Investigation of Distribution Transformer Loss of Life in Electric Vehicles Parking Lot Integrated System

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***Abstract*—Nowadays, the operation of the smart distribution system (SDS) is more complicated with the penetration of electric vehicles (EVs), due to EVs' uncertainties as well as the capability of vehicle-to-grid (V2G). On the other hand, distribution transformers (DTs) which have to meet the demand of EVs are one of the essential components of SDS; indeed, their failure can lead to irreparable damage. The cause of most of these failures is overloading and high ambient temperature. The overloading increases the temperature of the various parts of the DTs, especially hot spot temperature (HST). Increasing this temperature reduces the nominal life of the DTs. With a high number of EVs in the future, and as a consequence high energy demand which has not been taken into account in proper operating program, it could lead to the overloading of DTs. So, in this paper, the loss of life (LOL) of a DT that feeds the residential loads and an EV parking lot (EV PL) is investigated. The maximization of the profit of the distribution system operator (DSO) is considered in two different parts i.e. with/without the appropriate operation coefficient (OC) of DT. Also, two different scenarios are applied i.e. charging mode (CM) of EVs and charging/discharging mode (CDM) of EVs. The results show that if the OC is not properly considered, the LOL of the transformers will be significantly high, implying a higher total ownership cost.**

Keywords—Distribution transformer, Electric vehicles parking lot, Loss of life, Operation coefficient.

I. INTRODUCTION

Nowadays, electric vehicles (EVs) with the capability of Vehicle-to-Grid (V2G), that are usually located in EV parking lots (EV PLs), are a solution to answer the air pollutions' concerns in largest cities all around the world. Of course, most of the EVs, which will be added to the smart distribution system (SDS) in the future, would highly consume energy. Therefore, if there is no suitable operation program, the distribution transformers (DTs) that feed the EVs will most probably be highly overloaded. This overloading leads to increasing the winding temperature and consequently hot spot temperature (HST). So, the nominal life of DTs would decrease, drastically.

In recent years, numerous studies have been considered the impact of EVs on operation of the SDS. In [1], the cost of distribution system operator's (DSO's) is minimized considering EV PL that participates in energy, reserve, and regulation markets. The network losses by optimal sitting of EV PL is minimized in [2]. In [3], the effect of EV PL is evaluated on SDS expansion planning to minimize the investment cost and expected energy not supplied.

In [4-6], the effect of EV PL is investigated by the aim of maximizing the DSO profit in a single-level and bi-level model. Also, some studies such as [7-12] have been fully explored the required relations for calculation of HST in DTs, loss of life (LOL), total losses and load ability of DTs in sinusoidal and harmonic and overloading conditions. Recently, some publications have been focused on effect of EVs on HST, overloading and LOL of DTs. Considering two types charging level of EVs and developing a thermal model of DT HST and LOL of DT are calculated in [13]. The thermal aging and LOL of DT under high penetration level of fully EVs charging loads is computed in [14]. A centralized model is suggested in [15] to optimize the transformer LOL with the benefits for EVs' owner. The smart charging method is proposed in [16] to minimize electricity consumption costs and avoid transformer overloading and reducing LOL. In [17] a comprehensive method is proposed to evaluate the deteriorating impact of several EVs penetration levels on the loss of DT life. However, LOL of DTs has not been addressed in the literature considering the uncertainties of EV PL and suggesting a model with the aim of maximization profit of DSO as owner of EV PL in two scenarios i.e. charging mode (CM) of EVs and charging/discharging mode (CDM) of EVs.

The rest of the manuscript is organized as follows. A brief review of modeling of EV PL and distribution transformer loss of life are developed in Sections II and III, respectively. Problem formulation is presented in Section IV. Simulation results are discussed in Section V. Finally, conclusions are reported in Section VI.

