Impact of EV Charging-at-work on an Industrial Client Distribution Transformer in a Portuguese Island

R. Godina, N.G. Paterakis
Univ. Beira Interior, Covilhã, Portugal
radugodina@gmail.com,
nikpaterak@gmail.com

O. Erdinç
Yildiz Technical University, Istanbul, Turkey, and INESC-ID, Inst. Super Tecn., Univ. Lisbon, Lisbon, Portugal
ozanerdinc@gmail.com

E.M.G. Rodrigues, J. P. S. Catalão
Univ. Beira Interior, Covilhã, Portugal, and INESC-ID, Inst. Super Tecn., Univ. Lisbon, Lisbon, Portugal
erodrigues0203@gmail.com,
catalao@ubi.pt

***Abstract*—This paper analyses the impact of the penetration of electric vehicles (EVs) charging loads on thermal ageing of a distribution transformer of a private industrial client that allows EVs to charge while their owners are at work and at three different working shifts during a day. Furthermore, the system is part of an isolated electric grid in a Portuguese Island. In this paper, a transformer thermal model is used to estimate the hot-spot temperature given the load ratio. Real data were used for the main inputs of the model, i.e. private industrial client load, transformer parameters, the characteristics of the factory and electric vehicle parameters.**

Keywords—distribution transformer; EV charging; loss-of-life; battery SOC; transformer ageing

I. INTRODUCTION

Generalized concerns regarding urban air pollution, climate change, and dependence on expensive and unstable supplies of fossil fuels have lead researchers and policy makers to investigate alternatives to conventional petroleum-fueled internal combustion engine vehicles, such as EVs.

The employment of EVs is more challenging than hybrid vehicles since the main source of energy is electricity. Even though the EVs would be largely used for transportation, from the point of view of a System Operator they could be essentially viewed as a distributed storage resource. Thus, when EVs are not used to satisfy their primordial role, they could provide a range of ancillary services to the power system such as back-up power, regulation, operating reserves, etc. By applying such services also peak shifting could be supported by the use of EVs [1].

With a growing number of EVs connected to power systems for charging, there is a concern that existing distribution networks may become extra loaded than anticipated when they were planned. Low penetration levels could result in a reduced impact but, as the number of EVs increases, it may occur a real possibility of the local distribution networks being congested [2].

A simultaneous charging of a large number of vehicles can induce to grid inadequacy concerning available capacity and security. Such events can be avoided, if the EVs are appropriately integrated within the grid. Integrating the EV within the grid could be a significant opportunity, if they are controlled properly. In this way simultaneous charging of a large number of vehicles becomes practical [3].

Without the integration, the grid could suffer excessive voltage drops, feeder congestions, line overloads, etc. Consequently, insular networks that have weaker structures than the mainland ones could be more seriously affected.

Implementation of smart grid technologies in insular areas has been increasing with the installation of diverse test systems in other islands around the world. Even if the interconnected power system structure is considered to be more rigid in terms of stability, insular areas that can also offer an essential basis for potential islanding operation requirements may be seen as perfect test beds for the pre-evaluation of the smart grid concept before adopting it in for wider areas such as largely populated cities, entire regions composed of several cities, or even to an entire country [4].

Distribution networks are designed to deliver electricity to the final customers and their planning is usually based on the estimated electricity demand. As a consequence, there is a general need to develop modelling techniques to help quantify the impact that high penetration level of EV charging loads may have on distribution networks and thus guarantee that this environmentally positive technology is not unnecessarily constrained. Distribution transformers are essential links in distribution networks which will begin to experience exceptional loads from EV charging. A number of different studies have been carried out to assess whether the existing electricity network and mainly the transformer insulation temperature could withstand the widespread adoption of EVs [1-2][5-7].

Oil-immersed distribution transformers are one of the most common equipment that is found in distribution networks. For example, distribution system of Azores uses almost exclusively oil-immersed distribution transformers with some of them upgraded not long ago [8]. Thus, transformers in their current form are expected to continue to be in service for many years to come due to its widespread use intrinsic high reliability and simplicity. Therefore, the influence of characteristic smart grid operations such as EV charging on transformer life and performance considerations must be properly evaluated.

