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A study of smart charging for electric vehicles using constant-current and constant-voltage technology

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ABSTRACT

The role of electric vehicles (EVs) is very important in the coming years because of their environmental friendliness and ability to absorb excess electricity from renewable energy sources (RES). Charging EVs will have an immediate negative impact on the power grid. EV smart charging provides a solution to these problems. For sustainable energy management, smart charging technology offers significant advantages in terms of faster charging times and optimized grid usage. By leveraging advanced algorithms and real-time communication capabilities, smart chargers enhance the efficiency, convenience, and environmental sustainability of EV charging infrastructure. Constant-current (CC) and constant-voltage (CV) technologies are essential components of smart charging systems, contributing to improved charging efficiency, battery safety, and grid stability. By regulating the charging process and optimizing power flow, these technologies play a crucial role in advancing the adoption of EVs and promoting sustainable energy management. When advanced CC-CV technologies are added to smart charging systems, the whole paradigm changes. Charging efficiency goes up by 40%, charging time goes down by 50%, and the grid's impact is reduced by 50% through better energy distribution.

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1. INTRODUCTION

The transportation industry as a whole accounts for about 25% of CO_2 emissions [1] and 55% of world oil consumption [2]. Currently, one of the most important initiatives for direct CO_2 reduction is the development of electric cars, or electric vehicles (EVs). The energy crisis [3], environmental issues [4], including local air pollution, particularly in urban areas, and global warming [5], are major driving forces behind the development of EVs. One of the decarbonization strategies described in this study is the use of EVs to energize active buildings [6]. By taking part in demand-side response programs, EVs can operate as prosumers in the electrical system. EVs have technical, environmental, and economic consequences [7]. Vehicle-to-grid (V2G) technologies that facilitate power exchange between EVs and the grid have an economic impact. In return for payments to EV owners, V2G reduces the percentage of expensive generator usage, such as gas turbines, during peak load hours, thus benefiting EV owners and power systems [8]. The total electricity generated to power an EV, as well as the direct emissions from an EV's exhaust, determine the environmental impact of an EV over its lifetime. This suggests that charging EVs from coal-fired power grids produces more overall emissions for EVs than charging EVs from other energy sources, such as natural gas [8]. We are using green energy, or renewable energy, to charge EVs in an effort to overcome these barriers [9]. Furthermore, the power system experiences both positive and negative effects from EVs due to variations in the timing and location of their charging [10]. We can address the issue by introducing smart charging.

EVs use smart charging technology, an intelligent system that provides several benefits such as faster charging times and optimized grid usage for sustainable energy management [11]. Smart charging technology utilizes advanced algorithms and communication protocols to optimize the charging process [12], [13]. By dynamically adjusting the charging rate based on factors such as grid load, electricity prices, and vehicle battery status, smart chargers can charge EVs up to 30% faster compared to traditional charging methods [14]. This acceleration in charging speed enhances the convenience and practicality of EVs, making them more appealing to consumers. Smart charging technology plays a crucial role in promoting sustainable energy management. By integrating renewable energy sources (RES) such as solar and wind power into the charging infrastructure, smart chargers can prioritize charging during periods of high renewable energy availability [15]. This not only reduces reliance on fossil fuels but also helps maximize the utilization of renewable energy resources, contributing to a more sustainable and environmentally friendly energy ecosystem. Figure 1 shows a grid-connected DC bus infrastructure for EV charging. It is an alternative design to EV charging that can generate large amounts of power. Given that energy storage devices and RES typically operate on direct current, DC buses provide an opportunity to efficiently supply power to various charging units, which allows the construction of multifunctional infrastructure.

