Predicción de la pérdida de vida del transformador de potencia en Escenarios de mantenimiento y gestión de la demanda

Forecasting of power transformer life loss under Maintenance and Demand Side Management Scenarios

L. Rosero[1], V. Bocanegra [2], A. Pavas[3], I. Durán[4]

[1] PAAS-UN, Facultad de Ingeniería., Universidad Nacional de Colombia, Colombia. Email: lsroseroz@unal.edu.co
[2] PAAS-UN, Facultad de Ingeniería, Universidad Nacional de Colombia, Colombia. Email: vlcardenasbo@unal.edu.co
[3] PAAS-UN, Facultad de Ingeniería, Universidad Nacional de Colombia, Colombia. Email: fapavasm@unal.edu.co
[4] MEEP-ECIJG, Escuela Colombiana de Ingeniería Julio Garavito, Colombia. Email: ivan.duran@escuelaing.edu.co

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RESUMEN

La operación del transformador de potencia tiene un impacto en la confiabilidad de los sistemas eléctricos debido a su importancia y costo. La operación se deriva del monitoreo y la condición de salud. La condición de salud se utiliza frecuentemente para modelar la tasa de fallas del transformador y para cuantificar los efectos esperados de acciones como mantenimiento y gestión de demanda. Los modelos actuales para evaluar la tasa de fallas y la vida útil requieren simulación de la vida del transformador, que son computacionalmente caros y con resultados inciertos. Este artículo presenta un nuevo enfoque para analizar la vida útil de un transformador y su desempeño de confiabilidad esperada, modelando la condición de salud considerando mantenimiento y gestión de demanda. El método muestra ventajas al cuantificar los efectos del mantenimiento y demanda para prolongar la vida útil. El método se aplica a un transformador y se enumeran los efectos esperados sobre la confiabilidad y la vida útil.

PALABRAS CLAVE: Gestión de Demanda, Gestión de Activos, Condición de salud, Tasa de fallas, Confiabilidad, Transformador de Potencia.

ABSTRACT

Power transformers performance has an impact on reliability of electric systems due to its importance and cost. Its performance can be derived from operation monitoring and its health condition. Health condition is frequently used to model transformer failure rate and to quantify the expected effects of actions like maintenance and demand management. Current models for assessing failure rate and expected useful life require simulation for the whole transformer life, which are computationally expensive and with results uncertain. In this paper, a new approach to analyze useful life of a transformer and its expected reliability performance is presented, resorting to health condition modelling, considering the application of maintenance and management of load profiles. The method shows advantages in quantifying the effects of maintenance and loading conditions as a strategy to extend useful life. The method is applied to a single transformer and the expected effects on reliability and useful life are listed.

KEYWORDS: Demand side management, Asset management, Health condition, Failure rate, Reliability, Power transformer.

1. INTRODUCCIÓN

Power Transformer is one of the most important components in an electrical system. It also represents a high investment and importance. Along the years, different strategies and studies had been developed in order to improve the performance of the assets and the electric grid itself, that is the reason why the lines of investigation of Demand side management (DSM) and

Asset management (AM) can work together to proportionate a better performance of the power transformer and a lengthening of its useful life.

Growing demand is a concern of electric systems due to the improvements needed to keep a good service. For this reason, DSM focuses on following the demand behavior and changing habits through different strategies depending on the characteristics of the customer. On the other hand, AM comprises some strategies focused on improving assets performance. One of the problems to mitigate in assets is the ageing, generally accelerated. For this, one of the strategies is to extend the useful life by applying maintenance schemes [1].

For this, it is necessary to know the condition of the transformer due to its ageing depends on many factors. This part will be evaluated forward. After knowing the condition of the transformer, it is possible to determine whether a maintenance is needed or can be useful as a precaution for the transformer.

Then, the question is how these concepts of DSM and AM are related and can work together to give a better performance of the asset? Well, as the transformer gets old quickly when it is overloaded, then by managing the demand of the transformer it is possible to slow down its ageing and the choosing of a maintenance scheme to be applied according to these conditions.

