Coordinating Electric Vehicle and Distributed Generations for Mitigating Unbalance Considering Travel Commitment

Md. Rabiul Islam, *Student Member*, *IEEE*, Haiyan Lu, *Senior Member*, *IEEE,* M. J. Hossain, *Senior Member*, *IEEE,* Li Li, *Member*, *IEEE*

***Abstract*— Growing penetration of uncoordinated electric vehicle (EV) charging raises challenges to manage electricity generation and degrades grid performances such as increased voltage imbalance, higher neutral current and energy losses in low voltage (LV) distribution grids. On the other hand, increasing penetration of renewable energy (RE) and EV charging as distributed energy sources offers opportunities for managing demand response and grid performances. Although several EV charging strategies have been proposed, most of them did not take into account for heterogeneous EV charging fleet and intermittent nature of RE, thus utilization of RE and LV distribution grid performance are not ideal. This paper proposes a centralized control method that simultaneously coordinates EV charging and distributed energy sources by considering dynamic energy tariff, energy generation from RE sources, each EV user's hardware characteristics, and EV's travel requirements. The potentially increased computational burden and communication overhead due to the large number of constraints considered is managed by using an improved local controller. The local controller sends information about EV charging priority and required energy to the central controller based on EV hardware characteristics (such as battery storage capacity, present state of charge, the maximum power rating of EV charger) and one day ahead of EV's travel requirements. The central controller then uses these information along with energy tariff information from retailer, and real-time grid performances to tune charging and discharging power of each EV, and to coordinate power dispatch of distributed energy sources. The efficacy of this control method is evaluated by applying to a simulated Australian LV grid. The simulation results show that this method can reduce neutral current and voltage imbalance by maximizing the usage of renewable energy resources and ensuring the EV's travel requirements.**

***Index Terms*— smart charging, neutral current, voltage unbalance, distributed generation, travel requirement.**

I. Introduction

Decreasing fossil fuel usages can significantly reduce emission of greenhouse gases (SO_2, CO_2, and NO_x) [1]. Electric Vehicles (EVs) and renewable energy (RE), as useful distributed generations (DGs), are promising alternatives to fossil fuels in the transport and electricity industry. However, a higher level of penetration of uncoordinated EV discharging and RE based DGs in low voltage (LV) distribution grid can increase voltage imbalance, and decrease voltage [2], [3]. The grid imbalance can result in energy losses [2], transformer losses [2], neutral conductor cost [4], operation, and maintenance costs [4] [5]. Furthermore, grid imbalance can reduce the voltage and hosting capacity of grids [5]. How to reduce grid imbalance while allowing a high level of penetration of EVs and RE-based DGs in distribution grids has recently attracted more and more academic and industry peoples. Moreover, the uncoordinated integration of DGs and EVs also causes transformer overloading during certain periods of a day (e.g., peak demand periods), thus, it is desirable to coordinate both EVs and DGs.

Some coordination methods have been proposed in the literature. The United Kingdom (UK) consumer survey categorizes EV charging methods into two kinds: 1) user managed EV charging or time of use method and 2) grid operator controlled charging or smart charging method [6]. ToU method recommends to charge EVs in off-peak periods which reduces EV charging cost [7, 8]. The EV coordination approaches based on ToU method may cause higher peaks than usual at night time in the distribution grids with a higher level of EV penetration. Furthermore, the user managed EV charging (or ToU) does not consider to maintain grid performance. Therefore, it is efficient for LV distribution grids with a low level of EV penetration. Although it can reduce charging cost, it cannot flatten the load curve, utilize the renewable energy, and optimize the grid performance in real time. Smart charging methods [9]-[17] were proposed to overcome these weakness of ToU. Using smart charging methods, EVs can be coordinated with optimum charging or discharging rate to improve voltage [9], congestion [10], transformer overloading [11], energy loss [12] [13] , voltage unbalance [14] , neutral current [15] , and charging cost [11] [16]. In [17], one method was proposed to charge EVs in an average charging rate throughout the planned plugged in duration [17] to flatten EV charging load throughout a day. However, although this method can reduce peak demand but cannot maximize the usage of renewable energy.

RE based DGs used to schedule EV charging for minimizing charging cost [18], maximizing aggregators benefit [19], and increase the state of charge (SOC) capacity of EVs [20]. These studies did not quantify the grid performances with increasing penetration of both EVs and DGs with its uncertainty in a LV distribution grid. The RE based DGs generation uncertainty is considered for coordinating EVs in [21] whereas EV user's travel requirement is ignored.

EV user's driving distance requirements in their daily lives should be taken into account during managing grid performance, and demand-generation in a LV distribution grid.

A few studies [10], [22], [23], [24], [25] took into account the required driving distance of EV user's. EV charging cost is reduced by managing congestion to meet the predicted required driving distance [10]. The grid performance is improved by assuming that required travel mileage of each EV is 32.7 km per day [22] , or average daily driving distance of 53 km [25], or start charging once plugged in once a day after arriving home [23], or the SOC threshold (if reduces to 30%) [24]. Therefore, these studies do not consider individual EV user's required driving distance. The Japanese travel survey also shows that it is challenging to predict the required driving distance of an EV user [26]. Furthermore, the UK consumer survey regarding smart charging [6] shows that EV users want to charge their EVs at least charging cost by meeting their driving distance. To the Author's best knowledge, none of existing EV coordination methods in the literature including reviewing articles [27-29] exhibits all of the following features:

- Be able to maintain or optimize grid performance,
- Be able to reduce the peak demand or mitigate unusual peak at a certain time of a day,
- Be able to maximize the usage of renewable energy and/or reduce EV charging cost, and
- Be able to consider individual EV user's travel requirement.

Motivated from the survey outcome [6] [26], this study aims to develop a control strategy to coordinate EV charging that has the above features. To enable all these features, the control strategy needs to achieve multiple objectives which is challenging in practice and increases communication overhead. For reducing such communication complexity, this control strategy uses one central controller and a number of local controllers which are installed at each EV. Each local controller gathers information about individual EV and sends processed information to the central controller at each time step to optimally coordinate EV charging or discharging power based on the proposed EV charging strategy and DGs dispatch. The key contributions of this paper are:

- developed a novel local controller, which estimates energy requirements and EV charging priority based on individual EV user's upcoming travel requirements, planned plug-in duration, and characteristics of EV users' hardware (i.e., chargers).
- proposed a convenient EV charging or discharging strategy which coordinates EVs based on energy requirement, priority, energy tariff, and amount of RE-based DGs dispatch in real-time.
- proposed a new unbalance mitigation method that simultaneously coordinates phases, DGs, and EVs to mitigate voltage unbalance and compensate neutral current.

