# Comprehensive Transformer Monitoring with Application in Hydro Power Plants

J. Menezes, L. Frisk, K. Hagman ABB AB, Sweden
Prabakaran S, ABB Ltd, India
D. Trišić, V. Maksimović, JP EPS Beograd, Ogranak Drinsko-Limske HE, HE Bajina Bašta, Serbia
R. Hedding ABB Inc. Retired

***Abstract:*** This paper enlightens results from the transformer monitoring with respect to hot spot temperature and insulation loss of life calculations with an application in pump storage hydro power plant. It was piloted using the algorithm mentioned by IEC and IEEE standards and data are analyzed from different transformers. This paper shows the effectiveness of calculation method and direct measurement of top oil temperature on hot spot temperature calculation. It shows the different temperatures in transformer and insulation loss of life affect against loading. It also highlights the challenges to apply the algorithm and conclusions based on the field data.

***Keywords:*** Asset management, condition monitoring, loss of insulation life

## I. INTRODUCTION

Power transformers are one of the most important equipment in power systems since the cost of damage, time to rebuild and subsequent outage costs are huge. Life of power transformers depend on the life of its insulation paper whose deterioration is affected by temperature, moisture and gas content. The effects of moisture and gases on insulation paper's deterioration can be controlled and maintained to a minimum level. Therefore the deterioration of the insulation paper is largely affected by temperature. The no-load and load-losses created by the transformer core and windings will generate high temperatures and if not controlled in a timely manner can damage the dielectric properties of the insulation. In particular, as temperature distribution inside the power transformer is not uniform, the insulation paper around the hot spot temperature will be deteriorated the most. Therefore, the standards state the transformer's life depends on the life of the insulation paper, which is influenced by the hot spot temperature.

The hot spots in the transformer and their temperature give an approximate estimate of the longevity of the transformer. The transformers are generally filled with oil to provide insulation and also to act as coolants. In addition to oil, paper is provided for inter-winding insulation. However in due time there is a gradual degradation of the insulation materials which may lead to short-circuit or flash over which can be catastrophic. To avoid such catastrophic situations it is required to regularly monitor the internal temperature of the transformer and perform the required preventive maintenance. Hence, monitoring the transformer temperature is a good alternative to predict the loss of life.

The IEC Standard 60076 Part 7 Loading Guide for Oil-Immersed Power Transformers [1] helps us in calculating the effect of aging insulation and its exposure to high temperatures. The dynamic ratings for power transformers can be developed by calculating the loss of life and the winding hottest-spot temperature. Such ratings can be used by system operators during contingency conditions, which will allow them to overload transformers for a predetermined time. These transformer dynamic ratings can also be used to create settings criteria for thermal relays.

## II. TRANSFORMER ONLINE MONITORING APPLICATION

Generally transformers are protected by different protection methods which use voltages and currents to detect abnormal conditions. In order to operate the protection methods, high magnitude of current is required. However, these methods will not help when there are a contingency conditions where the transformers need to be overloaded. Using the standard guidelines, engineers can create continuous, long term emergency and short term emergency transformer ratings. Operators can use these ratings until the contingency conditions are overcome. However, there is a chance of reaching critical temperatures when the transformers operated at emergency ratings [3].

The contingency conditions can also occur when transformers are already at 80 % - 90 % of their full nameplate rating and extra capacity is needed. Depending on a utility's criteria, transformers may be allowed to be overloaded, while still maintaining transformer integrity, to keep continuity of the load for economical or reliability reasons. To make these decisions, we must comprehend the thermal effects that oil and winding temperatures have on the life of the insulation. Transformer manufacturers guarantee the longevity of their product as long as it is operated under the temperature specifications of IEEE or IEC standards.

In order to achieve the transformer online monitoring of temperature and their life, ABB numerical IED is developed with an algorithm in accordance with IEC standard 60076 Part 7 and IEEE standard C57.92-1995. This algorithm will help to calculate the top oil temperature, hot spot temperature and transformer insulation life based on empirical formulae as mentioned in standards [1,2]. Further to the algorithm, the numerical IED is developed with add-on features like:

- Sensor less transformer monitoring
- support different transformer types
- support different cooling types
- minimal instrument transformer connection
- cope with on line tap changer

The numerical IED allows the user to select the transformer type, cooling types and current transformers availability, thereby the application can work for any system condition. Also the user can select the method on which the transformer temperature and life calculation should be made. The application can work with measured top oil temperature or measured ambient temperature or with monthly average ambient temperature set values. Then it calculates the hot spot temperature either from the measured top oil temperature or calculated top oil temperature based on the sensor availability. Since the algorithm works based on the load current and ambient temperature, future predictions of transformer temperature also possible by the user to utilize freely the transformer for contingency conditions. In addition to that the application will calculate the transformer insulation loss of life and using this the user can plan for maintenance activities appropriately.

## III. THE PILOT

The numerical IED with transformer online monitoring is challenging especially considering the transformer temperature and life shall be calculated with limited sensors. Also it gives flexibility to the user like limited CT connection for the winding currents and working with real time system conditions. In order to validate all features including usability of the numerical IED for transformer online monitoring, the function was prototyped in a pilot installation over a period of a calendar year. Also it is interesting to study the transformer loss of life while it is in operation based on the load and ambient conditions.

The Bajina Bašta Pump-Storage Plant (PSPP) is located in the vicinity of town Perućac on river Drina. Its two turbines operate with a net hydraulic head of approximately 600 meters between an upper reservoir located on the top of Tara mountain and the lower lake formed by a dam on Drina river. Each generator/motor-transformer unit has rating of 315MVA, 11/242kV, and 428.6 rpm. Due to transport limitations, step-up transformer for each unit in PSPP is built by parallel connection of two tanks of 160MVA each.

Beside PSPP there is another conventional HPP with four generators of 109.6MVA each. HPP is constructed within the dam and are used as stand-alone generators.

A 220kV substation connecting these units to the national grid is located 8km away.

Bajina Bašta pump-storage plant is crucial for everyday operation of the Serbian power system. The two units are typically operated in the generator mode during the day to cover peak loads and in the pump mode during the night. Thus, the power plant is very much suitable to test the application because the system normally works for maximum 8 hours and it has both modes of operation such as generation and pumping.

For the pilot, from the plant one generator transformer and one auxiliary transformer T5 are selected. These transformers are equipped with top oil temperature measurement and high voltage side CT measurement. Also the plant has ambient temperature measurement. Here, transformer T2-1 and T2-2 are connected in parallel and formed as transformer T2. Both have similar design parameters, therefore testing on two different transformers with same design will help us to validate our application. Selected transformers to the numerical IED are shown in Figure 1.

