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PS1–Experience and New Requirement for Transformer for Renewable Generation

Advantages of the loading and ambient temperature profile assessments for solar collector power transformer based on dynamic loading model

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SUMMARY

Nowadays, the global targets for a sustainable power system require ambitious solutions in order to connect renewable and alternative energy resources to the electric power grid. This paper presents a methodology for dimensioning step-up power transformers for large photovoltaic power plants from an optimization methodology based on technical and financial variables. Solar power generation is an intermittent energy resource, therefore the power transformers connected to the grid are usually underused, i.e. transformers are operating below their power rating. An economic analysis in combination with fulfilling technical requirements can be used during the procurement process to reduce the installation cost and promote the faster expansion of renewable power generation.

Solar power generation loading cycle have unique features compared to other renewable energy resources such as wind power. Optimization of the transformer should be performed based on these features. The study is designed as a practical verification of the loading and temperature profile where dynamic loading modeling based on the well-known IEEE Std C57.91-1995 method is applied to calculate the hotspot accurately. To verify the thermal performance and that temperature limits are not exceeded at high load, computational fluid dynamics (CFD) are used.

The proposed methodology of applying dynamic loading models applied in combination with Total Ownership Cost (TOC) analysis can substantially reduce the weight and footprint of the transformer, bringing better cost-benefit, and longer service life with higher reliability to the investor. Based on the successful application of this method, other applications could also be investigated for optimization, such as wind farm collector power transformers, which have a different loading pattern but are also underutilized when dimensioned for steady state loading.

KEYWORDS

Collector Transformer, Dynamic Loading Model, Aging, CFD Computational Fluid Dynamic, Solar, Loading Profile, Ambient Temperature Profile, TOC Total Ownership Cost.

1 INTRODUCTION

Power transformers are usually designed conservatively to withstand extreme combined scenarios of loading and weather conditions. For renewable power generator step-up (GSU) transformers, there is a strong interdependency between load and weather conditions, such that the extreme scenario would not actually occur in practice. The transformer would therefore always operate far from the maximum temperature limits. This imposes an important constraint during the design process [1]. Dimensioning the power transformer for a solar power plant without taking into consideration the loading profile is likely to overestimate the total size of the equipment. As a solar farm operates only a few hours a year at the maximum capacity, this over-dimensioning utilizes more material and increases the total size, weight, footprint, and raw material consumption, so this approach could have been used to dimensioning this equipment.

An alternative strategy is to design the transformer with dynamic overloadability. Overload implies some risks during power system operation, especially when the load profile exceeds the nameplate rating of some of the power devices in the system. Transformer overload limits are separated into long-term emergency overload, which mainly affects the expected lifetime of the device, whereas short-term emergency overload generates additional risks. This study proposes to identify such risks and to determine limitations and guidelines, in order to minimize risks to an acceptable level. The proposed methodology is based on thermal models using the dynamic overloadability approach for a real case representing a GSU power transformer installed at a large photovoltaic power plant.

Studies on dimensioning of power transformers for grid connection of renewable power generation has earlier been presented with a focus on wind power [2], [3]. The load from a solar power plant is different from wind power in that it follows a recurring 24 hour cycle, but is similar in that the load can go from zero to full load over a short time, and that the expected load over the entirety of transformer operation can be clearly quantified at the transformer design stage.

2 PROPOSED METHOD

The proposed method starts from input data considering a continuous load for the whole day, i.e., flat curve and ambient temperature according to standards [4]. Figure 1 shows the workflow of the method, in which the initial power S is the maximum total power S_{max} of the solar farm.
The first step in the proposed optimization algorithm is the insertion of S_{max}, ambient temperature, loading curve function, hotspot limit, top oil limit, and equivalent unitary aging. Thereafter, the second stage, represented by the second block, the parameter values of *i*) resistivity losses; *ii*) eddy losses; *iii*) stray losses; *iv*) core losses; *v*) the weight of the core and coil; *vi*) weight of the tank and *vii*) the volume of fluid; are determined as a function of the total power. Then the Annex G algorithm of the IEEE Standard is started [4].

The proposed method calculates the maximum hotspot and top oil temperature considering the loading curve profile, as well as equivalent aging. The algorithm verifies if any one of these three outputs exceeds the limit imposed by the well-established international standard. If no constraints are found, a reduction of 1 MVA in the total size of the transformer is performed and the iterative process continues. Otherwise, the algorithm stops and shows the latest calculation value of the power which is approved in these three criteria.

