Enhancement in Grid Performance Using Coordinated V2G Approach with Residential EV Charging Demand

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***Abstract*—The recent advancement in the battery technologies is promoting the adoption of electric vehicles (EVs) worldwide. The large-scale penetration of EVs will impose significant EV charging demand on the residential area of the distribution network. This significant EV charging demand at home may coincide with the peak demand of the distribution system, resulting in enhanced system's peak demand. Which may create a bottleneck in supplying capacity and necessitates time consuming grid upgradation. This paper aims to reduce the peak demand of distribution systems using charging/discharging scheduling of the EVs in the residential area. The strategy proposes a home energy management system which coordinates EVs for G2V and V2G modes both at residential parking zone (RPZ). More realistic scenarios are generated by using a normal distribution for EV arrival times, initial state of charge (SOC) levels, and battery capacities. The results are compared with the uncoordinated charging which includes the V2G mode only and signify that the proposed strategy is able to reduce peak demand, reduce electricity costs, improve node voltage profiles, decrease power losses, and provide financial benefits to EV owners.**

***Index Terms*—Electric vehicles, residential parking zones, dynamic electricity pricing, G2V, V2G, EV energy management system.**

NOMENCLATURE

i/*h*/*z*	Index for EVs/ time (hour)/RPZ
m, n, r	Index for buses
$\alpha(h)$	Dynamic electricity pricing at hth hour ($/kWh)
$\beta(z)$	Financial benefit for zth RPZ using proposed EVMS (V2G+G2V) ($)
$BI(mr, n)$	Current flow between the mth and rth buses in the branch throughout the nth state of the system
$BI^{max}(mr, n)$	Maximum current flow through the branch between mth and rth bus during the nth system state
$C_b(i, z)$	Battery capacity of ith EV charging at zth RPZ (kWh)
C_c/C_d	G2V/V2G Charger rating (kW)
Δt	Time-interval between two consecutive hours (min)
$\delta(m, n)$	Power angle at the mth bus under the nth state of the system (°)
$\delta(r, n)$	Power angle at the rth bus under the nth state of the system (°)
$E_{EV}(i, z)$	Energy consumed of ith EV charging at zth RPZ (kWh)
$E_{cg}(i, z)$	Energy consumed by ith EV at zth RPZ (kWh) in G2V mode only (kWh)
$E^{'}_{cg}(i, z)$	Energy consumed by ith EV at zth RPZ in proposed EVMS (V2G+G2V) (kWh)
η_c	Charging efficiency of EVs batteries
$E_{dg}(i, z)$	Energy supplied by ith EV at zth RPZ in V2G mode (kWh)
$E(i, z)$	Net energy transaction between ith EV and zth RPZ (kWh)
$\mho_u$	Number of states in one day set
N	System state
N_B	Total no. of buses in the distribution system
N_{EV}	Total no. of EVs in the RPZ
N_z	Total RPZ in the residential area
$P_{EV}(i, z)$	Power demand of ith EV charging at zth RPZ (kW)
$P_D(m, n)$	Nominal demand, active power, at the mth bus in the nth state of the system (MW)
$P_G(m, n)$	Generation of active power at the mth bus in the nth state of the system (MW)

