

Impact of the Charging Station on the Quality of Voltage and Frequency in the Microgrid

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ABSTRACT

This paper presents the impacts of Electric Vehicle Charging Stations (EVCSs) on voltage and frequency quality in the Microgrid. It addresses security analysis, voltage and frequency quality, as well as issues related to EVCSs. In this paper, modeling and simulation method is utilized to evaluate the impact of Charging Stations (CSs) in Microgrid power systems using PowerWorld software. Potential attacks may occur when malicious actors intrude and control the operating states of CSs in the power grid, as well as potential vulnerabilities in the process of using EVs in Microgrid, are simulated and analyzed. Based on this, the paper proposes power grid attack scenarios based on charging/discharging operations with a large number of EVs on generator buses. Simulation results show the negative impacts of charging/discharging operations on the grid through frequency and voltage fluctuations. Specifically, from the simulation results, it can be observed that Bus 8 is not suitable for installing a charging station due to its weak stability at all power levels. Furthermore, the remaining generator buses can only accommodate charging stations with power levels starting from 30% of the proposed initial capacity to maintain system stability.

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1. Introduction

The increasing use of EVs is creating a strong motivation for the development and expansion of electric CSs, driven by the significant benefits that EVs offer. Many countries have set specific targets and implemented incentives to encourage people to transition from gasoline-powered cars to EVs. The rapid response of manufacturers in deploying CSs is also generating unexpected growth in this field. However, this deployment speed also brings challenges in terms of security, especially for the EV ecosystem and microgrids. To address this issue, the research in this paper focuses on identifying vulnerabilities that may exist in the EV ecosystem, which could be exploited to manipulate the EV charging process and even launch attacks on the power grid.

In this day and age, climate change along with the scarcity of fossil fuels and advancements in battery technology have spurred several automobile manufacturers worldwide to invest in developing new models of battery-powered vehicles, known as EVs [1]. Governments in various countries across the globe have positively supported the use of EVs through tax incentives, parking fee reductions, freedom of movement in restricted traffic areas, bus lane usage, and many other benefits [2]. One key difference of EVs compared to Internal Combustion Engine (ICE) vehicles is their connection to the grid through CSs.

The electricity demand for EVs charging is currently not a significant concern. However, the development of EVs along with the expansion of CSs in the future may lead to increased electricity demand, which could affect the operation of Microgrid power systems, either positively or negatively [3], [4]. In reality, if EV charging is not restricted during peak hours, it may challenge the operation of the electricity system and misuse the energy generated by renewable energy sources (RES) [3], [4].

Consequently, unrestricted charging may lead to additional investments in generation and transmission capacity, increase wear and tear on distribution components, and pose issues regarding power quality [4], [5]. Additionally, issues related to grid attacks, threatening national security and the economy, also need to be taken into account.

A quick and clearer approach to addressing the aforementioned issue is modeling the steady-state operation of Microgrid power systems through the modeling of power grid topologies. PowerWorld Simulator is a software used to simulate the steady-state, transient, and stable/unstable states of power systems by evaluating output waveforms and collected data. This means that it simulates the variations of system parameters over time, usually in small time intervals, and calculates their average values. Although there is no built-in support for configuring the specific charging/discharging states of CSs in PowerWorld Simulator software [6], we can overcome this by simulating a Battery model and increasing the load value to represent the operation of the CS in the power grid. For the discharging state of the battery, we simulate the scenario of injecting (generating) reverse power into the grid during the transient stability analysis mode.

To address this issue, numerous articles have proposed various methods along with different modeling and mathematical approaches. In [7], the article proposes the use of battery energy storage systems to mitigate power fluctuations in PV-Diesel systems within Microgrid networks. The study focuses on determining the correlation between battery capacity and daily solar irradiance variations. It provides a linear regression-based model to estimate the optimal battery capacity without the need for detailed simulation studies. In [8], the impact of EVCS loads on the distribution grid is investigated. Negative effects of EVCS loads on the distribution grid include increased peak power demand, reduced power reserves, voltage instability, and reliability issues. The research also proposes a strategy to determine the locations of EVCSs on the distribution grid based on the Voltage Stability, Reliability, and Power loss (VRP) index by optimizing the distribution of CSs to minimize the impact on grid operation parameters, thereby stabilizing voltage, increasing reliability, and reducing power losses. In the context of rapidly increasing EV usage demands, managers require the construction of clean and safe infrastructure systems. In [9], a detailed analysis of the security of EVCS management systems is presented. The analysis identified several security vulnerabilities and highlighted the insecurity of these systems against remote attacks. Additionally, the research group simulated the impact of attacks on the power grid and proposed risk mitigation measures on the IEEE standard diagram using power system simulation software, demonstrating significant impacts on the grid frequency with different scenarios. Manufacturers have responded positively to these recommendations.

