Physics-based Thermal Model of Shunt Reactors

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Abstract

While holding several constructive similarities with power transformers, shunt reactors' thermal behavior differs significantly from transformers. Yet, the most common approach is to estimate the temperature distribution of shunt reactors using the same thermal model developed for power transformers. While adjusting some of the empirical coefficients of the model may lead to minimizing the deviations in the predicted temperatures, due to the exponential nature of the solid insulation life consumption, small deviations in the hottest spot temperature may represent several years or decades of difference in the expected lifespan. A physics-based thermal model was included in the IEEE C57.91 in the 80s, traditionally referred to as the "Annex G" model. Rather than using time constants and exponential functions to predict the temperature gradients under different loading conditions, the model utilizes a model similar to a Runge-Kutta method, on a sequential calculation procedure based on an initial value, using small enough time steps. For each time step, equations are used to calculate the heat generated and dissipated by the different elements of the transformer, estimating the temperature variation for the average winding and the hotspot region. Considering the differences in the variation of losses and heat dissipation as a function of the system voltage, the so-called "Annex G" model was adapted for shunt reactors. A comparison of the results with measurements and results from other models is presented in this article.

1. Introduction

Reactive power compensation is crucial for maintaining voltage stability and improving power quality in high-voltage AC lines, cables, and HVDC converters (LCC). This is especially important today due to the increasing penetration of renewable generation and the interconnection of different electrical systems via cable connections. Additionally, reducing reactive energy increases system capacity by focusing resources on active power. Shunt reactors play a significant role in this process, offering unique characteristics and applications.

Alternatives to mitigate reactive energy losses (due to capacitance in current lines) include the use of High Voltage DC (HVDC) lines, Secondary Voltage Regulators (SVR), Static VAR Compensators (SVC), and Static Synchronous Compensators (STATCOM) [1]. Given the high need for reactive power compensation, it is also important to consider the capability to control reactive power (Q) in both directions with HVDC converters using LCC technologies.

The choice among these methods depends on the specific requirements of each case, and often a combination of these solutions is employed. For instance, the Yggdrasil project, discussed later in this paper, utilizes a hybrid approach to optimize performance.

In long transmission lines, especially under light load or no-load conditions, the voltage at the receiving end tends to increase due to the capacitive effect generated between overhead transmission lines and the ground (earth), the capacitive charging current. This phenomenon is known as the Ferranti Effect. To control this effect, shunt reactors are required to restore it to design levels by "consuming"

(removing) part of the reactive power generated by the capacitive effect of the transmission lines. Shunt reactors can be built for any transmission voltage, allowing direct connection to the transmission system without the need for an intermediate transformer. This flexibility reduces losses and allows for installation in optimal locations within the system. For instance, in a recent project for powering offshore platforms in the North Sea directly from shore through 250km of 145kV sea cable, it was necessary to add a bank of shunt reactors to compensate for the cable's capacitive effect [2][3].

Shunt reactors can operate in continuous or switched mode, depending on system requirements. They can be classified as fixed (SR) or variable (VSR). While the first is available both as dry-type or liquid-filled, the variable shunt reactors are only liquid-filled.

Fixed-rating shunt reactors are a traditional technology with no means of regulation. Controllability is achieved by switching them in and out according to load variations. This method can lead to step changes in the system voltage level, inducing additional stress on other system components. To minimize this drawback, several small shunt reactors can be used in combination, smoothing these step variations and facilitating better controllability. Alternatively, VSRs can be employed, which enable continuous compensation of reactive power through the use of a tap changer to adjust the inductance of the power line or cable to which they are connected [4].Though less common than core type, shell technology type and air core type can also be used for manufacturing shunt reactors.[5]

2. Difference Between Transformers and Shunt Reactors.

For better understanding the differences between traditional thermal model based on transformers design applied to shunt reactors and "Annex G" adapted for shunt reactors, we will review the differences between the two devices:

A. Transformers:
- Series component: Transformers are connected in series with the grid. Line current circulates through them.
- Short circuit power: They handle the full short circuit power of the grid during faults.
- Forces on windings: Experience large forces on the windings occasionally.
- Forces on core: Subject to smaller forces on the core.
- Testing: Tested with secondary short-circuited, requiring around 10% of rated power.