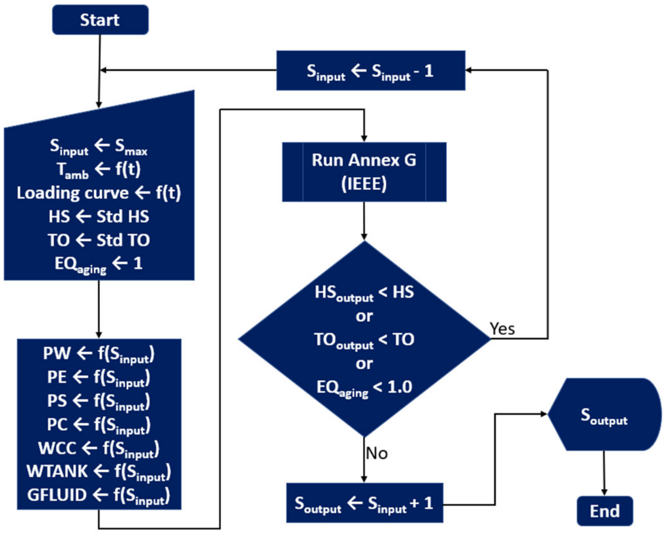

Figure 1 – Method workflow.

The ambient temperature Tamb is a time-dependent variable which is represented as an array of values. The maximum step considered is one hour, i.e., temperature measurements are collected hourly and input into the optimization algorithm. The loading curve applied to the GSU collector transformer throughout an entire year is also a time-dependent function that represents one of the most important and sensitive input information in the proposed model. In addition, the maximum hotspot (HS) and the maximum top oil (TO) temperature limits as per international standards, are needed in the optimization algorithm. Both hotspot and top oil are considered long-time emergency loading instead of normal cycle, since the total time with solar radiation during a day is less than 24 hours but more than a few minutes. Long-time emergency loading permits the hotspot and top oil temperature to exceed the normal cyclic temperatures and may be applied to transformers carrying non-continuous loads. In this research, the temperature limits established in the IEEE guide is considered, i.e. 140 °C for hotspot and 110 °C for top oil temperature [5]. These temperature values are defined in accordance with the thermal limits of the mineral oil and thermally upgraded insulation paper. In case of high-temperature class materials, such as aramid paper and/or ester fluid, these values can be increased and, consequently, the size of the transformer can be reduced.

Loss of insulation life must also be quantified as less than 1.0 p.u. equivalent aging (EQ_{aging}). As long as none of HS_{output}, TO_{output}, or EQ_{aging} exceed the maximum allowed value, the method reduces the total size of this transformer by 1 MVA until converge to the optimum transformer size that fulfills all restrictions.

3 TEMPERATURE CORRECTION

The method also corrects the effect of the losses on the equipment lifetime based on the temperature levels in which it is exposed. Thus, during colder months, losses are lower than other months comparing with the same load. In the cold days, when the transformer starts the operation at the beginning of the morning, the ambient temperature is low and due to the thermal inertia of the whole equipment, sometimes the transformer does not reach the higher temperature because there is insufficient time to stabilize the oil temperature, consequently, the load losses are minor.

Figure 2 shows the temperature diagram inside the transformer, where it is possible to observe the cooling media flow path inside the equipment. Points 1 is the lowest temperature found in the equipment, commonly referred to as Bottom Oil. As the heat-generating sources are the windings and the core, the oil flows through two elements, and the temperature increases progressively from the bottom to highest parts of the tank.

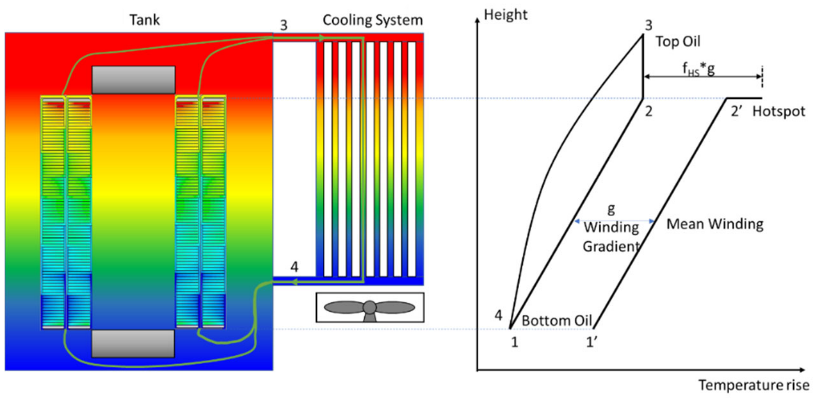

Figure 2 - Temperature map versus tank height.

Considering a 100 MVA transformer at 75°C, the ohmic losses are 264.3 kW, the winding eddy losses are 33.6 kW and the stray losses are 39.2 kW, in case, the reference temperature change to 45°C, the ohmic losses become 238.7 kW, the winding eddy losses become 30.4 kW and the stray losses become 43.4 kW, resuming the load losses at 75°C is 397.1 kW while the load losses at 45°C is 372.4 kW, 7.8 % lower. In this sense, this example shows the importance to correct the losses through the real temperature during loading cycle and ambient temperature. The load factor L_f can be represented by two different approaches: *i)* Average loading; *ii)* Average overtime of the root mean square (RMS) values of the instantaneous load.

This paper proposes a third approach method, average overtime of the RMS values of the instantaneous load considering instantaneous temperature correction, which is recalculate the load losses and consider this value to optimize the equipment and recalculate the Total Ownership Cost (TOC).

