Fast and Extreme Fast Charging Integration for Electric Vehicles: Impact on an Industrial Distribution Network

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Abstract- Governments and leading corporations all over the world are now focusing their efforts on transitioning the transportation sector to a much more energy-efficient and less polluting model. Consequently, electric vehicles (EV) have experienced remarkable progress in recent years and are becoming an increasingly popular choice among consumers. This technological advance, coupled with roadmaps for the near future and new regulations, explains the exponential increase in EV sales worldwide. Therefore, in terms of the electrical power systems to which the EV charging stations are connected, a completely unforeseen scenario arises. The main objective of this paper is to evaluate this future scenario, considering as a case study an industrial distribution network with the addition of EV charging stations based on different technologies and power levels. For this purpose, a typical electrical system developed by IEEE is taken as a basis and modified according to recent international standards, and subsequently, the model is quasi-dynamically simulated using DIgSILENT PowerFactory software. To develop a realistic model, the main characteristics of EV charging infrastructures are examined. Results of power flows and voltage profiles throughout one day are presented and reviewed to reveal the challenges that need to be addressed given the widespread deployment of EVs. Hence, these electrical systems are proven in advance whether they are prepared to support the growing demand for this type of transport vehicle.

Keywords: Distribution grid, electric vehicle, extreme fast charging, network simulation, Power Factory, renewable energy.

1. Introduction

Evidence of the dangerous consequences of climate change is emerging daily and reducing greenhouse gas (GHG) emissions has become a critical requirement. As indicated by the latest report of the International Energy Agency (IEA) in [1], the transportation industry is the sector most dependent on fossil fuels. Furthermore, based on indicators presented by the European Environmental Agency (EEA) in [2], 76% of the GHG emissions in the European Union (EU) are produced by road transport. The amount of GHG emissions caused by road transport is almost 44% above the net zero emission (NZE) target set for 2030 [1]. Therefore, the electrification of road transport is increasingly becoming crucial to reduce fossil fuel consumption and the resulting GHG emissions.

To stay on track with the NZE scenario, it is expected that electric vehicle (EV) sales will grow from 8% in 2021 to 58% in 2030, based on the IEA's latest update [3]. And, for the first time in history, the EV battery manufacturing capacity announced in [4] is sufficient to meet projected 2030 demand needs in the NZE scenario. To support this assumption, governments around the world have launched several initiatives to encourage the use of EVs. A good example of this is the incentives provided by almost all European Union (EU) member states for the purchase of EVs and/or their infrastructure [5]. Additionally, the EU reached an agreement on October 28, 2022, and decided to ban the sale of new diesel and gasoline cars from 2035 onwards [6], obtaining a formal response from the Parliament and the Council on February 14, 2023. These moves are not only taken in Europe; on December 8, 2021, the United States (US) Environmental Protection Agency (EPA) issued Executive Order 14057 [7], which calls for federal fleets to reach 100% NZE vehicles by 2035.

Another significant issue when considering the adoption of EVs is their charging infrastructure. Even though it has improved in recent years, studies developed in [8] and [9] reveal that the number of public EV charging stations foreseen for installation during the next few years is likely to be below the size of the targeted EV market. To address this problem, efforts are being undertaken by the European Commission to ensure the implementation of an efficient infrastructure to reduce GHG emissions [10]. By 2026, the European Commission states, at least one EV charging station should be available for every 60 km on all main roads of the EU. Looking at one EU member country, Spain, as an example, its current national legislation imposes, as of January 1, 2023, a minimum number of EV charging stations in public places [11]. Regarding residential buildings, [12] lays down the minimum mandatory requirements for EV charging stations both in new buildings and in those with renovations to their electrical circuit. All the above leads to an unprecedented and novel scenario, which places the emphasis on EVs as an attractive alternative to conventional vehicles.

