Innovative Impact Assessment of Electric Vehicles Charging Loads on Distribution Transformers using Real Data

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Abstract

Widespread adoption of electric vehicles (EVs) could bring social and economic benefits. The effort of promoting the use of EVs in transportation is indispensable to meet the climate change related targets and to reduce the dependency on the ever unstable prices of diminishing fossil fuels. However, there are still many uncertainties in the market regarding the acceptability of EVs by the final consumer. As a new contribution to earlier studies, this paper assesses the impact of EV charging load on the dielectric oil deterioration of two real power distribution transformers (PDT), one residential and one industrial, located in the insular grid of São Miguel Island. A PDT thermal model is used to estimate the hot-spot temperature given the load ratio. Real data are used for the main inputs of the model, namely, the daily residential load curve, the daily private industrial client load curve, the PDT parameters, time-of-use rates and EV parameters.

Keywords: Battery; distribution transformer; EV charging; loss-of-life; transformer ageing.

Nomenclature

V	Relative ageing rate.
d	The daily distance covered by an EV.
d_R	The maximum range of the EV.
μ	The natural logarithmic mean.
σ	The standard deviation of the corresponding normal distribution.
Θ_a	The average ambient temperature in °C.
Θ_h	Winding hottest-spot temperature in °C.
Θ_o	Top-oil temperature in °C.
$\Delta\Theta_{hi}$	Hot-spot-to-top-oil (in tank) gradient at start in K.
$\Delta\Theta_{oi}$	Top-oil (in tank) temperature rise at start in K.
$\Delta\Theta_{or}$	Top-oil temperature rise at rated current in K.
$\Delta\Theta_{hr}$	Hot–spot temperature rise at rated current in K.
R	Ratio of load loss to no-load loss at rated current.
K	Load factor (load current/rated current).
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).
k_{11}	Thermal model constant.
k_{21}	Thermal model constant.
k_{22}	Thermal model constant.

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τ_o	Average oil time constant.
τ_w	Winding time constant.
H	Hot-spot factor.
E_i	The initial SOC of an EV battery.
g_r	Average winding to average oil (in tank) temperature gradient at rated current in K.
V_n	Relative ageing rate during interval *n*.
Δt_n	Time interval.
N	Total number of time intervals.
P_{EV}	EV rated charging power in W.
P_d	Domestic loads in W.
P_r	Distribution transformer rated power in W.
P_f	Factory load in W.
P_T	Total load in W.
L	Loss of life.
D	The difference over a small time step.
Dt	Time Step.
t	Period of the day in time units (h or min).

Indices

a	Ambient Temperature
d	Domestic
EV	Electric Vehicle
f	Factory
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

Table of abbreviations

ACAP	Portuguese Automobile Association
DN	Distribution network
EV	Electric vehicle
LOL	Loss of life
ONAN	Oil natural air natural
PDF	Probability density function
PDT	Power distribution transformer
RES	Renewable energy sources
SG	Smart grid
SOC	State of charge

1. Introduction

Concerns regarding urban air pollution, the climate change, and the dependency on instable and costly supplies of fossil fuels have compelled policy makers and researchers to explore other possibilities to conventional fossil-fuelled internal combustion engine vehicles. One such alternative is the introduction of electric vehicles (EVs) to replace conventional vehicles [1] [2] [3]. The broad adoption of such a means of transportation could signify a drastic reduction in greenhouse gases emissions and a compelling argument for the collective attempts to meet the emission mitigation goals [4] [5] [6]. As a result, during the last few years the electrification of transportation has been increasingly drawing attention.

The wide adoption of EVs is more challenging in comparison with the use of conventional and hybrid vehicles since the main energy source is electricity and therefore, the electric power systems should be qualified to accommodate new challenges and take advantage of the opportunities that are associated with the EV recharging load [7]. Moderate penetration levels might have a low impact on the grid. Nevertheless, as the number of EVs increases, a real possibility of the electric power systems being overloaded emerges – especially in the existing distribution network (DN) [8] [9].

An event of a large number of EVs charging – if occur simultaneously – can lead to grid inadequacy in terms of security and available network capacity. This situation can be averted in such cases where the EVs are appropriately incorporated into the electric power system. For the EVs point of view, an occasion of a high number of EVs charging at the same time could eventually be realistic [10]. Without a proper assimilation, the electric power system may possibly suffer excessive voltage drops, feeder congestion, etc., especially in the case of an isolated electrical grid, such as the one of São Miguel Island, Azores – a region that lacks a suitable plan for EV integration into the local electric power system.

The smart grid (SG) is defined as an electricity network that is capable of integrating in a smart way the actions of all users connected to it, with the intention to successfully distribute secure, economic, and sustainable electricity supplies [11]. The SG eases the accommodation of renewable energy resources (RES) into the present grid with a higher distributed nature to support the mitigation of carbon emissions. The latest progress made by researchers in the SG field has led to the prediction of the connection of distributed RES and EVs to the power network and the various technical challenges that come from this new paradigm. Thus, the overcoming of such obstacles has to be done appropriately [12].

Recently, the implementation of SG enabling technologies in insular areas has been increasing rapidly, with the installation of diverse test systems in islands around the world. Even though the interconnected power system structure is deemed to be more rigid as regards to stability, isolated areas which could offer an essential foundation for potential islanding operation requirements could be seen as perfect testing ground for the pre-evaluation of the SG paradigm [13].

The traditional DN is mainly designed as a passive network intended to deliver energy to the consumers [14]. Thus, there is the necessity to create and improve new models and methods with the purpose of assessing the impact that high penetration level of EV charging loads could have on the DN. This is also justified since there is a need to make sure that a high penetration of EVs does not overload the grid without reason, which ultimately adds to the existing efforts of reduction of the environmental impact by the human activity. Power distribution transformers (PDTs) are essential DN infrastructure that could suffer unparalleled charging loads due to the EVs. Several researchers investigated such themes, aiming to evaluate if the current existing electricity network and the PDT dielectric oil may resist to the penetration of EVs on a large scale [15] [16] [17] [18] [19] [20]. In [15] the authors focused on identifying PDTs that are most vulnerable in cases of overloading as a result of the implementation of EVs through the employment of a binomial probability model that estimates the probability of a specific PDT to experience overloading. In [16] a study in which the effect of EVs charging on a local residential transformer by means of an Monte Carlo simulation that was utilised to foresee the final state of charge (SOC) of daily driving for a hybrid EV model and an EV model is performed. In [17] a method to assess the effect of EVs charging on overhead PDTs is described, also presenting a novel smart charging algorithm that regulates EVs charging relying on the assessed PDTs temperatures. In another study [18] the way in which high penetration of EVs will influence the development of home energy management and PDT systems with the intention of decreasing the effect of EV battery charging on PDTs by using real load consumption data from Austin, Texas, is assessed. In [19] a model to investigate the effect of large scale penetration rates of additional power to restore the full level of EV battery SOC on the dielectric oil deterioration of PDTs through UK generic low voltage DN model is presented.