The method that utilizes average load has been presented a good approach, however, when the load variation increases, this method shows an unreal composition of load losses. For example, if a 100 MVA transformer is substituted for an 80 MVA transformer, the equivalent increase of loading is 25% higher, though it can be applied only for constant loading or with small variations. In this sense, the RMS load factor approach represents the real load for intermittent loading.

4 CASE STUDY

4.1 Real Loading and Temperature Profiles

The real loading curves and seasonal behavior of the ambient temperature are used to perform the life loss analysis. Therefore, a real case example is presented in Table I, in which the hourly average temperature per day is described throughout a year.

Table I – Annual average temperature (left) and annual average load in per unit (right).

	Average - Temperature [°C] / Loading [p.u.]											
h	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	13.4 / 0	13.9 / 0	13.6 / 0	12 / 0	10.1 / 0	8.9 / 0	7.7 / 0	8.9 / 0	9.1 / 0	10 / 0	10.9 / 0	12.1 / 0
1	12.8 / 0	13.2 / 0	13 / 0	11.4 / 0	9.4 / 0	8 / 0	6.7 / 0	7.8 / 0	8.1 / 0	9 / 0	10.1 / 0	11.4 / 0
2	12.1 / 0	12.5 / 0	12.4 / 0	10.7 / 0	8.6 / 0	7.1 / 0	5.7 / 0	6.7 / 0	7.1 / 0	8 / 0	9.3 / 0	10.6 / 0
3	11.4 / 0	11.8 / 0	11.8 / 0	10 / 0	7.8 / 0	6.2 / 0	4.8 / 0	5.6 / 0	6.2 / 0	7 / 0	8.5 / 0	9.9 / 0
4	10.7 / 0	11.2 / 0	11.3 / 0	9.3 / 0	7.1 / 0	5.4 / 0	3.8 / 0	4.6 / 0	5.3 / 0	6.1 / 0	7.7 / 0	9.2 / 0
5	10.2 / 0	10.5 / 0	10.7 / 0	8.7 / 0	6.3 / 0	4.6 / 0	2.9 / 0	3.7 / 0	4.5 / 0	5.3 / 0	6.9 / 0	8.6 / 0
6	10.8 / 0.1	10.2 / 0.1	10.1 / 0	8 / 0	5.6 / 0	3.8 / 0	2.2 / 0	3 / 0	3.9 / 0.1	6.3 / 0.1	8.9 / 0.2	10.1 / 0.2
7	12.4 / 0.6	12.2 / 0.4	11.9 / 0.3	9.5 / 0.2	6.5 / 0.1	3.9 / 0.1	2.2 / 0.1	4 / 0.1	6.9 / 0.4	8.8 / 0.7	11 / 0.8	11.9 / 0.8
8	14.1 / 0.9	14 / 0.9	13.7 / 0.8	11.6 / 0.7	9 / 0.6	6.8 / 0.5	5.7 / 0.5	7 / 0.7	9.9 / 0.8	11.5 / 0.9	13.2 / 1	13.8 / 0.9
9	15.8 / 1	15.7 / 1	15.3 / 0.9	13.7 / 0.8	11.6 / 0.7	9.9 / 0.7	9.2 / 0.7	10.4 / 0.8	12.8 / 0.9	14 / 1	15.2 / 1	15.6 / 1
10	17.4 / 1	17.3 / 1	16.9 / 1	15.6 / 0.9	13.9 / 0.8	12.9 / 0.7	12.4 / 0.7	13.5 / 0.8	15.4 / 0.9	16.3 / 1	17 / 1	17.2 / 1
11	18.7 / 1	18.6 / 1	18.1 / 1	17.2 / 0.9	15.9 / 0.8	15.4 / 0.7	15.1 / 0.7	16.1 / 0.8	17.5 / 0.9	18.1 / 1	18.4 / 1	18.5 / 1
12	19.8 / 1	19.7 / 1	19.1 / 1	18.4 / 0.9	17.5 / 0.8	17.3 / 0.7	17.3 / 0.7	18 / 0.8	19.1 / 0.9	19.5 / 1	19.5 / 1	19.5 / 1
13	20.5 / 1	20.4 / 1	19.8 / 1	19.2 / 0.9	18.4 / 0.8	18.4 / 0.7	18.7 / 0.7	19.3 / 0.8	20.2 / 0.9	20.5 / 1	20.2 / 1	20.2 / 1
14	20.9 / 1	20.9 / 1	20.1 / 1	19.5 / 0.8	18.9 / 0.8	19 / 0.7	19.3 / 0.7	19.9 / 0.8	20.6 / 0.9	20.9 / 1	20.5 / 1	20.5 / 1
15	21 / 1	21 / 1	20.1 / 0.9	19.4 / 0.8	18.6 / 0.7	18.7 / 0.7	19.1 / 0.7	19.9 / 0.8	20.5 / 0.9	20.8 / 1	20.4 / 1	20.5 / 1
16	20.7 / 0.9	20.6 / 0.9	19.6 / 0.9	18.7 / 0.8	17.6 / 0.6	17.5 / 0.6	17.8 / 0.6	18.8 / 0.7	19.4 / 0.8	20 / 0.9	19.7 / 0.9	20.1 / 0.9
17	19.9 / 0.8	19.8 / 0.8	18.7 / 0.7	17.4 / 0.4	15.9 / 0.2	15.4 / 0.2	15.5 / 0.3	16.8 / 0.4	17.5 / 0.5	18.5 / 0.6	18.5 / 0.7	19.1 / 0.8
18	18.8 / 0.4	18.6 / 0.3	17.4 / 0.1	16.4 / 0.1	15.1 / 0	14.4 / 0	14.4 / 0	15.5 / 0	15.6 / 0.1	16.6 / 0.1	17 / 0.2	17.8 / 0.3
19	17.6 / 0	17.8 / 0	16.8 / 0	15.6 / 0	14.2 / 0	13.5 / 0	13.4 / 0	14.3 / 0	14.5 / 0	15.5 / 0	15.9 / 0	16.8 / 0
20	16.7 / 0	17 / 0	16.1 / 0	14.8 / 0	13.4 / 0	12.5 / 0	12.3 / 0	13.1 / 0	13.4 / 0	14.3 / 0	14.9 / 0	15.9 / 0
21	15.8 / 0	16.1 / 0	15.4 / 0	14.1 / 0	12.5 / 0	11.6 / 0	11.2 / 0	11.9 / 0	12.2 / 0	13.2 / 0	13.9 / 0	14.9 / 0
22	14.9 / 0	15.3 / 0	14.7 / 0	13.3 / 0	11.7 / 0	10.6 / 0	10.1 / 0	10.7 / 0	11.1 / 0	12 / 0	12.8 / 0	13.9 / 0
23	14.1 / 0	14.5 / 0	14.1 / 0	12.5 / 0	10.8 / 0	9.7 / 0	9.1 / 0	9.5 / 0	10 / 0	10.8 / 0	11.8 / 0	12.9 / 0

