Multi-Objective EV Charging and Comfort Management Considering V2G Functionality and Distribution System Constraints

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***Abstract*—Planning electric vehicle (EV) charging management has become a significant issue as the percentage of EVs on the road rises. The adverse effects of EVs on the distribution system (DS) can be mitigated by carefully managing their charging. In addition, the vehicle-to-grid (V2G) service enables EVs to supply energy when the power system needs it. In this study, the proposed multi-objective optimization model, which is developed in the form of mixed-integer quadratically constrained programming (MIQCP), examines the comfort of EVs participating in the grid ancillary services in an EV parking lot (EVPL) concept and the cost of the EVPL operator simultaneously. Moreover, the effect of the proposed model on the important variables of the DS, such as power flow, voltage, and line losses, is examined. The developed model is evaluated using the IEEE 33-bus test system with four different case studies and a 15-minute time resolution. Thanks to the multi-objective approach, the results demonstrate that the comfort of EVs during ancillary services can be raised by taking the cost of charging and comfort violation into account jointly.**

***Index Terms*—Ancillary services, comfort violation, distribution system, electric vehicle, optimal power flow.**

NOMENCLATURE

Abbreviations

EV	Electric Vehicle
EVPL	EV Parking Lot
SoE	State-of-Energy

Sets and Indices

i, j	Set of buses.
k	Set of electric vehicles.
t	Set of time periods.

Parameters

ΔT	Time resolution.
$card(h)$	Cardinality of EV set.
$CE_{i,k}^{EV}$	Charging efficiency of EV k [%].
$CR_{i,k}^{EV}$	Charging rate of EV k [kW].
$DE_{i,k}^{EV}$	Discharging efficiency of EV k [%].
$DR_{i,k}^{EV}$	Discharging rate of EV k [kW].
$P_{i,t}^{Load}$	Active power consumption of bus i during t [p.u.].
$Q_{i,t}^{Load}$	Reactive power consumption of bus i during t [p.u.].
$R_{i,j}$	Resistance of line (i,j) [p.u.].
$S_{i,j}^{Max}$	Power capacity of line (i,j) [p.u.].
$SoE_{i,k}^{EV,arr}$	SoE of EV k at arrival time [kWh].
$SoE_{i,k}^{EV,des}$	Predefined desired SoE of EV k [kWh].
$SoE_{i,k}^{EV,max}$	Battery capacity of EV k [kWh].
$SoE_{i,k}^{EV,min}$	Minimum allowable battery capacity of EV k [kWh].
$T_{i,k}^{d}$	Departure time of EV k.
$T_{i,k}^{a}$	Arrival time of EV k.
V_i^{min}/V_i^{max}	Minimum and maximum voltage of bus i.
$X_{i,j}$	Reactance of line (i,j) [p.u.].

Decision Variables

$Com\_Vio_{i,k}^{EV}$	Relative comfort violation of EV k at departure time.
$f_{i,j,t}^{active,P}$	Active power flow of line i,j during t [p.u.].
$f_{i,j,t}^{reactive,Q}$	Reactive power flow of line i,j during t [p.u.].
$P_{i,j,t}^{Loss}$	Active power losses of line i,j during t [p.u.].
$P_{i,k,t}^{EV,ch}$	Charging power of EV k during t [kW].
$P_{i,k,t}^{EV,dsch}$	Discharging power of EV k during t [kW].
$P_{i,t}^{f}$	Total active power delivered from the substation bus i during t [p.u.].
$Q_{i,j,t}^{Loss}$	Reactive power losses of line i,j during t [p.u.].
$Q_{i,t}^{f}$	Total reactive power delivered from the substation bus i during t [p.u.].
$SoE_{i,k,t}^{EV}$	SoE of EV k during t [kWh].
$SoE_{i,k}^{-/+}$	Auxiliary variable for comfort violation calculation.
$SoE_{i,k}^{EV,final}$	Final SoE of EV k in departure time[kWh].
$u_{i,k,t}^{EV,ch/dsch}$	Binary variable for charging/discharging decision.
$u_{i,k}^{+/-}$	Binary variable for comfort calculation.
$V_{i,t}^{Bus}$	Voltage magnitude of bus i during t [p.u.].

