

# Weekend Charging Impact of EVs on a Residential Distribution Transformer in a Portuguese Island

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**Abstract**—The adoption of electric vehicles (EVs) on a large scale can lead to significant social and economic benefits. The effort of promoting the use of EVs in road transportation is essential to meet the climate change targets and manage the ever unstable prices of perilously diminishing fossil fuels. On the other hand, there are still many uncertainties in the market regarding the acceptability of EVs by the final consumer. In this paper the effect of high penetration of EVs on thermal ageing of a real residential distribution transformer, part of an isolated electric grid, is analysed. A weekend scenario conditioned by off-peak tariff is studied. A transformer thermal model is used to estimate the hot-spot temperature ( $\theta_h$ ) and top-oil temperature ( $\theta_o$ ) given the load ratio in São Miguel, a Portuguese Island. Real data are utilised for the main inputs of the model, i.e. transformer parameters, residential load, peak and off-peak tariffs and EV parameters. Conclusions are finally drawn.

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

## NOMENCLATURE

### Estimation of the Transformer Loss of Life (LoL)

$g_r$	Average winding to average oil (in tank) temperature gradient at rated current in K.
$H$	Hot-spot factor.
$I_{SoC}$	The initial SoC of an EV battery.
$K$	Load factor (load current/rated current).
$k_{11}$	Thermal model constant.
$k_{21}$	Thermal model constant.
$k_{22}$	Thermal model constant.
$LoL$	Loss of life.
$N$	Total number of time intervals.
$N$	Any given number.
$R$	Ratio of load loss to no-load loss at rated current.
$T$	Period of the day in time units (h or min).
$t_d$	The daily travel distance covered by an EV.
$t_{dr}$	The maximum travel range of the EV.
$\Delta t_n$	Time interval.
$R_r^a$	Relative ageing rate.
$R_m^a$	Relative ageing rate during interval $n$ .
$X$	Exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent).
$Y$	Exponential power of current versus winding temperature rise (winding exponent).
$\tau_o$	Average oil time constant.
$\tau_w$	Winding time constant.
$\mu$	The natural logarithmic mean.

$\sigma$	The standard deviation of the corresponding normal distribution.
$\theta_a$	The average ambient temperature in °C.
$\theta_o$	Top-oil temperature in °C.
$\Delta\theta_{o,i}$	Top-oil (in tank) temperature rise at start in K.
$\Delta\theta_{o,r}$	Top-oil temperature rise at rated current in K.
$\theta_h$	Winding hottest-spot temperature in °C.
$\Delta\theta_{h,i}$	Hot-spot-to-top-oil (in tank) gradient at start in K.
$\Delta\theta_{h,r}$	Hot-spot temperature rise at rated current in K.

### Indices

$a$	Ambient Temperature
$d$	Daily Travel
$dr$	Maximum Travel Range
$EV$	Electric Vehicle
$h$	Hot-spot
$i$	At start/initial
$n$	Index of the time interval
$o$	Top-oil
$r$	Rated Load
$t$	Period of the day index in time units [h or min].
$w$	Winding

### Acronyms

ACAP	Portuguese Automobile Association
EV	Electric vehicle
GHG	Greenhouse gas
LoL	Loss of life
ONAN	Oil natural air natural
PDF	Probability density function
SoC	State of charge

## I. INTRODUCTION

Currently the sales of EV are increasing worldwide and also in such a developed market as U.S. However, EVs represent less than 1% of all new EVs sold, nonetheless [1]. Up to this point, due to such factors as an almost absent charging infrastructure, a restricted driving range, and prolonged charging battery times have delayed the EV technology challenge to grow into a large-scale viable alternative to conventional fossil-fuelled internal combustion engine vehicles [2].

An increasing penetration of EVs has the potential to considerably diminish the oil dependency, to reduce the noise and greenhouse gas (GHG) emissions, and to increase the energy efficiency of the transportation sector.

Various automotive brands have manufactured pioneering models of EVs and in several countries from Europe the battery charging infrastructure for EVs is continually developed and increased. Besides, various research projects and funding programs have been initiated, targeting the development of different segments of the EV technology. Enterprises, researchers and policy makers indicate that in the not-too-distant future EVs could reach a substantial market penetration [3]. An effective penetration of EVs, however, relies on how well their effect on the electric grid is conveyed. The penetration levels of EVs estimated over the next ten years are anticipated to have a negligible impact on the power system. Yet, local distribution grids, mostly the ones that supply high populated cities, could have a necessity for an improvement of the distribution infrastructure in order to adjust to the charging requirements of EVs [4].