II. Coordination Problem and Proposed Control Method

Usually, EV users plug-in their electric vehicles at their homes. Recently, workplaces (office buildings, universities, and shopping malls) are offering EV charging infrastructures to their staff for charging their EVs [18]. When an EV is connected to the grid for acquiring driving distance, it starts charging immediately with rated EV charger rating. This charging method is known as user managed charging (UMC) or immediate EV charging (UCM) [17]. To spread EV charging over the planned plug-in time, [17] recommends the average rate (ARCM) charging method. The total required EV charging demand is divided by the total plug-in duration for obtaining the EV charging rate in ARCM method. The benefit of ARCM method is that the EV charging demand is spreading throughout a day instead of charging EVs in off-peak period (TOU method or valley filling and peak saving method [30]) and avoid unusual peak at off-peak period. But both commonly used TOU and ARCM method is not utilizing the benefit of RE energy as well as improving grid performance.

The proposed method considers grid performance as an optimization problem by following an EV charging strategy. The grid performances such as voltage, energy loss, load leveling, peak shaving, voltage unbalance, neutral current, or other vital performances could be considered a single or multi-objective optimization problem. In our study, the voltage unbalance factor and neutral current are considered an optimization problem (1). The voltage unbalance factor is the ratio of negative sequence voltage (V_-) to positive sequence voltage (V_+). The neutral current is the summation of three-phase currents. The multi-objective optimization problem (1) is solved using a non-dominated sorted genetic algorithm (NSGA II) by considering constraints (2)-(6).

$$F_{objective} = \begin{cases} \min\left(I(t)_{neutral}\right) \\ \min\left(\sum_{mv \in MVnode} VUF(t)^{mv}\right) \end{cases} \quad (1)$$

subject to constraints:
- planned plug-in duration of each EV (T_p),
- EV storage capacity :

$$P(\kappa,t)_{EV\_SOC\_min} \le P(\kappa,t)_{EV\_SOC} \le P(\kappa,t)_{EV\_SOC\_max} \quad (2)$$

- proposed EV charging/discharging rate

slow: $$0 \le P(\kappa,t)_{EV\_ch/dch} \le 0.25 \times P(\kappa,t)_{EV\_ch/dch\_max} \quad (3.1)$$

flexible: $$0 < P(\kappa,t)_{EV\_ch/dch} \le P(\kappa,t)_{EV\_ch/dch\_max} \quad (3.2)$$

maximum: (3.3)
$$0.6 \times P(\kappa,t)_{EV\_ch/dch\_max} < P(\kappa,t)_{EV\_ch/dch} \le P(\kappa,t)_{EV\_ch/dch\_max}$$

- voltage constraint : $$0.95 \text{ p.u} \le V(t)^{mv} \le 1.05 \text{ p.u} \quad (4)$$

- power flow constraint :

$$\begin{aligned} &P(t)_{schedule} + \sum_{\sigma \in NPV} P(\sigma,t)_{PV} + \sum_{\gamma \in NEV_d} P(\gamma,t) + P(t)_{ext} = \\ &\sum_{\alpha \in NRES} P(\alpha,t)_{res} + \sum_{\phi \in NEV_c} P(\phi,t)_{ch} + \sum_{br \in Nbranch} P(br,t)_{loss} \end{aligned} \quad (5)$$

- import power constraint : $$0 \le P(t)_{ext} \le P(t)_{\max\_ext} \quad (6)$$

where, t denotes a time step (one hour) , t = 1,2,…,24 and a day has 24 hour window (D_w), κ denotes EV,

$VUF(t)^{mv} = \frac{|V(t)_-|^{mv}}{|V(t)_+|^{mv}}$, $I_{neutral}$ is the neutral current at a time step (t), $P(t)_{schedule}$ is the amount of scheduled generation of a distribution grid at a time step, $P(br,t)_{loss}$ denotes power loss at a time step, mv denotes to all measuring node MVnode. σ,γ,α,φ,br denotes to all PV installed with BES (NPV), all discharging EV (NEV_d), all residential load (NRES), all charging EVs (NEVc), and all branch (Nbranch).

In this study, coordinating EV charging follows the storage capacity boundary (minimum value of the state of charge EV_SOC_min and maximum value of the state of charge EV_SOC_max) as shown in (2) and proposed charging or discharging (EV_ch/dch) rate (slow, flexible, and maximum charging group) as shown in (3). In a time step (t), the distribution grid will import power from external grid $P(t)_{ext}$ within the allowed import power $P(t)_{max\_ext}$ limit (6). The voltage should be regulated between 0.95 p.u to 1.05 p.u, as shown in (4) according to the Australian standard [5]. The proposed method has to be conducted in smart grids, which is described in the later subsection, and the crucial prerequisites are:

- EV owners have an agreement with the DSOs regarding the minimum plug-in duration.
- EV owners are willing to inform required driving distance and planned plug-in duration in a day ahead.
- EV owners are allowed to change the distance of driving needed, and the modified required driving distance must be less than planned by keeping the entire plug-in duration.
- EV charging or discharging infrastructures are installed in both home and office parks.
- EV owners allow the DSOs to control the charging or discharging process.