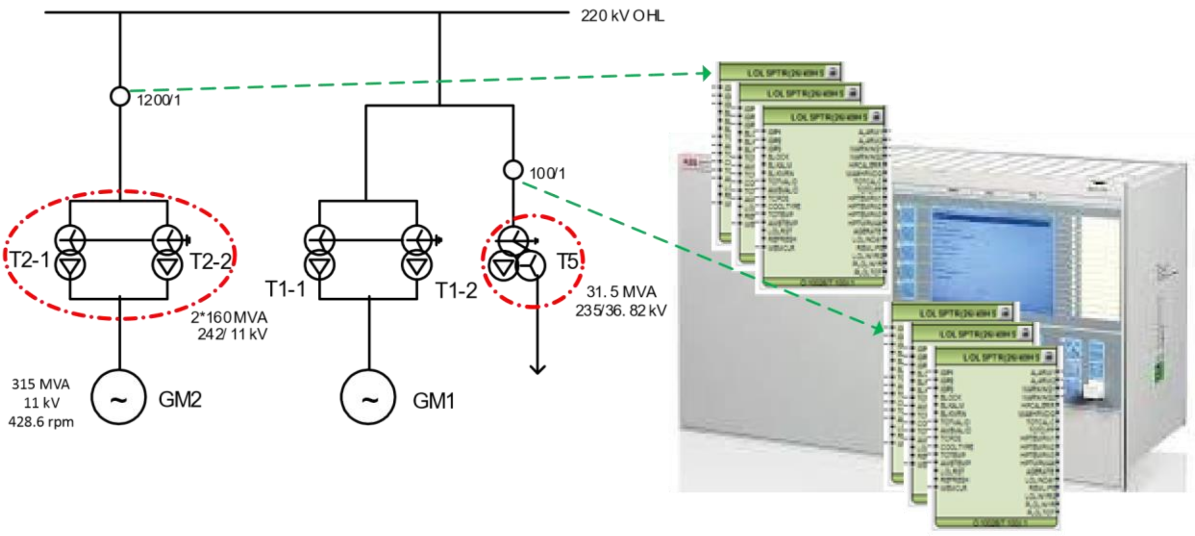



Figure 1 Configuration overview for the pilot transformer units

In order to validate the complete application of transformer online monitoring in numerical IED, different methods are selected between application instances and divided among three transformers. Table 1 shows the complete allocation of application function instances with different transformers. For the pilot, the application instances are divided based on 4 inputs. They are, mode of top oil temperature (direct measurement, calculated from measured ambient temperature and monthly average ambient temperature set value), time constant (from standard or calculated based on transformer mass values), current selection for the load factor (maximum out of 3 phase currents or average of 3 phase currents) and calculation method (using IEC standard or IEEE standard). In the specified transformers, there is no provision to measure hot spot temperature directly.

The configuration for the numerical IED is made based on the available system conditions. For the monthly average ambient temperature, the data was taken from weather statistics. All three transformer manufactures are different and among them one is from ABB. The ABB transformer is relatively new installed one compared to other two transformers which have been in service since 1975. The off- line tap changer for transformers $T_{2\text{-}1}$ and $T_{2\text{-}2}$ are mostly fixed to a specific position. The on- line tap changer for transformer T5 is in permanent operation. Regarding the cooling type switchover, it depends on load current for T2 transformer and top oil temperature for T5 transformer.

*Table 1. Function instance / configuration allocation*

| Config. / Instance No. | XFMR Identification | Inputs | | | |
|---|---|---|---|---|---|
| | | **Top oil Temperature** | **Time Constants** | **Current Selection** | **Calculation Method** |
| 1 | $T_{2-1}$ | Direct Measurement | Standard | Maximum | IEEE |
| 2 | $T_{2-2}$ | Direct Measurement | Calculation (Mass based) | Maximum | IEC |
| 3 | $T_{2-2}$ | Direct Measurement | Standard | Average | IEC |
| 4 | $T_5$ | Direct Measurement | Standard | Average | IEEE |
| **Config. / Instance No.** | **XFMR Identification** | **Inputs** | | | |
| | | **Top oil Temperature** | **Time Constants** | **Current Selection** | **Calculation Method** |
| 5 | $T_5$ | Calculated from Monthly Model Ambient | Standard | Maximum | IEC |
| 6 | $T_5$ | Calculated from Monthly Model Ambient | Calculation (Mass based) | Maximum | IEC |

## IV. Challenges and Results

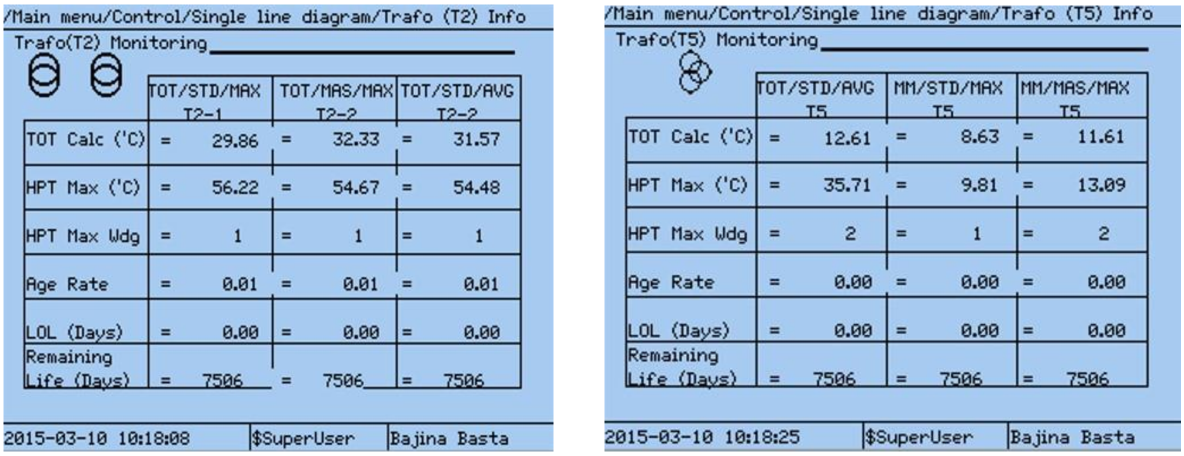
The numerical IED with transformer online monitoring application was put on trial service in March 2015. Since then, operating experience was completely in accordance with expectations [4]. However during the period of pilot installation and running time, there were some challenges. Later with more studies and minor adjustments in the configuration it was applied and successfully completed the pilot execution. The most critical part was to get the transformer parameters of the very old transformer T5 and all required type test data or heat run test data to validate the algorithm.