This paper presents a model based on real data that allows the evaluation of the effect of EVs charging loads on the thermal ageing of an industrial client power distribution transformer which in turn is a part of an isolated electrical grid of São Miguel Island, Azores, Portugal.

The model takes into account the uncertainty of EV battery charging loads, i.e., the randomness of individual charge starting time, initial battery-state-of charge (SOC) and charging modes.

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 and critical analysis are presented and discussed. Finally, the conclusions are drawn in Section IV.

II. METHODOLOGY

A. EV battery charging profiles

The charging load of an EV is an addition to the existing load. EVs are remarkably different from other electrical loads due to their highly mobile and unpredictable nature. There are three key factors which could affect the effect of EVs on distribution networks, specifically the charging characteristics of the EVs, the driving profile and electrical energy tariff incentives.

While the EV market grows, more and more car manufacturers enter the competition. As a consequence, a growing supply of EVs with different characteristics is available today [9]. Consequently, in order to be more realistic, five different types of EVs are used in this study. The latest EV types including BMW i3, Renault ZOE, Nissan Leaf and Kia Soul are considered. Data for the charging types and duration of the five EVs are presented in Table I [10-13].

The percentage of BMW i3 is chosen in this study as high as 40% since it is the fastest selling EV in Portugal according to the ACAP – the Portuguese Automobile Association. Renault ZOE, Nissan Leaf and Kia Soul are assumed to have a 20% market penetration since these brands already appear to have a significant share in the EV market [14].

In the last few years, EVs are becoming technologically appealing with the advancement of lithium-ion battery technology which offers the advantage of higher power and energy density. Due to the potential of obtaining higher specific energy and energy density, the adoption of Li-ion batteries is expected to grow fast in EVs. Nearly all EVs available in the market today use Li-ion batteries because of its mature technology. The capacity of the battery for light vehicles in EVs is in the range of 6 kWh to 35 kWh. The charging time varies from 14 hours for slow charging batteries to less than an hour for fast charging batteries [9]. As a result of the fact that lithium-ion batteries dominate the most recent group of EVs in development [6], in this paper it is assumed that the considered EVs employ lithium-ion batteries.

All the EVs utilized in this case study have Lithium-Ion batteries and in this study a simplified charging profile of such batteries is utilized. When the battery SOC is low, the charger operates at rated current, which enables a great percentage of the battery charge being re-established during the initial charging hours. The process undergoes until is reached the maximum battery voltage during charging, at which the current drops as the charger preserves a constant voltage [7]. Also, for simplicity, the effect of ambient temperature on the EV battery charging characteristics is not taken into account in this study.

TABLE I. CHARGING TYPES AND DURATION OF THE 5 EVS

EVs	Ref.	% of EV	Slow Charge		Fast Charge	
			Power kW	*Time h*	*Power kW*	*Time h*
BMW i3	[10]	40%	7.4	3	50	30m-1h
Renault ZOE	[12]	20%	7.4	3	43	30m-1h
Nissan Leaf	[13]	20%	6.6	5	44	30m-1h
Kia Soul	[11]	20%	6.6	4-5	50	30m-1h

Furthermore, the EV battery charging process is assumed to be continuous as soon as it starts up until the battery reaches its full capacity. The power demand throughout the whole charging process is frequently presented by the charging profile, which may be different from vehicle to vehicle depending on battery type and charging mode.

B. Model of EV Charging Load

In this study the typical charging profile of lithium-ion EV batteries is taken into account, and the stochastic behavior of the initial EV battery SOC is assessed using a probability density function (PDF) associated to travel distances. The charging demand of an EV is given by the initial battery SOC, the charging start time, and the charging characteristics. The initial SOC of an EV battery is determined by the travel habit of the EV before recharging and can be perceived as a random variable associated to the travel distance. Based on a Portuguese study of the general travel information regarding Portuguese drivers of conventional vehicles in 2011 in Lisbon area [15], a probability distribution of daily travel distance can be reconstructed as shown in Fig. 2.