II. MODELING OF ELECTRIC VEHICLE PARKING LOT

Usually all EVs have a battery as well as the V2G capability. Therefore, in the near future, with increasing the application of EVs, their batteries can provide a high-availability storage system for the SDS. In this way, the EVs can act as an active element. Thus, the power stored in the batteries can sell to the SDS. The initial state of energy (SOE), arrival/departure time (t^{arv}/t^{dep}) of the EVs to/from the PL are the main uncertainties of EVs. Some studies are shown that the behavior of the EVs can be modeled with appropriate probability distribution function such as a truncated Gaussian distribution [1]. The modeling of EVs is shown by (1) - (3).

$$SOE_{EV}^{ini} = f_{TG}\left(X;\mu_{SOE};\sigma_{SOE}^{2};\left(SOE_{EV}^{ini,\min};SOE_{EV}^{ini,\max}\right)\right) \tag{1}$$

$$t_{EV}^{arv} = f_{TG}\left(X;\mu_{arv};\sigma_{arv}^{2};\left(t_{EV}^{arv,\min};t_{EV}^{arv,\max}\right)\right) \tag{2}$$

$$t_{EV}^{dep} = f_{TG}\left(X; \mu_{dep}; \sigma_{dep}^{2}; \left(\max(t_{EV}^{dep,\min}, t_{EV}^{arv}); t_{EV}^{dep,\max}\right)\right) \quad (3)$$

In the presence of the EVs to the EV PL, required data such as initial and desired SOE of the EVs, the battery specifications and departure time are obtained from the EV owners. By computing the energy needed for each EV, the time and charging/discharging power of the EVs is determined by proper energy management system.

III. Distribution Transformer's Loss of Life

The HST (θ_{HS}) in DTs winding is very critical in estimation of LOL of the paper insulation, as well as quality of insulation oil and DTs operation. It must be mentioned that existence of such a spot in DTs winding is inevitable, but it is essential to decrease its temperature to protect the winding insulation from premature fatigue [18]. This temperature is affected by DT total losses (P_{total}) and environment temperature (θ_A). Moreover, the load loss (P_{LL}) of windings and also no-load loss (P_{NL}) of iron core contribute in HST and LOL of DTs [7, 18]. Therefore, over-load and over-voltage change the total loss and as a consequence, the HST more drastically. Equations (4) to (10) show the calculation procedure for lifetime of DTs [7, 10, 18]. If HST exceeds 110 ℃, the aging acceleration factor (F_{AA}) is more than one, so the life of DTs is dramatically reduced.

$$P_{total} = P_{NL}\,(V/V_{Rated})^2 + P_{LL\text{-}R}\,(S/S_{rated})^2 \quad (4)$$

$$\theta_{HS} = \theta_A + \theta_{TO} + \theta_g \quad (5)$$

$$\theta_{TO} = \theta_{TO\text{-}R} \times ((P_{LL} + P_{NL})/ (P_{LL\text{-}R} + P_{NL}))^{0.8} \quad (6)$$

$$\theta_g = \theta_{g\text{-}R} \times (P_{LL} / P_{LL\text{-}R})^{0.8} \quad (7)$$

$$F_{AA} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_{HS} + 273}\right) \quad (8)$$

$$F_{EQA} = \sum_{t=1}^{24} F_{AA_n}\,\Delta t \Big/ \sum_{t=1}^{24} \Delta t \quad (9)$$

$$\%LOL = F_{EQA}.t.100/Nominal\ Life \quad (10)$$

IV. Problem Formulation

Usually proper operation of SDS is aiming the minimization costs or maximization profits of DSO. So, in this manuscript, the objective function is maximization of DSO's profit that is achieved by revenue and cost terms. The DSO provides a part of the customers' demand and the EVs' charging power from the wholesale market (WM). Furthermore, a part of the customers' demand is provided by the power purchased from the EV owners. Therefore, the objective function that is shown in (11) is composed of the revenue from selling energy to customer (P^L, PR^L), the cost of energy purchased from the WM (P^s, Pr^s), the revenue from the energy sold to EV owners (P^{ch}, Pr^{ch}), the cost of energy purchased from EV owners for supplying load (P^{dch} , Pr^{dch}), and the cost of battery depreciation ((P^{dch}, C^{cd}) that this term is paid to each EV owner to encourage that attends to V2G programs), respectively. The constraints related to the objective function are described in the following. Since DSO is the owner of the EV PL, in addition to the SDS constraints, the EV constraints must also be met by DSO.

