Security of Supply with V2G Technology

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Abstract: The increasing adoption of electric vehicles is expected to substantially raise electricity demand. This could require significant grid investment to maintain secure electricity supply, which has traditionally been provided through infrastructure upgrades. The potential of smart technologies like Vehicle-to-Grid (V2G) to contribute to security of supply has prompted the need to quantify their impact. We hypothesize that the F-Factor methodology can effectively quantify V2G's security of supply contribution. Applying F-Factor analysis to V2G through optimization modelling and sensitivity studies, we find that key parameters like V2G charger ratings, EV battery capacities, and load profile peakiness significantly influence the results. We conclude that the F-Factor provides a valuable tool for assessing V2G's potential to enhance security of supply, with implications for more efficient grid planning in the context of transport electrification.

Keywords: Electric vehicles, Optimization, Security of supply, Vehicle-to-Grid

Introduction

- Backdrop of the Study

With the growing use of electric vehicles (EVs), the transportation industry is becoming more and more electrified, which represents a dramatic change in the direction of environmentally friendly and sustainable transportation. Battery technology advancements, power demand management technologies like demand-side response, and EV charging technologies like smart charging, vehicle-to-building (V2B), and vehicle-to-grid (V2G) are also driving this transition (Amann et al., 2022).

Adopting EVs has significant positive effects on the environment, including lower emissions and a decreased dependency on fossil fuels, but there are drawbacks as well, mainly with regard to power consumption (Giannelos et al., 2023a). Because charging an EV adds a significant amount of power load, the widespread usage of EVs can result in a huge increase in peak electricity demand. Therefore, significant investments may be required to improve the grid infrastructure in order to maintain the same level of supply security. These investments might be made in smart technologies in addition to traditional ones. In particular, it has been demonstrated that the introduction of new smart technologies and ideas, such as demand response systems, smart charging, and V2G, may make it possible to manage the increased load more effectively and make it easier for EVs to be seamlessly integrated into the current energy ecosystem (Borozan et al., 2022a). This research is driven by the pressing need to maximize the potential benefits of electric vehicles (EVs) for the grid while addressing the issues raised by their rapid deployment. Electricity grids are under increasing pressure as nations set lofty goals for EV adoption in order to fulfill climate goals. Since traditional methods of grid reinforcement are frequently expensive and time-consuming, it is critical to look at cutting-edge approaches that can improve grid resilience and offer flexibility.

In this context, V2G technology appears to be a promising answer. With the help of V2G, EVs could become useful distributed energy resources rather than just loads by allowing bidirectional power flow between them and the grid. This capability might potentially lessen or postpone the need for expensive grid upgrades while also greatly reducing peak demand pressures and improving system stability. But in order to reap the full rewards of V2G, reliable techniques for measuring its impact on grid security and dependability must be developed.

By permitting the bidirectional flow of electricity from the grid to EVs and vice versa, V2G can be viewed in this context as an investment option that can lower peak demand (Most et al., 2020). As a result of reducing peak loads and minimizing grid overloading, V2G contributes to a more constant and dependable supply of energy for customers, which has been demonstrated to be equivalent to providing security of supply (Ilo et al., 2019). Given that V2G technology can help ensure a reliable supply of power, the question of how to measure this contribution now arises. To this end, the current study introduces the F-Factor technique, which enables the measurement of V2G technology's contribution to supply-side electrical security. This methodology is being used to V2G for the first time with the current study.

Additionally, the necessity to close the gap between the theoretical potential and real-world use of V2G technology is what motivates this research. Even while V2G has been shown to be technically feasible in several studies, there are still no established techniques for evaluating its usefulness to the grid, especially in terms of supply security. This disparity prevents the creation of suitable market mechanisms and regulatory frameworks that may encourage the deployment of V2G and appropriately reward EV owners for the grid services they render. It should be noted that the regulatory frameworks in place at the moment do not specify any formal approach for quantifying the contribution of smart technology to supply security. For instance, the Distribution Network Operators in Great Britain adhere to Engineering Recommendation P2/6 (Electricity Networks Association, 2006) as their guideline for distribution network planning. The implementation of electrification in the transportation sector and the shift to a smart grid in general may be hampered by an inconsistent approach (Beulertz et al., 2019; Charousset-Brignol et al., 2021; Giannelos et al., 2023b; Münster et al., 2020).

Therefore, in order to account for the security contribution of non-network solutions like V2G, an update to the planning standards is required. Within this framework, the current research formalizes a method for quantifying the security contribution of V2G dubbed F-Factors. This method is both qualitatively and quantitatively crystallized through a case study.