One of the most common elements that are found in DN is the PDT with an oil-immersed core. The DN of Azores uses almost exclusively oil-immersed PDTs – some of them upgraded very recently [21]. In addition to that, PDTs in their existing form are estimated to be the mainstream option for the years to come, due to their reliability and extensive use. Thus, the impact of specific SG practices such as EV charging on PDTs life and performance considerations must be evaluated in detail.

The contribution of this study is threefold:

- To present a model that allows the evaluation of the effect of EVs charging loads on the dielectric oil deterioration of two real PDTs, one supplying a residential area and the other a private industrial client, which in turn are part of the isolated electrical grid of São Miguel Island, Azores, Portugal.
- To utilise a method that takes into account the uncertainty of EV battery charging loads, for instance the variability of the travel habits of the EV user before recharging – recorded in 2011, the battery SOC at the beginning of the charging process and different charging strategies.
- The study of a particular case of an island with scenarios of high penetration of EVs and the EV charging at work during 3 different shifts considering an industrial load.

The remainder of the paper is organized as follows: in Section 2, the employed methodology is elaborated. In Section 3, the DN of São Miguel, Azores is presented and two cases are studied, one assessing the impact of EVs charging through the PDT of a residential area and another concerning an industrial client. Simulation results are also provided and discussed. Finally, conclusions are drawn in Section 4.

2. Methodology

2.1 EV battery charging profiles

The charging of EVs is an addition to the existing load. EVs are noticeably distinct when compared to other electrical loads, as a result of their highly mobile and unpredictable nature. Currently, three key factors that could affect the influence of EVs on DN exist, namely, the unique nature of the EV charging process, the driving profile and electrical energy tariff incentives.

With the growth of the EV market more and more car manufacturers enter the competition. Hence, a large number of EV types with different characteristics are available today [22]. As a result, in order to be more realistic, five different types of EVs are used in this study. The latest models of real EVs were used in this study – BMW i3, Renault ZOE, Ford Focus Electric, Nissan Leaf and Kia Soul [23] [24] [25] [26] [27].

In the last few years EVs are becoming technologically tempting due to the progress of Lithium-ion (Li-ion) battery technology that is capable of offering the advantage of higher power, as well as higher energy density. Given that Li-ion batteries are generally preferred as the main power source of the current EVs [28], in the present study it is implicitly considered that EVs in this case-study employ such type of batteries. In fact, virtually all EVs that are available in the market today use this battery type due to its mature technology. The battery capacity 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 [29].

All the EVs considered in this study employ Li-ion batteries and to understand better effect of charging on the daily baseline load profile, the charging behaviour of a Li-ion battery is briefly described. While the SOC of the battery is low, then the charger functions at rated current, therefore it allows a great quantity of the battery SOC being re-established in the course of the initial charging hours. In practice, the process of charging a Li-ion battery, despite being represented by simplified characteristics, is described by a relation that reflects the mutually dependent occurrences of battery SOC and charger type [30]. The process pursues until the limit of the battery voltage is reached, at which the current falls while the EV charger preserves a constant voltage. The EV battery charging process is assumed to be continuous as soon as it is initiated until the full capacity of the battery is reached.

2.2 Model of EV Charging Load

In this paper and for both case studies the charging profile of Li-ion EV batteries is utilized, and the stochastic behaviour of the EV battery SOC at the starting point of the charging process is calculated using a probability density function (PDF) associated with the driving range as in [19] [31]. The EV charging demand is given by the initial battery SOC, the charging start time and characteristics. Travel habits of the EV before the recharging process define the SOC at the beginning of the charging process of an EV battery and can be perceived as a random variable associated to the driving range. Using as a basis a study on the general travel information regarding Portuguese drivers of conventional vehicles recorded in 2011 in Lisbon area [32], a PDF of day-to-day driving range can be constructed as expressed by (1):

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

By knowing the average daily driving range, the SOC at the beginning of a recharge cycle, that is the residual battery capacity, is calculated utilizing (2), assuming that each trip is initiated with 100% SOC and that the SOC descents linearly during the course of the journey (2):

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

A typical average value for travel distance is 100 km [33].

By replacing (2) into (1) and switching the variable from d to E, and by succeeding the journey of one day, the PDF of the SOC of the battery is expressed as follows (3):

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

The PDF is truncated between 25% and 95% of battery SOC with parameters as in [34]. Since the equation is truncated at 25% and 95% of battery SOC it means that at the beginning of each charging process the battery can range from 25% to 95% of SOC depending on the travel habits of EV users. Consequently, EVs that are at, for example, 92% SOC – charge within minutes while the ones that are at, for instance, 26% will take hours to reach the full charge in the slow charging mode.

Based on the information drawn from both PDF, it is possible to estimate the residual battery capacity at the beginning of a recharge cycle. Both the electricity tariff rate structure and the objective of the use of the EVs by the users, which is an uncertain factor, influence the initial plug-in instance of the EV and the battery charging process.

2.3 The Loss of Life of the PDT

Since the PDT is a vital part of the DN, a proper conservation of mineral-oil-tilled PDTs is of a high importance in power systems and therefore, the necessity of implementing a caring methodology concerning PDT loading emerges [35].

The PDT insulation system is essentially created from paper and oil and both are subject to experience deterioration. Load intensification has an effect on the increase of the Θ_h and subsequently the thermal deterioration of the paper is affected [36] [37] [38].

As the distribution of the temperature is uneven, the most deteriorated section of the PDT will be the one with the highest temperature [39]. Thus, the Θ_h temperature directly affects the life duration of PDTs [19].By definition, the Θ_h is the highest temperature of any spot in the PDT winding. By experiencing elevated electrical loads it originates high core-winding temperatures which in turn cause chemical breakdown of insulating oil and insulating paper [36] [37].

