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Comparative Realistic Objectives Oriented Optimization Framework for EV Charging Scheduling in a Distribution System

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***Abstract*—The integration of large-scale electric vehicles (EVs) into the distribution system has emerged as a critical topic of research with the proliferation of EVs over the years. To mitigate the negative effects of EVs on the distribution system (DS), in this study, the optimal operation of an EVPL is investigated with a model in the form of mixed-integer quadratic constrained programming (MIQCP) that aims to minimize a variety of realistic objectives including active power losses, charging cost or voltage deviations while taking DS constraints into account. Also, uncertain behavior of the EVPL has been considered via machine-learning based forecasting by using historic data. The effectiveness of the proposed model has been evaluated using a 33-bus test system with 15-minute time granularity and compared to models that had various objective functions.**

***Index Terms*—Electric vehicle, mixed-integer quadratic constrained programming, optimal power flow, power losses.**

NOMENCLATURE

The abbreviations, sets and indices, parameters, and variables used throughout the study are stated below.

Abbreviations

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

Sets and Indices

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

Parameters

ΔT	Time granularity.
A, B, C	Binary for objective selection.
$CE_{i,h}^{EV}$	Charging efficiency of EV h [%].
$CR_{i,h}^{EV}$	Charging rate of EV h [kW].
$P_{i,t}^{Demand}$	Active power demand of bus i in period t [pu].
$Q_{i,t}^{Load}$	Reactive power demand of bus i in period t [pu].
$R_{i,j}$	Resistance of branch (i, j) [pu].
$S_{i,j}^{Max}$	Maximum power capacity of branch (i, j) [pu].
$SoE_{i,h}^{EV,des}$	Desired SoE of EV h [kWh].
$SoE_{i,h}^{EV,init}$	Initial SoE of EV h [kWh].
$SoE_{i,h}^{EV,max}$	Maximum SoE of EV h [kW].
$SoE_{i,h}^{EV,min}$	Minimum SoE of EV h [kW].
$T_{i,h}^{d}$	Departure time of EV h.
$T_{i,h}^{a}$	Arrival time of EV h.
V_i^{min}/V_i^{max}	Minimum and maximum voltage of bus i.
$X_{i,j}$	Reactance of branch (i, j) [pu].

Decision Variables

$f_{i,j,t}^{active,P}$	Active power flow of branch i, j in period t [pu].
$f_{i,j,t}^{reactive,Q}$	Reactive power flow of branch i, j in period t [pu].
$P_{i,h,t}^{EV,ch}$	Charging power of EV h in period t [kW].
$P_{i,j,t}^{Loss}$	Active power losses of branch i, j in period t [pu].
$P_{i,t}^{f}$	Total active power transferred from the substation bus i in period t [pu].
$P_{i,t}^{Load}$	Active power load of bus i [pu].
$Q_{i,j,t}^{Loss}$	Reactive power losses of branch i, j in period t [pu].
$Q_{i,t}^{f}$	Total reactive power transferred from the substation bus i in period t [pu].
$SoE_{i,h,t}^{EV}$	SoE of EV h in period t [kWh].
$V_{i,t}^{Bus}$	Voltage of bus i in period t [pu].

I. INTRODUCTION

A. Motivation and Background

Climate change, with increasing adverse effects, is one of the greatest challenges of our generation. Governments, companies, and non-governmental organizations are taking significant efforts to reduce CO_2 emissions, which one of the main elements of greenhouse gases and one of the primary causes of climate change, by 2050. The transportation sector accounts for 23% of energy-related global CO_2 emissions [1]. Therefore, electric vehicles (EVs) are expected to play an important role in reducing CO_2 emissions. However, the effects of increasing energy demand on power systems as a result of widespread EV use must be addressed in a sustainable manner. Uncoordinated charging of EVs can have a number of negative consequences, including supply-demand imbalance, voltage deviation, harmonic problems, overloading of power system assets, and line losses [2]. Electric vehicle parking lots (EVPLs) are a critical component of the integrated electrified transportation ecosystem, which operates on park and ride principle, allowing EV owners to continue their journey via subway, tram, ship, or bus after parking their EVs for a long or short period. On the other hand, during this parking period, the EVPL owner can participate in ancillary services to the distribution system (DS), such as peak load limitation based on the DS operator's (DSO) signals, to ensure a safe DS operation [3].