• Literature Review

Power transformers and electrical transmission and distribution lines are two examples of the conventional technologies that have historically been invested in to ensure the security of the electricity supply (Greenwood et al., 2020). Smart grid technologies, like V2B, dynamic line rating (Giannelos et al., 2018a), demand side response (Giannelos et al., 2017, 2018, 2018b), coordinated voltage control (Konstantelos et al., March 2017), energy storage (Giannelos et al., 2019), and soft open points (Giannelos et al., 2015, 2016), have, however, been developing over the past few years. There have been requests for the modification of the notion of security of supply to include such non-network solutions due to the advancement of technology and plans for the widespread implementation of such technologies (Giannelos et al., 2021).

The first study by EPRI in 1976 (Public Service Electric & Gas Company, 1976) acknowledged the potential of energy storage to provide supply security by highlighting the fact that utilities can consider long-duration storage devices (like pumped hydro storage) as sources of dependable capacity because they can discharge during times of peak demand. After that, research concentrated on techniques for estimating the contribution of energy storage to supply security, such as dynamic programming as described by Sioshansi et al. (2014), while taking system functioning and power system voltages into account. That being said, this approach was more concerned with disruptions than with lowering peak demand. The effective load-carrying capability of energy storage, a proxy for its security contribution, was calculated by the authors in Konstantelos, (2018) using a probabilistic methodology based on chronological Monte Carlo simulations. This methodology took into account the energy storage's capacity to charge during partial outage conditions, such as when only a portion of the substation transformers are online. The intricacy of this methodology necessitated lengthy solution times, sometimes even weeks, which made it impractical to carry out extensive sensitivity assessments. Furthermore, Abdullah et al. (2013) calculate energy storage's security contribution when it's utilized to smooth a wind farm's output, once more with an emphasis on outages.

The energy storage security contribution is computed by the authors in Leite da Silva et al. (2006) by concentrating on energy storage assets that are installed at islanded microgrids as opposed to on the main grid. The previously described methods concentrated on energy storage and did not take electric vehicles (EVs) into account.

Current study on V2G technology is centered on how it will affect the distribution grid and whether it will reduce the need for traditional reinforcements. The writers of Mastoi et al. (2023) stress the value of V2G technology, especially in times of outage, and they propose that V2G can improve grid resilience. Sultan et al. (2022) mention the possibility of V2G to improve supply security and provide a list of further possible advantages. According to Owens et al. (2022), V2G can function as a component of an aggregator business model, in which the aggregator optimizes each vehicle's charge and discharge to act as a load and bulk energy resource in concert. In addition, Bayani et al. (2022) examine the effects of electrifying transportation, including how EVs can function as distributed power resources or loads while taking V2G technology into consideration. This implies that V2G has a part to play in maintaining grid stability and giving customers a reliable supply of electricity. Additionally, V2G can facilitate the integration of variable distributed renewable power, according to O'Neill et al. (2022), which may have a favorable effect on grid sustainability and stability. The authors of Tirunagari et al., (2022) discuss how EVs can affect the energy and power sectors and improve supply security of electricity by using smart charging and V2G.

The authors of Sachan and Adnan (2018) examine how different electric vehicle (EV) charging techniques affect distribution grids with an emphasis on lowering network peak load demand and enhancing voltage stability. In order to maximize charging prices and network restrictions, the research presents a stochastic model that takes into account the fluctuation of EV availability, such as arrival and departure times, as well as wind power generation. The report suggests a coordinated charging method to maximize EV integration while reducing expenses and grid losses. It also suggests modifying the grid infrastructure to improve EV integration without significantly reinforcing it.

Furthermore, a method for figuring out how many electric cars (EVs) can fit into a distribution network securely without going over its capacity is suggested by Sachan and Kishor (2016). Using a performance index, it transfers EV loads from impacted feeders to neighboring feeders in order to evaluate the effect of contingencies on EV charging. In order to minimize operational expenses and ensure grid stability during emergencies, the project also designs a communication network for smart charging.

Next, Sachan et al. (2020) investigate the effects on the power grid of several charging infrastructures, such as dispersed, quick, and battery swapping. Based on variables such as availability, driving habits, and charging expenses, it contrasts various infrastructures and concludes that distributed infrastructure has superior regulation power and is the most economical option. The study also assesses smart charging tactics and comes to the conclusion that, in comparison to uncoordinated charging, intelligent, coordinated charging—particularly power factor control—minimizes the effects of peak loads and improves grid performance.