In this specific case, higher temperatures are observed around 13 up to 15 hours, i.e., from 1:00 pm to 3:00 pm. The highest ambient temperature values throughout the year are verified in January/February and November/December. At the same time, during these same months, the highest power generation levels are also observed, in per unit. The rated power generation of the solar power plant is 1.0 p.u., which at steady state load and standard ambient temperature would require a power transformer rated at 100 MVA. The maximum average hourly load of 0.98 p.u. occurs at 10:00 am in December, i.e. the intermittent behavior of photovoltaic power generation demands only a few hours per year for the nominal rated power of the GSU transformer. Applying the loading curve with the data from the Table I, according to the methodology described in Section 2, the curve in Figure 3 is obtained.

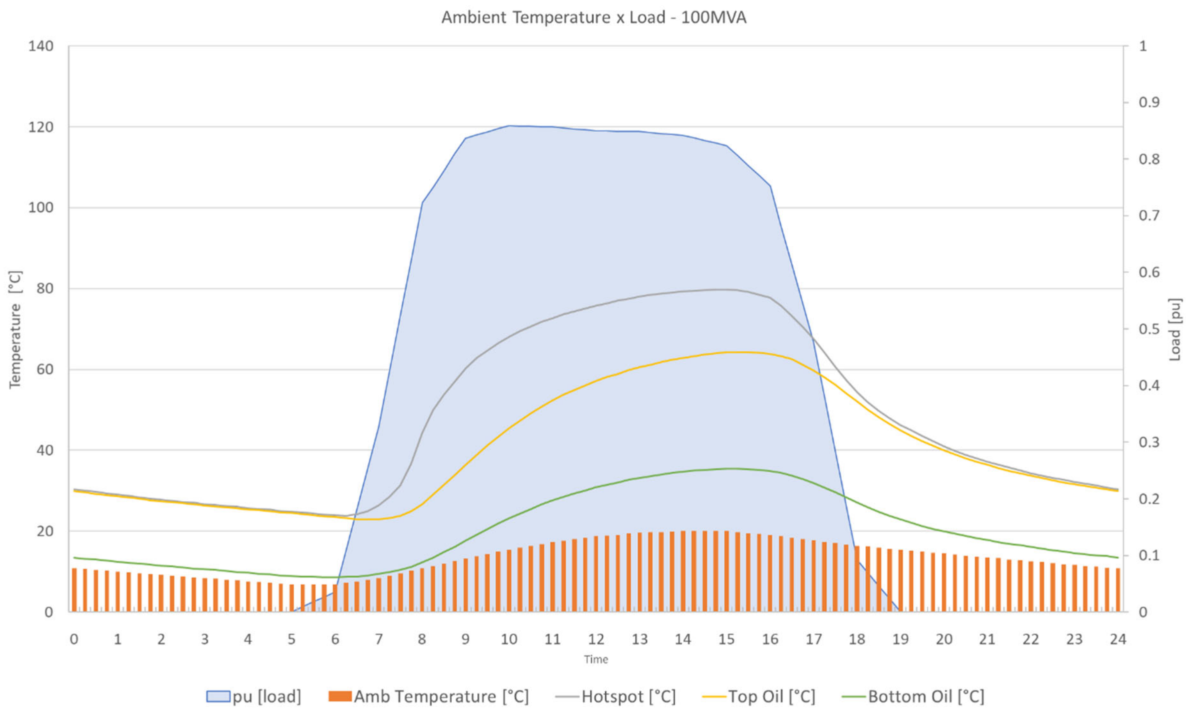

Figure 3 – Annual average loading and temperatures for a 100 MVA transformer.