B. *Literature Review*

The integration of EVs into DS has been the subject of numerous studies in recent years. Some of these studies are examined in this section.

Gan et al. [4] investigated co-operation of planning of the power and transportation networks considering the optimal location of fast charging stations using a mixed-integer quadratic constrained programming (MIQCP) model that aims to minimize total cost, which includes travel time, line losses, efficiency losses, and charging cost. However, voltage deviation minimization was not mentioned. Zhao et al. [5] proposed a two-stage optimization model to maximize the hosting capacity of EVs in DS without jeopardizing DS constraints. In [5], voltage deviation minimization was not taken into account and quadratic terms in the power flow were resolved with piece-wise linear approximation. Jia et al. [6] developed a bilevel optimization model in which a load aggregator managing EVs and flexible loads seeks to maximize revenue through reserve and power scheduling at the upper level, while DSO at the lower level tries to maximize social welfare by taking into account power flow constraints into account. However, power losses were not considered. Xie et al. [7] proposed a bilevel optimization model in which a company that owns EV fleet and EVPL seeks to maximize its revenue through optimal pricing and charging planning at the upper level, while market clearing occurs at the lower level to minimize operation costs, which include electricity purchase and generation costs. Additionally, optimal power flow optimization was performed and solved using convex relaxation to optimize market clearing while accounting for line losses. However, loss minimization oriented optimization model was not considered. Mozaffari et al. [8] proposed a multi-objective optimization model for selecting the optimal long-term distribution system expansion strategy and the optimal EVPL siting, taking into account the EVPL owner's revenue and maintenance, operation, and line loss costs. To ensure voltage stability in DS with vehicle-to-grid (V2G), Zhong et al. [9] proposed an auction mechanism that takes DS constraints into account. However, line losses were neglected and quadratic terms in determining voltage deviation were not considered. Moradijoz et al. [10] suggested a bilevel optimization model for DS extension planning in which the upper level maximizes revenue for the DSO considering distribution loss and investment costs, and the lower level maximizes revenue for the EVPL in terms of interaction between market and charging costs while taking into account charging and discharging planning. The developed model was solved by Immune-Genetic Algorithm in [10]. Tavakoli et al. [11] analyzed a bilevel optimization model in the form of mixed-integer linear programming in which an EV aggregator and a company that owns wind farms and conventional energy production aim to maximize their revenues by participating in regulation services at the upper level and to maximize social welfare for market clearing at the lower level. However, power flow and line losses were not mentioned. Sadati et al. [12] introduced a bilevel optimization model based on Conditional Value at Risk (CVaR), in which the distribution corporation's goal was to maximize profits from EVPL and upstream grid interactions, while the EVPL owner's goal was to maximize income from EV and distribution company interactions with bidirectional power flow. Although power flow was taken into account, power loss and flow equations were considered in a linearized way and power loss was not one of the aims of this study. Lv et al. [13] devised an optimal power and traffic flow strategy using a model that minimized the cost of power generation, electricity, and travel. While second-order cone relaxation was used to account for quadratic terms, line losses and voltage deviation minimization were not considered in [13]. Mehta et al. [14] investigated the optimal charging scheduling of EVs using a multi-year cost-benefit analysis aimed at minimizing infrastructure costs, line loss costs, and EV charging costs. However, voltage deviation minimization was not considered. Wang et al. [15] investigated optimal siting and sizing of photovoltaic, battery storage, and charging stations, as well as DS expansion planning, using a model aimed at minimizing line losses, investment costs, and queue time in the shared EV concept. Although there are many valuable studies in the literature, there is no study that compares a line loss-oriented optimization model with a voltage deviation and cost minimization focused model.