I. Introduction

The number of EVs on the road has been sharply rising. Global energy demand for electric vehicles (EVs) is predicted by the International Energy Agency (IEA) to be 800 TWh in 2030 when current policy plans are taken into account, 1100 TWh, which is twice Brazil's current total energy demand, if pledged policies are implemented, and 1500 TWh if the IEA's 2050 net zero emission plans are followed [1]. Supply-demand mismatches, voltage deviations, harmonic problems, and overloaded system assets are just a few examples of the negative effects that could result from EVs' increased energy use and deteriorate the quality of the power. As a result, EV charging management needs to be handled carefully. Additionally, EVs can participate in ancillary grid services via vehicle-to-grid (V2G) function when the power system requires them [2].

A. Literature Review

The current literature contains a wealth of insightful research that examine distribution system (DS) constraints and V2G. Some of these studies are presented in this section:

Mazumder and Debbarma [3] suggested a model that, by taking V2G into account, promises to minimize the cost of EV charging and the peak-to-average ratio. In the provided model, voltage limitations and different charging types were also examined. It was assumed, nonetheless, that the vehicles had achieved the required value by the time the charging and discharging period was over and the model was solved with the water cycle algorithm. With a model aimed at minimizing active power losses and taking into account the charging and discharging management of EVs, Velamuri et al. [4] examined the problem of distributed generation (DG) siting and sizing. In the model with various charging modes, EV comfort was not examined. Ahmad and Sivasubramani [5] investigated the maximum number of EVs that can be integrated into the existing power system, taking into account the economic and emission dispatch problems. It has been shown that the V2G feature in the suggested model makes it possible to incorporate more EVs into the DS. Guo et al. [6] evaluated the combined effect of dynamic network configuration problem and V2G operation on distribution system operation with a strategy aimed at minimizing active power losses and switching costs. The study assumed that EVs be charged to at least a predetermined value at the time of departure while taking into account the power flow equations. Ginigeme and Wang [7] examined at how V2G may be integrated into the power system without taking power flow into account, using a model they proposed for several objective functions such peak demand, load profile deviation, degradation, and charging cost. In order to guarantee voltage stability in DS with V2G, Zhong et al. [8] presented an auction process that takes DS constraints into consideration. Line losses were disregarded, though, and quadratic terms were not taken into account when calculating voltage deviation. In order to minimize distribution system losses, Singh et al. [9] designed a model that schedules the charging and discharging of V2G-equipped EVs. In addition, the uncertainties of EVs as well as cost-benefit analysis and the reconfiguration of the distribution system utilizing different methodologies were analyzed. In a game theory-based model put forth by Chen et al. [10], EVs participate in regulation services in order to maximize their profits, the EV aggregator aims to maximize its profits, and all EVs aim to maximize social welfare in the cooperative situation. In order to minimize V2G charging and battery aging costs and increase the parking lot's load factor by reducing power deviations, Maigha et al. [11] carried out a multi-objective optimization study in residential parking lots. The proposed model has been solved using the augmented-constraint method. Zahedmanesh et al. [12] proposed a virtual energy hub which combines a technical and commercial operation of an integrated system comprising an electric transportation system with a battery-powered bus charging station with an integrated photovoltaic system. Additionally, they suggested a cooperative decision-making strategy for the virtual energy hub, where the active and reactive power flows and the economic operation of the system are scheduled using a novel three-stage cooperative control system. Baghali et al. [13] investigated the potential effects of EVs on reducing the load shedding in heavily loaded DSs. A network equilibrium model was utilized, which integrates market clearing in DSs and traffic flow balance in transportation systems. This model captures the decentralized interactions between key stakeholders in transportation and distribution networks as well as the spatial distribution of EV traffic in response to endogenously determined incentive signals. To mitigate the computational challenges brought by the non-convex network equilibrium model, they also developed an equivalent convex reformulation with guaranteed global convergence. Kiani et al. [14] suggested a three-layer hierarchical distributed framework for optimal scheduling of EV charging, which includes a DS operator (DSO), EV aggregators (EVAs), and EV parking lot (EVPL). An iterative algorithm based on the alternating direction method of multipliers (ADMM) and the DistFlow model was developed to solve the scheduling problem. The framework aims to minimize charging cost, reduce peak load, and regulate voltage. To improve the performance of the optimization framework, a neural network-based load forecasting model is implemented to consider uncertainties related to residential load demand. Kazemtarghi et al. [15] investigated the impact of EVs on power quality, voltage profile, and frequency stability of the power grid. The authors presented a detailed model of a practical bidirectional onboard charger to measure the total harmonic distortion in the grid current caused by EVs. The study considers various EV power levels, grid voltage levels, and EV modes of operation. Additionally, the authors developed an optimal frequency support strategy that utilizes available EVs in V2G mode to improve the frequency stability of the grid in the event of frequency fluctuations.