2.3.1 Assessment of Θ_h temperature through exponential equations

In the case of ever-increasing steps of loads, Θ_o and winding Θ_h rise until a step equivalent to load factor *K*. As a consequence, equation of the top-oil $\Theta_o(t)$ temperature is shown in the following expression (4):

$$\Theta_o(t) = \Delta\Theta_{oi} + \left\{ \Delta\Theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\Theta_{oi} \right\} \times \left(1 - e^{-t/(k_{11} \times \tau_o)} \right) \tag{4}$$

The hot-spot temperature rise $\Delta\Theta_h(t)$ is as follows (5):

$$\Delta\Theta_h(t) = \Delta\Theta_{hi} + \left\{ H \times g_r \times K^y - \Delta\Theta_{hi} \right\} \times \left[k_{21} \times \left(1 - e^{-t/(k_{22} \times \tau_w)} \right) - (k_{21} - 1) \times \left(1 - e^{-(t \times k_{22})/\tau_o} \right) \right] \tag{5}$$

For decreasing step of loads situations, the Θ_o and winding Θ_h are reduced until a step corresponding to a *K* [36]. The equation of the top-oil temperature $\Theta_o(t)$ is expressed as following (6):

$$\Theta_o(t) = \Delta\Theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x + \left\{ \Delta\Theta_{oi} - \Delta\Theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x \right\} \times \left(e^{-t/(k_{11} \times \tau_o)} \right) \tag{6}$$

The Θ_h increase is set by (7):

$$\Delta\Theta_h(t) = H \times g_r \times K^y \tag{7}$$

In conclusion, by taking into consideration $\Theta_o(t)$ and $\Delta\Theta_h(t)$ from (4) and (5) in case of increasing load steps, and (6) and (7) in case of decreasing load steps and by taking into account the ambient temperature Θ_a the complete hot-spot temperature $\Theta_h(t)$ expression is estimated as follows (8):

$$\Theta_h(t) = \Theta_a + \Theta_o(t) + \Delta\Theta_h(t) \tag{8}$$

2.3.2 Assessment of Θ_h temperature through differential equations

When heat-transfer principles are applied to the PDT situation, the differential equations for Θ_o (inputs *K*, Θ_a and output Θ_o) is:

$$\left[\frac{1 + K^2 R}{1 + R} \right]^x \times (\Delta\Theta_{or}) = k_{11} \tau_o \times \frac{d\Theta_o}{dt} + \left[\Theta_o - \Theta_a \right] \tag{9}$$

The differential equation for Θ_h rise (inputs *K* and output $\Delta\Theta_h$) is most easily solved as the sum of two differential equations where:

$$\Delta\Theta_h = \Delta\Theta_{h1} - \Delta\Theta_{h2} \tag{10}$$

The two equations are:

$$k_{21} \times K^y \times (\Delta\Theta_{hr}) = k_{22} \times \tau_w \times \frac{d\Delta\Theta_{h1}}{dt} + \Delta\Theta_{h1} \tag{11}$$

and

$$(k_{21} - 1) \times K^y \times (\Delta\Theta_{hr}) = \left(\tau_o \middle/ k_{22}\right) \times \frac{d\Delta\Theta_{h2}}{dt} + \Delta\Theta_{h2} \tag{12}$$

the solutions of which are combined in accordance with equation (8). The final equation for the Θ_h is:

$$\Theta_h = \Theta_o + \Delta\Theta_h \tag{13}$$

If the differential equations are converted to difference equations, then the solution is quite straightforward, even on a simple spreadsheet. The differential equations (7-11) can be written as the following difference equations, where *D* stands for a difference over a small time step. Equation (7) becomes:

$$D\Theta_o = \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\Theta_{or}) - [\Theta_o - \Theta_a]\right] \tag{14}$$

The D operator implies a difference in the associated variable that corresponds to each time step Dt. At each time step, the *n*th value of $D\Theta_o$ is calculated from the $(n-1)$th value using:

$$\Theta_{o(n)} = \Theta_{o(n-1)} + D\Theta_{o(n)} \tag{15}$$

Equations (9) and (10) become:

$$D\Delta\Theta_{h1} = \frac{Dt}{k_{22}\tau_w} \times \left[k_{21} \times \Delta\Theta_{hr} K^y - \Delta\Theta_{h1}\right] \tag{16}$$

and

$$D\Delta\Theta_{h2} = \frac{Dt}{\frac{1}{k_{22}}\tau_o} \times \left[(k_{21} - 1) \times \Delta\Theta_{hr} K^y - \Delta\Theta_{h2}\right] \tag{17}$$

The n^{th} values of each of $\Delta\Theta_{h1}$ and $\Delta\Theta_{h2}$ are calculated in a way similar to equation (13). The total Θ_h rise at the n^{th} time step is given by:

$$\Delta\Theta_{h(n)} = \Delta\Theta_{h1(n)} + \Delta\Theta_{h2(n)} \tag{18}$$

Finally, the Θ_h temperature at the nth time step is given by:

$$\Theta_{h(n)} = \Theta_{o(n)} + \Delta\Theta_{h(n)} \tag{19}$$

2.3.3 The PDT calculation of loss of life.

In case of the thermally upgraded paper the equation of the ageing rate V is expressed as follows [37]:

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)} \quad (20)$$

The ageing rate V [40] corresponds to the deterioration of paper insulation at a temperature Θ_h which is higher or lower than 110ºC, with respect to the ageing rate at 110ºC [36]. The loss of life (LOL) of cellulose insulation which calculated using the differential equations can also be expressed with difference equations. The fundamental differential equation is:

$$\frac{dL}{dt} = V \quad (21)$$

implying:

$$DL_{(n)} = V_{(n)} \times Dt \quad (22)$$

and:

$$L_{(n)} = L_{(n-1)} + DL_{(n)} \quad (23)$$

The LOL equation L can also be rewritten and for the duration of the time segment t_n is expressed as following:

$$L = \int_{t_1}^{t_2} V dt \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n \quad (24)$$

3. Simulation Results

3.1 The PDT Proprieties

In order to determine transient solutions for Θ_o and Θ_h a thermal model is developed and proposed for the PDT and can be applied to both three-phase and to single-phase PDTs.

The PDT power rating and cooling system is provided by the insular DSO. The properties of both PDTs used in this paper are obtained from Ravetta et al. [41] that presented the data of a real 250 and 630 kVA (P_r) oil PDTs with Oil Natural Air Natural (ONAN) cooling where a natural convectional flow of hot oil is utilized for cooling. The constants are taken from [36]. Both PDTs properties are drawn from [42] and [43].

3.2 Structural elements of the insular grid

The Azores are a Portuguese autonomous region and a 9 islands archipelago located in the North Atlantic, circa 3900 km from the east coast of North America. São Miguel Island is the capital and most populated island. The island has around 140,000 inhabitants and covers an area of 760 km². In this paper, a part of São Miguel medium voltage DN is investigated.

The research portrayed in this paper focuses on two different cases in which the evaluation of the effect of EVs charging loads on the dielectric oil deterioration of two real oil-immersed PDTs, one supplying a residential area and the other a private industrial client, which are referred to as case study 1 and 2, respectively. The EVs staring time of charging is selected by taking into account the daily habits of São Miguel's people and the off-peak tariff. In this regard, data are provided under SiNGULAR project [44].

