Overloading Analysis of an Industrial Client Distribution Transformer in a Portuguese Island

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Abstract—**In this paper an analysis is made of the impact of emergency loading made by several inductive loads on the thermal ageing of a distribution transformer belonging to a private industrial client. The analyzed system is a fragment of an isolated electric grid in a Portuguese Island. A transformer thermal model is used to estimate the hot-spot temperature and top-oil temperature given the load ratio. Real data are used for the main inputs of the model, i.e., private industrial client load, transformer parameters and the characteristics of the factory. Finally, a smart transformer protection method is proposed by the authors with the aim of monitoring and protecting it from similar upcoming challenges.**

Keywords—distribution transformer; smart relay; loss-of-life; battery; transformer ageing; industrial client.

I. INTRODUCTION

One of the utmost important components as well as one of the most cost-intensive elements in a power network is the transformer. An efficient transmission and distribution of electricity through different voltage levels is attainable by utilizing transformers. Any outage of this element could affect the reliability of the entire network and could have a considerable economic impact on the system. Therefore, the reliability of this crucial element should be investigated [1].

Good planning and precise controlling have to be taken into account in order to benefit from the operation of power and distribution transformers with efficiency. Usually, transformers are designed to operate within the intervals of its nameplate ratings. However, distribution transformers are occasionally loaded above nameplate ratings due to existing possible contingencies on the transmission lines, failures or faults in power systems, or economic considerations [2-3].

Consequently, in such cases when the power transformer overloading exceeds the limit of its nameplate ratings – risks are taken and consequences occur which can generate failures as a result. In situations when overloading occurrences are not operated with proper caution, the transformer can have additional damage which is not always visibly apparent. The aforementioned type of failures can be categorized as short-term and/or long-term failures. One of the most significant consequences of overloading power transformers is the increased aging [4]. Consequently, new methods to mitigate the ageing and loss-of-life (LOL) of the transformer is a research topic of renewed interest in literature and the purpose being to make this indispensable part of the electric system more sustainable, and subsequently, to safeguard the overall sustainability of the entire system [5].

In general, as a result of the low load factor and other additional requirements, the operation efficiency of power transformers is reduced. The transformers are commonly designed and operated with loading between 40%–60% which is justified by the purpose of maintaining reliability during contingencies [6]. For instance, circa 25% of distribution resources in the United States of America are used only for 440 h of peak load [7].

In addition, as a result of load growth, an upgrade of power transformers at substations is required. The outdated method which resides in the reinforcement actions due to an increasing load is highly costly. As a result, utilities have the tendency to intensify the operation of the already installed assets which results into highly utilized systems [8]. Therefore, innovative and original solutions for load modification in the grid have to be implemented during contingencies with the intention of decreasing the LOL. Thus, the transformer utilization efficiency can be improved and economic savings can be reached by postponing reinforcements and as a consequence, the general sustainability also is increased [7].

The overloading of distribution transformers causes an increase of operation temperature. It is a fact that the operating temperature has an influence on the ageing of distribution transformers. As the operating temperature varies with the loading of a transformer, it is important to model the heat transfer characteristics between windings and oil. The purpose is to make a prediction of the θ_h in the transformer as a function of the load by taking the cooling characteristics into consideration [9-11].

In this paper, a part of São Miguel medium voltage distribution network was used as a case study. A transformer that supplies a private industrial client was chosen. The subject of this case study is a transformer substation which supplies one private industrial client through a 250kVA, 10kV/0.4kV oil-immersed transformer. The private industrial client is a factory that produces sugar out of sugar beet. During February of 2014 several measurements were performed at the transformer substation and the energy consumption of industrial client was recorded, thus a daily baseline load profile was created. In this paper an analysis of the impact of several inductive loads on the thermal ageing of distribution transformer of the private industrial client during a certain day in which emergency loading events were needed is made. Given the results, the monitoring systems are a subject of research since they are considered essential to ensure the reliability and sustainability of the transformer. Finally, a smart transformer protection method is then proposed.

This paper is organized as follows: in Section II, the employed methodology is developed. Then, in Section III, the distribution network of São Miguel, Azores, as well as the simulation results of the anomaly and critical analysis are presented and discussed. The aspects of protection and monitoring systems are analyzed in section IV and a smart relay is proposed. Finally, the conclusion is drawn in Section V.

