EV Charging Scheduler for Overloading Prevention of a Distribution Transformer Supplying a Factory

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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 a new smart electric vehicle (EV) charging scheduler. Firstly, the consequence of the penetration of EVs on the dielectric oil deterioration of the DT of the industrial unit is estimated. The workplace allows the EVs to charge while their owners are working at three different working shifts during a day. Secondly, the EV charging scheduler is tested and the result scenarios are analyzed. This paper shows that the scheduling solution enables the industrial unit to avoid overloading the DT. It also allows to reduce the loss-of-life (LoL) of the DT, while recharging all EVs connected at the beginning of each working shift.**

Keywords—distribution transformer; EV charging scheduler; 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_{sl}	A pre-set limit.
P_T	Total load in W.
P_Ω	The remaining EV load that is superior to the P_{sl}.
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
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

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 is a factory that manufactures sugar out of sugar beet. 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. 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 of the EV charging scheduler is presented. The simulation results are discussed in Section V. 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 as follows: Renault ZOE, BMW i3, Nissan Leaf and Kia Soul. The characteristics of the studied EVs and the charging types are taken from [8].

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 Nissan Leaf, Renault ZOE, and Kia Soul have a significant presence in the EV market [10] 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 [11]. 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 [12]. 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 traveled distance is considered to be 100 km [13].

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 [14]. 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 [13-16].

The ageing rate R_r^a [15] 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) [16]. As observed in the IEC 60076-7 standard [16], 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:

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

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. [17]. 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 [18]. 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. In Fig. 1 is depicted a simplified layout of the analyzed low voltage grid.

Various measurements were made during a day and an 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 [19]. Additionally, baseline load profile details are obtained through the SiNGULAR project [20].

Even though 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 [21]. Yet, in the study of this paper, higher penetration ratios are assessed. Predominantly, 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 [22], could contribute to higher penetration levels of EVs. For this reason, such levels could be encountered in insular areas in the future [23].

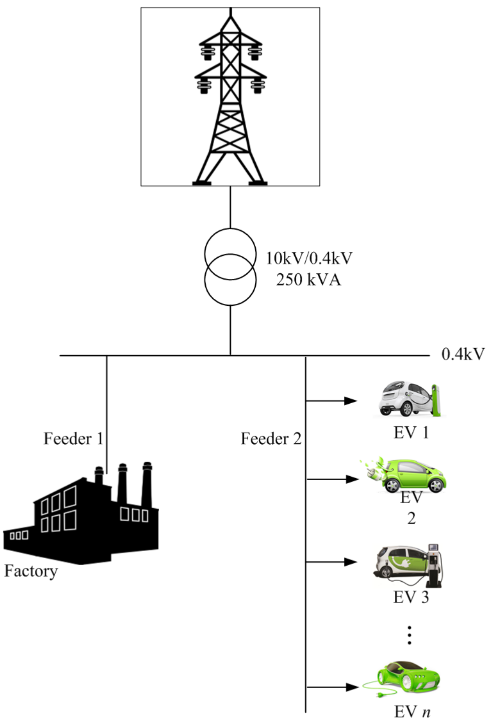

Fig. 1. The hot-spot temperature of the distribution transformer.

IV. THE EV CHARGING SCHEDULER

Knowing the overload that of the DT at the start of each working shift, a solution is proposed consisting of a scheduling solution. The aforementioned solution comprises a model that effectuates the estimation of the impact of EVs charging on the dielectric oil deterioration of the studied DT and then executes an optimized scheduling of the charging of the EVs. Through the development of such solution it is possible to allow the prevention of the overloading of the DT. The objective of the rescheduling process is to recharge all the EVs appropriately meanwhile preventing the overloading of the DT at any time of the day.

In the beginning, a pre-set limit (P_{sl}) of the allowable load needs to be introduced in the scheduler with the intention of limiting the summation of the factory loading and the charging loads of EVs. P_{sl} is set to be less or equal than 95% of the DT's loading limit with the purpose to keep at least 5% of the DT's capacity. The purpose to keep a small percentage unutilized is to always ensure a certain reserve. The functioning of the device resides in collecting the data of the parameters of the DT, SoC of the EVs' batteries, the load of the factory and the Θ_a and then to reschedule the EVs that exceed the P_{sl} of the scheduler. A data logger and a display device will also be part of the scheduler with the purpose of displaying all the information of the registered recordings and the modelled data. It will also be possible an interactive utilization of the device with operations such as the easy setting of a new P_{sl}. Lastly, the scheduler will also have a wireless transmitter with the aim of transmitting the information to an exterior platform. This will allow a universal access by all types of portable devices. The scheduler's operation can be observed in Fig. 2.

