EV Charging Effect on a Distribution Transformer Supplying a Factory with Local PV Generation

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***Abstract*—The aim of this paper is to avoid overloading a private customer distribution transformer (DT) in a Portuguese insular area through the means of solar PV microgeneration. Firstly, the consequence of the penetration of electric vehicles (EV) on dielectric oil deterioration of a DT in an industrial unit is estimated. The workplace has local PV generation, allowing the EVs to charge while their owners are working at three different working shifts during a day. Secondly, the model is tested and the resulting scenarios are analyzed. This paper shows that the solar PV microgeneration decreases the overloading of the DT due to a lower daily load profile. It also contributes to the reduction of the loss-of-life (LoL) of the DT.**

Keywords—distribution transformer; solar PV microgeneration; loss-of-life; battery; transformer ageing; industrial client.

NOMENCLATURE

Variables

LoL	Loss of life.
N	Total number of time intervals.
n	Any given number.
P_{EV}	EV rated charging power in W.
P_f	Factory load in W.
P_{PV}	PV rated charging power in W.
P_T	Total load in W.
t	Period of the day in time units (h or min).
Δt_n	Time interval.
R_r^a	Relative ageing rate.
R_{rn}^a	Relative ageing rate during interval *n*.
Θ_a	The average ambient temperature in °C.
Θ_o	Top-oil temperature in °C.
Θ_h	Winding hottest-spot temperature in °C.

Indices

a	Ambient Temperature
EV	Electric Vehicle
h	Hot–spot
i	At start/initial
n	Index of the time interval
o	Top-oil
PV	Photovoltaic System
r	Rated Load
t	Period of the day index in time units [h or min].

Acronyms

ACAP	Portuguese Automobile Association
DN	Distribution network
EV	Electric vehicle
DT	Power distribution transformer
Li-ion	Lithium-ion batteries
LoL	Loss of life
ONAN	Oil natural air natural
PDF	Probability density function
SoC	State of charge

I. INTRODUCTION

The enthusiasm attributed to EVs witnessed in academia is comprehensible since they are fascinating technically. When compared with conventional vehicles, they offer better acceleration, the possibility to charge at home and with lower energy costs, lower maintenance costs, less vibration and are almost silent. Electric vehicles (EVs) could be a part of a much needed approach towards tackling such problems as the environment deterioration and the decrease of available fossil fuels. Policy makers, researchers and enterprises are beginning to promote the adoption EVs and make them as an important part of a set of technologies necessary for reducing the energy consumption and carbon-dioxide emission. Consequently, the energy optimization of EVs has turned into a hot topic in academia. The increased concern in extending EV driving ranges has led many researchers to investigate the energy management strategy of EVs [1].

Due to the EVs mobility properties and energy storage, the penetration of a large number of EVs will be significant for the full use of renewable energy sources which happen to present several obstacles. Such trend is backed by various studies currently published on the charging behaviors of the EVs [2]. A real event, such as the local distribution networks (DN) being congested could occur if the penetration of EVs increases [3]. The charging behavior of a high number of EVs could influence the DN and also the transport systems. Hence, to study their charging behaviors and scheduling becomes a necessity [4]. One of the utmost important and expensive elements of the electric DN are DTs. By the reason of DTs having a strategic location they exert a major influence on the overall reliability of the transmission and distribution electric systems [5]. Consequently, DTs could be one of the most affected elements of the DNs given that during certain periods they will be overloaded – an effect of the charging of EVs, thus, decreasing their useful life [6].

The introduction of such paradigms as smart grid in insular regions has been growing with the implementation of a varied range of test systems in numerous islands around the world.

Given that the DN of islands has quite some differences when compared to the DNs form the mainland, isolated areas could provide a much needed foundation for promising islanding operation requirements on and be the basis of future testing grounds for the study of the smart grid [7].