1.1 Literature Review

During an early overview of the works published by other authors, it is worth mentioning the valuable information found in [13]–[15] on the current situation of EVs. This has provided a more in-depth knowledge of the most important requirements and characteristics of this type of vehicle and its infrastructure. Moving further from a technical perspective, the transformer constraints in a residential distribution network are demonstrated in [16]. Another interesting approach is presented in [17], in which a MATLAB model that includes the contribution of solar photovoltaic (PV) generation units in addition to EVs is studied. To define the most representative and realistic EV charging profiles, and thereby improve the present study, a comprehensive dataset of residential charging profiles collected in Sweden and Norway is analyzed in [18]. Regarding the control of EV charging stations, a model is proposed in [19] to analyze whether parking lots can act as an energy resource. To understand the relationship between EV batteries and their energy usage, a battery aging model that considers both per-calendar and per-cycle aging is discussed in [20].

Publications related to EV fast charging have also been reviewed. In [21], the technology and elements required for the extremely fast charging (XFC) stations are introduced, and three key standards and protocols for fast and XFC connectors are defined: CHAdeMO, CSS, and GB/T.

These studies and publications contribute significantly to the background of the research field and set the baseline for the present work. However, none of the state-of-the-art documents cover the new requirements recently imposed by governments, nor do they address electrical systems with other types of consumers. Hence, in this highly relevant work at present, the performance of a power electrical network under an industrial consumer profile to face the increased electrical demand coming from EV charging stations is assessed. Furthermore, distributed generation (DG) concepts with the integration of renewable energy sources (RES), such as solar PV and wind energy, are discussed in this paper. Thus, quasi-dynamic simulations of a power system are conducted, addressing challenges such as the prediction of the demand and power covered by RESs.

2. Methods

A power distribution network of an industrial nature is tested with the DIgSILENT PowerFactory computation software. This simulation tool represents one of the most comprehensive and authoritative methods for analyzing and certifying electrical power systems. Furthermore, the potential of DIgSILENT PowerFactory becomes even more appealing for the simulation of smart grid-based solutions, such as the basis of this research: DG units using RESs, and connection of EV charging stations into power systems.

Quasi-dynamic simulations are performed to obtain a detailed and accurate assessment. For this purpose, several operating parameters of the electrical network, such as the consumption or generation, are modified, defining a given profile. In DIgSILENT PowerFactory, multiple load flows are solved at user-defined time intervals to analyze the time dependence of the system and predict its future behavior. For this precise research, since the conditions do not require a very exhaustive detail, all quasi-dynamic profiles are considered adequate to be defined using an hourly time step. Therefore, the nominal power of each electric load or generation unit in the power network is scaled as a function of the hour of day. By comparing the reference system based on the literature and the model designed and simulated in DIgSILENT PowerFactory, all the elements of the electrical network are validated. Once the model has been verified to be no different from the reference case, RES generation units and EV charging stations are included to perform the simulations of this research and evaluate their impact on the power system.

2.1 Electrical Power Network

As the starting line of this research, the electrical distribution network of industrial characteristics, published under the IEEE Standard (Std.) 399–1997 [23], is modeled and verified in DIgSILENT PowerFactory. The nature of this electrical system is influenced by the type of consumers involved, which are mostly electric motors. This power distribution network is divided into two feeders and consists of 42 nodes, operating from 0.48 kV to 69 kV depending on the proximity to the customers. After validating the model, the authors conduct further studies [24] to assess the impact of RESs integration. Thus, based on global installed capacity scenarios forecasted for 2050 [25] wind and solar PV energy are available, as shown in Fig. 1.