2. Methodology

As mentioned before, DSM is a strategy that focuses in changing the consum profile. In this case, as it is considered a power transformer, then the strategies considered in DSM are simplified and taken as load shifting and valley filling. By loading the transformer differently it is possible to change its ageing behaviour and then the expected. Then, an evaluation of AM for the transformer is developed by considering the effects of DSM applied.

2.1. Demand management side

In the considered cases, there are three demand profiles, one residential, one from industrial sector and one as constant load. By simulating these demand profiles with the electrical-thermal model of the transformer, it is possible to observe how the asset ages under these conditions. Fig. 1 shows these profiles.

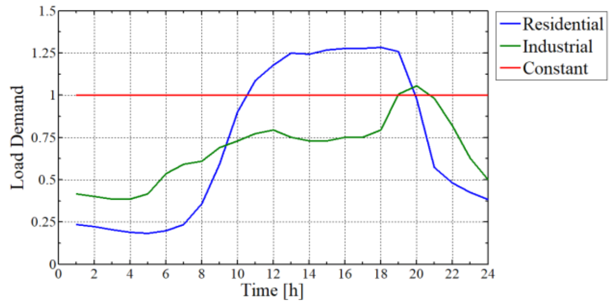

Figure 1. Initial load demands considered. **Source:** Own elaboration.

It was also considered a temperature profile due to the natural variation of temperature along the day which affects also de assets performace. This profile is shown in Fig. 2.

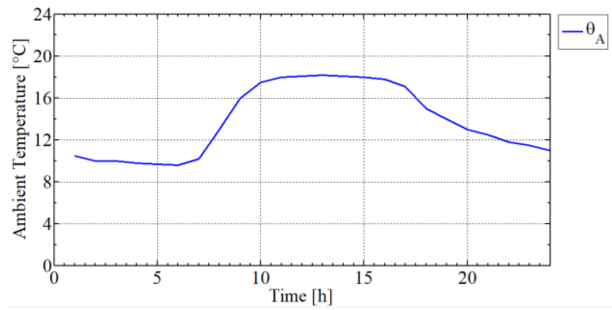

Figure 2. Ambient temperature profile considered. **Source:** Own elaboration.

The model composed by two differential equations which are Eq. 1 and 2 [2]:

$$\frac{I_{pu}^2\beta+1}{\beta+1}[\Delta\theta_{TO\_R}]^{\frac{1}{n}} = \tau_{oil}\frac{d\theta_{TO}}{dt} + [\theta_{TO}-\theta_A]^{\frac{1}{n}} \quad (1)$$

$$I_{pu}^2[\Delta\theta_{H\_R}]^{\frac{1}{m}} = \tau_H\frac{d\theta_H}{dt} + [\theta_H-\theta_{TO}]^{\frac{1}{m}} \quad (2)$$

This system represents the heat exchange between the air and the oil, and between the hottest spot and the oil. The solution of this system provides the temperatures in the oil and in the hottest spot of the transformer, θ_{TO} and θ_H respectively. Fig. 3 shows these temperatures. Here it can be seen that these exchanges of heat depend highly in the load curves, so evidently temperatures will be higher with higher load peaks. These temperatures are to related to the ageing of the transformer, which can be modeled by the Arrhenius Law according to Eq. 3 [3] [4]:

$$K_0 = Ae^{-B/\theta} \quad (3)$$

From this, it is possible also to find the ageing factor F_{AA} and the loss of life of the transformer as shown in Eq. 4 and 5 [3] [4].

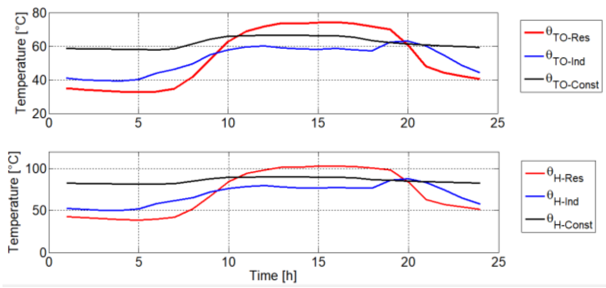

Figure 3. θ_{TO} and θ_H for different load demands. **Source:** Own elaboration.