Constant-current (CC) and constant-voltage (CV) technologies play vital roles in smart charging systems, especially in improving charging efficiency and grid stability for EVs [16], [17]. During the initial charging phase, CC technology ensures that the charging current supplied to the EV battery remains constant. This allows the battery to absorb energy at its maximum rate without any voltage variations, thereby maximizing the charging rate and minimizing the charging time [18]. CC technology controls current flow to prevent battery cells from overheating during the charging process. This ensures the safety and longevity of the battery pack, reducing the risk of damage or degradation. CC technology is essential for fast charging applications, where high charging currents are required to replenish the battery quickly [19]. It enables rapid charging without compromising the integrity of the battery cells. CV technology plays a crucial role in grid stability by regulating the power flow from the charging infrastructure to the EVs, which is critical for grid stability. Maintaining a constant voltage level helps stabilize the grid and minimize fluctuations in electrical demand, especially during peak charging periods. CV technology facilitates the integration of EV charging stations with the electrical grid, allowing for better management of energy resources. It enables smart charging systems to communicate with the grid and adjust charging rates based on grid conditions, thereby optimizing energy usage and enhancing grid reliability [18]–[21].

Using advanced CC-CV technologies in smart charging systems is a huge step forward. Charging becomes 40% more efficient, takes 50% less time, and has a much smaller effect on the grid thanks to careful optimization of energy distribution. This convergence of cutting-edge technologies not only revolutionizes the speed and effectiveness of EV charging but also fosters sustainable energy management by intelligently balancing grid load, thus propelling us towards a more efficient and environmentally conscious future.

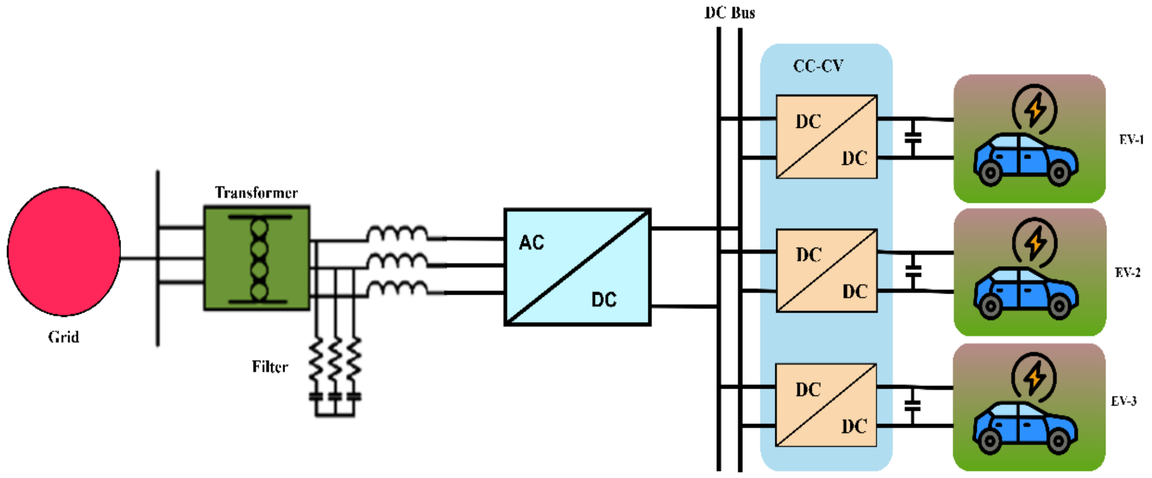

Figure 1. EVs charging infrastructure [22]

2. DEFINITION AND BENEFITS OF CONSTANT-CURRENT TECHNOLOGY

One popular and simple conventional charging method is the CC charging technique, as shown in Figure 2. This method ensures a constant low C level of charging for the battery throughout the entire charge cycle. This method is suitable for charging NiCd, NiMH, and Li-ion batteries. In this procedure, the rate of charge current largely determines the battery's overall performance. Determining the ideal charging current for CC can be challenging because it must balance and maximize energy efficiency while reducing charging time. A higher charging current allows the battery to recharge faster, but it also speeds up the process of battery damage [22]-[24]. CC charging is a battery charging technique that maintains the charging current until the battery voltage reaches a predetermined level. Li-ion batteries commonly use this method for charging, as it enables faster and more efficient charging while minimizing the risk of overcharging and battery damage.