B. Shunt Reactors:
- Parallel component: Shunt reactors are connected in parallel with the grid. Current circulating through them is a function of line voltage and its impedance.
- No short circuit currents: They do not pass short circuit currents.
- Forces on windings: Experience limited forces on the windings.
- Magnetic forces on core: Subject to very large magnetic forces on the core, occurring 100 or 120 times per second.
- Testing: Cannot be tested with secondary short-circuited, requiring full-rated power.

The mechanical integrity, manufacturing precision, and long-term stability of the shunt reactor core are crucial. Poor management can lead to increased noise, excessive vibrations, fatigue in external steel parts, leaks, and potential damage to bushings and accessories. Ensuring high-quality manufacturing processes is essential for the reliable operation of shunt reactors.

Shunt reactors are vital for maintaining voltage stability and improving power quality in high-voltage AC lines and cables. Their cost efficiency, reliability, and flexibility make them an essential component in modern power systems. Understanding the differences between shunt reactors and transformers helps in selecting the appropriate equipment for specific applications.

3. Thermal Model

The life expectancy of transformers and shunt reactors depends essentially on the operating temperatures for the traditional Arrhenius model. Moreover, the temperature of the hottest point insulated with cellulose-based materials is typically considered the most critical aspect of such equipment.

The most typical way to measure the loading is by using an instrument transformer (current transformer) to measure the current passing through the equipment. While in transformers the percentual loading is defined by measured current versus rated current, in shunt reactors the voltage defines the loading.

Except for the VSR, the impedance in shunt reactors is constant and they are always connected at line voltage with a fixed voltage reference point. The increase in voltage is followed by an increase in the current, resulting in a percentual loading defined by the square of the variation of the system voltage. It can also be tracked by measuring the current.

Different from power transformers, shunt reactors operate continuously around their rated capacity, driven by the system voltage. As a result, especially in the cases of "continuous operation" (instead of switched) the shunt reactors are assumed to be at rated capacity continuously.

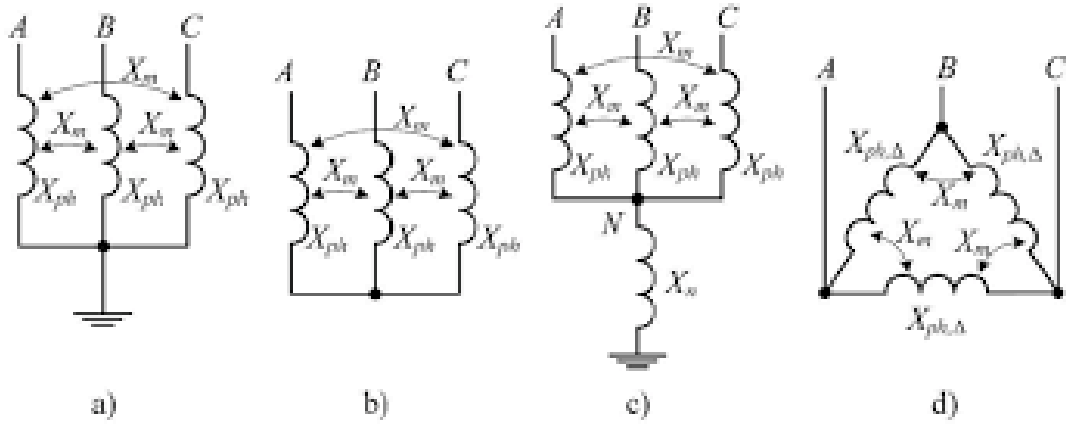

Figure 1. Winding's connection scheme of three-phase shunt reactor: a) star with grounded neutral; b) star with an isolated neutral; c) star with neutral grounding reactor; d) delta.

Per the IEEE C57.91 [6] and IEEE C57.100 [7], the nominal life expectation for a thermally upgraded paper operating continuously at its nominal temperature is 180,000 hours. Converted to years, this value results in 20.5 years. Since the usual life expectancy for transformers ranges between 35 and 40 years, the motivation to develop accurate thermal models for shunt reactors is evident.

In a nutshell, a thermal model can be defined as a system of equations developed to predict the temperature of specific points or regions of the transformer or shunt reactor based on the design parameters or temperature rise test results and the instantaneous value of loading and ambient temperature. The traditional models are based on applying "correction factors" to be applied to the rated condition gradients.