Maximize

$$\sum_{t=1}^{24}\left(\sum_{b=2}^{N_b}\left(P_{b,t}^{L}.\mathrm{Pr}_t^{L}\right) - \sum_{sb=1}^{N_{sb}}\left(P_{sb,t}^{s}.\mathrm{Pr}_t^{s}\right)\right).\Delta t + \sum_{s=1}^{N_s}\rho_s \sum_{EV=1}^{N_{EV}}\sum_{t=1}^{24}\left(\begin{array}{l}\left(P_{EV,t,s}^{ch}.\mathrm{Pr}_t^{ch}\right)\\ -\left(P_{EV,t,s}^{dch}.\mathrm{Pr}_t^{dch}\right)-\left(P_{EV,t,s}^{dch}.C^{cd}\right)\end{array}\right).\Delta t \quad (11)$$

$$P_{sb,t}^{s}.\eta^{Trans} + \sum_{EV} P_{EV,t,s}^{dch} = P_{b,t}^{L} + \sum_{EV} P_{EV,t,s}^{ch} \quad (12)$$

$$V^{\min} \le V_{b,t,s} \le V^{\max} \quad (13)$$

$$0 \le I_{b,t,s} \le I_{b,t}^{max} \quad (14)$$

$$0 < \mathrm{P}_{sb,t}^{s} \le \mathrm{P}_{sb,t}^{s,\max} \quad (15)$$

$$\mathrm{SOE}_{EV,t,s}^{\min} \le \mathrm{SOE}_{EV,t,s} \le \mathrm{SOE}_{EV,t,s}^{\max} \qquad \forall EV, t, s \quad (16)$$

$$\mathrm{SOE}_{EV,t,s} = \mathrm{SOE}_{EV,t-1,s} + \left(P_{EV,t,s}^{ch}.\eta^{ch}\right) - \left(\frac{P_{EV,t,s}^{dch}}{\eta^{dch}}\right) \forall EV, t \succ t^{arv}, s \quad (17)$$

$$\mathrm{SOE}_{EV,t,s} = \mathrm{SOE}_{\mathrm{EV,t,s}}^{\mathrm{arv}} + \left(P_{EV,t,s}^{ch}.\eta^{ch}\right) - \left(\frac{P_{EV,t,s}^{dch}}{\eta^{dch}}\right) \forall EV, t = t^{arv}, s \quad (18)$$

$$0 \le P_{EV,t,s}^{ch} \le X_{EV,t,s}^{ch} \times R_{EV}^{ch} \qquad \forall EV, t, s \quad (19)$$

$$0 \le P_{EV,t,s}^{dch} \le (1 - X_{EV,t,s}^{ch}) \times R_{EV}^{dch} \qquad \forall EV, t, s \quad (20)$$

$$SOE_{EV,t,s} = \mathrm{SOE}_{\mathrm{EV,t,s}}^{\mathrm{dep}} \qquad \forall EV, t^{dep}, s \quad (21)$$

The power balance constraint is shown in (12). Note that the EVs in the PL act as a source or as a load. Bus voltage and line current limits are shown in (13) and (14). The maximum allowable power of DT ($P^{s,max}$) is shown in (15). Based on (16) the SOE of each EV is between the minimum and maximum values. According (17) and (18), the SOE of the previous hour, the charging/discharging power, charge/discharge efficiency (η^{ch} , *and* η^{dch} , respetively) and initial SOE of EVs (SOE^{arv}) are the main factors of EVs' SOE at each hour. In (19) and (20), the limitations of charging/discharging power of each EV are shown. Also, charging and discharging of each EV are not simultaneous. X^{ch} is a binary variable that shows the charge status of EVs. Finally based on (20) management of charging/discharging of EV should be accurate in which at departure time, the EV's SOE is reached the desired value (SOE^{dep}). Also, in this work a linear load flow is used that is fully explained in [1, 4].

V. Simulation Results

For evaluating LOL of a DT, the low voltage system is implemented based on a typical 53 bus 415 V residential systems that is fed by 1000 kVA DT with an EV PL which is shown in Figure 1. The maximum capacity of EV PL is 200 EVs. The customers' demand and electricity tariffs are illustrate in Figure 2 [19]. The discharging tariff is 23 $/MWh. Also, it is assumed that the energy price from WM is 25% lower than the market energy price. The necessary data for modeling of EV PL and DT is shown in Table 1 [4, 20]. In the flowing, the results are investigated in 2 different parts, i.e., with/without the appropriate OC of DT and 2 scenarios, i.e., CM and CDM.