Two different percentages of EVs are used for the two different cases under investigation. The percentage of BMW i3 was chosen in both case studies as high as 40% since it is the fastest selling EV in Portugal according to the Portuguese Automobile Association (Associação Automóvel de Portugal – ACAP) [45]. Renault ZOE and Ford where selected to have a 20% market penetration since these brands already appear to have a significant share in the conventional vehicle market [45]. Data for the charging types and duration of the five EVs are presented in [42] for the first case study and for [43] the second case study.

The present market outlook of EVs can be considered globally low, not exceeding a 7% share in leading countries such as Norway [19]. On the other hand, in this paper, very high penetration levels are examined. Particularly for an insular area, such as São Miguel, the relatively high transportation cost of fossil fuels, the presence of rich potential of RES, and the opportunities that emerge from the efficient management of an EV fleet [13], are factors that have led 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. In addition, supporting initiatives made by governments frequently have a tendency to aim specific areas such as islands and as a result, potential funding programs or tax reduction schemes to endorse the acquisition and use of EVs are highly expected to significantly encourage customers to exchange their fossil-fuelled internal combustion engine vehicles with EVs [46].

3.3 Case Study 1

For this case study a PDT that supplies a residential area is chosen. The part of the medium voltage DN and an identification of several outputs are withdrawn and can be seen in [42]. For this case study the

PDT substation PT80 which supplies 292 households through a 630kVA, 10kV/0.4kV oil-immersed PDT is used.

During the summer of 2014 a number of measurements were performed at the PDT substation PT80 and the energy consumption of 292 households was collected. Plus, the daily temperature records were made for the aforementioned period as shown in Fig. 1. The baseline load profile is withdrawn from [42]. It may be observed that a 630 kVA PDT is oversized for a 140 kW of peak in daily baseline load profile, even if in Azores higher consumption is witnessed during the summer [21].

"Figure 1 can be observed at the end of the document".

The EV load demand can be affected to some extent by the electricity tariff structure. For this model the current electricity tariff of Azores Islands that entered into force in 2015 is taken into account. Even though a three rate tariff for domestic consumers currently exists in Azores, for this study the two rate tariff is used. The off-peak tariff is 190% lower than the peak tariff and it is initiated instantly after 22:00 [47].

Based on the data collected from the PDF it is possible to apply the PDT thermal model, using the load ratio as an input to obtain the Θ_h and Θ_o. For this case study one day and a half of the baseline load profile of the summer period of the PDT substation PT80 is used.

The total load (in kW) on the PDT is the summation of the n_d domestic loads P_d and loading from n_{EV} randomly selected EVs:

$$P(t) = \left| n_d P_d(t) + \sum_{EV=1}^{n_{EV}} P_{EV}(t) \right| \tag{25}$$

A fitting algorithm is applied to assess the impact of EVs charging loads on the dielectric oil deterioration of PDT based on the previously presented methodology. Battery charging of the electric vehicles inflicts an extra load on the PDT. By hypothesizing that a PDT supplies several EVs in a neighbourhood, different charging time and load profiles are obtained for the PDT. The algorithm integrates data obtained from the PDF and calculates the Θ_h and the PDT LOL due to EVs charging loads.

Two different scenarios are studied, the first being with different initial SOC of the EVs based on the PDF function, plus different penetration ratios of EVs are considered in this study for the household neighbourhood, beginning with 75% penetration and then with 80%, 85%, 90%, 95% and 100%. Also, it is considered that 50% of the EV owners charge their cars in slow charging mode and the other 50% in domestic fast charging mode since the model can be applied for both. Finally, it is assumed that 55% of EVs begin charging at 22:00 or are scheduled to do so since as seen before, for Azores the off-peak tariff is 190% lower than peak tariff and it becomes available exactly at 22:00 of each day, as for the remaining 45% of EVs, it is assumed that these users are not very concerned with off-peak tariffs and that the EVs charging are set to begin at 07:00 or are scheduled to do so, when users wake up and go to work and the slow charging mode is used after home arrival, usually after 18:00. These specific percentages are chosen as such due to the reason of being just under and/or above the PDT loading limit, other percentages are redundant.

The second scenario explores a case where during the weekend and at the rule of the same off-peak tariff all the EVs are scheduled or the users chose to charge or the EVs are set to charge at 22:00 and all the owners charge their cars in slow charging mode. The impact on the daily baseline load profile of the PDT substation PT80 made by the energy consumption of the EVs at several penetration ratios from both scenarios is shown in Fig. 2 and in Fig. 4, respectively, where (hh:mm) signifies the time in hours and minutes. The starting times of charging for the first scenario is chosen due to the fact that EV users typically do not have a need for fast recharging since they dispose of sufficient time - 3 to 8 h (depending on the charge level) during the non-working period of the day or after 22:00 at the residence with the intention of skipping the drawback of recurring to a public charging station.

By analysing Figs. 2 and 4 it can be concluded that for a penetration of EVs of more than 75% the PDT is overloaded. It is then possible to assess the PDT insulation ageing affected by the Θ_h and the LOL of the PDT which is presented in Figs. 3 and 5, respectively.

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"Figure 3 can be observed at the end of the document".

"Figure 4 can be observed at the end of the document".

"Figure 5 can be observed at the end of the document".

Using the ageing equations (20) and (24), the LOL of the PDT can now be determined. The LOL of the PDT is presented in percentage and also in hours and minutes for each day of EV charging which means that from the PDT expected life at 0% penetration (180000 hours) is withdrawn a number of hours for each day of charging. The results can be seen the Table 1.

"Table 1 can be observed at the end of the document".

From Fig. 2 to 5 and from the Table 1 it can be concluded that the off-peak tariff will encourage users to prefer a certain hour of charging, in this case, 22:00, that will cause a concentration of EVs charging at the same time which in turn will generate an overloading of the PDT, a sudden increase of the Θ_h and consequently will affect the PDT lifetime.

In both scenarios it can be concluded that for more than 75% of EV penetration the PDT will overloaded resulting in a growth of the Θ_h of the PDT. The LOL increases with the increase of EV penetration in both scenarios.

By analysing the results obtained from Table 1 it can be concluded that the PDT LOL is only affected after a certain amount of EV penetration which is relatively high. If the EV users keep this profile of charging every day the PDT will have a deteriorating LOL after some time.

3.4 Case Study 2

This case focuses on a PDT that supplies a private industrial client. A part of the medium voltage DN and an identification of several outputs and can be seen in [43].

In this case study the PDT substation PT1094 is used which supplies one private industrial client through a 250kVA, 10kV/0.4kV oil-immersed PDT.