The second most critical part is to find the total transformer insulation loss of life. If the transformer is new and it is in operation along with the numerical IED then, it is possible to get the total transformer loss of life with online loading data and ambient temperature. But in the case of transformers which is already in service and the new numerical IED is adopted to find the total transformer insulation life. Then the user need to get the already lost insulation life to set in the application which is practically unpredictable. In the absence of transformers lost insulation life data, the numerical IED is only able to calculate the transformer insulation loss of life for the period of transformer observation time.

Another interesting challenge is to get the measurement/signal data from the transformer to the relay control room where the numerical IED is placed. This plant was put in operation since 1982 when the original protection scheme was designed using discrete electromechanical relays with induction discs. Hence getting the new wiring connection to the numerical IED from the all current transformers, online tap changer of the transformers and cooling type indicators are not easy.

Also there was only one CT is available from the HV winding side of the parallel transformers T2-1 and T2-2. However the application can handle the situation with one side winding current (in the case of 2 winding transformer), the current from HV side CT is halved and connected to the IED. The other winding current which is calculated from the application is verified with measured currents and it states that the current calculation is happening as expected.

The following figures come from recordings captured during unit actual operation. Figure 2 shows the on-line service values. This facilitates easy visualization of transformer monitoring parameters.



/Main menu/Control/Single line diagram/Trafo (T2) Info

Trafo(T2) Monitoring

| | TOT/STD/MAX T2-1 | TOT/MAS/MAX T2-2 | TOT/STD/AVG T2-2 |
|---|---|---|---|
| TOT Calc ('C) | = 29.86 | = 32.33 | = 31.57 |
| HPT Max ('C) | = 56.22 | = 54.67 | = 54.48 |
| HPT Max Wdg | = 1 | = 1 | = 1 |
| Age Rate | = 0.01 | = 0.01 | = 0.01 |
| LOL (Days) | = 0.00 | = 0.00 | = 0.00 |
| Remaining Life (Days) | = 7506 | = 7506 | = 7506 |

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/Main menu/Control/Single line diagram/Trafo (T5) Info

Trafo(T5) Monitoring

| | TOT/STD/AVG T5 | MM/STD/MAX T5 | MM/MAS/MAX T5 |
|---|---|---|---|
| TOT Calc ('C) | = 12.61 | = 8.63 | = 11.61 |
| HPT Max ('C) | = 35.71 | = 9.81 | = 13.09 |
| HPT Max Wdg | = 2 | = 1 | = 2 |
| Age Rate | = 0.00 | = 0.00 | = 0.00 |
| LOL (Days) | = 0.00 | = 0.00 | = 0.00 |
| Remaining Life (Days) | = 7506 | = 7506 | = 7506 |

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Figure 2: Build in HMI with online monitoring parameters

The analysis of various configurations and their operating modes of monitoring the transformers based on the parameters mentioned in table 1 is made together with the results and conclusions.

Figure 3 and 4 shows the captured data from transformer T2-1 for 10 days with load factor, measured ambient temperature, calculated top oil temperature and the difference between the measured & calculated top oil temperature. This shows an average difference of 5 °C which is well below the acceptable limit as per the IEC standard.

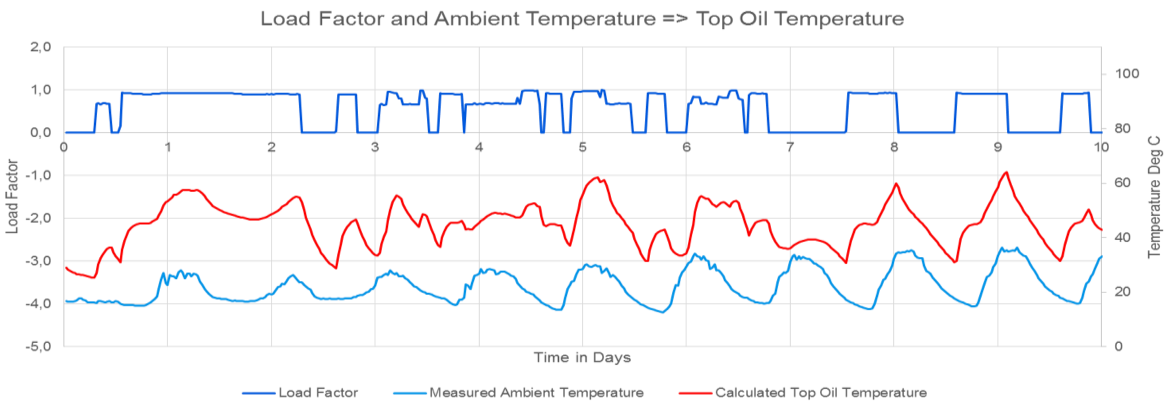


Figure 3: Transformer T2-1 Load Factor, measured ambient temperature and top oil temperature

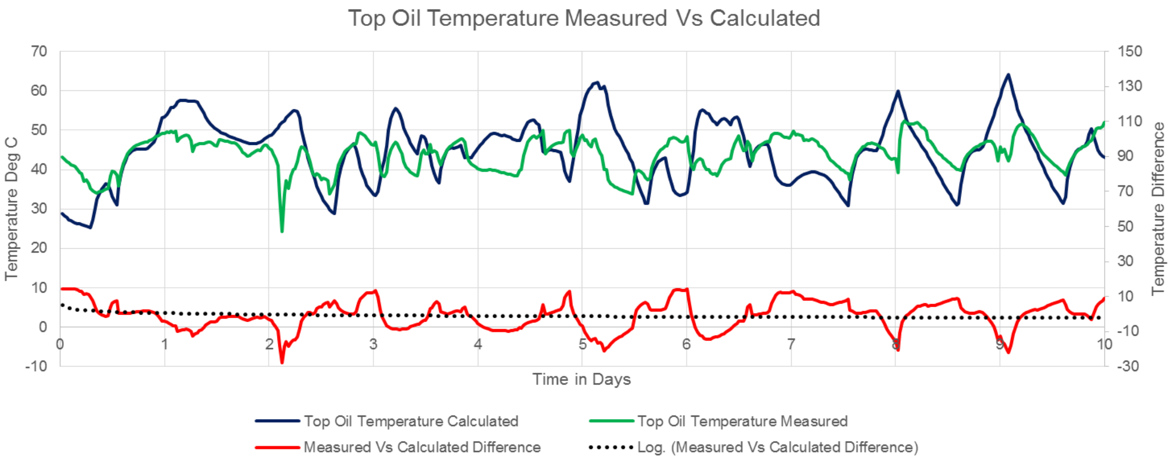


Figure 4: Transformer T2-1 Measured and Calculated Top Oil Temperature Difference

Similarly, with different configurations among the different transformers the data was captured. Based on the results and operation experiences the applications works as per the expectations. But when there is no measured ambient temperature, the results shows high difference in measured and calculated top oil temperature. During this situation the application works based on the weather statistical data. The deviation starts from the set ambient temperature; in this case it is more than 12°C in ambient temperature. This inaccuracy was reflected in top oil temperature calculations and shows more than 18 °C difference. This miscalculation is due to the improper set ambient temperature data and if the error is removed from the results then it is within the acceptable limits.