The distribution networks were projected to deliver electricity by considering how many customers live in a specified area and by taking into account the preceding electricity demand data of that region. A large penetration of EVs will modify the customer demand patterns, and substantial EVs penetration could result in negative consequences on the network [5]. Especially if employed in islands, where an increasing installation of several test systems in different insular regions can be witnessed [6].

Distribution transformers could be the most affected since during certain periods they will be overloaded due to the charging of EVs, thus, decreasing their useful life. Consequently, utilities have to create strategies to properly integrate the EVs [7] and thus lay the ground for state-of-the-art modelling techniques aiming to study and measure the impact that large penetration degrees of EVs might have on distribution networks. Such modelling methods would contribute to not limiting needlessly the rate of the EV penetration. Studies were made with this purpose to estimate if the existing electricity distribution network and the transformer insulation oil could tolerate a high penetration of EVs [4-5].

One of the most standard elements that are part of distribution networks are the distribution transformers with oil-immersed core. Naturally, oil-immersed distribution transformers are very much common in the Azores distribution network [8]. Furthermore, currently functioning transformers are estimated to continue operational during a long period of time given that is so common, highly reliable and devoid of complexity. Hence, as demonstrated in earlier research works [9-10], the insulation oil life and operation of the transformer affected by such operations as EV charging require detailed and accurate assessment.

During weekends and limited by an off-peak tariff, is assessed in this paper the effect of a high penetration of EVs charging loads on the dialectic oil ageing of an existent residential distribution transformer operating on an isolated distribution network. A transformer thermal model is applied to determine the  $\theta_o$  and  $\theta_h$  once set the load ratio. As main inputs of the model real data are utilised such as the residential load, transformer specifications, peak and off-peak tariffs and EV parameters. The aforementioned model also contemplates the uncertainties associated to EV battery charging behaviours, i.e.,

the randomness of EV charge initial instants, the starting state of charge of the battery (SoC) and the type of the charging mode.

The paper is organised as follows: in Section II, the used methodology is established. In Section III, the distribution network of São Miguel, Azores, in addition to the simulation results, are shown and examined. To finish, conclusions are presented in Section IV.

## II. METHODOLOGY

### A. Estimation of the Transformer Loss of Life (LoL)

A fitting maintenance of oil distribution transformers is a recognised and established requirement in power systems. As so, the basis for a thoughtful approach rises regarding the transformer loading conditions. The goal is benefiting from the availability of oil transformer and long duration service for longer periods of time. The power transformer's insulation system is fundamentally made of paper and oil and both experience accelerated ageing under heavy loading conditions. Rapid rise of the load ends in an increase of the  $\theta_h$ . This impacts the thermal decomposition of the paper. The temperature distribution is uneven in a transformer, thus the hottest section happens to be the most negatively affected. Therefore, the LoL of the transformer undeniably depends on the  $\theta_h$  [11].

The relative ageing rate for the thermally upgraded paper is above 1 for  $\theta_h$  greater than 110 °C which signifies that the insulation ages quicker when compared to the ageing rate at a reference  $\theta_h$ . However, is lower than 1 for  $\theta_h$  less than 110 °C [12]. The  $\theta_h$  is the hottest temperature of any point in the transformer winding. By facing great electrical loads high core-winding temperatures are created in the transformer, thus causing chemical breakdown of insulating paper and oil [11].

The  $\theta_o$  rise model is characterized through the increase in the losses which is a consequence from a rise in the loading of the transformer and as a consequence, of the global temperature. The temperature fluctuations rely upon the overall thermal time constant of the transformer. However, such constant also depends on the thermal capacity of the transformer and also on the rate of heat transfer to the environment [13].

In steady state all the transformer thermal losses are proportional to the  $\theta_o$  temperature rise. In transient conditions, the  $\theta_h$  is characterised as a function of time, for varying load current and  $\theta_a$  [12]. The oil insulation system of a transformer in working conditions is vulnerable to numerous types of technical problems, such as electrical, thermal, environmental and mechanical ones. The consequences of each of those aforementioned problems or the interaction outcomes between them influence the insulating system's ageing.