The private industrial client consists of a factory that produces sugar out of sugar beet. It employs 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 assumed in this paper that the workers are evenly distributed throughout the working shifts.

During the summer of 2014 several measurements were made at the PDT substation PT1094 and the energy consumption of industrial client was recorded and as a consequence a daily baseline load profile is generated and can be observed in [43]. It is also given the power factor of the PDT – approximately 0.95. It may be observed that a 250 kVA PDT is properly sized for a 140 kW of peak in daily baseline load profile, considering that a typical value for an inferior size PDT would be 167 kVA which is not satisfactory [21].

The total load $P(t)$ (in kW) on the PDT is the sum of the factory load $P_f(t)$ and loading from n_{EV} randomly selected EVs:

$$P(t) = \left| P_f(t) + \sum_{EV=1}^{n_{EV}} P_{EV}(t) \right| \quad (26)$$

For this case study one day of the baseline load profile of the summer period of the PDT substation PT1094 is used and two different scenarios are examined.

3.4.1 Scenario 1

For the first scenario different penetration ratios of EVs for each working shift are considered for this industrial client, beginning with 35% penetration and then with 40%, 45%, 50%, and 55 %. The number of EVs in this case can be calculated simply by dividing the 120 employees by 3 shifts, resulting in 40 workers per shift. Thus, for instance, 50% of EVs translates in 20 EVs charging per shift. These specific percentages are chosen as such due to the reason of being just under and/or above the PDT loading limit, other percentages are redundant. Finally it is assumed that the EVs start or are scheduled to charge at the beginning of each working shift.

The effect on the daily baseline load profile of the PDT substation PT1094 created by the energy consumption of the EVs at several penetration ratios from the first scenario is shown in Fig. 6. The daily baseline load profile is also shown as 0% penetration ratio.

By analysing Fig. 6 it can be observed that for a penetration of EVs of more than 40% the PDT is overloaded. Also, from the information obtained from the model and presented in Fig. 6, it is possible to assess the PDT insulation ageing affected by the Θ_h which is presented in Fig. 7 and subsequently to calculate LOL at the designated penetration ratios of the PDT. The LOL of the PDT is presented in percentage and in hours and minutes for each day of EV charging which means that from the PDT expected life at 0% penetration is subtracted the number of minutes or hours for each day of charging. The results can be seen in the Table 2.

"Figure 6 can be observed at the end of the document".

"Figure 7 can be observed at the end of the document".

"Table 2 can be observed at the end of the document".

3.4.2 Scenario 2

The second scenario is as follows: all EVs are charged with fast charging mode beginning with 15% penetration and then with 20%, 25%, 30%, and 35%. The same percentages are set as the preceding scenario in order to observe the difference between slow and fast charging modes. 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 consequence on the daily baseline load profile of the PDT substation PT1094 made by the energy consumption of the EVs at several penetration ratios from the second scenario is shown in Fig. 8.
By observing Fig. 8 it can be noticed that for a penetration of EVs of more than 15% the PDT is profoundly overloaded and even at inferior penetration ratios it is overloaded. Also, from the information obtained from the model and presented in Fig. 8, it can be assessed the PDT insulation ageing affected by the Θ_h which is presented in Fig. 9. By means of the ageing equations (5) and (6), the LOL of the PDT can now be determined. The results can also be seen in the Table 2.

"Figure 8 can be observed at the end of the document".

"Figure 9 can be observed at the end of the document".

3.4.3 Critical Analysis

By analysing the results obtained from Table 2 it can be concluded that the PDT LOL is only affected after a certain amount of EV penetration which is relatively high. If the EV users make such profile of charging a routine the PDT will have a deteriorating LOL after some time.

The comparison of both scenarios at 35% EV penetration in the Figs. 10 and 11 highlights the level of impact in the PDT ageing by using fast charging over slow charging. By analysing Figs. 6 to 9 and Table 2 it can be concluded that each beginning of a shift will influence users to prefer the first hour of charging, that will originate a concentration of EVs charging at the same time which in turn could cause an overloading of the PDT, a sudden increase of the Θ_h and thus will affect the PDT lifetime.

"Figure 10 can be observed at the end of the document".

"Figure 11 can be observed at the end of the document".

By observing the first scenario it can be concluded that for more than 40% of EV penetration the PDT will be overloaded resulting in an increase of the Θ_h of the PDT. The LOL slightly increases with the increase of EV penetration in this scenario.

In an improbable event of the second scenario occurring, the LOL of the distribution PDT 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.

4. Conclusions

In this paper a model to estimate the influence of simultaneous EVs charging on the dielectric oil deterioration of two PDTs, one at a residential area and other at a private industrial client, was applied. Two different case studies were examined, one focusing on a residential area during working days and weekends and another concerning a private industrial client with several penetration ratios at three different working shifts. The power rating of both PDTs and the cooling system were provided by the local DSO. Since the PDT insulation ageing is mainly affected by the Θ_h and by knowing the load ratio a PDT thermal model was utilized to calculate the Θ_h. The main inputs to the model, including residential load, PDT parameters, and five different vehicle parameters were taken from real data. Dielectric oil deterioration was then calculated and analysed. Since both PDTs have a significant capacity to be used for a side activity – this study shows that even though it has, it still can be overloaded after a specific increase of EV penetration. The developed methodology was applied to assess the impact of multiple EVs charging in the same residential area and it showed that off peak tariff can have an influence over EV users and affect the PDT lifetime. The results show that the LOL of the PDT is only affected after a certain amount of EV penetration, which is relatively high. In both case studies the penetration ratios that reach the limit of the transformer were studied; thus, if the penetration of the EVs increase from these scenarios onward then a more accelerating deterioration of the oil is expected. The second case study showed also that while charging at the workplace, the slow charging mode was recommended over the fast mode. Even if the slow charging mode was selected by the users the vehicles will always be 100% charged at the end of each working shift and without drastically affecting the PDT lifetime when compared to the fast charging mode.