Commonly it is considered that the distribution of travel distance is of lognormal nature, with zero probability of occurrence of the negative distances, and a "tail" prolonging to infinitum for positive distances. The PDF of the EV travel distance can be expressed as:

$$(d;\mu,\sigma)=\frac{1}{d\sqrt{2\pi\sigma^2}}\times e^{-\frac{(\ln d-\mu)^2}{2\sigma^2}},\qquad d>0 \tag{1}$$

where d is the daily distance covered by a vehicle, μ is the ln mean and σ is the standard deviation of the corresponding normal distribution. For the case of vehicle travel distance in Portugal in 2011 as shown in Fig. 1, μ=2,995 and σ=0,768.

Knowing the average daily travel distance, the SOC at the beginning of a recharge cycle that is the residual battery capacity can be estimated using (1) by assuming that the SOC of an EV decreases linearly with the distance of the journey:

$$E_i=\left(1-\frac{d}{d_R}\right)\times 100\ \% \tag{2}$$

where E_{i} represents the initial SOC of an EV battery, d is the daily distance covered by a vehicle, which is a random variable conditioned to a lognormal distribution and d_R is the maximum range of the EV and by assuming that each itinerary starts with 100% of SOC. A general average value for the travelled distance is 100 km [16].

By substituting (2) into (1) and changing the variable from d to E, the PDF of the battery SOC after the travel of one day is obtained as follows (3):

$$h(E;\mu,\sigma)=\frac{1}{d_R(1-E)\sqrt{2\pi\sigma^2}}\times e^{-\frac{[\ln(1-E)-(\mu-\ln d_R)]^2}{2\sigma^2}},\qquad 0<E<1. \tag{3}$$

and is plotted in Fig. 2 truncated at 25% and 95% of battery SOC with parameters as in [17].

Depending on the information withdrawn from both PDF, it is achievable to assess the residual battery capacity at the beginning of each recharge cycle. In this paper the initial time of battery charging is influenced by the beginning of each working shift and the purpose of the use of the EVs by the users which is uncertain factor as seen in Fig.1.

C. Distribution Transformer Loss of Life

An adequate preservation of mineral-oil-tilled distribution transformers is of a very important in power systems, consequently a necessity is created to adopt a caring approach concerning transformer loading, in order to benefit as much as possible from their availability and long term service.

The insulation system of a distribution transformer is essentially made of paper and oil which suffers from ageing. Unexpected rise of the load results in a rise of the hot-spot temperature and subsequently affects the thermal decomposition of the paper [18-19].

As a result of the temperature distribution not being uniform, the hottest section of the transformer will consequently be the most damaged. Hence, the hot-spot temperature directly affects the life duration of transformers [6].

The proportion at which the ageing of paper insulation for a hot-spot temperature is increased or decreased compared with the ageing rate at a reference hotspot temperature (110ºC) [18] is the relative ageing rate V [19].

The relative ageing rate for the thermally upgraded paper is above one for hot-spot temperatures superior to 110 ºC which makes the insulation to age faster compared to the ageing rate at a reference hotspot temperature, and it is lower than one for hot-spot temperatures inferior to 110 ºC [2].

For thermally upgraded paper, that is chemically modified to fortify the stability of the cellulose structure, the relative ageing rate V is [19]:

$$V = e^{\left(\frac{15000}{110+273}-\frac{15000}{\theta_h+273}\right)} \tag{4}$$

After a period of time, the loss of life L is as follows:

$$L = \int_{t_1}^{t_2} V dt \text{ or } L \approx \sum_{n=1}^{N} V_n \times t_n \tag{5}$$

By definition, the hotspot temperature is the hottest temperature of any spot in the transformer winding. As it experiences higher electrical loads then it originates high core-winding temperatures which in turn cause chemical breakdown of insulating oil and insulating paper.

The simple notion of the top-oil temperature rise model is that an increase in the losses is resultant from an additional growth in the loading of the transformer and then an increase of the global temperature in the transformer. The temperature oscillations are dependent on the overall thermal time constant of the transformer which in turn is determined by the rate of heat transfer to the environment and the thermal capacity of the transformer.