In case of increasing step of loads, the  $\theta_o$  and winding  $\theta_h$  temperatures rise to a level matching a load factor of  $K$ . The equation of the top-oil  $\theta_o(t)$  temperature is represented by:

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

The  $\theta_h$  rise  $\Delta\theta_h(t)$  is represented by the following equation:

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

In case of decreasing step of loads, the  $\theta_o$  and winding  $\theta_h$  temperatures decrease to a level matching  $K$  [12]. The equation of the top-oil temperature  $\theta_o(t)$  is represented by:

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

The  $\theta_h$  rise is represented by:

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

At last, the overall hot-spot temperature  $\theta_h(t)$  equation is calculated with  $\theta_o(t)$  and  $\Delta\theta_h(t)$  from Eq. (1) and (2) for increasing load steps, Eq. (3) and (4) for decreasing load steps and adding the ambient temperature  $\theta_a$  at the end:

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

The rate at which the paper insulation's ageing for a  $\theta_h$  is increased or decreased when compared with the ageing rate at a reference  $\theta_h$  (110°C) [12] is the relative ageing rate  $R_r^a$  [14]. In case of thermally upgraded paper, chemically altered to improve the stability of the cellulose structure, the relative ageing rate  $R_r^a$  is represented by the following equation [14]:

$$R_r^a = e^{\left( \frac{15000}{110+273} - \frac{15000}{\theta_h+273} \right)} \quad (6)$$

For a designated time period, the LoL throughout the time interval  $t_n$  is expressed by the following equation:

$$LoL = \int_{t_1}^{t_2} R_r^a dt \quad \text{or} \quad LoL \approx \sum_{n=1}^N R_{rn}^a \times t_n \quad (7)$$

In order to discover the transient solutions for  $\theta_o$  and  $\theta_h$  – a thermal model is generated and proposed.

The transformer's properties utilised in this paper are taken from Ravetta et al. [15]. In this publication was presented the specifications of a real 630 kVA ( $P_r$ ) oil transformer with Oil Natural Air Natural (ONAN) cooling system where natural convectional flow of hot oil is employed for cooling.

### B. The battery charging profiles of EVs

The operation of charging of EVs is an accumulation to the existing load. Yet EVs are considered to be remarkably distinct from other electrical loads – a consequence to their mobile and random nature. Three fundamental factors could influence the effect of EVs on distribution networks – the driving profile of the EVs, the charging requirements of the type of EV battery and electrical energy tariff incentives [9-10].

The EV market is expanding every day and progressively car manufacturers enter into the race. Thus, an emergent number of EVs with distinct features were released until today [5]. Consequently, with the purpose to add more realism, five distinct EVs are utilised in this paper. Five models of actual available EVs in the market where utilised – Kia Soul, Renault ZOE, Ford Focus Electric, Nissan Leaf and BMW i3. Data for the battery duration and charging modes can be seen in [9]. The high percentage – 40% – of BMW i3 was selected as such in this model as it is the most purchased EV in Portugal in line with the Portuguese Automobile Association (ACAP) [16]. The choice of Renault ZOE and Ford was made by reason of both having a 20% market penetration as both aforementioned brands already occupies a substantial part in the conventional vehicle market [16].

Presently, Lithium-ion batteries have become a hot topic in the academia due to their high energy, power density, weak memory effect, low self-discharging rate and long cycle life which suitably fits the power demand of EVs. Such batteries currently meet the specific operational and environmental demands for EVs power devices. SoC is utilised to monitor the charge and discharge process of the battery and predict the operation range of the EVs. The battery capacity for light EVs is usually in the range of 6 kWh to 35 kWh. The EV charging time period varies from 14 hours in case of slow charging batteries to < 1h in case of fast charging batteries [18]. By the reason of Lithium-ion batteries leading the market for the current group of EVs in development [17], it is made the assumption in this paper that the case-study EVs utilise Lithium-ion batteries.

