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***Abstract*—In the future, the widespread adoption of electric vehicle parking lots (EVPLs) may introduce operational challenges like voltage limit violations in distribution networks. However, EVPLs can potentially relieve these voltage limit violations by acting as flexible loads and providing reactive power support. In this paper, the impact of EVPLs on the optimal operation of the distribution network is investigated with a focus on their potential capability for reactive power support in a scenario that the distribution system operator (DSO) is committed to pay a penalty cost to customers if voltage limits are violated. Our results show that flexible charging of Electric Vehicles (EVs) and reactive power support from EVPLs, especially in the case where there exists a penalty cost for voltage violation, has a major impact on reducing the system cost. It can also pave the way for deploying more generation from distributed generation (DG) and renewable energy sources (RES) as well as reducing the voltage violation penalty costs.**

Keywords—EV Parking Lot, Reactive Power Support, Voltage Violation Cost, Distribution System Operation

I. INTRODUCTION

The charging and discharging of electric EVs can have significant impacts on the distribution system management. On the positive side, EVs can provide a source of distributed energy storage that can be used to balance the variability of renewable energy sources [1]. EV charging can be managed to coincide with periods of excess renewable generation, which can help to reduce curtailment and increase the utilization of renewable energy sources [2]. Additionally, EVs can provide voltage support and reactive power compensation through smart charging strategies that respond to system needs [3]. However, on the negative side, high levels of uncoordinated EV charging can lead to the overloading of distribution transformers and other distribution system components, which can result in voltage instability and equipment damage [4]. To mitigate these negative impacts, distribution system operators need to develop effective strategies for managing EV charging and discharging, including the use of smart charging algorithms, the deployment of advanced monitoring and control systems, and the development of appropriate policies and regulations [5].

The impacts on the distribution system, which could be resulted from the charging and discharging patterns of EVs is the main concept of several studies [6]. In this regard, authors in [7] proposed an optimized pattern for the charging and discharging of EVs with the aim of maximizing the efficiency of the distribution system. Energy security and the independency concept can also be the benefit of EV charging integration into the distribution system, as investigated in [8]. In [9] EV parking lots have been incorporated into energy and reserve markets using a bi-level method. This research aimed to minimize costs and address distribution grid constraints using an innovative approach. Authors in [10] proposed a charging and discharging scheduling plan for small-scale parking lots in order to achieve frequency stability inside the distribution system. A similar scheduling plan has been investigated in [11] using operating envelopes.

Authors in [12] presented a model for scheduling EV charging, which employs an optimal AC power flow to achieve the most efficient scheduling in terms of energy cost and EV demand supply. To achieve comparable objectives, [13] proposes a decentralized model for EV charging strategies based on game theory. In [14], various EV charging lot allocation strategies are studied to analyze their impact on the distribution system. The authors of [15] put forth a novel approach that employs a decentralized bi-level stochastic optimization technique to optimize the operation of multi-agent multi-energy networked microgrids with the integration of various energy storage technologies. By addressing the coordination of multiple agents, managing uncertainty in energy demand and supply, and incorporating multiple energy storage technologies, the authors aim to overcome the challenges associated with microgrid operation. In [16] the authors proposed an approach for EV parking lot charging/discharging in which both the demand response and energy consumption cost are considered in their objective function formulation.

Although there are several studies to investigate the role of EV charging stations and parking lots, their potential role in providing reactive support to the power system has not been investigated thoroughly. Moreover, a formulation that can quantify the voltage violation penalty cost that DSO should pay to the consumers as compensation for an unsatisfied power quality index has not been proposed in the literature. This paper tries to fill the mentioned gap by investigating the role of EVPLs in decreasing the distribution system costs and improving the system voltage condition by acting as a flexible active load and providing the system with reactive power

support when the voltage violation penalty cost is included in the system cost besides the other operational costs.

II. PROBLEM FORMULATION

The problem of the DSO is conceived as an optimization problem where the objective function is minimizing the operational cost considering the operational constraints of the whole system such as grid, EVPL, DG, RES, and loads. Objective function as well as constraints are explained below.