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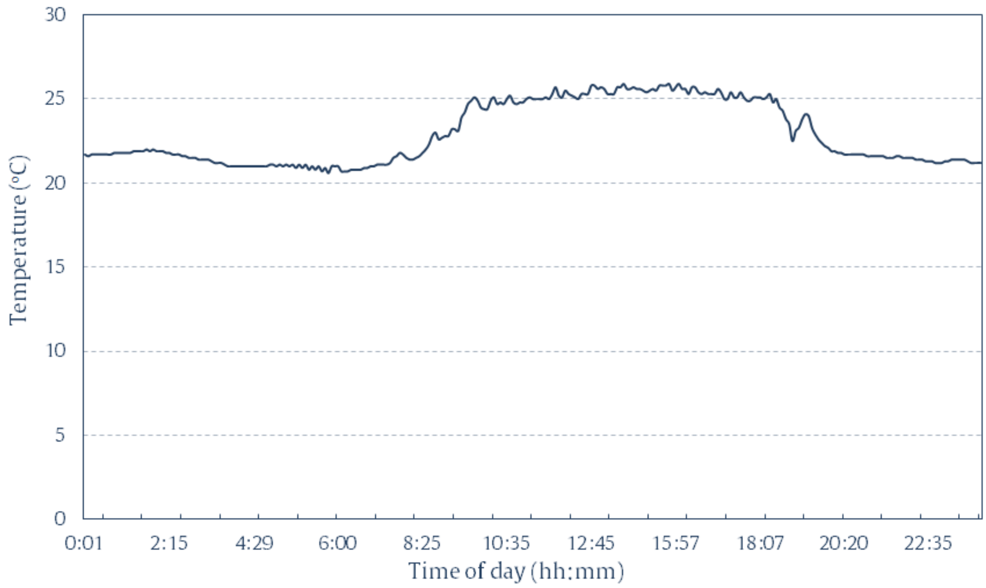

Fig. 1 – Temperature of a typical summer day in São Miguel.

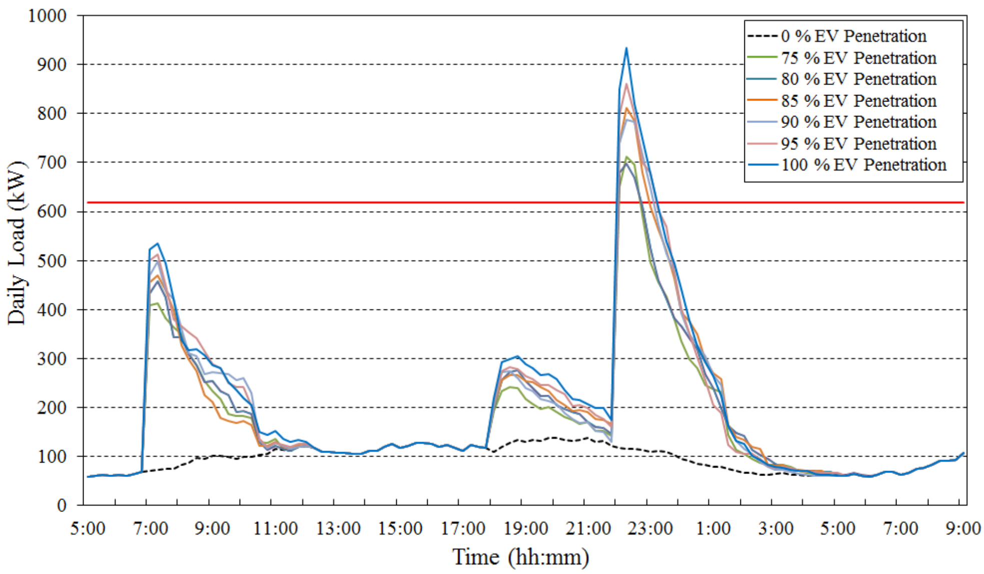

Fig. 2 – The daily baseload profile (case 1, scenario 1).

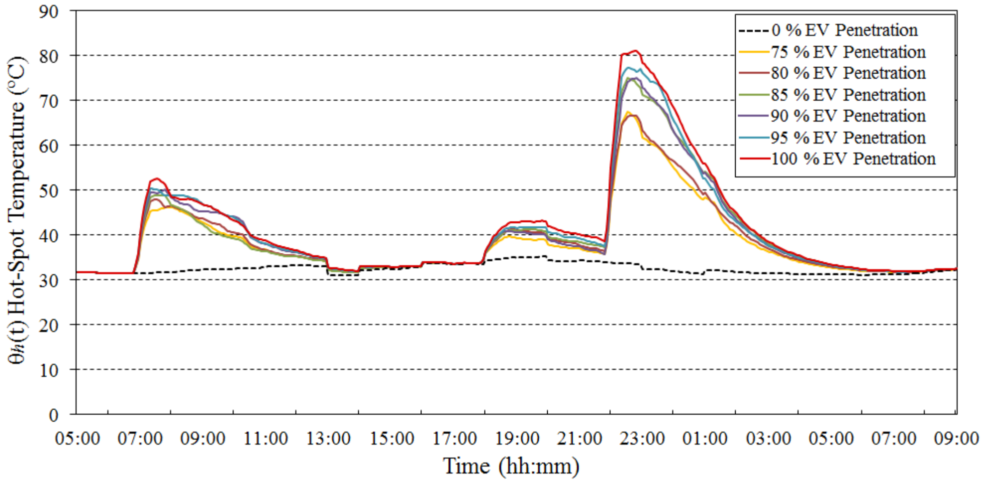

Fig. 3 – The Θ_h of the PDT (case 1, scenario 1).

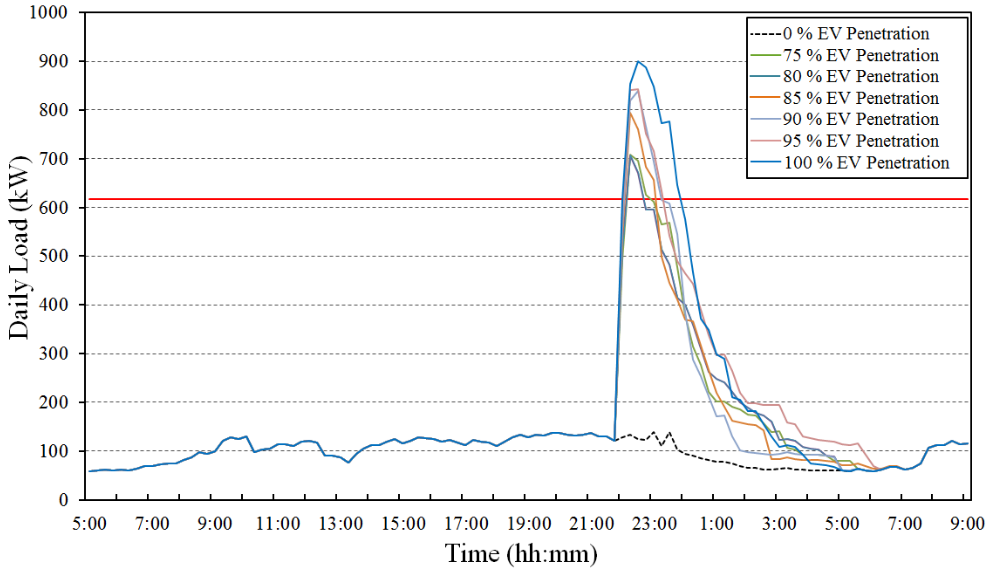

Fig. 4 – The daily baseload profile (case 1, scenario 2).