II. METHODOLOGY

A. Estimation of the Transformer Loss of Life (LOL)

Correct preservation of mineral-oil-tilled distribution transformers is particularly important in power systems. Consequently, there is a necessity to adopt a serious approach concerning transformer loading, with the purpose of benefit as much as possible from their availability and long duration service. The insulation system of a power transformer is fundamentally made of paper and oil which suffers from ageing. The sudden rise of the load results in an increase of the θ_h and subsequently influences the thermal decomposition of the paper [9-11].

Given that the temperature distribution is not uniform, the hottest segment of the transformer will be the most damaged as a result. Therefore, the θ_h directly affects the life duration of transformers [12-13].

The relative ageing rate for the thermally upgraded paper is > 1 for θ_h greater than 110 ºC and signifies that the insulation ages faster when compared to the ageing rate at a reference θ_h, and it is < 1 for θ_h less than 110 ºC [14]. By designation, the θ_h is the hottest temperature of any location in the transformer winding. If the transformer experiences large electrical loads then high core-winding temperatures are created which in turn result in the chemical breakdown of insulating oil and insulating paper [15].

The fundamental idea behind the θ_o rise model is that a rise in the losses is a consequence of an escalation in the loading of the transformer and consequently of the total temperature in the transformer. The temperature oscillations depend on the overall thermal time constant of the transformer. In turn, such constant depends on the rate of heat transfer to the environment and the thermal capacity of the transformer [15].

TABLE I.   USED TRANSFORMER PARAMETERS

Symbol	Definition	Value	Units
g_r	Average winding to average oil temperature gradient at rated current	15.9	Ws/K
H	Hot-spot factor	1.25	
k_{11}	Thermal model constant.	0.5	
k_{21}	Thermal model constant.	2	
k_{22}	Thermal model constant.	2	
P_r	Distribution Transformer Rated Power	250	kVA
R	Ratio of load loss to no-load loss at rated current	5.957	
x	Exponential power of total losses versus top-oil temperature rise	0.8	
y	Exponential power of current versus winding temperature rise	1.3	
$\Delta\theta_{o,r}$	Top-oil temperature rise at rated current	41.5	K
τ_0	Average oil time constant	210	Minutes
τ_w	Winding time constant	10	Minutes

The overall transformer losses are proportional to the θ_o rise in the steady state. In transient conditions, the θ_h is defined as a function of time, for varying load current and ambient temperature [9]. The oil insulation system of a transformer under working conditions is vulnerable to quite a few types of stresses, such as thermal, electrical, environmental and mechanical. The consequence of each stress factors or the effects of their interaction has an influence on the ageing of the insulating system. In the case of the increasing step of loads, the θ_o and winding θ_h rise to a level corresponding to a load factor of K. The top-oil $\theta_o(t)$ temperature is as follows:

$$\theta_o(t) = \Delta\theta_{o,i} + \left\{ \Delta\theta_{o,r} \times \left[\frac{1+R\times K^2}{1+R} \right]^x - \Delta\theta_{o,i} \right\} \times \left(1 - e^{-t/(k_{11}\times\tau_o)} \right) \quad (1)$$

where $\Delta\theta_{o,i}$ is top-oil (in tank) temperature rise at start in °K, $\Delta\theta_{o,r}$ is top-oil temperature rise at rated current in K, R is the ratio of load loss to no-load loss at rated current, K is the load factor (load current/rated current), x is the oil exponent, k_{11} is a thermal model constant and τ_0 is average oil time constant.

The hot-spot temperature rise $\Delta\theta_h(t)$ is as follows:

$$\Delta\theta_h(t) = \Delta\theta_{h,i} + \left\{ H\times g_r \times K^y - \Delta\theta_{h,i} \right\} \times \left[k_{21}\times\left(1-e^{-t/(k_{22}\times\tau_w)}\right) - (k_{21}-1)\times\left(1-e^{-(t\times k_{22})/\tau_o}\right) \right] \quad (2)$$

where $\Delta\theta_{h,i}$ is hot-spot-to-top-oil (in tank) gradient at start in K, H is the hot-spot factor, g_r is the average winding to average oil (in tank), y is the winding exponent, k_{21} and k_{22} are thermal model constants and τ_w is a winding time constant.