A. Proposed local controller

To coordinate EVs for solving the optimization problem (1) by ensuring required driving distance, least energy cost, and grid imbalance, if directly solved, would need several information such as the distance of driving needed, vehicle characteristics, EV storage capacity, maximum EV charging rating, and mode of EV integration (charging or discharging) to be collected by a central controller, which requires complex communication infrastructure, increase computation time and challenging in practice. To reduce such complexity, we propose an idea of using a novel local controller at each EV to which allow the EV user to enter the required driving distance ($Trip_d$) and planned plug-in duration (T_p) in a day ahead. This local controller can convert the required driving distance to the needed energy (SOC_{req}), as shown in (7). The distance of driving needed ($Trip_d$) is divided by driving distance per kWh (D) to obtain the required energy (SOC_{req}). This local controller also stores registration information such as minimum (SOC_{min}) and maximum battery energy capacity (SOC_{max}), maximum EV charger capacity ($PEV_{\_ch/dch\_max}$), and driving distance per kWh (D) for a particular EV. According to the manufacturer's recommendation, the minimum battery storage SOC_{min} needs to be kept as a constraint (2). Therefore, the required battery storage ($SOC_{battery\_req}$) is the summation of SOC_{min} and SOC_{req}, as shown in (8). The required energy ΔSOC of each EV can be calculated by subtracting $SOC_{battery\_req}$ from the current status of battery storage SOC_{now} at a time step (t). Therefore, the value of the required energy ΔSOC at a time step (t) is shown in (9). To ensure the necessary driving distance, EVs should be charged based on the proposed prioritization criteria. The prioritization criteria depend on planned plug-in duration (T_p), the minimum required plug-in time (T_{min_req}), and maximum battery storage capacity (SOC_{max}). The distance of driving needed is divided by the maximum EV charger rating ($PEV_{\_ch/dch\_max}$) to obtain the minimum plug-in time required (T_{min_req}) as shown in (10). The local controller counts the total plug in duration of an EV at each time step (T_c). The remaining plug-in time (T_{rem}) is obtained by subtracting the planned plug-in time (T_p) from the total plug-in duration at a time step (T_c) as shown in (11).

$$SOC(\kappa)_{req} = \frac{Trip_d(\kappa)}{D(\kappa)} \quad (7)$$

$$SOC(\kappa)_{battery\_req} = SOC(\kappa)_{req} + SOC(\kappa)_{\min} \quad (8)$$

$$\Delta SOC(\kappa,t) = SOC(\kappa)_{battery\_req} - SOC(\kappa,t)_n \quad (9)$$

$$T(\kappa)_{\min\_req} = \frac{SOC(\kappa)_{req}}{P(\kappa,t)_{EV\_ch/dch\_\max}} \quad (10)$$

$$T(\kappa)_{rem} = T(\kappa)_p - T(\kappa)_c \quad (11)$$

$$\begin{aligned}
&\text{If} \quad \Delta SOC(\kappa,t) > 0 \\
&\{ \\
&T(\kappa)_{rem} > T(\kappa)_{req}, \qquad \text{priority=0} \\
&T(\kappa)_{rem} \le T(\kappa)_{req}, \qquad \text{priority=1} \\
&T(\kappa)_c > T(\kappa)_p, \qquad \text{priority= -1} \\
&\}
\end{aligned} \quad (12.1)$$

$$\begin{aligned}
&\text{If} \quad \Delta SOC(\kappa,t) < 0 \\
&\{ \\
&SOC(\kappa,t)_{now} < SOC(\kappa)_{\max}, \qquad \text{priority =0} \\
&SOC(\kappa,t)_{now} = SOC(\kappa)_{\max}, \qquad \text{priority =1} \\
&T(\kappa)_c > T(\kappa)_p, \qquad \text{priority=0} \\
&\}
\end{aligned} \quad (12.2)$$

The prioritization criteria are shown in (12). If ΔSOC is greater than zero, an EV's battery storage cannot achieve the required driving distance. If ΔSOC is less than zero, an EV's battery storage can achieve the required driving distance. When an EV's battery storage cannot achieve the required driving distance (ΔSOC >0), the proposed control method recommends a higher priority (priority =1) if the remaining plug-in time (T_{rem}) is less than the minimum required plug-in time (T_{req}). Otherwise, it recommends a lower priority (priority =0). On the other hand, if an EV's battery storage can achieve the required driving distance (ΔSOC < 0), then the proposed control method recommends a higher priority (priority =1) if the respective EV reaches its maximum capacity. Suppose EVs are connected after the planned plug-in duration, In that case, the proposed method allows only discharge with lower priority (priority =0) if ΔSOC < 0 but does not allow to charge by setting negative priority (priority = -1) if ΔSOC >0.

The local controller determines required ΔSOC and priority information at each time step (t) and updated periodically to the central controller in a day. The benefit of the proposed local controller is that it reduces the volume of required information by a central controller after processing several information, which reduces computation time and communication overhead.

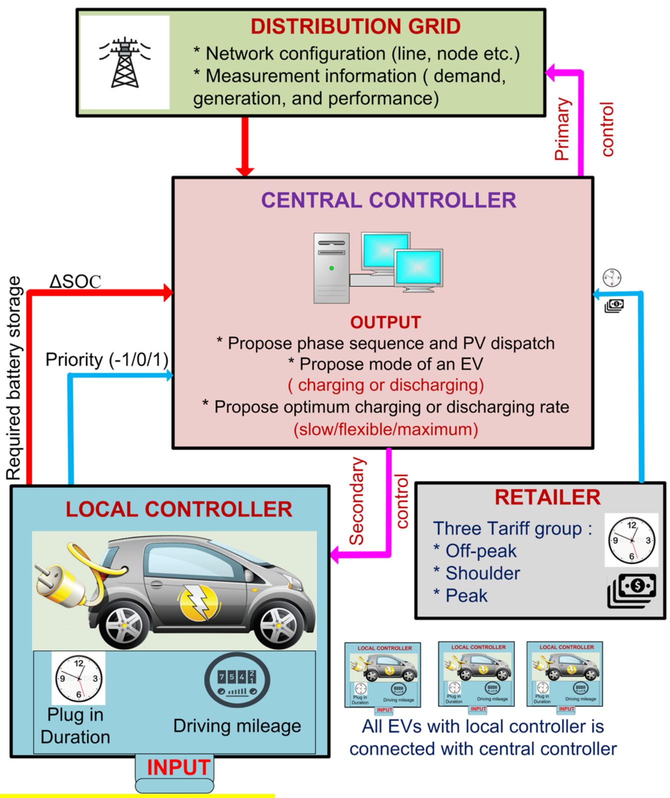

Fig. 1. Proposed control method

B. Proposed Central Controller

The central controller receives required ΔSOC and priority information from the local controller and the retailer's tariff information at each time step (t). This study recommends registering their EVs by providing EV user identification number, vehicle information, minimum plug-in duration, and EV location, and this information is stored in a central controller. The proposed control method is illustrated in Fig.1. The central controller receives information from a local controller, retailers, and distribution grid. The proposed central controller solves the optimization problem into two control step:

i) Primary control: coordinate phases and PV power dispatch.

ii) Secondary control: coordinate EV charging and discharging.

The central controller re-sequence phases of a distribution grid and recommends optimum charging or discharging rate to each EV local controller.