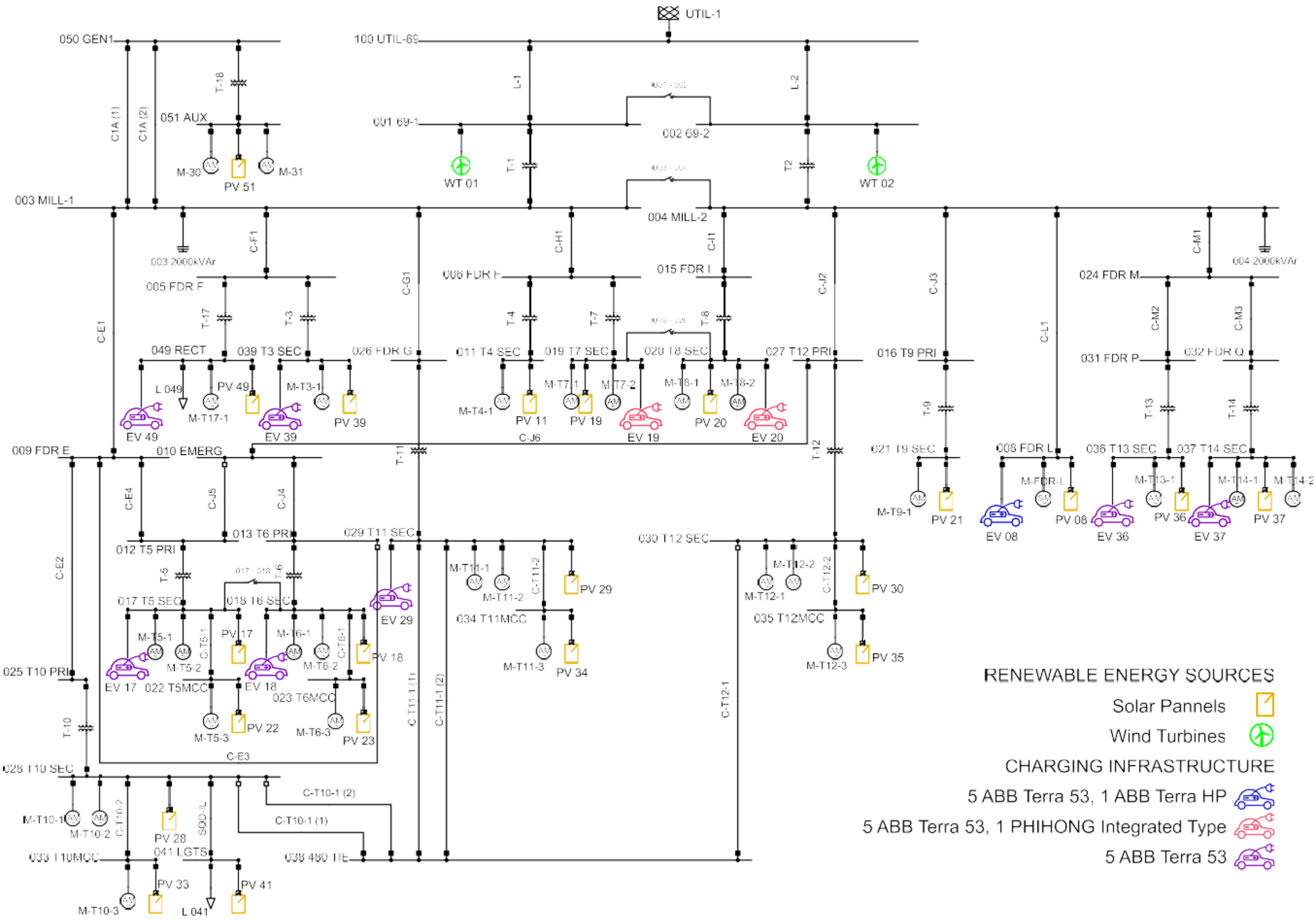

Fig. 1. Modified Industrial Power System based on IEEE Std. 399-1997.

2.2 EV Charging Infrastructure

Based on the overview published by Tu, Feng, and Lukic in [21], the most convenient EV charging station models for the purpose of this study are described in Table 1. As a novelty in this study, since no similarities have been found in the literature, EV charging stations have been deployed according to the geographical proximity between the nodes of the distribution network, and their consumption. Therefore, the power demand of all consumers connected to the power network in Fig. 1 has been examined to conclude that fast charging and XFC stations are installed in the 10 nodes with the highest energy consumption, i.e., buses 8, 17, 18, 19, 20, 29, 36, 37, 39 and 49.

Table 1. Technical characteristics of EV charging stations.

