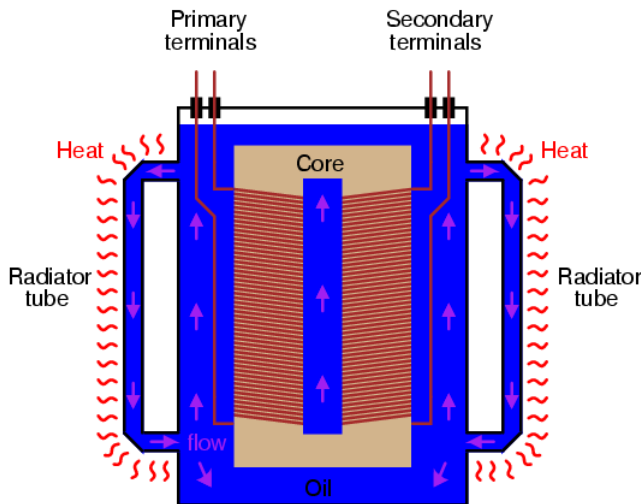


Figure2: Fluid flow pattern within a power transformer

There are several methods of estimating hotspot temperature of transformers. In this paper, three different methods are illustrated and compared as follows:

A. Method I

In this method, winding hot-spot temperature is calculated from the top oil temperature measurement and transformer parameters provided by the manufacturer as follows:

$$\theta_H = \theta_{TO} + \Delta\theta_{HR} * K^{2m} \quad (1)$$

Where, θ_H is hotspot temperature, $\Delta\theta_{HR}$ is rated hotspot temperature gradient, K is per unit current and m is a constant.

This method is simple and requires only top-oil temperature measurement and current on winding measured through SCADA system. However, it requires additional hardware and fails to provide accurate results in case of rapid load change as time constant of oil in the cooling duct is much shorter than the top oil time constant.

B. Method II

This approach is purely computational and does not require any additional hardware. In this approach, some of the above mentioned limitations are overcome by including more detailed modeling of the transformer. In this method, hotspot temperature is calculated using the following equation:

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \quad (2)$$

Where, θ_A is ambient temperature, $\Delta\theta_{TO}$ is top-oil rise over ambient.

Top-oil temperature rise at a time after a step load change can be written as:

$$\Delta\theta_{TO} = (\Delta\theta_{TO,u} - \Delta\theta_{TO,i})(1 - \exp^{-\frac{t}{\tau_{TO}}}) + \Delta\theta_{TO,i} \quad (3)$$

where subscript i and u denote initial and final temperatures, respectively.

Transient winding hot spot rise over top-oil temperature is given by:

$$\Delta\theta_H = (\Delta\theta_{H,u} - \Delta\theta_{H,i})(1 - \exp^{-\frac{t}{\tau_w}}) + \Delta\theta_{H,i} \quad (4)$$

This method does not require any additional hardware and hence is cost effective. It provides reasonably accurate result during steady state operation. However, under sudden load variations, the oil circulation does not respond immediately and hence, provides underestimated result for sudden increase in load current.

C. Method III

This model is based on fluid flow conditions occurring in transformer during transient condition [9]. At each time step the losses are calculated and corrected for the resistance change with temperature. Corrections for fluid viscosity changes with temperature were also incorporated into the equations.

Winding hot spot temperature at any time t is calculated as follows:

$$\theta_{h,t} = (Q_{gen,hs} - Q_{lost,hs} + M_w C_{P_w} \theta_{h,t-1}) / M_w C_{P_w} \quad (5)$$

Where $Q_{gen,hs}$ is heat generated at the winding, $Q_{abs,hs}$ is heat absorbed in time Δt at the hot-spot, M_w and C_{P_w} are mass of windings and specific heat of windings, respectively. Heat generated and lost at hot-spot can be calculated as follows:

$$Q_{gen,hs} = K^2 [P_{hs} \cdot K_{hs} + P_{ehs} / K_{hs}] \Delta t \quad (6)$$

$$Q_{lost,hs} = [(\theta_{h,t-1} - \theta_{w,0}) / (\theta_{h,r} - \theta_{wo,r})] (P_{hs} + P_{ehs}) \Delta t \quad (7)$$

Where K is the ratio of actual current in the winding to rated current, P_{hs} is winding I^2R loss at hot spot temperature, K_{hs} is a temperature correction factor, P_{ehs} is winding eddy loss at hot-spot temperature, $\theta_{w,0}$, $\theta_{wo,r}$ are actual and rated temperature of oil in ducts at hot-spot, and $\theta_{h,r}$ is rated hot-spot temperature.