The below Figures 5(a-f) shows the result of transformer T2-1 with configuration as per instance 1. Figure 5a shows the load factor and it is certainly visible that the transformer was shut down for nearly one month. Due to this transformer shut down, the transformer life is more or less maintained which can be seen from Figure 5f.

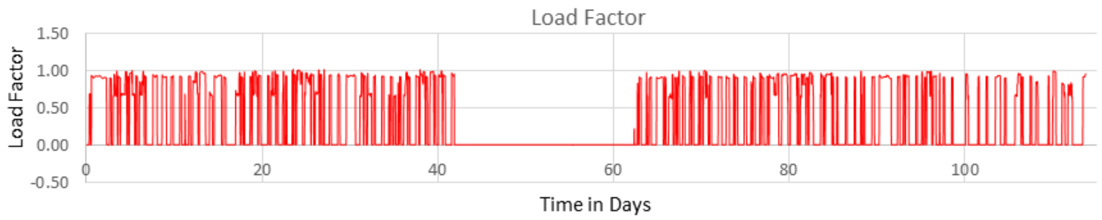


Figure 5a: Transformer T2-1 Load Factor (Instance 1)

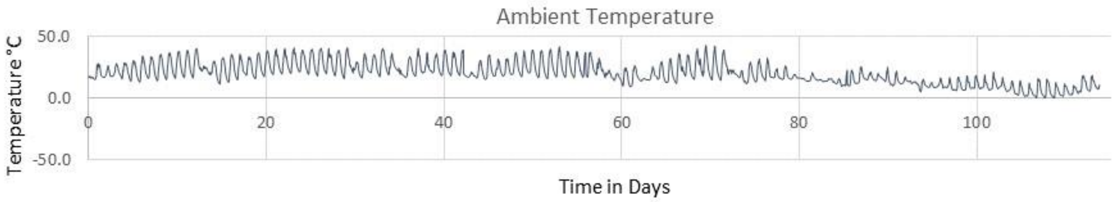


Figure 5b: Transformer T2-1 Measured Ambient Temperature (Instance 1)

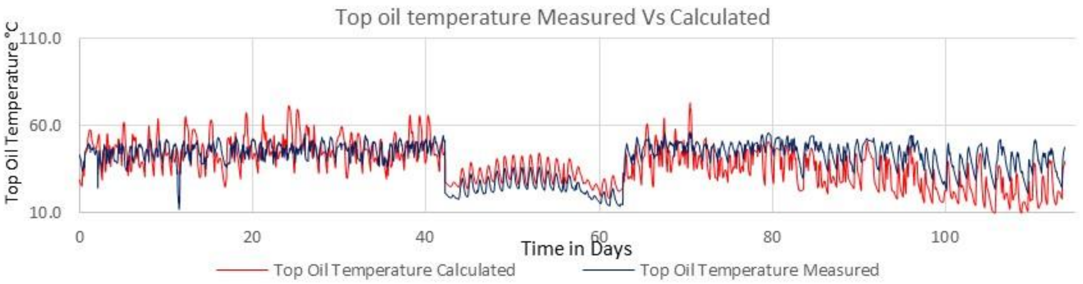


Figure 5c: Transformer T2-1 Measured and Calculated Top Oil Temperature (Instance 1)

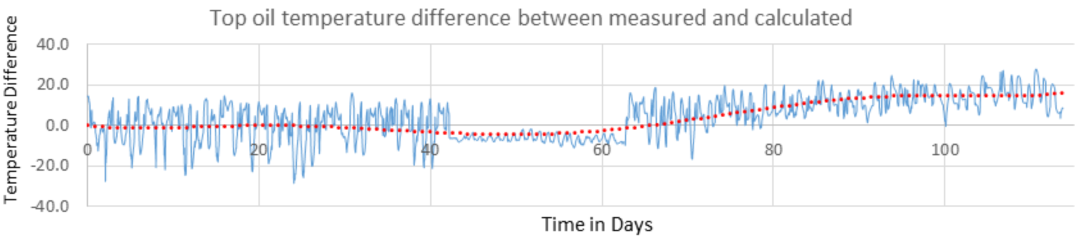


Figure 5d: Transformer T2-1 Measured and Calculated Top Oil Temperature Difference (Instance 1)

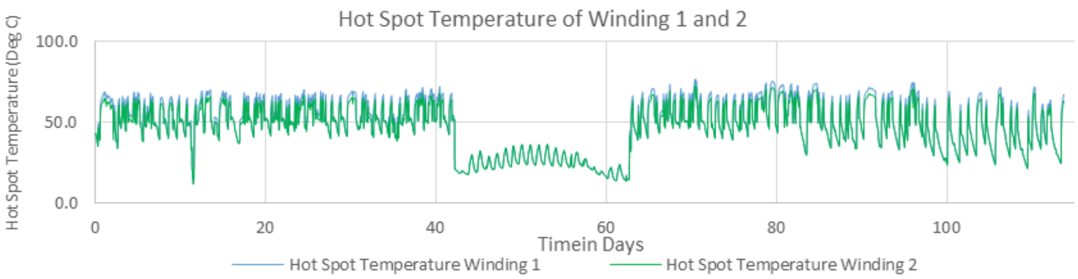


Figure 5e: Transformer T2-1 Calculated Hot Spot Temperature (Instance 1)

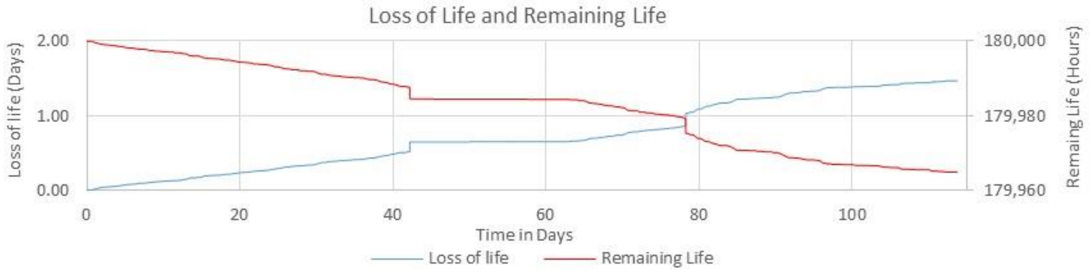


Figure 5f: Transformer T2-1 Loss of Life and Remaining Life (Instance 1)

The below Figures 6(a-d) shows the result of transformer T2-2 with configuration as per instance 2. Figure 6d shows the difference between the measured and calculated top oil temperature which is in the average of 12 °C.

