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The impact of electric vehicles and photovoltaic energy integration on distribution network

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ABSTRACT

The transition towards an eco-friendly and lasting energy system is enabled by the presence of electric vehicles (EVs) and the utilization of renewable energy resources. Despite its intermittent occurrence, solar energy empowers sunny areas to capture renewable energy from sunlight and produce electricity continuously all day long. This energy will be able to smooth the consumption peaks during peak hours and ensure the electrical network flexibility by being injected at various voltage levels. Electric vehicles are supplied by low voltage recharging stations and are seen as power loads that, if rapidly and simultaneously recharged, could potentially affect the stability of the electrical grid. This paper introduces an intelligent method for electric vehicle charging designed to mitigate the impact of simultaneous charging, specifically addressing voltage drop issues. Furthermore, this study demonstrates the positive impact of integrating photovoltaic energy into the distribution network, serving as support, and alleviating the afore cited impact. The simulation results obtained using MATLAB/Simulink illustrate the effectiveness of the proposed strategy in charging electric vehicles, particularly in reducing the observed voltage drop. There is a notable enhancement in voltage drop across all study cases, amounting to a 27 V improvement compared to charging without the proposed method.

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1. INTRODUCTION

The worldwide market for electric cars sales has been increase significantly in the last few years. 4,700,000 battery electric vehicles (BEVs) were sold in 2021 compared to 1,400,000 in 2018 as stated by the International Energy Agency (IEA) [1]. In addition, the demand for electricity from battery electric vehicles has increased to 28,000 GWh in 2021[2] and will keep rising as more vehicles are sold. This significant emergence of electric vehicles in the transportation sector along with their integration into the electrical grid will impact the load curve of highly integrated areas. The proportion of clean energy in the mix of electricity production reached a record of 28.6% in 2021 as a result of increases in power production from all renewable sources, solar PV represents 3.4% which is not negligible, enormous photovoltaic farms have been set up and the energy they generate is injected into various levels of the electricity grid [3].

The incorporation of the photovoltaic energy and electric vehicles on the same network raises concerns about the effects on the electrical network stability. Electric vehicles are now typically incorporated into the distribution network for the purpose of recharging which is categorised into different approaches. According to previous research [4], there are five modes of charging for electric vehicles, slow recharging (with the alternating current (AC) up to the power output of 3.7 kW which is mostly expected at private recharging stations, enhanced charging (increasing from 3.7 kW to 22 kW), fast charging (output surpassing 22 kW), charging within this mode may employ direct or alternating current. Contactless charging system commonly employs wireless power transfer (WPT) technology to recharge the battery, this innovative method is versatile, capable of operating at various voltage levels, level 1 pertains to a recharging voltage between 110/120 V, level 2 operates at 220/240 V, while level 3, also known as direct current fast charging (DCFC), utilizes 200/800 V and can supply a power output of up to 20 kW [5]. Lastly, battery replacement or battery swapping, in this infrastructure, an electric vehicle owner acquires a fully recharged battery by replacing their depleted one at a swapping station. This infrastructure consumes less power compared to fast charging setups, although each station must have a robust grid connection [6]. The first three charging procedures need a connection to the electrical distribution network, each charging strategy will undoubtedly have an impact on the network, especially with a high current demand on the network during peak hours.

Electric vehicles (EVs) linked to the power grid have the potential to lead to issues such as transformer overload, harmonics, and voltage imbalances, thereby affecting the distribution network [7]. The integration of EVs within network may result in voltage variations that may exceed the thresholds set by local laws and power quality. Additionally, the increased power demand from plug-in electric vehicles (PEVs) substantially raises the current flowing through various branches of the distribution network and this heightened current flow elevates conductor temperatures and reduces their operational lifespan. Concerning power transformers, prolonged overloading due to simultaneous connections of PEVs can significantly increase the windings temperature, speeding up the aging process and heightening the risk of system failures occurring in the short or medium term, impacting other equipment [8]. According to study by Nwaigwe *et al*. [9], when renewable energy sources are present, photovoltaic energy in this case electric power can move bidirectionally along the distribution grid and even extend into the local station. This elevates the risk of harm to the utility grid, potentially causing issues like voltage surges, fluctuations in frequency, and heightened energy losses. Indeed, the integration of PV power into the AC distribution network may have additional consequences due to harmonics created by the inverter that transforms the DC voltage supplied by the solar system into AC voltage that may be linked to the grid [10]. Moreover, the integration of the PV in the distribution network can have an impact on the normal operation of the protections pre-installed in the network, according to Sun *et al*. [11], PV stations will also produce short-circuit current in addition to the power system when a distribution network short-circuit fault occurs, changing the short-circuit current level affecting the operation of the protective system.