$Q_D(m,n)$	Nominal demand, reactive power, at the mth bus in the nth state of the system (MVAR)
$Q_G(m,n)$	Generation of reactive power at the mth bus in the nth state of the system (MVAR)
$soc_i(i,z)$	Initial SoC level of ith EV charging at zth RPZ
$soc_f(i,z)$	Final SoC level of ith EV charging at zth RPZ
$soc_{req}(i,z)$	Required SoC level to charge the ith EV charging at zth RPZ
soc_L/soc_U	Lower/upper bounds of SoC levels of EVs batteries
$S_{EVMS}(i,z)$	Switching mode of EVMS for ith EV at zth RPZ
$soc_{dis}(i,z)$	Discharging SoC level of ith EV at zth RPZ
soc^{Δ}_{min}	Minimum threshold SoC level of EVs batteries
$T_{cg}(i,z)$	Charging time of ith EV at zth RPZ (min)
$T_{dg}(i,z)$	Discharging time of ith EV at zth RPZ (min)
$T(i,z)$	Total time taken by ith EV at zth RPZ (min)
$\vartheta/K_1/K_2$	Non-zero real positive integers
$V(m,n)$	Voltage magnitude at mth bus under the nth state of the system
$V(r,n)$	Voltage magnitude at rth bus under the nth state of the system
$\Upsilon^z_{G2V,pur}$	Total energy purchasing cost at zth RPZ in G2V mode (\$)
$\Upsilon^z_{(EVMS,pur)}$	Total energy purchasing cost at zth RPZ in proposed EVMS (V2G+G2V) mode (\$)
$\Upsilon^z_{(EVMS,sell)}$	Total energy selling cost at zth RPZ in proposed EVMS (V2G+G2V) mode (\$)
$y(mr)$	Admittance of the linked line between mth and rth bus (℧)

I. INTRODUCTION

A. Motivation

In the present scenario, electric vehicles are gaining attention due to various environmental, social, and economic concerns. This significant increase in EV adoption may leads to adverse impact on the grid's performance [1]. The intermittent behaviour of the temporal and regional load of EV charging will cause a major shift in the energy demand profile. EVs charging will take place either at commercial parking lots, fast charging stations, or in residential areas [2]. According to recent studies, between 50 and 80% of EV charging events will take place at home, while 15 to 25% of EV owners will charge their vehicles at commercial parking lots [3]. Less than 10% of the rest EVs will use public charging stations for quick charging because they are going on long trips or have an emergency [4]. Therefore, residential EV charging can plays a significant role to impact the distribution system's demand profile. This necessitates the need of system upgradation. This requires significant works and financial commitments [5]. Smart EV charging is an appealing substitute that offers coordinated charging and discharging controls to help EVs handle the irregular charging profile of EV charging, since 90% of the time EVs are in the idle or parked state [6]. Hence, the investigations of impact of residential EV charging and its demand management is essential with upcoming inrush of EVs in the market.

B. Literature review

In literature a lot of worked has been done investigate and control EV charging demand while reducing the negative effects on the distribution system using various optimization strategies in refs. [7], [8]. Ref. [9] EV charging demand model is developed considering stochastic behaviour of EV charging and suggested that 45% extra EVs can be accommodated using the intelligent charging of EVs. Ref. [11] introduces smart charging strategies to reduce technical impacts on the distribution system. Ref. [12] introduces the EV aggregator based approach in which a decentralized iterative algorithm is introduced to manage EV charging/discharging schedule aiming to meet the daily mobility energy requirement of an EV fleet with respect to the day-ahead schedule of the EV aggregator. Refs. [13] optimizes the schedule patterns for EV charging and discharging in both global and local contexts, with the aim of reducing overall charging costs, particularly in the presence of a large EV population. Ref. [14] incorporated the concept of vehicle-to-grid (V2G) and vehicle-to-home (V2H) to reduce system peak demand. Several earlier research focus on V2G, with EV charging management solutions in parking facilities being the specific focus. It has been proposed to use an autonomous EV parking coordination framework to utilize EV batteries for various V2G applications in [15]. Ref. [16] investigates that EV charging demand leads to the increment in load peak-to-valley difference, particularly in the residential areas. The authors introduce a collaborative scheduling model for photovoltaic output and V2G electric car charging and discharging based framing residential communities. Which results in reduced peak demand and electricity costs. The large scale integration of renewable energy resources can play a significant role in balancing the energy demand at the smart grids, however, it needs a capital investment. Therefore, Ref. [17] suggested a simplified RTP-based coordinated approach to defer the higher investment in integration of DERs that results in reduction of the impact of EV charging on system losses, voltage deviations as well as in the total charging cost of EV users. However, it did not investigate the impact V2G at home.