In the case of the decreasing step of loads, the θ_o and winding θ_h decrease to a level corresponding to a K [9]. The top-oil temperature $\theta_o(t)$ can be calculated as follows:

$$\theta_o(t) = \Delta\theta_{o,r} \times \left[\frac{1+R\times K^2}{1+R} \right]^x + \left\{ \Delta\theta_{o,i} - \Delta\theta_{o,r} \times \left[\frac{1+R\times K^2}{1+R} \right]^x \right\} \times \left(e^{-t/(k_{11}\times\tau_o)} \right) \quad (3)$$

The hot-spot temperature rise is as follows:

$$\Delta\theta_h(t) = H\times g_r \times K^y \quad (4)$$

At long last, with $\theta_o(t)$ and $\Delta\theta_h(t)$ from Eq. (1) and (2) for increasing load steps, and Eq. (3) and (4) for decreasing load steps and plus the ambient temperature θ_a the overall hot-spot temperature $\theta_h(t)$ equation is as follows:

$$\theta_h(t) = \theta_a + \theta_o(t) + \Delta\theta_h(t) \quad (5)$$

The rate at which the ageing of paper insulation for a θ_h is decreased or increased compared with the ageing rate at a reference θ_h (110ºC) [9] is the relative ageing rate V [10].

In case of thermally upgraded paper, that is chemically altered to improve the stability of the cellulose structure, the relative ageing rate V is [10]:

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h+273}\right)} \qquad (6)$$

Completed a given period of time, the loss of life L during the time interval t_n is as follows:

$$L = \int_{t_1}^{t_2} Vdt \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n \qquad (7)$$

In order to determine the transient solutions for θ_o and θ_h – a thermal model is conceived and proposed for the distribution transformer.

B. The ageing characteristics

The degradation of the paper can make the transformer yield regarding a few mechanisms: the frail paper can be separated from the transformer windings and obstruct ducts. The water is a product of degradation and builds up in the paper, decreasing its resistivity. At the limit, local carbonizing of the paper raises the conductivity thus overheat – as a consequence the conductor fails [15].

Due to motives mentioned above it is essential to know the state of the transformer and the operating condition. The Montsinger low dictates that raising the average lifetime temperature 8 degrees over the maximum permissible operating temperature causes a reduction up to half of the expected lifetime of the paper oil [16]. The average lifetime temperature can be assessed with the load duration curve of the transformer as in Fig. 1. With this average lifetime temperature the LOL can be determined with the Montsinger curve of Fig. 2. For instance, if the maximum permissible operating temperature is 90 °C and the average lifetime temperature is 98 °C, the total lifetime reduction is 50%. This signifies that the expected lifetime for a transformer of 50 years is reduced to 25 years if the maximum permissible operating temperature is surpassed in average by 8°C. If the transformer suffers LOL then the condition curve of Fig. 2 has to be suitably revised. Such curve defines the condition of the equipment beginning with 100% (new) and going down to 0% (LOL being 0).

Overloads superior to those aforementioned above may be carried in emergencies. However, some LOL beyond normal will occur.
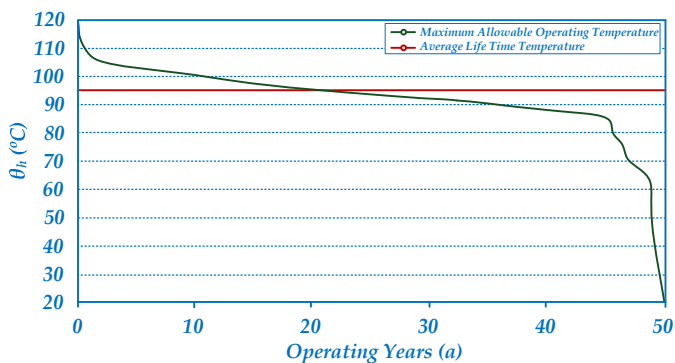
As seen before, the rate of deterioration is a function of time and temperature and is commonly expressed as a percentage LOL. Fig. 3 illustrates that the LOL for 65 °C transformer insulation could be about 1% for one 24-hour emergency operation at 145 °C. One 8-hour operation at 155 °C, or ten 2-hour operations at 145 °C, etc., given the emergency operation is preceded by operation at an average continuous θ_h not exceeding 110 °C [3].