In addition, the authors' previous work [16] examines the impact of ancillary services on EV comfort violation but does not consider DS constraints. However, despite the fact that the literature is filled with worthwhile studies, none of them examine the effect of EV comfort on DS during ancillary services.

B. Contributions and Paper Organization

In this study, developed multi-objective optimization model examines the optimal operation of an EVPL with V2G capability taking into account the comfort of EV owners and the cost of the EVPL owner. The model developed in mixed-integer quadratically constrained programming (MIQCP) form also shows the effects of comfort violations and cost minimization on the distribution system. The primary contributions of this study are as follows:

- To the best of the authors' knowledge, this is the first study in the literature to investigate the impact of taking into account EV comfort on DS constraints during ancillary services, such as V2G. Furthermore, with the multi-objective model, the cost minimization of the EVPL owner and the minimization of the comfort violation of the EV owners are simultaneously examined, and a comparative analysis is presented.
- The IEEE 33-bus distribution test system, quadratic expressions in voltage and power loss calculation, and 50 different EV kinds are all taken into consideration to strengthen the reliability of the proposed model.

The remaining sections of the paper are structured as follows. The mathematical formulation of the suggested optimization model is presented in Section II. After that, Section III analyzes the input data and results. Section IV concludes with a discussion of key findings and future research.

II. Methodology

Objective functions (OFs) of the proposed multi-objective model are defined in (1). First objective is aimed at minimize the charging cost as stated in (2). Second objective function in (3) aims to minimize average comfort violation during the V2G operation.

$$\min\{OF1, OF2\} \tag{1}$$

$$OF1 = \sum_i \sum_k \sum_t P^{EV,ch}_{i,k,t} * Price_t \tag{2}$$

$$OF2 = \frac{\sum_i \sum_k Com\_Vio^{EV}_{i,k}}{card(k)} \tag{3}$$

The equations for balancing active and reactive power can be found in (4) and (5), respectively. The sum of power drawn from the substation bus ($P^f_{i,t}, Q^f_{i,t}$) and power flow in the connected linees ($f^{active,P}_{i,j,t}$, $f^{reactive,Q}_{i,j,t}$) equals the sum of the active and reactive power demand of the bus ($P^{Load}_{i,t}, Q^{Load}_{i,t}$) and the power losses ($P^{loss}_{i,j,t}, Q^{loss}_{i,j,t}$) in the line. Also, active and reactive power losses are determined by (6) and (7).

$$\sum_i \sum_k \sum_t P^{EV,dsch}_{i,k,t} + P^f_{i,t} + \sum_{j \in \Omega^j_l} f^{active,P}_{i,j,t} - \sum_{j \in \Omega^i_l} f^{active,P}_{i,j,t} = P^{loss}_{i,j,t} + P^{Load}_{i,t} + \sum_i \sum_k \sum_t P^{EV,ch}_{i,k,t} \tag{4}$$

$$Q^f_{i,t} + \sum_{j \in \Omega^j_l} f^{reactive,Q}_{i,j,t} - \sum_{j \in \Omega^i_l} f^{reactive,Q}_{i,j,t} = Q^{loss}_{i,j,t} + Q^{Load}_{i,t} \tag{5}$$

$$P^{loss}_{i,j,t} = R_{i,j} * \frac{(f^{active,P}_{i,j,t})^2 + (f^{reactive,Q}_{i,j,t})^2}{V_0^2} \tag{6}$$

$$Q^{loss}_{i,j,t} = X_{i,j} * \frac{(f^{active,P}_{i,j,t})^2 + (f^{reactive,Q}_{i,j,t})^2}{V_0^2} \tag{7}$$

To ensure the reliable operation, technical active and reactive power limits of the linees are defined through (8)-(11). The voltage drop along the buses is stated in (12). Limits of voltage magnitude is defined in (13).