$$F_{AA} = \exp\left[\frac{15.000}{\theta_{H,R}+273} - \frac{15.000}{\theta_H+273}\right] \qquad (4)$$

$$L_{life} = \int_{t_1}^{t_2} F_{AA} dt \qquad (5)$$

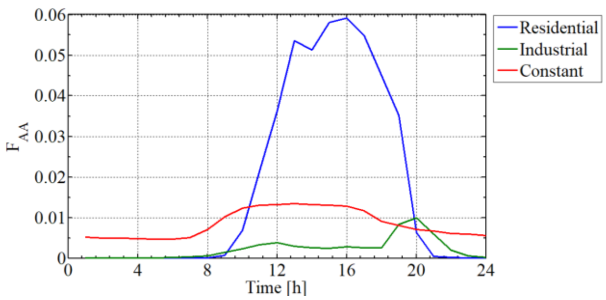

Figure 4. F_{AA} for different load demands. **Source:** Own elaboration.

Under these conditions, F_{AA} of Fig. 4 was obtained. As it can be seen, the ageing is higher for the residential load, which has higher peaks of load. On the other hand, the ageing factor F_{AA} for constant load profile follow closely the form of the ambient temperature. For instance, asset ages quickly when there are load peaks above 1 pu. Then implementing strategies from DSM is useful for reducing the fast aging of the transformer. For these, two scenarios of demand side management are considered.

2.1.1. Load Shifting

It consists in reducing peak loads through its transfer to another point of valley time. This strategy is applied to residential load due to its higher peaks [5].

2.1.2. Valley Filling

This strategy consists in filling valley hours in order to obtain a flatter load profile. This strategy was implemented with the industrial demand profile [5]. Fig. 5 shows the results of modifying these loads. And then in Fig. 6 the new ageing factor for these new loads.

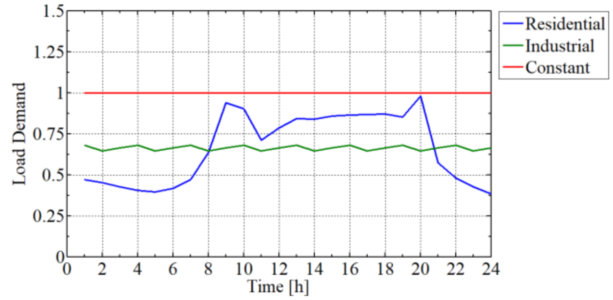

Figure 5. Managed load demands considered. **Source:** Own elaboration.

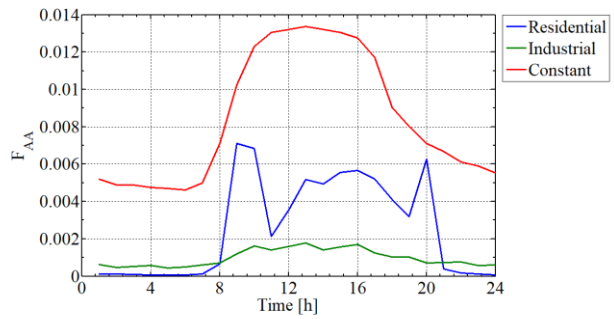

Figure 6. F_{AA} with Managed loads. **Source:** Own elaboration.

Therefore, it can be seen the impact of loading a transformer under and above 1pu. In Fig. 7 and 8, loss of life is presented for both cases. As expected, the loss of life of the asset is reduced after modifying load, resulting in a higher reduction in the residential case.

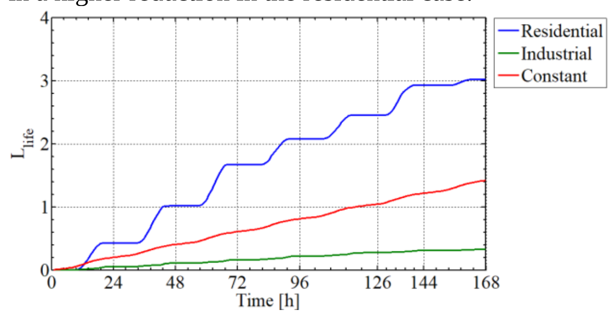

Figure 7. Initial loss of life. **Source:** Own elaboration.

