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Bidirectional Electric Vehicle Charging for Grid Flexibility and Renewable Integration

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Abstract. The growing infiltration of renewable energy sources (RES) has completely changed the nature of the global power system raising some key issues like intermittency and grid instability. So is in consideration with the reality that as the current numbers of electric vehicles and their rapidly growing numbers exist, the combined capacity of battery storage in electric vehicles reveal colossal opportunities in relation to electric cars as a distributed source of energy. The paper will examine the technical feasibility, operational principles, and the possible utility of bidirectional charging of EVs, also referred to as Vehicle-to-Grid (V2G) to control the functioning of the grid and facilitate the incorporation of renewable energetic sources. We discuss the system architecture, control algorithm and market applications of V2G technology through a combination of theoretical analysis and through case studies; we find that V2G can greatly improve grid stability, curtailment of renewable energy, and offer economic gains to an EV owner. Nevertheless, to unlock this potential, it is crucial to adequately overcome some of the critical challenges such as battery degradation, cybersecurity threats, and coordination challenges. The findings present technical and policy data regarding the enhancement of EVs integration as flexibilities in the grid.

Keywords: Electric cars, Charging piles, Vehicle-to-grid, Bidirectional charging, Grid regulation

1. Introduction

The quest by some countries to lessen the effects of the climate change besides ensuring carbon neutrality has increased the use of clean sources of energy especially the use of renewable sources of energy like the wind and solar energy. Admittedly, these technologies are of highly sensitive influence in terms of mitigating the emission of greenhouse gasses, the inability and variability of the technologies complicate stability and reliability of the power systems. This intermittency raises demand on grid flexibility that may be provided by demand response and distributed energy storage application to level grid frequency, voltage and supply-demand balance [1].

On that note, electric vehicles (EVs) tend to be considered a disruptive technology. They are accepted due to the blistering development of the battery technology, the decrease in the cost of the technology, the government stimuli, and changes of the mobility policies. EV batteries are a storage of distributed energy in large scale that exists as a giant, and is not used in long durations of time.

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This hidden potential can be utilized through bidirectional charging which is the ability to convert EVs into active participants in the grid that could inject power when required in peak demand or receive surplus generation when it was overproduced [2].

The concept of bidirectional charging (this is enabled, in particular, with the assistance of the Vehicle-to-Grid (V2G) systems) will enable the EVs to store the surplus of renewable energy during the periods of the low demand and provide the power to the grid during the periods of peak. This not only tends to enhance the grid capacity and integration of renewable but offers economic options to EV owners via energy arbitrage. The individuals would be allowed to purchase electricity during off-peak periods and sell it during on-peak periods at a higher rate that will force them to take financial incentive to be actively involved in the grid activity. Nonetheless, there are numerous technical, financial, and regulatory issues that should be regarded with mass penetration of V2G technology. These are battery degradation, interoperability between vehicle-grid operator, cybersecurity, and it assist in coming up with suitable compensation schemes to its participants. This paper presents a methodological view of the architecture, control policies, applications, and policy aspect of bidirectional charging to follow that this is an imperative component of the design of a sustainable and resilient future power system [3].

2. Technical control principles and architecture

2.1. Core definition

The reality is called Bidirectional charging where one can not only charge the EVs in the grid, but also can deliver power to the grid besides, through the bidirectional power converter. As compared to traditional unidirectional chargers that can only convert AC to DC to flow in the grid-to-vehicle (G2V) direction, V2G systems enable bidirectional supply of power and thus enables EVs to act as distributed controllable power sources and provide auxiliary services needed by the grid operator, including frequency control, voltage support, peak load shaving, and emergency reserve power.

In conjunction with intelligent control algorithms, the stability of power flow, voltage, and current, as well as charge the battery in the most efficient manner will be guaranteed by the use of bidirectional chargers [4].

2.2. System components

An integrated bidirectional (V2G) system architecture includes four main elements: on-board charger (OBC), charging station, grid interface, and a cloud-based control platform. On-board Bidirectional Charger (OBC): It is the OBC which manages the conversion of core power i.e. converting grid alternating current (AC) to direct current (DC) to charge the battery, and convert battery DC back to AC to discharge to the grid. More recent OBCs are built with modern power electronics which is based on Silicon carbide (SiC) MOSFETs and Insulated Gate Bipolar transistors (IGBTs) to generate high efficiency, better thermal characteristics and almost lower losses. Moreover, they include smart algorithms to implement real-time curve adjustments of charging and discharging currents, between energy delivery needs and battery degradation issues.

The charging stations: In addition to the normal charging feature, the V2G stations shall also have an improved insulation control, earth fault faults and the bi-directional energy control. Decay and overvoltage are the clear signs of the safety of equipment and its users. The metered online energy allows amendment against finances as well as give working feedback to the control platform.