To have an improved understanding of the influence of EV charging on the daily baseline load profile – a classic charging profile of a Lithium-ion battery is shown in Fig. 1 [18]. In fact, the Lithium-ion battery charging process, with simplified circumstances can be represented by a function that replicates the mutually dependent events of charging type and battery SoC [17]. On the other hand, with the intention of simplifying, the impact of the  $\theta_a$  on the battery charging specifications is not considered in the case study of this paper. In addition, the EV battery charging process is perceived as continuous from the initial instant until full capacity of the battery is accomplished. The power demand during the course of the entire charging event of the EV is often offered by the charging profile, which could be slightly distinct since is conditioned by the type of battery and charging mode [9-10].

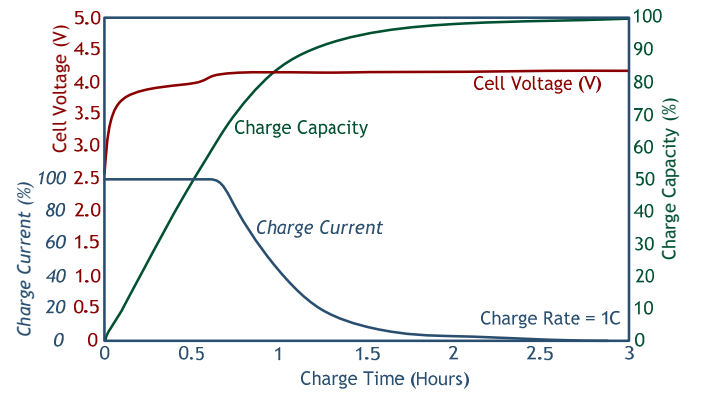


Fig. 1. Charging Profile of a Lithium-Ion Battery [18].

### C. EV Charging Load Model

In order to create a functioning model, the characteristic charging profile of Lithium-ion EV batteries is utilised. The stochastic behaviour of the initial EV battery SoC is calculated by employing a probability density function (PDF) related to the travel distances. The EV charging demand is conditioned by the charging start time, the initial battery SoC, and the charging nature. The travel details of the EV before recharging define the initial SoC of an EV battery. Such information can be considered a random variable related to the travel distance. A probability distribution of daily travel distance can be shaped as shown in Fig. 2 based on a study in [19] from which the general travel information regarding Portuguese drivers of conventional internal combustion engine vehicles in 2011 was taken.

It is frequently assumed that the distribution of the travel distance has a lognormal representation, with 0% probability of existence in case of negative distances, and a “tail” extending to the infinite in case of positive distances. The PDF of the travel distance of an EV from the model is as follows:

$$(t_d; \mu, \sigma) = \frac{1}{t_d \sqrt{2\pi\sigma^2}} \times e^{-\frac{(\ln t_d - \mu)^2}{2\sigma^2}}, d > 0 \quad (8)$$

As for the EV travel distance based on the study from [19] as shown in Fig. 2, the  $\mu$  is 2,995 and  $\sigma$  is 0,768.

After the calculation of the average daily travel distance, the initial SoC of a recharge cycle can be assessed using (9) However, only by considering that the SoC of an EV decreases linearly with the distance of each travel:

$$I_{SoC} = \left(1 - \frac{t_d}{t_{dr}}\right) \times 100 \% \quad (9)$$

A standard average value for travel distance is 100 km [10] if considering that each journey initiates with 100% SoC. Replacing (9) into (8) and substituting the variable from  $t_d$  to  $I$ , the PDF of the battery’s SoC after one day journey is expressed as:

$$h(I; \mu, \sigma) = \frac{1}{t_{dr}(1-I)\sqrt{2\pi\sigma^2}} \times e^{-\frac{[\ln(1-I) - (\mu - \ln t_{dr})]^2}{2\sigma^2}}, 0 < I < 1 \quad (10)$$

and shown in Fig. 3 truncated at 25% and 95% of battery SoC with criteria such as in [10]. The residual battery capacity at the start of each recharge cycle of the EV battery can be determined through the data taken from both PDF. The initial time of the charging of the EV battery is influenced by the electricity tariff rate and the intention of the utilisation of the EVs by the costumers – an uncertain factor as observed in Fig. 2.

## III. SIMULATION RESULTS

### A. Details of the insular electric grid

São Miguel Island is the greatest and most populated island of the Azores autonomous region. In this paper, is utilised as example a part of the island’s medium voltage distribution network. A transformer that supports a residential area is selected. The portion of the medium voltage distribution network and the identification of a few outputs can be seen in Fig. 4.