Fast Charger Model	Power	Efficiency (η)	Charging Time
ABB Terra 53	50 kW	94.0%	58 minutes
PHIHONG Integrated Type	120 kW	93.5%	25 minutes
ABB Terra HP	350 kW	95.0%	9 minutes

Additional information shown in Table 1 is the charging time of an EV, expressed in minutes, for each of the fast charger models. To calculate this parameter, Eq. (1) previously elaborated by the authors in [26] is used, considering reasonable but conservative values of the capacity and state-of-charge (SOC) of the batteries. Both values are assumed with the knowledge that a high capacity and a low SOC mean more load requirements and, therefore, a more unfavorable scenario for the electrical power system.

$$t_{charge} = (1 - SOC/100) \cdot Cap_{battery}/(P_{charger} \cdot \eta_{charger}) \qquad (1)$$

where t_{charge} is the time required to charge the EV, based on SOC and battery capacity. Given the above discussed, 75 kWh is adopted for the battery capacity ($Cap_{battery}$), according to the specifications of the most advanced vehicles of the Tesla company, and the SOC of the batteries of 40%. On the other hand, $P_{charger}$ and $\eta_{charger}$ are specific parameters for each of the chosen charger models, representing the maximum power that can be supplied by the charging station (in kW) and the charger efficiency (%), respectively.

As shown in Table 1, it is verified that the charging time of none of the charger models considered for this research surpasses one hour. Therefore, the load profile associated with EV charging is designed with an hourly timestep, assuming an adverse environment.

3. Case Development

Various case studies are developed to understand the impact of fast charging and XFC stations on the industrial power system displayed in Fig. 1. Depending on the size of the consumer being served by the EV charging stations, different units are selected for connection. To cover basic services, five ABB Terra 53 stations are installed at all nodes with EV charging points. This involves connecting an electric load whose nominal power corresponds to the specifications of these five fast charging stations, i.e., 250 kW and an efficiency of 94%. For special purposes, in the three industrial consumers with the highest demand, which are supposed to have the highest charging needs, XFC stations are installed. To better explain the above, a detailed description of the EV charging infrastructure available at each node is presented in Table 2.

Table 2. EV charging stations operating at each node.

Buses	Charging Infrastructure	Nominal Power
8	1 ABB Terra HP and 5 ABB Terra 53	567.50 kW
19, 20	1 PHIHONG Integrated Type and 5 ABB Terra 53	347.20 kW
17, 18, 29, 36, 37, 39, 49	5 ABB Terra 53	235.00 kW

Apart from the nominal power shown in Table 2, hourly profiles are created for each of the loads in the electrical network to conduct a quasi-dynamic analysis. In this study, three types of profiles are identified: the consumption profile of industrial consumers, the fast charging profile that covers regular demands, and the XFC profile that meets extraordinary requirements. Therefore, Fig. 2 shows the hourly profiles defined in DIgSILENT PowerFactory to perform time simulations over a whole day. Thus, the nominal power is not constant throughout the day but is influenced by a scaling factor expressed in per unit (pu), which represents a percentage of the electric load value.

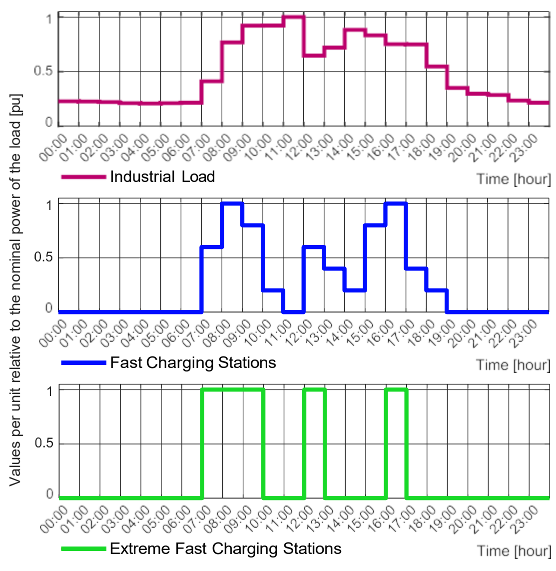

Fig. 2. Time-load profiles for quasi-dynamic simulations.