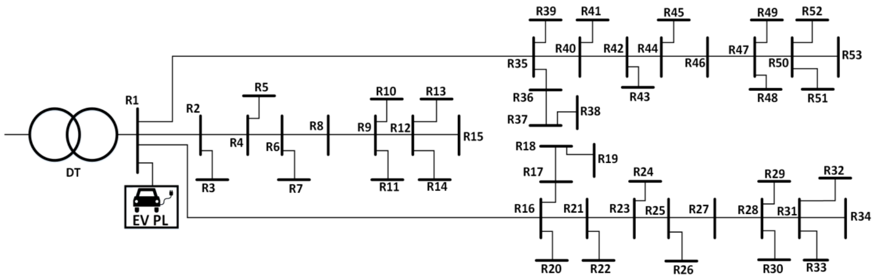

Fig. 1. Low voltage 415 V networks (53 nodes) with residential customers and an EV PL

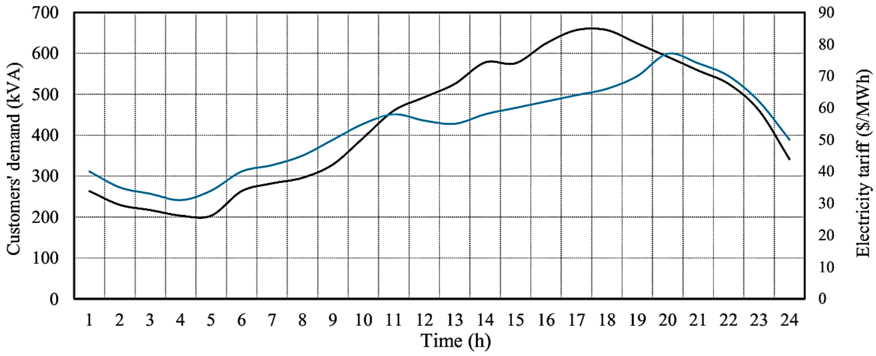

Fig. 2. The customers' demand and electricity tariff

TABLE I. REQUIRED DATA FOR DT AND EV PL'S MODELING

EVs' Uncertainty	Mean (μ)	Standard Deviation (σ)	(min, max)
SOE^{arv} (%)	50	25	(30,60)
t^{arv} (h)	8	3	(7,10)
t^{dep} (h)	20	3	(18,22)
EVs' Specifications			
C^{cd}	10 $/MWh	η^{ch}	90 %
$C^{battery}$	20 kWh	η^{dch}	95 %
$R^{ch\ or\ dch}$	4 kWh	SOE^{dep}	≥ 17 kWh
SOE^{min}	2 kWh	SOE^{max}	18 kWh
DT's Specifications			
P_{NL}	1400 w	$\theta_{TO\text{-}R}$	60 °C
$P_{LL\text{-}R}$	10500 w	$\theta_{g\text{-}R}$	5 °C

In this work, the OC for DT is assumed 0.75 of nominal capacity, i.e., 750 kVA. This coefficient of DTs usually imposes the least cost on the SDS [10]. Also, θ_A is considered 30 °C.

Also, θ_g and θ_{g-R} are hot spot rise over top oil temperature in case of any transients, and in under rated condition, respectively.

Moreover, θ_{TO} and θ_{TO-R} are transformer top oil temperature rise over ambient temperature in case of any transients and in under rated condition, respectively. F_{EQA} is the equivalent F_{AA} for the time period of interest, Δt is time interval that in this work, i.e., it is 1 hour.

A. System with CM of EVs

Firstly, considering the CM of EVs, the profit of DSO as well as the HST and LOL of a DT is evaluated with/without OC. Table II and III show the profit of DSO and F_{AA} and LOL of DT over 24-hour period, respectively. With the penetration of EVs, the DSO obtain more profit between 19.90% to 22.3%. However, based on Table III if the proper OC for DT is not considered when the energy is sold to the EV PL and customers' demand, the life of DT will be greatly reduced. Regardless of this coefficient, there is a 7-days reduction of life over a 24-hour period. But by defining OC, the *LOL* of DT is tragically reduced to 19 hours. Figure 3 shows the operational schedule of SDS. Figure 4 illustrates the HST of DT.

TABLE II. PROFIT OF DSO IN CM ($).

Program	without EVs	CM without OC	CM with OC
Energy sold to load	572.482	572.482	572.482
Energy sold to EVs	0	127.550	114.284
Energy purchased from WM	451.959	552.657	542.184
Profit	120.522	147.375	144.582

TABLE III. F_{AA} AND LOL OF DT IN CM.