The impact of the separate integration of these two components photovoltaic energy and electric vehicles has been mentioned above. In the following sections, we will investigate several studies that dealt with the coexistence of these two components in the same network, as well as their influence on the distribution network. According to Nayak *et al*. [12], due to the growing integration of intermittent distributed energy sources like PV wind energy and electric vehicles, contemporary power systems become vulnerable to fluctuations in frequency. In study by Schinke and Hirsch [13], the authors focused on analyzing the effect of combining electric vehicles and photovoltaic (PV) energy on the voltage stability of distribution grid supplying residential households. The simulation results have shown that the percentage of voltage deviations at household nodes depends on the penetration rate of PV and EVs on the distribution network, maximum voltage overruns reached 10% in two scenarios, when PV integration was substantially greater than EV integration and when both PV and EV integration was considerable and equal. Under conditions of substantial electric vehicle integration and a comparatively moderate level of photovoltaic (PV) integration, normal system behavior was observed. This was interpreted as the result of PVs helping to balance the electric vehicle demand with their energy input.

To address the observed voltage irregularities, a reactive energy control strategy was implemented. This control mechanism reduced the likelihood of voltage deviations by 16% in the studied scenarios, although it did not eliminate these deviations. Previous study [14] presents the impact of integrating these components on network voltage supplying commercial buildings. Three case studies were reviewed, and the influence of EVs integration on electrical network was assessed on the transformer and the cables load, the voltage at the farthest point, and the daily dissipation of energy. The transformer was running normally without connecting EVs and PV, however the integration of EVs alone generate an overrun of 100% of the nominal load for a few hours before returning to normal operation by connecting the PV units. Similarly in research by Kelly *et al*. [15], authors show the effect of EV integration on secondary transformers. It identifies instances where secondary transformers were overloaded, exceeding 20% of their capacity, during various time intervals in three investigated distribution networks. It is also demonstrated in previous study [14] that, the cable load has grown because of EV integration while keeping within the usual operating range, not to mention the effects of the PV integration improvement of the curve. Regarding the voltage at the furthest point, larger voltage dips occurred when EVs were connected for charging, causing voltage values to drop below permissible ranges. The voltage profile improved when there was PV producing, and the lowest value that was recorded was within acceptable bounds. The introduction of electric vehicles for charging led to a 56% rise in energy losses compared to the baseline scenario (with no electric vehicles or PVs). However, when PV production was incorporated, it only resulted in a 4% increase in energy losses above the baseline.

In this article, we observe how the integration of PV generation has greatly reduced the negative effects of the electric vehicle's integration for recharging on various low voltage distribution network features, Oruganti *et al*. [16] also affirms the positive impact of integrating photovoltaic energy with EVs fast charging infrastructures on network stability. The V2G integration of electric vehicles was a different configuration that was covered in study by Vita and Koumides [17], this study examined several scenarios where PV and EVs were present on a distribution network while including V2G architecture. This EVs configuration was designed to be able to function in bi-directional mode through the bidirectional chargers, which supply electrical power to the distribution grid and many related services [18]. Vita and Koumides [17] conducted a study to examine how the integration of PV generation and EVs affects the voltage fluctuation in a phase that experienced an earth fault within a 40 ms. The findings of five simulated cases revealed that the voltage curve of the defective phase at the moment of the failure changes depending on the case. The crushing of the voltage of the malfunctioning phase was noticed in the base scenario, which was dramatically improved when PVs and EVs were integrated into the network. By combining the electric vehicle cluster operating in vehicle-to-grid (V2G) mode with the photovoltaic (PV) systems, we could establish the most suitable voltage level that closely aligns with the nominal value.