III. CASE STUDY

The Azores are a Portuguese autonomous region, is an archipelago situated in the North Atlantic and is comprised of 9 islands.
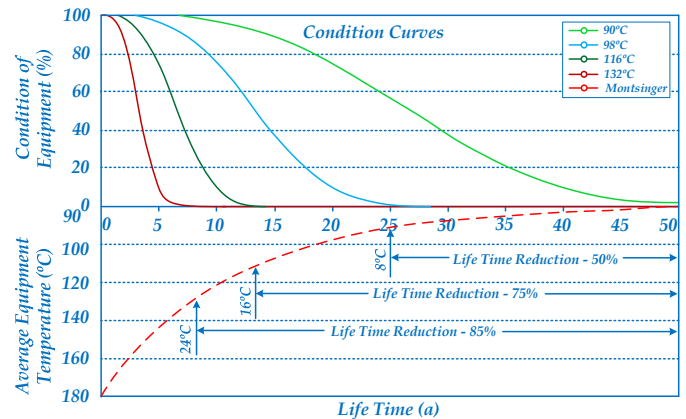

Fig. 2. Temperature - lifetime phase diagram and the Montsinger law.
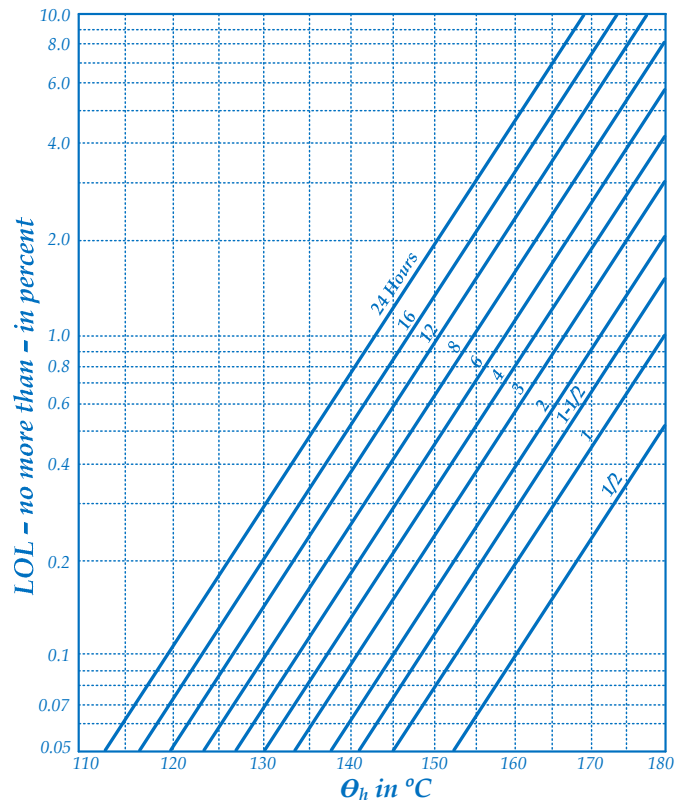

Fig. 3. LOL versus θ_h for different time periods.

Fig. 1. Load duration curve.

São Miguel Island is the key and most populated island in the archipelago and covers 760 km². On the island live circa 140,000 inhabitants. For this study, a part of São Miguel medium voltage distribution network was utilized as a sample for investigation. A transformer exclusively connected to a private industrial client was selected. Fig. 4 displays a part of the medium voltage distribution network and the classification of several outputs. For this case study the transformer substation PT1094 was utilized which supplies one private industrial client through a 250kVA, 10kV/0.4kV oil-immersed transformer.

The characteristics of the transformer used in this paper are drawn from Ravetta et al. [17] that presented the data of a real 250 kVA oil transformer with Oil Natural Air Natural (ONAN) cooling in which a natural convectional flow of hot oil is used for cooling. The properties are presented in Table I. The private industrial client is a factory that produces sugar out of sugar beet and has many inductive machines. It employs around 120 workers and operates in 3 working shifts of 8 hours each. The first working shift starts at 08:00, the second at 16:00 and the third at 00:00. It is presumed in this paper that the workers are evenly distributed throughout the working shifts.

During the month of February 2014 several measurements were realized at the transformer substation PT1094 and the energy consumption of the industrial client was documented. As a result, a daily baseline load profile was created as shown in Fig. 5. It is also given the power factor of the transformer – around 0.95. It can be observed that a 250 kVA transformer is properly designed for a 140 kW of the peak in daily load profile, considering that a typical value for an inferior size transformer would be 167 kVA which would not be qualified [18].