In this method, hotspot temperature is calculated in every minute based on current load on the transformer and calculated temperature in the previous iteration. For example, as shown in Figure3, hotspot temperature $T2$ is calculated based on current load $L2$ and previously computed temperature $T1$. This method is computationally complex and requires several transformer parameters. However, it provides reasonably accurate results both during steady state and transient state of operation. Moreover, this does not require additional hardware and hence cost effective.

III. ASSET LIFE ESTIMATION

When current flows through transformer windings, typically 1-5% of the transmitted power is lost as heat energy [12]. Part of this heat energy is dissipated into air through radiator and remaining heat increases the temperature of winding and cooling oil. Transformer internal temperatures (top oil, bottom oil, duct oil, and hotspot) depend on fluid flow conditions occurring in transformer during transient condition, ambient temperature variation, and transformer asset data. These internal temperatures are calculated from definition of energy conservation i.e. heat generated by windings in Δt time is summation of heat absorbed and heat lost by windings.

The equations were formulated so that temperatures obtained from the calculation at the prior time $t1$ are used to compute the temperatures at the next instant of time $t1 + \Delta t$ or $t2$ as shown in fig. 3. The time is incremented again and the last calculated temperatures are used to calculate the temperatures for the next time step. At each time step, losses are calculated and corrected for the resistance change with temperature. Corrections for fluid viscosity changes with temperature were also incorporated into the equations. Calculated hotspot temperature is then used to calculate the transformer insulation aging and loss of life.

Insulation aging acceleration factor is calculated from hot-spot temperature as follows:

$$F_{AA} = e^{\left[\frac{B}{\theta_{HR} + 273} - \frac{B}{\theta_H + 273} \right]} \quad (8)$$

Where θ_H is hot-spot temperature, θ_{HR} is rated hot-spot temperature and B is transformer life with rated hot-spot.

Insulation aging acceleration factor is used to calculate the equivalent aging factor of the transformer as follows:

$$F_{EQA} = \sum_{n=1}^N F_{AA}^n \Delta t_n / \sum_{n=1}^N \Delta t_n \quad (9)$$

where N is total number of time intervals, Δt_n is time interval in hours, and F_{AA}^n is aging acceleration factor for the temperature which exists during the time interval Δt_n .

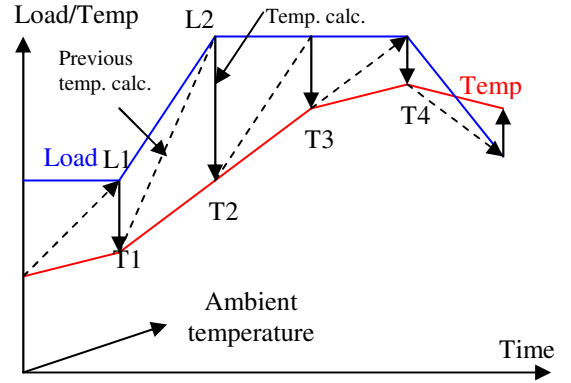


Figure3: Conceptual principle of the hot spot temperature calculator.

IV. SYSTEM ARCHITECTURE

Proposed asset management system architecture is presented in Figure4. The system usually resides in a data center and it receives data from a variety of sources and makes the right decision using the various optimization algorithms discussed in this paper and sends the control signals to the transformer and also displays real time feedback to the operator who monitors the situation. The system is discussed in brief as follows:

A. Input

The system requires input parameters from various sources to be able to take the right decision. It receives most of the data it requires from various web services. It receives ambient temperature at the asset location from web services like the National Weather Service [13] or Yahoo! Weather API [14]. It uses the dynamic pricing signal and the expected load at various points in time from utility web services. The utility can predict the expected load from historical data using data mining tools. These various web services are polled at periodic intervals when the decisions have to be made and are sent to the various analytic modules. The SCADA data is also made available to the analytics modules for calculation. The

profile of the transformer like the cost of the transformer, the expected age of the transformer are obtained from the utility database.

