B&H Electrical Engineering, Volume 20, Issue 1, 2026
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0001

Original scientific paper

Submitted: March 11, 2025

Accepted: October 12, 2025

ELECTRIC VEHICLES AS PARTICIPANTS IN THE FLEXIBILITY SYSTEM

M. Previšić[1,2], M. Majstorović[1], I. Šimović[1], L. Medić[1], D. Grabovac[1]

Abstract: Integrating electric vehicles (EVs) into the transportation system represents a crucial step towards achieving sustainable mobility and reducing greenhouse gas emissions. Technological advancements continuously enhance the performance and availability of EVs, making them significant players in the flexibility of energy grid systems. Electric vehicles not only provide an environmentally sustainable alternative to conventional vehicles but also act as mobile battery systems. These systems can be optimized for energy consumption management, balancing supply and demand in the electrical power system. Given the increasing share of renewable sources, the flexibility of EVs becomes essential. The analysis of home EV charger integration was conducted using the DIgSILENT PowerFactory software tool, utilizing quasi dynamic simulation. The simulations were performed on a rural network near Mostar on the weekday with the highest consumption, July 18, 2023. The simulation results indicated that the increase in the share of chargers significantly impacts the electrical grid. In the case of connecting 5% of chargers from the total number of consumers on the transformer station, an increase in network losses was recorded, but the transformer load remained below 100%. When the share increased to 15% of the total consumers, losses also increased, leading to transformer overload. However, by implementing load management strategies, where 50% of the 15% of consumers at overloaded transformer stations engage in demand response, system losses are mitigated, and transformer loading conditions are effectively optimized. This paper demonstrates that smart charging, along with strategies for optimizing charging times, can significantly reduce peak loads on transformers, improve the overall efficiency of the electrical power system, and simultaneously provide financial savings for end users.

Keywords: Electric vehicles, flexibility, distribution network

INTRODUCTION

The global energy transition requires fundamental transformations of energy systems. A key strategy in this process is the electrification of a wide range of energy services in end-use sectors, such as buildings, transportation, and industry. Road transport represents a central element in the decarbonization of the transport sector, as it is responsible for more than three-quarters of emissions from transportation and one-fifth of global energy-related emissions [1]. As part of efforts to achieve zero emissions on road transport by 2035 (for all newly registered vehicles in Europe), as set by Regulation (EU) 2019/631, a 15% reduction in the average emissions of new cars and light commercial vehicles is required by 2025. Amendments introduced by Regulation (EU) 2023/851 set a target of a 55% reduction in emissions from new passenger cars and a 50% reduction for new light commercial vehicles by 2030 [2]. As a result, many governments are progressively adopting policies in favor of electric vehicles (EVs). Integrating EVs into the power grid disrupts the conventional energy flow, bringing benefits and drawbacks. One of the key benefits, in the context of EV charging, is providing flexibility. Flexibility, in this context, refers to the system's ability to adapt to sudden fluctuations in energy production and consumption [3]. Depending on the time of day, the week, the season, or other influencing factors, the distribution of charging sessions may vary significantly [4]. Therefore, flexibility in EV charging can be achieved through power adjustments (altering charging speeds), energy (vehicle-to-grid mode (V2G) or incomplete charging sessions), and time (splitting sessions or, as further explored in this paper, postponed charging) [5].

1. ELECTRIC VEHICLES AND CHARGING INFRASTRUCTURE

EVs represent an integrated system of interconnected subsystems that utilize various technological components and energy storage methods. EVs can operate solely on electric power, relying exclusively on batteries as their energy source, or they can be combined with internal combustion engines (ICE), resulting in a hybrid configuration.

Based on the propulsion system, EVs are classified into four main categories:

This paper was submitted to the Conference of the South-East European Regional Council of CIGRE (SEERC 2025), held in Sarajevo, Bosnia and Herzegovina, on June 4–5, 2025.