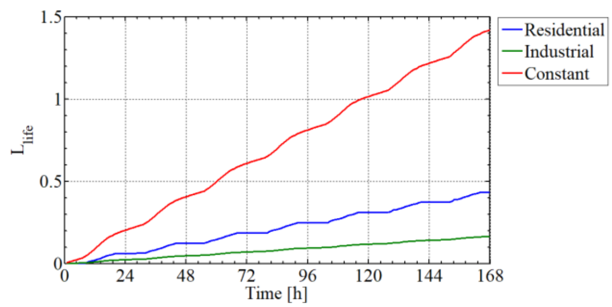

Figure 8. Managed loss of life. **Source:** Own elaboration.

2.2. Maintenance Implementation

After developing an initial approach of impact of loading in a transformer, Maintenance is considered. Among the maintenance schemes, there are: Corrective Maintenance (CM), Time-Based Maintenance (TBM), Condition-Based Maintenance (CBM) and Reliability-Centered Maintenance (RCM) [1]. All these maintenance schemes intend to improve reliability and performance of the transformer. In order to apply the different maintenance schemes to an asset, first it is necessary to talk about the health condition. The health condition can be calculated from several condition indexes that give information about how old the asset is. Evidently, each one of these indexes has its own importance and will affect the transformer performance differently, that is why it is necessary to make a weighted sum to calculate the health condition like in Eq. 6. For this, an r_i value is given according to each index ageing [6] [7].

$$HI = \frac{\sum_{i=1}^{n} \omega_i r_i}{\sum_{i=1}^{n} \omega_i} \qquad (6)$$

Table 1. Health indexes considered [8] [10]

Index	Weight
DGA	5
Load History	3
Furans	2
Age (F_{aa})	8
Humidity	4

Source. Modified from [8] [10]

3. Transformer Health Indexes

3.1. DGA

Std IEEEC57-104 [9] [10] proposes some initial values in ppm and growging rates for all of the gases. These gases are (H_2), (CH_4), (C_2H_2), (C_2H_4), (C_2H_6) y (CO). The sume of this is (TDCG) and is the one that provides the information about this health index.

Table 3. DGA evolution of r_i [8] [10]

Condition	Total of gases [ppm]	r_i
Good	TDCG ≤ 720	0
Acceptable	120 ≤ TDCG ≤ 1920	0,33
Poor	1920 ≤ TDCG ≤ 4630	0,66
Very Poor	TDCG > 4630	1

Source. Based on [8] [10]

3.2. Furans

Furans in the oil are the product of transformer paper ageing, which is one of the vitals of it. The quantity of furans can be calculated from Eq. 7 where F is the content of Furans in pmp and t is the operation time [10] [11].

$$\log(F) = -1{,}8308 + 0{,}0578t \qquad (7)$$

Table 2. Furans evolution of r_i [8] [10]

Condition	Furans Content [ppm]	r_i
Good	0,00 - 0,10	0
Acceptable	0,10 - 0,25	0,25
Caution	0,25-0,50	0,50
Poor	0,50-1,00	0,75
Very Poor	> 1,00	1

Source. Based on [8] [10]

3.3. Age of the transformer

The age as health index is calculated differently in several references. In [6], this index takes given values that set a respective r_i from year 0 to year 40 of the transformer. In this case, itis considered the F_{AA} as the health index. As we could verify, the managing of load can reduce the ageing of the transformer then that is how this health index will be calculated.

3.4. Loading factor

This health index identifies the load peaks that have a big impact in the asset condition. As we are considering managing load profiles, then it is expected an improvement of this health index after applying modifcations [2].