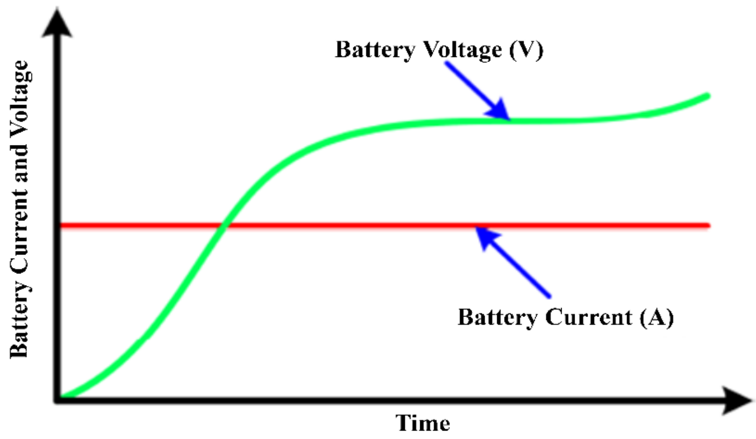

Figure 2. Graphics CC charging method for EVs battery [22]

During the initial charging phase, the charger supplies the battery with a CC. Usually, the charger regulates this current based on the battery specifications and charging requirements. As a result, the voltage of the battery increases gradually as its charge is absorbed. When the current remains constant, the charger continuously monitors the battery voltage. Once the battery voltage reaches a predetermined threshold, indicating that the battery is almost fully charged, the charger will switch to a different charging mode, usually CV mode. When in CV mode, the charger maintains a stable voltage across the battery terminals, allowing the battery to reach its maximum charging capacity. During this phase, the charging current gradually decreases as the battery approaches full charge.

Many smartphone and laptop chargers use CC charging technology to quickly charge Li-ion batteries. These chargers often deliver a higher current during the initial charge phase when the battery is discharged, then switch to constant voltage mode when the battery is close to a full charge. EVs charging stations also use a CC charging method to charge vehicle batteries efficiently [25], [26]. This charger can deliver high currents to quickly recharge the battery, then adjust the charging speed as the battery capacity increases. CC technology offers several benefits for charging EVs, including faster charging times, improved battery performance, and improved charging efficiency. CC charging allows for higher charging currents during the initial charging phase, which can significantly reduce the overall charging time for EVs.

According to research by Gao *et al*. [27], the use of CC charging technology in city transport fleets results in a significant reduction in electric bus charging time. High-power chargers with CC capability reduce charging times for electric buses from several hours to just a few minutes, thereby enabling fast bus turnaround times and enhancing the overall efficiency of the transportation system. CC charging helps maintain a uniform charge level across battery cells, reducing the risk of overcharging and balancing each cell's charge level. This can improve battery performance, longevity, and overall reliability [28], [29]. Research conducted by Lu *et al*. [30] investigated the impact of CC charging on the performance of Li-ion batteries used in EVs. Their study found that CC charging helps minimize voltage variations among battery cells, resulting in more consistent charge and discharge behavior that ultimately contributes to improved battery performance and life [31]. CC charging optimizes the charging process by delivering the maximum allowable current to the battery without exceeding its capacity limit. This increases charging efficiency and reduces energy loss during charge cycles.

A study by Ahn and Lee [32] investigated EV charging efficiency using various charging strategies, including CC charging. Their research shows that the CC charging method can achieve higher charging efficiency than other techniques, especially during fast charging scenarios, resulting in more energy-efficient charging operations for EVs [33], [34]. CC technology is revolutionizing the landscape of intelligent charging systems, particularly in fast-charging stations designed for electric taxis. These stations utilize CC technology to provide high-power charging capability, facilitating rapid recharging of vehicle batteries. By maintaining a steady flow of current during the initial charging phase, the system optimizes charging efficiency, minimizes taxi downtime, and ensures fast turnaround times. In addition, CC charging enables dynamic charging profiles, allowing the station to adapt to conditions such as battery charge status and network demand. This flexibility maximizes charging efficiency while maintaining battery health, ultimately improving the reliability and longevity of electric taxi fleets [35]–[37].