In this paper, a simulation model of the grid-connected energy storage system is modeled using PowerWorld to determine the potential impacts of the CS model in the Microgrid system. The scenario arises when malicious actors intrude and cause adverse effects on the grid, specifically by controlling the charging/discharging of a large amount of power onto the grid, causing power flow imbalances in the power system. In the Section 2.1, the overview of the CS model in the simulation and the adverse effects on the grid through EV are presented. The Section 2.2 mainly focus on the BESS model in the PowerWorld software to simulate charging/discharging scenarios. The variations in voltage and frequency of the simulated power system of the IEEE 9-Bus system are discussed in Section 2.3. Finally, Section 2.4 conducts comparative experiments on the charging/discharging state impacts of the CS on the Microgrid grid, including evaluations of system operation data in each scenario and proposing future works.

2. Methodology

2.1. Trends in intrusion and attacks on the Power Grid by EV

The infrastructure of future smart EVCSs includes the integration of renewable energy sources and energy storage systems, as depicted in Figure 1 [11].

In the study of EV Systems, Francillon et al. [12] clarified the threat posed by relay control attacks on smart lock and keyless start systems of EVs. Wouters et al. [13] discovered security vulnerabilities related to error encryption algorithms and lacking interactive authentication in the key-to-vehicle authentication process. Tencent's security research team identified 14 security vulnerabilities in the

electronic control units of BMW models [14]. Keuper et al. [15] also indicated the vehicle's connectivity to Wi-Fi networks and described how to exploit entertainment system vulnerabilities in vehicles to control functions such as the center screen and speakers through CAN network messages. This poses significant security challenges in both the automotive industry and the national power grid. According to [15], the paper presented methods of EV impact on grid through CSs via Table 1 below.

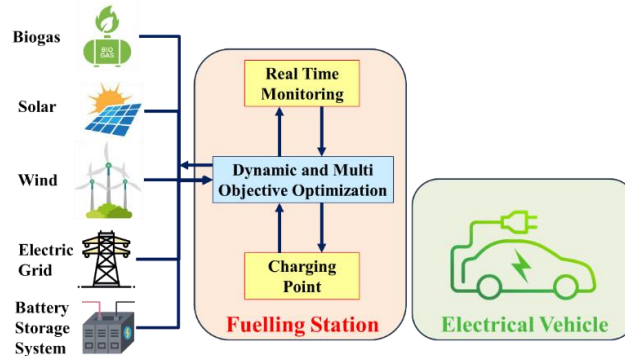


Figure 1. Block diagram of the principle of the grid-connected EVCS system.

Table 1. Comparison of attack cases of EV on the power grid

Attack types	Attack forms	Attack targets	Consequences	Solutions
Jamming attack	Active	EV infrastructure and CSs	EVs cannot be charged	Cloaking and acoustic
Spoofing attack		EV, EVCS	Private data leakage, EVCS infected	Digital signature
Data dimension attack	Active\ Passive	Data transmission	Data is stolen and corrupted	Authentication, Encryption
DoS attack	Active	Charging pile, EVCS, EV, Smart Grid	EVCS can not work	Authentication, IDS
Botnet attack	Active	Charging pile, EVCS, EV, Smart Grid	Loss of control	Authentication, IDS
Sybil attack	Active	Global Controller	Network congestion and energy shortage	Authentication, Trust assessment test

According to Table 1, various types of network attacks on EV charging systems and corresponding protective technologies are presented. Among them, the most dangerous and directly impactful to the power grid is the Botnet attack. It utilizes a Botnet to execute multiple network attacks, potentially causing chaos in the system and damaging the smart grid. Specifically, attackers may exploit vulnerabilities in server-side request forgery (SSRF) to use compromised EVCS. Attackers may also make use of a large number of infected EVCSs to initiate simultaneous charging operations or reverse the current flow back into the smart grid by enhancing the discharge power supply. Both of these attacks destabilize the smart grid, causing power imbalance issues and consecutive incidents. According to [16], when the frequency exceeds the specified value of 4 - 5% (~0.3Hz) for a long period of time, it causes damage to the equipment operating in the electrical system. Besides, the voltage is also limited within $\pm 0.05pu$. In case the system frequency or voltage is outside the range of $\pm 0.3Hz$ or $\pm 0.05pu$, it is called "Unstable". On the contrary, we classify it as "Stable".

