Scenario Based Analysis of an EV Parking Lot Equipped with a Roof-Top PV Unit within Distribution Systems

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***Abstract*—The electrification of the transportation area draws significant attention recently regarding mainly the environmental concerns and many vehicle manufacturers have already launched several commercial electrical vehicle (EV) types. The EV parking lots herein play an important role and need further analysis in terms of considering the possible impacts of simultaneous EV charging based extra power demand on distribution systems. In this study, a scenario based analysis of an EV parking lot equipped with a roof-top PV unit is realized in terms of the impacts on various operating conditions in a distribution system. Various scenarios are created for EV charging considering different brands and models of EVs with random initial state-of-energy and arrival time. The variability of the solar radiation during daytime and seasons are also considered. All the aforementioned analyses are conducted in ETAP (Electrical Transient Analyzer Program) environment.**

Keywords—electric vehicles, distribution system operation, parking lots, roof-top PV units.

I. Introduction

A. Motivation and Background

Over the past decades, there has been a significant increase in energy consumption of the modern world due to the extraordinary quickening rate in the industrialization and urbanization. Fossil-based resources have been extensively harnessed especially in the energy production process causing undesirable side effects such as natural pollution. Today, it is not possible to ignore the unprecedented rate of greenhouse gas emission (GHG) paving the way for drastic increase in the number of some governmental protocols (e.g. Kyoto Protocol) to reduce CO_2 emission by numerous countries' endeavors. A recent research reveals that almost 27% of total energy consumption and 33% of GHGs in the world are related to the transportation sector [1]. Moreover, several surveys such as that conducted by European Environment Agency have shown that the air quality standard which is set by World Health Organization is not met in many European countries due to high concentration of air pollutants caused by road vehicles [2]. As a result, there has been a consensus on the need of revolution in transportation system while considering increased awareness about global warming and climate change which opened a door for integrating environmentally friendly electric vehicles (EVs) in the transportation system instead of fossil fuel-based conventional cars. Thus, it is clear that zero-emission sustainable transportation system can be obtained by taking the advantages of vast range of EVs' benefits.

Apart from all tremendous advantageous, there are severe operational challenges associated with the high penetration of EVs into the electric power system. Some of the most fundamental problems that may be faced by system operators are overloading of the transformers, voltage/frequency fluctuations, load transients and other power quality issues [3]. To address these main technical drawbacks, the solutions in charging stations level can improve control axioms as well as management strategies to prevent undesired conditions (such as disturbances and outages) with cooperating operators. Furthermore, such solutions may lead the use EVs as distributed storage units or loads in the regulation services and demand response programs to meet system requirements.

In fact, EVs require a considerably large amount of time to be charged due to their battery low charging limits. These long durations generally prevent the usability of EVs even for short distance urban transportation. Also, a detailed research by National Household Travel Survey revealed that EVs' parking duration is at least 5 h in a workplace environment [4]. Thus, these factors provide important insights into the problems that may be faced especially in EV parking lots (PLs) by taking advantage of EV charging coordination possibility during long parking periods in order to increase the social acceptance of EVs in the community while ensuring uninterruptible power flow. One of the most common charging behaviors can be categorized as residential and workplace charging [5].

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Furthermore, PLs are generally available at heavily populated massive community areas such as sport centers, shopping malls, airports, and so on [6].

Harnessing the renewable energy sources such as solar photovoltaic (PV) is considered as one of the most promising green solutions to charge EVs in the PLs when considering numerous technical, economic opportunities and environmental impacts [7].

Covering PLs with rooftop PV systems is a widely used method in order to utilize solar radiance during the day, and this offers feasible solutions in terms of reducing grid dependence, losses and increasing system performance with using energy efficiently. Also, this installation does not require any new land due to large amount of parking areas existing all over the world. As an example, it was reported that there is 19 billion square meters suitable place in United States according to statistical data in this manner [8].

In the last few decades, there has been a strong trend towards integrating PV equipped PLs into the power grid and they gain importance worldwide due to aforementioned benefits in order to provide a sustainable network management. However, it should be pointed out that there are some major problems encountered by the PL-charging stations to deal with such as the time-varying charging requirements of EVs, random arrival/departure times, expected duration time at the station, and a wide variety of EVs. Moreover, the amount of demanded power as well as the initial state-of-energy (SOE) can also cause undesirable impacts on the demand side and operational problems. On the power supply perspective, the uncertain nature of on-site generation PV system brings about severe challenges in terms of providing stability. In this sense, it is vital to develop an appropriate management strategy for PLs to overcome all these problems by addressing the mentioned uncertainties.