1) Primary control

The primary control utilizes distribution network operator (DNOs) and PV owner's resources. The proposed control method recommends DNOs to install the phase selector switch at each node in a distribution grid. The phase selector switch has the ability to change a phase sequence from (A, B, C, N) to either (B, C, A, N) or (C, A, B, N). In this study, three-phase sequences (A,B,C,N), (C,A,B,N), and (B,C,A,N) are represented as 0,1,and 2. Furthermore, the central controller includes PV owners (installed with BES) in the control process. The recommended single phase PV owners (installed with BES) are asked to install a switch box which has the ability to switch from phase A to either phase B or phase C. These switches are installed with a ZigBee wireless receiver to receive control information, and are designed with TRIAC, a snubber circuit, and over-voltage protection [31] . These switches are the re-sequencing phases after receiving the control information from the central controller as shown in Fig.2.

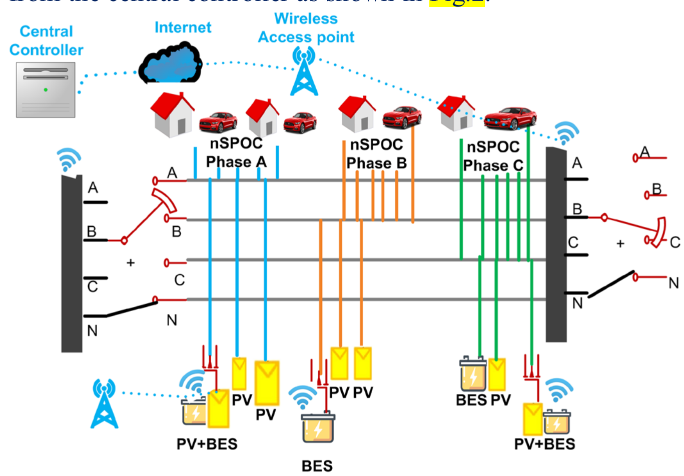

Fig. 2. Proposed primary control method

Both contributors (DNOs and PVs) jointly participate in the execution of the primary control method. In the primary control, the central controller collects measurement information such as the lump sum of demand (residential and EV charging) and generation per phase per node, node voltage, VUF, neutral current at the supporting feeder, and the amount of PV output power between phases of the contributing PV systems at a time step. The central controller controls both node and PV switches to achieve minimal voltage imbalance and neutral current by solving the optimization problem (1) subject to:

$$P(\delta,t)_{PV\_BES\_min} \le P(\delta,t)_{PV\_BES} \le P(\delta,t)_{PV\_BES\_max} \quad (13)$$

$$\sum_{\delta\in nPV} P(\beta,t)_{PV} + \sum_{\kappa\in nBES} P(\delta,t)_{PV\_BES} = Y \quad (14)$$

$$\sum_{\Omega\in NRES} P(\alpha,t)_{res} = U,\ \sum_{\nu\in NEV_c} P(\phi,t)_{EV\_ch} = H \quad (15)$$

$$\sum_{\mu\in nEV_d} P(\gamma,t)_{EV\_dch} = Z \quad (16)$$

where Y, U, H, and Z are constants whose values remain unchanged before and after control. δ denotes all PV system installed with BES, β denotes all PV system without BES, α denotes all residential loads, φ denotes all charging EVs, and γ denotes all discharging EVs in a distribution grid.

The integration of a single phase PV in a distribution grid may increase grid imbalance and energy loss [2] if the PV's dispatch is not coordinated in real- time [32] . In this study, it is considered that a single-phase PV system is installed with or without BES. In this study, the effect of solar irradiance, solar cells and converter efficiency are not considered in PV power modelling. The converter output of a PV system (installed without BES) is considered at a time step (t). The output of a PV system (installed with BES) can be made dispatchable by controlling the respective BES's discharging rate (13). The proposed control strategy recommends the optimum PV (installed with BES) power at the respective phase. The amount of delivered single-phase PV power (installed with BES) between the phases is controlled by a phase selector switch. In this study, the total amount of delivered single phase PV and BES power per node remains the same at a time step. The total power generation from PV (P_{pv}), and battery energy storage (P_{BES}), remains unchanged before and after control, as shown in (14). The total residential demand (P_{RES}), electric vehicle charging demand (P_{EV_ch}), and EV dispatched power (P_{EV_dch}) of a distribution grid remain the same as shown in (15)-(16) and voltage constraints are maintained (4).

2) Secondary control

The efficacy of coordinating phases and PV's dispatch (primary control method) prior coordinating EVs is evaluated in authors' previous article [15]. After executing the primary control method, the central controller coordinates EV charging and discharging. The central controller receives each EVs required energy ΔSOC and priority (-1/0/1) from a local controller, tariff information from the electricity retailer, measurement and configuration data from the distribution grid. Usually, retailers distribute energy tariffs into three categories: 1) off-peak, 2) shoulder, and 3) peak tariff in Australia [33]. In this study, the off-peak tariff period is considered from 01 Hr to 07 Hr because of the less residential and industrial load. The shoulder tariff period (8 Hr to 17 Hr) offers a cheaper tariff rate than peak tariff but a higher tariff rate than the off-peak period. It is also observed that PV solar energy is available from 8 Hr to 17 Hr, which is also fitted with the shoulder tariff period. There has a higher residential load demand in the peak tariff period (from 18 Hr to 24 Hr). Based on-grid tariff, ΔSOC, and priority of each EV, the central controller, recommends charging or discharge EVs by following the proposed charging or discharging group strategy as shown in (3.1-3.3). The central controller coordinates EVs to achieve an optimal solution by following the proposed charging or discharging strategy, as shown in Fig.3. If the central controller receives information from an EV's local controller that respective EV's required energy (ΔSOC >0), the central controller recommends charging EV with optimum charging rate within the proposed charging group for solving the optimization problem by maintaining constraints. The optimum charging rate depends on priority information and tariff period. If the required driving distance is not achieved, and priority becomes high (Priority=1), the proposed control method recommends an optimum maximum charging rate without considering the tariff period to ensure the required driving distance. On the other hand, if the remaining plug-in time is more than the minimum required plug-in time (Priority=0), the proposed control method recommends charging at a flexible charging rate during availability of PV solar energy, at maximum charging rate during the off-peak