C. *Contributions and Paper Organization*

In this study, the optimal charging scheduling of EVs is examined through the development of a model in the form of MIQCP that aims to provide a comparative analysis between a variety of different realistic objective functions those can be utilized by a DS operator. The followings are the main contributions of this study:

- To the best of the authors' knowledge, this is the first study in the existing literature to examine line losses minimization, voltage deviation minimization, total charging cost minimization and uncontrolled charging simultaneously in the EVPL concept.

- Quadratic terms in the determination of line losses and voltage variation are taken into account in the MIQCP form.

The remainder of the paper is organized as follows. Section II encapsulates the mathematical formulation of the proposed optimization model. Afterwards, input data and obtained results are analyzed in Section III. Finally, Section IV discusses significant conclusions and future research.

II. METHODOLOGY

Objective function of the proposed model is minimize either the total active power losses along branches, total charging cost or voltage deviation at the buses as described in (1). Thanks to (2), only one objective function is activated in every optimization period.

$$\min A * \sum_{i} \sum_{j} \sum_{t} P^{loss}_{i,j,t} + \tag{1}$$

$$B * \sum_{i} \sum_{h} \sum_{t} P^{EV,ch}_{i,h,t} * Price_t + C * \sum_{i} \sum_{j} \sum_{t} (V_{i,t} - V_{j,t})$$

$$A + B + C = 1 \tag{2}$$

The equations for the active and reactive power balance are given in (3) and (4). The sum of power transferred from the substation bus ($P^f_{i,t}$, $Q^f_{i,t}$) and power flowing through the branch ($f^{active,P}_{i,j,t}$, $f^{reactive,Q}_{i,j,t}$) equals the sum of the 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 branch. Active and reactive power losses, which vary according to the amount of power flowing through the branch, are calculated by (5) and (6).

$$P^f_{i,t} + \sum_{j \in \Omega^j_l} f^{active,P}_{i,j,t} - \sum_{j \in \Omega^i_l} f^{active,P}_{i,j,t} = P^{loss}_{i,j,t} + P^{Load}_{i,t} \tag{3}$$

$$Q^f_{i,t} + \sum_{j \in \Omega^j_l} f^{reactive,Q}_{i,j,t} - \sum_{j \in \Omega^i_l} f^{reactive,Q}_{i,j,t} = Q^{loss}_{i,j,t} + Q^{Load}_{i,t} \tag{4}$$

$$P^{loss}_{i,j,t} = R_{i,j} * \frac{(f^{active,P}_{i,j,t})^2 + (f^{reactive,Q}_{i,j,t})^2}{V_0^2} \tag{5}$$

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

Taking into account the quadratic terms, active branch power ($f^{active,P}_{i,j,t}$) and reactive branch power ($f^{reactive,Q}_{i,j,t}$) remain within the feasible space defined by (7)-(10). The voltage drop between adjacent buses determined in (11). Maximum and minimum limits of voltage magnitude is defined in (12). Equation (13) states that total load of bus i ($P^{Load}_{i,t}$) equals demand of the bus ($P^{Demand}_{i,t}$) and sum of the charging power of EVPL in the related bus.

$$-S^{max}_{i,j} \leq f^{active,P}_{i,j,t} \leq S^{max}_{i,j} \tag{7}$$

$$-S^{max}_{i,j} \leq f^{reactive,Q}_{i,j,t} \leq S^{max}_{i,j} \tag{8}$$

$$-\sqrt{2} * S^{max}_{i,j} \leq f^{active,P}_{i,j,t} + f^{reactive,Q}_{i,j,t} \leq \sqrt{2} * S^{max}_{i,j} \tag{9}$$

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

$$V^{min}_i \leq V^{bus}_{i,t} \leq V^{max}_i, \quad \forall i, t \tag{12}$$

$$P^{Load}_{i,t} = P^{demand}_{i,t} + \sum_{i} \sum_{h} \sum_{t} P^{EV,ch}_{i,h,t}, \quad \forall i, h, t \tag{13}$$

Formulations (14)-(18) includes the mathematical modelling of the EV. Thanks to the (14), charging power can not exceed the maximum charging power of the related EV. Inequality (15) guarantees that EV charging process occurs securely within a specified minimum and maximum SoE range. Equation (16) defines the relationship between the SoE variation and the charging power of the EV during the parking period. The EV reaches the desired SoE value at the departure time as expressed in (17) to prevent the comfort violation of the EV in terms of unmet energy requirement. Equation (18) shows the initial SoE value of the EV at the arrival time.