The blue curve represents the average loading in the maximum loading is no more than 0.9 p.u.; the gray curve is the dynamic profile of the hotspot temperature inside the winding, with a maximum temperature of 80 °C approximately. Top oil and bottom oil are represented by yellow and green curves respectively and the orange bars represent the ambient temperature. With 1.0 p.u. corresponding to 100 MVA, the output data is: Maximum hotspot temperature of 79.8 °C at 15 hours and 0 minutes; Maximum top fluid temperature of 64.4 °C at 15 hours and 21 minutes and; Equivalent aging: 0.179 p.u., i.e., 10 minutes and 44 seconds a day.

As an example, a transformer with thermally upgraded paper can operate for its entire life with 110 °C at the hotspot [5], [7], which means that if the transformer faces a constant loading and a constant temperature, the equivalent aging factor is unitary, i.e., after 150,000 h the DP of the paper will reach the end-of-life criteria. In case the aging factor is higher than 1.0 p.u., it means that the transformer is subjected to accelerated aging and vice-versa.

In Figure 4, the maximum hotspot, top oil temperatures and equivalent aging as per standards are the gray, yellow and green lines respectively. The minimum transformer size for the top oil temperature point of view is 63 MVA, for hotspot temperature is 64 MVA and 68 MVA for the minimum equivalent aging. In this context, the minimum allowable transformer size is 68 MVA.

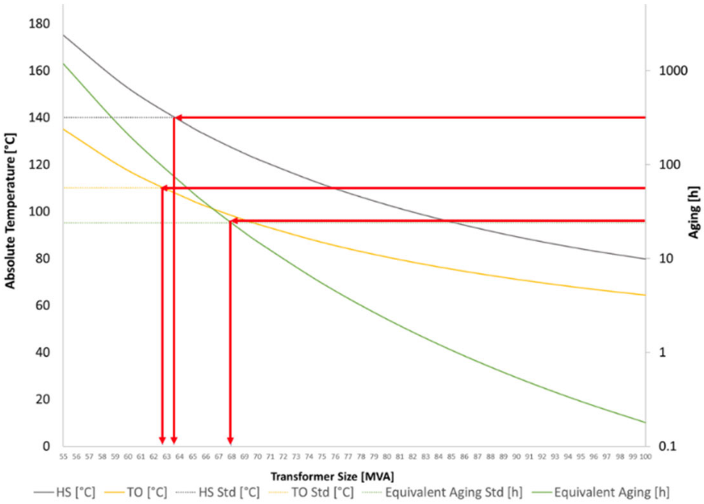

Figure 4 – Absolute temperature of hotspot, top oil and equivalent aging limits.

Calculation results of the IEEE Annex G dynamic thermal model with the same loading curve and ambient temperature curve applied to a 68 MVA transformer is shown in Figure 5. The output data are: Maximum hotspot temperature of 127.3 °C at 14 hours and 9 minutes; Maximum top fluid temperature of 98.3 °C at 15 hours and 9 minutes and; Equivalent aging of 0.994 p.u., i.e., 23 hours and 52 minutes a day.