B. Hot Spot Temperature Calculator

The hot spot temperature calculator uses the current that is expected to flow through the transformer coil if the extra load is applied, the type of the transformer and the ambient temperature data to calculate the hot spot temperature using the algorithms discussed in Section II.

C. Age Impact Calculator

The age impact calculator uses the aging characteristics of the transformer and the output of the hotspot temperature calculator for the various expected loads on the transformer to estimate the impact it will have on the age of the transformer. The monetary impact on the transformer life is then calculated from the impact in the age of the transformer and the cost of the transformer.

D. Risk/Profit Optimizer

The Risk/Profit optimizer compares the loss due to the loss in age of the transformer to the profit from carrying the extra load in the transformer and arrives at the decision on whether to accept the overload or not. Mathematically this is represented as follows:

$$\text{Maximize } E \left[\sum_{t=1}^T x^t P^t - \text{Loss}^t(x^1, \dots, x^T) \right]$$

Where x^t is the optimal amount of power to carry in time slot t , P^t is the predicted price in time t , and $\text{Loss}^t(\cdot)$ is equivalent loss of life of the transformer for carrying power x .

E. Controller

The decision that was taken by the risk/profit optimizer is then effected in the by the controller which communicates the decision to the control systems which takes the appropriate actions to control the load on the transformer.

F. Monitor

As the system makes the decisions based on the various load conditions, it also makes the decisions available to the operators through the intranet site, which the operators can view through a web browser and take appropriate actions as necessary.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

To validate the technical and economical feasibility of the solution, proposed asset management system was installed on 5 Fortum transformers. Capacity of each of this transformer was 31.5 MVA. Three hot-spot temperature calculation methods were compared. In the first method winding hot spot temperature was calculated from the measurement of the top oil temperature by installing a low cost temperature sensor outside the transformer tank. In the second method hot-spot temperature was calculated from SCADA and limited asset

data whereas in method 3 hot-spot was calculated using SCADA and extensive asset data.

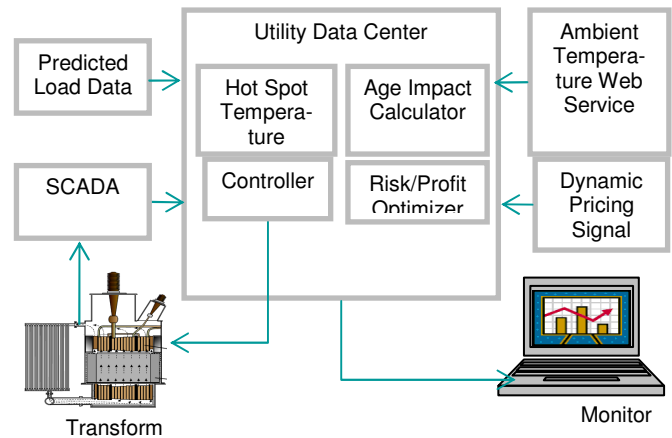


Figure4: Architecture of the asset management system through virtual sensing.

We did the experiment for three months and compared the effectiveness of the three methods. Sample experimental results for 3rd and 5th May, 11 are presented in Figures5-7 for verifying the effectiveness of the virtual sensing. From the experimental results, it is observed that in most cases, method 1 overestimates the hot-spot temperature compared to methods 2 and 3. This reflects the reality because in method 1, duct oil temperature is assumed same as the measured top oil temperature, however there will always be time lag between the top-oil temperature rise and the duct oil temperature rise. This phenomenon results in winding hotspot temperature greater than actual hot-spot temperature. It is also observed that method 2 underestimates hot-spot temperature compared to method 1 and method 3. This phenomenon is quite natural because it does not consider the winding cooling duct and/or conductor temperature variation with dynamic load change. Experimental results show that method 3 provides very close estimation of actual hot-spot temperature. Therefore, method 3 was adopted for the asset management system.

For a predicted load pattern, hot-spot temperature and hence the aging and loss of life (\$) of a transformer was calculated and compared with the financial incentives for carrying power as shown in Figure8. Figure8 shows that in hours 1-14 and 19-24, transformer will be willing to take more load as financial incentive is much higher than loss of life. Unfortunately, grid does not offer the transformer to carry more load. In between 14-19 hours, reverse situation has happened where grid offered to take more load but transformer may not be willing to carry the requested amount as above certain overload, loss of life will be much higher than incentive. Thus this guidance could be very useful for the transformer operator to take judicious decision on allowing overload for better management of power transformers.