In steady state, the total transformer losses are proportional to the top-oil temperature rise. In transient conditions, the hot-spot temperature is characterized as a function of time, for varying load current and ambient temperature [18]. The oil insulation system of a transformer under working conditions is exposed to several categories of stress, such as thermal, electrical, environmental and mechanical. The effect of each stress factors or the interaction effects of them affect the ageing of the insulating system.

For increasing step of loads, the top-oil and winding hot-spot temperatures rise to a level corresponding to a load factor of K. The top-oil temperature is as follows:

$$\theta_o(t) = \Delta\theta_{o,i} + \left\{\Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x - \Delta\theta_{o,i}\right\} \times \left(1 - e^{-t/(k_{11}\times\tau_o)}\right) \tag{6}$$

The hot-spot temperature rise is as follows:

$$\Delta\theta_h(t) = \Delta\theta_{h,i} + \{H \times g_r \times K^y - \Delta\theta_{h,i}\} \times \left[k_{21} \times \left(1 - e^{-t/(k_{22}\times\tau_w)}\right) - (k_{21} - 1) \times \left(1 - e^{-(t\times k_{22})/\tau_o}\right)\right] \tag{7}$$

For decreasing step of loads, the top-oil and winding hot-spot temperatures are reduced to a level corresponding to a load factor of K [18]. The top-oil temperature can be calculated as follows:

$$\theta_o(t) = \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x + \left\{\Delta\theta_{o,i} - \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x\right\} \times \left(e^{-t/(k_{11}\times\tau_o)}\right) \tag{8}$$

The hot-spot temperature rise is as follows:

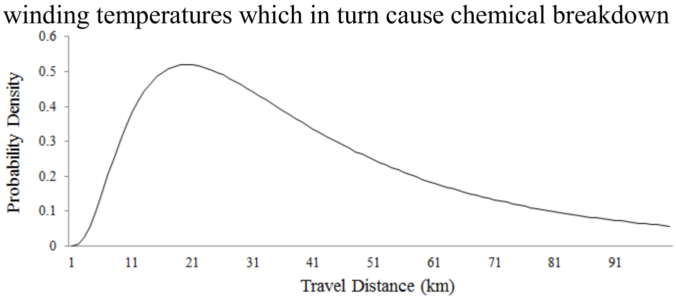

Fig. 1. Probability distribution of daily vehicle travel distance.

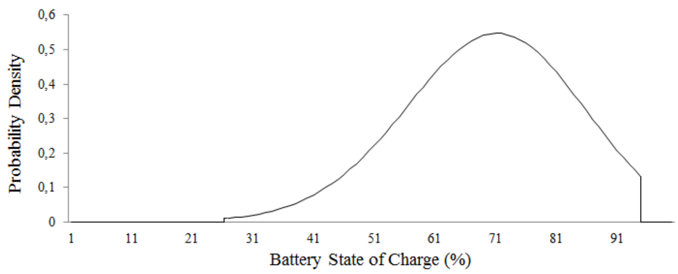

Fig. 2. Probability density of battery SOC after one day of driving.

$$\Delta\theta_h(t) = H \times g_r \times K^y \qquad (9)$$

At the end, having $\theta_o(t)$ and $\Delta\theta_h(t)$ from Eq. (6) and (7) for increasing load steps, and Eq. (8) and (9) for decreasing load steps, the overall hot-spot temperature equation is expressed as follows:

$$\theta_h(t) = \theta_a + \theta_o(t) + \Delta\theta_h(t) \qquad (10)$$

To originate and study the transient solutions for top-oil and hot-spot temperatures – a thermal model is developed and proposed for the distribution transformer.

The properties of the distribution transformer used in this paper are extracted from Ravetta et al. [20] that presented the data of a real 250 kVA oil transformer with Oil Natural Air Natural (ONAN) cooling where a natural convectional flow of hot oil is utilized for cooling. The properties are shown in Table II.