4. Results and Discussion

In this work, knowledge of the energy impact of fast and XFC stations is obtained by performing quasi-dynamic simulations on an industrial power network using DIgSILENT PowerFactory. Two parameters of the electrical system from which significant information can be drawn are thus assessed: capacity of the elements such as transformers or lines (expressed as a percentage), and node voltages (expressed in pu) of the electrical distribution network.

Table 3 shows the loading percentages of the electrical system components that suffer significant changes when comparing different case studies. The most limiting elements of this electrical distribution network are the transformers. Those with the highest percentage of performance are T-17 and T-14, both exceeding 80% in the EV Scenario. In case these high operating conditions are continued or increased over time, severe damage to the transformers could occur. As shown in Fig. 3, this situation reveals that the overloading of the elements is temporary, from 8 a.m. to 10 a.m., when workers start their work. No special attention is given to the minimum loading of elements, so no further details are given in this section.

Table 3. Quasi-dynamic results: maximum loading of elements.

Element	Baseline	EV Scenario	Increase
T-14	61.93%	82.96%	34.0%
T-11	47.31%	61.04%	29.0%
T-17	68.44%	85.42%	24.8%
T-5	57.95%	71.61%	23.6%
T-6	57.64%	71.24%	23.6%
T-1	43.20%	51.61%	19.5%
T-3	65.16%	77.29%	18.6%
T-2	65.39%	76.45%	16.9%
C-L1	45.21%	51.14%	13.1%
T-13	64.04%	72.36%	12.9%
T-8	63.98%	72.13%	12.7%
T-7	63.99%	72.11%	12.7%

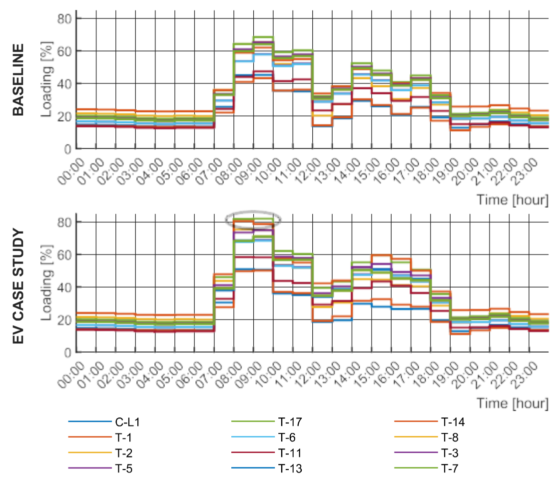

Fig. 3. Quasi-dynamic results: time-loading profiles.

Table 4 shows the voltage values of the ten most significant nodes, those to which the electric vehicle charging infrastructure is connected. Voltages of all nodes of the distribution network in the EV Scenario are found to decrease due to the demand increase, thereby challenging the power supply reliability. As a general guideline, a certain fluctuation allowance is assumed in the operation of the node voltage, generally 5% above and below the nominal voltage, i.e., between 0.95 pu and 1.05 pu. With these design criteria in mind, buses 17 and 37 are slightly lower than the minimum voltage limit due to the connection of the EV charging infrastructure. Results in Fig. 4 show the temporal distribution of voltages during the simulation, demonstrating that, similarly to what happens with the overloaded elements, this issue arises punctually, between 9 a.m. to 10 a.m. No special attention is given to the maximum voltage of nodes, so no further details are given in this section.

As demonstrated by the results of element overloads and node undervoltages, the negative effects to be expected in power systems are observed. While these findings are not extremely frightening, they are highly relevant to understand the limitations that will arise, based on the trends of mass deployment of EVs. Thus, a major finding to highlight from these results is the critical need for improvements and advances in electrical power systems, to avoid potential damage to electrical elements caused by overloads and significant supply disruptions due to low voltages.

Table 4. Quasi-dynamic results: minimum voltage of nodes.