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

$$\begin{aligned} SoE^{EV,min}_{i,h} \leq SoE^{EV}_{i,h,t} \leq SoE^{EV,max}_{i,h}&, \\ \forall i, h, t \in [T^a_{i,h}, T^d_{i,h}]& \end{aligned} \tag{15}$$

$$\begin{aligned} SoE^{EV}_{i,h,t} = SoE^{EV}_{i,h,t-1} + CE^{EV}_{i,h} * P^{EV,ch}_{i,h,t} * \Delta T&, \\ \forall i, h, t \in (T^a_{i,h}, T^d_{i,h}]& \end{aligned} \tag{16}$$

$$SoE^{EV}_{i,h,t} = SoE^{des}_{i,h}, \quad \forall i, h, \ if \ t = T^d_{i,h} \tag{17}$$

$$SoE^{EV}_{i,h,t} = SoE^{init}_{i,h}, \quad \forall i, h, \ if \ t = T^a_{i,h} \tag{18}$$

III. TEST AND RESULTS

In this study, the effects of an EVPL on the DS are examined in the form of MIQCP. The proposed model mainly aims to provide a comparative analysis along different possible DS operator objectives. The devised strategy is evaluated in General Algebraic Modeling System (GAMS) environment using LINDO commercial solver, which is quite effective at solving MIQCP problems. The optimization horizon is set to 24 hours with a time granularity of 15 minutes. Finally, in all case studies, the global optimum is reached.

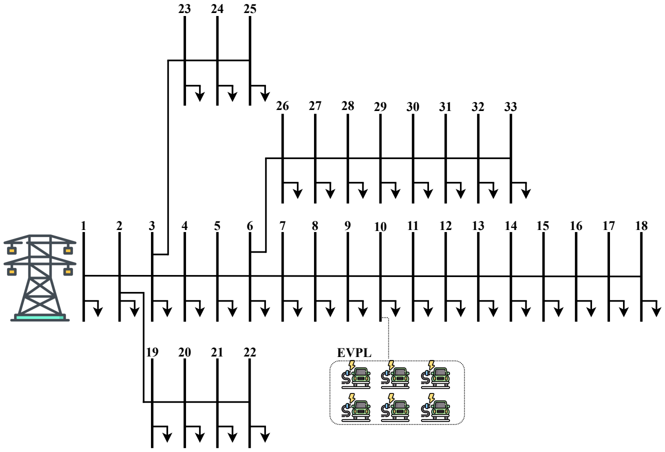

Fig. 1. Scheme of modified 33-bus distribution system.

A. Input Data

IEEE 33-bus distribution test system [16] is used to validate the optimization model, and an EVPL with sufficient parking space is located on Bus-10 as depicted in Fig. 1. Per-unit (pu) system is used for ease of calculation. The base power and voltage are configured to be 100 kVA and 12.66 kV, respectively. Total active power demand and price variation are acquired from [17] with a 15 minute time frequency and depicted in Fig. 2. Power demand is scaled and distributed across the busses according to [16].

It was forecasted that 253 EVs will arrive at EVPL during the day through a machine learning-based algorithm using real parking data as indicated in our previous research [18]. Figure 3 demonstrates the arrival and departure times of all EVs. To increase the accuracy of the tests, ten different EV types with varying specifications are used.