$$-S^{max}_{i,j} \le f^{active,P}_{i,j,t} \le S^{max}_{i,j} \tag{8}$$

$$-S^{max}_{i,j} \le f^{reactive,Q}_{i,j,t} \le S^{max}_{i,j} \tag{9}$$

$$-\sqrt{2} * S^{max}_{i,j} \le f^{active,P}_{i,j,t} + f^{reactive,Q}_{i,j,t} \le \sqrt{2} * S^{max}_{i,j} \tag{10}$$

$$-\sqrt{2} * S^{max}_{i,j} \le f^{active,P}_{i,j,t} - f^{reactive,Q}_{i,j,t} \le \sqrt{2} * S^{max}_{i,j} \tag{11}$$

$$V^{bus}_{j,t} = V^{bus}_{i,t} - \frac{R_{i,j} * f^{active,P}_{i,j,t} + X_{i,j} * f^{reactive,Q}_{i,j,t}}{V_0} + (R^2_{i,j} + X^2_{i,j}) * \frac{(f^{active,P}_{i,j,t})^2 + (f^{reactive,Q}_{i,j,t})^2}{2V_0^3}, \quad \forall i,j,t \tag{12}$$

$$V^{min}_i \le V^{bus}_{i,t} \le V^{max}_i, \quad \forall i,t \tag{13}$$

Formulations (14)-(21) encompass the mathematical models for the charging and discharging behaviors of the EVs. As expressed in (14) and (15), charging and discharging power can not exceed the specified power rates. Thanks to the (16) and (17), charging and discharging can not occur simultaneously. To provide safe operation for EV batteries, state-of-energy (SoE) range is limited by (18). The relationship between the variation in SoE and the charging power of the EV during the parking period is defined in (19). At the departure time, SoE of the related EV can not exceed desired SoE as defined in (20). At arrival time, equation (21) computes the initial SoE value of the EV.

$$0 \le P^{EV,ch}_{i,k,t} \le CR^{EV}_{i,k}, \quad \forall i,k,t \in (T^a_{i,k}, T^d_{i,k}] \tag{14}$$

$$0 \le P^{EV,dsch}_{i,k,t} \le DR^{EV}_{i,k}, \quad \forall i,k,t \in (T^a_{i,k}, T^d_{i,k}] \tag{15}$$

$$P^{EV,ch}_{i,k,t} \le M * u^{EV,ch/dsch}_{i,k,t}, \quad \forall i,k,t \in (T^a_{i,k}, T^d_{i,k}] \tag{16}$$

$$P^{EV,dsch}_{i,k,t} \le M * (1 - u^{EV,ch/dsch}_{i,k,t}), \quad \forall i,k,t \in (T^a_{i,k}, T^d_{i,k}] \tag{17}$$

$$SoE^{EV,min}_{i,k} \le SoE^{EV}_{i,k,t} \le SoE^{EV,max}_{i,k}, \quad \forall i,k,t \in [T^a_{i,k}, T^d_{i,k}] \tag{18}$$

$$SoE^{EV}_{i,k,t} = SoE^{EV}_{i,k,t-1} + CE^{EV}_{i,k} * P^{EV,ch}_{i,k,t} * \Delta T - \frac{P^{EV,dsch}_{i,k,t} * \Delta T}{DE^{EV}_{i,k}}, \forall i,k,t \in (T^a_{i,k}, T^d_{i,k}] \tag{19}$$

$$SoE^{EV}_{i,k,t} \le SoE^{des}_{i,k}, \quad \forall i,k, \ if \ t = T^d_{i,k} \tag{20}$$

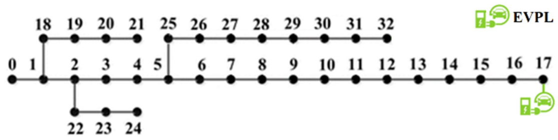

Fig. 1: Modified IEEE 33-Bus distribution system.

$$SoE^{EV}_{i,k,t} = SoE^{init}_{i,k}, \quad \forall i,k, \ if \ t = T^{a}_{i,k} \tag{21}$$

Comfort violation of each EV is determined by (22)-(26). Final SoE value at the departure time is specified in (22). Equation (23) determines the unmet energy demand. In (24) comfort violation is determined as a percentage of unmet energy to battery capacity. Thanks to the inequalities (25) and (26), $SoE^{+}_{i,k}$ and $SoE^{-}_{i,k}$ can not take value simultaneously.