For the case study analyzed in this paper, a part of São Miguel medium voltage DN was utilized. A specific DT substation was selected that supports an industrial unit through a 250kVA, 10kV/0.4kV oil-immersed DT. The industrial unit has local solar generation from an array of 72 solar modules. It has 120 employees that work in 3 working shifts of 8 hours each. The initial working shift begins at 08:00, the second at 16:00 and the third at 00:00. In this study is assumed that the workers are evenly distributed throughout the working shifts.

In this paper, a model based on real data is presented. Such model permits the estimation of the impact that the battery charging of EVs on dielectric oil deterioration of the DT of the industrial unit with local PV generation. Also, the studied part of the DN is a section of an isolated electrical grid of São Miguel Island, Azores, Portugal.

The paper is organized as follows. In Section II the methodology is presented. The case study is addressed in Section III. In Section IV the operation and simulation results are discussed. Finally, the conclusions are made in Section VI.

II. Methodology

A. EV battery charging profiles

In order to form a simpler model, the charging load of the battery of an EV is added to the existing load [8]. Increasing quantities of automotive manufacturers decide to enter into the EV market. Therefore, an increasing quantity of EVs with distinct qualities and elements are available today [9]. In this paper 4 different types of EVs were selected for the study in question. The chosen EVs are: Renault ZOE, BMW i3, Ford Focus Electric and Tesla Model S. The characteristics of the studied EVs and the charging types are taken from [8] and [10].

The chosen percentage of penetration of BMW i3 is 40% since evidence point to it being the EV that shares the highest chunk of the market in Portugal according to the ACAP – the Portuguese Automobile Association. Since the remaining EVs such as Renault ZOE, Ford Focus Electric and Tesla Model S have a significant presence in the EV market [11] the choice for them to share together 20% of market penetration each seems plausible. Lithium-ion (Li-ion) batteries in the last few years have become a very popular storage system choice for the automotive industry in manufacturing of EVs. The reason of such preference is its long lifetime and high power density [9]. Consequently, Li-ion batteries became the most popular option for the newest EVs released into the market [12]. The selected EVs for this study are assumed to have Li-ion batteries.

B. Model of EV Charging Load

In case of the model of EV charging load the classic EV Li-ion batteries charging profile is taken into consideration, and connected to travel distances is the stochastic behavior of the initial SoC of the EV battery. The SoC is estimated by utilizing a probability density function (PDF).

The EVs charging load demand is offered by the starting battery SoC, charging initial instant time and its proprieties. The SoC of an EV battery in this case study is estimated by the travel habit of the EV user prior to the plug-in event for recharging and can be considered a random variable related to the travelled distance. The input data for the model is taken form a study that released general travel information concerning Portuguese drivers of internal combustion engine vehicles in 2011 in Lisbon area [13].

Therefore, with the aforementioned data the probability distribution of the covered travel distances can be produced as can be observed in [8]. A characteristic average value for the EV travelled distance is considered to be 100 km [14].

Generally, it is 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 [15]. Based on data taken from both PDF from [8], it is possible to initiate the estimation of the battery SoC at the initial instant of every charging cycle. In the study of this paper the starting time of the battery charging of EVs is affected by the starting time of each working shift and also by the purpose of utilization of the EVs by the users.

C. Estimation of the Transformer Loss of Life (LoL)

A correct preservation of mineral-oil-tilled DTs in power systems is of a high importance. Consequently, new challenges require solutions concerning DT’s loading. The purpose is to profit as much as possible from the DTs due to their extended duration in service. The isolation system of a DT is normally formed of oil and paper which deteriorate over time. Unexpected rises of the load produce a rise of the hot-spot temperature (Θ_h) and as a result affects the thermal decomposition of the paper [14-17].