The article from Pierce in 1994 [8] brought an innovation to the thermal models, by utilizing an approach that can be seen as a physics-based Runge-Kutta numerical integration. The model integrates the distribution of thermal energy in a transformer using a sequential calculation over a small enough time step. It starts with the calculation of the heat generated in the windings and in the core for the instantaneous loading condition. A portion of this heat is absorbed by the components, increasing temperature, and a portion is transferred to the insulating liquid. In turn, a portion of this heat is absorbed by the insulating liquid, and the balance is dissipated to the ambient. Thus, reproducing the equation from [8] for the conservation of energy, the following may be written:

$$\begin{array}{c}\text{Heat Generated by}\\ \text{Windings}\\ \text{in Time } Dt\end{array} = \begin{array}{c}\text{Heat Absorbed by}\\ \text{Windings}\\ \text{in Time } Dt\end{array} + \begin{array}{c}\text{Heat Lost by}\\ \text{Windings}\\ \text{in Time } Dt\end{array} \qquad (1)$$

A relevant advantage of this model is that it does not use time constants. To be accurate, it does use a time constant for the windings. Yet, this time constant is used to validate the defined time step and to calculate the thermal capacity of the windings. Differently from the "traditional models", there is no calculation of exponential variation of temperatures using this or any other empirically estimated time constant. The derivative of the temperature with time is directly related to the masses and properties of the materials.

Rather than reproducing here the equations from the original model from Pierce, we will focus on the implemented changes to extend the model to include the physical representation of a shunt reactor. The most relevant modification is the variation of core losses with the loading. Due to the complexity of its calculation, a series of cases were evaluated and a correlation between the loading condition and the core losses was defined. The equations used to recalculate the losses condition are:

$$XK_2 = \frac{KVA_2}{KVA_1} \qquad (2)$$

$$TK_2 = \frac{(TK + TWR)}{TK + TKVA_1} \qquad (3)$$

$$PW_2 = XK_2 \cdot PW_1 \cdot TK_2 \qquad (4)$$

$$PE_2 = XK_2 \cdot PE_1/TK_2 \qquad (5)$$

$$PS_2 = XK_2 \cdot PS_1/TK_2 \qquad (6)$$

$$PC_2 = XK_2{}^{\alpha} \cdot PC_1 \qquad (7)$$

$$P_{total\,2} = PW_2 + PE_2 + PS_2 + PC_2 \qquad (8)$$

Where:

KVA_i	Loading condition at *i* iteration
TK	temperature factor for resistance changes
TWR	rated average winding temperature
$TKVA_1$	*Temperature base for losses data*
PW_i	Winding ohmic (I^2R) losses at *i* iteration
PE_i	Winding Eddy losses at *i* iteration
PS_i	Stray losses at *i* iteration
PC_i	Core losses at *i* iteration
α	Exponent correlation core losses and loading
$P_{total\,i}$	Total losses at *i* iteration

Another modification implemented into the model is the estimation of the temperature of the core, which will be more deeply discussed in a future paper.

As a validation of the method, the developed spreadsheet was used to reproduce the heating-up portion of a temperature rise test of 3 different shunt reactors. The measured values of top oil were compared with the values predicted by the method. In addition, a "typical" loading curve of shunt reactors will be used to simulate the cyclic loading conditions.

4. Results Obtained

The thermal model was applied to three different shunt reactors representing the warm-up period of a temperature rise test. The three sets of comparisons will be presented here.

A. Case 1 – 3 Phase Shunt Reactor 50MVAr – 230kV
Test condition = 60.5MVAr (10% overvoltage)

It is not uncommon to restrict the cooling system during the temperature rise test, to accelerate the stabilization process and, eventually, shorten the duration of the temperature rise test, but it makes the comparison of the curves more challenging. The measured curve indicates the operators probably covered some of the radiators, resulting in some overheating. Yet, the simulation resulted in a behavior very similar to the measurement. As previously mentioned, the method does not use "time constants" that can be manipulated. The resultant temperature is obtained by the equations with balances of energy and the numerical integration method. The final difference was 0.7°C.

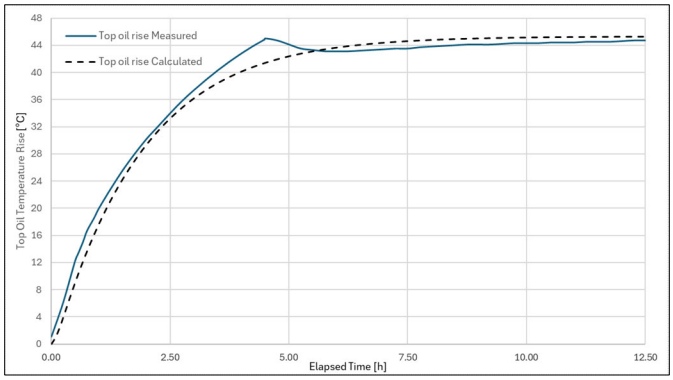

Figure 2. Comparison of the measured temperature with the simulation results, for the warm-up period of the temperature rise test.