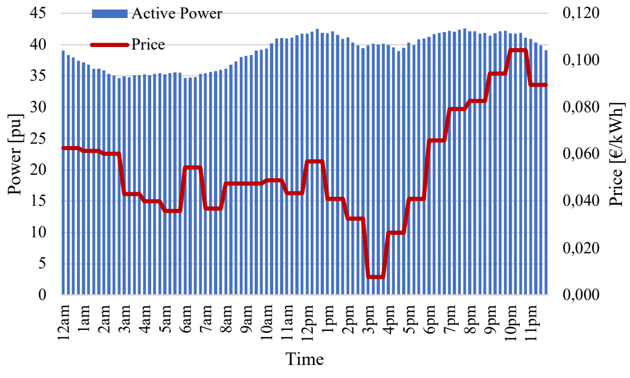

Fig. 2. Variation of total active power demand and price during the simulation.

B. Simulation and Results

Several case studies are conducted to evaluate the effectiveness of the proposed model as follows:

- *Base Case:* There is no EVPL in the distribution system.
- *Case-1:* EVs are being charged immediately as they arrive.
- *Case-2:* EV charging scheduling according to total charging cost minimization oriented model.
- *Case-3:* EV charging scheduling according to total voltage deviation minimization oriented model.
- *Case-4:* EV charging scheduling according to loss minimization oriented model.

The numerical results from the case studies are demonstrated in Table I. In comparison to the Base Case, all case studies show a significant increase in the total active power loss in the lines. It is obvious that EVs have a significant impact on line losses and voltage deviation. Case-3 results in the highest line losses and costs and the lowest load factor, despite the fact that the total voltage deviation is minimized. When the results are analyzed in terms of load factor, which is one of the indicators of the efficient utilisation of power system assets, Case-4 achieves the highest load factor. Although total charging cost is minimized in Case-2, it is seen that the negative effects of EVPL on DS increase due to increasing line losses and decreasing load factor. The cost increase is negligible in comparison to the enhancements to the DS operation.

TABLE I
COMPARISON OF THE OBTAINED RESULTS ACROSS THE CASE STUDIES

Case	Total Active Power Loss [kWh]	Total Voltage Deviation [kV]	Load Factor [%]	Total Charging Cost [Euro]
Base Case	3474.50	69.2805	91.75	-
Case-1	3886.85	75.0217	87.97	222.553
Case-2	3915.45	75.0180	82.17	188.389
Case-3	3933.45	75.0155	77.22	246.872
Case-4	3882.65	75.0222	90.74	233.462

Figure 4 illustrates the voltage variation of the Bus-10 in the optimization horizon for each case study. When electricity prices are low, the EVPL operator in Case-2 draws more power from the grid than in other case studies. As a result, the voltage profile is affected significantly. On the other hand, it is evident that minimizing voltage deviation in Case-3 results in an increase in voltage drop at certain points in order to maintain a voltage profile similar to that in Base Case. In comparison to the other cases, Case-4 produces the most stable voltage pattern.

The distribution of total active power losses in the lines among the case studies is depicted in Fig. 5. In comparison

$$V_{j,t}^{bus} = V_{i,t}^{bus} - \frac{R_{i,j} * f_{i,j,t}^{active,P} + X_{i,j} * f_{i,j,t}^{reactive,Q}}{V_0} + (R_{i,j}^2 + X_{i,j}^2) * \frac{(f_{i,j,t}^{active,P})^2 + (f_{i,j,t}^{reactive,Q})^2}{2V_0^3}, \quad \forall i,j,t \tag{11}$$