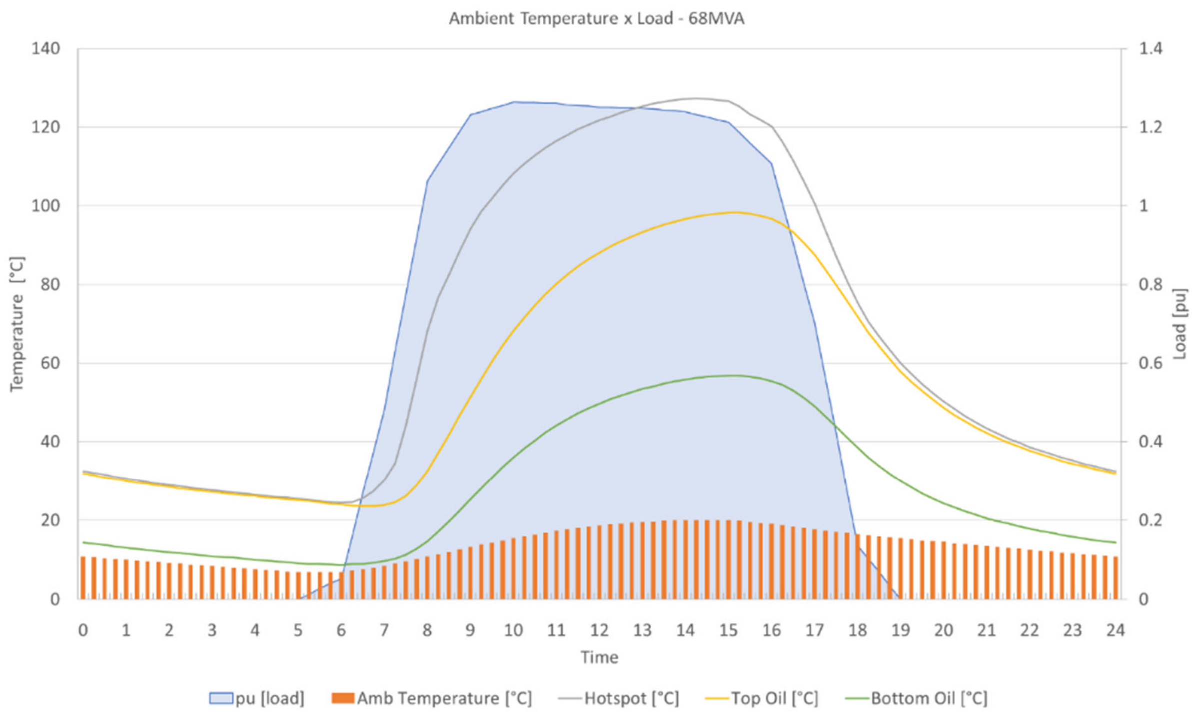

Figure 5 –Annual average loading and temperatures for a 68 MVA transformer.

4.2 Capitalization and Total Ownership Cost

The minimum technically viable size of the power transformer does not necessarily correspond to the minimum TOC. The 68 MVA represents the smallest rating for the GSU transformer. Economic analysis is required to verify how this corresponds to minimum TOC. An important aspect is the capitalization of losses. Focusing only on the initial investment cost of the transformer, or neglecting to distinguish between the difference in the capitalization of no-load losses and the capitalization of load losses, will result in a suboptimal transformer design.

In order to simulate the real case and calculate the TOC to compare the RMS load approach with and without temperature correction, some values were inserted in the model to test its sensitivity. The average energy price of the first year in operation is 0.02033 USD/kWh taken from the closing price of the last auction of solar power plant in Brazilian regulation marketing [8]. The average annual increase in energy cost is 1.52% per year according to a weighted index of the energy price provided by the World Bank [9]. Figure 6 shows the worldwide energy price index.

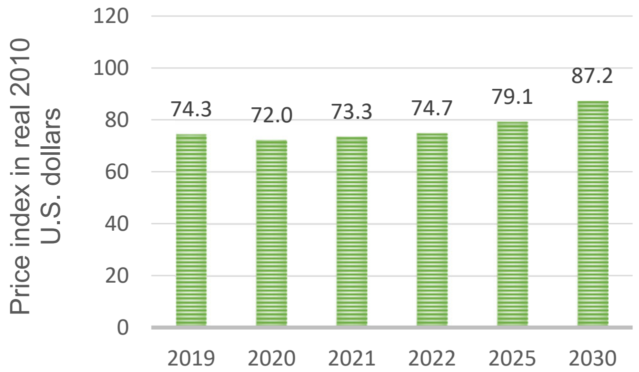

Figure 6– Price index of energy worldwide from 2019 to 2030 in 2010 U.S. dollars

Source: Adapted from Statista, 2020

From 2020 to 2030, the average increment is from 72.0 to 87.2, so, the annual average increase estimate price is 1.52% per year in the next 10 years. Another important data is the weighted average cost of capital (WACC). The estimated WACC of the energy transmission companies is 6.6% per year [10] and this value is used in this analysis. Finally, the cost of the transformer installed and commissioned in the substation, i.e., the final price given from the manufacturer, is also required as input. The transformer equipment cost has strong correlation with commodities prices due to the big amount of material used for the manufacturing. A good way to obtain the initial price of the investment (IP) is to have a knowledge of the prices of the main transformer elements needed. A good approximation is to get the initial investment cost of the transformer is given by (4.1),

$$\text{IPrice} = f_{price}(m_{copper}w_{copper} + m_{iron}w_{iron} + m_{oil}w_{oil}) \qquad [4.1]$$

The m_{copper} is the total mass of the copper and w_{copper} is the price of the copper given in kg/USD; m_{iron} is the total mass of the iron electric steel and w_{iron} is the price of the iron given in kg/USD and; m_{oil} is the total mass of the oil and w_{oil} is the price of the cooper given in kg/USD. These three cost by themselves do not represent the total cost of the equipment. For that reason, a price factor, f_{price}, is inserted into this model to consider all others costs elements such as engineering costs, manufacturing costs, others materials, taxes, transportation, installation, commissioning and the profit of the manufacture [11]. The total ownership cost calculated is show in Table II, in p.u., by using the methods previously introduced with 5500 USD/kW for no load losses and 2500 USD/kW for load losses.