The ageing rate R_r^a [16] is related to the deterioration of the paper isolation in which a Θ_h decreases or increases when associated with the ageing rate at standard Θ_h (110ºC) [17]. As observed in the IEC 60076-7 standard [17], R_r^a, in case of the thermally upgraded paper is expressed by:

$$R_r^a = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)} \tag{1}$$

After any given time interval has passed, the LoL equation throughout the time period t_n is given by the following expression:

$$LoL = \int_{t_1}^{t_2} R_r^a dt \quad \text{or} \quad LoL \approx \sum_{n=1}^{N} R_r^a \times t_n \tag{2}$$

With the intention of estimating the transient solutions for the top-oil temperature in °C (Θ_o) and Θ_h – a thermal model is created and proposed for the DT as in [8].

The DT’s characteristics on which this study is based are selected from Ravetta et al. [18]. In the aforementioned publication, the proprieties of a currently existing 250 kVA oil transformer with Oil Natural Air Natural (ONAN) cooling are available. Complementary characteristics are given in [8].

III. Case Study

São Miguel Island is the main island of The Azores – a Portuguese autonomous region [19]. In this paper, a section of São Miguel medium voltage DN is utilized for the case study. A DT that supports an industrial unit is selected in the model as well. The section of the medium voltage DN can be seen in [8]. The DT substation PT1094 was utilized and which supports the factory via a 250kVA, 10kV/0.4kV oil-immersed ONAN DT. The industrial unit has local solar generation from an array of solar modules. In Fig. 1 is depicted a simplified layout of the analyzed low voltage grid.

Various measurements were made during a day and a half in February 2014 at the DT substation PT1094. The energy consumption of the industrial unit was then documented. Consequently, a daily baseline load profile was formed as can be observed in [8]. The power factor of the DT was provided as well and is roughly 0.95. The addressed 250 kVA DT in this study is properly designed for a 140 kW of peak in daily baseline load profile. A typical value for an inferior size DT is 167 kVA which would not be adequate [20]. Additionally, baseline load profile details are obtained through the SiNGULAR project [21].

Although the sales of EVs have been increasing, EVs are only part of just 0.02% of the overall vehicle market in Portugal. However, the evolution of the sales looks promising by 2020 [22]. Yet, in the study of this paper, higher penetration ratios are assessed. Mostly, in case of islands, the high transportation cost of fossil fuels, the existence of diverse renewable energy sources, and the opportunities that could spawn from the efficient management of an EV fleet [23], could contribute to higher penetration levels of EVs. For this reason, such levels could be encountered in insular areas in the future [24].

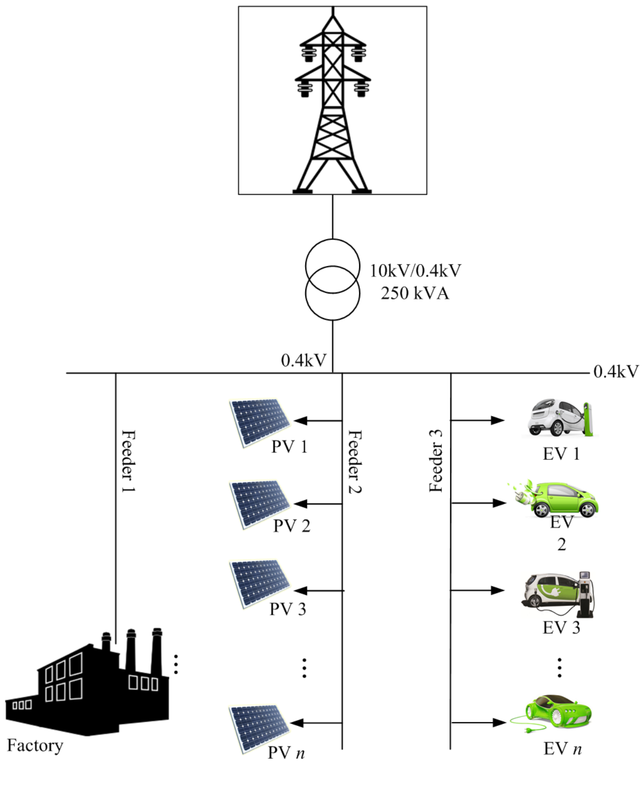

Fig. 1. The hot-spot temperature of the distribution transformer.