$$SoE^{EV,final}_{i,k} = SoE^{EV}_{i,k,t}, \forall i,k, \ if \ t = T^{d}_{i,k} \tag{22}$$

$$SoE^{EV,final}_{i,k} = SoE^{des}_{i,k} + SoE^{+}_{i,k} - SoE^{-}_{i,k}, \forall i,k \tag{23}$$

$$Com\_Vio^{EV}_{i,k} = \frac{SoE^{-}_{i,k} * 100}{SoE^{EV,max}_{i,k}}, \forall i,k \tag{24}$$

$$SoE^{+}_{i,k} \leq M * u^{+/-}_{i,k}, \quad \forall i,k \tag{25}$$

$$SoE^{-}_{i,k} \leq M * (1 - u^{+/-}_{i,k}), \quad \forall i,k \tag{26}$$

III. TEST AND RESULTS

In this work, the MIQCP method is used to examine the impact of the V2G enabled EVPL on the DS. Using a Python environment and the Gurobi commercial solver, the effectiveness of the established technique is assessed. The optimization model has 96 time frames, with a 15-minute resolution.

A. Input Data

The optimization model is validated using the IEEE 33-bus distribution test system [17], with Bus-17 designated as the location for the EVPL. Figure 1 shows the modified topology of the IEEE 33-Bus distribution system. 100 kVA and 12.66 kV are the base power and voltage settings, respectively. To reflect price changes, EXIST Transparency Platform's [18] Turkey Day-ahead prices are used. Figure 2 shows the 33-bus's power demands as well as price information.

Furthermore, data from Europe's best-selling EVs in 2022 [19] are collected to generate relevant EV data, such as battery capacity, charging/discharging power, etc. The 50 most-selling EVs are selected to create an EVPL pool, from which 200 EVs are randomly chosen for the 33-bus distribution test system. The appropriate arrival and departure times for EVs are generated. Specifically, 75% of the arrival times are randomly distributed between 4:30 PM and 7:00 PM, while the departure (disconnect) time is set at 11:30 PM. The remaining EVs are considered secondary cars and are parked during the day. Also, the charging rate is specified as 22 kW.

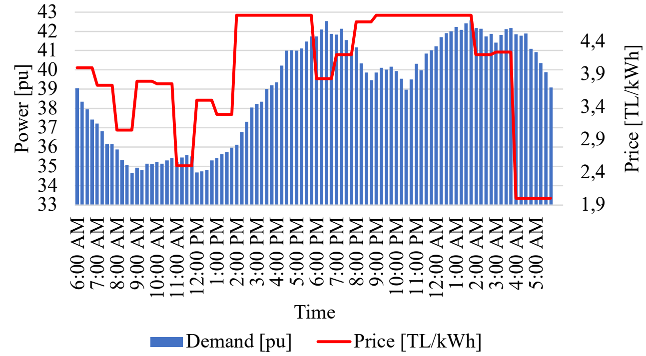

Fig. 2: Active power demand and electricity tariff.

TABLE I: Comparison of the results for the case studies

	Base Case	Case-1	Case-2	Case-3
Total Charging Energy [kWh]	-	969.26	1928.01	1005.47
Total Discharging Energy [kWh]	-	1275	1275	1275
Voltage Deviation [%]	6.422	6.395	6.49	6.39
Total Active Power Loss [kWh]	5286.25	5274.25	5413.50	5280.75
Charging Cost [TL]	-	3380.342	7286.546	3499.287
Comfort Violation [%]	-	15.43	5.68	14.57

B. Simulation and Results

In order to evaluate the efficacy of the proposed model, several case studies were carried out, which are expounded upon below:

- Base Case: There is no EVPL in the distribution system.
- Case-1: Cost minimization-oriented EV charging management
- Case-2: Multi-objective EV charging management in which comfort violation minimization is the first objective and cost minimization is the second objective
- Case-3: Multi-objective EV charging management in which cost minimization is the first objective and comfort violation minimization is the second objective

The outputs of the mentioned cases for the IEEE 33-bus distribution test system are depicted in Table I. As can be seen in the table, while the discharging energy remained constant across all cases due to the contract, the EVs were charged the most in Case-2 with 1928 kWh. This is because the vehicles wanted to approach their desired energy levels more closely to reduce discomfort. In Case-3, the EVs were charged 36 kWh more than in Case-1, resulting in approximately a 5.5% improvement in comfort violation. However, Case-2 had the best comfort rate with a 5.68% degradation. Although there was not much difference in voltage fluctuation and active power loss between the values, Case-2 caused the most loss, and this is because the EVs want to protect their comfort regardless of the grid conditions. It can be observed that there is less active power loss and voltage deviation compared to the Base Case in Case-1 and Case-3, thanks to the approximately 300 kW of V2G power due to the