A. Objective Function

The DSO's objective function, as represented in (1), is minimizing the total operational cost consisting of the DGs and RES generation cost, the cost of trading reactive and active power with the upstream grid as well as the cost for voltage violation that the DSO is committed to paying to consumers. The DSO is committed to supplying the consumers with an acceptable voltage range. In this regard, there are different compensation mechanisms if the voltage is not within the acceptable range [17] and [18]. In this paper, we assumed that there is two range of voltage violation. The first range is within 0 and VV^a (proper voltage range) where the DSO should not pay any compensation to consumers. The second range is within VV^a and VV^{max} (critical voltage range) where the DSO must pay compensation to consumers according to (2) and (3). $S_{i,t}^L$ is the nominal load of consumers. VV^a and VV^{max} can be set based on the distribution system voltage requirements and standards. For our study, we assumed that $VV^{max} = 0.1$ and voltage violation cannot be exceeded from this amount anyway. VV^a in our study is equal to 0.05 meaning that for voltage violation more than this value the DSO should perform a monetary compensation.

$$Min\ C_D = \Delta T \sum_{t=1}^{T} \Big(k_t^P . P_t^{DN} + k_t^Q . Q_t^{DN} + \sum_{i=1}^{NB} \Big[c_i^{RES} . P_{i,t}^{RES} + \sum_{n=1}^{N_i^{DG,seg}} c_{i,n} . P_{i,n,t}^{DG} + C_{i,t}^{vv} \Big] \Big) \quad (1)$$

$$VV_{i,t} = |V_{i,t} - 1| \quad (2)$$

$$C_{i,t}^{vv} = \begin{cases} 0 & : if\ VV_{i,t} < VV^a \\ (VV_{i,t} - VV^a)\, S_{i,t}^L\, c^{VV} & : if\ VV_{i,t} > VV^a \end{cases} \quad (3)$$

B. Constraints

The constraints of the optimization problem are the operational constraints of different DSO-owned facilities. The constraints related to the distribution grid (reactive and active power flow), DG & RES, and Energy Storage System (ESS) have been extracted from [19] as represented in (4)-(9), (12)-(15), and (16)-(19), accordingly. $Q_{i,t}^{EVPL}$, $P_{i,t}^{EVPL}$, $P_{i,t}^{ESS,ch}$, $P_{i,t}^{ESS,dc}$, $Q_{L,i,t}^{Fix}$, $P_{L,i,t}^{Fix}$ indicate reactive and active EVPL power, ESS charge and discharge power, nonflexible reactive and active nonflexible load in different buses.

$$P_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}\left(V_i - V_j\right) + \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}\left(\theta_i - \theta_j\right) \quad (4)$$

$$P_i = \sum_{j=1, i\neq j}^{N_B} P_{i,j} \quad (5)$$

$$Q_{ij} = \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}\left(V_i - V_j\right) - \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}\left(\theta_i - \theta_j\right) \quad (6)$$

$$Q_i = \sum_{j=1, i\neq j}^{N_B} Q_{i,j} \quad (7)$$

$$P_i = P_t^{DN} - P_{i,t}^{EVPL} + P_{i,t}^{RES} + P_{i,t}^{DG} + P_{i,t}^{ESS,dc} - P_{i,t}^{ESS,ch} - P_{L,i,t}^{Fix} \quad (8)$$

$$Q_i = Q_t^{DN} - Q_{i,t}^{EVPL} + Q_{i,t}^{DG} - Q_{L,i,t}^{Fix} \quad (9)$$

$$V_{min} \leq V_i \leq V_{max} \quad (10)$$

$$\left(P_{ij}\right)^2 + \left(Q_{ij}\right)^2 \leq \left(S_{ij}\right)^2 \quad (11)$$

DGs generation must meet the ramp rate and capacity limitations as indicated in (12)-(14). In addition, RES uncertainty is modelled via the chance-constrained formulation as represented in (15). $\delta_{i,t}^{ESS}$ is a binary that stands for ESS discharging/charging status. and η_{dc} and η_{ch} indicate the discharge and charge efficiency.