During these measurements, in the course of a certain period, the transformer was overloaded due to an abnormal event caused by the inductive machines that operate in this factory. The data recorded in such event is presented in Fig. 6 and by analyzing it is possible to apply the transformer thermal model, using the load ratio as an input to acquire the values of θ_h and θ_o temperatures which can be seen in the Fig. 7 and 8, respectively. Using the ageing equations (6) and (7), transformer LOL can now be determined. The LOL of the transformer is approximately 308 days which means that from the transformer expected life at normal operation (7500 days) is withdrawn the number of days that this transformer lost. Overall, merely for this day of transformer a typical operation the LOL in percentage was 4.21%.
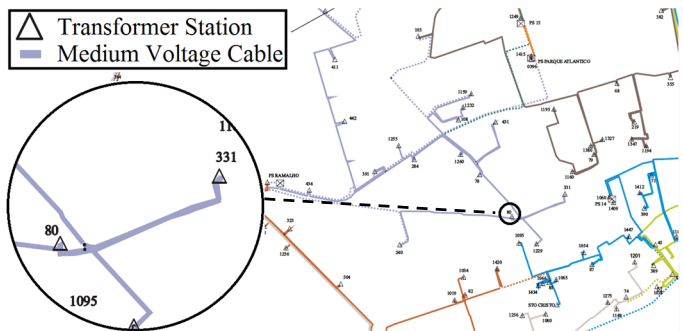

Fig. 4. A part of São Miguel medium voltage distribution network and the identification of PT80 output [18].

IV. ASPECTS OF PROTECTION AND MONITORING SYSTEMS

The transformers are one of the most expensive elements of equipment found in the utility's inventory. The business crescendos and the globalization constantly pressure utilities to do more with less. This causes an increasing need for tools to support not only the transformer protection but the intelligent monitoring of their status, activities, and history – a task that could be undertaken by smart relays. From time to time overcurrent relays are planned to provide fault protection and also be responsible for some level of overload protection.
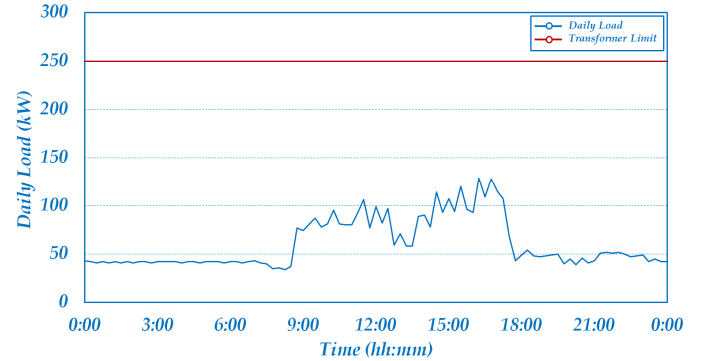

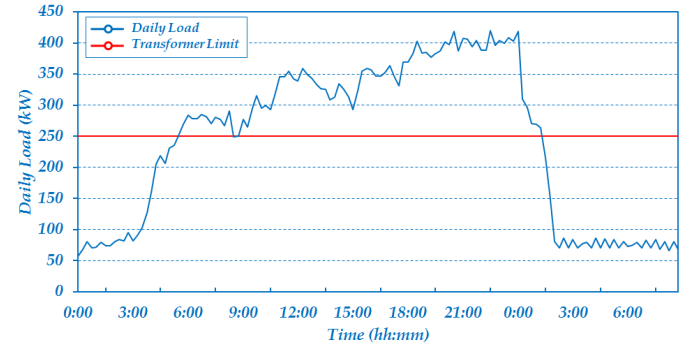Fig. 5. Daily baseline load profile.

Fig. 6. The daily load profile during the anomaly.
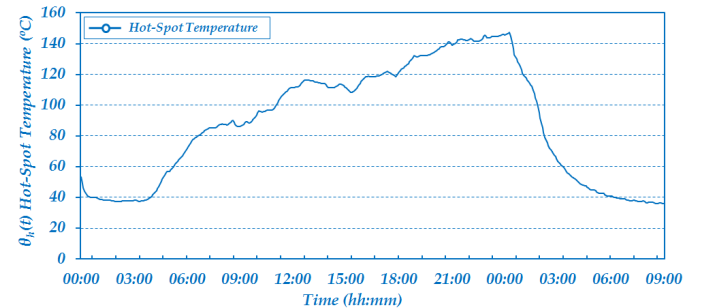

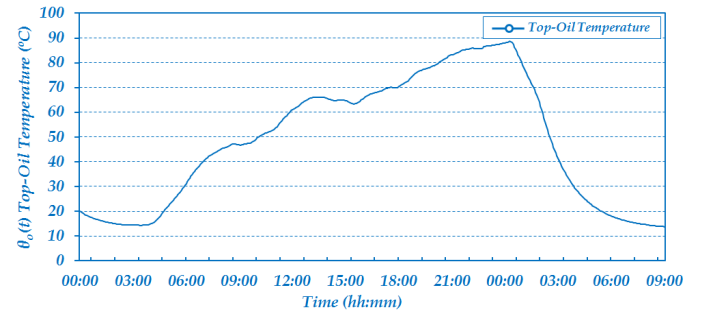Fig. 7. θ_h of the distribution transformer.