2.2. The proposed charging station model

In recent years, the Western Electricity Coordinating Council (WECC) has undertaken the development, validation, and publication of a set of models for simulating renewable energy systems in positive sequence power system simulation tools to perform large-scale stability simulations [10].

Information and details regarding the research and testing of the model's characteristics are published in [17] and [18].

The materials referenced in these documents provide information on setup for simulating renewable energy system models [9]. With these updates, researchers have the capability to simulate, for research purposes in terms of the stability and operation of Battery Energy Storage Systems (BESS). The proposed model is based on [19], followed by supplementation and modifications based on suggestions and feedback after several discussions with the WECC REMTF Adhoc group on BESS models and some sponsorship from EPRI. The schematic presenting the CS model [20], [21] is constructed in simulation software as depicted in Figure 2.

In the REEC_C block, the crucial point that transforms it from a PV model to a BESS (Battery Energy Storage System) form is the transfer function depicted in Figure 3. It represents a simple charge and discharge block of the storage battery; without it, the REEC_C model would be no different from REEC_A and would operate solely as a PV. Figure 4 illustrates the entire mathematical model of the REEC_C converter, with all parameter annotations presented in [22].

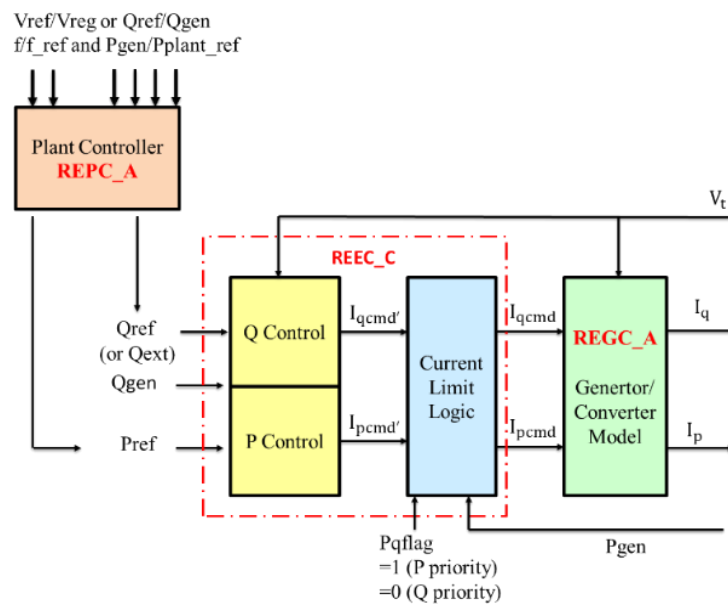


Figure 2. Model of a storage battery electric machine.

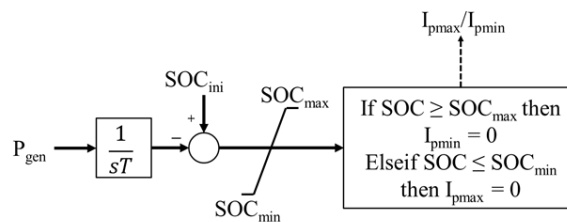


Figure 3. Transfer function of the BESS charging/discharging mechanism.

Where, SOC is defined as the available energy expressed as a percentage of the rated capacity of the battery. In the battery industry, energy stored in batteries is typically represented in terms of Ah (ampere-hours), but this ambiguity can lead to confusion and misunderstanding. Instead of Ah, the energy stored in batteries should be represented in terms of Wh (watt-hours), kWh (kilowatt-hours), or MW*h (megawatt-hours). Based on these considerations, the theory suggests that State of Charge (SOC) should be calculated as follows:

$$SOC = \frac{E_{available}}{E_{Rated}} = \frac{P_{available} \times T_{Charging \text{ or } DisCharging}}{P_{Rated} \times T_{Rated \text{ Charging or DisCharging}}} \quad (1)$$