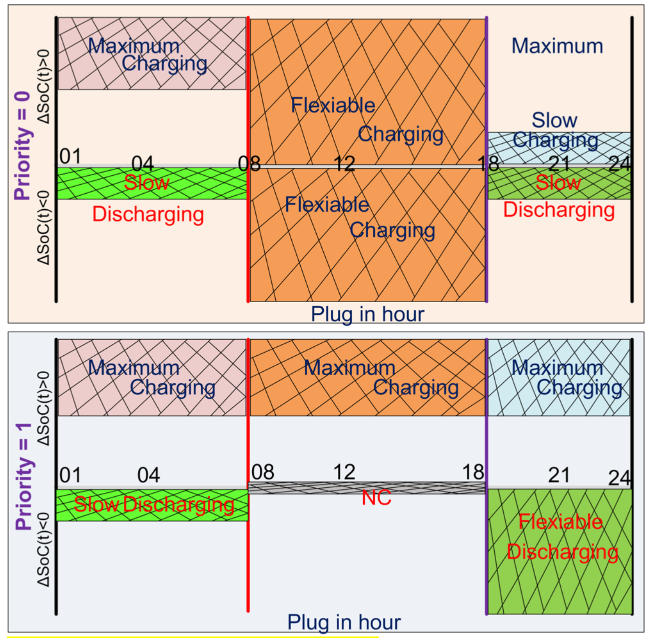

Fig. 3. Proposed secondary control metthod

period, and at slow charging rate in peak period. EVs are charging till achieving the required battery storage ($SOC_{battery\_req}$) and continue charging in the shoulder tariff period through flexible charging rate to store surplus renewable energy. After achieving the required driving distance, the proposed control method recommends discharging EVs through a medium discharge rate in the peak tariff period, whereas slow discharge in the off-peak tariff period. The benefit of charging during solar energy availability and discharging EVs in peak tariff period reduces overall EV charging cost. The proposed EV charging strategy recommends an optimum charging rate within a charging group (slow/flexible/maximum) based on priority and energy tariff to achieve an optimum solution of (1) subject to the constraint (2) to (6). The charging group's benefit allows a range of optimization space for obtaining an optimum charging rate rather than a constant charging rate throughout a day.

The proposed smart EV charging method improves the grid performance and delivers charging power based on the needs of EV owners. The proposed method considers the driving distance and provides power through different charging group strategies rather than variable charging or discharging procedures in [34]. The efficacy of proposed control method will be evaluated over existing control methods through an experimental simulation of an Australian distribution grid in the next Section.

III. Experimental Setup

The proposed control method is evaluated via simulation of an electrical low voltage distribution feeder in Queensland, Australia whose details are presented in [32]. This test distribution grid is modelled and simulated in Dig-SILENT PowerFactory. Each residential consumer (total 1020) is connected to the feeder consisting of 44 nodes and offered a time-varying demand tariff. The used average demand tariffs provided by the major retailers in Australia and residential demand based on real metering data (5 minutes) is shown in Fig.4 [35]. For modelling purposes, the power factor of each residential consumer is set to be 0.96, lagging. The load is modelled as constant active power (P) with a power factor of 0.96 lagging. It is considered that the residential loads are equally distributed among phases in a distribution grid.

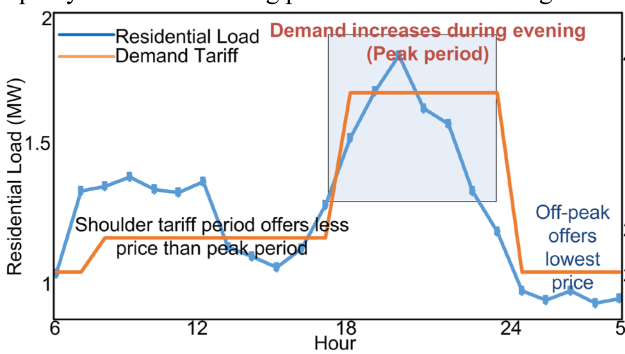

Fig. 4. Demand tariff and residential demand

It is assumed that each resident owns an EV that is connected to the distribution network. In this study, single-phase EVs were considered having EV charger capacity: Level 2 HCS-40 (7.7 kW); Level 2 HCS-50 (9.6 kW); Level 2 HCS-60 (11.5 kW); and Level 2 HCS-80 (15.4 kW). In this article, EV batteries are modelled as a constant load with a unity power factor while charging and dispatched generation sources with a unity power factor while discharging. This study assumes that EVs can be charged everywhere (the charging infrastructures are available in both home, office, and shopping areas). Statistical information on required driving distance, arrival and departure time of a day, and plug-in duration of an EV fleet are important for estimating EV charging demand and coordinating EVs. This information for an EV is estimated from the Smart-Grid Smart-City (SGSC) customer trial data [36], travel pattern based on trading and office hours, and considering charging facilities available in local offices. This study assumes that the required driving distance is 30-140 miles per day and requires 22-30 kWh per 100 miles, which depends on a particular electric vehicle model [37].

The distribution grid is connected to the external grid and schedules import power for each hour a day. The DNOs manage the distribution grid by importing or exporting energy from the external grid subject to grid constraints. Furthermore, the rooftop photovoltaic (PV) solar system delivers power to the distribution grid. The rooftop PV capacity ranges from 3-5 kWp. This study considers a dispatchable source of PV units installed with a battery storage, whereas PV units without battery storage are considered a non-dispatchable source. To investigate the proposed control method's efficacy, reactive power compensation equipment is not considered in this study.

IV. Results and Discussion

This section evaluates the proposed control method using the experimental setup described in the previous section assuming loads are unequally distributed among phases and the degree of imbalance (μ) is 35% according to (17). The degree of imbalance presents the percentage of total load changes between phases. When the value of μ is 0%, loads are equally distributed among phases ($P_{\{A,bal\}}$, $P_{\{B.bal\}}$, $P_{\{C,bal\}}$). The increasing value of μ transfers a portion of load from two phases (phase A and phase B) to another phase (phase C). The maximum imbalance is achieved when μ is 100%. It means that only phase C is serving to all loads whereas phase A and phase B is not serving any load.

$$
\begin{aligned}
P_A &= P_{\{A,bal\}} - \mu \\
P_B &= P_{\{B,bal\}} - \mu \\
P_C &= P_{\{C,bal\}} + 2\times\mu
\end{aligned}
\tag{17}
$$

where $\mu = \%of\,\dfrac{P_{total}}{3}$, $P_{total} = \sum_{\alpha=A,B,C} P_{\{\alpha,bal\}}$

To investigate the efficacy of the proposed control method, the obtained results are compared with the performance of the following three existing approaches:

- uncontrolled charging [17],
- average rate charging [17], and
- variable charging and discharging method [34].