According to this study, the injection of energy stored in the batteries of electric vehicles, as well as the generation of PV units, might compensate for a portion of the shattered voltage in the case of an earth fault. However, study by Rao and Rangaswamy [19] highlights a negative impact that the integration of electric vehicles in V2G mode could have on the distribution network when combined with photovoltaic (PV) integration. It reports that V2G electric vehicles use an alternating current/direct current converter for charging and these charging units may be influenced by the intermittent nature of power sources like solar and wind. Turan *et al*. [20] presents another diagram that can mix EVs and PVs; this one deals with an EV charging point that uses both PV energy and the medium voltage electrical network. The status of the electrical network feeding the busbar of the electric car charging station without and with the PV units was compared. The simulation outcomes in this research disclosed a 4.26% decrease in energy losses when the network was integrated with the PV panel station for electric vehicle charging in summer conditions, in contrast to using the grid alone. According to Rabie *et al*. [21], charging and discharging EVs without appropriate control technology can lead to grid disruptions, causing voltage and frequency fluctuations. However, when EVs are intelligently managed during charging and discharging, they can contribute positively to maintaining the quality of the electric power grid. Based on the literature reviewed in this introduction section, numerous studies have addressed the topic of integrating electric vehicles (EVs) and photovoltaic (PV) systems into the electrical distribution network and their impacts. Various techniques to address these impacts have also been proposed.

In this paper, we initially introduce several methods proposed in existing writings to alleviate the consequences of this integration. Subsequently, we simulate, using MATLAB Simulink, the impact on the voltage while integrating electric vehicles based on a case study. Next, we incorporate a photovoltaic system into the same network to simulate the combined effect of both components on the electrical distribution network. Finally, a method for controlling the power recharge of electric vehicles is proposed and simulated to improve the negative impact of EV integration on the network's voltage. This paper is structured as: i) The section 2 introduces two approaches put forth in existing literature to address the effect of integrating EVs and PV; ii) In section 3, we introduce our proposed smart strategy for EV recharging; iii) Section 4 delves into the simulation findings of integrating EVs and photovoltaic systems into the distribution grid; and iv) Section 5 presents the conclusion of the paper.

2. STATE OF ART: PV AND EVS INTEGRATION IMPACT ON THE DISTRIBUTION NETWORK

2.1. Intelligent recharging station

Within these research studies, Rusek and Goňo [4] has introduced a charging station concept for electric vehicles aimed at minimizing its impact on the distribution network. Notably, this concept is not applicable to fast recharging, this implies the utilization of a current that surpasses the battery's ampere-hour capacity by a significant margin. Consequently, high charging currents are typically associated with advanced DC recharging stations designed for EVs with charging capacities of up to 100 kW. The figure 1 illustrates the envisioned electric car recharging station concept. This concept presents an electric vehicle charging station that handles electric car charging by connecting to the distribution network using measurement, control, and communication module to gather the kWh available on the distribution network to recharge EVs. The station also provides a two-way link for electric cars to the network, allowing energy to flow in both directions network-EVs and EVs-network as needed. This proposal demonstrates the significance of duplicating these electric vehicle-charging stations in the network, as well as their advantages over charging at private charging stations. Moreover, the interaction of the measurement, control, and communication unit with the inverter enables the latter to unplug from the electrical grid if there is an EV malfunction or anomaly that may harm the network. This research conducted a practical test on a charging station with a power of around 7 kW for a vehicle power of up to 30 kW operated utilizing the "long term" approach with low charging current to identify any potential impact of this charging on the distribution network.

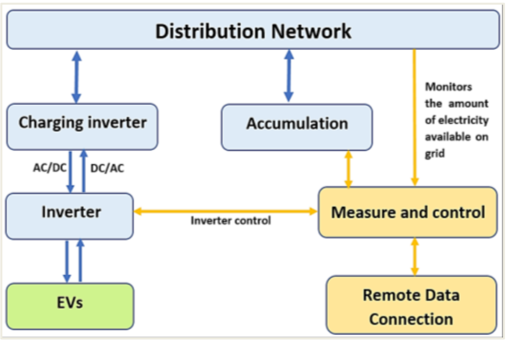

Figure 1. Architecture of EVs charging station [4]