Table 4. Loading factor evolution of r_i [8] [10]

Condition	r_i
Good	0,05
Acceptable	0,25
Caution	0,50
Poor	0,80
Very Poor	1,00

Source. Based on [8] [10]

3.5. Moisture

According to Std IEEEC57-106 [12] the quantity of moisture in oil depends on the interaction of the paper insulation, but does not increase under exterior insulation, then some autors consider this index as the percent of saturation which relates the initial water content W_c and the solubility of water in oil S_0 as sets Eq. 8. And S_0 calculated according to Eq. 9.

$$\%\text{Sat} = W_c/S_0 \qquad (8)$$

$$\log_{10} S_0 = (-1567/\theta_{TO}) + 7{,}0895 \qquad (9)$$

4. Health Condition And Reliability

In this part, the analysis of reliability is developed in order to observe the effects of DSM strategies applied. For this, health indexes, health condition and failure rate are simulated for both scenarios: initial loads and managed loads. Failure rate is evaluated with Eq. 10, where A, B and C are constants [10].

$$\lambda(\mathrm{HI}) = Ae^{B\cdot HI} + C \qquad (10)$$

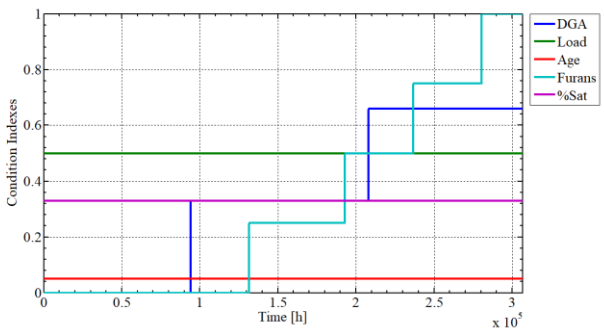

Figure 9. Initial health indexes. **Source:** Own elaboration.

In Fig. 9 it is presented the evolution of health indexes with initial load demand and in Fig. 10 the same health indexes for managed load demand.

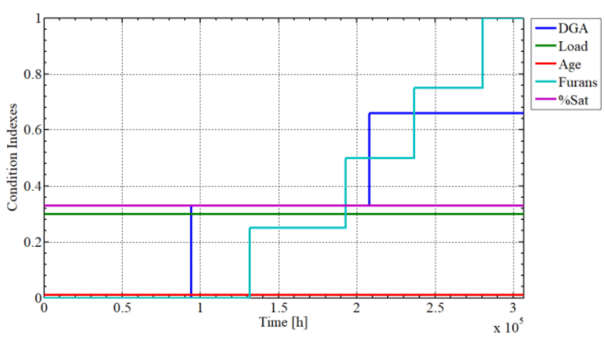

Figure 40. Health indexes for managed load. **Source:** Own elaboration.

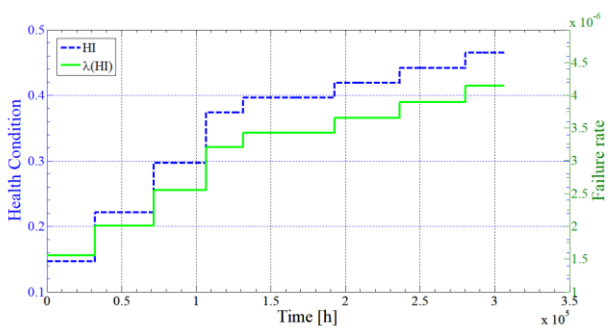

Figure 11. Initial health condition and failure rate. **Source:** Own elaboration.

Fig. 11 and 12 show the HI and failure rates λ(HI) for both scenarios. It is possible to observe that in managed scenario, HI and λ(HI) have reduced in scale in comparison to the initial case, which a clear proof of improvement

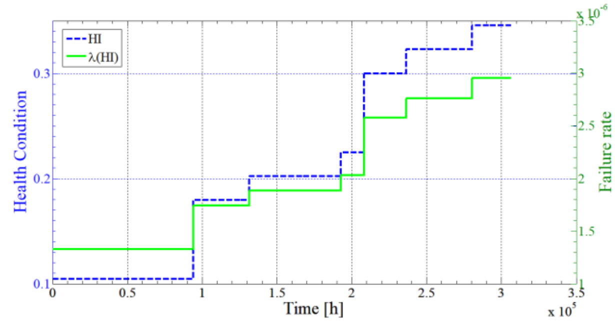

Figure 5. Health condition and failure rate for managed loads. **Source:** Own elaboration.