B. *Literature Overview*

There are considerable number of studies in the literature evaluating PLs impact on the distribution system from different aspects to deal with uncertainties by causing PV integration and EVs. Among them, Kuss et al. [9] presented a co-benefits analysis for large scale plug-in EVs penetration on the demand side and mid-day PV generation on the supply side. Also, the effects of curtailed power from PV and peak capacity requirements were investigated. Detailed research about the PV potential of 48 parking lots was analyzed in Ref. [10] to increase charging capacity of EVs with green energy sources. The topic of coordinating and optimization of the charging/discharging behaviors of EVs with different operational objectives such as maximizing load factor, minimizing losses and load flow or voltage/frequency regulation, is a widely investigated concept in the literature. Zhang et al. [11] formulated a non-cooperative game framework for PL EV charging scheduling. In the game defined, each EV acts as a player to maximize their own utility function within the constraint of charging limits and transformer limit. However, in this study, the stochastic nature of EVs such as arrival/departure time or future electricity prices were not taken into account. Xi and Sioshansi [12] suggested a price/quantity-based mechanism in which load aggregator optimizes charging behaviour of EV fleet according to sending price signals from system operator. Clement-Nyns et al. [13] investigated the impact of coordinated EV charging on the distribution feeder with the perspective of minimizing losses, voltage deviations and maximizing load factor. Rezai et al. [14] presented an online intelligent energy management strategy in order to provide optimal and coordinated EV charging in a PL while maximizing EV owners' satisfaction. The uncertainties caused by EVs, renewable energy resources and load were taken into consideration in [15] for developing the best strategy to charge EVs which was actually based on unit commitment methodology. The objective function includes decreasing carbon emission and increasing profit. Goli and Shireen [16] presented smart charging strategies including the issue of meeting the demanded power of EVs by PV based energy generation system for the purpose of providing grid stability and maximizing the utilized available power amount as much as possible. Huang et al. [17] focused on design optimization of an EV charging station including PV and wind based energy generation, battery energy storage units with the aim of minimizing cost of station while ensuring power balance and optimal operation. Essential management strategy for coordinated or uncoordinated PL demand via integration of optimal combination of solar based distributed generation (DG) and storage units considering the variation of charging prices was suggested in [18]. Chukwu et al. [19] described the mathematical formulation to estimate vehicle-to-grid (V2G) PL power capacity and also the impact of PV canopy on this capacity enhancement were studied. However, the uncertain power output of PV depending on the weather conditions was not taken into account. Solar parking plant sizing criteria and its effect on the power grid were examined in recent studies [20].

C. *Content and Contributions*

In this study, a scenario based analysis of an EV PL equipped with a roof-top PV unit is investigated considering various operating conditions in a distribution system. The simulations of the proposed structure are conducted in ETAP (Electrical Transient Analyzer Program) environment with the physical location limits. The major contributions of this study can be summarized as follows:

- The effect of combining EV PL and roof-top PV unit connected to the same distribution system point is taken into consideration.
- The impact of intermittent nature of PV system is investigated considering different seasonal weather conditions such as the variability of the solar radiation during daytime.
- One of the most well-known uncertainties of EVs such as arrival times and their initial SOE are also considered. Incorporating different brands and models EVs are assumed to be connected to the PL randomly.

- This study aim to examine the combinatorial impacts of PV generation system and PL operation in a perspective of line losses and voltage regulation.

D. Paper Organization

The rest of the paper is organized as follows: Section II presents the necessary background information and mathematical formulation of EV charging model. Hereafter, Section III carries out numerical simulations of the proposed framework with different scenarios and afterwards, their corresponding results are demonstrated. Finally, Section IV highlights the significant conclusions and future work.

II. System Model and Problem Formulation

A. Main Features of System Model

The proposed PL-charging station scheme which enables bidirectional power and information flow with main distribution grid is illustrated in Fig. 1. In order to make realistic assumptions and observe the effect of EVs based uncertainties on the grid, two distinct types of living places which are heavily residential and commercial populated regions are considered There are numerous charging pots with controller-managed switchers in the PLs, in which their demanded power is procured by both roof-top PV energy supply units and the main grid. Also, the control center is responsible for developing management strategies to prevent possible overloads and outages in this framework.