[1] *JP „Elektroprivreda HZ HB" d.d. Mostar, Bosnia and Herzegovina*
[2] *Correspondence email: mia.previsic@ephzhb.ba*

1. Hybrid Electric Vehicles (HEVs) – These vehicles combine an ICE with an electric propulsion system, resulting in higher efficiency and lower fuel consumption. At lower power demands, they operate on electric drive, while at higher speeds, the vehicle relies on the ICE. The batteries are charged through the ICE or regenerative braking, further enhancing energy efficiency and reducing harmful emissions.
2. Plug-in Hybrid Electric Vehicles (PHEVs) – PHEVs use a combination of an ICE and an electric propulsion system. They primarily operate on electric power, with the ICE activating when the battery charge level is low, enabling battery charging or extending the vehicle's range. In addition to regenerative braking, PHEV batteries can be charged from an external power grid, further optimizing the vehicle's energy efficiency.
3. Battery Electric Vehicles (BEVs) – BEVs rely entirely on battery power, utilizing electrical energy stored in batteries that can be recharged from an external power grid. The vehicle's range significantly depends on various factors, including driving style, road conditions, vehicle specifications, battery type, and the vehicle's age.
4. Fuel Cell Electric Vehicles (FCEVs) – These vehicles generate electricity through chemical reactions in fuel cells, with hydrogen being the most commonly used fuel. The energy produced in the fuel cells is transferred to the electric motor (EM), which drives the vehicle's wheels. Additional energy is stored in batteries or supercapacitors for later use.

Based on power and charging speed, EV chargers can be classified into three levels: Level 1, Level 2, and Level 3. Level 1 charging operates at 120 V AC and is the slowest charging method, typically used in home settings. A full vehicle charge usually requires an entire night. Level 2 charging uses 240 V AC, allowing faster charging with a maximum power output of up to 19.2 kW. This type of charging is commonly used at charging stations, homes, parking lots, and shopping centers. Level 3 charging, also known as DC fast charging, enables electric vehicles to charge up to 80% State of Charge (SoC) in less than 30 minutes, with a maximum power output of up to 150 kW. This charging method is available at commercial charging stations [6].

1.1. Global Trends in the Development of Electric Vehicles and Charging Infrastructure

Nearly 14 million new EVs were registered worldwide in 2023, bringing the count of EVs to 40 million. The number of EVs sold in 2023 was 3.5 million higher than in 2022, representing an annual growth of 35%. This number of EVs is more than six times higher than in 2018, just five years ago. EVs accounted for approximately 18% of total car sales in 2023, marking a significant increase compared to 14% in 2022 and just 2% in 2018. These figures indicate the accelerated growth of the EV market, further driven by the development and expansion of charging infrastructure, as shown in Figure 1 [7].

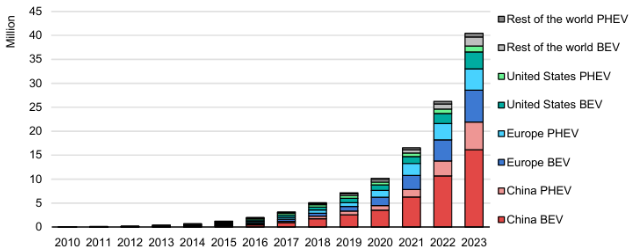

Figure 1: Trend in the development of EVs from 2010 to 2023 [7]

Despite the continuous global growth in EV sales, the market remains highly concentrated in a few regions. In 2023, nearly 60% of new EV registrations were in China, approximately 25% in Europe, and 10% in the U.S., together accounting for almost 95% of total global sales. On the other hand, EV sales in other parts of the world, including countries with developed automotive markets such as Japan and India, remain limited. However, in regions like Africa, Eurasia, and the Middle East, EVs are rare, making up less than 1% of total car sales. EV sales remained strong in the first quarter of 2024, surpassing the results from the same period in 2023 by about 25%, reaching over 3 million vehicles sold. As of 2023, PHEV sales are growing faster than BEV sales. These trends highlight changes in consumer preferences and the evolution of market dynamics in the EV sector. It is crucial to emphasize that various incentives for purchasing EVs also significantly impact the growth dynamics of the EV market. For example, Germany, a key region for the EV market in Europe, has seen a gradual reduction in subsidies, leading to a slowdown in overall EV sales growth. In early 2023, the removal of subsidies for PHEVs resulted in a decrease in their sales compared to 2022. In December 2023, all subsidies for EVs were eliminated following the adoption of the Climate and Transformation Fund decision. As a result of these changes, the share of EV sales in Germany fell from 30% in 2022 to 25% in 2023, which negatively impacted the overall share of EV sales in the region [7].