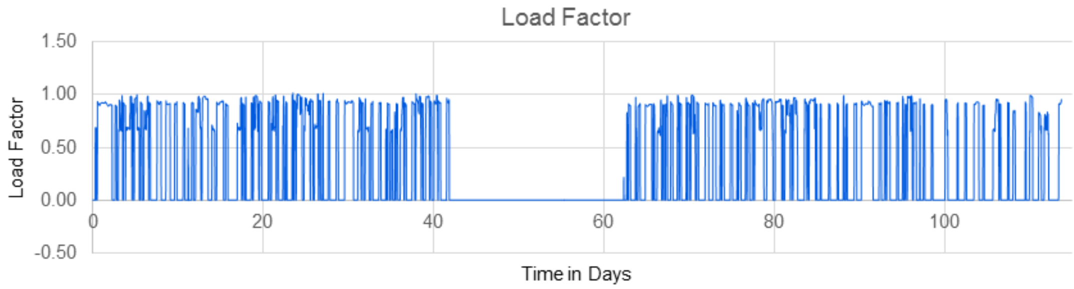


Figure 6a: Transformer T2-2 Load Factor (Instance 2)

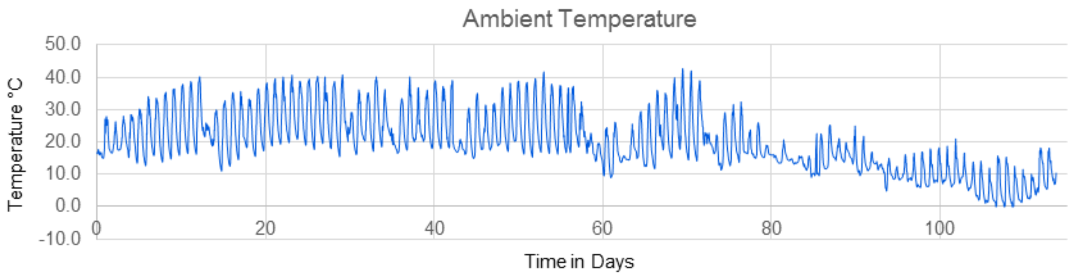


Figure 6b: Transformer T2-2 Measured Ambient Temperature (Instance 2)

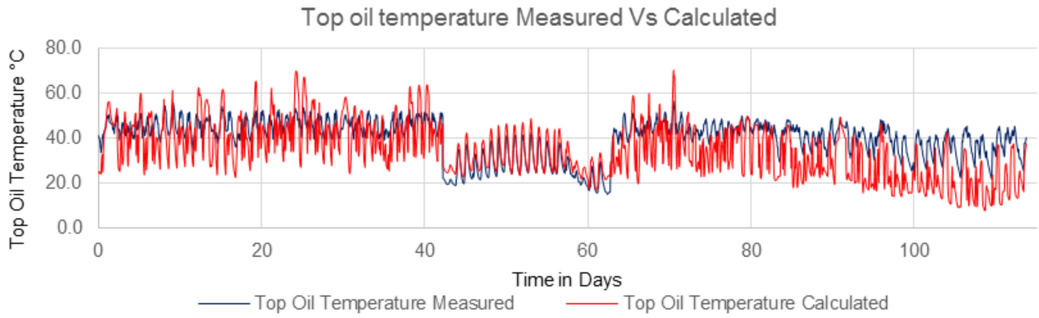


Figure 6c: Transformer T2-2 Measured and Calculated Top Oil Temperature (Instance 2)

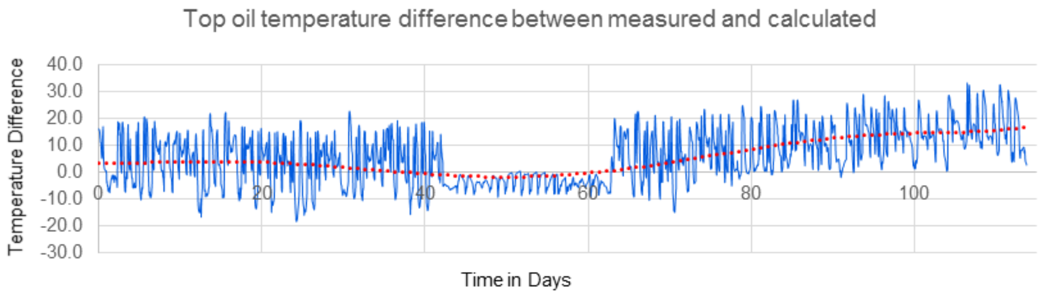

Figure 6d: Transformer T2-2 Measured and Calculated Top Oil Temperature Difference (Instance 2)
The below Figures 7(a-d) shows the result of transformer T2-2 with configuration` as per instance 3. In this case the transformer oil time constant is taken from standard, based on the transformer rating. Whereas in configuration 2, the transformer oil time constant is calculated using the transformer mass of different parts. Since the results from configuration 2 and configuration 3 are same, the calculation of oil time constant as per the dimension of transformer is equally working well when there is no direct data to set. This results confirms that calculation of oil time constant with transformer mass parameters works fine.

The other difference in this configuration with reference to configuration 2 is current selection for load factor calculation is average, where in configuration 3 it is maximum. Since this is at a generation station, the phase current magnitudes are the same. Therefore, using average, or maximum values has little effect on this case.