In uncontrolled charging, EVs are charged at the maximum EV charging rate ($PEV_{\_ch/dch\_max}$) whenever they are plugged into the distribution grid. The EV charging continues at the maximum charging rate until achieved the maximum battery

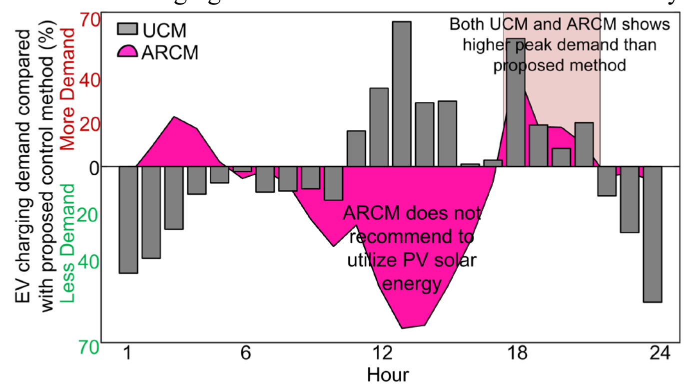

Fig. 5. EV charging demand compared with UCM and ARCM

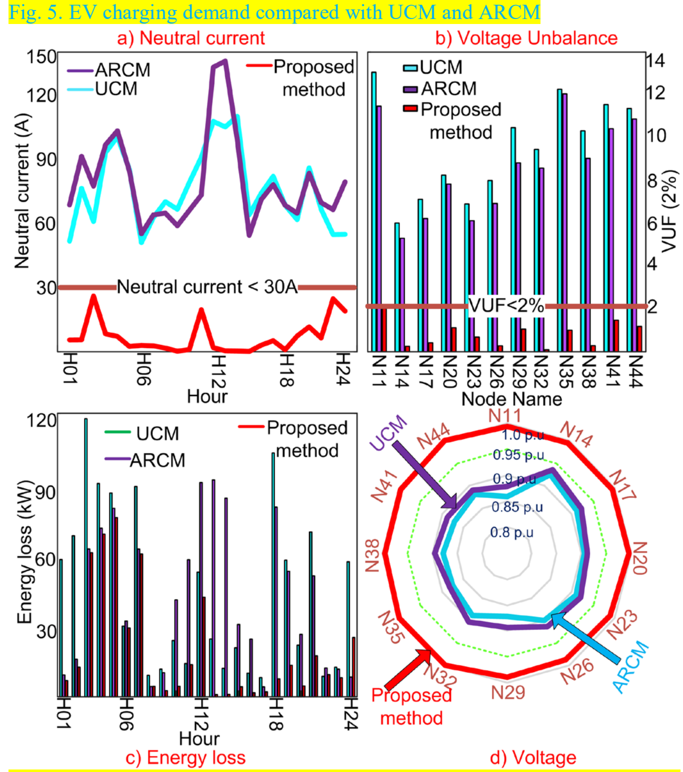

Fig. 6. Proposed control method compared with UCM and ARCM (Grid performances)

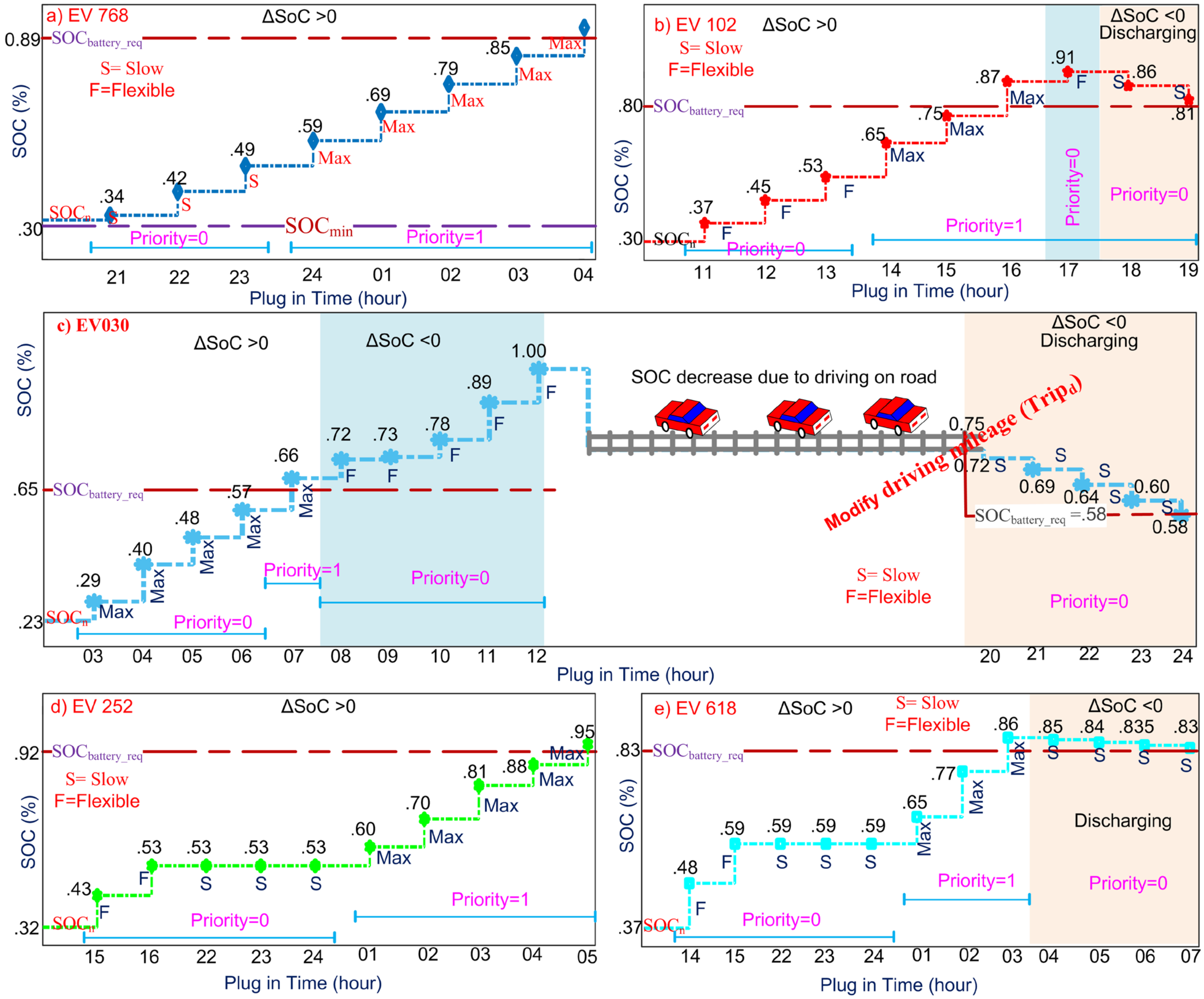

Fig. 7. Acquired required EV storage (driving distance) using proposed EV charging strategy