There are nearly ten times more private chargers than public ones, with most EV owners using home charging. Home charging is currently the most common method for charging electric vehicles. The availability of home charging varies significantly between regions, and this variation is closely linked to differences between urban, suburban, and rural areas, as well as socioeconomic groups. In densely populated urban environments, where most of the population lives in multifamily buildings, access to home charging is limited. As a result, EV owners in these areas rely more heavily on public charging infrastructure. This is particularly evident in South Korea, one of the most densely populated countries in the world, which has the highest ratio of public charging capacity relative to the number of EVs. In addition to home charging, private charging infrastructure also includes other chargers that are not publicly accessible, such as those reserved for employees, fleet vehicles, or specific facility users. Although the number of private chargers significantly exceeds the number of public ones, public charging infrastructure and its interoperability are key factors for broader adoption and more equitable access to EVs. In 2023, the number of public chargers increased by over 40%, with the growth of fast chargers outpacing the growth of slow chargers. By the end of 2023, fast chargers accounted for more than 35% of the total public charging infrastructure [7].

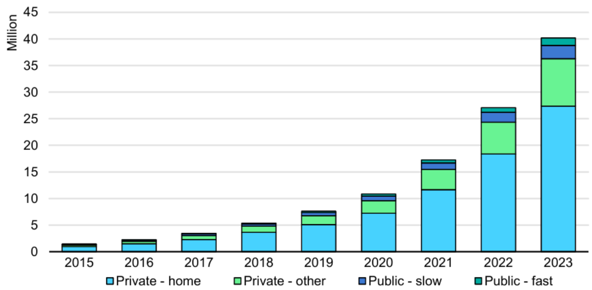

Figure 2: Trend in the development of Electric Vehicle Supply Equipment from 2015 to 2023 [7]

By the end of 2023, the European Union has reached an agreement on the Alternative Fuels Infrastructure Regulation (AFIR), which requires the installation of public fast chargers every 60 km along the main transport corridors of the European Union (Trans-European Transport Network [TEN-T]). This regulation will ensure the availability of 1.3 kW of publicly accessible chargers for each registered BEV and an additional 0.8 kW for each registered PHEV. Accurately planning the optimal number of chargers can be challenging due to varying supply and demand dynamics in different countries. Insufficient public charging infrastructure (a high EV: EVSE ratio) can cause significant inconvenience for users, while excessive infrastructure (a low EV: EVSE ratio) may be economically unsustainable. Finding the right balance is crucial to ensuring optimal infrastructure utilization and meeting the needs of EV users [7].

1.2. Trends in the Development of Electric Vehicles and Charging Infrastructure in Bosnia and Herzegovina

EVs and their charging infrastructure in Bosnia and Herzegovina (B&H) are still in the early stages of development and are present in limited numbers. The first EV charging station in B&H was built in 2016 in Sarajevo and is owned by the Residence Inn Marriott Hotel. This charging station is equipped with two Mode 3 Type 2 connectors, which provide standardized and efficient EV charging [8]. Mode 3 refers to an EV charging method connected to specialized Electric Vehicle Supply Equipment (EVSE). It represents a permanent connection to the AC grid and includes integrated control and safety functions. Type 2 refers to the connector type commonly used in Europe and complies with the IEC 62196 standard. It supports single-phase and three-phase AC charging, with allowable power levels of up to 17 kW for single-phase AC and up to 50 kW for three-phase AC charging. Figure 2 shows a map of EV charging stations in B&H. Charging stations marked in yellow are privately owned and located within restaurants, hotels, shopping centers, and other facilities. Stations marked in green are publicly accessible and free to use. Charging stations marked in blue are also public, but their charging services are subject to fees. The total number of charging stations is approximately 167, with the majority in major cities such as Sarajevo, Banja Luka, Mostar, and Tuzla [9].

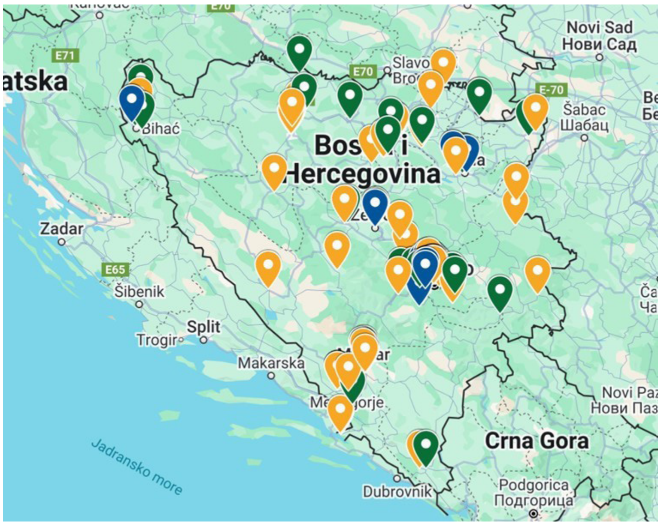

Figure 3: Map of EV Charging Stations in B&H [9]

The total number of vehicles registered in B&H in 2023 is 1,295,224 compared to 1,233,783 vehicles registered in 2023, representing an increase of almost 4.98%. ICE vehicles account for 99.48% of the total registered vehicles, while the remaining share consists of electric vehicles (EVs) [10]. Table I presents the number of registered vehicles classified by propulsion type.