A thorough analysis of current guidelines and procedures for integrating electric vehicle (EV) charging stations with utility grids is given by the authors in Sachan et al., 2022. In order to provide secure, dependable, and interoperable grid integration, the paper highlights the significance of standards and best practices. The article also addresses technical issues and makes suggestions for further implementation and study on the use of V2G technology and distributed energy resources (DER) in power system operations.

Using a chicken swarm optimization (CSO) algorithm, the authors of Sachan et al., (2021) describe a revolutionary method for the ideal placement and operation of electric vehicle (EV) charging stations. The planning and operational elements are combined in the study to create a multiobjective framework that takes grid reliability, voltage stability, and cost into account. The evaluation of three charging strategies—bidirectional V2G, coordinated charging, and uncoordinated charging—shows that coordinated charging and V2G are superior to uncoordinated charging in terms of grid stability and efficiency. Nevertheless, no methodology for quantifying V2G's contribution to the supply of power is presented in any of the research that is currently available. As such, the current research presents the first thorough approach for quantifying the contribution of V2G technology to supply security in the literature. Take note that the majority of the literature, including Black and Strbac (2007), Denholm and Sioshansi (2009), Drury et al. (2011), and Thatte (2012), quantifies the energy storage capacity value using reliability metrics and technoeconomics. Mean time to repair or mean time before failure are two examples of grid asset dependability metrics that are not taken into account by the F-Factor technique. F-Factors, on the other hand, emphasize the greatest peak reduction attained.

F-Factor in V2G Operation

There are ways to reduce peak demand when charging and discharging electric vehicles (EVs) using V2G chargers. To be more precise, the EVs can be charged during times when system demand is relatively low. This charge is then released during times when demand is peak or near-peak, which eventually results in reduction. This may result in the costly traditional network strengthening that would otherwise be necessary for the safe accommodation of power flows being delayed or displaced (i.e., prevented). It can also help with supply security since, in times of high demand, the unexpected loss of a vital network component could cause disruptions in the power supply to customers. These can be prevented by using V2G to reduce peak demand. In the current research, the F-Factor metric is applied for the first time to assess the security contribution of V2G technologies. According to Eq. (1) below, the F-Factor metric is specifically defined as the ratio of the ideal reduction in peak electricity consumption, denoted by P, over the power capability of the V2G technology, denoted by C. This metric is dimensionless in this sense because the numerator and denominator are measured in the same units; as a result, it is frequently stated in percentage terms.

$$F = \frac{P}{C} \qquad (1)$$

The mathematical optimization model, which is described in sub-Sect. "The optimization model," has an optimal solution as its numerator. With the use of V2G, this model can reduce peak demand as efficiently as possible. Conversely, the denominator is not the result of an optimization research; rather, it is an input parameter.