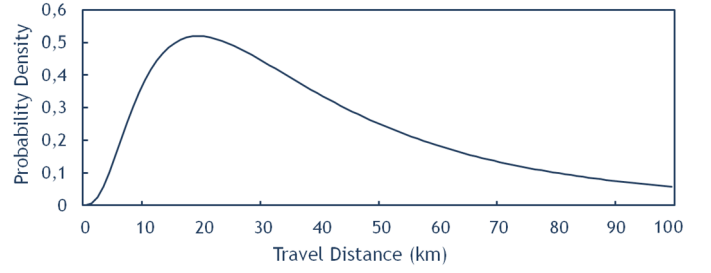


Fig. 2. Probability distribution of daily vehicle travel distance.

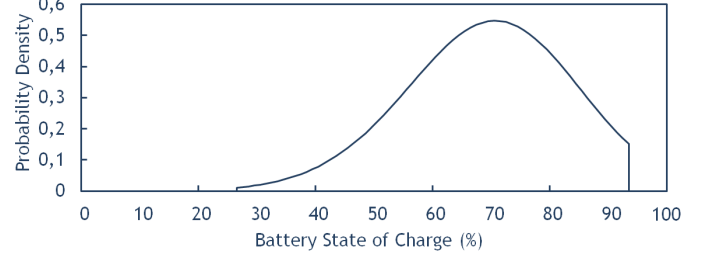


Fig. 3. Probability density of battery SoC after one day of driving.

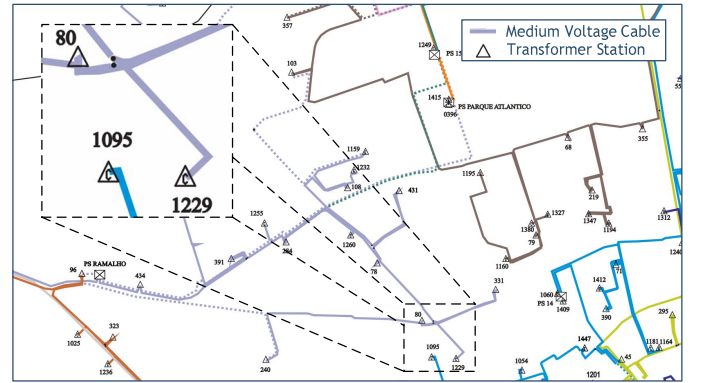


Fig. 4. Part of São Miguel’s medium voltage DN and the identification of PT80 output.

In this paper the transformer substation PT80 is utilised as an example. The substation supplies 292 dwellings via a 630kVA, 10kV/0.4kV oil-immersed transformer. In this regard, data are provided under SiNGULAR project [20]. The Fig. 5 shows a simplified layout of the analysed low voltage grid.

During the period of the summer of 2014 numerous measurements were executed at the transformer aforementioned substation. Consequently, the sum of the energy consumption of the 292 dwellings was registered and a daily baseline load profile was made as shown in [9]. It is entirely justifiable that the 630 kVA transformer is oversized for a 140 kW of peak in the daily baseline load profile. In the Azores greater energy consumption is often observed during the summer period [8].

The electricity tariff could influence to some degree the demand of the load by the EV owner. For the model utilised in this study the currently existing electricity tariff of Azores Islands was considered. Such tariff became official in 2015. Presently a three rate tariff for domestic consumers can be chosen by an EV user in Azores. Yet, in this paper was utilised the two rate tariff. The peak tariff is 190% higher than the off-peak tariff and it is instantly triggered after 22:00 [21].

### B. Discussion of Results

The present status of the EV market share can be considered underdeveloped, yet, in this study, mostly high penetration levels are taken into consideration. The reason is that in such a case of an insular area the high potential of renewable energy sources, the costly fossil fuels of the transportation sector, and the opportunities that materialise from a well-organized and efficient control of an EV fleet [6], could contribute to high penetration levels. Such levels are likely to be encountered in insular areas in the future [4].

Additionally, legislative incentive initiatives often tend to gradually target more and more such areas as islands. As a consequence, possible tax reduction regulations or subsidy programs to encourage the acquisition and utilisation of EVs are could greatly motivate vehicle customers to replace their internal combustion engine vehicle with an EV. Based on the data taken from the PDF the transformer thermal model can now be applied by utilising the load ratio as an input to acquire the values of  $\theta_h$  and  $\theta_o$ . For the case study in this paper one day and a half of the summer season of the baseline load profile of the transformer substation PT80 is applied.