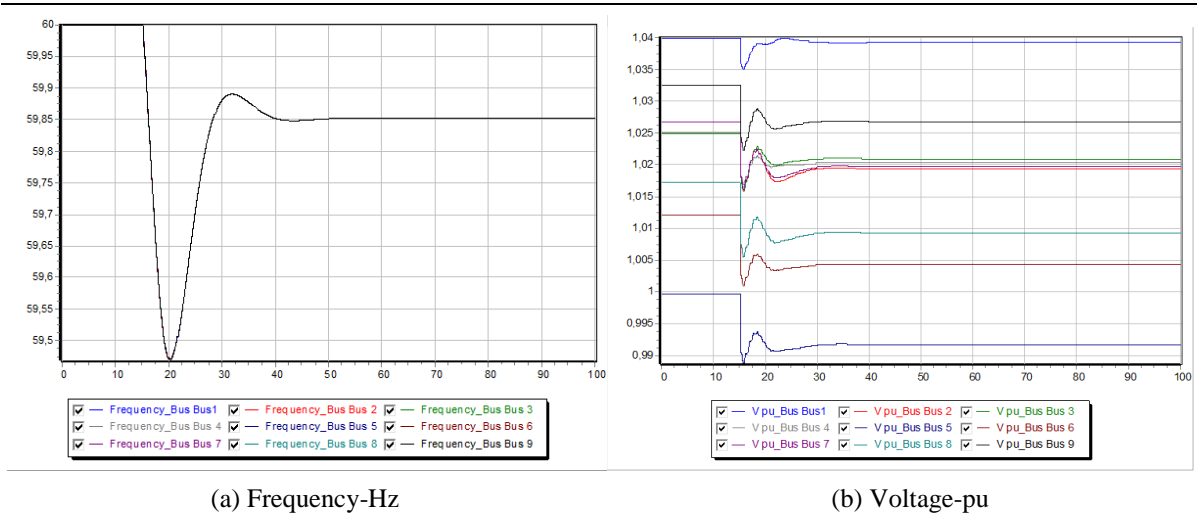


Figure 5. System parameters under Attack Scenario 1.

Attack Scenario 1: The IEEE 9-Bus system operates at the nominal frequency (60Hz), then, the load on Buses 5, 6, and 8, representing compromised EVCS, is increased by 7.2MW at $t = 15s$. On average, this load increase corresponds to approximately 3,000 EVs charging on Level 2 EVCS, or 196 EVs charging on Level 3 EVCS, or a combination of about 1,000 EVs charging on Level 2 EVCS and 131 EVs charging on Level 3 EVCS [24].

Attack Scenario 2: A hypothetical situation where the power grid faces the challenge of reverse power flow back into the grid by releasing a large number of EVs connected through the bidirectional current feature of the compromised EVCS [25]. To simulate this scenario, we use the photovoltaic (PV) model REGC_A with exciter REEC_C [26], similar to the power device of EV batteries when charged through EVCS. In the experiments, we select a Chevy Volt with a charging/discharging limit of 3.3 kW as our connected EV [27]. In the paper, the release of power is simulated by suddenly discharging at a power of 51.7 MW at time $t=15s$ at bus 5, equivalent to around 15,000 electric cars releasing energy. On the grid, 15,000 EVs will be distributed on several regional load clusters that is shown on a bus in the grid diagram. Bad guys will hack into the control system, causing 15,000 cars to connect to the charging station at the same time and discharge back to the grid, causing disruption to the electrical system. As depicted in the simulation results in Figure 6, the attack has succeeded as it has caused instability in the system, pushing the frequency high and exceeding the upper limit.

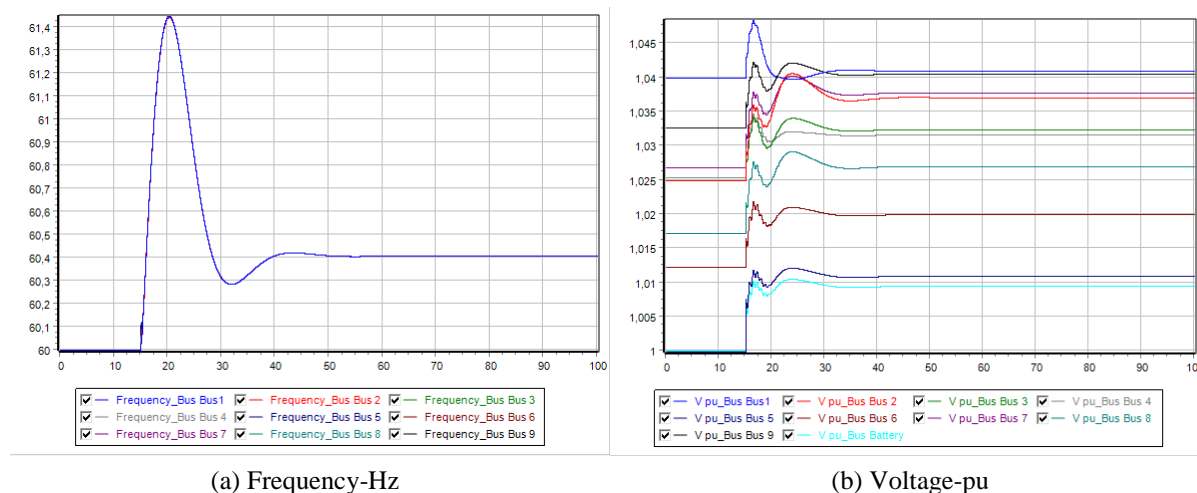


Figure 6. System parameters under Attack Scenario 2.