Program	without EVs	CM without OC	CM with OC
F_{AA}	0.0685	1.759	0.1940
F_{EQA}	0.0028	0.0733	0.0081
LOL (%)	3.81E-05	9.77E-05	1.08E-04
LOL (*h*)	6 h 51 min	**7 days 7 h 59 min**	19 h 28 min

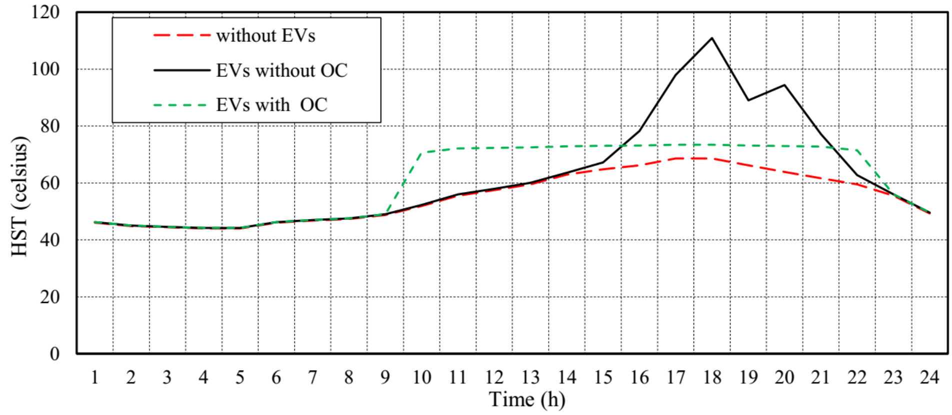

Fig. 3. Power purchased from WM (Ps), customers' demand (P_{load}) and Charging power (P_{ch}) of all EVs in scenario 1

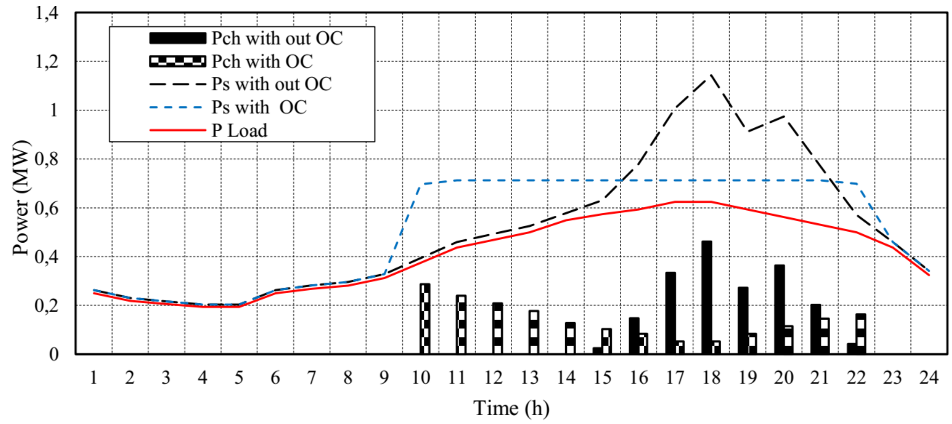

Fig. 4. Hot spot temperature of DT over 24-hour in scenario 1

From Figure 3, DSO sells 1.849 MWh to all EVs with/without OC. From Tables II, and III, and Figures 3 and 4, the results regardless of EV PL are also added for better comparison. The reason behind the reduction of DT life is illustrated in Figures 3 and 4, respectively

Regardless of OC, since most EVs depart the EV PL between 18:00h to 20:00h and at these times the price of energy sold is high, therefore, the highest energy sold to EV owners is occurred, especially at 18:00h that the customers' demand is the highest, i.e., 0.624 MW.

So, at 18:00h, HST exceeds 110 ºC and the F_{AA} is more than 1. This amount of F_{AA} dramatically reduces the life of DT. But by choosing the suitable OC, the DSO sells the energy to the EV owners in all the times.

In fact, by selecting proper OC, at the peak customers' demand especially at 17:00h and 18:00h, DSO sells the minimum energy to EV owners to prevent further HST increase. In this case, the LOL is greatly reduced to 19 hour.

