Electric Vehicles Contributions to Voltage Improvement and Loss Reduction in Microgrids

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***Abstract*— This paper investigates the impact of Plug-in Electric Vehicles (PEVs) on the voltage improvement and loss reduction in MicroGrids (MG). The proposed model in this paper aims to minimize the total expected voltage deviation of the MG, while being subject to economic policies. The studied MG consists of PEVs, Renewable Energy Sources (RES), Energy Storage Systems (ESSs), and Distributed Generations (DGs), and the MG is able to participate in day-ahead energy markets. The uncertainties in arrival and departure time of PEVs, RES outputs, and day-ahead market prices are stochastically taken into account and the PEVs are modelled to be capable of charging or discharging active power and/or absorbing or injecting reactive power. A four-quadrant operation mode of a PEV is developed in this paper and incorporated in a mix-integer non-linear programming (MINLP) optimization formulation. The advantages of exploiting PEVs in an MG for enhancing voltage profile and loss reductions are then scrutinized. In order to demonstrate the effectiveness of the proposed model, various case studies are conducted on a modified 18-bust IEEE test system.**

***Index Terms*—Microgrid (MG); Plug-in Electric Vehicles (PEV); Renewable Energy Sources (RES); Energy Storage Systems (ESS); voltage improvement; loss reduction; stochastic programming.**

I. NOMENCLATURE

A. Indices

e	Index of ESS.
i	Index of DG.
k	Index of market price scenarios.
n,m	Index of buses.
pv	Index of photovoltaic (PV).
s	Index of RES scenarios.
t	Index of time.
v	Index of PEV.
wt	Index of wind turbines (WT).

B. Parameters

C^{EXP}	MG expected operation cost.
$D^{P}_{n,t}, D^{Q}_{n,t}$	Active and reactive demand of bus n at time *t*, respectively.
$S_{\upsilon}^{nominal}, S_{nm}$	Apparent power of PEV v and line connecting bus *n* and *m*, respectively.
Y_{nm}	Admittance of line connecting bus *n* to bus m.
φ_{nm}	Phase angel of line connecting bus *n* to bus *m*.
$\eta_{\upsilon} / \eta_{ess}$	PEV and ESS Efficiency factors.
γ_{υ}	Active power bid of PEV v .
σ_{υ}^{EXP}	Expected coefficient for PEV v .
$\mu_{\upsilon}, \mu''_{\upsilon}, \mu'''_{\upsilon}$	Cost function coefficients of absorbing or injecting reactive power by PEV v .
λ_{kt}^{DA}	Day-ahead (DA) market price at scenario *k* and time *t*.
π_{k}, π_{s}	Probability of scenarios k and *s*, respectively.

C. Variables

$E_{\upsilon,kst}$	Energy of PEV v in scenarios *ks* at time *t*.
$P_{\bullet,kst}, Q_{\bullet,kst}$	Active and reactive power of $\bullet$ in scenario *ks* at time *t*.
$SOC_{e,kst}$	State of Charge (SOC) for ESS e in scenario *ks* at time *t*.
$V_{n,kst}$	Voltage magnitude of bus *n* in scenarios *ks* at time *t*.
VD_{ks}	Voltage deviation of MG in scenario *ks*.
$VP_{n,kst}$	Voltage profile of bus *n* in scenario *ks* at time *t*.
VPI	Voltage improvement index of MG.
$\theta_{n,kst}$	Voltage magnitude of bus *n* in scenario *ks* at time *t*.
$\beta_{\upsilon,kst}, \alpha_{\upsilon,kst}$	Binary variable representing active and reactive power of PEV v in scenario *ks* at time *t* (1: charge / absorb; 0: discharge / inject).