Table I: Number of registered vehicles in B&H classified by propulsion type [10]

Vehicle type	Number of registered vehicles
Internal Combustion Engine Vehicles (ICEV)	1,288,534
Hybrid Electric Vehicles (HEV)	5,915
Plug-in Hybrid Electric Vehicles (PHEV)	11
Battery Electric Vehicles (BEV)	763
Fuel Cell Electric Vehicles (FCEV)	1

The regulatory framework for EVs in B&H is still in the development phase. However, on January 8, 2024, the Government of the Federation of Bosnia and Herzegovina

(FB&H), at the proposal of the Federal Ministry of Energy, Mining and Industry, adopted a decision to subsidize the purchase of EVs with a total amount of 1,000,000 BAM. Half of this amount is intended for private companies and entrepreneurs as incentives for purchasing EVs, with the same amount allocated for subsidies to individuals (natural persons). The subsidy for purchasing a BEV is 10,000 BAM, while for purchasing a PHEV, the amount is 7,000 BAM. Funds for purchasing EVs may be allocated to private companies and entrepreneurs for the purchase of a maximum of two vehicles, and to individuals for the purchase of one vehicle. The technical requirements for eligible vehicles are BEVs with CO_2 emissions of 0 g/km and PHEVs with CO_2 emissions of less than 50 g/km [11].

2. FLEXIBILITY OF ELECTRIC VEHICLES - BENEFITS AND DRAWBACKS

EVs are new participants in the power system that bring additional variability and unpredictability. If EVs and their charging infrastructure are seen as new passive consumption within the grid, there is an inevitable increase in peak load, which negatively impacts both the distribution and transmission networks, further complicating the maintenance of the power system's stability [12] [3]. Therefore, EVs encounter technical, economic, and institutional obstacles in the process of integrating into the distribution network. On the one hand, the connection of EVs further burdens the grid, which can lead to equipment degradation, increased losses, and network congestion. On the other hand, it can impact supply quality, causing voltage dips, increased harmonic distortion, and phase imbalance. To overcome these challenges, the distribution system operator (DSO) must reinforce the infrastructure, enhance real-time network monitoring, and develop advanced control and charging management methods. However, these impacts depend on the percentage of EVs in the system, the grid topology, and the acceptance of end users [13].

For instance, the "My Electric Avenue" project gathered 200 households in the UK, providing them with Nissan Leaf EVs integrated with Esprit Technology, which utilizes demand-side response strategies and can postpone or limit charging to prevent grid overload. The findings indicated that a significant grid load occurs when 30% or more households in a neighborhood charge EVs at the same time. It is estimated that by 2050, approximately 32% of the low-voltage (LV) network in the UK could require upgrading if 40% to 70% of vehicles in the UK are electric. However, the implementation of demand-side response systems can mitigate issues related to voltage and overload, and it is estimated that such a coordination system could generate savings of up to £2.2 billion in network infrastructure investments by 2050 [14].

EVs, as mobile energy storage units, hold considerable potential for enhancing flexibility in the power grid. They can be used to supply homes (V2H), buildings (V2B), or the grid (V2G) [13]. EVs with smart bidirectional chargers can receive signals from the DSO regarding the current grid conditions and, if required, interrupt, initiate, or reduce the charging power. Therefore, V2G smart charging can reduce peak load by 3 20% [15], fill the consumption valley, reduce grid imbalance [5], manage congestion, regulate voltage, balance phases in the LV network [16], contribute to the stabilization of secondary and tertiary reserves [3], enable faster recovery of the grid after faults, operate in island mode or delay infrastructure upgrades. To mitigate the challenge of centrally controlling each EV, it is proposed that the EVs within the network be organized into smaller clusters, each managed by a central management unit. These units then coordinate and synchronize the bidirectional power flow (G2V and V2G). The highest level of flexibility within the system can be achieved through parking spaces designated for slow EV charging, as the vehicle remains connected to the charger for an extended period, allowing charging based on the grid's requirements while maintaining the desired SoC upon disconnection from the grid. On the other hand, vehicles using fast charging stations typically remain connected for a brief period, which makes them highly inflexible to the grid (as they cannot provide reserves or adapt to grid fluctuations). Medium-speed charging stations, with intermediate charging speeds, offer some potential for system flexibility, as they enable moderately customized charging [12].