2.2. Reactive power control impact on grid voltage volatility

Besides, in the previous study [13], Schinke and Hirsch have suggested a strategy for the control of voltage violations observed on the distribution network during the integration of both PV and EVs. This strategy based on the control of the reactive energy of the PV units and EVs to control the voltage within the appropriate range, apart from the many used reactive energy compensation approaches [22]. As a reminder, the results of the simulation without this method gave rise to significant voltage violations, especially for the case 2 while applying a high percentage of PV plants and a moderate integration of EVs to the test network voltage and case 5 with similar high proportions of EVs and PV units. for the bare minimum (case 1), with no EVs or renewable energy, the maximum voltage deviation was -5.44. The case 3 characterized by a substantial presence of electric vehicles (EVs) and a controlled integration of photovoltaic generators, the resultant voltage variations have an average value of zero and approach a normal distribution. In case 4, where there was a moderate integration of both PV and EVs, the probability of exceeding the positive voltage limit was extremely low at 0.02%. The simulations of these five scenarios were conducted in accordance with the specifications outlined in VDE-AR-N 4105 [23], which is the German standard requirements for the EVs connection to distribution networks.

Regarding distribution grid, the active power has a negative sign because from the point of view of active energy flow. It is delivered from the network to the electrical loads. Reactive power control involves maintaining an acceptable power factor based on the active power of the PV units, in order to mitigate voltage violations. This is illustrated below (assuming S_{Emax} represents the maximum apparent power) :

- In power generation systems where the total of maximum apparent power (∑SEmax) is 3.68 kVA or less, the power factor (cos(Φ)) varies from 0.95 under-excited to 0.95 over-excited, and no directives are furnished by the network operator.
- For power generation systems where 3.68 kVA < ∑SEmax ≤ 13.8 kVA: refer to the characteristic graph in Figure 2, as specified by the network operator, maintaining a power factor (cos(Φ)) range of 0.95 under-excited to 0.95 over-excited.
- For power generation systems where ∑SEmax exceeds 13.8 kVA: follow the diagram in Figure 3, provided by the network operator, with a power factor (cos (Φ)) varying between 0.90 under- and 0.90 over-excited.

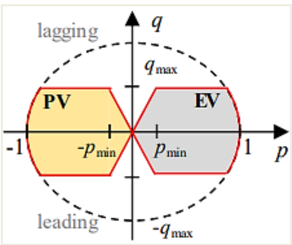

Figure 2. Permissible range of reactive power for a power generation system: 3.68 kVA < ∑SEmax ≤ 13.8 [23]

Improved requirements applied presented in Figure 4, while reactive power supply needs are indicated in for PV units (yellow regions) and EVs (grey areas Starting from 0 and reaching up to qmax, the supply of reactive power is gradually increased until reaching a level of pmin=0.2 p.u. This signifies the implementation of reactive energy control even when the active power values of the electric vehicle (EV) and photovoltaic (PV) units are at their minimum. In this context, the active power of PV units is negative as they feed energy into the network, whereas the active power of EVs is positive since they draw energy from the network.

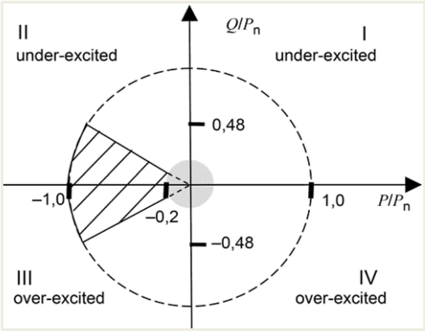

Figure 3. Boundaries for reactive power in a power generation system: ∑SEmax>13.8 kVA [23]

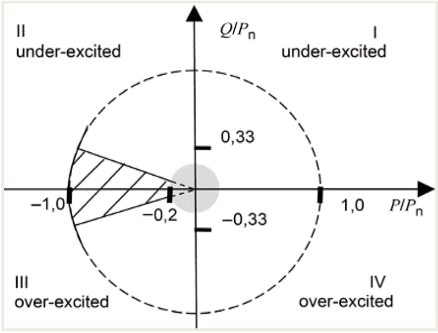

Figure 4. Improved Requirements [13]

3. RESEARCH METHOD

3.1. Methodology

Building upon the principle linking voltage drop to the available power in an electrical distribution network [24], the concept of this paper revolves around reducing the voltage drop caused by electric vehicle charging through the control of the active power supplied by the grid. Where P is the power at the line termination, Q is the reactive power at the line termination, R is the line resistance, X is the line reactance and Un is the rated voltage. It is evident from (1) that to decrease the voltage drop, we can act on the active power of the electrical grid to deliver less electrical power while still meeting the charging requirements of electric vehicles.

$$\Delta U = \frac{PR+QX}{U_n} \tag{1}$$

Another approach has been adopted in this article, based on a fundamental theory, Kirchhoff's law [25] as in Figure 5. The (2) concretely explains the theory, and practically, in our case study, we relied on this theory to improve voltage drops caused by electric vehicle charging through the integration of photovoltaic energy to support the electrical distribution network.

$$\sum I \text{ at junction point} = 0 \tag{2}$$

To support our method, we simulated the system under study using MATLAB Simulink, as has been done in several previous references, in the field of electric vehicle charging control [26], [27], integration of PV and EVs into the distribution network using advanced techniques [28], [29] to yield conclusive results.