The PVs used in this case study for both scenarios are assumed to be SunPower model X21-345 with a module efficiency of 21.5% and 345 W of nominal power [25]. An array of 72 solar modules were used in an attempt to highlight the effect that the PVs can have in diminishing the daily load of the factory.

IV. Simulation Results

Two scenarios were modelled for the purpose of the study, a slow charging of EVs scenario and a fast charging of EVs scenario. The percentage of EVs and charging capacity of their batteries and charging duration for both slow and fast scenarios can be observed in Table I.

Following to the implementation of the EV models various simulations were completed and several results were achieved. In the case of a slow charging mode the result show how after certain penetration of EVs the daily load exceeds the transformer's nameplate rating. Currently, the present status of EV market share can be believed to be low. However, in leading countries such as Norway the sales of EVs reach one-fifth of all passenger car sales [26]. However, in this study, high to very high penetration ratios are modelled. The penetration ratios range from 55% to 75% for both scenarios.

The behavior of the daily load in the case of the slow charging mode for EV penetration ratios ranging from 55% to 75% can be observed in Fig. 2. The behavior of the Θ_h in the same case can be seen in Fig. 3. For a penetration ratio of 55% of EVs a case with the PV array was modelled for comparison purposes. The behavior of the daily load profile can be seen in Fig. 4 and the respective Θ_h in Fig. 5. It can be observed that the inclusion of PVs lower the daily load of the factory. Upon close inspection of the results it can be deduced that all EVs are successfully charged until the end of each working shift, ending the charging process three to four hours earlier.

The start of a shift will sway users to initiate the charging, that will concentrate all EVs charging at simultaneously, causing an overloading of the DT. By employing the ageing equations R_r^a and LoL, the loss-of-life of the DT can now be determined for then slow charging scenario with and without the PV array. The results can be seen in Table II.

With a similar behavior as the previous scenario, all employees plug in their EVs to charge at the start of each working shift. In the second scenario, the behavior of the daily load in the fast charging mode can be observed in Fig. 6. The behavior of the Θ_h in the same case can be witnessed in Fig. 7. For the same penetration ratio of 55% of EVs a PV array was modelled for comparison purposes. The behavior of the daily load profile can be seen in Fig. 8 and the respective Θ_h in Fig. 9. The DT's loss-of-life can then be determined for the fast charging scenario with and without the PV array. The results for all EV penetration ratios can be seen in Table III.

TABLE I. Charging Capacity and Duration of the 4 EVs

EVs	% of EV	Slow Charge		Fast Charge	
		Power kW	***Time h***	***Power kW***	***Time h***
BMW i3	40 %	4.6	8-10	7.4	3
Renault ZOE	25 %	3.7	6	7.4	3
Ford Focus Electric	25 %	3.68	6-7	7.36	3-4
Tesla Model S	10 %	16.8	3.5	16.8	3.5

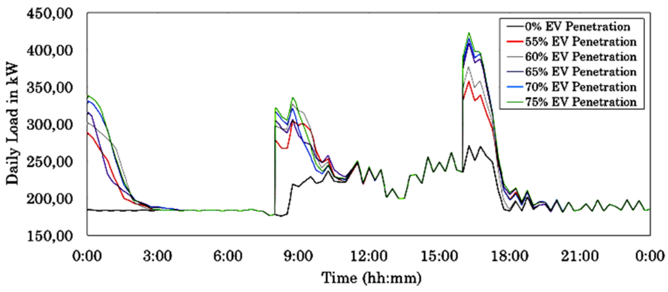

Fig. 2. The daily baseline load profile of the first studied scenario.