III. Simulation and Results

A. *Structural components of the insular grid*

The Azores, a Portuguese autonomous region, is an archipelago located in the North Atlantic and is composed by 9 islands. São Miguel Island is the main and most populated island in the Portuguese archipelago of the Azores. The island has around 140,000 inhabitants and covers 760 km².

In this paper, a part of São Miguel medium voltage distribution network was used as an example. A transformer that supplies a private industrial client was chosen. Fig. 3 shows a part of the medium voltage distribution network and an identification of several outputs. For this case study the transformer substation PT1094 was used 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. It employs circa 120 workers and operates in 3 working shifts of 8 hours each. The first working shift begins at 08:00, the second at 16:00 and the third at 00:00. It is assumed in this paper that the workers are distributed throughout the working shifts equally.

During the summer of 2014 several measurements were performed at the transformer substation PT1094 and the energy consumption of industrial client was recorded, thus a daily

TABLE II. Used Transformer Parameters

Symbol		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	ºK
τ_o	Average oil time constant	210	Minutes
τ_w	Winding time constant	10	Minutes

baseline load profile was created as shown in Fig. 4. It is also given the power factor of the transformer – approximately 0.95. It may be observed that a 250 kVA transformer is correctly sized for a 140 kW of peak in daily baseline load profile, considering that a typical value for an inferior size transformer would be 167 kVA which is not adequate [8].

B. *Simulation Results*

The present status of EV market share globally can be considered low, not exceeding 7% in leading countries such as Norway [6]. However, in this study, higher penetration levels are examined. Mainly for an insular area, such as São Miguel, the relatively high transportation cost of fossil fuels, the existence of rich potential of renewable energy sources, and the opportunities that arise from the efficient management of an EV fleet [4], induces the authors to believe that the penetration levels that are likely to be met in such areas in the future will be significantly higher than in continental areas. Additionally, governmental incentive initiatives usually tend to target preferably areas such as islands and as a result, tax reduction schemes or potential subsidiary programs to promote the purchase and use of EVs are very likely to massively motivate users to replace their conventional car with an EV.

By taking into account the data collected from the PDF it the transformer thermal model can be applied by using the load ratio as an input to obtain the hot-spot and top oil temperatures. For this case study one day of the baseline load profile of the summer period of the transformer substation PT1094 was used and two different scenarios are examined.

An applicable algorithm is implemented to evaluate the impact of EVs charging loads on the thermal ageing of distribution transformer based on the methodology previously described. Battery charging of the electric vehicles imposes an

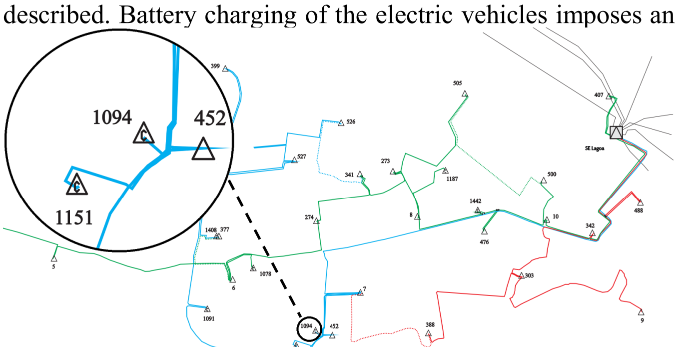

Fig. 3. A part of São Miguel medium voltage distribution network and the identification of PT1094 output [8].

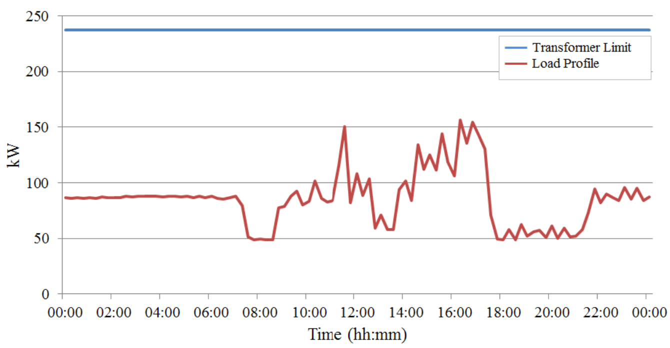

Fig. 4. The daily baseline load profile of the transformer substation PT1094.

extra load on the distribution transformer. Assuming that a distribution transformer supplies several EVs, different charging time and random load profiles are obtained for the transformer. The algorithm integrates data obtained from the PDF and calculates the hot-spot temperature and the transformer's loss of life due to EVs charging loads.