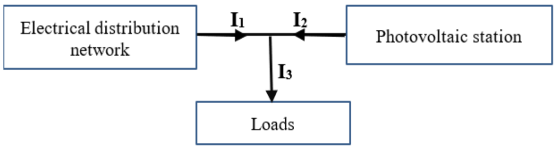

Figure 5. Kirchhoff's Law applied in this study case

3.2. System structure

The diagram in Figure 6 illustrates the schematic of the suggested electric vehicle charging setup. This setup comprises a low-voltage electrical distribution grid connected to a photovoltaic system, the characteristics of which are indicated in Table.1. This network supplies power to electric vehicles according to case studies as mentioned in Table 2.

The EVs selected for these study scenarios have a power recharging range from 26 kW to 29 kW. For the first case, only one EV is plugging into the charging unit. As we progress through the cases, an additional electric vehicle is plugging to reach four EVs for the fourth case. In all the mentioned cases, the PV system is not integrated to the network. To assess the influence of electric vehicle recharging on the grid, we conducted simulations for the different scenarios outlined in Table 2. We measured the effects of the incremental introduction of EVs on the voltage levels of the grid.

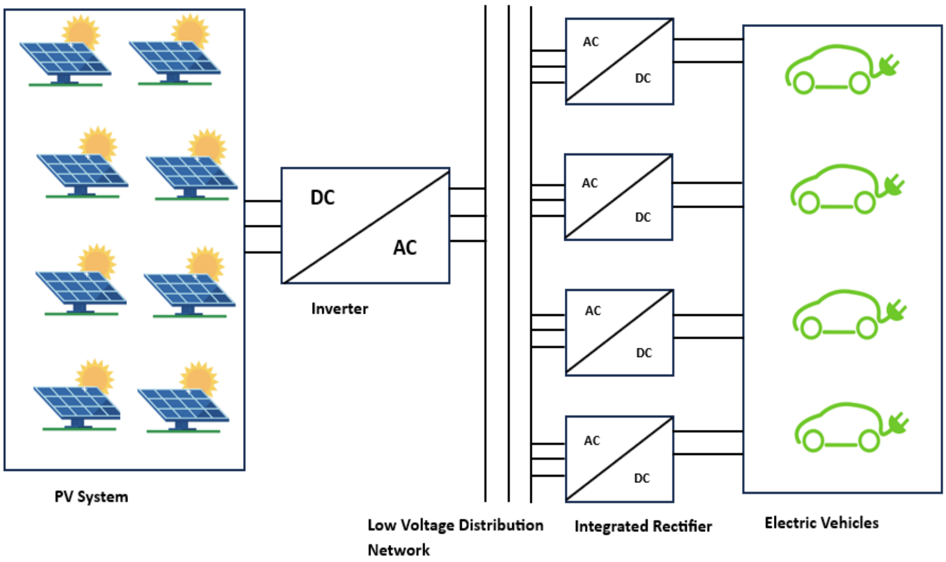

Figure 6. Diagram of the proposed EV recharging station

Table 1. Electrical distribution network characteristics and PV system specifications

Distribution network characteristics			Photovoltaic system characteristics			
	Power (KVA)	Voltage Vrms (V)	Voltage at MPP (V)	Current at MPP (A)	Power (kWc)	Number of PV panels
High voltage-source	100,000	120,000	520	600	280	700
Transformer HV/MV	47,000	120,000/ 20,000				
Transformer MV/LV	250	20 000/380				

Table 2. Specific cases chosen for study

Cases		Power (kW)	LV Voltage (V)
Case 1	EV1	22	380
Case 2	EV1	22	380
	EV2	26	
Case 3	EV1	22	380
	EV2	26	
	EV3	27	
Case 4	EV1	22	380
	EV2	26	
	EV3	27	
	EV4	25	