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Grid Interface/Communication Unit: This unit ensures ongoing two-way dialogue of data between the Electric Vehicle (EV) or charging station as well as between the utility or the grid operator. It relays important real-time parameters including the state-of-charge (SOC) of the vehicle, its battery temperature and discharge power. The grid operator can use this information to provide coordinated power dispatch requests due to grid conditions, and to make sure that the vehicle is available and ready to drive. The illustration of the Grid Interface/Communication Unit including the distribution of these parameters to the grid system that optimizes the power distribution is given in Figure 1.

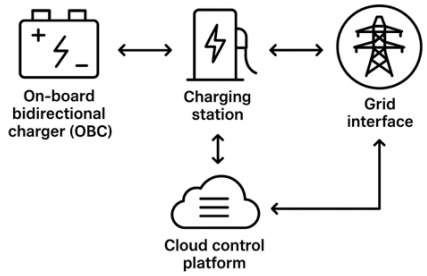

Figure 1. Grid interface/communication unit

Cloud control platform: Thousands of EVs and charging stations are informed on a central cloud server and the process of charge and discharge optimization is performed based on the dynamic of electrical prices, loads forecasted on the grid, and renewable generation dynamics (Han et al., 2020). The predictive algorithms and machine learning will enable the platform to forecast the highest load hours, renewable curtailment, and emergencies circumstances therefore giving the system and user the utmost efficiency and revenue [5].

3. Use cases and requirement analysis

3.1. Load balancing and grid peak shaving

The demand of electricity is generally highly volatile regarding the changes on a daily and seasonal basis. This volatility creates an opportunity for V2G: EVs can be charged during off-peak hours when electricity prices are low and discharge back to the grid during peak hours when prices are high.

This process, known as peak shaving and valley filling, reduces the reliance on fossil-fuel-based peaking power plants. Consequently, it enhances overall system performance and reduces carbon emissions. Japanese and Danish simulators indicate that V2G coordinated efforts will result in a reduction of peak loads by approximately 10 per cent in a system and also, an improvement in voltage stability. On top of that, EV aggregation can allow utilities to be responsive to local affects on loads in a nondeterminate manner, a quality that has the side effect of smoothing out demand spikes and increasing transmission capacity. Besides technical benefits, peak shaving via V2G could result in a dramatic financial benefit in terms of reduction of the generative cost, as well as elimination of purchasing new peaking plants [6].

3.2. Emergency and backup power

Besides the capability to operate the regular grid, the bidirectional charging of EVs can equally be incorporated on a decentralized basis on a mobile basis as an emergency source of power in case of

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a natural calamity, power failure or a breakdown of the infrastructure [7]. Unlike the conventional backup generators, EVs have a high rate of deployment, portability, and the use of clean energy. As a case in point, in 2011 when an earthquake and tsunami struck Tohoku, Japan, there was rampant destruction of the hospital, telecommunications networks and emergency phone lines. V2G EVs offered emergency electricity to critical infrastructure that allowed the use of medical machinery, lighting, and communications units in the short (temporarily) [8].

The V2G technology has the capacity to strengthen the community as well by establishing emergency microgrids. Clusters of EVs can provide power to remote or underserved locations, reducing the reliance on centralized grid infrastructure. Modeling studies of hurricanes in coastal regions suggest that a fleet of 500 to 1000 EVs could provide continuous power to critical services for 24 to 48 hours [9]. These applications reduce reliance of diesel generators, reduce emissions and provide cost-effective and speedy response due to crisis.

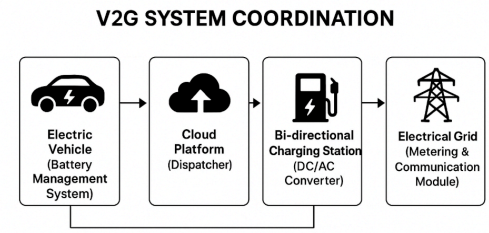

Figure 2. V2G system coordination

Figure 2 illustrates the coordination of such a V2G system. Smart control platforms are essential in these scenarios to prioritize power delivery to critical loads, prevent excessive battery discharge that would compromise EV mobility, and optimally dispatch the available energy.

The predictive programs compute the grid restoration timetables and adjust the pace of discharge to ensure the process becomes successful as possible. The large social resource of aggregated emergency capacity can be utilized with the rise in EV adoption since the increased V2G technology value in society underlines the nature of its social significance of the technology, greater than standard economics on the grid.

3.3. Markets and supporting services

Bidirectional EVs have the potential to provide a range of valuable ancillary services to electricity markets, including frequency regulation, spinning reserve, reactive power support, and voltage control. Its architecture is illustrated in Figure 3. Unlike traditional centralized storage, which may have slower response times, aggregated EV fleets managed via real-time communication can respond to grid disturbances within seconds, providing rapid frequency regulation and enhancing grid stability [10].