$$P_{i,n,min}^{DG} \leq P_{i,n,t}^{DG} \leq P_{i,n,max}^{DG} \quad (12)$$

$$\Delta_{i,min}^{DG} \leq P_{i,t}^{DG} - P_{i,t-1}^{DG} \leq \Delta_{i,max}^{DG} \quad (13)$$

$$\left(P_{i,t}^{DG}\right)^2 + \left(Q_{i,t}^{DG}\right)^2 \leq \left(S_{i,t}^{DG}\right)^2 \quad (14)$$

$$0 \leq P_{i,t}^{RES} \leq \overline{P_{i,t,fore}^{RES}} + \sigma_{i,t,fore} . \Phi_a^{-} 1(1 - \eta) \quad (15)$$

ESS operational constraints are as represented in (16)-(19). $\delta_{i,t}^{ESS}$ is a binary that defines the charging/discharging status of the ESS. $\eta_{in}$and η_{out} are the charge and discharge efficiency.

$$0 \leq P_{i,t}^{ESS,ch} \leq P_{i,max}^{ESS,ch} . \delta_{i,t}^{ESS} \quad (16)$$

$$0 \leq P_{i,t}^{ESS,dc} \leq P_{i,max}^{ESS,dc}\left(1 - \delta_{i,t}^{ESS}\right) \quad (17)$$

$$E_{i,min}^{ESS} \leq E_{i,t}^{ESS} \leq E_{i,max}^{ESS} \quad (18)$$

$$E_{i,t}^{ESS} = E_{i,0}^{ESS} + \Delta T \sum_{t=1}^{j} \eta_{in} . P_{i,t}^{ESS,ch} - \eta_{out} . P_{i,t}^{ESS,dc} \quad (19)$$

The operation of EVPL has been modeled via (20)-(30). In this regard, the EVPL is modeled similarly to a battery. The parameters for this model are derived from the characteristics of various EV classes parked in the EVPL, as well as the Probability Density Function (PDF) describing the arrival and departure patterns of EVs. Similar to previous studies in the field, Truncated Normal Distribution (TND) stands for the arrival and departure of EVs to determine the number of arriving and departing EVs during a day. Equations (20)-(30) represent the charge and discharge power of the EVPL, the energy stored in the EVPL, and the output active and reactive power of the EVPL. Positive sign of reactive power of EVPL stands for the reactive power consumption. In these equations, N, E, Cap, cl, arr, and dep represent the number of EVs, energy level, EV capacity, EV class, and arrival and departure, respectively. Additionally, Sh_{cl} and $C_i^{PL,ins,ch}$ indicate the share of the EV class within the EVPL and the capacity of total installed EV chargers, respectively.

$$E_{i,t}^{PL} = E_{i,t-1}^{PL} - E_{i,t}^{dep} + E_{i,t}^{arr} + \Delta t \eta_{ch} P_{i,t}^{PL,ch} \quad (20)$$

$$N_t^{Ev,arr} = N^{EV,ent}\left(F_{t+0.5}^{TND,arr} - F_{t-0.5}^{TND,arr}\right) \quad (21)$$

$$N_t^{Ev,dep} = N^{EV,ent}\left(F_{t+0.5}^{TND,dep} - F_{t-0.5}^{TND,dep}\right) \quad (22)$$

$$E_{i,t}^{arr} = N_{i,t}^{Ev,arr}(\sum_{cl} Cap_{cl}^{Ev}\, SOC_{cl}^{arr} Sh_{cl}) \quad (23)$$

$$E_{i,t}^{dep} = N_{i,t}^{Ev,dep}\left(\sum_{cl} Cap_{cl}^{Ev}\, SOC_{cl}^{dep} Sh_{cl}\right) \quad (24)$$