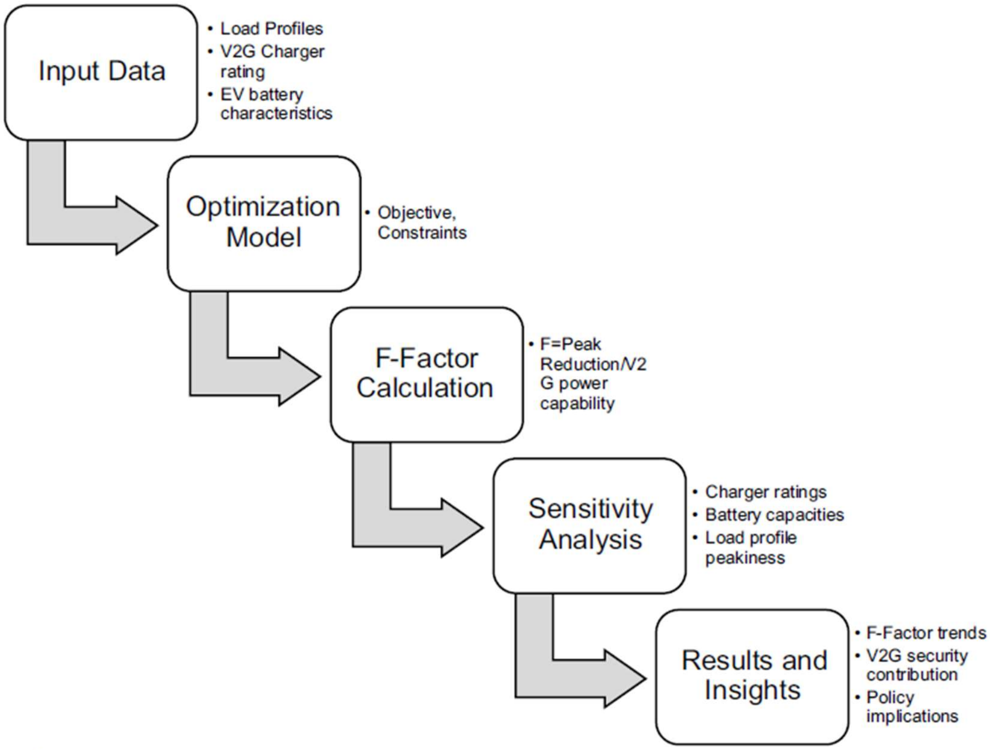

Fig. 1 V2G F-Factor methodology framework diagram

1. Enter data: This first part includes all of the necessary information needed to perform the analysis. Included in it are load profiles, which show the typical patterns of electricity use; V2G charger ratings, which specify the infrastructure's power capability; and EV battery capacities, which indicate the fleet of vehicles' potential for energy storage. These inputs immediately impact the potential security contribution of V2G technology and serve as the basis for our following evaluations.
2. Optimization model: The optimization model is the essential component of the methodology. By carefully planning V2G operations, the mathematical formulation seeks to reduce peak electricity usage. To ensure practical and realistic answers, the model adds a number of constraints, such as charger power limits and EV state of charge limitations. Through the resolution of this optimization issue, we ascertain the highest possible peak reduction that V2G technology can achieve.
3. Calculation of the F-Factor: After optimization, we determine the F-Factor, which measures the security contribution of V2G. The optimization model's calculated achieved peak demand decrease divided by the total V2G power capability is the F-Factor. This indicator offers a consistent way to assess how well V2G is improving grid security.
4. Sensitivity analysis: We carry out thorough sensitivity analyses to acquire a deeper understanding of the variables affecting V2G's security contribution. These investigations investigate the effects of changes in important parameters on the F-Factor, including charger ratings, battery capacity, and load profile characteristics. Understanding the resilience of V2G's contribution in various circumstances and system configurations requires completing this stage.
5. Findings and conclusions: The last section of our framework focuses on analyzing and interpreting the results of our analyses. Here, we evaluate the total security impact of V2G technology, look at F-Factor developments in a variety of scenarios, and draw policy recommendations. This stage converts our technological discoveries into useful information that policymakers, grid operators, and other energy industry stakeholders may use.

Outcomes

1. V2G charger rating: The F-Factor either tends to go down or stays the same when the rating of V2G chargers goes up. This is because the definition of the F-Factor is the ratio of the reduction in peak demand to the power capabilities of V2G. Lower F-Factor values result from higher-rated chargers' larger peak reductions, but this reduction is outpaced by a rise in power capabilities.
2. Duration of an EV battery: Higher F-Factor values are typically the outcome of longer battery life. This is due to the fact that larger batteries have the potential to reduce peak demand while maintaining V2G power capabilities. Beyond a certain saturation point, nevertheless, more capacity does not further lower peak demand.
3. Peakier load profiles have been found to produce greater F-Factor values in comparison to flatter profiles. This is due to the fact that even with very little energy inputs from EV batteries, V2G technology can more successfully eliminate sharp peaks.
4. Peak demand duration: F-Factor values decrease with longer peak demand durations. This illustrates the difficulty in maintaining peak reduction over protracted times with constrained storage capacity.

- They draw attention to the potential of V2G to improve grid security for operators, especially in regions with demand patterns that are peaky.

- They offer a mathematical foundation for policymakers to include V2G in grid security guidelines and incentive programs.

- To optimize security contribution, they advise V2G technology developers to concentrate on maximizing battery capacity and charging rates.

Conclusions

V2G charger rating: As the rating of V2G chargers rises, the F-Factor either tends to fall or stay constant. This is because the ratio of peak demand decrease to V2G power capability is defined as the F-Factor. Lower F-Factor values result from higher-rated chargers' larger peak reductions, but this reduction is outpaced by a rise in power capabilities.

Duration of an EV battery: Higher F-Factor values are typically the outcome of longer battery life. This is due to the fact that larger batteries have the potential to reduce peak demand while maintaining V2G power capabilities. Beyond a certain saturation point, nevertheless, more capacity does not further lower peak demand.

Peakier load profiles have been shown to produce greater F-Factor values when compared to flatter patterns. Even with very little energy inputs from EV batteries, V2G technology can more successfully reduce sharp peaks.

Peak demand duration: F-Factor values decrease with longer peak demand durations. This illustrates the difficulty in maintaining peak reduction over protracted times with constrained storage capacity.

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