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Vehicle-to-Grid (V2G) Optimal Scheduling for Grid Peak Demand Management and Emission Reduction: A State-of-the-Art Review

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SUMMARY

The recent explosive adoption of electric vehicles (EVs) all over the world is attributed to their remarkable contribution to reducing the global energy crisis, greenhouse gas (GHG) emissions, and enhancing the energy independence of the countries. As plug-in electric vehicles (PEVs) depend on electricity grids for charging their batteries, they are going to be an indispensable part of future power utility grids. The large-scale proliferation of PEVs poses detrimental effects on the reliable and stable operation of utility grids. The huge charging power requirement of PEVs causes peak demand to increase enormously on the utility grid leading to so many problems like line congestion, increased power losses, voltage instability, frequency limit violations, increased emissions from fossil-fuel-based power plants, overloading of transformers and other grid components & their consequent life reduction, etc. Hence, a new smart grid technology called Vehicle-to-Grid (V2G) which enables bidirectional power exchange between PEVs and the grid has been introduced so that utility grids can use it for regulating grid operation. By optimal V2G scheduling of PEVs and by meeting the large charging power requirements of PEVs from the renewable energy sources (RESs) integrated into the utility grid, the problem of increased peak demand and its other associated harmful impacts on the grid as well as on the environment can be considerably reduced leading to smoother grid operation and cleaner environment. This paper presents a state-of-the-art review of the latest research works done in optimal V2G scheduling of PEVs to flatten the grid power demand profile and RES integration to the utility grid to reduce GHGs. Literature review reveals that V2G technology offers a promising solution to effectively handle the huge peak demand and GHG emissions of the EV-RES-integrated utility grid. Further directions to carry out the research works on optimal scheduling of V2G and RES are also proposed.

KEYWORDS

Plug-in Electric Vehicles, Vehicle-to-Grid scheduling, renewable energy sources, Grid peak demand, Greenhouse gas emissions, Optimization techniques

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I. INTRODUCTION

Due to the great threats of global warming and other environmental hazards, there is an urgent need to reduce GHG emissions globally to make the earth planet cleaner and safer for humans and other living kinds. The 2015 Paris Agreement sets a global goal to reach net zero emissions in the second half of the century[1]. All the countries have set their own ambitious zero-carbon targets and are implementing short-term and long-term innovative plans to reach carbon peaks at the earliest and become carbon-neutral economies, although it takes many years to achieve the same. The European Union (EU), USA, Japan, and many other countries have already approved and announced a carbon neutrality target for 2050. China which tops the list of most polluting countries sets goals to peak carbon emissions before 2030 and become carbon neutral by 2060.

The transportation and electricity sectors are the main sources of GHG emissions on the earth planet[2]. The transportation sector with traditional internal combustion engine (ICE) vehicles and the electricity sector with conventional fossil-fuel-based power plants are significantly producing GHG emissions contributing to serious environmental degradation and global warming. Since global warming is a global warning for all countries, urgent, serious, and effective steps must be taken to reduce emissions to mitigate their disastrous effects on climate change to save the globe.

PEVs have tremendous potential to benefit both transportation and electricity sectors. EVs which can be connected to the grid are called Plug-in Electric Vehicles (PEVs) which include Battery Electric Vehicles (or All-Electric Vehicles) (BEVs/AEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)[3]. PEVs, being zero or low emission vehicles, can replace the currently highly polluting ICE vehicles and thus, remarkably reduce GHG emissions from the transportation sector. But PEVs require huge power to charge their batteries which makes them depend on electricity sector. Hence, a large-scale penetration of PEVs requiring immense charging power has detrimental effects on the reliable and stable operation of utility grids. The huge charging power requirement of PEVs causes huge peak-valley differences in grid load profile leading to so many problems like increased emissions from fossil-fuel-based power plants, line congestion, increased power losses, voltage instability, frequency limit violations, overloading of transformers and other grid components & their consequent life reduction, harmonic distortion, phase imbalance, etc.