Superscript max/min, C/D, and A/I within the above notions represent the maximum/minimum values, charge/discharge and absorb/inject of the corresponding symbols. Set $\bullet$ runs from 1 to $N_{\bullet}$

II. INTRODUCTION

PLUG-IN Electric Vehicles (PEVs) are widely utilized as a clean and efficient substitution of the custom vehicles, potentially leading to a significant reduction in emissions and environmental concerns [1]. Accordingly, many studies have been contributed substantially to the PEVs deployments in the grid and their characteristics modeling and analysis [1]-[10]. In general, the PEV studies can be divided into two categories: (1) Circuit topologies and control methods of PEV chargers and power electronic challenges [2]-[4], and (2) Incorporation of

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PEVs in the grid and system-wide analysis [1], [5]-[10]. The current research falls in the latter focus category. References [5]-[7] have considered the integration of PEVS for optimal system operations. A scheduling method for industrial MicroGrids (MG) with PEV involvement is presented in [5], however, their charging capability is ignored. In [6], an optimal management model for an active distribution system is presented, where PEVs deployment is considered and they can be charged or discharged. Furthermore, the authors investigated the impact of the State-Of-Charge (SOC) on optimal active management of the system. It is stated in [7] that the presence of PEVs result in a significant uncertainty in the grid, therefore, the Normal and Weibull probability distribution functions are utilized to capture such uncertainties. The ability of Plug-In-Hybrid-Electric-Vehicles for reactive power compensation based on the power electronic mechanisms is scrutinized in [8]. A model for integration of PEVs in the energy and reactive power markets is investigated in [9], however, the inherent uncertainty in PEVs and DGs is ignored. In [1], an architecture for active and reactive power management of electric vehicles is presented contemplated in a smart grid environment. An innovative approach for smart operation of electric vehicle chargers in a distribution system is presented in [10].

Intermittent Renewable Energy Sources (RESs), as an integral parts of the MGs, brings a significant source of uncertainty in the optimal operation of MGs as well. Furthermore, MGs can transact in energy markets via bidding strategies where another source of uncertainty in electricity market prices is introduced to the MG operators (MGO) [11]-[13]. In [11], a new framework is presented that formulates the optimized power scheduling and bidding of an MG. Moreover, uncertainty in Wind Turbine (WT) units and Photovoltaic (PV) units are considered. A bidding strategy for an MG is presented in [12], where uncertainty of WT and PV units and market prices are contemplated. Further, the risk in MG bidding in real-time power markets is assessed. Reference [13] investigates the bidding strategy from an electric vehicle aggregator point of view for their participation in the day-ahead energy market, where stochastic and robust programming are utilized to capture the uncertainties in the energy market and driving requirements, respectively. Neither of [11]-[13] considered the AC configuration of the system, while this paper models the MG in an AC setting. Besides, although the main objective of the aforementioned papers aims to cope with the economic issues, this current article aims to improve technical concerns of MG operations subjected to a pre-specified economic range.

This article presents an optimization model for minimizing the total expected voltage deviation of an MG subjected to an allowable range of operational cost. In the studied MG, Distributed Generations (DG), Energy storage Systems (ESSs), WT and PV units are considered. Moreover, MG can transact in day-ahead energy markets via bidding. The PEVs are modeled in such a way that they can charge (or discharge) active power and/or absorb (or inject) reactive power. The uncertainties associated with the RESs, day-ahead market prices, and in arrival and departure time of PEVs are well captured by stochastic programming, with the main interest in investigating the impact of PEVs on voltage improvement and loss reduction in an MG. Discussions are presented on the trade-offs between the permissible operational cost level and the voltage improvement in the MG.

The rest of the paper is organized as follows. PEVs modelling and corresponding formulations are introduced in Section III. The proposed stochastic optimization formulation is presented in Section IV. Numerical case studies are conducted and discussed in Section V. And finally comes the conclusions in Section VI.