This paper aims to investigate the scheduling of electric vehicles (EVs) parked in residential parking zones, assuming all vehicles are available at home in the evening when their owners return from work until the beginning of their next trip in the morning. The optimal scheduling of electric vehicles (EVs) is conducted through a EV energy management system (EVMS) which provides coordinated control of the charging/ discharging of EVs under the dynamic pricing environment parked in the residential parking zones. The impact of proposed EVMS also investigated over the G2V mode only. The simulations have been carried out on the 33-test bench distribution system. The salient contributions of this work are as

- The proposed EVMS not only eliminate the severe EV charging demand during the peak hours of distribution system but also reduces its own peak demand using V2G technology.
- The proposed methodology improves EV owners' financial benefits significantly.
- The methodology does not use any optimization techniques; instead, it uses a simplified analytical approach.

The proposed EVMS methodology is presented in section II. The simulation results are presented in section III, Finally, the conclusions and future scope of the research work are summarized in section IV

II. PROPOSED METHODOLOGY

The large-scale integration of EVs will create a huge amount of peak power demand at the distribution system. The concept of smart distribution with the advancement in integration of renewables, energy storage systems, smart metering and various dynamic pricing signal invite new dimension to manage this severe EV charging demand during the overloading period at the system. In this context, the emerging EV home charging demand cannot be matched by renewables, say solar PVs, as it occurs during evening or night hours. Whereas, the use of energy storage devices increases the cost of the charging. EV charging demand is observed in the night hours, which are already peak demand hours, whereas EVs users have a natural tendency to charge their vehicle as they arrive home. This work suggested EVMS model which discharges EVs in V2G mode as they arrive at the residential parking zones (RPZs) till the specified SoC limits and after attaining that limit EVs trigger to charge till the required SoC level. The EV owners have a definite diversity in residential EV home charging owing to its usual arrival behavior. So proposed methodology also avoids the rebound effect of the EV charging demand at the system.

A. *EV charging model in G2V mode*

Let N_R residential nodes are connected in the distribution system. The residential area is assumed to be considered Nz RPZs with having N_{EV} vehicles at each. All the EVs are assumed to be arrive at RPZ during the arrival period followed by the normal distribution. The SoC initial/final levels, battery capacities are normally distributed over a specified ranges respectively. Considering that the EV starts to charge as it arrives at the RPZ, the EV energy charging demand is derived using (1)-(8). The charging time/ energy consumed by ith EV at zth RPZ are formulated using (1) and (2) as

$$\begin{aligned} &T_{cg}(i,z) = soc_{req}(i,z) C_b(i,z) \Delta t / C_c(h) \times \eta_c; \\ &\forall\, i \in N_{EV}; \forall\, z \in N_Z \end{aligned} \tag{1}$$

$$\begin{aligned} &E_C(i,z) = (soc_{req}(i,z) \times C_b(i,z) / \eta_c; \\ &\forall\, i \in N_{EV}; \forall\, z \in N_Z \end{aligned} \tag{2}$$

Where, $soc_{req}(i,z)$ is the required SoC level of ith EV at zth RPZ, where $C_b(i,z)$ is the capacity of battery of the ith EV at zth RPZ are expressed as

$$soc_{req}(i,z) = soc_f(i,z) - soc_i\,(i,z) \tag{3}$$

$$C_b(i,z) = \vartheta \times randan\,[K_1, K_2] \tag{4}$$

The EV charging model has the following constraints

1) SoC constraint: SoC level should be balanced within the SoC lower and upper bounds to prevent adverse effect impact on the health of batteries.

$$soc_i(i,z) \geq soc_L \tag{5}$$

$$soc_f(i,z) \leq soc_U \tag{6}$$

2) All the EV should be charged over the night expressed as

$$\sum_{i=1}^{N_{EV}} E_{EV}(i,z) = 0.85\, E_{EV}^{\max} \tag{7}$$

Finally, the hourly aggregated EV charging demand is formulated as

$$P_{EV}(h) = \sum_{z=1}^{N_z} \sum_{i=1}^{N_{EV}} E_{EV}(i,z)/\Delta t \tag{8}$$