Based on the formerly presented approach an applicable algorithm is applied in order to calculate the effect that the charging loads of EVs have on the distribution transformer's thermal ageing. The charging of an EV battery inflicts an extra load on the distribution transformer. Distinct load profiles and initial charging times are attained for the distribution transformer considering that one supports several dwellings with EVs in a neighbourhood. The algorithm calculates the  $\theta_h$  and the transformer's LoL due to EVs charging loads by assimilating the data acquired from the PDF.

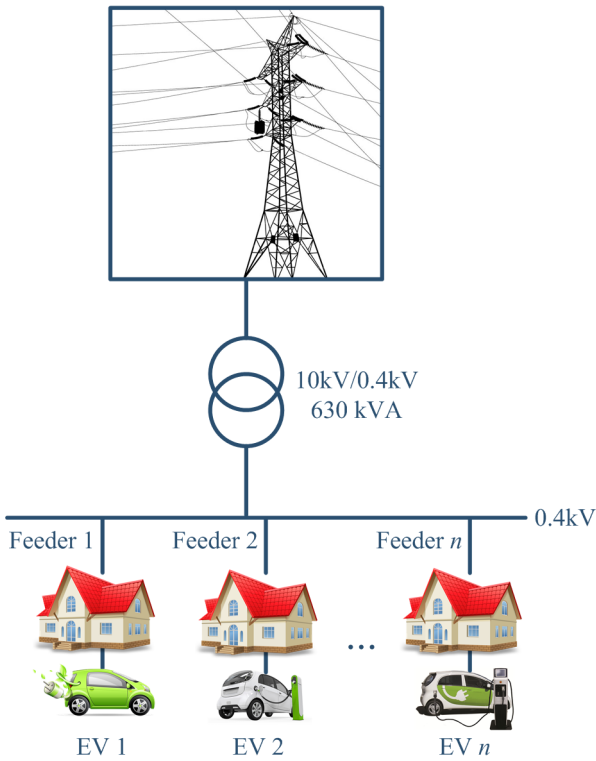


Fig. 5. The daily baseline load profile of the transformer substation PT80.

The scenario analysed in this paper comprises different penetration ratios of EVs considered for the household neighbourhood, ranging from 75% penetration to 100%. Besides, it is presumed that 100% of the EV owners charge their cars in slow charging mode since during overnight they can find the vehicle fully charged. The starting time of charging for this scenario was chosen to be at 22:00 due to the fact that consumers will likely be influenced by the off-peak tariff and will charge at home in order to avoid the trouble of charging at a public charging station. Likewise, in this study, the charging demand of multiple EVs is a direct sum of the charging demand of discrete EVs to the daily baseline load profile. The resultant impact from the energy consumption of the EVs on the daily baseline load profile of the transformer substation PT80 at various penetration ratios is shown in Fig. 6. Through the analysis of Fig. 6 we can deduce that for a penetration of EVs of more than 75% the distribution transformer is overloaded. From the information acquired from the model and presented in Fig. 6, it can be calculated the transformer insulation ageing influenced by the  $\theta_o$ ,  $\theta_h$  and the LoL of the transformer which is presented in Fig. 7 and 8, respectively.

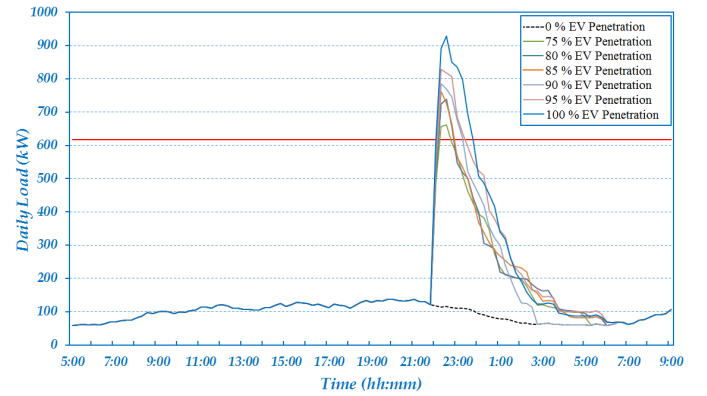


Fig. 6. The daily baseline load profile with the two studied scenarios.