3. ANALYSIS USING THE DIGSILENT POWERFACTORY SOFTWARE PACKAGE

DIgSILENT PowerFactory (DIgSILENT PF) enables modeling, simulation, and analysis of power systems. It is used for verifying distribution network compliance, stability analysis, voltage control, short-circuit analysis, and power flow studies. The software includes predefined components (transformers, generators, loads, transmission lines, etc.), simplifying network modeling.

Models are stored locally, ensuring data protection. Users create projects, model networks using toolbar icons, and perform power flow analysis. DIgSILENT PF supports static (power flow, short-circuit), dynamic (stability), and quasi-dynamic simulations (transient system changes).

3.1. Network Modeling in DIgSILENT PF

In the DIgSILENT PF software package, a section of the medium-voltage network in the vicinity of Mostar was modeled, specifically the 10 kV feeder, which is supplied from the substation via transformer TR1 110/35/10 kV. Network elements were assigned specific names, and all relevant data for each element (line, busbar, transformer, load, photovoltaic power plant, EV charging station) were entered, as shown in Figure 4.

ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0001

EV charging stations were integrated into the network as General Loads, using the symbol for charging stations. Additionally, two photovoltaic power plants (PVPP) were connected to the network: PVPP 1 and PVPP 2. For PVPP modeling in the selected part of the network, the Solar Calculation model was used. PVPP 1 has an installed capacity of 15 kW and is connected to the TS 15 (160 kVA), while PVPP 2 has an installed capacity of 15 kW and is connected to the TS 2 (250 kVA). The most common conductor type used in the analyzed section of the distribution network is steel-aluminum AlFe 3x50 mm².

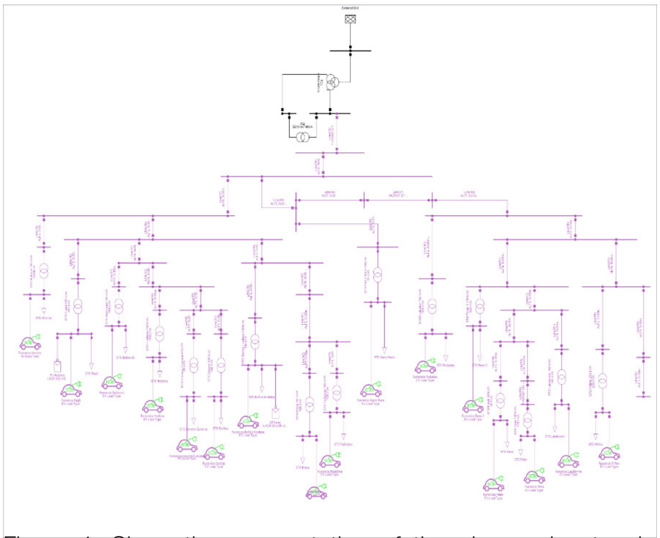

Figure 4: Shematic representation of the observed network, section of the 10 kV feeder

3.1.1. Modeling of Electric Vehicle Charging Stations

DIgSILENT PF enables the creation of load models and quasi-dynamic models defined by users to achieve the adaptable behavior of equipment in the power system. Two object classes can be modeled by users: TypQdsl and ElmQdsl. For simulating EV charging behavior, the “DIgSILENT Electric Vehicle” template from the global library, which belongs to the TypQdsl class, can be utilized. This simulation is performed using the QDSL (Quasi-Dynamic Simulation Language) model.

When opening the model, the Basic Data tab is displayed first, allowing users to input parameters and variables related to EVs, as shown in Figure 5. In quasi-dynamic simulation, EVs will begin charging within a predefined timeframe (set using the parameters “EarliestArrival” and “LatestArrival”). The model allows configuration of whether the charging station supports fast charging (parameter “fastcharging”), battery capacity in MWh, and the state of charge (parameter “SOCmax”) to which the battery needs to be charged. The start of charging will be randomly selected within the specified timeframe. To reflect variations in daily driving distances, the battery’s state of charge will also be randomly determined.