Voltage limit constraints

$$V_{\min} \leq V(m,n) \leq V_{\max}; \forall\, htN, h \in \Omega_u \tag{9}$$

Power balance constraints

$$\begin{aligned} P_G(m,n) - P_D(m,n) = V(m,n) \sum_{r=1}^{N_B} \\ V(r,n) y(mr) \cos(\Theta(mr + \delta(r,n) + \delta(m,n)) \end{aligned} \tag{10}$$

$$\begin{aligned} Q_G(m,n) - Q_D(m,n) = -V(m,n) \sum_{r=1}^{N_B} \\ V(r,n) y(mr) \sin(\Theta(mr) + \delta(r,n) - \delta(m,n)) \end{aligned} \tag{11}$$

Thermal limit constraints

$$B\mathrm{I}(mr,n) \leq BI^{\max}(mr,n); \forall\, hrtN, n \in \Omega_u \tag{12}$$

B. *Proposed EVMS in V2G and G2V modes*

A proposed EVMS operates EV as it arrives at RPZ in G2V mode if system demand exceeds desired level, as long as the SoC is above the minimum threshold. Once the minimum threshold SoC is reached, EVMS trigger EVs to operate in G2V mode till their required SoC level. Thus, EVMS communicates with EVs bidirectional smart plugs based on predefined minimum threshold limit of EVs batteries' SoC level.

$$S_{EVMS}(i,z) = \begin{cases} V2G, & P_D(h) < P_D^{\max},\ soc(i,z) > soc_{\min}^{\Delta} \\ G2V, & soc(i,z) \leq soc_{\min}^{\Delta} \end{cases} \tag{13}$$

In this mode, the total time taken by ith EV at zth RPZ is formulated as

$$T(i,z)=\left\{\begin{array}{l} T_{cg}(i,z);\forall soc(i,z)\le soc_{\min}^{\Delta} \\ T_{dg}(i,z)+T_{cg}(i,z);\forall soc(i,z)>soc_{\min}^{\Delta} \end{array}\right\} \tag{14}$$

Here, $T_{cg}(i,z)$ is referred from the equation (1) whereas, $T_{dg}(i,z)$ is formulated as

$$T_{dg}(i,z)=soc_{dis}(i,z)\,C_b(i,z)\eta_c\Delta t/C_d(h) \tag{15}$$

The net energy transaction (drawn/supplied) between EVs and zth RPZ is formulated as

$$E(i,z)=\begin{cases} E_{cg}^{'}(i,z), & \forall\,\mathrm{soc}(i,z)<\mathrm{soc}_{\min}^{\Delta} \\ -E_{dg}(i,z)+E_{cg}(i,z), & \forall\,\mathrm{soc}(i,z)>\mathrm{soc}_{\min}^{\Delta} \end{cases} \tag{16}$$

Here, $E_{cg}^{'}(i,z)$ is referred from the equation (2) whereas, $E_{dg}(i,z)$ is formulated as

$$E_{dg}(i,z)=soc_{dis}(i,z)\,C_b\,(\mathrm{i,z})\,\eta_c \tag{17}$$

$$soc_{dis}(i,z)=soc_i(i,z)-soc_{\min}^{\Delta} \tag{18}$$

C. Financial benefits to EV owners

The EV are assumed to be charged under the dynamic pricing environment for electricity. The financial benefit to the EV owners are calculated based on its charging/ discharging periods are formulated as

$$\Upsilon_{(G2V,pur)}^{j}=\alpha(h)\times E_{cg}(h,z) \tag{19}$$

$$\Upsilon_{(EVMS,pur)}^{j}=\alpha(h)\times {E_{cg}}'(h,z) \tag{20}$$

$$\Upsilon_{(EVMS,sell)}^{j}=\alpha(h)\times 0.6\times E_{dg}(h,z) \tag{21}$$

Financial benefit for zth RPZ using proposed EVMS is expressed as

$$\beta^{z}=\left(\Upsilon_{(G2V,pur)}^{z}-\Upsilon_{(EVMS,pur)}^{j}\right)-\Upsilon_{(EVMS,sell)}^{j} \tag{22}$$