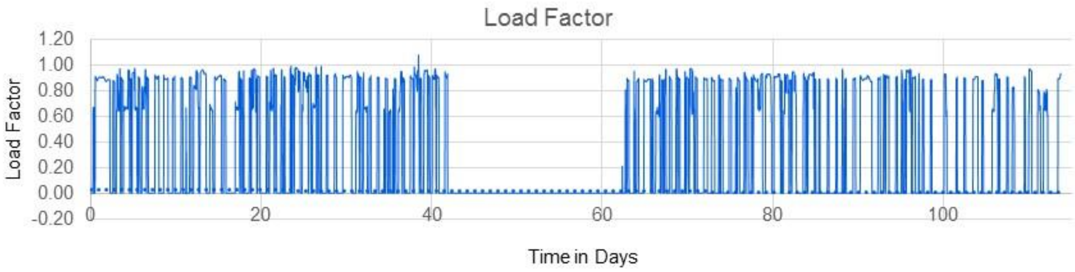


Figure 7a: Transformer T2-2 Load Factor (Instance 3)

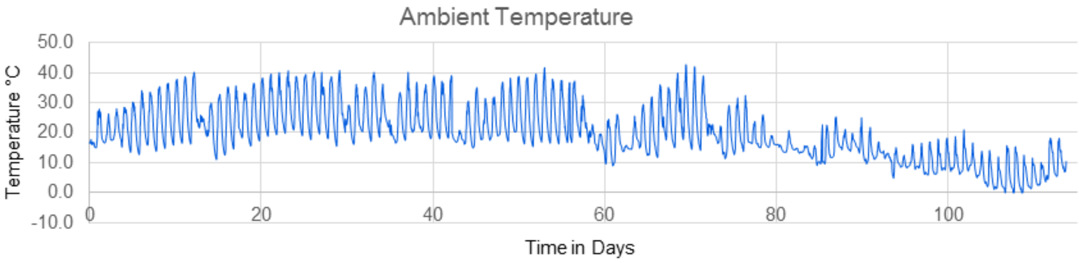


Figure 7b: Transformer T2-2 Measured Ambient Temperature (Instance 3)

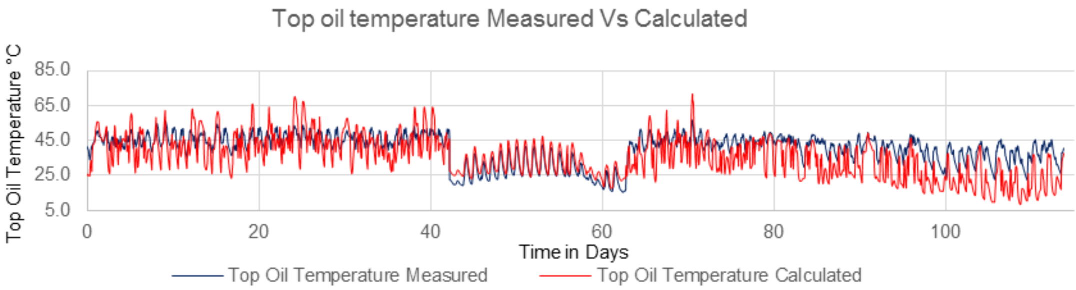


Figure 7c: Transformer T2-2 Measured and Calculated Top Oil Temperature (Instance 3)

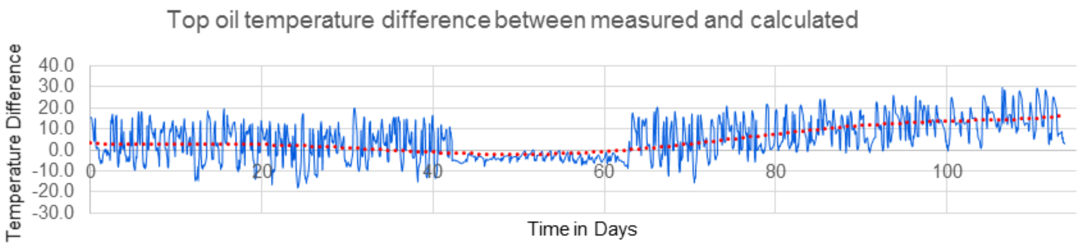


Figure 7d: Transformer T2-2 Measured and Calculated Top Oil Temperature Difference (Instance 3)

Figures 8(a-d) shows the result of transformer T5 with configuration as per instance 4. In this case the top oil temperature measured or calculated is exactly following the ambient temperature since the transformer T5 is mostly very lightly loaded. It shows the temperature rise due to the loading is very less effective when the transformer is loaded within the normal operating limits.

Also as mentioned earlier in this paper, all data for the transformer T5 is not available and therefore a recently designed transformer specification data which has similar rating are set and executed. This effect shows the constant difference between the measured and calculated top oil temperature throughout the period of observation as recent design of transformers are quite improved from earlier days designed transformers [5].

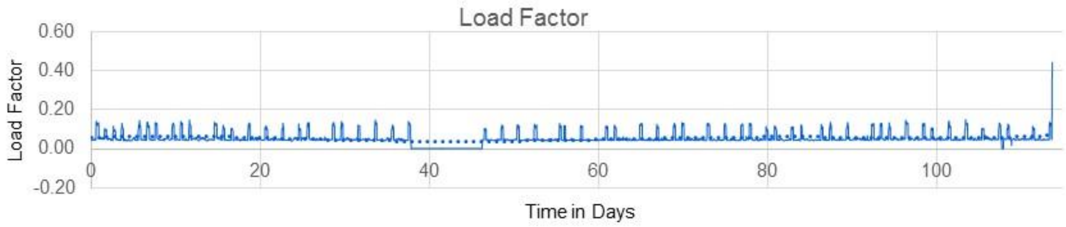


Figure 8a: Transformer T5 Load Factor (Instance 4)

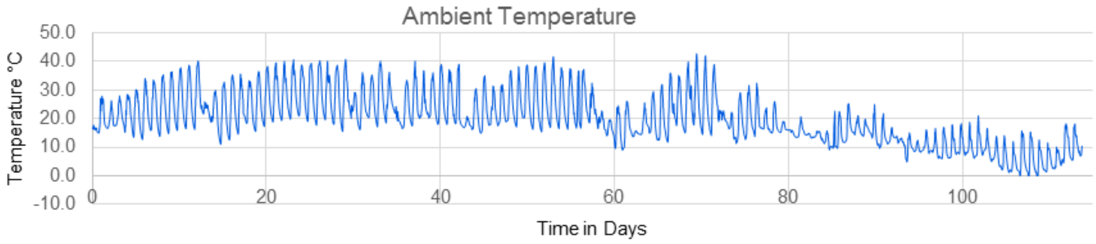


Figure 8b: Transformer T5 Measured Ambient Temperature (Instance 4)