$$0 \le P_{i,t}^{PL,ch} \le C_i^{PL,ins,ch} \quad (25)$$

$$0 \le P_{i,t}^{PL,ch} \le N_{i,t}^{EV,par}\left(\sum_{cl} P_{cl}^{ch,max}\, Sh_{cl}\right) \quad (26)$$

$$N_{i,t}^{EV,par} = N_{i,t-1}^{EV,par} + N_{i,t}^{Ev,arr} - N_{i,t}^{Ev,dep} \quad (27)$$

$$E_{i,t}^{PL,min} \le E_{i,t}^{PL} \le E_{i,t}^{PL,max} E_{i,t}^{PL,min} = N_{i,t}^{EV,par}(\sum_{cl} Cap_{cl}^{Ev}\, SOC^{min} Sh_{cl}) \quad (28)$$

$$E_{i,t}^{PL,max} = N_{i,t}^{EV,par}(\sum_{cl} Cap_{cl}^{Ev}\, SOC^{max} Sh_{cl}) \quad (29)$$

$$\left(P_{i,t}^{PL}\right)^2 + \left(Q_{i,t}^{PL}\right)^2 \le (S_i^{PL})^2 \quad (30)$$

III. Simplification

Equations (2) and (3) in the problem formulation section, make it necessary to proceed with the optimization via metaheuristic algorithm. However, such algorithms, due to their weakness and lack of correctness proof are not in the interest these days. In this regard, firstly to write (2), which uses the absolute value function, in another form, the binary variable $u_{i,t}^1$ is used as represented in (31) where $u_{i,t}^1 = 1$ stands for $V_{i,t} > 1$ and $u_{i,t}^1 = 0$ stands for $V_{i,t} < 1$. Its proof is obtained if $u_{i,t}^1$ is equal to 0 and 1 in the (31). Then $VV_{i,t}$ is obtained via (32). (31) and (32) have been written in another form according to (33) and (34), respectively.

$$\left(2u_{i,t}^1 - 1\right).\left(V_{i,t} - 1\right) >= 0 \quad (31)$$

$$VV_{i,t} = \left(2u_{i,t}^1 - 1\right).\left(V_{i,t} - 1\right) \quad (32)$$

$$2u_{i,t}^1 V_{i,t} - V_{i,t} - 2u_{i,t}^1 + 1 >= 0 \quad (33)$$

$$VV_{i,t} = 2u_{i,t}^1 V_{i,t} - V_{i,t} - 2u_{i,t}^1 + 1 \quad (34)$$

The proof is obtained via setting $u_{i,t}^1$ equal to 1 and 0. If $u_{i,t}^1 = 1$ from (31) and (34) we will have:

$$\begin{cases} 2V_{i,t} - V_{i,t} - 2 + 1 >= 0 \\ VV_{i,t} = 2u_{i,t}^1 V_{i,t} - V_{i,t} - 2u_{i,t}^1 + 1 \end{cases}$$

Therefore;

$$\begin{cases} V_{i,t} >= 1 \\ VV_{i,t} = V_{i,t} - 1 \end{cases}$$

In addition, if $u_{i,t}^1 = 0$ from (31) and (34) we will have:

$$\begin{cases} 0 - V_{i,t} - 0 + 1 >= 0 \\ VV_{i,t} = 0 - V_{i,t} - 0 + 1 \end{cases}$$

Therefore;

$$\begin{cases} V_{i,t} <= 1 \\ VV_{i,t} = 1 - V_{i,t} \end{cases}$$

This way, it has been shown that (31) and (34) stand for (2). Then, to remove the if-condition from (3), the binary variable $u_{i,t}^2$ is utilized where $u_{i,t}^2 = 1$ stands for $VV_{i,t} > VV^a$ and $u_{i,t}^2 = 0$ stands for $VV_{i,t} < VV^a$. Its proof is obtained if $u_{i,t}^2$ is equal to 0 and 1 in (35). Then $VV_{i,t}$ is obtained via (36). (31) and (36) have been written in another form according to (37) and (38)(34), respectively.