Given the data collected from the PDF, the DT thermal model can now be applied by utilizing the load ratio as an input to obtain the Θ_h and Θ_o temperatures. The total load $P_T(t)$ (in kW) on the transformer is represented by the sum of the factory load P_f and loading from n_{EV} randomly selected EVs:

$$P_T(t) = P_f(t) + \sum_{EV=1}^{n_{EV}} P_{EV}(t) \quad (3)$$

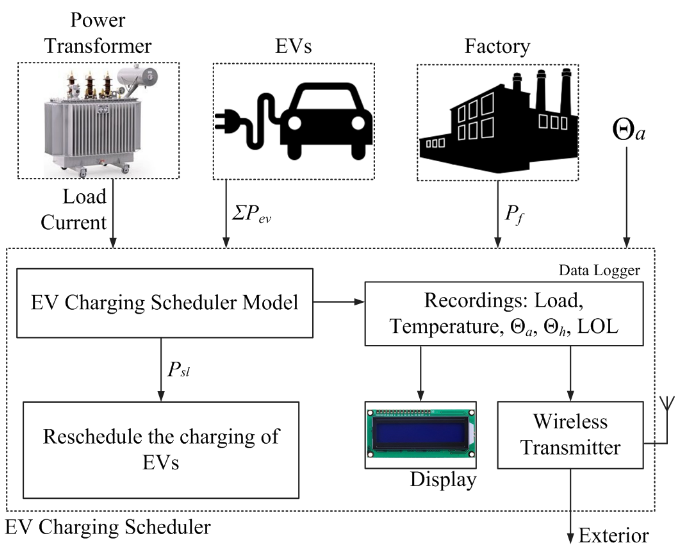

Fig. 2. The schematic of the operation of the proposed scheduler.

In this paper for the loading scenarios a day of the baseline load profile of the month of February of the DT substation PT1094 is utilized and two distinct scenarios are generated an analyzed.

As previously observed, $P_T(t)$ represents the addition of the loads of the factory with the EVs. However, $P_\Omega(t)$ is the EV load left behind that is higher than the P_{sl} in any given instant t:

$$P_\Omega(t) = P_T(t) - P_{sl}, \quad \forall\; P_T(t) > P_{sl} \tag{4}$$

The EV charging scheduler functions as follows: initially, a charging time frame is established, then, readings are made of the DN data, the EV charging data, the factory load and Θ_a. To conclude, estimates the Θ_a and LoL. Instantaneously after this operation is concluded the scheduler attests if P_T is equal or higher than P_{sl}. If so, then the scheduler is triggered and the EV load P_Ω which was left behind is rescheduled to the following charging time frame. The time frame utilized in this model is 15 minutes. In conclusion, if all the EVs complete their charging process then the scheduler enters in stand-by awaiting new EV to connect. Then the process restarts.

V. Simulation Results

A. Scenario 1

Following to the implementation of the EV scheduler model various simulations were completed and several results were achieved. In the case of a slow charging mode in Fig. 3 can be seen how the operation of the scheduler allows avoiding the overloading of the DT when compared with Fig. 5 form [8] at various penetration ratios, up to 60%. A minor improvement of the Θ_h can be observed when compared with the first scenario observed in [8] through the comparison between Fig. 6 from [8] and Fig. 4.

In Table I can be observed all the results of the saved LoL when compared with the scenario without the EV charging scheduler. A contrast between the rescheduled charging of EVs at 60% penetration and non-scheduled charging can be witnessed in Fig. 5. The minor improvement of Θ_h observed in this case is of 7.54% and is displayed in Fig. 6.

Also, a simulation in extreme conditions was performed with the purpose of testing the limits of the EV charging scheduler with the intention of measuring until what limit the scheduler is reliable. From the results can be deduced that with a P_{sl} of 75% and at an EV penetration ratio of 100% the entire fleet of EVs charge prior to the end of the working shift as depicted in Fig. 7. However, a great improvement of LoL can be observed in such an extreme case, 76.76% of LoL of the day is saved by using the scheduler as can be deduced from Fig. 8.

TABLE I. LoL saved with the EV charging scheduler Vs without the EV charging scheduler

P_{sl} limits	LoL (t)	LoL %
70%	36.11 min	0.0003
75%	39.91 min	0.0004
80%	44.09 min	0.0004
90%	53.46 min	0.0005
95%	59.64 min	0.0006

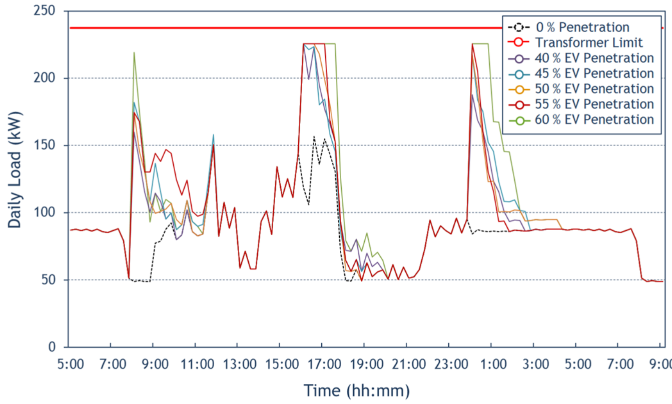

Fig. 3. The daily baseline load profile in slow charging mode with the Scheduler in operation.