3.3. The control technique of smart EV charging

In this manuscript, we introduce a recharging station model for EVs with the aim of mitigating the influence of direct EV integration on the distribution network, specifically focusing on voltage considerations. The following schematic diagram in Figure 7 describes this station, which is equipped with a measurement, supervision, and control unit that collects real-time data from the distribution network, EV charging station, and based on these elements, acts on the rectifier (coverts AC to DC power) to regulate the recharging power of EVs. Concretely this unit controls the output of the rectifier depending on the available power on the grid. Subsequently, a photovoltaic unit is integrated into the network to assess its impact on the studied network's voltage. The block diagram in Figure 8 illustrates the detailed principle of our proposed method in this article.

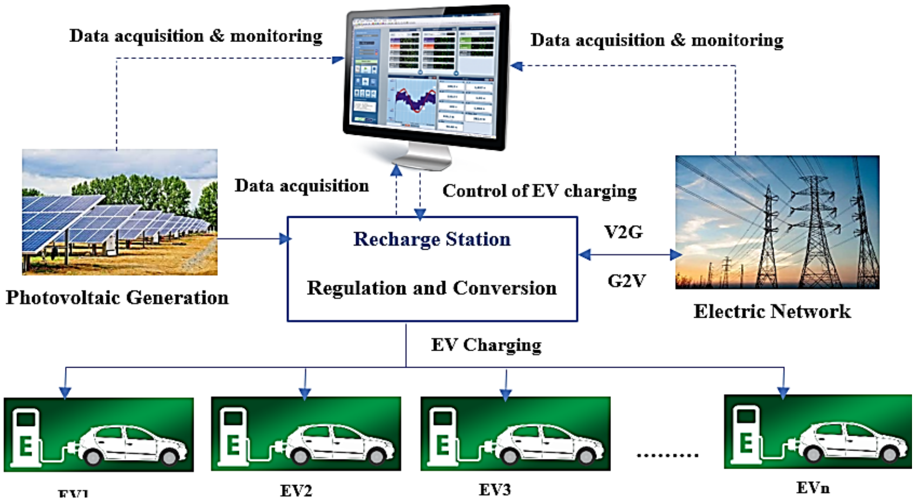

Figure 7. Schematic diagram of recharging unit for EVs

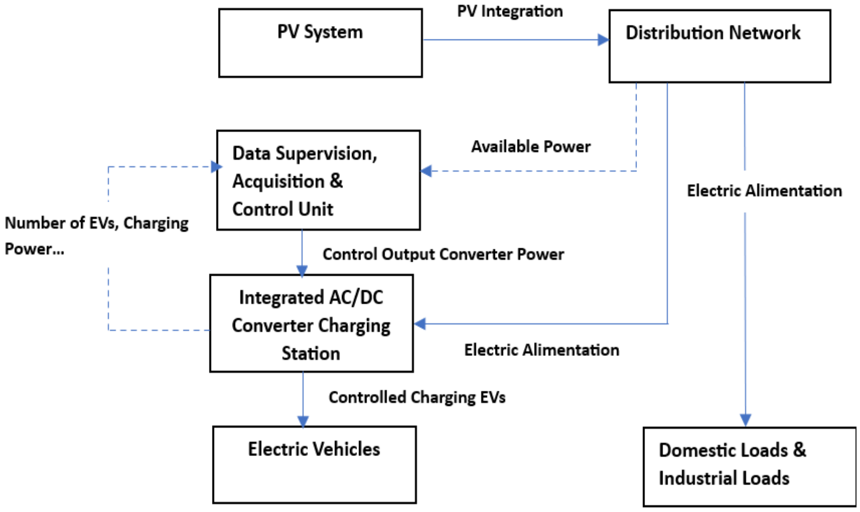

Figure 8. Block diagram of proposed charging method

4. RESULTS AND DISCUSSION

4.1. Electric vehicles integration impact

The simulation of the 4 study cases presented in Table 2 resulted in significant voltage drops as illustrated in Figure 9. The depicted voltage corresponds to a single phase, and the effect is identical for the remaining two phases as well. In addition to the observed voltage drops, the voltage signal also experienced distortions as depicted in Figure 10. Simulation diagram under MATLAB Simulink is illustrated in Figure 11.