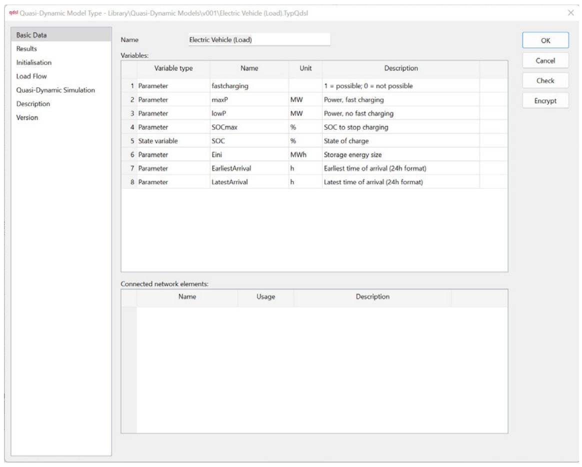

Figure 5: Configuration of parameters for Quasi-Dynamic simulation

When opening the Results tab, as shown in Figure 6, parameters such as the current time, estimated charging start time, charging power, and other relevant data are defined.

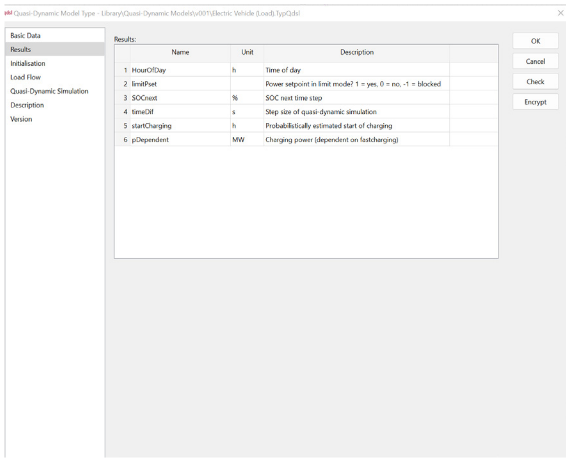

Figure 6: Results tab

In the Initialisation tab, shown in Figure 7, conditional commands are set for fast or slower charging, the time when vehicles begin charging, and the initial state of charge of the vehicles. In the Load Flow tab, the charging constraints are displayed, as shown in Figure 8.

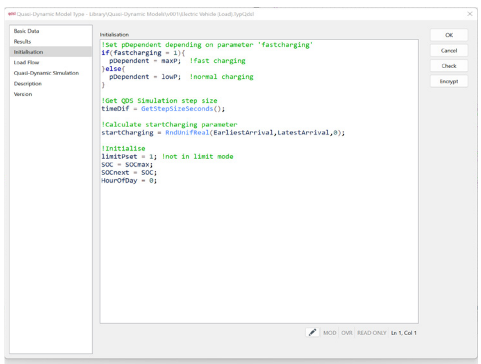

Figure 7: Initalisation tab

EV charging stations were integrated into the network as General Loads, using the symbol for charging stations. Additionally, two photovoltaic power plants (PVPP) were connected to the network: PVPP 1 and PVPP 2. For PVPP modeling in the selected part of the network, the Solar Calculation model was used. PVPP 1 has an installed capacity of 15 kW and is connected to the TS 15 (160 kVA), while PVPP 2 has an installed capacity of 15 kW and is connected to the TS 2 (250 kVA). The most common conductor type used in the analyzed section of the distribution network is steel-aluminum AlFe 3x50 mm².

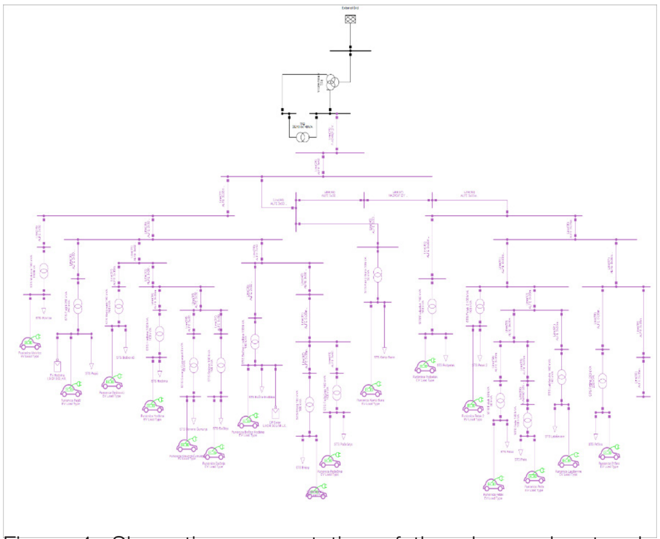

Figure 4: Shematic representation of the observed network, section of the 10 kV feeder