Fig. 8. θ_o of the distribution transformer.

In many cases, the overload event of transformer operation is performed by Control Centre load dispatchers as this function is highly complex for the most simple overcurrent relays to effectively operate [19-20]. With the intention of keeping a reliable protection, it is mandatory to monitor the temperatures. Additional prolongation of maximal load after a certain limit pressures the ageing to a critical point. The present thermal digital relays can calculate the ageing [20].

Frequently, in many practical cases it is not anticipated that the shape of diagrams would change too much. Principally it is not expected on small transformer units with fixed consumers. On the other hand, it seems too unreliable to protect a transformer merely with a simple contact thermometer for θ_h measurement and overcurrent protection set-up to a high p. u. current value. Conferring wih the experienced staff in power utility companies no one would consent a very risky transformer loading without holding comprehensive information regarding the θ_h and the ageing [20-21].

A monitoring system essentially offers additional security which is not sufficient, thus it does not offer new content. Initially, a benefit is the option for the on-line decisions in circumstances of network faults. For instance, in every moment the monitoring system can deliver in a clear form an overloading possibility of the transformer. An insistent problem in both thermal monitoring systems and digital relays is how to assess the θ_h produced by the complex heat transfer events inside a transformer. During the occurrence of a fault in a transformer, the damage is proportional to the fault time period. As a result, the transformer needs to be disconnected as fast as possible from the grid. Swift reliable protective relays are consequently used for recognition of faults. Monitors can equally identify faults and they can sense irregular situations which could possibly develop into a fault [22]. The voltage level and the size of the transformer do influence the extent and choice of the protective tools. Monitors could prevent faults and protective relays hinder the damage in a case of an incident of a fault. The budget for the protecting equipment is low when compared to the total cost and the cost implicated in case of transformer damage [23].

Today frequently diverse opinions exist regarding the range of transformer protection. Generally, it is relatively typical that transformers with an oil conservator are equipped with the following equipment [22] for transformers inferior to 5 MVA: ground fault protection, gas detector relay (Buchholz relay), overcurrent protection and overload protection. For transformers superior to 5 MVA the following are available: ground fault protection, gas detector relay (Buchholz relay), oil level monitor, differential protection, overcurrent protection, pressure relay for tap-changer compartment and overload protection (temperature monitoring systems or thermal relays).

In a power system power transformer protection relays are obligatory to be qualified to distinguish internal faults from the remaining operating conditions, and current differential relays have been normally used for transformer protection. The relays, however, continue vulnerable to malfunctioning over-excitation conditions and during magnetic inrush as a result of the magnetizing current becoming significant [24].

A. Transformer Condition On-Line Monitoring

It is broadly accepted that the risks associated with overloading can be substantially mitigated if the transformer conditions are carefully monitored throughout the overload period. The monitoring of winding θ_h and dissolved gas-in-oil and furan-in-oil become a major support to the operator when the transformer endures overload conditions [5].

B. Smart Relay

Through the means of the transformer standard [9] IEC 60076-7 which provides the terms that define the transformer θ_h calculation and with data from the θ_o, θ_a, current and voltage transducers inputs, a smart transformer relay is proposed by the authors. Such a relay is able to provide distinctive asset management functionality. This service covers overload tracking with the temperature (known as adaptive overload), predictive overload early warning and automated load shedding based on temperature and/or current levels. Combined with the LOL estimation, this smart transformer relay offers protection, monitoring and control for the transformer in one integrated solution. The foundation of the smart transformer relay is the capacity to model the transformer behavior through an adequate process [5]. Such types of smart transformer relays allow a wide range of unique monitoring, protection, control and communication devices in one integrated platform as proposed by the authors in Fig. 9.