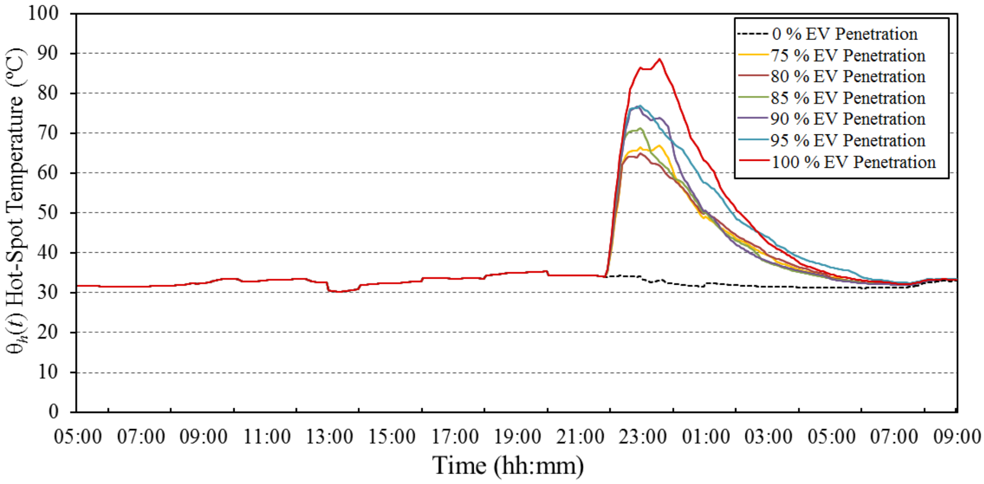

Fig. 5 – The Θ_h of the PDT (case 1, scenario 2).

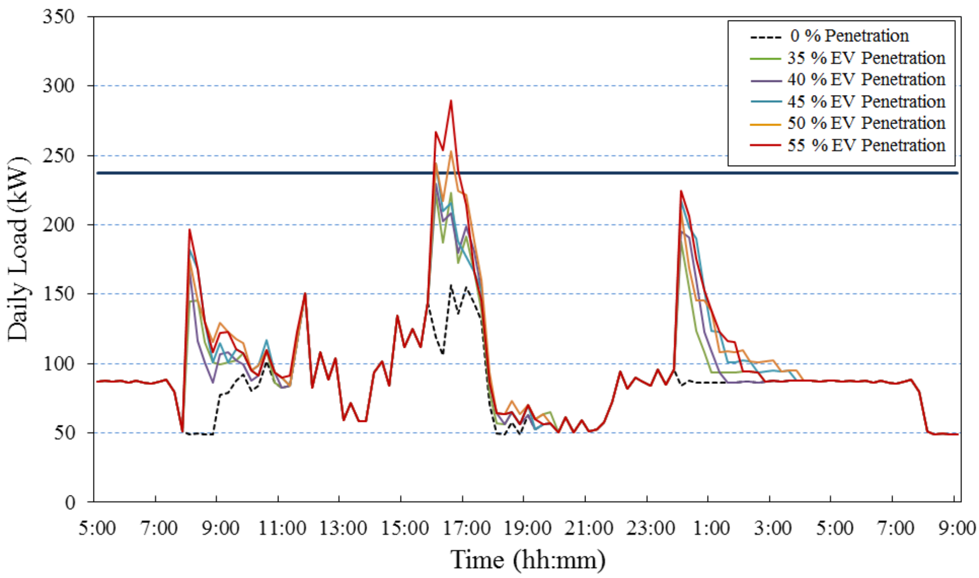

Fig. 6 – The daily baseload profile (case 2, scenario 1).

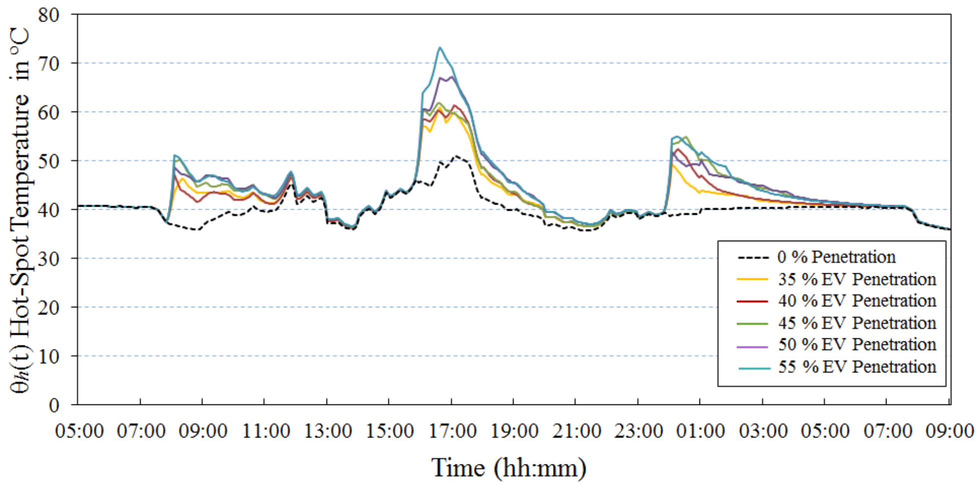

Fig. 7 – The Θ_h of the PDT (case 2, scenario 1).

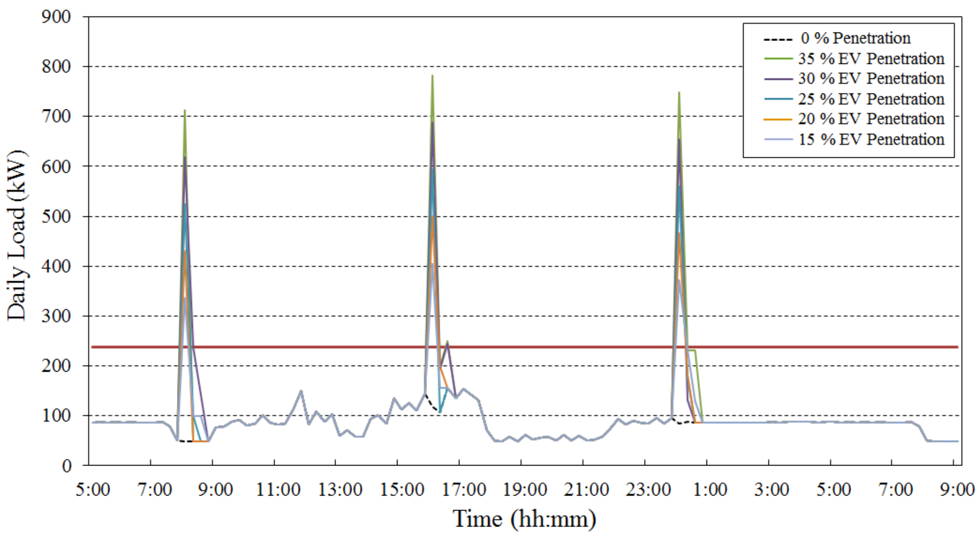

Fig. 8 – The daily baseload profile (case 2, scenario 2).