B. System with CDM of EVs

Based on Table IV, the DSO's profit increases from 92.48% to 92.53%. One of the reasons for this increase is the EVs' participation in the V2G program. Some demand of customers is fed by discharging energy of EVs. Moreover, the price of this energy is lower than the price of energy purchased from the WM.

According to Table V, nominal life reduction of DT without proper OC has increased to 10 days. Based on Figure 5, the cause of further LOL of DT is EVs' participation in V2G program.

In this mode, DSO charges an EV lot many times to purchase cheaper energy from EV owners to meet customers' demand with electricity tariff and thus, gain more profit. For this reason, DT in some interval time especially at 13:00h and 18:00h charge about 150 EVs that it leads to 10 % overloading of DT.

So, HST exceeds 110 ℃ and the F_{AA} is more than 1 (see Figure 6). Also, F_{EQA} over 24-hour is more than 2, and consequently, the LOL of DT is 10 days.

Of course regarding Figures 6 and 7, in some time intervals especially at 17:00h and 20:00h, the HST is significantly decreased, due to high energy purchased from EV owners for feeding customers' demand. But overall, the LOL of DT is very high. With proper OC, the charging and discharging power of EVs in all the time intervals are balanced and due to avoiding any overloading of DT, the HST is restricted to 73 ℃.

This temperature is led to the LOL of DT is dramatically decreased and be 19 hours. Also, the DSO's profit in this case reduces lower than \$0.5. It is noted that the charging and discharging energy with/without OC are 5.279, 5.362 MWh and 3.015, 3.076 MWh respectively.

TABLE IV. PROFIT OF DSO IN CDM ($).

Program	without EVs	CDM without OC	CDM with OC
Energy sold to load	572.482	572.482	572.482
Energy sold to EVs	0	318.350	316.822
Energy purchased from EVs	0	70.762	69.364
Battery depreciation	0	30.766	30.158
Energy purchased from WM	451.959	557.252	557.790
Profit	120.522	232.052	231.991

C. Sensitivity analysis with CDM of EVs

In the following, a sensitivity analysis is performed in CDM with OC by changing two main factors, i.e., ambient temperature and EV PL's capacity. Table VI shows the effect of ambient temperature on LOL of DT.

TABLE V. F_{AA} AND LOL OF DT IN CDM.

Program	without EVs	CDM without OC	CDM with OC
F_{AA}	0.0685	2.4606	0.1898
F_{EQA}	0.0028	0.1025	0.00790
LOL (%)	3.81E-05	1.36E-03	1.05E-04
LOL (h)	6 h 51 min	**10 days 2 h 4 min**	18 h 59 min

TABLE VI. EFFECT OF AMBIENT TEMPERATURE ON LOL IN CDM.

Ambient temperature (ºC)	LOL in CDM with OC (h)
20	5 h 10 min
25	10 h
30	18 h 59 min
35	1 day 11 h 26 min

TABLE VII. EFFECT OF EVPL'S CAPACITY ON DSO PROFIT AND LOL OF DT IN CDM.

EV PL's capacity	DSO profit ($)	LOL in CDM with OC (h)
100	177.965	13 h 35 min
125	189.432	15 h 02 min
150	204.187	16 h 12 min
175	217.100	17 h 31 min
200	231.991	18 h 59 min

Also, Table VII shows the effect of EV PL capacity on DSO's Profit and LOL of DT. The ambient temperature is 30 ℃. By decreasing the capacity of EV PL, the DSO profit and LOL of DT due to less energy sold/purchased to/from EVs is decreased. By 50 % reduction of EV PL's capacity, the DSO's profit and its LOL are decreased to about 24 % and 5 h 24 min.

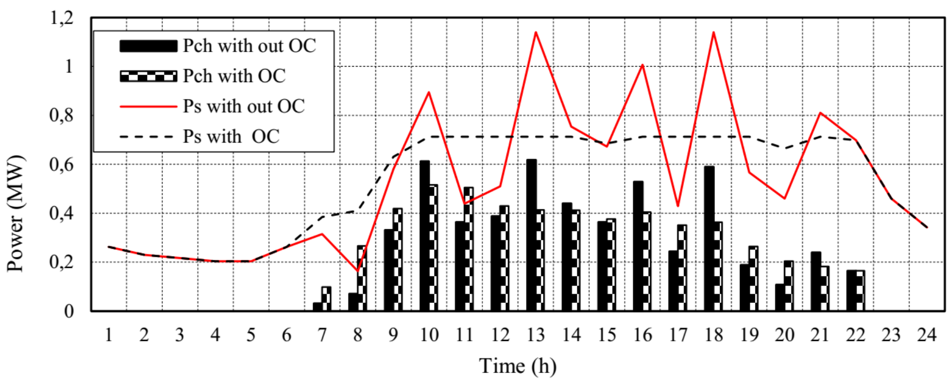

Fig. 5. Power purchased from MW (P_s) and Charging power (P_{ch}) of all EVs in scenario 2.