1) Scenario 1

For the first scenario different penetration ratios of EVs for each working shift were considered for this industrial client, begging with 35% penetration and then with 40%, 45%, 50%, and 55 %. Finally it is assumed that the EVs start to be charged at the beginning of each working shift.

The impact on the daily baseline load profile of the transformer substation PT1094 made by the energy consumption of the EVs at several penetration ratios from the first scenario is shown in Fig. 5. The daily baseline load profile is also shown as 0 penetration ratio.

By analyzing Fig. 5 we can extract that for a penetration of EVs of more than 40% the distribution transformer is overloaded. Also, from the information obtained from the model and presented in Fig. 5, it is possible to assess the transformer insulation ageing affected by the hot-spot temperature which is presented in Fig. 6 and subsequently to calculate loss of life *L* at the designated penetration ratios of the transformer.

Using the ageing equations (4) and (5), transformer loss of life can now be determined. The results corresponding to the transformer loss of life over a 24-hour period can be seen in the Table III.

2) Scenario 2

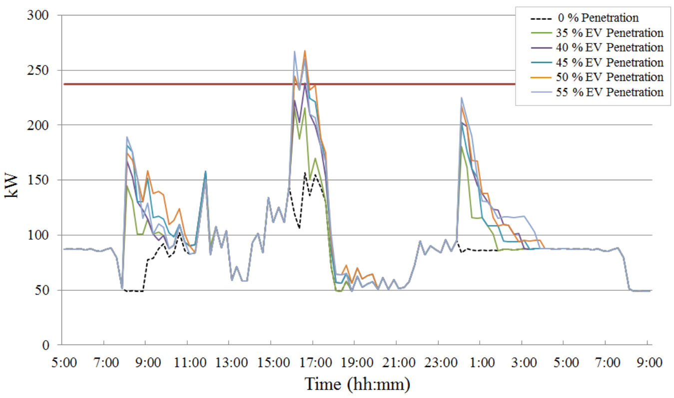

Fig. 5. The daily baseline load profile with the first scenario studied.

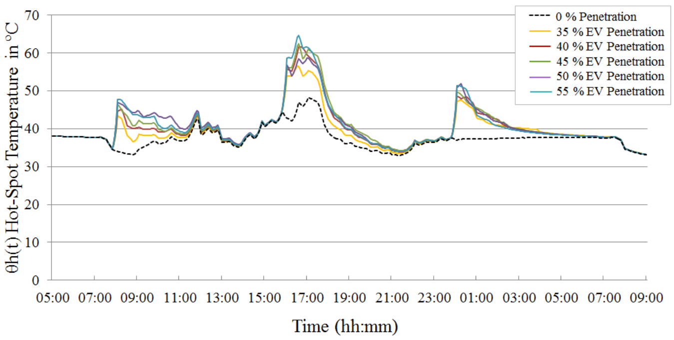

Fig. 6. Hot-spot temperature of the distribution transformer in Scenario 1.

The second scenario is in the following: all EVs are charged with fast charging mode begging with 15% penetration and then with 20%, 25%, 30%, and 35%. Just as in the previous scenario, it is assumed that the workers put their EVs to charge at the beginning of each working shift.

The impact on the daily baseline load profile of the transformer substation PT1094 made by the energy consumption of the EVs at several penetration ratios from the second scenario is shown in Fig. 7.

By analyzing Fig. 7 we can extract that for a penetration of EVs of more than 15% the distribution transformer is heavily overloaded and even at inferior penetration ratios it is overloaded. Also, from the information obtained from the model and presented in Fig. 7, it is possible to assess the transformer insulation ageing affected by the hot-spot temperature which is presented in Fig. 8. Using the ageing equations (4) and (5), transformer loss of life *L* of the transformer can now be determined. The results corresponding to the transformer loss of life over a 24-hour period can also be seen in the Table III.