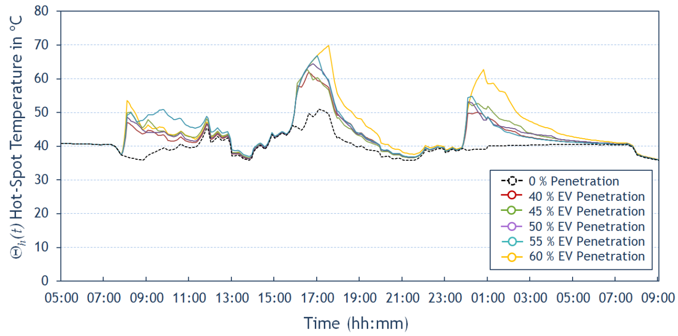

Fig. 4. The Θ_h Temperature in slow charging mode with the Scheduler in operation.

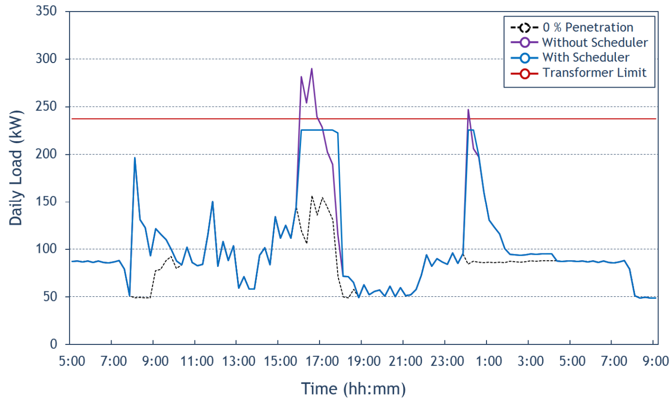

Fig. 5. Comparison in slow EV charging mode between the cases with the scheduler and without it at 60% EV penetration.

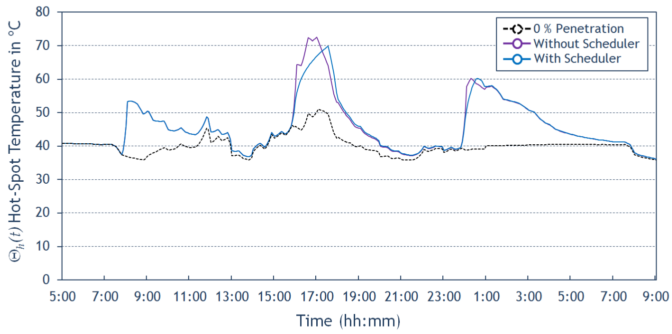

Fig. 6. Comparison of Θh between the cases with the scheduler and without it at 60% EV penetration.

B. Scenario 2

The following alternative extreme scenario was simulated with the EVs charging in the fast charging mode at 35% penetration. Similarly to the preceding scenario, it is implied that the employees initiate to charge the EVs at the start of the respective working shift. Supported by the results a large improvement occurs concerning the Θ_h when compared with the second scenario seen in [8]. In Fig. 9 a contrast between the rescheduled charging of EVs at 35% penetration and non-scheduled charging can be observed while. In the Fig. 10 and through means of Θ_h can be observed how much LoL could be saved when compared with a scenario in which the new EV charging scheduler is not utilized.

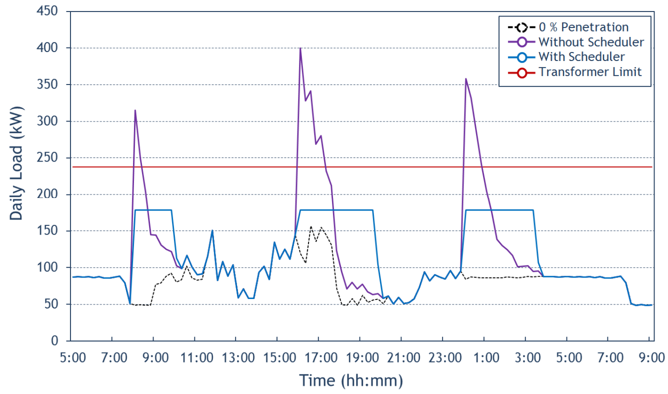

Fig. 7. Comparison of an extreme case with 100% EV Penetration with a scheduler at 75% limit or without it.