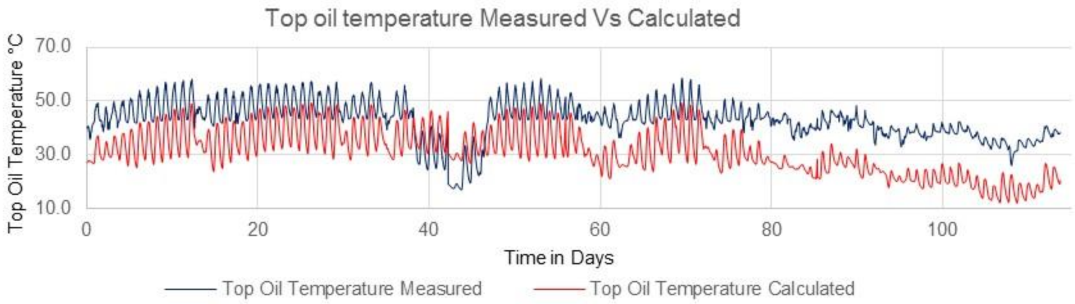


Figure 8c: Transformer T5 Measured and Calculated Top Oil Temperature (Instance 4)

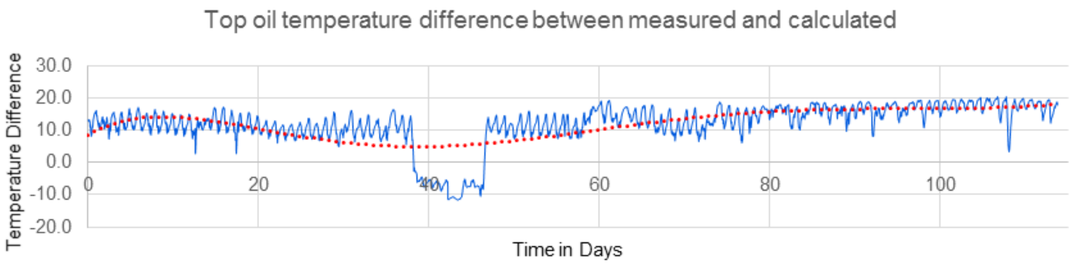


Figure 8d: Transformer T5 Measured and Calculated Top Oil Temperature Difference (Instance 4)

Figure 9(a-d) shows the result of transformer T5 with configuration as per instance 5. In this case the transformer top oil temperature is calculated based on the set monthly average ambient temperature. Whereas in configuration 4, the transformer top oil temperature is calculated based on the measured ambient temperature. As it is stated above, in this case also calculated top oil temperature follows the ambient temperature as it can be seen in Figure 9c. The other difference in this configuration is current selection for load factor calculation is average, whereas in configuration 4 it is maximum. Similarly, here also the effect is negligible. Important point to be noted here is, the difference between the measured and calculated top oil temperature is nearly the same for both cases of configuration 4 and configuration 5. This shows that the algorithm even without ambient temperature sensor also can work within tolerable inaccuracies. Here it confirms the application can work without sensor inputs.

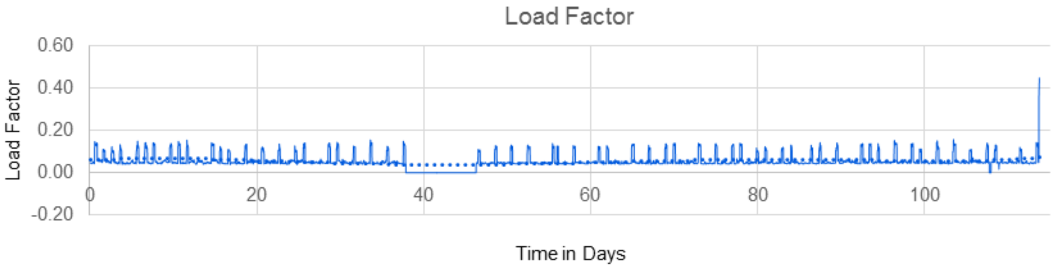


Figure 9a: Transformer T5 Load Factor (Instance 5)

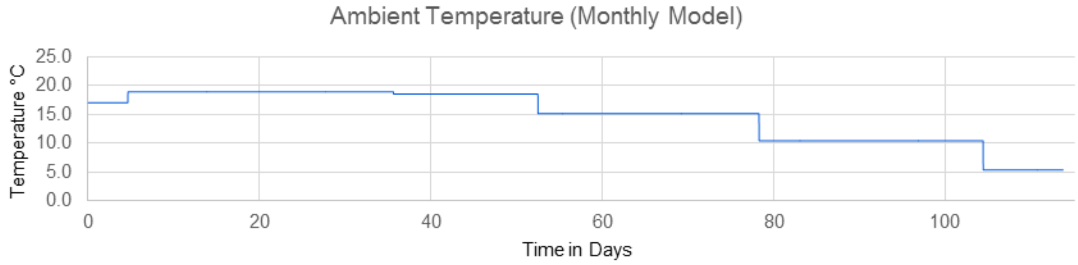


Figure 9b: Transformer T5 Measured Ambient Temperature (Instance 5)

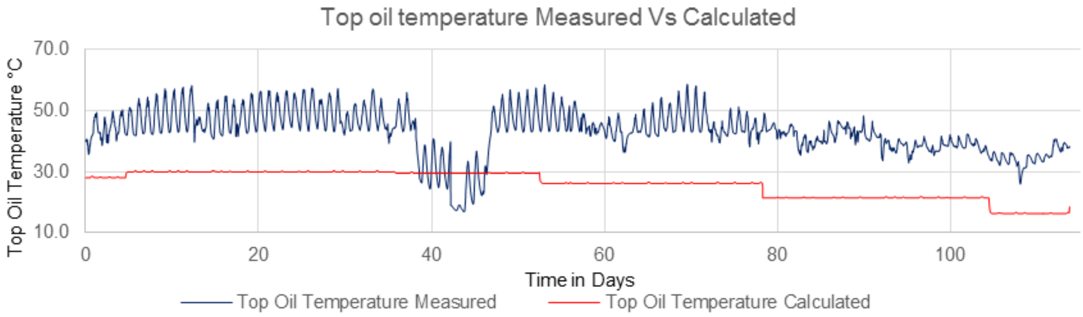


Figure 9c: Transformer T5 Measured and Calculated Top Oil Temperature (Instance 5)