On the other hand, a more basic application of the IEEE transformer loading standard with a different smart relay is proposed in [20], it has the capacity to monitor both the transformer's temperature and/or current and provide various ranked overload levels for trip or alarm.
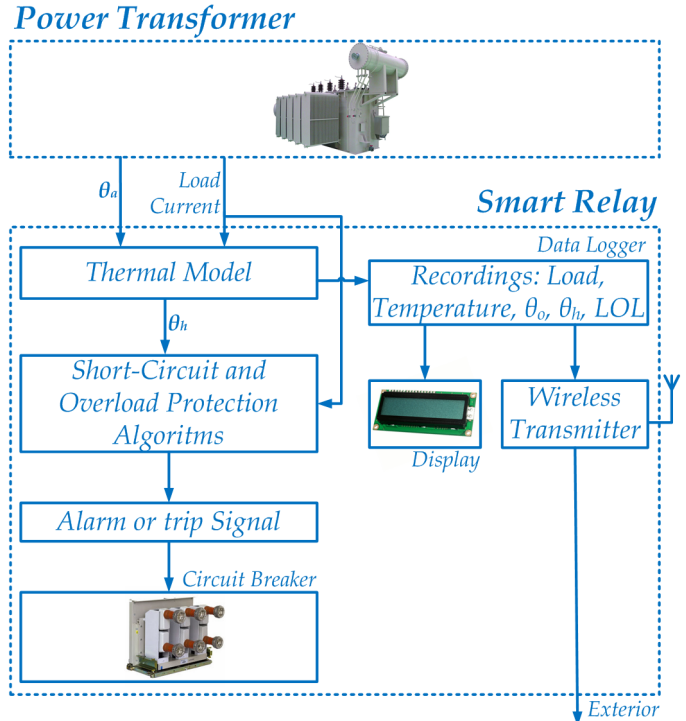

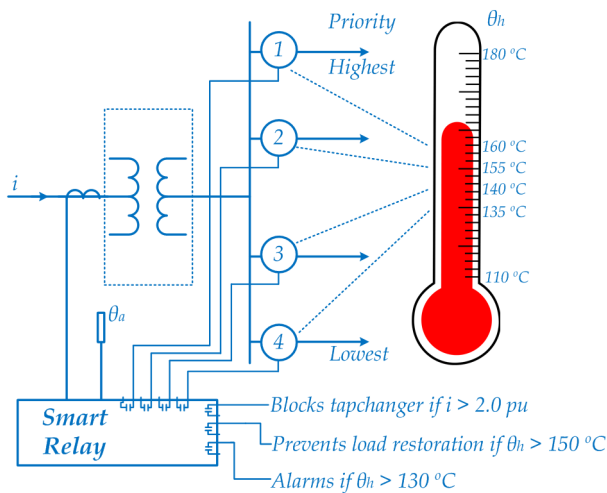Fig. 9. The proposed smart transformer relay.

Fig. 10. Transformer Relay - Load Shedding Model.

Such type of solution enables the utility to have the capacity to offer preferential service to customers and prevent redundant full-load transformer trips. Additionally, the tap changer can be blocked if the current is exceeding a pre-defined setting and avoid load restoration if θ_h is higher than a pre-defined level. The operation of such relay is described in Fig. 10 [20].

V. CONCLUSIONS

In this paper, the impact of load caused by inductive machines was analyzed on the thermal ageing of a distribution transformer of a private industrial client during a day where emergency loading events were needed. The system is part of an isolated electric grid in a Portuguese Island. A transformer thermal model was used to estimate the θ_h given the load ratio. Real data were used for the main inputs of the model, i.e. private industrial client load, transformer parameters and the characteristics of the factory. Finally, a monitoring and protection system was considered essential to ensure reliability and sustainability of the transformer, thus, a smart transformer relay was proposed in order to address upcoming challenges.

BIBLIOGRAPHY

[1] R. Murugan and R. Ramasamy, "Failure analysis of power transformer for effective maintenance planning in electric utilities," *Engineering Failure Analysis,* vol. 55, pp. 182-192, 2015.

[2] P. Sen and S. Pansuwan, "Overloading and loss-of-life assessment guidelines of oil-cooled transformers," in *2001 Rural Electric Power Conference*, Little Rock, AR, 2001.

[3] United States Department Of The Interior - Bureau Of Reclamation, "Facilities instructions, standards, and techniques - Volume 1-5 - Permissible Loading of Oil-Immersed Transformers and Regulators," Facilities Engineering Branch - Denver Office, Denver, Colorado, 1991.