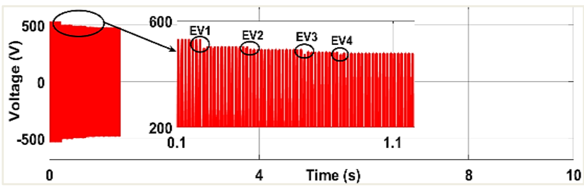

Figure 9. Voltage drops after EVs integration

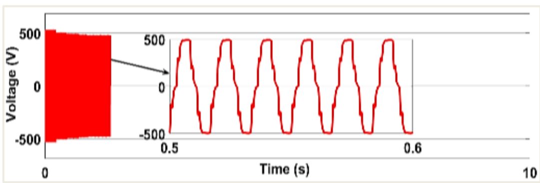

Figure 10. Voltage signal distortion

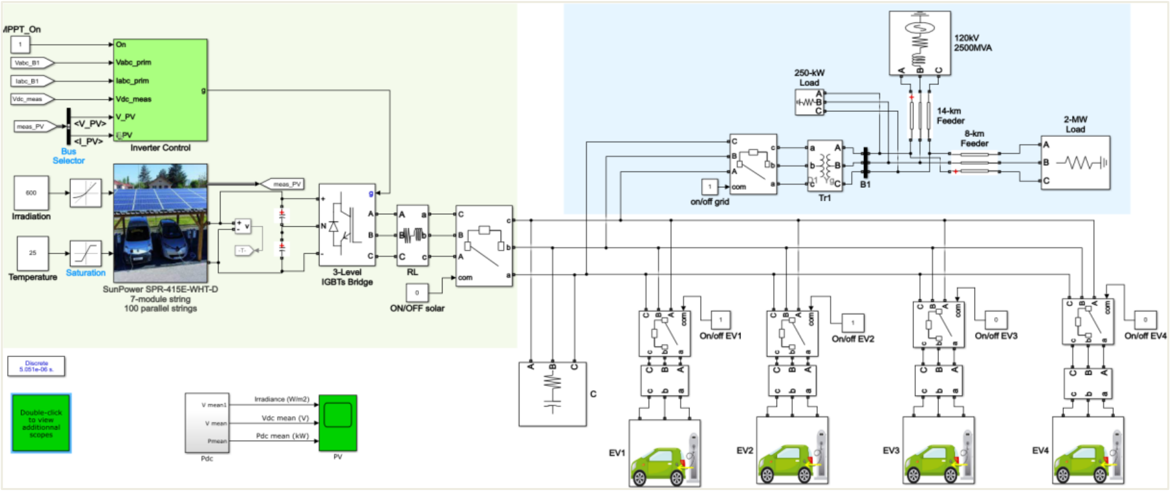

Figure 11. MATLAB/Simulink simulation diagram

For the first case, integrating an electric vehicle with a power of 28 kW caused the low voltage to drop from 380 V to 350 V, representing a voltage drop of 30 V. In the second case, adding another electric vehicle with a power of 29 kW caused the voltage to drop by an additional 5 V compared to the previous case. For the third case, adding another EV with a power of 27 kW resulted in a voltage drop of 15 V. In the last case, with the addition of a fourth vehicle with a power of 26 kW, the voltage dropped by 5 V, reaching a final voltage value of 325 V, which exceeds the normalized voltage limits of +/- 10% [30]. These results are depicted in Table 3.

Table 3. Low voltage distribution network variation

Cases	Power (kW)		LV Voltage Vrms (V)	Voltage Variation ΔV(V)
Case 1	EV1	28	380	-30
Case 2	EV1	28	380	-35
	EV2	29		
Case 3	EV1	28	380	-50
	EV2	29		
	EV3	27		
Case 4	EV1	28	380	-55
	EV2	29		
	EV3	27		
	EV4	26		

4.2. Photovoltaic integration with EVs

The incorporation of the PV system on the electrical network, with the presence of electric vehicles, resulted in compensation for the previously observed voltage drops as illustrated in Figure 12. Connecting the PV array in parallel with the low-voltage distribution network has effectively resolved the voltage drops previously observed when electric vehicles were integrated into the distribution network alone. However, the introduction of PV has not ameliorated the voltage signal distortions, as evidenced in Figure 13. On the contrary, it has accentuated them, and this is likely caused by the DC/AC inverter [31].