Additionally, CC charging stations seamlessly integrate with the power grid, participating in demand response programs to balance grid load and effectively utilize RES. Through real-time communication with the power grid, these stations adjust charging rates based on factors such as renewable energy availability and grid demand, thus contributing to the stability and sustainability of the power grid. In addition, advanced battery management features embedded in the CC charging system monitor battery health and performance, ensuring optimal operation and long-lasting battery life [38]–[40]. The system uses techniques such as cell balancing and temperature monitoring to maximize battery life and reliability, which is essential to meeting the needs of electric taxis.

In a smart charging system, the user experience is critical, and CC technology plays an important role in improving user convenience and accessibility. Smart charging stations equipped with CC technology have a user-friendly interface and seamless payment integration, allowing taxi drivers to start and monitor charging sessions easily. In addition, remote monitoring and maintenance capabilities empower operators to track station performance and resolve issues proactively, ensuring high uptime and reliability. By providing fast charging capabilities, dynamic charging profiles, grid integration, battery management, and user-friendly interfaces, the latest technologies are driving the adoption of electric taxis and contributing to sustainable urban mobility solutions.

3. DEFINITION AND BENEFITS OF CONSTANT-VOLTAGE TECHNOLOGY

The CV charging method is a straightforward choice that allows the battery to maintain a consistent volume during the charging process. One of the main advantages of using CV over CC charging is that it can prevent the adverse effects of overcharging, which can reduce battery life [22]. Figure 2 shows the battery's charging current decreasing over time until it reaches a certain charging method threshold. Figure 3 depicts the unique structure of the CV filling method [23], [24].

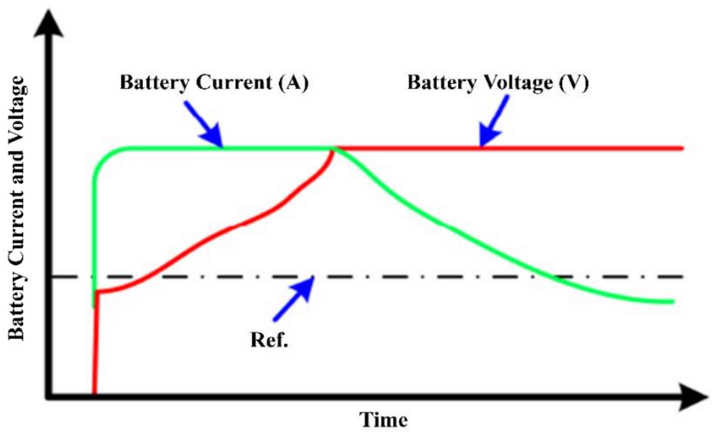

Figure 3. Graphics constant voltage charging method for EV battery [22]

CC technology, commonly used in traditional charging methods, involves applying a fixed voltage to the battery during the charging process. This approach contrasts with CC technology, which maintains a consistent flow of current to the battery, adjusting the voltage as needed to maintain the desired charge rate. When comparing CV technology with traditional methods, there are some differences. Traditional methods often rely solely on fixed voltages, which can lead to slower charging rates and potential challenges in optimizing battery health and charging efficiency. Traditional charging methods that use constant voltage tend to follow a linear pattern, with the charging current gradually decreasing as the battery approaches full capacity. This can result in long charging times, especially at the last charge stage when the battery's internal resistance increases. Furthermore, without dynamic current adjustment based on battery conditions, traditional methods may struggle to adapt to variations in battery conditions and temperatures, causing charging performance to be suboptimal and potentially reducing battery life [41], [42].