III. PEV MODELLING

This section presents the suggested model of the PEVs. The following assumptions are made: (1) PEVs are owned by individual owners and MGO must pay a cost for using them; (2) PEVs must be charged to their expected SOC, when they are leaving the parking lots; (3) Normal probability distribution is deployed to account for their uncertainty in arrival and departure time [6]; (4) PEVs can be charged (discharged) or/and absorbed (injected) reactive power by the MGO subject to some technical constraints, as follows:

$$\begin{aligned} &0 \le P^{C}_{\upsilon,kst} \le \beta_{\upsilon,kst} P^{C,max}_{\upsilon} \\ &0 \le P^{D}_{\upsilon,kst} \le (1-\beta_{\upsilon,kst}) P^{D,max}_{\upsilon} \\ &P_{\upsilon,kst} = P^{C}_{\upsilon,kst} + P^{D}_{\upsilon,kst} \end{aligned} \tag{1}$$

$$\begin{aligned} &0 \le Q^{A}_{\upsilon,kst} \le \alpha_{\upsilon,kst} Q^{A,max}_{\upsilon} \\ &0 \le Q^{I}_{\upsilon,kst} \le (1-\alpha_{\upsilon,kst}) \mathrm{Q}^{I,max}_{\upsilon} \\ &Q_{\upsilon,kst} = Q^{A}_{\upsilon,kst} - Q^{I}_{\upsilon,kst} \end{aligned} \tag{2}$$

$$\left(P_{\upsilon,kst}\right)^2 + \left(Q_{\upsilon,kst}\right)^2 \le \left(S^{nominal}_{\upsilon}\right)^2 \tag{3}$$

$$E_{\upsilon,kst} = E_{\upsilon,ks,t-1} + \eta^{C}_{\upsilon} P^{C}_{\upsilon,kst} \Delta t - \frac{1}{\eta^{D}_{\upsilon}} P^{D}_{\upsilon,kst} \Delta t \tag{4}$$

$$E^{min}_{\upsilon} \le E_{\upsilon,kst} \le E^{max}_{\upsilon}$$

(5)

$$E_{\upsilon,kst} = \sigma^{EXP}_{\upsilon} E^{max}_{\upsilon} \qquad \forall t = t^{departure}_{\upsilon} \tag{6}$$

PEVs' active power charge and discharge rates are restricted by (1). PEVs' reactive power absorb and inject rates are limited by (2). PEVs' active and reactive power are subject to the equality constraint in (3). The energy balance of PEVs storages are presented in (4). PEVs' storage capacity restriction is given in (5). Finally, according to the second assumption, PEVs must be charged to their expected SOC, which is satisfied in (6). Fig. 1 demonstrates the four-quadrant operation modes of PEVs. Take the first quadrant as an example, A PEV can be charged or/and injected active and reactive power simultaneously. However, concurrent charging and discharging of the active power or injecting and absorbing the reactive power is not feasible. Also, as Fig. 1 shows, active and reactive power of PEVs are restricted by curves highlighted in red dashed lines. Note that the MGO makes a revenue by charging PEVs. Nevertheless, MGO must pay the PEV owners for discharging PEVs and also for using their capacity in absorbing/injecting reactive power.