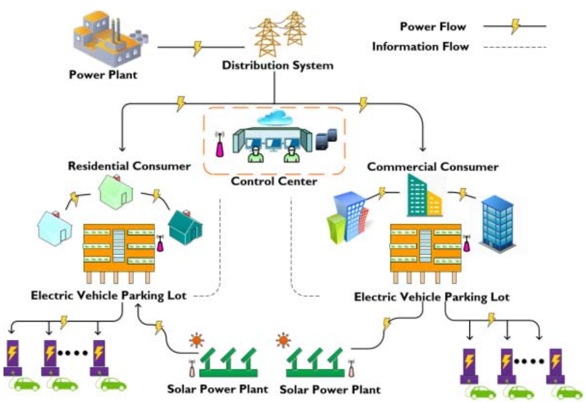

Fig. 1. Smart parking lot equipped with roof-top PV.

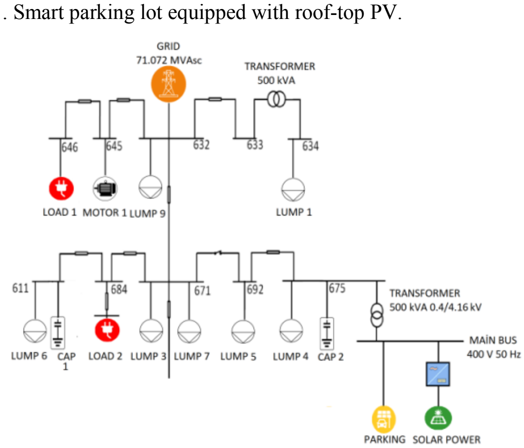

Fig. 2. Integration of solar parking lot within IEEE 13 Bus test system.

TABLE I. PV Panel Design Data

Panel ID	Power [W]	I_{sc} [A]	V_{dc} Max [V]	Power Tolerance [%]
KD235GX-LPB	232	8,48	600	11.8

TABLE II. PV Module Design Data

Number of Panels	V_{dc} [V]	P_{dc} [kW]	I_{dc} [A]
8*27=216	241.04	50.112	207.9

TABLE III. Inverter Design Data

DC Power [kW]	Voltage [V]	V_{max} /V_{min}	FLA [A]	Efficiency [%]	Imax [%]
51	230	110% / 0%	221.7	95	150
AC Power [kVA]	**Voltage [V]**	**Pfmax / Pfmin**	**FLA [A]**	**PF [%]**	**K Factor [%]**
48.5	400	100 / 80	69.93	100	150

This structure is built and integrated within IEEE 13 bus test system which has fixed loads, distribution lines, transformers and also PL with solar generation system as shown in Fig. 2. Both PL and PV plant are connected at low voltage distribution feeder bus with the rated voltage rating of 0.4 kV and the link between main grid and PL is provided through 500 kVA low voltage (0.4 kV) to medium voltage (4.16 kV) transformer. Meanwhile, the PV plant consisting of PV modules, inverters and necessary cabling is sized in accordance with physical limitations of a PL with the structural parameters considered as 73,3*44,37 meters and only one floor. First of all, Kyocera PV Panel [21] is modelled based on the open-circuit voltage; short-circuit current, and the other parameters as indicated in Table I. Considering PL dimensions, there should be used 8 series and 27 parallel PV modules to utilize available area as much as possible. As a result, maximum power generation and the other values of power plant are calculated as stated in Table II. The suitable inverters are modelled by taking PV modules' specifications into account and the sizing values are indicated in Table III. In order to increase the reliability, 6 inverter-PV module groups are used instead of 1 inverter-PV module with the maximum power generation capacity (232×6 kW).

B. Problem Formulation

In order to prevent overloading problems of the transformers and the other power system assets, the centralized controller should take into consideration the dynamics of an EVs, which are basically formulated in Eqs. (1)-(4) in follows:

$$SOE_t^{EV} = SOE_{t-1}^{EV} + CE^{EV} \cdot P_t^{EV} \cdot \Delta T \quad \forall t \in (T^a, T^d] \tag{1}$$

$$SOE_t^{EV} = SOE^{EV,ini}, \quad if \ t = T^a \tag{2}$$

$$SOE_t^{EV,res} \leq SOE^{EV,max} \ \forall t \in [T^a, T^d] \tag{3}$$

$$SOE_t^{EV,res} = SOE^{EV,max} \quad ,t = T^d \tag{4}$$

The SOE of EV is described in Eqs. (1) and (2) considering arrival and departure times and also the specifications of the EV battery. Inequality (3) is defined for determining the bounds of SOE in order to prevent over-charging. In Eq. (4), it is to be noted that EVs should be fully charged depending on the departure time of occupants. Herein, the readers should refer to [22] for a detailed explanation of the symbols used in (1)-(4).