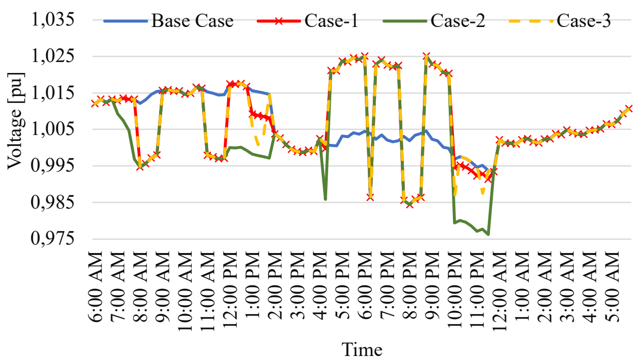

Fig. 3: Voltage variation of Bus-17 in all cases.

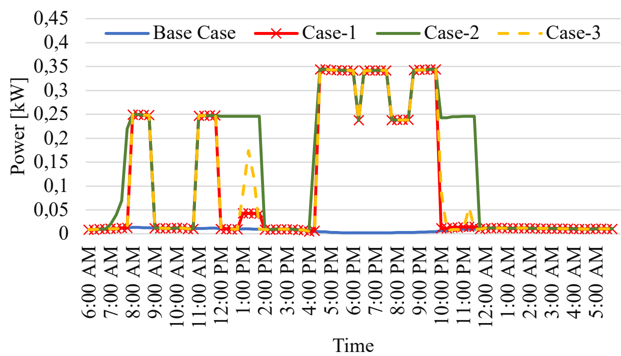

Fig. 4: Active power loss in the line between Bus-16 and Bus-17.

power contract. However, it should be emphasized that these objectives are not targeting neither power loss nor voltage drop in all cases. When comparing charging costs, it is observed that Case-2 is twice as expensive as a result of the additional charging load. This is due to Case-2 prioritizing comfort and attempting to maintain it without compromising the lower cost. When comparing Case-1 and Case-3, a difference of 120 TL is observed overall. Considering an average cost of 0.6 TL per vehicle, this rate is negligible despite a 5% improvement in comfort. Therefore, minimizing discomfort stands out as the most expensive method despite taking into account the charging levels of the vehicles.

Figure 3 provides the daily voltage profile of the Bus-17 according to the cases. As shown in the figure, all cases improved the voltage profile compared to the Base Case by selling electricity to the grid during the contract periods. Case-2, which prioritizes comfort, had a negative effect on the voltage at 1 PM and 11 PM compared to the other cases. Although Case-1 and Case-3 have almost the same voltage profile, there are occasional differences in Case-3 due to its consideration of comfort at a lower level.

The daily power losses through to the power flow in Bus-17 are compared for all cases in Figure 4. In the Base Case, where there is no EVPL in Bus-17, the losses are not significant, whereas the highest losses occur in Case-2.

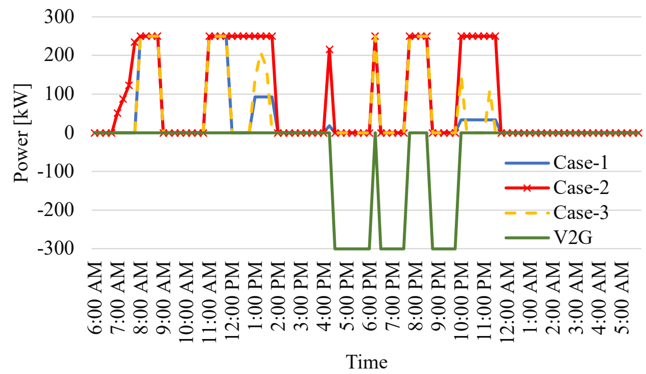

Fig. 5: Charging and discharging powers of EVs.

Particularly, additional losses occur in Case-2 during noon and midnight due to increased charging of the vehicles to minimize the discomfort.

The V2G and grid-to-vehicle (G2V) profiles of three cases are presented in Figure 5. As the contract is fixed for all cases, the V2G participation is the same for all cases. However, since Case-2 prioritizes comfort minimization, the vehicles in this case have been charged more compared to the other cases. Although Case-1 and Case-3 have similar charging profiles, the lower-level comfort minimization goal of Case-3 has led to changes in the charging rate at 1 PM and 11 PM.