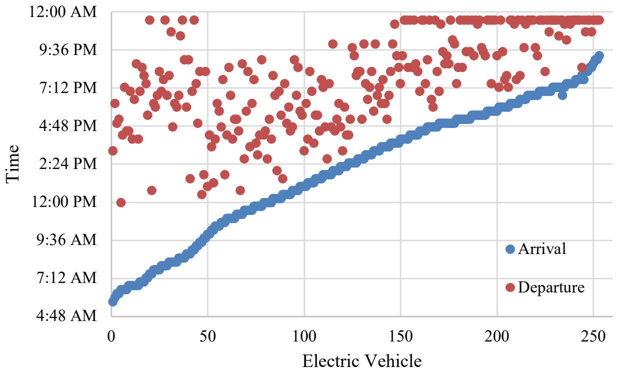

Fig. 3. Arrival and departure time of EVs

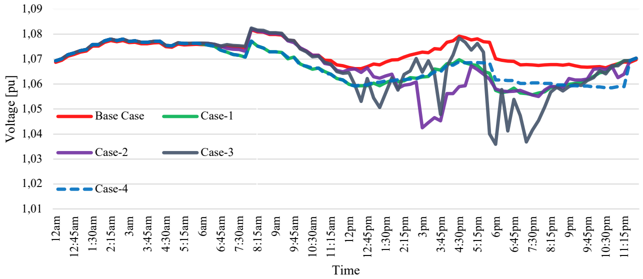

Fig. 4. Variation of the voltage of the Bus-10 with respect to time.

to the other case studies, Case-3 exhibits the highest active power loss. When electricity prices are low, losses increase significantly in Case-2. It is observed that the cost minimization oriented model has a noticeable effect on both the voltage and loss patterns. The power loss profile that is similar to the Base Case is achieved in Case-4.

Figure 6 illustrates the charging power and SoE variations of an EV parked in EVPL. Firstly, it should be mentioned that in all case studies, EV reaches the owner's desired SoE level without violating comfort. In Case-1 and Case-4, the EV begins charging immediately, whereas in Case-4, after for a while the EV continues charging more slowly to minimize power loss. In Case-2, charging process of the EV appears to be shifted to times when electricity is cheap. In Case-3, the EV's charging process is deferred until the evening hours in order to minimize voltage deviation.

IV. CONCLUSION

Optimal integration of electric vehicles into power systems has become a popular topic in academia and industry. Coordinated charging of EVs will mitigate the negative effects of EVs by taking into account factors affecting power quality such as line losses, voltage deviation, and load factor. The goal of this research was to develop a MIQCP-based loss minimization oriented EVPL management model and investigate its effects on the voltage profile and total cost. When the results are compared to those of other models, it is clear that the loss

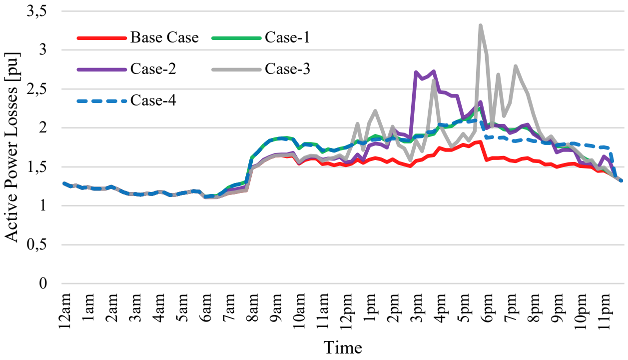

Fig. 5. Variation of the total line losses with respect to time.

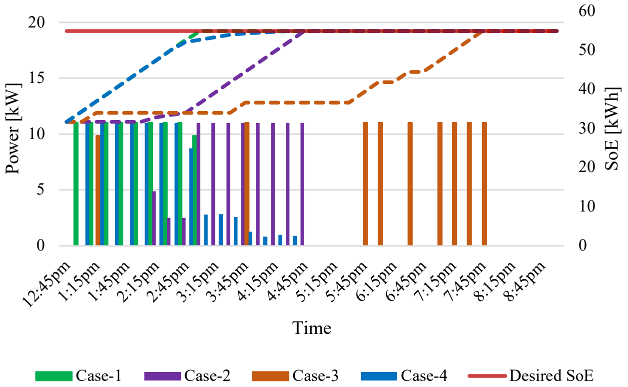

Fig. 6. SoE and power variations of a sample EV

minimization model is superior to the others. In future study, it is planned to examine the effect of renewable energy systems and multiple EVPLs.

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