III. Test and Results

A. Input Data

The comprehensive study is performed on an IEEE 13 bus test system to model the integration of PV plant and PL into a 4.16 kV medium voltage distribution system in ETAP environment as stated above by considering Newton-Raphson based load flow analysis. In order to investigate the impact of different power output level of PV plant on voltage deviation and losses in the network, several case studies are created considering the variability of the solar radiation during daytime and seasons. Also, it is assumed that PLs are located in two different areas such as heavily residential and commercial populated places to examine the grid performance during various arrival/departure times of EV users. A great deal of scenarios is created by taking into account the uncertain behavior of the initial SOE and arrival time of EVs. However, for the sake of clarity and simplicity, the results of only 5 scenarios are analyzed in this subsection.

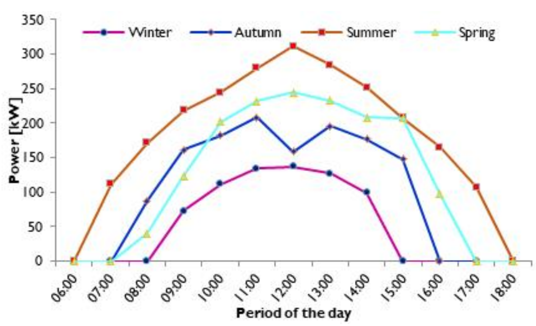

Fig. 3. PV plant daily power production curve for four seasons.

TABLE IV. Solar Radiation Data For every Seasons

Time	Solar Radiation [W/m^2]			
	Winter	Autumn	Summer	Spring
06:00	0	0	174	0
07:00	5	56	426	167
08:00	123	343	627	289
09:00	292	590	792	465
10:00	426	667	884	736
11:00	500	756	1008	840
12:00	510	585	1116	883
13:00	476	716	1022	845
14:00	382	647	911	758
15:00	232	547	755	613
16:00	64	124	604	378
17:00	0	0	411	60
18:00	0	0	200	0

TABLE V. The specifications of the Electric Vehicles [24]

Model of the Car	Battery Capacity (kWh)	Charging Power (kW)
Volkswagen E-Golf	24	7,2
BMW i-3	22	6,6
Mercedes B-Class	28	10,0
Tesla Model - S	85	17,2
Fiat 500E	24	6,6
Ford Focus Electric	23	6,6
Kia Soul EV	27	6,6
Mitsubishi i-MiEV	16	3,3
Chevy Volt	17	3,3
Nissan LEAF	24	6,6

In this study, four seasonal power curves are obtained due to the fact that PV plant power generation capacity actually depend on weather conditions and is changeable. The power production capacity of the PV plant is shown in Fig. 3 which is obtained using the real solar radiation data of Colorado [23] shown in Table IV.

In order to obtain a possible loading curve of a PL during day time usage, different types of EVs are chosen with the specifications shown in Table V [24]. Each PL (residential and commercial) are assumed to host 100 EVs and their arrival times are randomly determined. The distribution of arrival times are supposed to be in between 4 pm and 11 pm for the residential area as well as 7 am and 8 pm for commercial area. EVs are connected to the PL with again randomly determined SOE, which is assumed to change within the range of minimum and maximum capacities. Also, each EV is considered to be charged until reaching maximum SOE, which is equal to the EV battery capacity.

B. Simulation Results and Discussion

In this study, 2 case studies have been conducted as follows:

- **Case-1:** PL in residential area.
- **Case-2:** PL in commercial area.

Case 1: Residential Area

In this case study, 5 different scenarios are simulated for each season considering PL is located in residential area. The arrival times of EVs are randomly distributed. Residential end-users generally arrive their homes between 5pm to 11pm and the EVs should be connected to PL in order to obtain a fully charged battery for the next day. Figure 4 depicts the PL demanded power during the day based on 5 scenarios.