Through the analysis of Figures 5 and Figure 6, it is evident that the frequency of the simulated system experiences a sudden drop as a result of this attack. Importantly, the frequency decreases to

specified range $\Delta f = \pm 0.5\text{Hz}$. Therefore, the attacker has achieved the objective of inducing frequency instability and causing blackout in the power grid.

2.4. Attack Scenarios in the Proposed Microgrid system

The goal of section 2.3 is to introduce the idea, from verifying the published results of WECC on the IEEE-9 Bus diagram, we rechecks the accuracy and application on the 16-Bus Microgrid diagram in section 2.4. Through simulation and verification, we can see the impact of the charging station on the Microgrid diagram, such as the possibility of frequency and voltage fluctuations in the Microgrid system.

Attack Scenario 1: The IEEE 16-Bus system operates at the nominal frequency (60Hz), and at time $t=15\text{s}$, we initiate simultaneous charging on the loads with a total charging capacity of 3.84MW. This charging capacity corresponds to approximately 1000 EVs charging simultaneously on Level 2 EVCS or 96 EVs charging on Level 3 EVCS. With the aforementioned charging capacity, we divide it into smaller increments from 3.84MW down to 0.384MW, corresponding to power levels from 100% to 10% with each 10% decrease, to observe the impact [24].

Table 2 shows that the Microgrid system remains stable only when the simultaneous load at all load buses requires a power amount of 1.1536MW, corresponding to only 30% of the total load demanded by the scenario.

Attack Scenario 2: Simulating discharging activities by releasing a sudden discharge of 11.52 MW at time $t = 15\text{s}$, corresponding to approximately 3000 EVs discharging. The simulation is conducted with the original proposed model and divided into 2 cases: testing focused on CSs at each generator bus. After the testing process, Buses 2, Bus 11, Bus 14, and Bus 15 exhibit fluctuations. However, Bus 8 experiences a collapse of the entire system under the attack scenario. Furthermore, we use the power of 11.52MW as a standard to divide into multiple power levels to observe the impact of discharge power on the Microgrid.