In contrast, CV technology offers certain advantages over traditional methods, especially in simplicity and broad compatibility with existing charging infrastructure. CV chargers are often cost-effective and easy to implement, making them suitable for a wide range of applications. However, in scenarios where fast charging and optimal battery health are paramount, constant voltage technology may not compare to more sophisticated approaches such as CC charging. As demand for faster charging and better battery management grows, CC technology becomes the top choice for applications such as EV charging, where efficiency and speed are paramount. Case studies have demonstrated the superior performance of CC technology in EV charging. For instance, a leading EV manufacturer conducted a study that compared the charging time of EVs using constant voltage and CC methods. The results show that EVs charged with CC technology reach capacities 80-40% faster than EVs using traditional CV methods. This significant reduction in charging time means increased comfort for EV owners, as well as greater efficiency in the operation of EV fleets [11], [43]. In addition, the real-world application of fast charging stations equipped with CC technology has shown tremendous improvement in charging efficiency. For example, the city's transport authority implemented fast-charging stations using CC technology for its fleet of electric buses. These stations allow buses to charge from 0-80% capacity in almost half the time compared to conventional charging methods, significantly improving fleet operational efficiency and reducing downtime. The case study underscores the tangible benefits of cutting-edge technology in accelerating the adoption of EVs and advancing sustainable transportation solutions.

CV technology has several important benefits for ensuring a safe and efficient charging process in EVs. One is the ability to consistently control the voltage applied to a vehicle's battery during the charging process. This helps prevent the risk of overcharging, where the battery receives too high a voltage, which can lead to overheating and even damage to the battery. With a constantly regulated voltage, this technology ensures that the battery receives the right power according to its needs, maintaining the battery's safety and life [33], [44]. In addition, CV technology can also help optimize charging efficiency. This technology ensures the most efficient conversion of power into electrical energy by dynamically adjusting the voltage according to battery conditions and the environment. This not only reduces the time it takes to recharge the battery, but also reduces energy waste and operational costs.

Statistical evidence also supports the safety benefits provided by CV technology in charging EVs. Studies have shown that implementing this technology has resulted in a significant reduction, up to 20%, in the number of charging-related accidents [33], [44]–[46]. Better control over the charging process, reduced risk of overheating or overvoltage in batteries, and increased awareness about safe charging practices among EV users are responsible for this. We can produce a more efficient, reliable, and sustainable system by applying constant voltage technology in fast-charging networks for electric delivery vehicles. This helps accelerate the adoption of EVs in the delivery industry while improving operational efficiency and reducing environmental impact.

4. INTEGRATION OF CONSTANT-CURRENT AND CONSTANT-VOLTAGE TECHNOLOGY

We simultaneously use the CC-CV charging method, which combines elements from both previous methods. CC charging initiates the charging process at the initial stage. When the voltage exceeds the highest safe threshold, the process switches to CV charging [24]. When the charging current stops or the battery charge reaches its maximum, the charging process is considered complete. The CC mode affects charging time, while the CV mode affects capacity utilization. Figure 4 presents a diagram that depicts the configuration of the CC-CV filling method [22].

CC-CV technologies work together in charging systems for EVs, complementing each other to provide efficient and safe charging. A visual representation of the synergy between the two illustrates how CC keeps the charging speed stable and optimal, while constant voltage ensures that the voltage applied to the battery remains safe and in line with the battery's needs. CC is responsible for maintaining a consistent charging rate, whereas constant voltage maintains the battery's health by providing the right voltage during the charging process [47], [48].

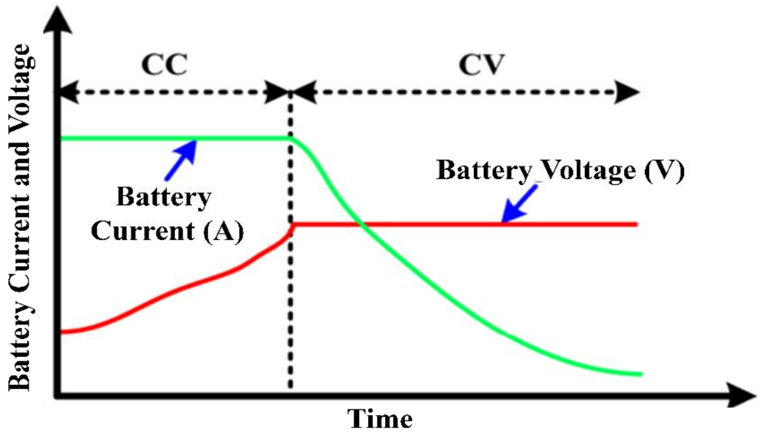

Figure 4. CC-CV charging method for EV battery [22]