energy capacity (SOC_{max}) [17]. This study assumes that an EV will be charged at the maximum EV charging rate ($PEV_{\_ch\_max}$) until achieving the desired driving distance.

The average rate charging method (ARCM) recommends charging EV at the average charging rate to achieve the desired driving distance. The required energy (ΔSOC_{req}) is calculated by subtracting the battery storage at the arrival from the required battery storage ($SOC_{battery\_req}$). The required energy (ΔSOC_{req}) is divided by the total planned plug-in duration (T_p) to obtain the average charging rate (P_{ARCM_ch}), as shown in (19).

$$\Delta SOC(\kappa)_{req} = SOC(\kappa)_{battery\_req} - SOC(\kappa, t_{start})_{now} \quad (18)$$

$$P(\kappa, t)_{ARCM\_ch} = \frac{\Delta SOC(\kappa)_{req}}{T(\kappa)_p} \quad (19)$$

The arrival, departure, and plug-in duration remain the same as the proposed control method. The required EV charging demand, neutral current, voltage imbalance, energy loss, and voltage profile are compared with the proposed control method, as shown in Fig. 5 and Fig. 6.

Fig.5 present the required EV charging demand using UCM and ARCM method compared (more or less demand in percentage) to the proposed control method. Both the UCM and ARCM methods require more EV charging power during the peak period, increasing EV charging cost, as shown in Fig.5. Though the ARCM method flattens load throughout a day, the ARCM cannot maximize solar energy utilization than the proposed control method. The proposed control method mitigates an unusual peak demand due to EV charging and improves grid performance. The proposed control method shows less than 25A at the supporting feeder and reduces up to 99.80% compared to the UCM and up to 99.78% to the ARCM, as shown in Fig.6 (a). The proposed control method reduces the VUF below 2% at all nodes, whereas the UCM shows a maximum VUF of 8.4%, and the ARCM shows 7.38%, as shown in Fig.6 (b). Furthermore, the proposed control method reduces energy loss as shown in Fig.6 (c). The proposed control method maintains the voltage above 0.95 p.u, whereas both UCM and ARCM method decreases voltage, as shown in Fig.6 (d).

The proposed control method mitigates voltage imbalance, compensates neutral current, energy loss, and voltage profile, and ensures driving distance for an EV user using the proposed EV charging/discharging strategy as shown in Fig. 3. EV users edit their driving distance and planned plug-in time into the local controller. For EV768, the required storage capacity is 89% of total storage capacity, whereas the present storage is 31% of full storage capacity. The entire plug-in duration is eight hours. The priority is low (priority= 0) during the first three hours, whereas the priority is high (priority= 1) at the rest of five hours. The proposed control method recommends optimum charging rate from slow charging group from 21 Hr to 23 Hr as the priority is low and optimum charging rate from maximum charging group from 24 Hr to 04 Hr as the priority is high to solve the optimization problem (1) as shown in Fig. 7 (a). During peak hours, the recommended slow charging rate reduced the EV charging demand, reducing overloading in the peak period.

From Fig. 7 (b), the EV102 is plugged in from 11 Hr to 19 Hr. The proposed control method achieves the driving distance by charging EV102 until 16 Hr. The proposed control method recommends charging EV102 despite achieving the driving

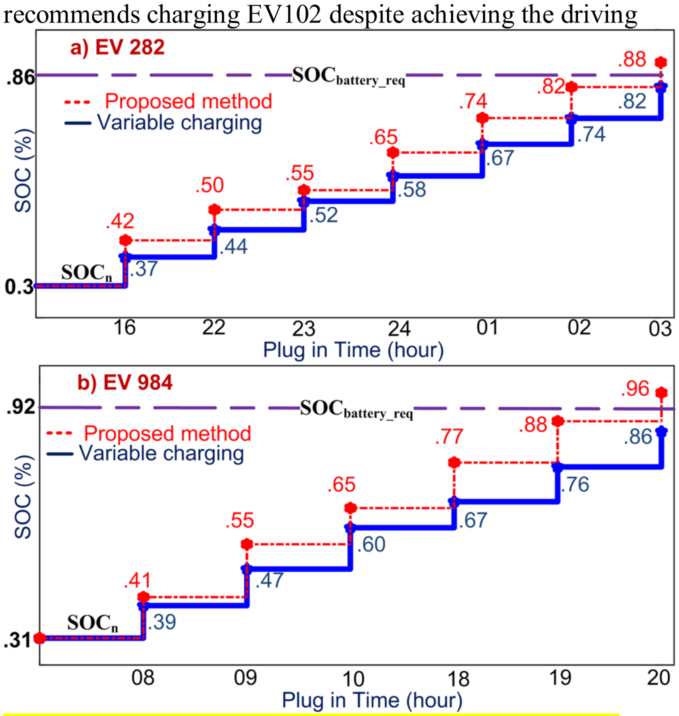

Fig. 8. variable charging VS proposed control method (driving distance)

distance at 17Hr to utilize the available PV solar energy. The stored excess energy is delivered to the distribution grid during the peak period (18 Hr to 19 Hr), as shown in Fig. 7(b). From Fig. 7(d)-7(e), EV 252 and EV 618 reduces EV charging demand in off-peak period because of getting benefit to charging EV during office hours (EV 252:15 Hr to 16 Hr and EV 618: 14Hr to 15Hr), which also utilizes the PV solar energy. The proposed control method ensures driving distance for EV 252 and EV618 despite slow charging in peak hours. The reduced EV charging demand during the off-peak period avoids unusual peaks in the off-peak period and reduces peak demand. The proposed control method allows an EV user to modify the required driving distance if the requirement is less than the planned driving distance. For EV030, the EV user planned a trip that requires 65% battery storage of total EV storage capacity, as shown in Fig. 7(c). Though EV 030 achieved the mileage of driving needed at 07 Hr, the EV030 gains energy to utilize the PV solar energy until it reaches the maximum storage capacity. The planned plug-in duration was from 03 Hr to 12 Hr. The EV user makes a trip, and battery storage reduces from 100% to 75%. The EV user changed the reduced trip plan and modifies the required driving distance, which allows discharging up to 58% of the battery storage capacity of total storage during peak period as shown in Fig. 7(c). EV030 discharges till the battery storage capacity reduces up to 58%. Fig. 5, Fig.6, and Fig.7 show that the proposed control method ensures the required driving distance by compensating neutral current and mitigating voltage unbalance.