Table II –TOC and TOC with temperature correction *versus* transformer size – base TOC at 100 MVA and RMS approach.

Power [MVA]	**100**	**95**	**90**	**85**	**80**	**75**	**70**	**65**	**60**	**55**
TOC [p.u.] - RMS	1.000	0.934	0.916	0.894	**0.877**	0.878	0.904	0.927	0.950	1.006
TOC [p.u.] - RMS with temperature correction	1.004	0.937	0.918	0.895	0.875	**0.874**	0.897	0.915	0.931	0.976

Table II shows that there is a different optimum point when temperature correction is considered. When TOC is calculated is it possible to observe that, there is a minimum optimum transformer size. The green color means the lower TOC prices and red color shows the higher TOC. For RMS approach without temperature correction (the first row) the optimum point is a transformer with 80 MVA rated power and TOC equaling 0.877 per unit. When temperature correction is considered (second row) a 75 MVA transformer is encountered with 0.874 per unit. As previously analyzed, the minimum allowable transformer size is 68 MVA due to the technical limitations of aging, top oil, and hotspot temperature. If only the technical limitation is taken into consideration in the procurement, the 68 MVA transformer will be chosen because that will be the most economical transformer. Considering the full TOC, the optimum transformer will be between 75MVA and 80 MVA, based on this loading and temperature profile.

5 ADDITIONAL DESIGN CONSIDERATION

5.1 Validation of winding hotspot temperature

The IEEE Annex G is a simplified thermal model. It is therefore recommended in those cases where needed, to validate the predicted winding hotspot temperature by state-of-the-art methods such of Computational Fluid Dynamics (CFD) during the design phase and fiber optic thermal measurement during the factory acceptance test. For the case study of the solar power GSU transformer, a 75 MVA design is subjected to CFD analysis according to the method described in [12], i.e. steady-state two-dimensional axisymmetric modeling with scaled losses. In [12] is shown that the two-dimensional modeling gives comparable results to three-dimensional modeling. Although the transformer as a whole is not in steady state, at 14h15 when the maximum winding hotspot occurs according to the IEEE Annex G dynamic thermal modeling shown in Figure 5, the load has been almost constant and slightly decreasing for several hours. This is much longer than the winding time constant. The transformer is therefore in quasi-steady state with the winding hotspot closely following the continuous temperature increase of the oil in the tank which has a longer time constant. It is therefore sufficient to perform steady state CFD analysis to capture the temperature rise of the winding over tank oil. Although unsteady CFD simulation can in principle be performed, it is computationally expensive [13] and does not add value to the design process. The values of bottom oil temperature and top oil temperature for the steady state CFD simulation are taken from the IEEE Annex G dynamic thermal model at the time of the maximum hot spot, i.e. the increased temperature of tank oil and the external cooling equipment performance at elevated temperature are considered as boundary conditions in the CFD analysis. The load is set to 100 MVA and the ambient temperature to 30 °C. The results are shown in Figure 7.

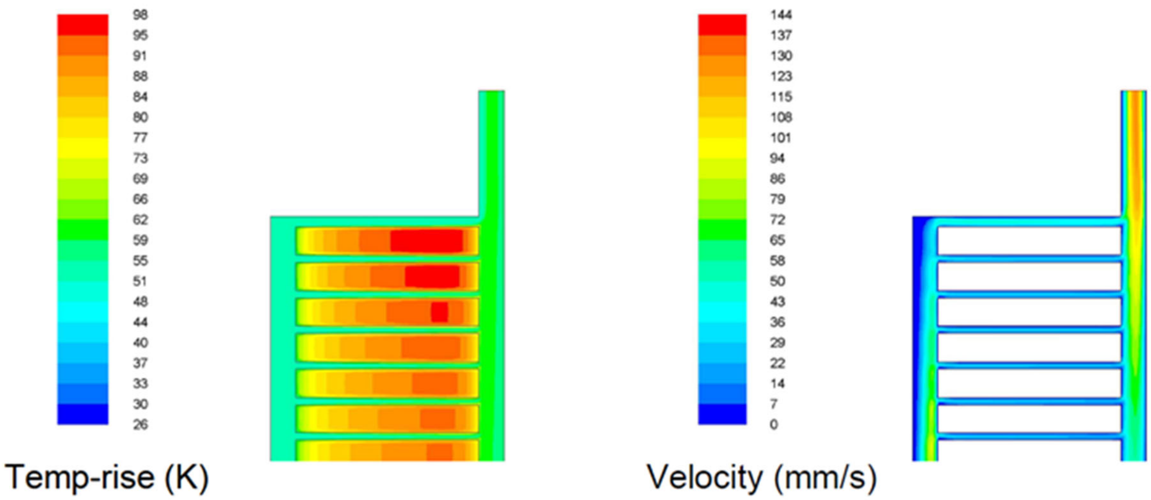

Figure 7 – CFD calculation temperature rise [K] above ambient air temperature (left) and fluid velocity contours [mm/s] (right)

The CFD results indicate a hotspot occurring in the top disc of the high voltage winding at a temperature of 128.4 °C, or 98.4 K temperature rise over ambient. This is slightly higher than what was predicted by the IEEE Annex G, 91.4 K. However, the value is lower than the maximum temperature in terms of ageing which means that the 75 MVA transformer is confirmed to fulfill all the required criteria.