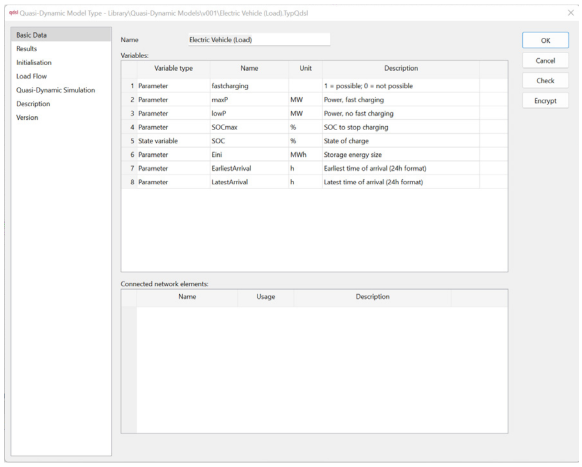

Figure 5: Configuration of parameters for Quasi-Dynamic simulation

When opening the Results tab, as shown in Figure 6, parameters such as the current time, estimated charging start time, charging power, and other relevant data are defined.

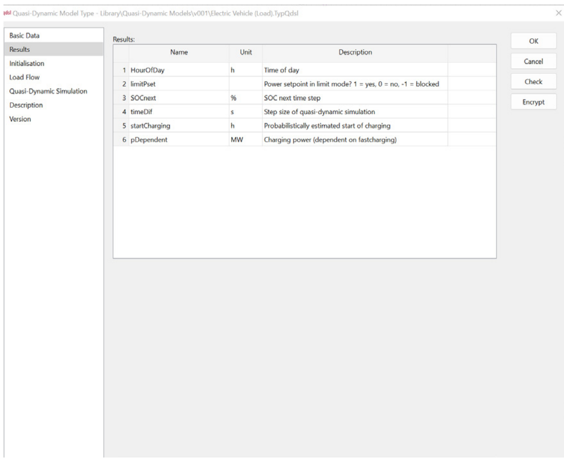

Figure 6: Results tab

3.1.1. Modeling of Electric Vehicle Charging Stations

DIgSILENT PF enables the creation of load models and quasi-dynamic models defined by users to achieve the adaptable behavior of equipment in the power system. Two object classes can be modeled by users: TypQdsl and ElmQdsl. For simulating EV charging behavior, the "DIgSILENT Electric Vehicle" template from the global library, which belongs to the TypQdsl class, can be utilized. This simulation is performed using the QDSL (Quasi-Dynamic Simulation Language) model.

When opening the model, the Basic Data tab is displayed first, allowing users to input parameters and variables related to EVs, as shown in Figure 5. In quasi-dynamic simulation, EVs will begin charging within a predefined timeframe (set using the parameters "EarliestArrival" and "LatestArrival"). The model allows configuration of whether the charging station supports fast charging (parameter "fastcharging"), battery capacity in MWh, and the state of charge (parameter "SOCmax") to which the battery needs to be charged. The start of charging will be randomly selected within the specified timeframe. To reflect variations in daily driving distances, the battery's state of charge will also be randomly determined.

In the Initialisation tab, shown in Figure 7, conditional commands are set for fast or slower charging, the time when vehicles begin charging, and the initial state of charge of the vehicles. In the Load Flow tab, the charging constraints are displayed, as shown in Figure 8.