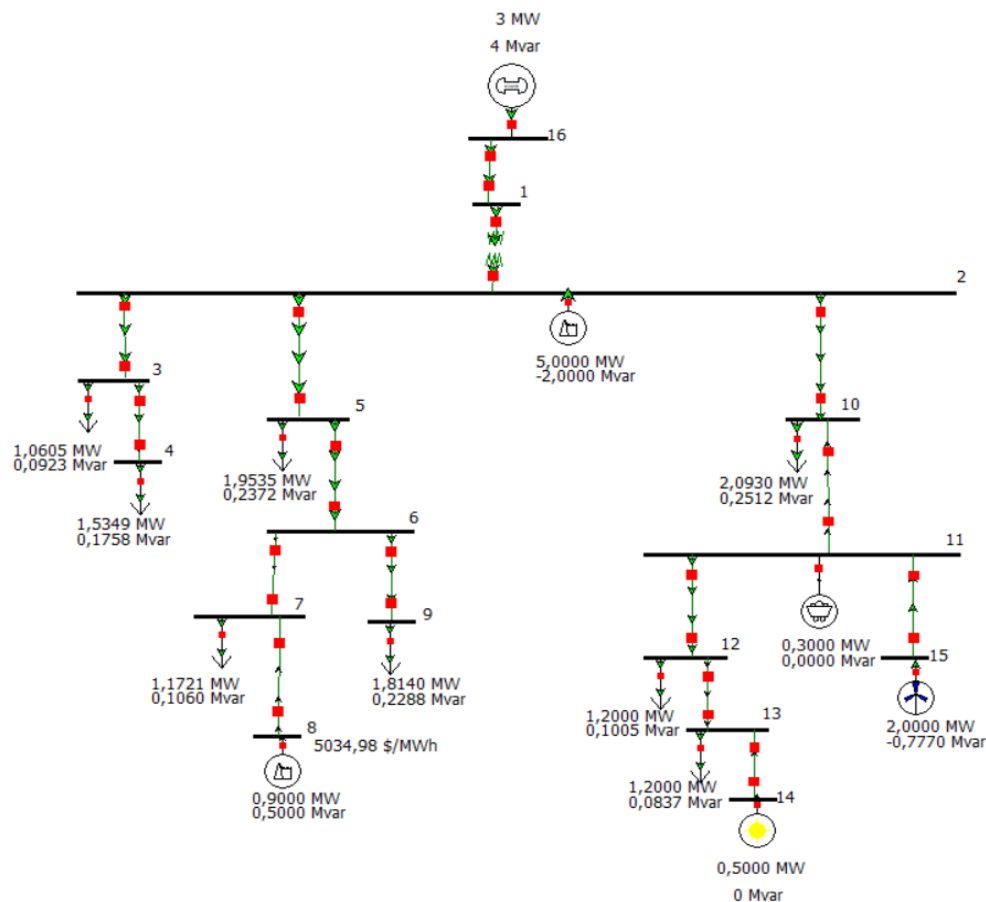


Figure 7. IEEE 16-bus Microgrid system.

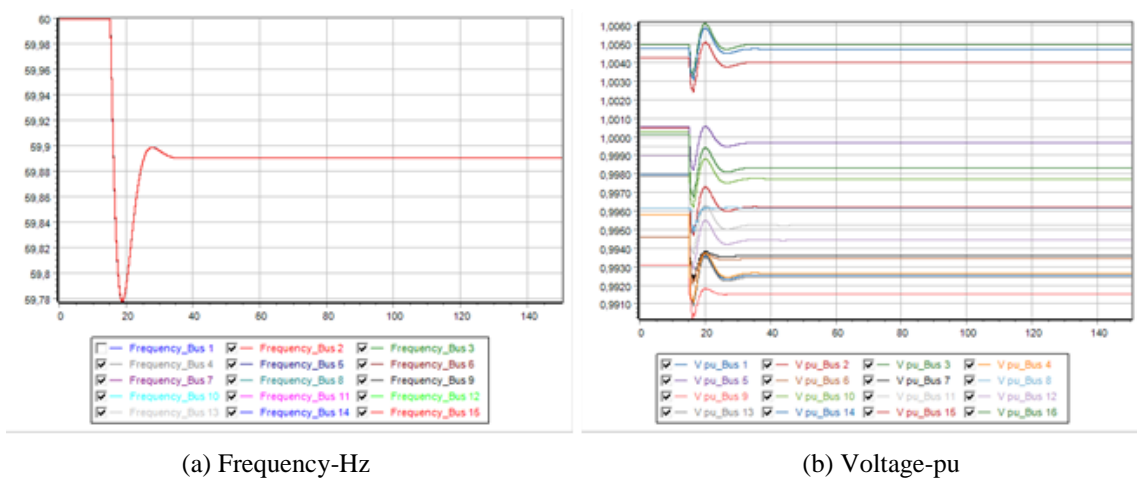


Figure 8. Parameters of the Microgrid 16-Bus under Attack Scenario 1.

Table 2. Comparison and Evaluation of the State of the Microgrid in Attack Scenario 1.

	Charging station power level (%)	P _{BESS} (MW)	Δf_{system} (Hz)	ΔU_{max} (pu)	Assessment
All bus loads	10	0.384	0.0868	0.0043	Stable
	20	0.768	0.1736	0.0087	Stable
	30	1.152	0.2602	0.0129	Stable
	40	1.536	0.7042	0.0221	Unstable
	50	1.92	0.8792	0.0276	Unstable
	60	2.304	1.0537	0.033	Unstable
	70	2.688	1.2309	0.0384	Unstable
	80	3.072	1.4048	0.0438	Unstable
	90	3.456	1.5781	0.0492	Unstable
	100	3.84	1.7448	0.0545	Unstable