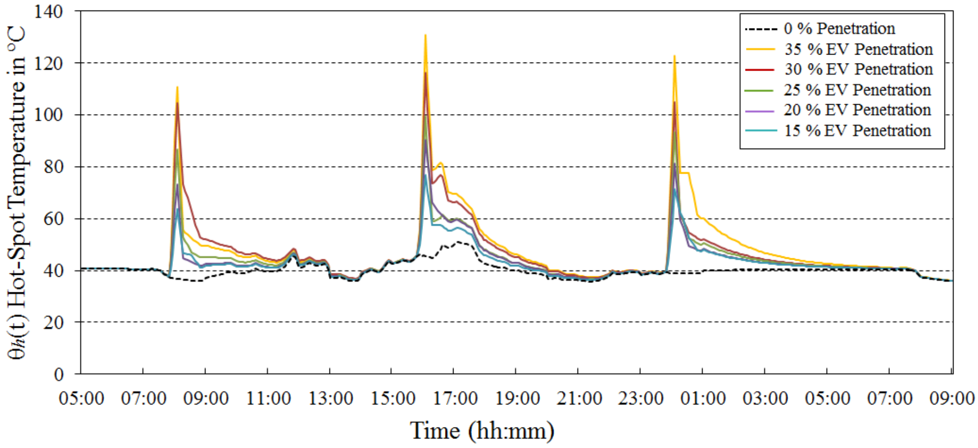

Fig. 9 – The Θ_h of the PDT (case 2, scenario 2).

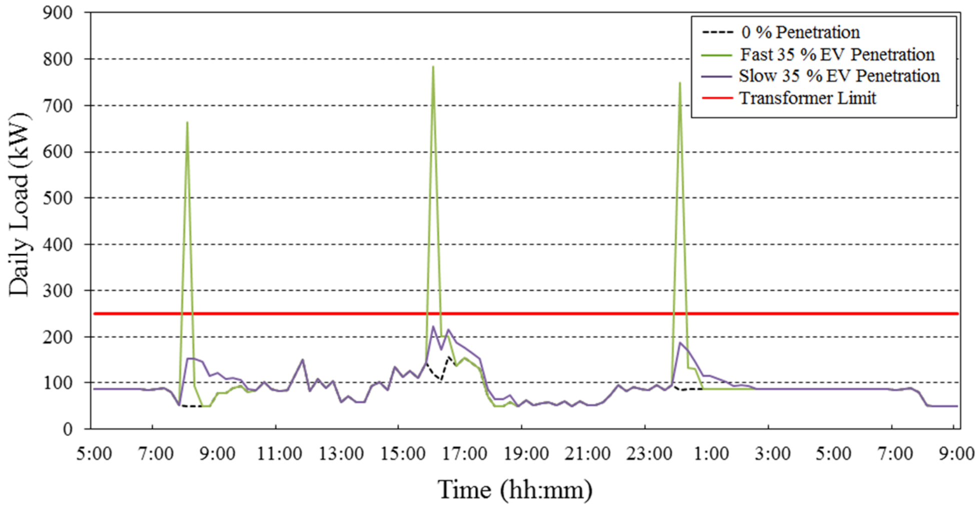

Fig. 10 – Comparison between scenario 1 and 2 of the daily baseload profile in case 2.

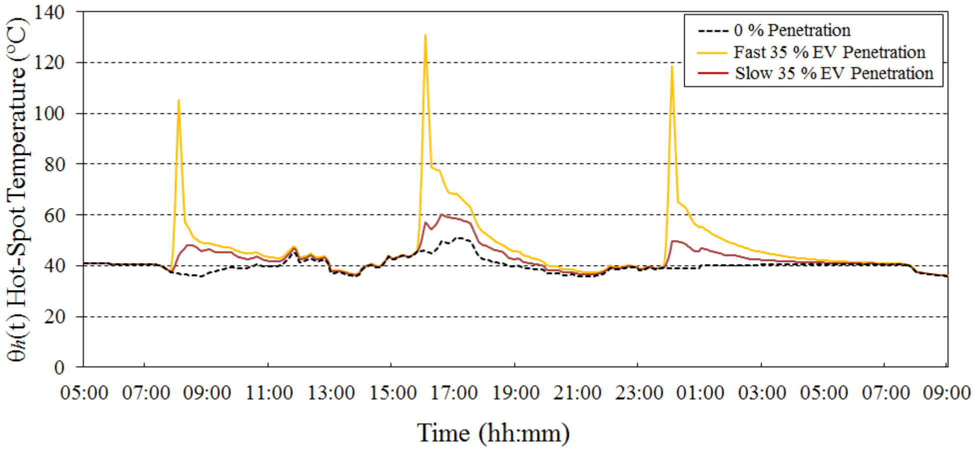

Fig. 11 – Comparison between scenario 1 and 2 of the Θ_h of the PDT in case 2.

Level of Penetration	Scenario 1		Scenario 2	
	LOL	*% LOL*	*LOL*	*% LOL*
0%	0h 00m	0	0h 00m	0
75%	0h 50m	0.0005	0h 38m	0.00035
80%	1h 09m	0.0006	0h 46m	0.0004
85%	1h 23m	0.0008	0h 54m	0.0005
90%	1h 41m	0.0009	1h 06m	0.0006
95%	2h 17m	0.0013	1h 24m	0.0008
100%	2h 50m	0.0016	2h 46m	0.0015

Table 1 – Daily transformer LOL due to EV Charging (Case 1)

Scenario 1			Scenario 2		
EV Penetration	*LOL (t)*	*LOL %*	*EV Penetration*	*LOL (t)*	*LOL %*
35%	0h 36 min	0.0003	15%	0h 58m	0.0005
40%	0h 40 min	0.0004	20%	1h 22m	0.0004
45%	0h 45 min	0.0004	25%	4h 23m	0.0024
50%	0h 58 min	0.0005	30%	16h 02m	0.0089
55%	0h 77 min	0.0007	35%	70h 22m	0.0391

Table 2 – Daily transformer LOL due to EV charging (Case 2).