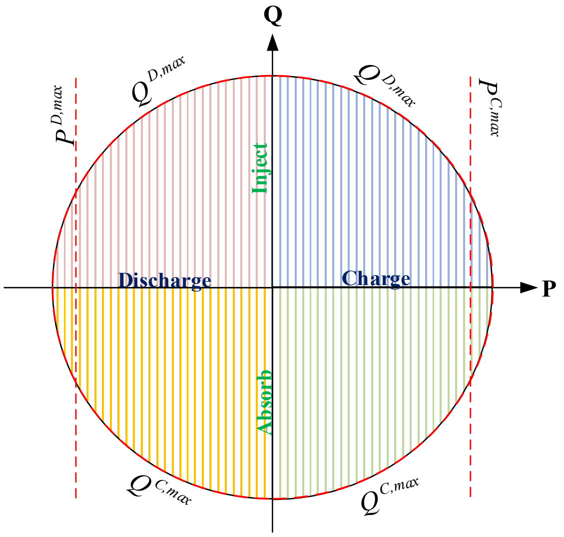

Fig. 1. Four-quadrant operation modes of PEVs

IV. PROBLEM FORMULATION

A meticulous evaluation of MG assets helps MGO meet the basic energy requirements during a specific interval within an acceptable economic range. Moreover, it is substantial to maintain the system technical and security constraints. Although PEVs have individual owners and are not physically considered as MG assets, MGO is allowed to utilize them when connected to the MG. This usage can enhance the MGO's flexibility for keeping the MG operation in an economic and secure range. In the proposed model, the MG total expected voltage deviation should be minimized in such a way that the total expected cost of the MG remains in the pre-specific secure region, hence, the MGO can take the advantages of PEVs.

A. Objective Function

The objective function of the proposed optimization problem is to minimize the total expected deviation of the MG bus voltages from the nominal value, as represented in (7), where VD_{ks} is defined in (8).

$$Obj = min \sum_{k=1}^{N_k} \pi_k \left(\sum_{s=1}^{Ns} \pi_s VD_{ks} \right) \tag{7}$$

$$VD_{ks} = \sum_{t=1}^{N_t} \sum_{n=1}^{N_n} \left| V_{n,kst} - 1 \right| \tag{8}$$

B. Optimization Constraints

As stated, the objective function must be minimized in such a way that the total expected cost of the MG lies in a pre-specified desirable level. In addition, the technical constraints of the individual units as well as those related to the MG network should be satisfied. The total expected operational cost of an MG is presented in (9), where C_k^{DA} stands for cost/revenue of transacting in day-ahead (DA) electricity markets (10), C_{ks}^{DG} denotes the cost of using DGs [5], C_{ks}^{ESS} indicates the degradation cost of utilizing ESS [12], and C_{ks}^{PEV} represents the cost/revenue of using PEVs (11). Constraint (12) represents that the total expected cost of MG must be lower than the pre-specified value. The positive (negative) values of C_k^{DA} and C_{ks}^{PEV} denote cost (revenue). Moreover, no cost is considered for using wind and PV units.

$$Cost^{MG} = \sum_{k=1}^{N_k} \pi_k \left(C_k^{DA} + \sum_{s=1}^{Ns} \pi_s \begin{pmatrix} C_{ks}^{DG} \\ +C_{ks}^{ESS} \\ +C_{ks}^{PEV} \end{pmatrix} \right) \tag{9}$$

$$C_k^{DA} = \sum_{t=1}^{N_t} \lambda_{kt}^{DA} \; P_{kt}^{DA} \tag{10}$$

$$\begin{aligned} C_{ks}^{PEV} = & \sum_{t=1}^{N_t} \sum_{\upsilon=1}^{N_\upsilon} \left[\gamma_\upsilon^D P_{\upsilon,kst}^D - \gamma_\upsilon^C P_{\upsilon,kst}^C \right] + \\ & \sum_{t=1}^{N_t} \sum_{\upsilon=1}^{N_\upsilon} \left[\mu_\upsilon \left| Q \right|_{\upsilon,kst}^2 + \mu_\upsilon'' \left| Q \right|_{\upsilon,kst} + \mu_\upsilon''' \right] \end{aligned} \tag{11}$$

$$Cost^{MG} \le C^{EXP} \tag{12}$$

Active and reactive power of DGs are limited by (13). Charging and discharging rates of ESSs are restricted in (14). The energy balance of ESSs and their storage capacity are satisfied by (15) [14]. Ramp up/down, minimum up/down time, and start-up and shut-down costs of DGs are also considered and can be found in [15]. The wind and PV models are taken from [11].

$$\begin{aligned} & P_i^{min} \le P_{i,kst} \le P_i^{max} \\ & Q_i^{min} \le Q_{i,kst} \le Q_i^{max} \end{aligned} \tag{13}$$

$$\begin{aligned} & 0 \le P_{e,kst}^C \le P_e^{C,max} \\ & 0 \le P_{e,kst}^D \le P_e^{D,max} \end{aligned} \tag{14}$$

$$\begin{aligned} & SOC_{e,kst} = SOC_{e,ks,t-1} + \eta_e^C P_{e,kst}^C \Delta t - \frac{1}{\eta_e^D} P_{e,kst}^D \Delta t \\ & SOC_e^{min} \le SOC_{e,kst} \le SOC_e^{max} \end{aligned} \tag{15}$$