B. Case 2 – 3 Phase Shunt Reactor 120MVAr – 275kV
Test condition = 142.81 MVAr (10% overvoltage)

While the measured curve shows some small oscillations, the agreement between it and the calculated values was impressive.

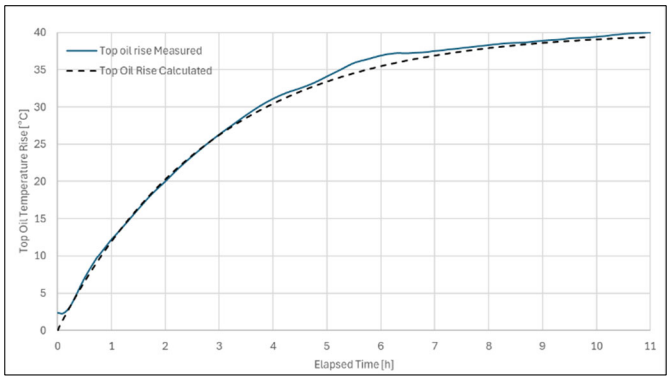

Figure 3. Comparison of the measured temperature with the simulation results, for the warm-up period of the temperature rise test.

C. Case 3 – 3 Phase Shunt Reactor 300MVAr – 275kV
Test condition = 357MVAr (10% overvoltage)

Due to limitations on the test field capacity, this using was tested at 85% of the rated capacity. The results had to be extrapolated to 110% overvoltage condition. Due to the positioning of the sensor, the measured "top oil" was more accurately represented by the temperature of the oil at the cooling duct rather than the calculated top oil. This is also calculated by the method used for the calculation of the hotspot temperature. The comparison of the two curves also reveals some oscillations in the measured values. The positioning of the top oil sensor affects the measurement. In this case the thermometer well is positioned right in front of the "stream" of oil coming out of the coils. This is the reason the measured temperature aligned with the "top cooling duct" better than with the estimated top oil.

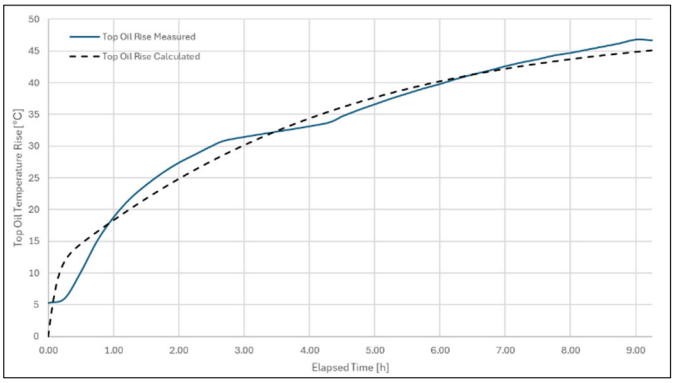

Figure 4. Comparison of the measured temperature with the simulation results, for the warm-up period of the temperature rise test.

D. Case 4 – Simulation of operating conditions

The data of the 50MVAr shunt reactor was used to simulate real-world loading cycles hypothetically defined.