$$\left(2u_{i,t}^2 - 1\right).\left(VV_{i,t} - VV^a\right) >= 0 \quad (35)$$

$$C_{i,t}^{vv} = u_{i,t}^2.(VV_{i,t} - VV^a)\, S_{i,t}^L\, c^{VV} \quad (36)$$

$$2u_{i,t}^2 VV_{i,t} - VV_{i,t} - 2u_{i,t}^2 VV^a + VV^a >= 0 \quad (37)$$

$$C_{i,t}^{vv} = (u_{i,t}^2 VV_{i,t} - u_{i,t}^2 VV^a)\, S_{i,t}^L\, c^{VV} \quad (38)$$

The proof is obtained via setting $u_{i,t}^2$ equal to 1 and 0. If $u_{i,t}^2 = 1$ from (37) and (38) we will have:

$$\begin{cases} 2VV_{i,t} - VV_{i,t} - 2VV^a + VV^a >= 0 \\ C_{i,t}^{vv} = (VV_{i,t} - VV^a)\, S_{i,t}^L\, c^{VV} \end{cases}$$

Therefore;

$$\begin{cases} VV_{i,t} >= VV^a \\ C_{i,t}^{vv} = (VV_{i,t} - VV^a)\, S_{i,t}^L\, c^{VV} \end{cases}$$

In addition, if $u_{i,t}^2 = 0$ from (37) and (38) we will have:

$$\begin{cases} 0 - VV_{i,t} - 0 + VV^a >= 0 \\ C_{i,t}^{vv} = (0 - 0)\, S_{i,t}^L\, c^{VV} \end{cases}$$

Therefore;

$$\begin{cases} VV^a >= VV_{i,t} \\ C_{i,t}^{vv} = 0 \end{cases}$$

This way, it has been shown that (37) and (38) stand for (3). In addition, quadratic constraints (11), (14), and (30) are written in a linearized form. To this end, the circle that stands for the quadratic constraint is replaced with a polygon inside the circle. This way, the new feasible area would be similar to the previous one, while set of linear constraints are replaced with quadratic constraint. After conducting the simplifications above, the DSO's problem is formulated via Mixed Integer Non-Linear Programming (MINLP).

IV. Simulation Results

A. Case study

We utilized the case study from [19] and made modifications by incorporating EVPLs into the system, as shown in Fig. I. This paper considers that there are 10 classes of EVs with an equal share as described in TABLE. I including their respective characteristics. Additionally, we define the parameters for TND as represented in TABLE. II. Moreover, we have considered two cases and two scenarios for our simulation. In case (a), it is assumed that there is no voltage violation penalty cost for the DSO, while in case (b) the voltage violation penalty cost is considered in the objective function of the DSO. Furthermore, in scenario 1, EVPL chargers cannot provide reactive power support, while in scenario 2, EVPL chargers are fully able to provide reactive power. Lastly, there are 3000 charging stations available across all EVPLs and it is assumed that every charger will be used by one car in the day.

The DSO's optimization problem that is formulated as MINLP is coded in Python and solved via the Apopt solver.

TABLE. I EV CLASSES AND CHARACTERISTICS

class	1	2	3	4	5	6	7	8	9	10
$P_{cl}^{ch,max}$ (kW)	7	10	10	7	10	7	5	5	7	10
Cap_{cl}^{Ev} (kWh)	15	20	20	15	20	15	10	10	15	20
SOC_{cl}^{arr}	0.33	0.33	0.16	0.4	0.1	0.45	0.5	0.2	0.33	0.2

TABLE. II TND CHARACTERISTICS OF EVLPS

EVPL type		Min	Max	Average	Standard deviation
Residential	Arrival	16	23	20	3
	Departure	6	11	8	3