Finally, as the AC configuration of the MG is taken into account through the AC power flow constraints in (16)-(18).

$$\begin{aligned} & \sum_{i=1}^{N_i} P_{n,i,kst} + P_{n,wt,kst} + P_{n,pv,kst} + P_{n,kt}^{DA} + \sum_{\upsilon=1}^{N_\upsilon} P_{\upsilon,kst} \\ & + \sum_{e=1}^{N_e} (P_{n,e,kst}^D - P_{n,e,kst}^C) - D_{n,t}^P \\ & = \sum_{m=1}^{N_m} V_{n,kst} V_{m,kst} Y_{nm} . cos \left(\theta_{n,kst} - \theta_{m,kst} - \varphi_{nm} \right) \end{aligned} \tag{16}$$

$$\begin{aligned} & \sum_{i=1}^{N_i} Q_{n,i,kst} + \sum_{\upsilon=1}^{N_\upsilon} Q_{n,\upsilon,kst} - D_{n,t}^Q \\ & = \sum_{m=1}^{N_m} V_{n,kst} V_{m,kst} Y_{nm} . sin \left(\theta_{n,kst} - \theta_{m,kst} - \varphi_{nm} \right) \end{aligned} \tag{17}$$

$$\begin{aligned} & P_{nm,kst}^2 + Q_{nm,kst}^2 \le \left(S_{nm}^{max} \right)^2 \\ & V_n^{min} \le V_{n,kst} \le V_n^{max} \end{aligned} \tag{18}$$

Thus far the objective function in addition to the optimization constraints have been elucidated. In what follows, a voltage improvement index is suggested to evaluate the MG voltage profile enhancement in presence of PEVs.

C. *Voltage Improvement Index*

As stated earlier, MGO can take the advantage of PEVs for boosting the MG voltage profile. PEVs are analogous to DGs and they can provide a fraction of the active and reactive power in the system locally, leading to a reduction in the MG network line flows and, as a result, MG power losses and MG voltage magnitude will be improved [16]. In order to assess the voltage improvement, the proposed index in [16] is deployed. The voltage profile for bus n is presented in (19), where V^{nom} is the nominal voltage magnitude of the system and it is usually taken as 1.0 p.u.

$$VP_{n,kst} = \frac{\left(V_{n,kst} - V^{min}\right)\left(V^{max} - V_{n,kst}\right)}{\left(V^{nom} - V^{min}\right)\left(V^{max} - V^{nom}\right)} \tag{19}$$

The overall voltage profile index for the considered MG is defined in (20).

$$VP = \frac{1}{N_n}\left(\sum_{k=1}^{N_k}\sum_{s=1}^{N_s}\pi_k \pi_s \sum_{t=1}^{N_t}\sum_{n=1}^{N_n} VP_{n,kst}\right) \tag{20}$$

Finally, the voltage improvement index for the MG voltage profile is presented in (21), which elaborates the proportion of *VP* of the MG with PEVs to *VP* of the MG without PEVs.

$$VPI = \frac{VP^{PEVs}}{VP^{Without\ PEVs}} \tag{21}$$

V. NUMERICAL RESULTS AND DISCUSSIONS

In simulating various scenarios accounting for the involved uncertainties, the Latin Hypercube Sampling (LHS) method [17] is employed to generate a set of scenarios and a scenario reduction by Kantorovich distance approach [18] is then applied. A modified IEEE 18-bus test system is considered as the microgrid test system [19]. The suggested Mix-Integer Non-Linear Programming (MINLP) optimization problem is solved in the GAMS environment. In order to evaluate the effect of PEVs on the voltage improvement and loss reduction in the studied MG, four distinct cases are considered as follows. In Case1, it is assumed that PEVs can charge/discharge and absorb/inject active and reactive power, simultaneously. Case2 is where PEVs can only provide reactive power. Case3 tests the conditions where PEVs can only charge/discharge active power. Finally, Case4 ignores the role of PEVs in the MG.