[4] W. Fu, J. McCalley and V. Vittal, "Risk assessment for transformer loading," *IEEE Transactions on Power Systems,* vol. 16, no. 3, pp. 346-353, 2001.

[5] R. Godina, E. M. G. Rodrigues, J. C. O. Matias and J. P. S. Catalão, "Effect of Loads and Other Key Factors on Oil-Transformer Ageing: Sustainability Benefits and Challenges," *Energies,* vol. 8, no. 10, pp. 12147-12186, 2015.

[6] H. L. Willis, Power Distribution Planning Reference Book, Boca Raton, FL, USA: CRC Press , 2004.

[7] M. Humayun, A. Safdarian, M. Degefa and M. Lehtonen, "Demand Response for Operational Life Extension and Efficient Capacity Utilization of Power Transformers During Contingencies," *IEEE Transactions on Power Systems,* vol. 30, no. 4, pp. 2160-2169, 2015.

[8] M. Humayun, M. Degefa, A. Safdarian and M. Lehtonen, "Utilization Improvement of Transformers Using Demand Response," *IEEE Transactions on Power Delivery,* vol. 30, no. 1, pp. 202-210, 2015.

[9] IEC 60076-7, "Loading Guide for Oil-immersed Power Transformers," 2005.

[10] C57.91-1995, "Guide for Loading Mineral-Oil-Immersed," IEEE Standard, 1995.

[11] H. Pezeshki, P. Wolfs and G. Ledwich, "Impact of High PV Penetration on Distribution Transformer Insulation Life," *IEEE Transactions on Power Delivery,* vol. 29, no. 3, pp. 1212-1220, 2014.

[12] K. Qian, C. Zhou and Y. Yuan, "Impacts of high penetration level of fully electric vehicles charging loads on the thermal ageing of power transformers," *International Journal of Electrical Power & Energy Systems,* vol. 65, pp. 102-112, 2015.

[13] H. Turker, S. Bacha, D. Chatroux and A. Hably, "Low-Voltage Transformer Loss-of-Life Assessments for a High Penetration of Plug-In Hybrid Electric Vehicles (PHEVs)," *IEEE Transactions on Power Delivery,* vol. 27, no. 3, pp. 1323-1331, 2012.

[14] A. Hilshey, P. Hines, P. Rezaei and J. Dowds, "Estimating the Impact of Electric Vehicle Smart Charging on Distribution Transformer Aging," *IEEE Transactions on Smart Grid,* vol. 4, no. 2, pp. 905-913, 2013.

[15] M. J. Heathcote, J & P Transformer Book, Oxford: Newnes, 2007.

[16] C. Sumereder, M. Muhr and B. Körbler, "Lifetime management of power transformers," *e&i Elektrotechnik und Informationstechnik,* vol. 120, no. 12, pp. 420-423, 2003.

[17] C. Ravetta, M. Samanna', A. Stucchi and A. Bossi, "Thermal behavior of distribution transformers in summertime and severe loading conditions," in *19th International Conference on Electricity Distribution*, Vienna, 2007.

[18] EDA S.A. - Electricidade dos Açores, "Caracterização Das Redes De Transporte E Distribuição De Energia Eléctrica Da Região Autónoma Dos Açores," Ponta Delgada, 2014.

[19] V. Galdi, L. Ippolito, A. Piccolo and A. Vaccaro, "Neural diagnostic system for transformer thermal overload protection," *IEE Proceedings - Electric Power Applications,* vol. 147, no. 5, pp. 415-421, 2000.

[20] D. Fedirchuk and C. Rebizant, "Managing Transformer Overload - Smart Relays," *IEEE Canadian Review,* no. 35, pp. 25-28, 2000.

[21] T. Weekes, T. Molinski and G. Swift, "Transient transformer overload ratings and protection," *IEEE Electrical Insulation Magazine,* vol. 20, no. 2, pp. 32-35, 2004.

[22] R. Nylén, "Power Transformer Protection - Application Guide," ABB Relays, Västerås, Sweden, 1988.

[23] "IEEE Std C37.91-2000 IEEE Guide for Protective Relay Applications to Power Transformers," IEEE , 2000.

[24] B. E. Lee, J.-W. Park, P. A. Crossley and Y. C. Kang, "Induced Voltages Ratio-Based Algorithm for Fault Detection, and Faulted Phase and Winding Identification of a Three-Winding Power Transformer," *Energies,* vol. 7, no. 9, pp. 6031-6049, 2014.