From the simulation results and collected data, the impact of CSs between the traditional power grid and the Microgrid shows differences in frequency and voltage fluctuations. Regarding frequency, when discharging power, there are differences in the response process between the traditional power grid and the Microgrid. Specifically, in the traditional power grid, the frequency peaks at $f = 61.4$ Hz at $t = 20$ s, then decreases, and stabilizes at $f = 60.4$ Hz at $t = 50$ s. On the other hand, in the Microgrid, the scenario with a CS at bus 2 with 100% power as initially assumed, the frequency value does not exhibit significant oscillations but steadily increases to 64Hz at $t = 80$ s. This highlights voltage fluctuations in the traditional power grid, which are more pronounced with larger fluctuations during transient and steady states compared to the Microgrid. Additionally, reducing the attack power indicates that smaller values have less impact on the grid. The proposed solution for the above attacks could be to predict incidents early for administrators by training a neural network to predict incidents using metrics through simulating attacks with many different power levels. Additionally, optimal locations for placing CSs to prevent and mitigate incidents can be determined. This can be observed in attack scenario 2 at bus 11, as shown in Table 3, indicating that the system becomes unstable with power levels around 40%, and vice versa. Furthermore, there are sensitive bus locations within the grid affected by CSs, such as bus 8 in the aforementioned scenario. The simulation scenarios where discharging power was applied in any amount all resulted in instability.

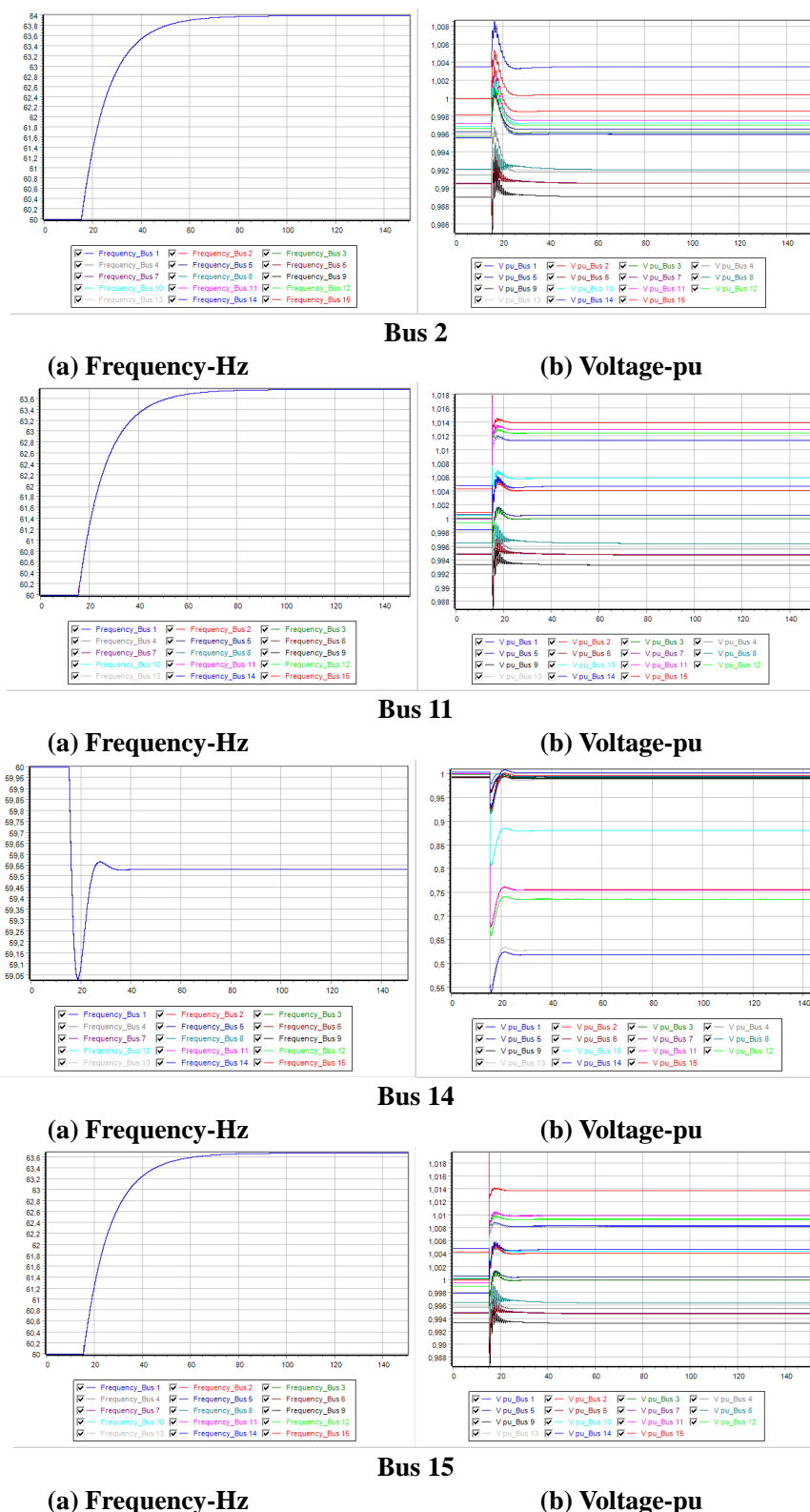


Figure 9. Parameters of the Microgrid 16-Bus under Attack Scenario 2

Through simulation modeling method, Table 3 presents simulation data with each power level of the charging station placed at different generator buses, showing the fluctuations of frequency and voltage in the system. It can be observed the impact of the charging station when placed at different locations along with power levels ranging from 10% to 100%. Based on the data, it can be remarked that Bus 8 cannot accommodate a charging station as it exhibits instability at any power level.