A. *Voltage Improvement*

Providing reactive power by PEVs and the connection to various buses helps supply reactive loads locally which in turn reduces the need for transferring reactive power in order to supply the reactive load. As a result, the line losses would be declined and the voltage profile would improve. In order to evaluate the impact of PEVs on the optimal operation of the MG, Fig. 2 depicts the voltage profiles corresponding to the four cases on 18 buses in one selected hour and scenario. Fig. 3 illustrates the voltage profiles of the four cases for 24-hour time period and one selected bus and scenario. As one can see, in the 1st and 2nd cases that PEVs are able to absorb/inject reactive power, the voltage profile is smoother than that in other cases as the reactive power is supplied locally by PEVs. In the 3rd case, since a fraction of active power is provided by PEVs, the voltage profile is improved compared to that in case 4; however, it does not affect the voltage profile as much as that observed in the first two cases. Table 1 demonstrates the value of the voltage profile improvement index (VPII) in different case studies. Observe that, by using PEV as an active and reactive power source, the voltage profile flourishes in comparison with the case that no PEV exists. However, the improvement in the voltage profile is not significant due to the PEVs' capacity. Indeed, the small capacity of PEVs in providing active and reactive power leads to a slight enhancement in voltage profile. Consequently, using larger PEV parking lots can result in a better and smoother voltage profile.

B. *Loss Reduction*

In this part, the active and reactive power losses in different cases are assessed. Table II delineates the active/reactive power losses for different considered cases. According to Table II, the active and reactive power losses in Case1 decline about 32.1% and 32.86%, respectively in comparison to Case4, where no PEV is contemplated. The reduction in active and reactive power losses in Case2 in comparison with those in Case4 is

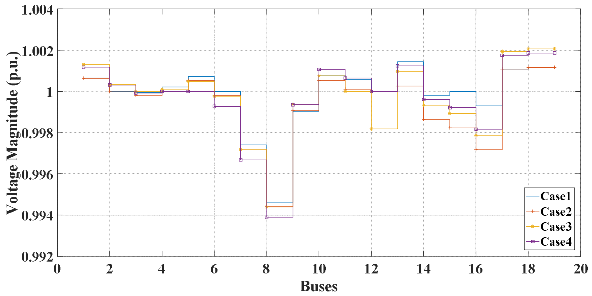

Fig. 2. Voltage profile for 18 buses in one selected hour.

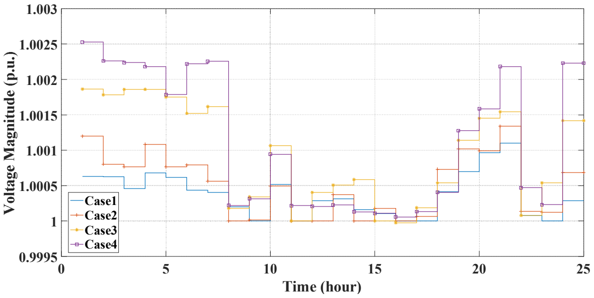

Fig. 3. Voltage profile for one selected bus in a 24-hour time interval.