The variable charging and discharging method described in [34] is applied to solve the optimization problem (1) to mitigate voltage unbalance and neutral current. EVs are coordinated by keeping the same plugin duration and follows the EV charging or discharging rate constraint (20). Though the variable charging or discharging method can compensate the neutral current below 30A and VUF below 2% at all nodes, all EVs do not achieve the required driving distance. Fig.8 shows that EV282 and EV 984 cannot achieve the necessary driving distance using the variable charging or discharging method [34] In contrast, the proposed control method guarantees to obtain the required driving distance.

$$0 \le P(\kappa,t)_{EV\_ch/dch} \le P(\kappa,t)_{EV\_ch/dch\_max} \qquad (20)$$

The proposed EV charging or discharging strategy ensures the required driving distance and efficiently utilizes the PV solar energy, and reduces the EV charging cost. The active power dispatch from PV solar energy and charging demand or discharging dispatch of EV is shown in Fig.9. The proposed control strategy recommends an optimum charging rate from either the maximum or flexible charging group from 8 Hr to 17 Hr while the PV solar energy is available. This strategy

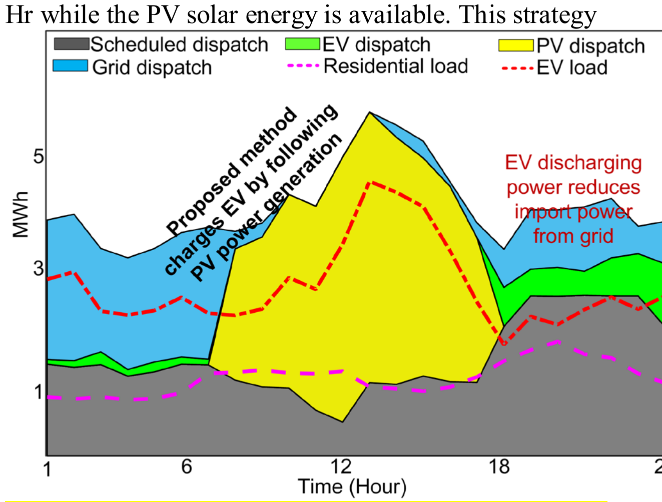

Fig. 9. Active power dispatch and demand in proposed control method

maximizes the utilization of PV solar energy, and a flexible charging group allows EVs to follow the real-time PV solar energy despite requiring battery storage. Fig.9 also clarifies that the EV charging demand proportionally follows the real-time PV power production. Therefore, the stored excess solar energy is delivered to the distribution grid in the peak period. EV dispatch power also reduces import power from the external grid during the peak period. Therefore, reducing import power in peak periods and efficiently utilizing solar energy reduces EV charging costs. The following benefits are obtained using the proposed control method:

i) The effect of imbalance due to uncontrolled EV charging and average rate charging method is investigated. It is observed that the grid imbalance increases the neutral current, voltage unbalance, and energy loss.
ii) The proposed method reduces neutral current, voltage unbalance, and energy loss by ensuring travel requirement, as shown in Fig.6 and Fig.7.
iii) The proposed EV charging strategy, as shown in Fig.3, recommends charging EV with an optimum charging rate from three charging groups. The slow charging group allows reducing EV charging demand, whereas the maximum charging group will enable EVs to charge quickly. The flexible charging group allows an optimum charging rate within the EV charger capacity. Charging EVs within a charging group enable EVs to obtain an optimum charging rate in real-time rather than a pre-defined constant charging rate.
iv) The proposed control method with novel EV charging group strategy utilize PV solar energy by changing EV charging demand (flexible charging group) based on produced PV solar energy. Therefore, the proposed EV charging strategy mitigates the uncertainty of PV power production.
v) EVs, which have less priority, are recommended to charge at a reduced charging rate (within the slow charging group) for decreasing peak demand. Furthermore, EVs are also advised to discharge in peak periods, as shown in Fig. 9. The proposed charging strategy recommends storing surplus renewable energy and delivering power at peak period, which reduces peak demand and reduces reserve (Battery storage) capacity cost.
vi) The proposed method guarantees to meet the required travel requirement, as shown in Fig.7. It is also observed that available EV charging facilities in office and home benefits both DNOs and EV users.
vii) The proposed method clearly shows efficacy over UCM [17] and ARCM [17] method, as shown in Fig.5 and Fig.6. On the other hand, though the variable rate charging method [34] mitigates unbalance, it [34] cannot guarantee to fulfill the travel requirement as shown in Fig.8.
viii) Apart from improving grid performance and meeting travel requirements, the proposed control method with the improved local controller is less demanding on the communication infrastructure and convenient for EV users.

V. Conclusion

This paper proposed an efficient yet simple control method that improves grid performances by considering multiple essential factors such as upcoming travel requirements, energy cost, PV power uncertainty, which also shows greater efficacy over recent methods used for coordinating EVs. The proposed method jointly coordinates EVs and PVs, which proves its robustness over exiting methods for mitigating voltage imbalance and neutral current. Furthermore, the proposed novel local controller reduces data volume to be computed and communicated between an EV and a central controller. To ensure driving needs based on plugged-in duration, the proposed EV coordination strategy allows EVs to charge at an optimum charging rate within the charging group boundary, reducing peak demand, and maximizes the uses of PV solar energy. After implementing the proposed control method on an Australian distribution grid, the obtained results also prove efficacy to mitigate grid imbalance by ensuring required driving distance with least EV charging cost and robust to manage EV charging demand- generation uncertainty. Therefore, the proposed control method is useful for both EV users and DNOs and efficient for a higher penetrated EV distribution grid.

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