Terminal	Baseline	EV Scenario	Decrease
037 T14 SEC	0.9543 pu	0.9493 pu	0.52%
018 T6 SEC	0.9564 pu	0.9528 pu	0.38%
017 T5 SEC	0.9510 pu	0.9476 pu	0.36%
049 RECT	0.9591 pu	0.9561 pu	0.32%
029 T11 SEC	0.9607 pu	0.9577 pu	0.31%
036 T3 SEC	0.9562 pu	0.9535 pu	0.28%
039 T3 SEC	0.9533 pu	0.9506 pu	0.28%
020 T8 SEC	0.9575 pu	0.9550 pu	0.26%
019 T7 SEC	0.9567 pu	0.9548 pu	0.20%
008 FDR L	0.9817 pu	0.9799 pu	0.19%

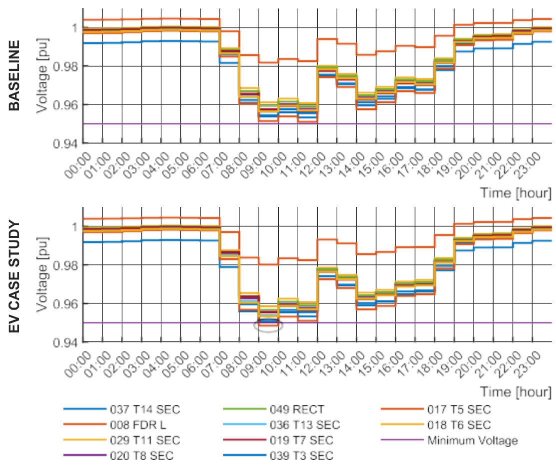

Fig. 4. Quasi-dynamic results: time-voltage profiles.

5. Conclusions

Electrification of road transport is increasingly becoming crucial to reduce fossil fuel consumption and the resulting GHG emissions. This, together with technological advances and global climate regulations, is leading to an innovative landscape in which EVs occupy an important place in the automotive sector. Hence, in this highly relevant work at present, the performance of a power electrical network under an industrial consumer profile to face the increased electrical demand coming from EV charging stations is assessed. As a novelty in this study, since no similarities have been found in the literature, EV charging stations have been deployed according to the geographical proximity between the nodes of the distribution network, and their consumption. To cover basic services, five fast charging stations are installed at all nodes with EV charging points. For special purposes, in the three industrial consumers with the highest demand, which are supposed to have the highest charging needs, XFC stations are installed. Furthermore, DG concepts with the integration of RESs, such as solar PV and wind energy, are discussed in this paper. Thus, quasi-dynamic simulations of a power system based on IEEE Std. 399-1997 are conducted, which means that various electrical variables are not constant throughout the simulation. With this analysis, it is possible to find out the key aspects that electrical power systems must face to ensure the quality of supply and address challenges such as the prediction of the demand and power covered by RESs. Two parameters of the electrical system from which significant information can be drawn are thus assessed in DIgSILENT PowerFactory: capacity of the elements such as transformers or lines (expressed as a percentage), and node voltages (expressed in pu) of the electrical distribution network.

Thanks to this work, the expected effects of introducing EV charging stations based on different power levels are observed. Looking at the loading of elements, it is evident that the most limiting elements of this electrical distribution network are the transformers. Overload percentages higher than 80% are found, which may cause damage to the element and a reduction of its useful lifetime if this excess capacity is maintained over time. Voltages of all nodes of the distribution network in the EV Scenario are found to decrease due to the demand increase, thereby challenging the power supply reliability. As a general guideline, a certain fluctuation allowance is assumed in the operation of the node voltage, generally 5% above and below the nominal voltage. With these design criteria in mind, some buses are slightly lower than the minimum voltage limit due to the connection of the EV charging infrastructure. While these findings are not extremely frightening, they are highly relevant to understand the limitations that will arise, based on the trends of mass deployment of EVs. Thus, a major finding to highlight from these results is the critical need for improvements and advances in electrical power systems, to avoid potential damage to electrical elements caused by overloads and significant supply disruptions due to low voltages.

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