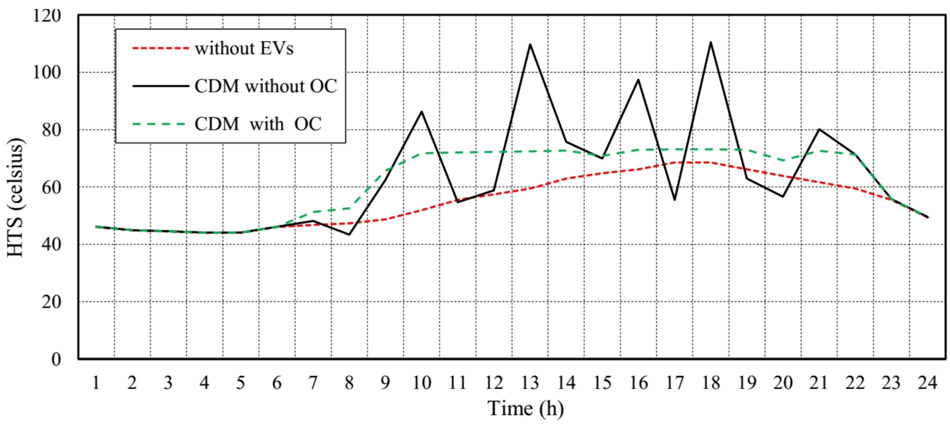

Fig. 6. Hot spot temperature of DT over 24-h in charging/discharging mode of EVs in scenario 2.

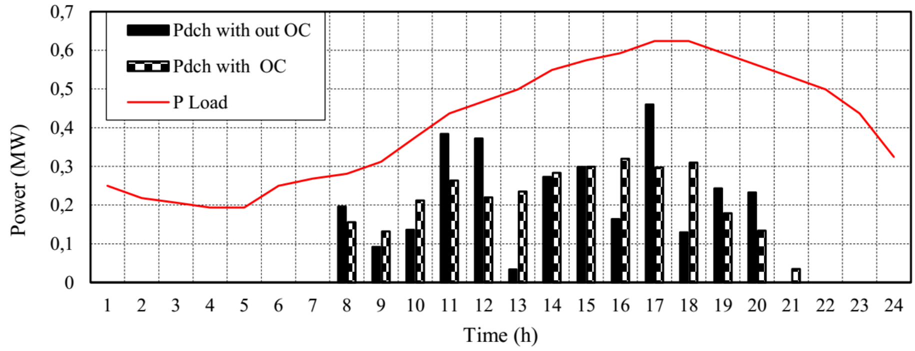

Fig. 7. Discharging power of all EVs for supplying customers' demand with and without operation coefficient of DT in scenario 2.

VI. Conclusions

In this paper, by modeling EV PL and offering a proper model for the maximization of profit of a distribution system operator, the LOL of a distribution transformer was investigated. Also, two scenarios (charging mode of EVs and charging/discharging mode of EVs with/without operation coefficient of the distribution transformer) were considered. The results show that by not considering the proper operation coefficient for a distribution transformer, the LOL in those two scenarios was very high, i.e., 7 and 10 days. In these scenarios, overloading of the transformer occurred in some time intervals which led to the hot spot temperature that exceeded 110°C. Regarding the operation coefficient, in spite of higher reduction of LOL (19:30 and 19 hours), the DSO's profit changed a little so that in charging/discharging mode this change was less than \$0.5. Therefore, the best mode for the operation with the penetration of EVs is charging/discharging mode with proper operation coefficient. Also, several factors such as ambient temperature and EV PL's capacity might affect the LOL of the distribution transformer. By a 10ºC reduction in ambient temperature and 50% reduction of EV PL's capacity in the best mode, the LOL decreased to 8h49min and 5h24min, respectively.

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