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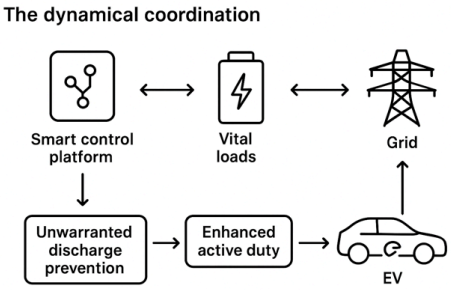

Figure 3. Dynamic coordination

Such services have a huge market potential. EV owners will additionally exploit idle capacity of the battery through the assistance of the markets of ancillary services. As an example, during pilot programs in California and the Netherlands, aggregated V2G teams were awarded between 250 and 500 U.S. dollars per automobile every year depending on the circumstances on the market and availability periods [11]. Furthermore, V2G facilitates renewable integration by having EVs absorb excess solar and wind generation during periods of low demand, thereby reducing renewable energy curtailment and increasing its productive utilization.

There is however, an impediment of behavior, as there is the technical barrier, in mass involvement. Some of the risks as the users see it relate to accelerated battery depreciation, reduced supply of the vehicle, and more sophisticated energy management. These have to be avoided by means of just compensation frameworks, open-minded planning, and predictive devices of battery control. Effective incentive schemes may include time-of-use (TOU) pricing with favorable off-peak rates, availability payments for enrollment, and performance-based rewards for actual grid service provision.

The integration of these factors in the policy and market strategy will result in more people adopting it and have the ability to maintain user satisfaction and battery health in the future.

4. Technical challenges and solutions

4.1. Battery degradation management

One of the most significant technical hurdles facing V2G systems is accelerated battery degradation. The charge/discharge (especially high charge/discharge) rate of the lithium-ion batteries can result in a process of aging the batteries and hence reducing the working life of the lithium-ion batteries, leading to higher costs of operation. It has been discovered that the standard EV batteries may reduce capacity by 3-5 percent annually in case of uncontrolled two-way utilization [12]. Strategy of adaptive battery management must be employed to contain this issue. These schemes maintain the constant monitoring of the state-of-charge (SOC) and the state-of-health (SOH) of the battery and consequently adjust the charging or discharging rates of the battery based on their age, temperature changes and the past use.

Advanced control algorithms can limit the depth-of-discharge (DOD), minimize current ramps, and optimize energy dispatch schedules to reduce mechanical and thermal stress on the battery. Empirical estimations indicate that, based on intelligent scheduling, the yearly reduction in capacity may decrease to less than 2 percent even in cases where V2G operations take place daily [13]. Also, future machine learning technologies have a potential to forecast battery degradation patterns as they

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forecast through real-time data related to operations, as well as the past performance. Such predictive models can empower utilities and fleet operators to fit V2G operations without violating battery life and guarantee technical feasibility and economic sustainability. Some examples can be seen in the pilot projects in California which have shown that predictive scheduling not only can increase the battery life and maximize income on grid services but also balance user convenience and system performance.

4.2. Safety and reliability

Bidirectional charging also presents new safety risks because of high voltage, high currents flowing, and constant cycling, which raises the potential of overheating, short circuiting and occurrence of thermal runaway. In order to provide operational safety, the layered protection features are used, such as overvoltage and overcurrent protection, insulation monitoring, and real-time thermal management [13]. Active cooling systems, regulated by temperature sensors such as thermocouples, mitigate the risk of overheating, maintaining the battery and power electronics within safe operating limits. Cybersecurity is equally critical. Given that V2G systems are in constant communication with grid operators and charging points, they are potential targets for cyberattacks.

4.3. Co-ordination and market integration

To achieve the most advantageous technical and economic benefit, it is difficult and is complicated but necessary to organize thousands of EVs, different charging points, and utility process. Cloud based control systems are used to gather data on the EVs and the stations to maximize the charge-discharge times, check the health status of the battery and also provide other related services such as frequency modulation or voltage assistance. The Multi-agent coordination algorithm will allow the dynamically reactive reaction of the local grid conditions, prices of electricity and varying renewable production to decentralized EV fleets to be optimally engaged without interfering with the stability of the grid.

Institutions serving the region are very keen on promoting mass integration. The policies should specify the compensation method that should be applied during the delivery of the energy, availability and participation of ancillary service, whereby the residential and commercial customer should have equal access to the services. Pilot projects and public-private partnerships are critical for testing solutions at scale, refining coordination algorithms, and validating market models prior to widespread deployment. Examples from European and Japanese V2G pilot projects have demonstrated that centralized fleet management can significantly reduce peak demand, optimize renewable energy utilization, and provide participants with tangible economic benefits.