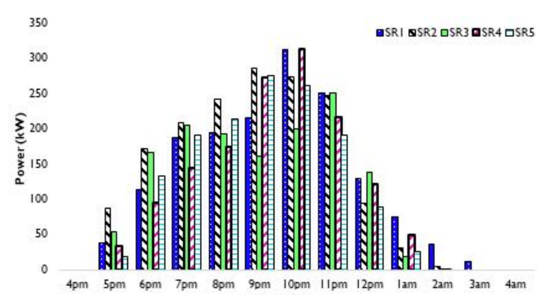

Fig. 4. Loading curve of the PL in residential area for each scenarios.

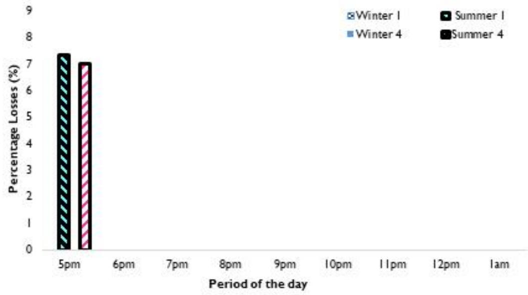

Fig. 5. The percentage of main line losses variation for the PL in residential area.

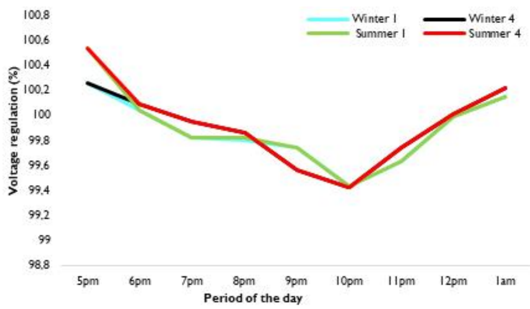

Fig. 6. The voltage regulation of the feeder bus in residential area.

It is clearly seen from Fig. 4 that there are some differences between scenarios which depend on randomly selected EV arrival times and SOE levels. The charging of numerous EVs is performed from 9pm to 11pm intensely causing the power demand to reach its highest points due to the fact that these periods are the mostly preferred hours to be connected to the charging stations in PLs. Figure 5 depicts the percentage of main line losses variation comparing the cases that the PL has a roof-top PV system or not. Herein and hereafter, the percentage of losses means the percentage of the losses within the overall power flow and is directly given as an output by ETAP. It can be indicated that there is a slight difference in only 5pm for summer as it is not possible to generate considerable power after 5pm due to low radiation values for both summer and winter. However, when specifically examining the situation at 5pm, it can be deduced from the Fig. 5 that PV unit generates more energy in Scenario-1 and meets the increased demand more than Scenario-4 for summer. As a result, the loss variation became less than Scenario-4.

Figure 6 depicts the percentage of voltage regulation of the feeder bus for PL in residential area, where the results are depicting the resulting voltage profile. The difference between winter and summer seasons is caused by the amount of PV power production during 5pm to 6pm. In fact, PV system does not generate energy for winter and the demanded power is only procured by the main grid. On the other hand, it is possible to generate energy from the PV unit depending on higher radiation values for summer to meet the PL demand paving the way for increasing voltage deviation. However, PV system cannot produce sufficient levels of energy after 6pm for both two seasons as mentioned before. Thus, the graph is nearly the same after 6pm due to the fact that there is no voltage regulation difference between two compared conditions. The voltage regulation is continuously decreasing until reaching 10 pm which is also the lowest value due to the maximum power consumption occurs at the mentioned period as shown in Fig. 6. However, the regulation begins to increase again for scenarios after 10pm when considering the increased consumption. As a consequence, it is to be noted that the amount of PV power generation certainly affects the voltage regulation as it actually causes to increase the feeder bus voltage regulation comparing the no-generation conditions.

Case 2: Commercial Area

In this case, 5 different scenarios are simulated for each seasons considering the PL located in commercial area. The EVs are assumed to be connected PL during 7am to 8pm in which arrival times are randomly selected and scenarios are created. The power consumption of PL is changing during the day and it causes to capture different maximum values in different time horizons for different scenarios as shown in Fig. 7. For example, the maximum power demand occurs between 9am to 10am for Scenario-1. On the other hand, this peak consumption occurs at 1pm for Scenario-2. These mentioned differences can be explained by taking into consideration various charging behavior and needs of EVs.