TABLE I

VOLTAGE PROFILE IMPROVEMENT INDEX (VPII)

Cases	VPII
VP^{Case1}/VP^{Case2}	1.0007
VP^{Case1}/VP^{Case3}	1.0035
VP^{Case1}/VP^{Case4}	1.0050

TABLE II
ACTIVE/REACTIVE POWER LOSSES FOR DIFFERENT CASES

Cases	Active Power Loss (kW)	Reactive Power Loss (kVAr)
Case1	726	2897
Case2	737	2842
Case3	1003	4615
Case4	1069	4315

TABLE III
SENSITIVITY ANALYSIS: OPERATIONAL COST VS. VOLTAGE PROFILE

Permissible Cost Level ($)	Voltage Deviation (p.u.)
20000	0.4694
21000	0.4122
22000	0.3821
23000	0.3566
24000	0.3372

around 31% and 34%, respectively. Observe that the reduction in reactive power loss in Case2 is higher than that in Case1. The reason lies in the fact that the entire PEV capacities are allocated to reactive power and as they can provide it locally, the overall reactive power losses of the MG dwindles more than that in Case1, where the capacity of PEVs is assigned to both active and reactive power. In Case3, where the PEVs can merely charge/discharge active power, the reduction in active and reactive power losses is not significant in comparison with that in the other studied scenarios. In essence, there is only around 6.2% and 7% reduction in power losses in comparison with Case4. We hence observed that the capability of PEVs in absorbing/injecting reactive power can diminish the active and reactive power losses in the MG.

C. Cost and Voltage Improvement Trade-offs

The objective of the suggested formulations is essayed to manage the MG voltage profile subject to an acceptable operational cost. Indeed, the technical issue is the first priority for the MGO and the economic concerns will follow. If the MGO is willing to adhere to additional costs of operation, the objective solution will be closer to its ideal value, as the optimization constraints become more flexible and relaxed. In order to demonstrate the impact of different permissible cost levels on the objective solution, Table III demonstrates a sensitivity analysis on the operational costs and the voltage deviations. According to Table III, as the desirable operational cost level goes up, the voltage deviation decreases, since the voltages become closer to their nominal values. For instance, when the allowable cost level jumps from 20,000$ to 24,000$, the voltage deviation decreases by about 39%.

D. Further Discussions

In this paper, PEV's arrival and departures are represented by a normal probability distribution. While the approach is generic enough to accommodate any other variation of the normal distribution (such as a wider-tailed family of distributions with greater robustness as an alternative to the normal distributions [20]) as well as other non-Gaussian family of distributions (e.g., Weibull, etc.) [21]-[23], this assumption is supported by multiple reasons: it is easy to work with mathematically and computationally; in many practical cases, the methods developed using such theory works quite well even when the distribution is not normal. According to Central Limit Theorem (CLT), with the increase in the sample size (sufficiently large), the distribution of the random variables approaches the normal distribution irrespective of the shape of the original distribution [24], [25]. Future research will focus on the physical correlation of the PEV parameters (e.g., arrival and departures) and different probability distributions. Future research will be foucsed on the impact and contributions of elctric vehicles, as an effective grid support mechanism, on power sytsem resilience [26]-[28]. We will also consider studying the performance of the suggested methodologies on larger test systems and linked to new AMI-enabled performance analytics in power distributyion grids [29].

VI. CONCLUSIONS

The main interest of this paper is on voltage improvement and power loss reduction of an MG in presence of PEVs, while its operational cost is remained within an acceptable range. A model of PEVs was deployed that can charge (or discharge) active power and/or absorb (or inject) reactive power. A stochastic optimization approach was pursued to account for differnet sources of uncertaitnies in an MG. Four distinct case studies were considered and applied to a modified IEEE 18-bus test system. Firstly, the impact of PEVs on the voltage enhancement was scrutinized and it was illustrated that PEVs can have positive effect on the voltage profile. Next, the power loss reduction was evaluated in different scenarios and it was demonstrated that PEVs with the ability to charge/discharge (absorb/inject) active (reactive) power can lead to a significant decrease in active and reactive power losses. Eventually, a sensitivity analysis was conducted to evaluate the impact of permissible MG operational cost levels on the voltage improvement. It was delineated that as the allowable cost range increases, the voltage deviation will be decreased.

Future research efforts can focus on development of a multi-objective optimization framework for MG optimal operation, where the total expected cost, voltage improvement, and emission reductions are simultaneously optimized as the main objectives.

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