5. Economic and policy considerations

The bidirectional charging would transform EVs into revenue generating resources since its owners can leverage on any fluctuation in prices in relation to time of the variation of electricity. During periods of peak demand or grid congestion, EVs will be empowered to inject power into the grid at high prices, and will insert it back at low prices at some other times when demand is low. Studies estimate that individual EV owners could achieve net annual savings (or revenue) of $200 to $400 under typical tariff schemes, which can offset the associated costs of battery degradation and vehicle maintenance [13]. At the system-wide scale, making use of V2G extensively reduces the required

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stationary storage and peaking generation capacity, which results in the reduction of the cost of electricity systems and improved the efficiency of the grid.

It is only possible to attain the economic benefits with the assistance of the government and regulatory clarity. A few examples of incentives that can be utilized to promote the adoption are dynamic electricity pricing, grid service payments, V2G-compatible chargers subsidies, and favorable interconnection standards. European Union has a decarbonization roadmap known as Fit for 55 that includes V2G expressly explicitly as it improves pilot projects and the market establishment. Similarly, the plan of New Energy Vehicle Development of China (2021-2035) targets the use of smart charging and V2G demonstrations to further enhance the integration of renewable energy. To accelerate deployment even, the public-private unions are known to legitimize the technical performance, market viability, and user acceptability in a real-world setting [14].

Besides offering monetary incentives, the structures implemented by policy makers ought to address cybersecurity needs, interoperability and fair-participation policy. Transparent compensation and self-evident market procedure boost trust and willingness of the users to participate in it, and it will result in the sustainable expansion of the V2G systems. The ultimate remedy is to integrate EVs as a distributed energy source, which is flexible and has the capability to provide resilience and low-carbon power grid with particular merits that translate into concrete benefits to consumers and utilities.

6. Conclusion

This paper has presented a comprehensive analysis of the technological architecture, operational mechanisms, and strategic policy considerations for bidirectional EV charging. The results support the argument V2G systems can be significant to provide the grid with additional flexibility, the ability to use renewable energy sources, and the economic benefit to the players. Technical advances in power electronics, communication and battery management then allow large-scale implementation. Nonetheless, realizing the full potential of V2G requires further research and development in several key areas, including predictive control algorithms, robust cybersecurity frameworks, and the design of equitable market structures. One of the most important operations in the achievement of the resilient, low-carbon, and smart energy future will be the inclusion of EVs in a decentralized and digitalized grid.

References

[1] Lund, H., & Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy, 36(9), 3578–3587.
[2] Sovacool, B. K., Noel, L., & Axsen, J. (2022). Flexibility and energy transitions: A review. Energy Research & Social Science, 89, 102642.
[3] International Energy Agency (IEA). (2024). Global EV Outlook 2024. Paris: IEA.
[4] Gough, R., Dickerson, C., Rowley, P., & Walsh, C. (2021). Vehicle-to-grid feasibility: A techno-economic analysis of EV energy storage. Applied Energy, 285, 116408.
[5] Kempton, W., & Tomic, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting renewable integration. Journal of Power Sources, 144(1), 280–294.
[6] Yilmaz, M., & Krein, P. T. (2013). Review of battery charger topologies and infrastructure for plug-in vehicles. IEEE Transactions on Power Electronics, 28(5), 2151–2169.
[7] Han, S., Han, S., & Sezaki, K. (2020). Development of an optimal V2G aggregator for frequency regulation. IEEE Transactions on Smart Grid, 11(3), 1963–1972.
[8] Shen, M., Li, Y., & Zhou, D. (2022). Safety analysis of V2G-enabled charging stations. Renewable Energy, 184, 1120–1132.

DOI: 10.54254/2755-2721/2026.KA30044

[9] Mwasilu, F., Justo, J. J., Kim, E. K., Do, T. D., & Jung, J. W. (2014). Electric vehicles and smart grid interaction: A review. Renewable and Sustainable Energy Reviews, 34, 501–516.
[10] Han, S., et al. (2020). Predictive control in vehicle-to-grid systems. IEEE Transactions on Power Systems, 35(6), 4513–4523.
[11] Kempton, W., & Letendre, S. E. (1997). Electric vehicles as a new power source for electric utilities. Transportation Research Part D, 2(3), 157–175.
[12] Tomic, J., & Kempton, W. (2007). Using fleets of electric-drive vehicles for grid support. Journal of Power Sources, 168(2), 459–468.
[13] Sovacool, B. K., et al. (2022). Distributed resilience: V2G and disaster recovery. Energy Research & Social Science, 88, 102554.
[14] Han, S., et al. (2020). Modeling V2G for disaster response. IEEE Access, 8, 137245–137256.