C. Critical Analysis

By analyzing the results obtained from Table III it can be concluded that the transformer life loss is very sensitive to hot-spot temperature variation because the ageing factor follows an exponential function. Therefore, EV charging indeed significantly affects transformer lifetime.

From the Figures 5 to 8 and from Table III we can conclude that each beginning of a shift will encourage users to prefer the first hour of charging, that will cause a concentration of EVs charging at the same time which in turn could provoke an overloading of the distribution transformer, a sudden increase of the hot-spot temperature and consequently will affect the transformer lifetime.

TABLE III. LOSS OF LIFE IN MINUTES AND HOURS OF THE TRANSFORMER

Scenario 1	Loss of Life in Minutes	Scenario 2	Loss of Life in Hours
35% EV Penetration	23 min	15% EV Penetration	0h 31m
40% EV Penetration	25 min	20% EV Penetration	1h 5m
45% EV Penetration	30 min	25% EV Penetration	2h 48m
50% EV Penetration	39 min	30% EV Penetration	11h 30m
55% EV Penetration	43 min	35% EV Penetration	58h 35m

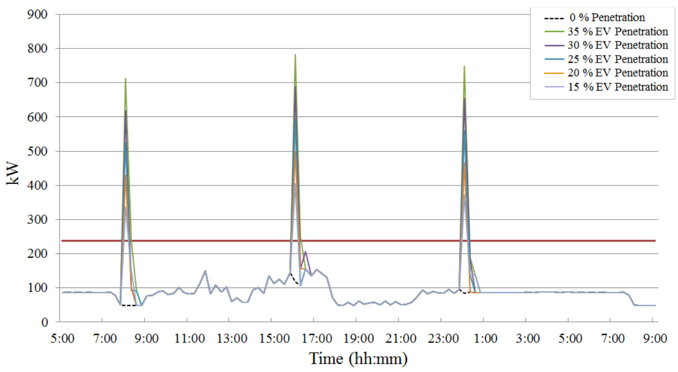

Fig. 7. The daily baseline load profile with the second scenario studied.

By applying the scenario 1 it can be concluded that for more than 40% of EV penetration the transformer will be overloaded resulting in an increase of the hot-spot temperature of the distribution transformer. The loss of life slightly increases with the increase of EV penetration in this scenario. Even if unlikely, by applying the second scenario – lying in 15% of the EV penetration, the loss of life of the distribution transformer is significantly higher. Thus, it is advised to avoid the fast charging mode since the slow mode takes at maximum 5 hours which is always less than a working shift of 8 hours.

IV. Conclusions

In this paper a model to evaluate the effect of EVs charging loads on the thermal ageing of power distribution transformer at a private industrial client was applied and described. Different charging scenarios with several penetration ratios were studied at three different working shifts. Since transformer insulation ageing is mainly affected by the hot-spot temperature, a transformer thermal model was used to estimate the hot-spot temperature given the load ratio. The main inputs to the model, including residential load, transformer parameters, and four different vehicle parameters were taken from real data. Thermal ageing was then calculated and analyzed. Given fact that the 250 kVA transformer has a significant capacity to be used for a side activity, it still can be overloaded after a certain increase of EV penetration. Also, while charging at the workplace, the slow charging mode is recommended over the fast mode since the vehicles will always be 100% charged at the end of each working shift without drastically affecting the transformer lifetime. In future works the scheduling of the charging of the EVs can be explored. As they are parked on the plant for 8-hours, an opportunity arises to apply several algorithms to determine the charging requirements for each vehicle and scheduling the charging accordingly. Other opportunity is to supply a portion of power consumption of the factory from the available energy in EV batteries via vehicle-to-home mode that can also be explored in a future study.

Acknowledgment

This work was supported by FEDER funds through COMPETE and by Portuguese funds through FCT, under FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010), UID/CEC/50021/2013 and SFRH/BPD/103744/2014, and also by funds from the EU 7th Framework Programme FP7/2007-2013 under GA no. 309048.