5.2 Full design

The method described in this paper is based on the electrical and cooling design of the active part of the collector GSU power transformer. When performing the full design of the transformer it is critical to consider all components and materials being able to handle the expected temperature and load, including mechanical parts such as tank, conservator, applied materials, and painting besides to take into consideration the cleats and leads capability under maximum loading and temperature, bushings and tap-changers ampacity, other metallic parts temperatures, due to the leakage flux density like core clamps and tank.

6 CONCLUSION

Large safety margins do not carry a direct relationship with the high reliability of the overall system but increase investment costs. This paper, therefore, intends to address the timely and as of yet unresolved question of how to optimize transformer size for a new photovoltaic power plant installation using the expected power generation curve as well as the varying ambient temperature at the installation location. The goal of the method proposed in this paper is an optimization process for dimensioning a GSU power transformer based on the conditions under which it will operate throughout its lifecycle while fulfilling all economic criteria, ultimately achieving the most cost-effective transformer solution.

Technically this work also aimed to deal with two issues, encountered by utilities, energy generators, and finance area, without any clear answer until now: how to optimize transformer size in a new project with real loading and temperature curve; and this technically optimized transformer fulfill all economic criteria. Both items together fit the final cost-effective transformer for a new installation.

A few researches on this subject were found in the technical literature, however, the temperature correction inside the winding is not considered in this same research, and neither a joint relationship is defined on the total ownership cost of the power transformer. In this context, this method is efficient and more appropriate for its intended purpose because find the most suitable technical equipment comparing its financial inputs data like the price of energy, WACC of the investor and transformer life expectance, therefore, it is an original method that has great potential to assist in the design of transformers for systems with intermittent loading.

In recent years, some investors have reduced attention to the topic of losses capitalization, just focusing on the initial price of the transformer, or not distinguishing the difference between the capitalization of no-load losses and the capitalization of load losses. To avoid a reduction in the revenue of electricity production, a deep analysis in this context was done which has demonstrated the importance to take into account the loading profile and the huge difference between capitalization of no-load and load losses.

Ultimately, when specifying a transformer according to the proposed method, it is important to validate the thermal performance using state-of-the-art methods such as CFD and fiber optic temperature measurement, and to consider all the other aspects of a full transformer design.

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BIBLIOGRAPHY

[1] Pacheco, P.; Cuesto, M.; Burgos, M., "Sizing Step-up Transformers for Solar Generation based on Load Profiles Predictability", 6th International Advanced Research Workshop on Transformers (ARWtr), Cordoba, Spain, October 2019.

[2] Zarei, T., Morozovska, K., Laneryd, T., Hilber, P., Wihlén, M. Hansson, O., "Reliability considerations and economic benefits of dynamic transformer rating for wind energy integration", Electrical Power and Energy Systems 106 (2019), pp. 598-606

[3] Laneryd, T., Gustafsson, A. "Dynamic thermal behaviour of wind power transformers", A2-103, Cigre Session 2020

[4] IEEE Standards for Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures, IEEE standard C57.154.2012, 2012.

[5] IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators, IEEE standard C57.91.2011, 2011.

[6] Kenney, J. F. and, Keeping, E. S. Root Mean Square in Mathematics of Statistics, 3rd edition, Princeton, NJ, pp 59-60, 1962.

[7] IEC Power Transformers – Part 7: Loading guide for mineral-oil-immersed power transformers, International Standard IEC 60076-7, ed 2.0, 2018

[8] ABSOLAR. Associação Brasileira de Energia Solar Fotovoltaica, http://www.absolar.org.br/infografico-absolar-.html., 2019.

[9] STATISTA (2020), Price index of energy worldwide from 2013 to 2030, Statista, , download: 08-08-2020. https://www.statista.com/statistics/252795/weighted-price-index-of-energy/, 2020.

[10] Lam, P. The rate of return for electricity distribution networks. Independent Pricing and Regulatory Tribunal of New South Wales, Discussion Paper DP-26, November 1988.

[11] Calil, W. V. (2020). Methodology for Specification of Generator Step-Up Transformers in Photovoltaic Power Plants Based on Real Loading Profile. Tese (Doutorado) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2020.

[12] Laneryd, T., Gustafsson, A., Samuelsson, B., Jiao, Y. "Selecting the right level of complexity for thermal modelling of transformer windings", A2-105, Cigre Session 2018

[13] Laneryd, T., Nordman, H., Hosain, L., "Increasing power transformer loading capacity through detailed dynamic thermal analysis of heat run test using CFD", 1140, Cigre International Symposium 2021, Ljubljana