After obtaining these failure rates for both scenarios, a Monte Carlo simulation is applied and obtaining as result a probability distribution of interruptions for those failure rates. Fig. 13 shows these distributions which has a significant reduction from initial to managed loads.

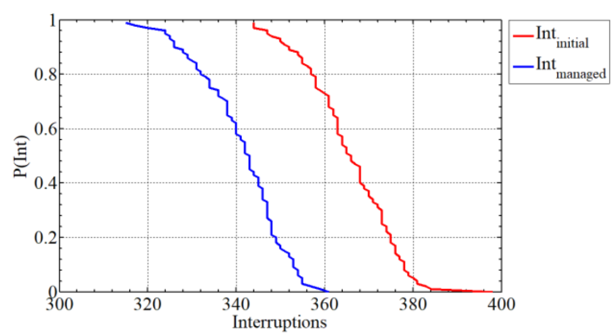

Figure 6. Probability of interruptions for initial and managed loads. **Source:** Own elaboration.

Therefore, an improvement of applying DSM strategy is verificable. Finally in this part, applying maintenance will be considered for both scenarios. It is considered a single maintenance scheme due to its applyment and analysis is extensive and can be studied deeply in others papers, and because the intention of this paper is to show that DSM and AM can work together, so as illustrative, only RCM is simulated in this case. For the simulation, it is considered that a maintenance can return one o several health indexes to their last condition affecting directly HI and λ(HI), as an extension of useful life.Fig. 14 shows the evolution of initial and managed failure rates and also the impact of applying maintenance in this scenarios. As can be seen, $\lambda_{\text{managed-TBM}}$ represents the higher reduction in failure rate and as expected, the useful life. This reduction is appreciable also in Fig. 15 where $\text{Int}_{\text{managed-TBM}}$ is the distribution with fewer interruptions.

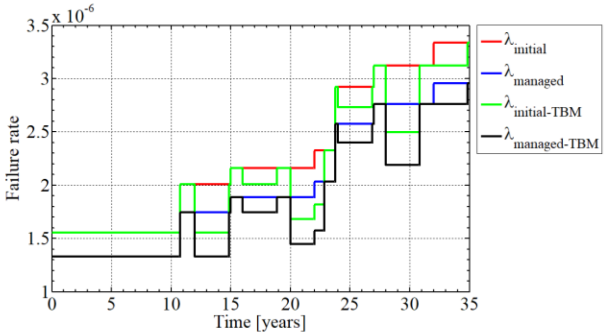

Figure 7. Failure rate for all scenarios. **Source:** Own elaboration.

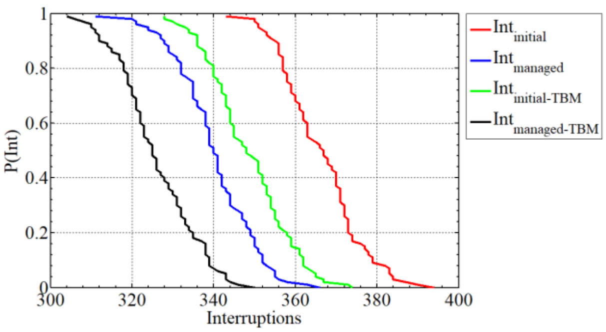

Figure 8. Probability of interruption for all scenarios. **Source:** Own elaboration.

Therefore, along the simulations presented in this article it can be seen how DSM and AM strategies can be applied in combination to obtain a better performance of the asset, in this case the power transformer. A deeper study in this combination would be convenient due to both topics are extensive and including and analyzing all scenarios possibles may give interesting results.

4.1. Conclusions

This paper presented a new approach to analyze useful life of the power transformer by studying the effects of loading and maintenance. After applying both DSM and AM strategies, the results verified that reducing peaks on loads, prevents the power transformer from ageing fastly, which has a high infuence on the health condition of the transformer. Likewise, this effect will be seen in loss of life of the transformer. And finally, by applying maintenance, it was possible to obtain the best performance of the transformer under the considered conditions.

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