It is extremely important for the power utilities to address the environmental and grid operation issues due to large-scale adoption of PEVs. First of all, the large charging power demand of PEVs must be met not by conventional fossil-based power plants but by RESs integrated to the utility grid to ensure significant reduction of GHG emissions from electricity sector. Next, to ensure smoother operation of PEV-integrated grid, PEVs must have vehicle-to-grid (V2G) capability which enables them to have bidirectional power exchange with utility grid. V2G is a new smart grid technology utilizing which PEVs can be optimally scheduled to draw their charging power from the utility grid during low-demand hours and discharge excess power from their batteries to the utility grid during high-demand hours. This reduces the charging cost to PEV-owners and smoothens the grid load profile. Thus, with this new concept of V2G, the problem of increased peak demand and its other associated harmful impacts on the grid as well as on the environment can be considerably reduced for the smooth operation of the utility grid and cleaner environment. Hence, the adoption of PEVs with V2G capability in transportation sector and integration of RESs to electricity sector is a win-win strategy for both sectors to reduce their environmental polluting emissions and to provide economic & reliable power to the electricity consumers of the power utilities. Therefore, there are rapid installation of RESs (like solar photovoltaics, wind, etc.) and accelerated adoption of PEVs around the globe[4][5]. This is further getting enhanced due to decreasing prices and, governments' increasing incentives and subsidies. The countries also can enjoy increased energy independence and reduce their oil imports saving enormously on foreign exchange along with environmental benefits. EVs sales are exponentially increasing despite the recent global COVID-19 pandemic, Russia- Ukraine war, etc. and the latest study reports indicate that the global EV fleet would be reaching 230 million in 2030[4].

There are many review/survey papers on EVs, their technology, potential benefits and barriers, impacts, etc. but only a few discuss optimal V2G scheduling of PEVs for grid peak demand management and emission reduction[3][6][7][8]. Hence, an attempt is made in this paper to present a review of the state-of-the-art research works done on this very important and future smart grid technological topic of optimal V2G scheduling of PEVs beginning with V2G concept, technology, types, impacts, challenges (Section-II), followed by optimal scheduling (Section-III), state-of-the-art literature review (Section-IV), conclusions and future directions for research on V2G (Section-V).

II. **V2G – CONCEPT AND IMPACTS**

A. V2G Concept

V2G is a new concept of transferring the power stored in the PEV battery to the grid (also called 'discharging' or 'V2G mode of operation' usually done during grid peak period) and from the grid to the PEV battery (also called 'charging' or 'G2V mode of operation' usually done during grid off-peak periods). PEVs are generally used only for 4-5% of the day and they are parked for the remaining 95- 96% of the day[9]. If PEVs can be connected to the grid when they are parked, then the stored power in their batteries can be transferred to the grid or vice versa. This concept of bidirectional power transfer between PEVs and the grid is referred to as Vehicle-to-Grid (V2G) concept [2]. The V2G concept schematic is shown in Fig.1.

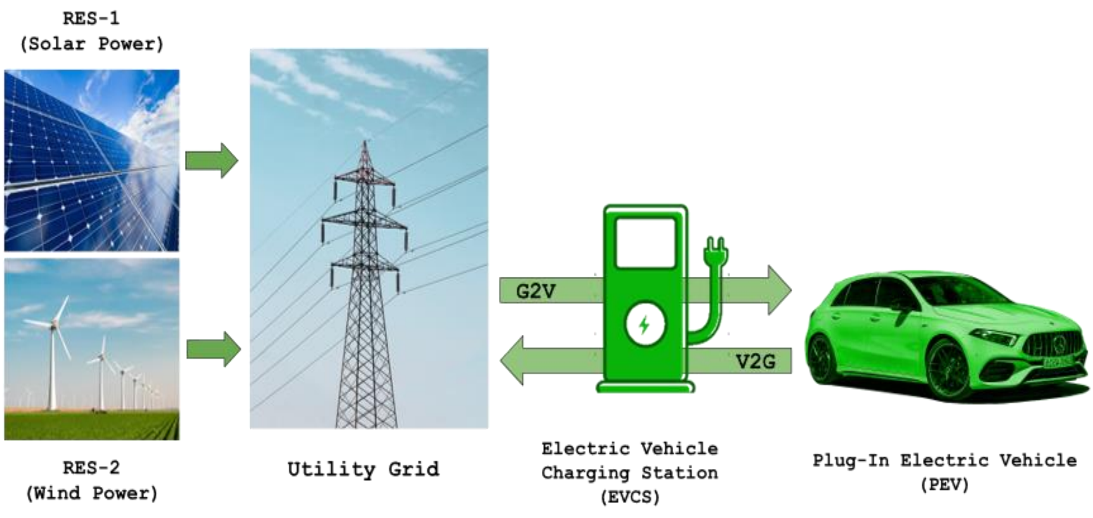

Fig.1 V2G Concept Schematic

B. V2G Impacts

The three major impact categories of V2G technology that are being investigated in recent research works are[7]: (i) Economic impacts (ii) Environmental impacts (iii) Grid impacts.