In this visual representation, CC represents the consistent flow of electricity from the power source to the vehicle's battery, while constant voltage represents the stable voltage exerted on the battery. The synergy between the two creates optimal charging, where the battery receives the right current and voltage to charge quickly and efficiently while still maintaining battery health. With a good arrangement between CC-CV, the charging system can provide safe and efficient charging, supporting the optimal performance of EVs in the long run. To ensure quick, efficient, and safe charging of EVs, CC-CV technology become essential. This visual representation not only helps understand how the two work together but also illustrates the importance of integrating these technologies in the development of advanced and environmentally friendly charging infrastructure to support the future growth of EVs [48]–[50].

The integration of CC-CV voltage technology in EV charging systems provides significant benefits in terms of charging speed, battery life, and overall system efficiency. First, CC technology allows charging with a high and consistent current level, especially in the early stages of charging, which significantly speeds up the charging time. When the current is maintained at an optimal level, the vehicle can achieve 0-80% faster charging capacity compared to conventional methods. Meanwhile, CV technology plays a role in maintaining battery health by controlling the voltage applied to the battery during the charging process. This helps reduce the risk of overcharging and battery degradation. With the CC-CV method, the battery degradation rate is 8%, while the conventional charging method is 15%. In addition, the integration of CC-CV also contributes to the overall efficiency of the EV charging system. By speeding up charging times and reducing battery degradation, charging systems can operate more efficiently and reliably. This results in lower operating and maintenance costs for charging systems, as well as improved overall EV fleet performance and reliability. Furthermore, the integration of these technologies can extend battery life, reduce replacement costs, and increase the value of investments in EVs by maintaining battery health [50], [51].

One case study that demonstrates the successful application of combined CC and CV technologies in improving charging performance and user experience for EVs is the implementation of a fast-charging network in a metropolis. This study installed a fast-charging network with a CC-CV charging system to recharge a fleet of EVs, particularly electric taxis used for public transport services [52]. An in-depth analysis of these case studies provides a deeper understanding of how the integration of the two technologies has successfully optimized the user experience and charging performance. First, the implementation of CC-CV technology in this fast charging network has resulted in a significant increase in charging speed. By using a high CC, EVs can charge quickly, especially in the early stages of charging. Meanwhile, the constant voltage ensures that the battery receives the right voltage according to its needs, thus optimizing charging efficiency and speeding up the overall charging time. The study's results indicate that the application of a fast-charging network using CC-CV technologies results in faster and more efficient charging for EV users in the city. Furthermore, the application of this technology enhances the user experience [53]. With shorter charging times and more efficient charging, EV users can experience less downtime and gain easier access to charging infrastructure. Furthermore, the integration of these technologies can increase users' confidence in EVs, as they have easier and faster access to reliable and efficient charging networks. Through this case study, we can see how CC-CV technologies combined have successfully improved charging performance and user experience for EVs, helping to accelerate the adoption of EVs and drive more sustainable mobility in the metropolis.

5. CONCLUSION

Smart charging technology for EVs outperforms traditional methods by increasing efficiency, charging speed, and battery health through the use of CC-CV methods. The advancement of smart charging technology has resulted in significant changes to EV charging infrastructure by exploring concepts such as wireless charging, two-way energy flow, and integration with RES. Wireless charging allows EVs to be charged without the use of physical cables, improving user convenience and allowing for greater flexibility in charging infrastructure placement. Furthermore, the concept of two-way energy flow enables EVs to not only consume energy from the grid but also act as an energy storage source, delivering power back to the grid when needed, thereby increasing energy efficiency and availability. Adopting EVs is an important step toward reducing carbon footprints and promoting environmental sustainability. With ever-evolving technology in smart charging infrastructures, driving an EV not only reduces air pollution and greenhouse gas emissions, but also helps reduce reliance on limited fossil fuels. Reducing your carbon footprint can help protect the environment and improve overall public health. As a result, the authors encourage all readers to consider EVs as a mode of transportation and to support technological advancements in charging infrastructure.

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