The percentage of main line losses variation in commercial area again both for summer and winter is demonstrated in Fig. 8 in which obvious differences can be observed comparing two seasons. For example, the loss reduction occurs during 7am to 5pm, and 9am to 2pm for summer and winter, respectively. The produced energy is higher in summer time as expected, and as a result a great deal of power need is supplied by PV unit.

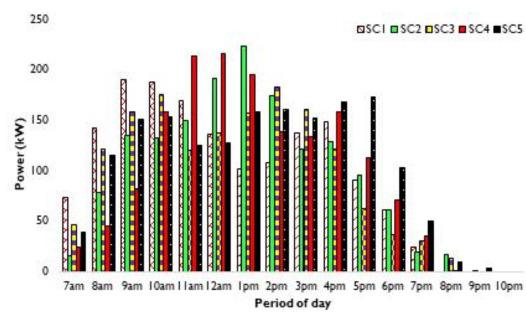

Fig. 7. Loading curve of PL in commercial area for each scenarios.

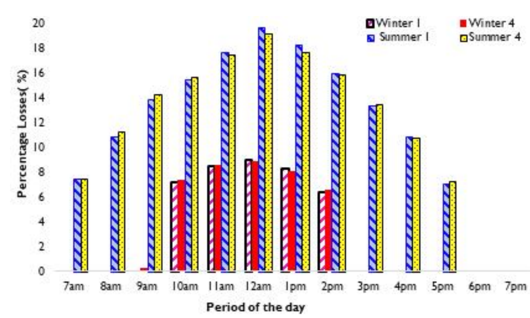

Fig. 8. The percentage of main line losses variation in commercial area.

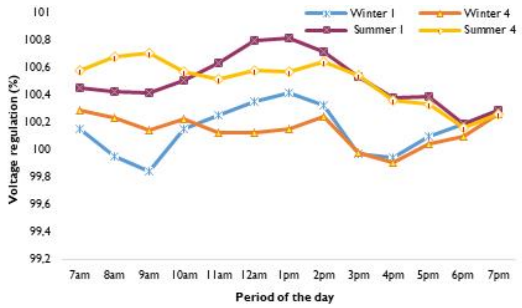

Fig. 9. The voltage regulation of the feeder bus in commercial area.

However, it is not possible to indicate that same situation is valid for the winter depending on the radiation level. Thus, it is obviously clear that the loss variation becomes higher in summer. On the other perspective, the differences between two scenarios for summer are caused by the power consumption of PL. For example, PL power need is 136 kW but it is 216 kW at 12am respectively for Summer-1 and Summer-4, while PV unit is producing 311 kW. Therefore, it directly affects the feeder voltage and leads to the aforementioned changes. The voltage regulation of the PL in commercial area is shown in Fig. 9 where the results are depicting the resulting voltage profile, and in which the regulation changes depending on the energy production capability of PV unit. Specifically, this regulation is continuously decreasing between 7am and 9am for winter due to high power demand. Also, the power consumption in Scenario-1 is higher than Scenario-4 for winter in these periods. On the one hand, the regulation is increasing as expected because of the fact that the number of arriving EVs is decreasing in Scenario-1 for winter between 9am and 10am. In addition, PV energy production is increasing, and this makes regulation more unstable. On the contrary, the voltage regulation begins to reduce in Scenario- 4 for winter due to the fact that the needed power is increasing, and PV unit cannot meet this demand during 10am to 12am. It can be deduced from the results and comments that the feeder voltage value is directly linked with PV unit energy production curve and power consumption of PL in each time period. The same remarks can be adapted to summer conditions. Moreover, the regulation is higher in summer conditions than winter for all scenarios similar to the case of residential area. It should be also stated that these results can help system operators to develop management strategies and deal with undesired situations according to possible scenarios.

IV. CONCLUSION

In this study, a scenario based comprehensive analysis was presented for PLs equipped with rooftop PV units by considering the uncertain nature of EVs. Various scenarios and case studies were conducted in ETAP environment with the aim of investigating possible impacts of randomly integrated EVs on the distribution network in terms of voltage deviation and losses. Moreover, the PV unit generation curve was obtained for every season to properly examine the impacts of varying on-site generation conditions. As a result, it can be stated that the PV unit can help to meet the demanded power of EVs in PLs while decreasing voltage deviations and losses according to the weather parameters. Also, these systems present a sustainable and economic way for network operation while ensuring PL requirements.

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