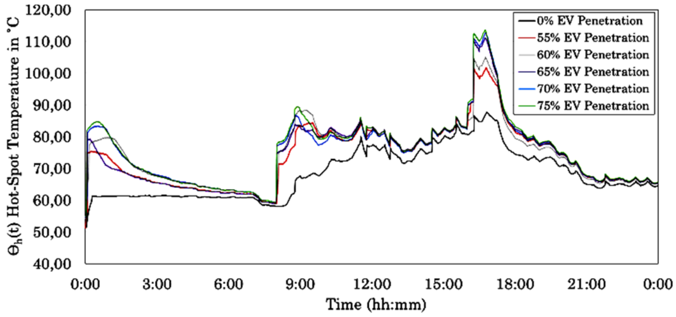

Fig. 3. The Θ_h temperature of the distribution transformer in Scenario 1.

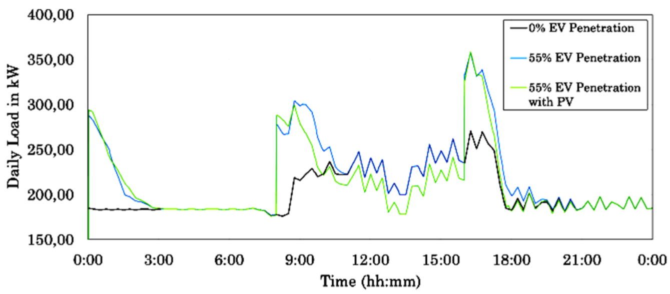

Fig. 4. The daily baseline load profile of the first studied scenario with PV.

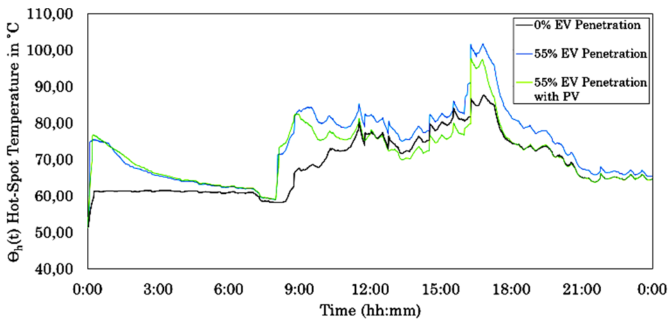

Fig. 5. The Θ_h temperature in Scenario 1 with PV.

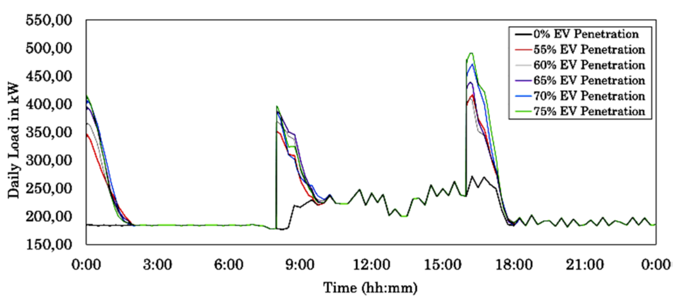

Fig. 6. The daily baseline load profile of the first studied scenario.

By analyzing the results from Tables II and III and if the EV owners charge their EVs regularly at work the DT will show a deteriorating LoL. Even in the case of Scenario 2 in which all of the EVs are charged with the fast charging option all them will still complete the charging process at the end of the working shift. However, the higher the penetration ratio of EVs, higher will be the LoL of the DT.

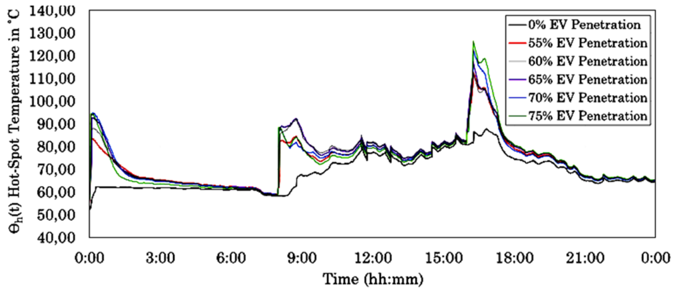

Fig. 7. The Θ_h temperature of the distribution transformer in Scenario 2.