To examine the impact of cases on vehicles, Figure 6 shows the V2G and G2V and energy levels of a single EV for all cases. In the Case-1, the EV immediately started charging because the electricity price was low and continued charging intermittently during the afternoon. However, due to the contract agreement in the evening, although it reached the desired energy level earlier, it lost its advantage in the evening. In this Case-2, the priority was to minimize the discomfort, so the vehicle charged itself at suitable times regardless of the electricity price. Additionally, it managed to maintain the desired energy level despite operating in V2G mode due to the contract at the end of the day. In Case-3, there was hierarchical cost and discomfort minimization, so a profile similar to Case-1 was drawn. However, the charging and discharging profile is more uniform compared to Case-1, and the energy graph fluctuates less.

IV. Conclusion

As EVs increasingly penetrate the power system, managing EV charging has grown to be an important problem. Controlled charging of EVs can lessen their negative effects on the power grid, and when necessary, EVs can inject power the grid by using their V2G feature, ensuring safe power system functioning. A crucial component of this concept is encouraging EV owners to take advantage of V2G services. Therefore, the comfort of the EV owner and the cost of the EVPL owner were taken into account when examining the optimal EV charging and discharging control in this study. Additionally, it investigated into how these objective functions affected DS

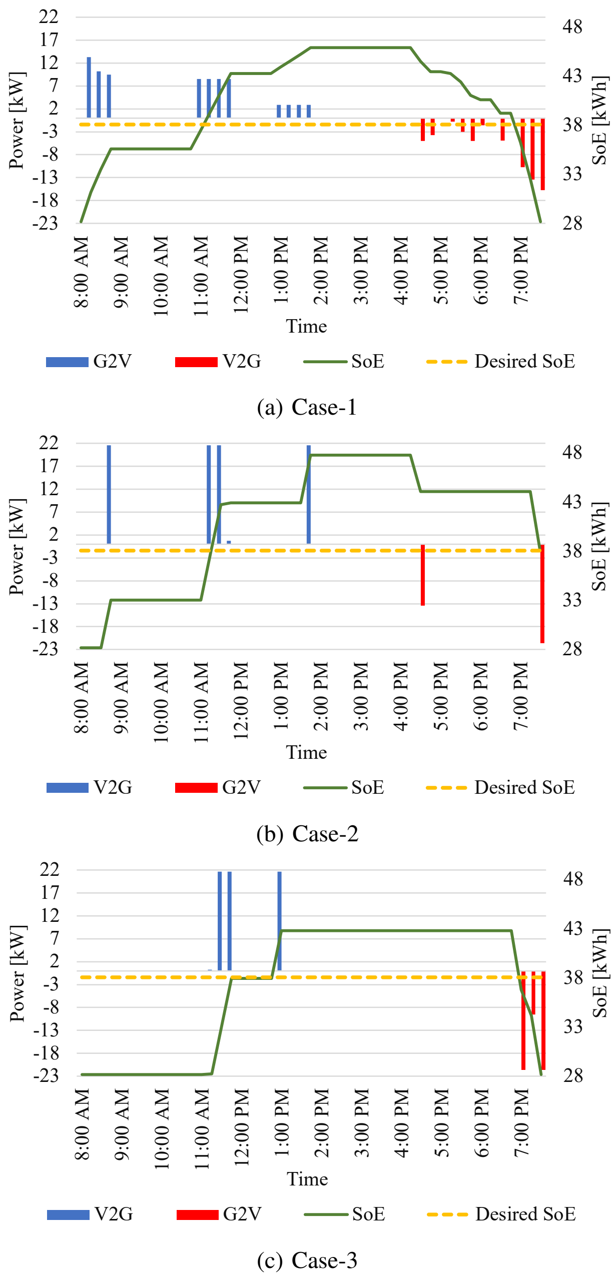

Fig. 6: SoE and power variations of an EV

factors including voltage, power loss, and line power. The findings demonstrate that comfort levels can be raised without appreciably raising costs. Additionally, active power loss and voltage deviation seem to be reduced as a result of V2G. The proposed multi-objective model and the bilevel optimization model will be compared in the upcoming study.

Acknowledgment

The work of Ozan Erdinç was supported by Turkish Academy of Sciences (TÜBA) under Distinguished Young Scientist Programme (GEBİP).

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