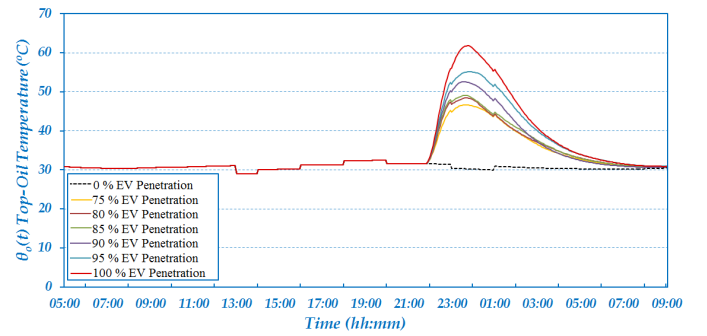


Fig. 7. The top-oil temperature of the distribution transformer.

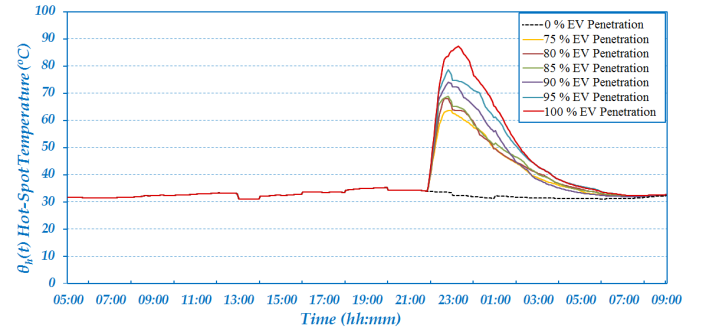


Fig. 8. The hot-spot temperature of the distribution transformer.



TABLE I. LOSS OF LIFE IN MINUTES OF THE TRANSFORMER

	LoL in minutes per day	% of LoL per day
0% EV Penetration	0.00	0.0000
75% EV Penetration	33.23	0.0003
80% EV Penetration	43.23	0.0004
85% EV Penetration	49.37	0.0005
90% EV Penetration	88.59	0.0008
95% EV Penetration	148.30	0.0014
100% EV Penetration	348.33	0.0035

The transformer LoL can now be calculated by utilising the equations (6) and (7) from Section II. The LoL of the transformer is assessed through the estimation of dissipated LoL in minutes for every day of EV charging. Such results can be seen in the Table I.

Through a careful analysis of Figs. 6, 7, 8 and of Table I it can be deduced that the influence of the off peak tariff on the consumers will persuade them to prefer a given starting time period of charging which in this specific case is 22:00. A simultaneous charging of EVs will be the consequence by such preference which in turn will overload the distribution transformer. The transformer could be overloaded for more than 75% of EV penetration. Such levels originate a rise of  $\theta_o$  and  $\theta_h$  of the distribution transformer. The LoL rises with the increasing levels of EV penetration. Through an accurate analysis of the results achieved in Table I it can be deduced that the LoL of the transformer is sensitive to  $\theta_h$  variation. Thus, the charging of EV batteries does impact the transformer LoL. By analysing this case study, it can be deduced that the effect of the off-peak tariff on the EV users will have an effect on the transformer's LoL. Hence, smart grid solutions could enable different management of residential electricity use, including the charging of EVs, therefore mitigating the charging of EVs effect on the distribution transformer's LoL.

#### IV. CONCLUSIONS

In this paper a model that estimates the influence of EVs charging loads on the thermal ageing of a power distribution transformer was developed. Knowing that the transformer insulation ageing is generally affected by the  $\theta_h$ , a transformer thermal model was utilised to calculate the  $\theta_h$  considering the load ratio. The core inputs to the model, such as the residential load, the characteristics of the distribution transformer, peak and off-peak tariff were obtained from real data. As a typical trait of remote islands, the transformer on which this study was based on is oversized. Consequently, the study concludes that in face of specific levels of EV penetration even oversized transformers could be overloaded. It can also be deduced that the current off peak tariff could influence the EV owners and consequently negatively impact the lifetime of the distribution transformer.

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