(i) Economic Impacts

From power grid perspective, the PEV charging load to be met will be huge requiring heavy investment cost to increase generation capacity and grid network reinforcement. But, by using V2G technology, the peak load can be drastically reduced using peak shaving technique. Thus, the investment cost can be significantly saved by utilizing the EVs as power generators which are readily available with their stored power in their batteries. Using V2G operation, the utility grid can purchase this stored battery power from EV owners/ aggregators to meet the huge EV charging load at cheaper cost than investing in new generation capacity addition to the grid. Saving can be further enhanced if, along with V2G technology, the RES is also utilized to meet the charging power requirement of EV load. From PEV owners/aggregators perspective, they can get financial benefit by smart charging/discharging of PEVs i.e., charging the PEVs during valley hours when the energy cost is less and discharging them during the peak hours thereby selling the power to the utility grid when the energy cost is high.

(ii) Environmental Impacts

PEVs are environmental-friendly as they are zero emission vehicles. However, they depend on electricity of the grid for charging their batteries and if that charging power is obtained from fossil-fuel fired power plants, then PEVs do not become environmental-friendly. But, if that charging power is obtained from RESs, then, that gives immense environmental benefit. To compare emissions of PEVs and ICEVs, “Well-to-Wheel” analysis is done which indicates that PEVs are environmental-friendly only if they depend on RESs for their charging electricity[10].

(iii) Grid Impacts

The charging load of large PEV fleets is huge on the power grid requiring the power generating plants to transfer a large amount of power to these PEV fleets through transmission and distribution network. The charging / discharging of an integrated PEV fleet under V2G has both positive and negative impacts on the power grid in various aspects like load profile, system components, system losses, voltage profile, phase imbalance, harmonics, stability, etc. Uncoordinated charging increases peak demand, overloads system components (like transformers, lines/cables, etc.), increases system losses, violates voltage limits, causes phase imbalance, introduces harmonics, and destabilizes the grid. However, smart (Coordinated) charging has positive impacts like flattening of grid demand profile, no-overloading of system components, reduced system losses, improved voltage profile, enhanced phase balance, no-harmonic generation, and stabilized grid. Charging management techniques [like TOU (time-of-use) price mechanism} also have positive impacts on grid. In summary, smart utilization of V2G technology offers immense benefits to utility grid operators by enabling economic, efficient, reliable, and secure operation of the grid, to PEV owners/aggregators by providing financial benefits for their participation in V2G operation. and to the environment by significantly reducing emissions thus making the entire operation economical, reliable and sustainable. The V2G deployment issues are discussed in[11].

III. **V2G – OPTIMAL SCHEDULING**

The optimal V2G scheduling, i.e., the smart (or coordinated or controlled) charging and discharging of PEVs, poses as one of the most challenging and interesting issues in research. To solve V2G optimization problems, various classical and modern artificial intelligence (AI)/heuristic optimization techniques are being used[6]. For simple and linear objectives, classical techniques like linear programming (LP), and Quadratic Programming (QP) are used to get best solutions. For more complicated V2G optimization problems, other classical techniques like mixed integer linear programming (MILP), non-linear programming (NLP), mixed integer non- linear programming (MINLP) are used. But these techniques face troubles in working with uncertain variables of real world V2G optimization problems. For complicated V2G optimization problems, alternatively, modern artificial intelligence (AI) / heuristic techniques are used. Important approaches amongst them are Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Meta-Heuristic Bat Algorithm (MHBA), Artificial Bee Colony (ABC) algorithm, etc. These approaches attempt to give global or near-global optimal solutions, but they have their own strengths and weaknesses.