Total benefits obtained by the RPZ,

$$\beta=\sum_{z=1}^{N_Z}\beta^{z} \tag{23}$$

III. SIMULATION RESULTS

Simulations are conducted on a standard 33 test bench distribution system. This 12.66 kV three-phase balanced distribution system includes 33 nodes, 37 lines, 32 sectionalizing lines, and 5 tie lines. The system utilizes a radial network topology with five open tie-lines. The distribution feeders are categorized as residential (N1–N15), industrial (N22–N29), and commercial (N16–N21, N30–N33), contributing 1295 kW, 1320 kW, and 1100 kW to the system demand, respectively [17]. For residential EV charging, all RPZs are assumed to be connected at nodes N1 to N15. The input parameters related to EV charging such as arrival/departure period, total number of EVs, SoC levels, battery capacity, charging/discharging rating etc. taken for the simulations are listed in TABLE 1. In simulations, the arrival time of EVs is distributed normally throughout the arrival period, i.e., 16:00 to 24:00 hrs. as depicted in Fig 1. The EV charging/ discharging is performed under the dynamic pricing signal taken from the ref [18] is presented in Fig. 2.

TABLE I
INPUT PARAMETERS

Parameter	Value
T_{AR}	16:00 - 24:00 hrs.
T_{DEP}	7:00 - 9:00 hrs.
N_{EV}, N_H, N_R	600,15,15
$soci$	0.2 - 0.75 %
soc_f	0.8 - 0.9 %
$C_b(i,z)$	25/30/35/40/45 [kWh]
$C_c(h)$	5.4 kW
$C_d(h)$	7.5 kW
Δt	60 hrs

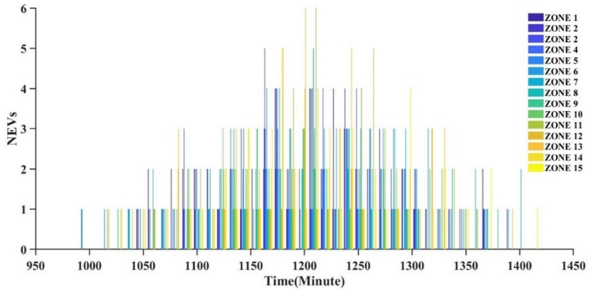

Fig. 1. Zone-wise arrival time of EVs in residential area

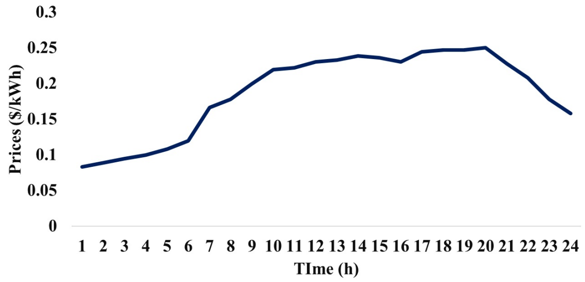

Fig. 2. Dynamic electricity pricing over a day

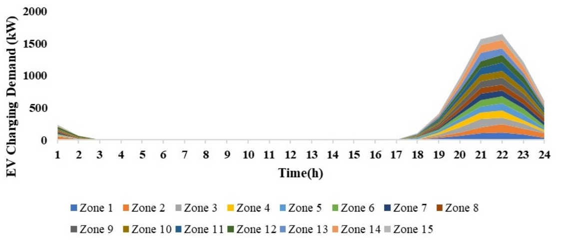

Fig. 3. Zone-wise EVs charging profile in the residential area using G2V mode only

The charging of EVs using uncoordinated RPZ charging has been performed using (1)-(8). The hour-wise residential EV charging load profiles of G2V mode so obtained is presented

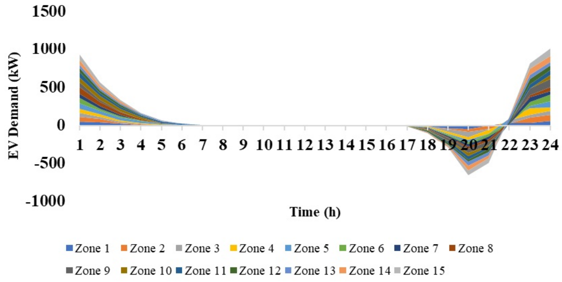

Fig. 4. Zone-wise EVs charging profile in the residential area using proposed EVMS (V2G+ G2V modes)