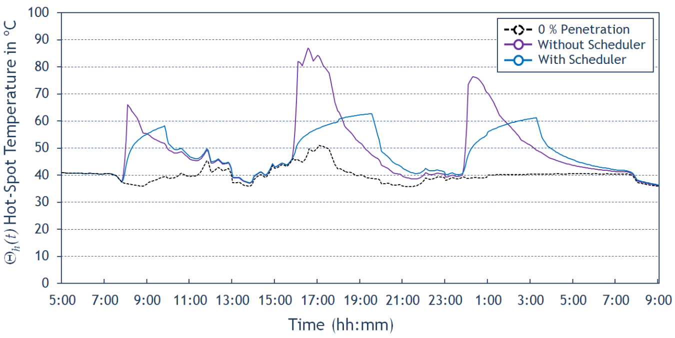

Fig. 8. Comparison of Θh of an extreme case with 100% EV Penetration with a scheduler at 75% limit or without it.

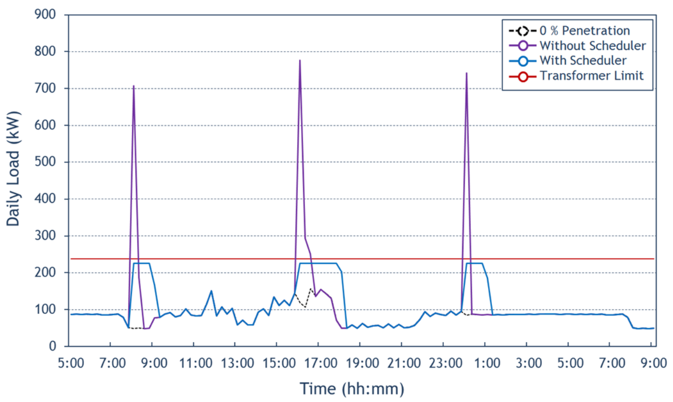

Fig. 9. Comparison in fast charging mode of an extreme case with 35% EV Penetration with a scheduler at 95% limit or without it.

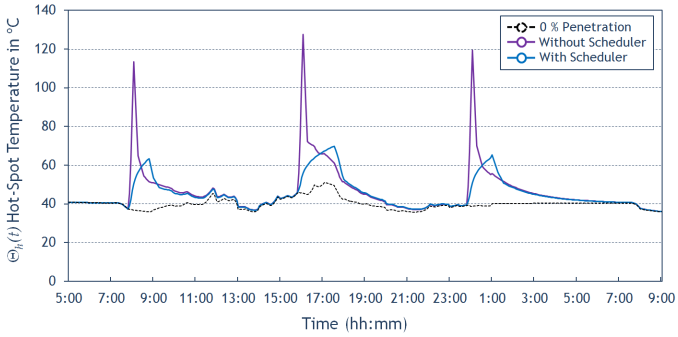

Fig. 10. Comparison in fast charging mode of Θh of an extreme case with 35% EV Penetration with a scheduler at 95% limit or without it.

Through the utilization of the EV charging scheduler a considerable amount of 98.08% of LoL was saved. Even in the case of utilizing the fast changing mode the outcome shows that the EVs reach 100% of charge at the end of any working shift, as a matter of fact, well ahead of the end.

When settling for the EV charging scheduler proposed in this paper the workers of the industrial unit can be certain that their EVs will always have 100% of SoC at the completion of every working shift under any conditions. The scheduler also effectuates the charging of every EV without exceeding the DT's loading limit. Consequently, such scheduling solution allows the DT to keep the LoL at a low rate.

VI. Conclusion

This paper focused on avoiding the overloading of a DT of an industry client in an insular region in Portugal through a new EV charging scheduler. Distinct scenarios of EVs charging at various EV penetration ratios were modelled. Given that the DT's ageing of insulation is generally affected by the 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, and characteristics of four distinct EVs, which were taken from real data. Subsequently, the thermal aging was then assessed and examined. The results pointed out that even though the design of the DT has a capacity to be utilized for a side activity, the DT can even be overloaded at a particular growth of EV penetration. To avoid the overloading of the DT at the start of every working shift, a new scheduling solution was analyzed. The solution consisted of a model that assesses the impact of EVs battery charging on the insulation deterioration of a real DT and further schedules the initial instant of charging in an optimal way. Such solution prevented the DT to be overloaded through the conception of the aforementioned EV scheduler. Also, it allowed for the complete charging of the entire EVs fleet without exceeding the loading limit of the DT. Thus, the scheduler allowed preserving the LoL of the DT.

Acknowledgements

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REFERENCES

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

[11] 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.

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

[13] 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.

[14] 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.

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

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

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

[18] 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.

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

[20] 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].

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

[22] 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 *Proc. EDST 2015*, Vienna, 2015.

[23] 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.