Some of the V2G optimization objectives which can be achieved to get desired V2G services are: Minimization of peak demand (i.e. minimization of load variance, peak-to-average ratio (PAR)), operation cost, emission, net charging cost to PEV owner/aggregator, power losses, voltage deviations, frequency limit violations; maximization of profit/revenue, customer preferences; cost-emission optimization, etc. V2G Optimization Constraints are of two main categories: (i) Power System Constraints (ii)PEV Constraints. Some of the power system constraints are (i) power balance constraints (ii) generation capacity limits (iii) generation ramp rate limits (iv) line thermal limits (v) voltage limits, etc. Some of the PEV constraints are: (i) PEV Battery charging/discharging power constraints (ii) PEV Battery State-of-charge (SOC) max/min limits (iii) PEV availability, etc.[12].

IV. **STATE-OF-THE-ART LITERATURE REVIEW**

Among the various impacts of V2G technology on the grid [13], the impacts of V2G scheduling on grid peak demand management (using peak shaving and valley filling techniques) and on the environment (emission reduction) have been chosen for review in this paper. The corresponding literature survey of recent research works has been carried out and is discussed as follows.

Major peak shaving technologies are Peak Load Plants (PLPs), Demand Side Management (DSM), Energy Storage Systems (ESSs), and Electric Vehicles (EVs) [14]. In [6], the V2G - concept & framework, types, services, advantages, and challenges - have been reviewed. A detailed review of various categories of peak shaving technologies/strategies has been carried out in [8] and [14]. In [15], two decentralized EV charge scheduling schemes, viz. (i) C-VF (Coordinated Valley-Filling) of the load curve using EV charging only (ii) C-VF-PS (Coordinated-Valley-Filling - Peak-Shaving) of the load curve using EV charging and discharging have been proposed for changing the shape of the residential community’s consumption profile. To meet the maximum consumption in the residential grid, a proposal for an aggregated coordination mechanism is made in the article [16]. Mixed-integer programming technique has been applied to minimize the energy price which benefits PEV owners and to handle maximum load grid constraints which benefit grid operators. Utilizing fully the V2G technology and EVs operational flexibilities, an algorithm based on a scheduling framework has been presented in [17] to achieve the goal of peak load reduction/shaving in smart buildings powered by a team of cooperative microgrids (TCM). To enhance the grid for incorporation of large-scale PEVs, a Distributed Resource Allocation (DRA) method using V2G technology has been introduced in [18]. A strategy to solve the dynamic economic/emission dispatch (DEED) problem including PEVs is presented in [12]. An analysis of DEED's influence on fuel cost and emission has been presented. During DEED, PEVs are used for shaving the peak demand and filling the valley. MHBA (Metaheuristic Bat Algorithm) and water filling algorithm have been applied. It is shown through the simulation results that PEVs are an effective method to tackle increasing maximum demand problem along with reducing operation & emission costs, thus saving huge amount of investment on peak load plants.

The review of impacts, benefits & challenges of V2G on distributed grids has been presented in [19]. The article [20] proposes an augmented epsilon-constraint (AUGMECON) based method for load profile peak-shaving and valley-filling using multi- objective co-optimizations for residential aggregated PEV fleet to achieve both PEV owners' objectives (such as minimizing charging cost and battery degradation) and grid operator's objectives (such as smooth maintenance of supply & demand). A fast-converging distributed demand response (DR) algorithm minimizes the PAR of the residential PEVs' aggregated daily load. In the study of [21], coordinated EV charging has been carried out for valley-filling by following a centralized approach.