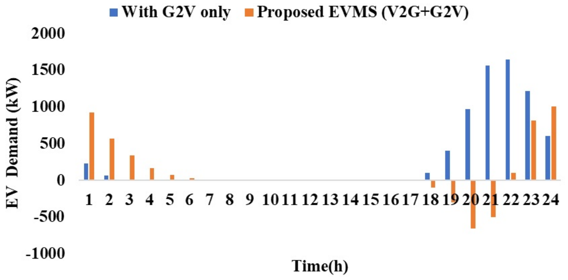

Fig. 5. Comparison of EVs charging/discharging demand in V2G and proposed EVMS (V2G+G2V)

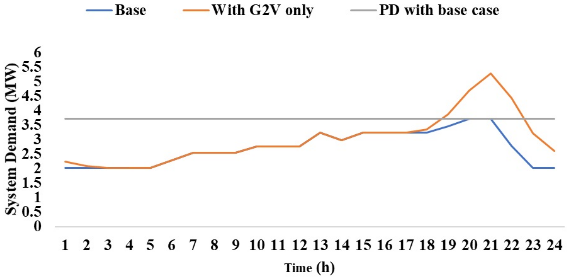

Fig. 6. System demand profiles in G2V mode

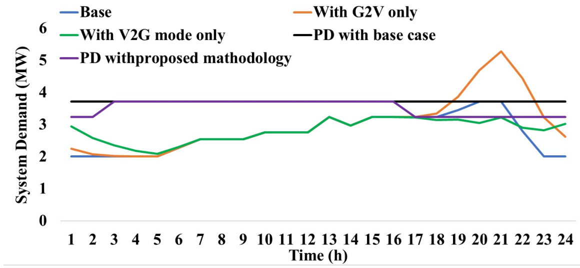

Fig. 7. System demand profiles in proposed EVMS (V2G+G2V)

in Fig. 3. Similarly, the hour-wise residential EV charging/discharging load profile of (V2G+G2V) mode is generated using (19) - (22) as shown Fig. 4. Fig. 5 displayed comparison of EV charging/discharging demand in V2G and proposed EVMS (V2G+G2V) mode; EV discharging is scheduled before midnight, and EV charging is schedule after midnight without substantially changing the peak demand. The zone-wise charging and discharging profiles acquired were based on residential and system load profiles, as shown in Fig. 6 and 7, respectively. Fig. 6. shows the comparison of the system load profile of the system with base case and uncoordinated charging with G2V mode and coordinate with (V2G+G2V) and base case with peak demand and peak demand with the proposed methodology. It has been observed that the G2V mode increases residential peak demand with coincident around 18:00 to 23:00 hrs. The process of loading has added effects on the system of distribution. Fig. 7. indicates that raising the peak demand drastically changed the distribution system's load profile in G2V mode. Moreover, the proposed EVMS methodology reduces the added effects of shift charging in the late midnight (off-peak) hours of 22:00 to 7:00 hrs (in the next day morning) and decreases the peak demand on the distribution system created by G2V mode. Furthermore, the EVMS method overcomes the stress load profile of the system as compared to the load profile of the base. Fig. 8. indicates the deviation of the node voltage profile at peak demand in the system after considering uncontrolled home charging in G2V mode and the base case and the coordinated proposed EVMS (V2G+G2V) mode with the system base profile. It has been observed that the proposed EVMS with V2G technology improves the node voltage profiles of the system.