Table 3. Comparison and Evaluation of the State of the Microgrid in Attack Scenario 2.

	Charging station power level (%)	P _{BESS} (MW)	Δf_{system} (Hz)	ΔU_{max} (pu)	Assessment
Bus 2	10	1.0752	0.0614	0,0005	Stable
	20	2.1504	0.1532	0.0011	Stable
	30	3.2256	0.3861	0.0017	Stable
	40	4.3008	0.7509	0.0022	Unstable
	50	5.376	1.2207	0.028	Unstable
	60	6.72	1.85	0.0036	Unstable
	70	8.064	2.4665	0.0043	Unstable
	80	9.216	2.9855	0.005	Unstable
	90	10.368	3.4961	0.0056	Unstable
	100	11.52	3.9985	0.0063	Unstable
Bus 8	10	1.0752	63.675	1.0671	Unstable
	20	2.1504	55.9474	2.96×10^{17}	Unstable
	30	3.2256	1.01×10^2	3.98×10^{23}	Unstable
	40	4.3008	94.2774	$6,34 \times 10^{22}$	Unstable
	50	5.376	99.6069	934.393	Unstable
	60	6.72	22.5876	42.942	Unstable
	70	8.064	51.5977	33.6812	Unstable
	80	9.216	36.7329	31.4117	Unstable
	90	10.368	44.151	66.4581	Unstable
	100	11.52	37.1797	27.0326	Unstable
Bus 11	10	1.0752	0.0612	0.0017	Stable
	20	2.1504	0.1605	0.0034	Stable
	30	3.2256	0.4019	0.005	Stable
	40	4.3008	0.7679	0.0066	Unstable
	50	5.376	1.2251	0.0082	Unstable
	60	6.72	1.8165	0.0102	Unstable
	70	8.064	2.3899	0.0122	Unstable
	80	9.216	2.8683	0.0139	Unstable
	90	10.368	3.3352	0.0154	Unstable
	100	11.52	3.791	0.017	Unstable
Bus 14	10	1.0752	0.0532	0.0332	Stable
	20	2.1504	0.0785	0.068	Unstable
	30	3.2256	0.0759	0.1047	Unstable
	40	4.3008	0.0454	0.1431	Unstable

	50	5.376	0.0335	0.1834	Unstable
	60	6.72	0.1505	0.2371	Unstable
	70	8.064	0.3173	0.2946	Unstable
	80	9.216	0.4998	0.347	Unstable
	90	10.368	0.7197	0.4025	Unstable
	100	11.52	0.9775	0.4611	Unstable
	10	1.0752	0.0609	0.0019	Stable
	20	2.1504	0.1579	0.0038	Stable
	30	3.2256	0.3931	0.0057	Stable
	40	4.3008	0.7493	0.0076	Unstable
Bus 15	50	5.376	1.1957	0.0094	Unstable
	60	6.72	1.7752	0.0117	Unstable
	70	8.064	2.3357	0.014	Unstable
	80	9.216	2.8022	0.0159	Unstable
	90	10.368	3.2562	0.0178	Unstable
	100	11.52	3.698	0.0197	Unstable

4. Conclusions

The paper discusses various attack scenarios considering the impact of EVCS in Microgrid. It also describes how they can disrupt the operation of the power grid while demonstrating the significant effects they can have on the grid. Specifically, the proposed situations include two cases: when a bad person invades and controls a large amount of charging/discharging capacity. Simulation results show that in scenario 1, when a large number of vehicles charge at the same time with a capacity of 3.84MW, the frequency is unstable with a value of 58.3Hz and a voltage of 0.0545pu, exceeding the allowable value. Besides, Scenario 2, when a large number of vehicles release power back to the grid, the system will become unstable. In the future work, the calculation of the aggregate transfer function includes mathematical models of the generators and chargers to evaluate the frequency and voltage response at different charge/discharge levels. In addition, it can be proposed to use Fuzzy to blur the data, thereby shortening the simulation process and considering the 1% level.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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