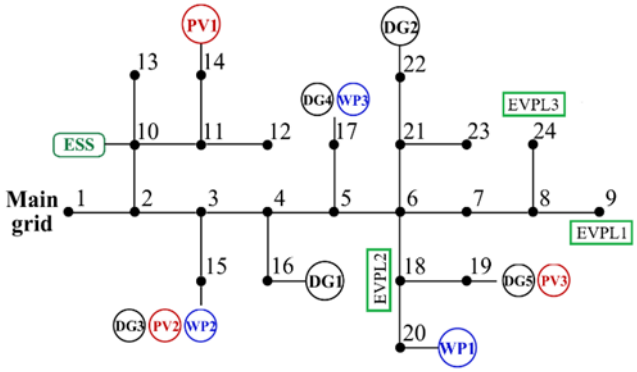

Fig. I. Distribution system topology

B. *Result and Discussion*

The charging power scheduling of the EVPL in scenario 1, where EVPLs cannot provide reactive power support, is depicted in Fig. II. It can be seen that the charging schedules of EVPLs are different from each other in both cases. This is because of their different locations in the power system where different network constraints result in different charging schedules. This way, the EVPLs charging schedule is determined based on the hourly power price and the power generation of DGs and RES meeting the voltage conditions all over the system to be within the maximum and minimum allowed values. Moreover, for each EVPL the charging schedule in case (a) is different from its charging schedule in case (b). In case (b), in which there is a voltage violation cost, decreasing voltage violation level is of more importance compared to case (a).

This way, the charging schedule is determined to assist the DSO in reaching a lower voltage violation level, as depicted in Fig. III, since modification in the charging schedule results in a change in hourly generation and trading power. This way, EVPL, by acting as a flexible load, will support the DSO to decrease the voltage violation all over the power system as represented in the TABLE. III. It is also seen that if the DSO must pay the voltage violation penalty, there will be a meaningful increase in its cost even with the modification in the charging schedule of EVPLs that results in a lower voltage violation in the whole system.

TABLE. III TOTAL SYSTEM COST IN SCENARIO 1

Case	VV	System cost
Case (a)	27.3365	18597.12
Case (b)	23.3558	21623.89

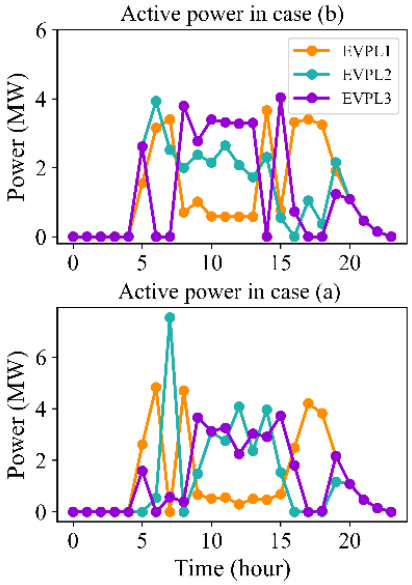

Fig. II. The active power of EVPLs for case (a) and case (b) in scenario 1

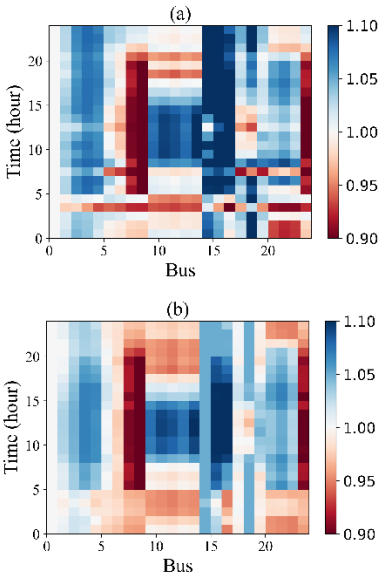

Fig. III System voltage for case (a) and case (b) in scenario 1

In scenario 2, EVPLs are equipped with reactive power support for the DSO. It is observed that the total system cost in this scenario for case (a) is 1.37% less than the system cost for the same case in scenario 2. This lower cost is expected as reactive power support from EVPL could result in a cheaper power supply mix due to improving the voltage situation in the system that enables DGs to generate more. This way, the total system cost is reduced. The reactive power support in scenario 2 has a higher impact on improving the system operation in case 2 where the total system cost in scenario 2 for case (b) is 11.23% less than the system cost for the same case in scenario 2. This highlights the importance of reactive power support from EVPLs when we consider the cost of