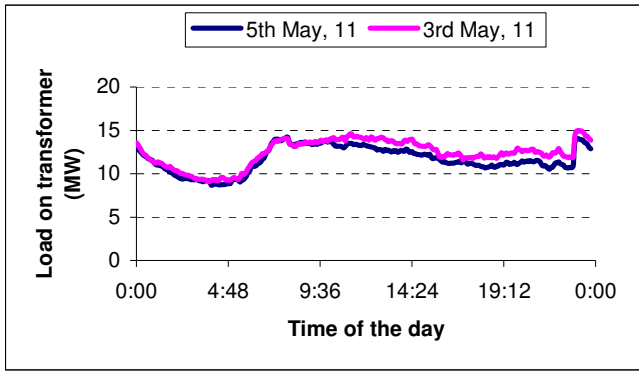


Figure5: Transformer load pattern for 3rd and 5th May, 2011.

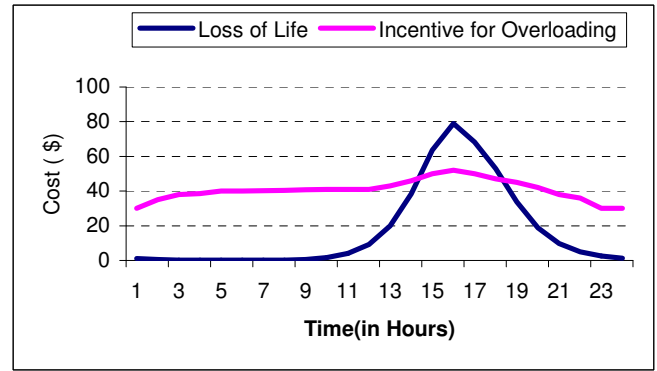


Figure8: Optimal loading decision of Tr. in real time market.

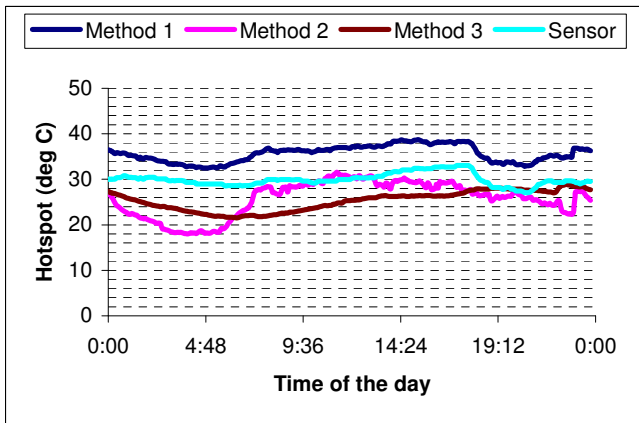


Figure6: Experimental verification of hotspot temperature calculations conducted on 3rd May, 11.

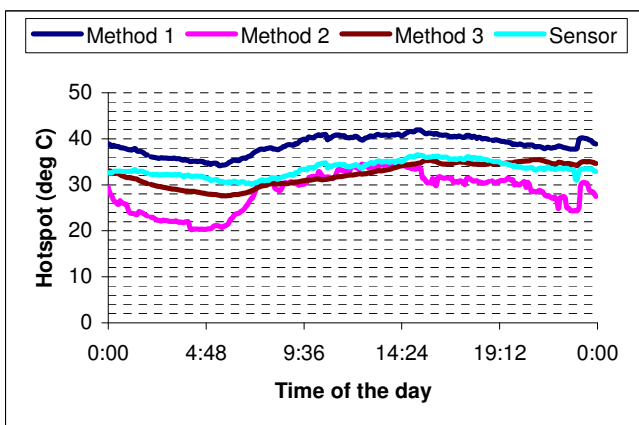


Figure7: Experimental verification of hotspot temperature calculations conducted on 5th May, 11.

VI. CONCLUSIONS

This paper proposes a low cost condition monitoring of power transfer through virtual sensing. It is purely analytical approach that provides accurate results within ± 5 to 7 deg C. Virtual hot-spot sensing and age-impact estimation were made using SCADA measurements (power flow), ambient temperature forecast, and transformer parameters alone. It also provides guideline to optimally utilize their assets in dynamic energy market and helps in making more profit while extending their life.

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