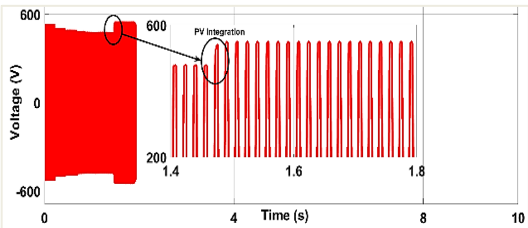

Figure 12. Grid voltage after the PV integration

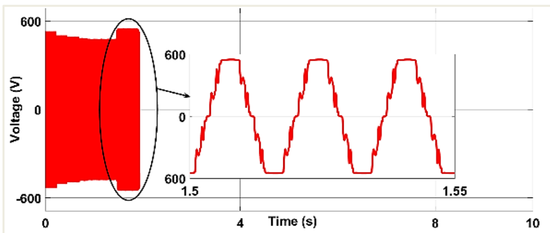

Figure 13. Voltage signal distortion with PV integration

4.3. Analysis of EVs integration on the distribution network using the proposed strategy

To assess the effects of integrating electric vehicles into the distribution network for charging with reduced charging capacity, we conducted simulation tests across various scenarios, as outlined in Table 4. After reducing the charging power of electric vehicles, voltage drops are still present but significantly lower than before, Figure 14. By acting on the control of the rectifier, which is the charger for electric vehicles, we can extract the available energy from the distribution network and distribute it to the electric vehicles to be charged in a way that the charging power does not exceed the limits resulting in voltages below normalized voltage values. Reducing the charging power of the first car from 28 kW to 13.6 kW resulted in an improved voltage drop of +15 V, for the second case, decreasing the power from 29 kW to 17.7 kW in the second instance maintained an acceptable voltage drop of -5V. The third reduction from 27 kW to 16.6 kW allowed us to achieve an enhanced voltage drop of +8V. In the fourth and final scenario, a decrease in the distribution network voltage drops by +4 V was achieved with a charging power of 12.5 kW, as compared to 26 KW.

The results of this paper highlight a significant improvement in voltage drops of 27 V compared to the baseline. This improvement can be attributed to the application of our method, which focuses on reducing recharging power of EVs. In contrast, study [13] adopted an approach centered on reducing the likelihood of voltage variations more than ±5 %. The results of this study demonstrated quantifiable improvements, with probability reductions of 25.4% and 27.85% for cases 2 and 5, respectively, bringing the probability down to 9%. This comparison underscores the different perspectives adopted in our two studies. While our approach translates into a direct improvement in voltage drops, the earlier study demonstrated effective management of events related to these drops, with particular attention given to risk reduction. These results suggest that different strategies may be complementary in the quest for increased stability in the electrical network.

Table 4. Simulation with lower charging powers

Cases	Power (kW)		LV Voltage (V)	Voltage Variation ΔV(V)
Case 1	EV1	13.6	380	-15
Case 2	EV1	13.6	380	-20
	EV2	17.7		
Case 3	EV1	13.6	380	-27
	EV2	17.7		
	EV3	16.6		
Case 4	EV1	13.6	380	-28
	EV2	17.7		
	EV3	16.6		
	EV4	12.5		

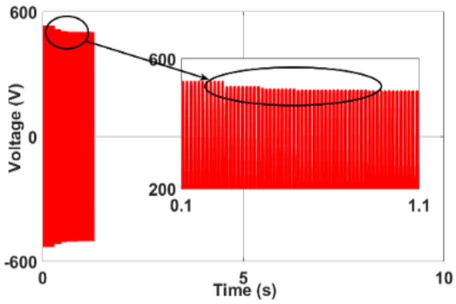

Figure 14. Voltage signal using the proposed smart recharging

5. CONCLUSION

In this article, the simulation findings highlight the negative consequences of a significant increase in electric vehicles integration into the low-voltage distribution grid, mainly characterized by voltage drops. Integrating photovoltaic energy into the same grid has raised the grid's voltage levels, although it has introduced an issue of distorted voltage signals. To tackle these challenges, the authors suggest a solution involving the control of electric vehicle charging power to alleviate the negative effects on the distribution grid. The simulations performed with MATLAB-Simulink for the proposed charging station show enhancements in voltage levels and signal quality, potentially leading to reduced energy losses.

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