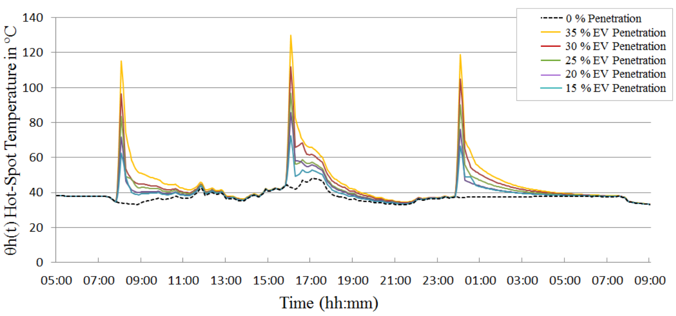

Fig. 8. Hot-spot temperature of the distribution transformer in Scenario 2.

References

[1] Q. Gong, S. Midlam-Mohler, V. Marano and G. Rizzoni, "Study of PEV Charging on Residential Distribution Transformer Life," *IEEE Transactions on Smart Grid,* vol. 3, no. 1, pp. 404-412, 2012.

[2] 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.

[3] R. Das, K. Thirugnanam, P. Kumar, R. Lavudiya and M. Singh, "Mathematical Modeling for Economic Evaluation of Electric Vehicle to Smart Grid Interaction," *IEEE Transactions on Smart Grid,* vol. 5, no. 2, pp. 712-721, 2014.

[4] O. Erdinc, N. G. Paterakis and J. P. S. Catalão, "Chapter 1 - Overview of Insular Power Systems: Challenges and Opportunities," in *Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids*, Boca Raton, Florida, CRC Press (TAYLOR & FRANCIS Group), 2015.

[5] R. Vicini, O. Micheloud, H. Kumar and A. Kwasinski, "Transformer and home energy management systems to lessen electrical vehicle impact on the grid," *IET Generation, Transmission & Distribution,* vol. 6, no. 12, pp. 1202-1208, 2012.

[6] 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.

[7] M. J. Rutherford and V. Yousefzadeh, "The Impact of Electric Vehicle Battery Charging on Distribution Transformers," in *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, USA, 2011.

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

[9] K. Young, C. Wang, L. Y. Wang and K. Strunz, "Chapter 2 - Electric Vehicle Battery Technologies," in *Electric Vehicle Integration into Modern Power Networks*, Springer, New York, 2013, pp. 15-56.

[10] Bayerische Motoren Werke, "The new BMW i3 - Launches November 2013.," BMW UK, Printed in the UK, 2013.

[11] Kia Motors Europe, "The new Kia," Kia Motors Europe, Frankfurt am Main, Germany .

[12] Renault S.A., "Renault ZOE Simply Revolutionary," Renault U.K. Limited Customer Relations, The Rivers Office Park, Denham Way, Maple Cross, Rickmansworth, Hertfordshire, 2013.

[13] ©2014 Nissan North America, Inc., "2014 Nissan Leaf Brochure," Dealer E-Process, 2014.

[14] ACAP, "Associação Automóvel de Portugal," [Online]. Available: http://www.acap.pt/pt/home. [Accessed 20 02 2015].

[15] N. B. R. d. C. Pereira, Eficiência energética no sector dos transportes rodoviários: metodologia para quantificação do excesso de energia consumida devido ao factor comportamental na condução de veículos automóveis ligeiros, Lisbon: Departamento de Ciências e Tecnologia da Biomassa - Universidade Nova de Lisboa, 2011.

[16] K. Qian, C. Zhou, M. Allan and Y. Yuan, "Modeling of Load Demand Due to EV Battery Charging in Distribution Systems," *IEEE Transactions on Power Systems,* vol. 26, no. 2, pp. 802-810, 2011.

[17] S. I. Vagropoulos and A. G. Bakirtzis, "Optimal Bidding Strategy for Electric Vehicle Aggregators in Electricity Markets," *IEEE Transactions on Power Systems,* vol. 28, no. 4, pp. 4031-4041, 2013.

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

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

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