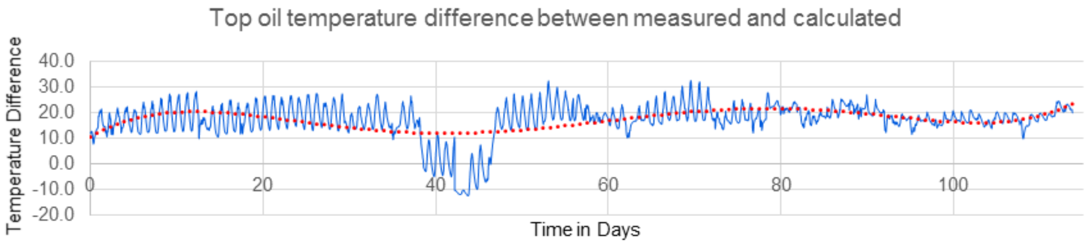


Figure 9d: Transformer T5 Measured and Calculated Top Oil Temperature Difference (Instance 5)

Figure 10(a-d) show the result of transformer T5 with configuration as per instance 6. In this case the transformer oil time constant is calculated using the transformer mass of different parts. Whereas in configuration 2, the transformer oil time constant is taken from standard based on the transformer rating. Since the results from configuration 5 and configuration 6 are same, once again it proves that the calculation of oil time constant using the dimensions of transformer works equally well when there is no direct data available.

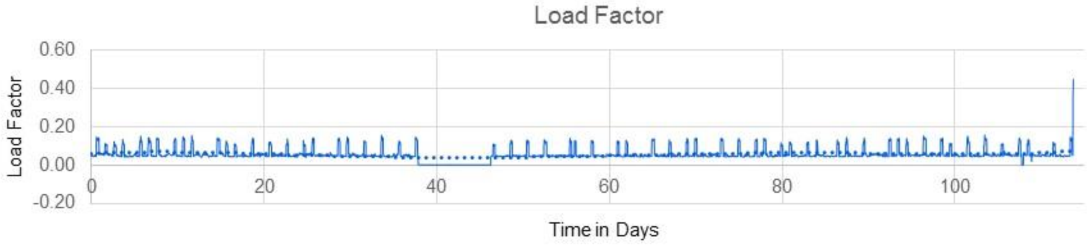


Figure 10a: Transformer T5 Load Factor (Instance 6)

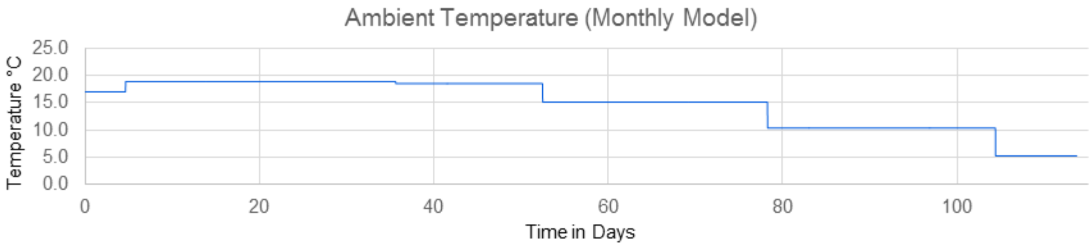


Figure 10b: Transformer T5 Measured Ambient Temperature (Instance 6)

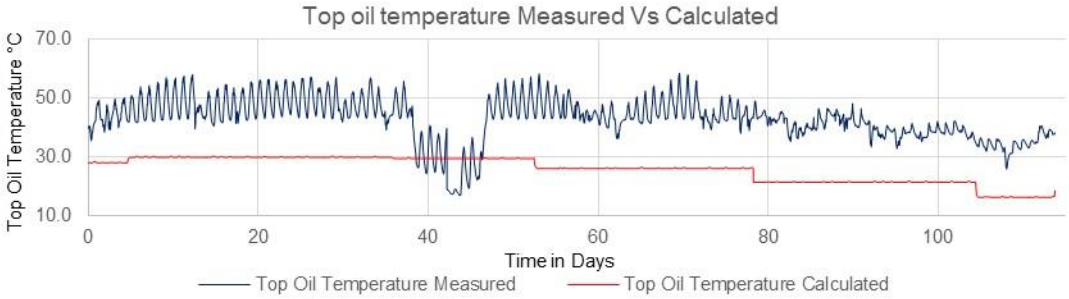


Figure 10c: Transformer T5 Measured and Calculated Top Oil Temperature (Instance 6)

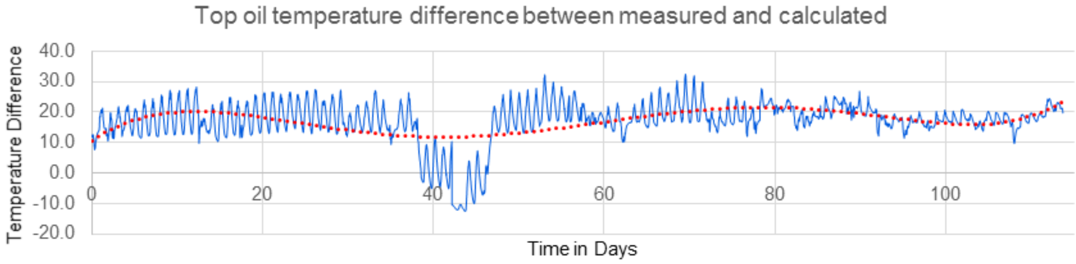


Figure 10d: Transformer T5 Measured and Calculated Top Oil Temperature Difference (Instance 6)

Based on the above results one can confirm that, the calculation method using either IEC standard method or IEEE standard method is not affect much unless and otherwise the insulation paper type is thermally upgraded. In this pilot installation the transformers use normal insulation paper type. Also, since these transformers do not have the provision to measure the hot spot temperature directly, the calculation of hot spot temperature is not part of this pilot.

Overall, the pilot results have proven that the monitoring application for transformer without sensors can be implemented in numerical relay on a standard hardware platform. The transformer monitoring application which is integrated with the ABB RET670 used in this installation is presented in Figure 11.

Figure 11 Installed RET670 with Transformer Monitoring Application in Bajina Bašta pump-storage

## V. Conclusion and Future Visions

Bajina Bašta pump-storage plant is crucial for everyday operation of the Serbian power system. The two units are typically operated in the generator mode during the day and in the pump mode during the night. Thus, monitoring of each unit in this hydro power plant is essential and the functionality developed can be used at this installation.

The pilot application yielded the results that were expected within limits, It's possible to get further improvements in the application design. Also there is a need to reduce the large number of transformer parameters needed to calculate loss of life during operation especially when dealing with old transformers. The transformer insulation loss of life prediction for a transformer which is already in service still it is very big challenge to predict in a proper manner and would require further research in this area.

## VI. References


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