Applying V2B (vehicle-to-building) concept to a university building, a mathematical model is presented in [22] to flatten its load curve (by shaving the peak portion and filling the valley portion of its load profile. In [23], for multiple PEV aggregators, a coordination strategy has been proposed to minimize the maximum demand and fill the valley of the load curve through PEV smart discharge/ charge processes during high demand and low demand periods respectively. To minimize the load variance, an investigation on V2G optimal scheduling has been carried out in [24]. The optimization algorithm uses the genetic algorithm (GA) and it is analyzed using different selections of target load and SOCs of EVs. To determine the EV fleet size capability of an existing power grid network in both V2G and uncoordinated operation modes considering economic emission dispatch (EED), an optimization model has been proposed in [25]. Properties and efficient algorithms for dynamic/online PEV charge scheduling based on Time-of-Use (TOU) pricing and peak load minimization have been discussed in [26].A holistic model to optimize weekly dispatch of microgrid generating sources including stochasticity of (a) PHEVs (b) solar/wind resources, and (c) load etc., is introduced in[27]. Gravitational Search Algorithm (GSA) & Water Cycle Algorithm (WCA) are the two heuristic-based approaches for cost and emission minimization. This work highlights that integrating RERs (Renewable Energy Resources) is important for decarbonization of the system and RERs volatility can be reduced by the connected PHEVs. In [28], EV penetration as dynamic load along with its V2G impact in a controlled or uncontrolled manner and utilization of PSO and ABC algorithms with short-term load shedding scenarios have been investigated in hybrid renewable energy based V2G MG.

Future search algorithm (FSA) is a recent nature–inspired meta-heuristic algorithm and it has been applied in [29] to tackle a multi-objective optimization problem. DGs and EV fleets scheduling is done together in radial distribution systems. The multi-objective function has been formulated using real power loss, average voltage deviation index (AVDI), voltage stability index (VSI) and greenhouse gas (GHG) emission. FSA has resulted in the lowest objective function when compared with different other latest heuristic approaches. A comprehensive assessment of electric vehicle development, deployment, and policy initiatives to reduce ghg emissions is carried out in [30]. A bi- objective model for the EED optimization of EV intelligent parking lot (IPL) has been studied in [31]. Two cases - with and without demand response program (DRP) have been studied using time of use (TOU) rate. The weighted sum and fuzzy decision-making algorithms have been used for finding solution to the optimization problem. It has been shown that the total emission and operation cost of the EV IPLs can be significantly reduced by applying DRP.

A multi-objective scheduling technique which is founded on augmented e- constraint method for EVs charging/discharging to minimize both the operational costs & pollution in a smart distribution system is proposed in [32]. The V2G capability and the actual drivers' patterns are considered to produce the solutions which are pareto-optimal. The Benders decomposition technique has been applied to solve the optimization model formulated for 33-bus distribution test system. It is shown in the results that both the operation cost and polluting emissions can be significantly reduced by the proposed EVs' smart charge/discharge scheduling technique. With the aim of scheduling EVs, the multi-objective-techno- economic-environmental optimization (MOTEEO) concept has been presented in [33]-[35]. Four optimization objectives, i.e., energy cost minimization, EV battery degradation, grid net power exchange and CO2 emissions have been modeled in the context of home micro-grid and for the first time optimized simultaneously while giving frequency regulation support to the grid. Further, an added objective of providing ancillary services to the grid by making use of EV batteries has been considered its influence on other objectives has been investigated. The results reveal a very significant improvement in achieving all the optimization objectives when compared to uncontrolled EV charging. The Authors of [34] have used the strategy of drawing and injecting power by deploying EVs to optimally dispatch MG energy resources. The cost of energy and cost of emission control have been considered in framing the objective function. It is shown through calculations that orderly drawing/injecting power by EVs with the TOU price applied not only effectively reduces the difference between peak and valley and the users' electricity cost, but also benefit the environment. In [35], a summary of the methods and techniques for PEV charging strategies is presented based on machine learning and probabilities approach. Deep reinforcement learning has been applied in [36] to minimize the charging time of PEVs which in turn smoothens the grid load profile. of the current designations.

V. CONCLUSIONS

In this paper, a state-of-the-art review of recent research works on optimal V2G scheduling of PEVs for grid peak demand management and decarbonization has been presented. The review study has revealed that the optimal V2G scheduling of PEVs has a great potential to offer a cost-effective solution to minimize the grid peak demand and emissions along with achieving many other objectives like minimizing cost, voltage deviations, etc. It is also observed that further investigation is still needed to effectively handle the huge charging power requirement of large-scale grid-integrated PEVs. It is observed in this review that the research works have been carried out mainly on peak shaving or valley filling techniques only, but only a few studies have considered both. Future research works may investigate more deeply the impact of optimal V2G scheduling on both peak shaving and valley filling of PEVs to make it more effective in grid peak demand management. Advanced methods based on machine learning, deep learning, reinforcement learning, etc., are still to be explored more for effective optimal V2G scheduling.

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