voltage violation penalty cost for the DSO. Fig. IV shows the active and reactive power of EVPLs for case (a) and case (b) in scenario 2. It can be seen that in this scenario, for both cases, EVPLs modify their charging schedule (compared to scenario 1 in Fig. II) to provide reactive power support for a major improvement in the system voltage situation as shown in Fig. V that leads to lower voltage violation and consequently lower system cost. From TABLE. IV, it is observed that when DSO commits to pay for the voltage violation of more than 0.05, the total voltage violation of the system will decrease by around 34%. This meaningful voltage violation reduction shows EVPLs can have a decent performance in supporting the system to improve the voltage situation.

TABLE. IV TOTAL SYSTEM COST IN SCENARIO 2

Case	VV	System cost
Case (a)	28.19	18352.35
Case (b)	18.63	19194.94

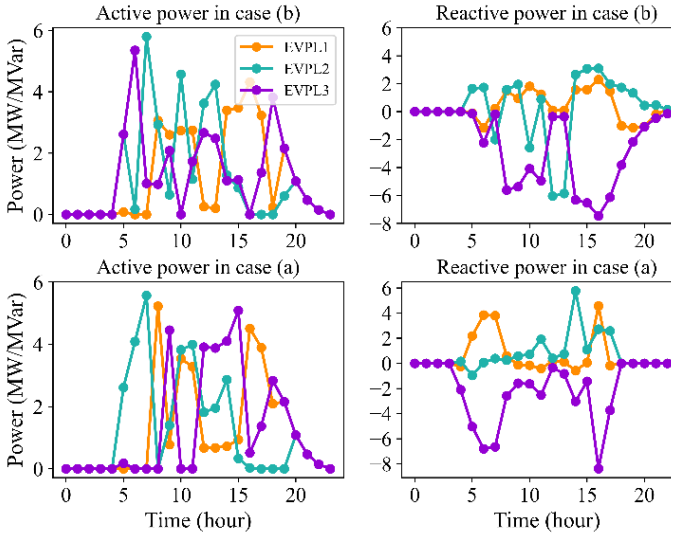

Fig. IV. The active and reactive power of EVPLs for case (a) and case (b) in scenario 2

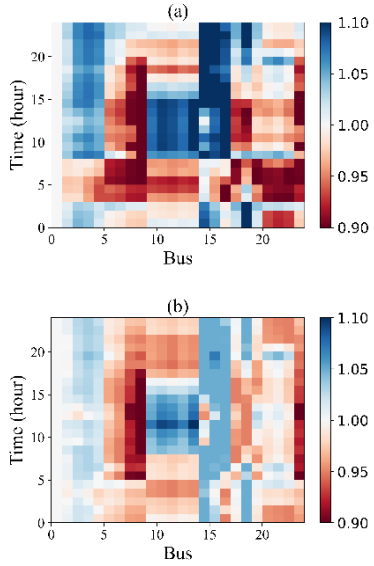

Fig. V System voltage for case (a) and case (b) in scenario 2

V. CONCLUSION

This paper examined how commercial EVPLs affected the distribution system operation, specifically by assessing their ability to provide reactive power support while considering the penalty cost incurred by DSO due to unauthorized voltage violations. This way, a new linear formulation was deployed to quantify the voltage violation index. Our findings demonstrated that EVPLs in the different parts of the system had different responses for supporting the DSO based on the network limitation in that area. In addition, the results showed that by equipping the EVPLs with the reactive power support capability the system cost decreased 1.37% for case (a) where the voltage violation penalty cost was neglected and 11.23% for case (b) where voltage violation penalty cost was considered. Therefore, the reactive power support provided by EVPLs had a significant influence on decreasing the overall system cost and on improving system voltage specially when DSO was committed to paying the voltage violation penalty to consumers. For future studies, it is needed to investigate the role of residential EVPLs in supporting the distribution system. In addition, the effect of EVPLs' size (capacity) and location should also be studied.

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