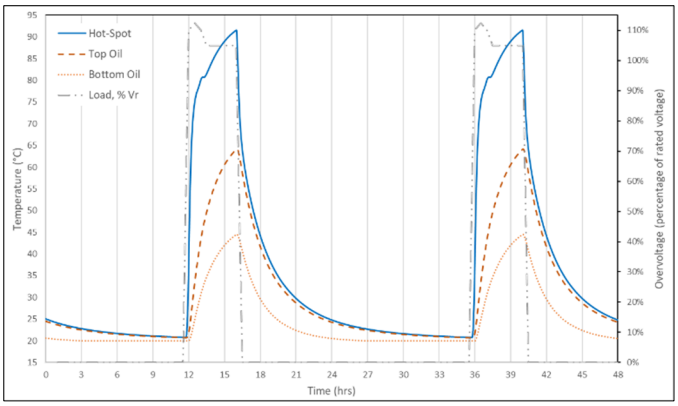

Figure 5. Loading curve and resultant temperatures for a 50MVAr shunt reactor

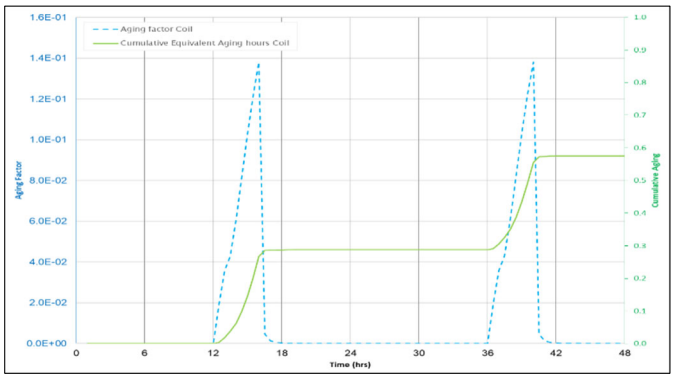

Figure 6. Calculated values of instantaneous and cumulative aging over two daily cycles. The total aging after 2 "days" reached 0.58 equivalent hours, indicating the end of paper life is not a probable failure mode for this unit.

The typical curve for shunt reactors in Sweden, which is expected to be similar to other countries, leads to them being loaded for approximately 4.5 hours every night. As the demand for energy in the grid drops, the system voltage rises. Thus, in our simulation, the shunt reactor is energized at midnight with a 10% overvoltage. After 15 minutes, the voltage increases to 112.5% for 30 min, resulting in a reduction of the voltage in the system. Next, the voltage is reduced to 110% for another 30 min and finally to 105% for 3 hours. The system voltage is expected to be again within the tolerances, and the shunt reactor remains de-energized until the next evening. To simplify the visualization, the ambient temperature was set to 20°C flat.

The chart represents the loading cycle starting at noon on a given day. As the same loading profile is repeated daily, the end of the simulation after 48 hours matches the initial conditions.

The light gray curve represents the voltage, as a percentage of the rated value, and its scale is indicated on the secondary axis. All other curves are temperatures and are indicated in the primary axis. It can be seen that after roughly 20 hours de-energized, the temperatures reach the ambient value of 20°C.

5. Online Monitoring

Online monitoring systems use measured values of voltage (or load current) to estimate the temperatures of equipment coils. The use of an accurate thermal model is crucial for ensuring the reliability of the indicated temperatures.
Thanks to the similarities between shunt reactors and transformers, it is common to apply transformer thermal model to shunt reactors. The development of a physics-based thermal model for shunt reactors, essentially a variation from the “Annex G” model presented originally by Pierce [8] represents a relevant advance for such systems.

6. Conclusions

The loading conditions of shunt reactors are very different from those of power transformers. And the effects of them over the equipment losses are also not the same. Thermal models developed for transformers may lead to relevant deviations if applied directly to shunt reactors.
While models such as the IEC 60076-7 [10] may work, they rely on empirically estimated time constants, whose reference values are mostly available for transformers, not for shunt reactors. Conversely, the developed model only uses a winding time constant to validate the time step and to calculate the thermal capacity of the windings. All temperature variations are directly related to the physical properties of the materials.
The thermal model calculations show a small difference in top oil temperature compared to measured values during the warm-up period temperature test, indicating good accuracy. This suggests that the use of this model for monitoring shunt reactors will lead to more accurate estimations of the lifespan.
Furthermore, this takes us to a new mathematical thermal model for shunt reactors, which can be directly implemented in digital monitoring systems. Nowadays, it is common to apply transformer monitoring systems to shunt reactors (reactors TMS). This new model opens the door to creating a real Reactors Monitoring Systems (RMS). Those reactors' on-line monitoring systems will provide a more accurate approach to reactors thermal behavior, improving in such a way all the basic functions of the system: hotspot temperature calculations, loss of life of the monitored device, and thus forecast of both variables (hotspot and loss of life). Forecast calculations are a very useful tool for renewable energy helping to dimension and operate reactors installed in renewable generation links based on the real requirements. For transformers, it has been estimated the difference between calculated and real losses of life is as large as 50% [9]. This difference can be even larger for shunt reactors subjected to daily on/off switching cycles.
Additionally, after being implemented in online monitoring systems, this new thermal model will allow for combining the predicted temperature with other measured parameters, e.g. dissolved gas content, supporting reactor condition assessment.
Finally, further research combining the proposed thermal mathematical model with online monitoring systems incorporating fiber optic direct hotspot temperature measurement will allow validation of this model.

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