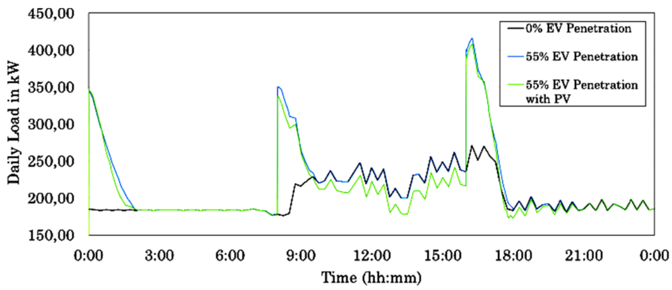

Fig. 8. The daily baseline load profile of the first studied scenario with PV.

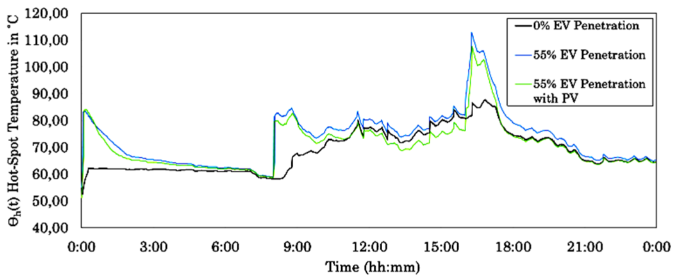

Fig. 9. The Θ_h temperature in Scenario 2 with PV.

TABLE II. THE LOL IN SCENARIO 1

EV Penetration (%)	Without PV		With PV	
	LOL (min)	LOL (%)	LOL (min)	LOL (%)
55	51h 40m	0.02871	30h 54m	0.01717
60	61h 18m	0.03401	32h 25m	0.01801
65	80h 59m	0.04499	37h 29m	0.02083
70	89h 35m	0.04977	42h 13m	0.02345
75	97h 54m	0.05439	46h 09m	0.02564

TABLE III. THE LOL IN SCENARIO 2

EV Penetration (%)	Without PV		With PV	
	LoL (min)	LoL (%)	LoL (min)	LoL (%)
55	64h 58m	0.03609	40h 24m	0.02244
60	73h 32m	0.04086	42h 32m	0.02363
65	83h 31m	0.04640	64h 39m	0.03592
70	110h 12m	0.06122	68h 06m	0.03783
75	151h	0.08389	82h 17m	0.04571

Also, by analyzing the results obtained in Figs. 2-10 and Tables II and III it can be witnessed that the inclusion of solar microgeneration through the PV array by the factory will lower the daily load profile and consequently the Θ_h and the LoL of the distribution DT. In the most extreme case, with 75% EV penetration and without the solar microgeneration the LoL of the DT is 54.5% lower than with the same case but with PV. This shows that the PV array can have a beneficial contribution to the efforts of lowering the overall daily load profile of the factory and specially, it mitigates the impact of the sudden charge of several EVs due to the fixed schedule of each working shift. Thus, resulting in a lower LoL of the DT.

V. Conclusion

This paper focused on avoiding the overloading of a DT of an industry client with local PV generation in an insular region in Portugal. A model was described to estimate the impact of EVs battery charging on thermal insulation ageing of the aforementioned DT. Distinct scenarios of EVs charging at various EV penetration ratios were modelled. Given that the DT's ageing of insulation is generally affected by Θ_h, a DT thermal model was conceived in order to assess the Θ_h. The key model inputs are the specification of the DT, the residential daily load profile, the characteristics of four distinct EVs and the PV array, all taken from real data. Subsequently, the thermal aging was assessed. The daily load decreased the overloading of the DT due to the local PV generation. It also allowed the reduction of the loss-of-life (LoL) of the DT, while recharging the EVs. Even in the most overloaded cases such as with 75% EV penetration and without solar microgeneration, the LoL of the DT is 54.5% lower than with PV.

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Bibliography

[1] P. J. Ramírez, D. Papadaskalopoulos and G. Strbac, "Co-Optimization of Generation Expansion Planning and Electric Vehicles Flexibility," *IEEE Transactions on Smart Grid,* vol. 7, no. 3, pp. 1609-1619, 2016.