The impacts on the overall system in terms of peak power demand, maximum active power losses are listed in the TABLE II. The results indicate that in G2V mode 42.00% rise in the peak system load, a 10% increment in the daily feeder demand, 89% and 90% increment in maximum active power losses. Whereas, minimum node voltage reduces to 0.8975 from 0.9181 p.u. It can also be observed from the table that the proposed EVMS (V2G+G2V) system demonstrates significant advantages over the G2V mode in terms of peak demand, system energy, power losses, and overall cost. It reduces the peak demand by 38% and the daily feeder demand by 6.05% compared to G2V. Additionally, the system significantly decreases the maximum active power loss by 57.46% while improving the minimum node voltage by 6.03%. TABLE III presents the detailed zone-wise financial benefits

TABLE II
IMPACTS ON OVERALL SYSTEM PERFORMANCE

Parameter	Base	G2V mode	Proposed EVMS V2G+G2V	Advantages over G2V
System Energy (MW)	3.72	5.28 (42%)	3.24 (−12.90%)	−2.04 (−38%)
Duration (h)	20:00 - 21:00	21:00	1:00	
Daily Feeder Demand (MWh)	65.09	71.90 (10.46%)	67.55 (3.78%)	−4.35 (−6.05%)
Max Active Power Loss (MW)	0.2025	0.383 (89.13%)	0.1629 (−19.55%)	−0.2207 (−57.46%)
Min Node Voltage (p.u.)	0.9131	0.8697 (−4.75%)	0.9222 (9.9%)	0.0525 (6.03%)

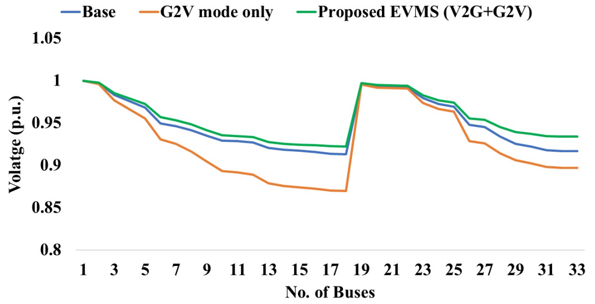

Fig. 8. Impact on node voltage profiles in both G2V mode and proposed EVMS (V2G+G2V)

TABLE III
FINANCIAL BENEFITS OF EV OWNERS USING PROPOSED METHODOLOGY

Prices/ Zones	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
G2V mode($)	97.84	97.03	98.09	89.86	92.50	88.33	86.14	93.05
Proposed EVMS ($)	12.52	9.49	10.68	9.87	12.28	9.12	9.72	10.70
Benefits ($)	85.42	87.54	87.41	79.99	80.22	79.21	76.42	82.35
Prices/ Zones	Zone 9	Zone 10	Zone 11	Zone 12	Zone 13	Zone 14	Zone 15	Total
G2V mode ($)	90.95	94.99	94.63	104.96	92.18	101.17	83.55	1405.38
Proposed EVMS ($)	8.84	10.56	11.75	11.93	10.42	9.15	8.67	155.70
Benefits ($)	82.11	84.43	82.88	93.03	81.76	92.02	74.88	1249.68

to the EV owners with and without proposed strategy. The overall benefit is obtained as the substantial reduction in total cost, amounting to an 88.93% decrease. These improvements highlight the efficiency and cost-effectiveness of the proposed EVMS (V2G+G2V) system.

IV. CONCLUSION

This paper proposes EV charging/discharging strategies in the residential area to avoid congestion during the peak demand hours of the distribution system. The proposed methodology suggests EVMS which coordinates EVs for G2V and V2G modes both. The proposed EVMS discharges EVs (V2G) upon arrival at RPZ till the prespecified SoC threshold limit while satisfying the necessary conditions of system demand as EV batteries' SoC level then charges (G2V) till the required SoC levels in order to reduce the peak demand at the system. The simulation results on a standard test bench signify that the proposed EVMS not only shift the EVs charging demand in light load period but also reduces the peak demand at distribution system. The study also examines the financial gains of the EVs owners against participation in the V2G mode which is around 88.93% gains against the proposed EVMS. The present work considers only one case study with a single load profile. More practical results may be drawn by extending the present work considering a variety of customers' load profiles while considering battery degradation cost. The work may also be extended by incorporating renewable energy resources at the RPZs.

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