[2] K. Hedegaard, H. Ravn, N. Juul and P. Meibom, "Effects of electric vehicles on power systems in Northern Europe," *Energy,* vol. 48, no. 1, pp. 356-368, 2012.

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

[4] C. Weiller and A. Neely, "Using electric vehicles for energy services: Industry perspectives," *Energy,* vol. 77, pp. 194-200, 2014.

[5] L. M. R. Oliveira and A. J. M. Cardoso, "Leakage Inductances Calculation for Power Transformers Interturn Fault Studies," *IEEE Transactions on Power Delivery,* vol. 30, no. 3, pp. 1213-1220, 2015.

[6] J. Sexauer, K. McBee and K. Bloch, "Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers," *IEEE Transactions on Power Systems,* vol. 28, no. 2, pp. 847-854, 2013.

[7] O. Erdinc, N. G. Paterakis and J. P. Catalão, "Overview of insular power systems under increasing penetration of renewable energy sources: Opportunities and challenges," *Renewable and Sustainable Energy Reviews,* vol. 52, pp. 333-346, 2015.

[8] R. Godina, N. Paterakis, O. Erdinc, E. Rodrigues and J. Catalão, "Impact of EV charging-at-work on an industrial client distribution transformer in a Portuguese island," in *2015 Australasian Universities Power Engineering Conference (AUPEC)*, Wollongong, Australia, 2015.

[9] S. S. Williamson, A. K. Rathore and F. Musavi, "Industrial Electronics for Electric Transportation: Current State-of-the-Art and Future Challenges," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 5, pp. 3021-3032, 2015.

[10] Tesla, "2012 Tesla Model S Specifications and Features," Tesla Communications, 2012.

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

[12] J. Jaguemont, L. Boulon and Y. Dubé, "Characterization and Modeling of a Hybrid-Electric-Vehicle Lithium-Ion Battery Pack at Low Temperatures," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 1, pp. 1-14, 2016.

[13] N. B. R. 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.

[14] 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.

[15] P. Zhang, K. Qian, C. Zhou, B. Stewart and D. Hepburn, "A Methodology for Optimization of Power Systems Demand Due to Electric Vehicle Charging Load," *IEEE Transactions on Power Systems,* vol. 27, no. 3, pp. 1628-1636, 2012.

[16] C57.91-2011, "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators," IEEE Standard, 2012.

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

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

[19] R. Godina, E. Rodrigues, N. Paterakis, O. Erdinc and J. Catalão, "Innovative impact assessment of electric vehicles charging loads on distribution transformers using real data," *Energy Conversion and Management,* vol. 120, pp. 206-216, 2016.

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

[21] SiNGULAR, "Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration," Grant Agreement No: 309048, FP7-EU, 2015. [Online]. Available: http://www.singular-fp7.eu/home/. [Accessed 2015].

[22] International Energy Agency, "Global EV Outlook - Understanding the Electric Vehicle Landscape to 2020," Similar Blue, Paris, 2013.

[23] R. Godina, N. Paterakis, O. Erdinc, E. Rodrigues and J. Catalão, "Electric vehicles home charging impact on a distribution transformer in a Portuguese island," in *2015 International Symposium on Smart Electric Distribution Systems and Technologies — EDST 2015*, Vienna, 2015.

[24] R. Godina, E. Rodrigues, J. Matias and J. Catalão, "Smart electric vehicle charging scheduler for overloading prevention of an industry client power distribution transformer," *Applied Energy,* vol. 178, p. 29–42, 2016.

[25] SunPower®, "SunPower® X-Series Residential Solar Panels | X21-335-BLK | X21-345," SunPower Corporation, 2016.

[26] B. Barton and P. Schütte, "Electric vehicle law and policy: a comparative analysis," *Journal of Energy & Natural Resources Law,* pp. 1-24, 2016.