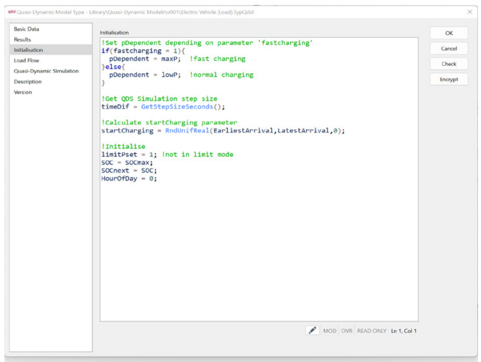

Figure 7: Initialisation tab

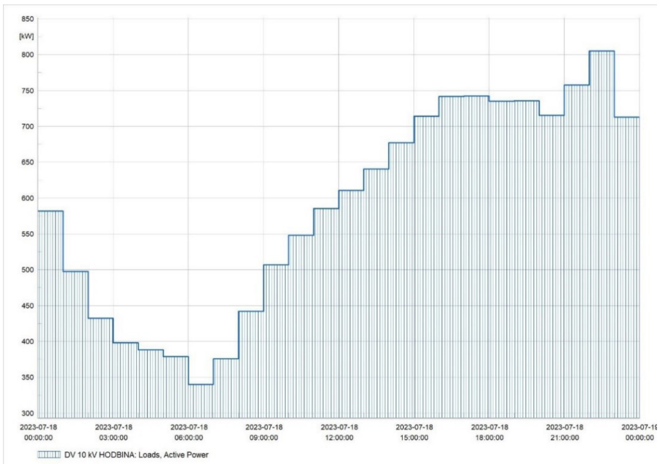

Figure 11: Consumption of the 10 kV feeder – first scenario

The quasi-dynamic simulation provided data on network losses, voltage levels, and transformer loads. Table II presents the network losses for July 18, 2023.

Table II: Network losses - first scenario

Name	Losses, P, range [kW]	Losses, P, min. [kW]	Losses, P, max. [kW]	Losses, P, average [kW]
Grid	9.3	2.7	12.0	6.8

The allowable voltage deviation for the 35 kV, 20 kV, and 10 kV networks must be maintained within ±10% of the nominal value, while for the low-voltage network, the permissible deviation ranges from +5% to -10% of the nominal value, according to the network regulations of JP "Elektroprivreda HZHB" d.d. Mostar. All voltage values are within the allowed limits, as shown in Table III.

Table III: Voltage conditions on 0.4 kV busbars – first scenario

Busbar [0.4 kV]	Ul, Value, min. [p.u.]	Ul, Value, max. [p.u.]	Ul, Value, average [p.u.]	Ul, Value, range [p.u.]
TS 1 0.4 kV	0.996	1.004	1	0.008
TS 2 0.4 kV	0.986	0.998	0.993	0.012
TS 3 0.4 kV	0.986	0.999	0.993	0.012
TS 4 0.4 kV	0.994	1.003	0.998	0.008
TS 5 0.4 kV	0.988	0.999	0.993	0.011
TS 6 0.4 kV	0.999	1.004	1.001	0.005
TS 7 0.4 kV	0.999	1.003	1.001	0.004
TS 8 0.4 kV	0.999	1.004	1.001	0.005
TS 9 0.4 kV	0.996	1.003	1	0.007
TS 10 0.4 kV	0.987	1.001	0.994	0.014
TS 11 0.4 kV	1.003	1.006	1.005	0.003
TS 12 0.4 kV	0.996	1.003	0.999	0.007
TS 13 0.4 kV	1	1.005	1.002	0.005
TS 14 0.4 kV	0.993	1.003	0.998	0.010
TS 15 0.4 kV	0.990	1.001	0.997	0.012
TS 16 0.4 kV	0,995	1.003	0.998	0.008

The most heavily loaded transformer in the relevant part of the network is TS 5 160 kVA, with a maximum load of 80.5%.

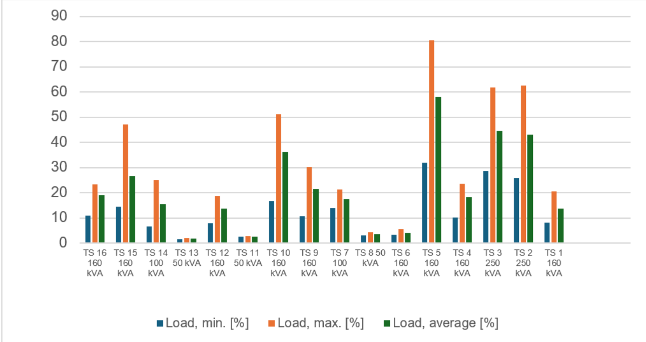

Figure 12: Transformers load - first scenario

3.2.2. Analysis Results for the Second Scenario

In this scenario, an analysis of the network state is conducted after connecting charging stations to each substation. The number of home EV charging stations per substation is determined by the number of metering points, i.e., the number of electricity consumers at that substation. This scenario considers the case where 5% of the consumers at a given substation are equipped with home charging stations.

It is assumed that consumers will start charging their EVs after work, between 5:00 PM and 11:00 PM. The number of charging stations to be connected to the observed part of the network is shown in Table IV.

Table IV: Number of connected charging stations at substations (5% of the total number of consumers)

Transformer	Total number of consumers	Number of charging stations at substation
TS 16	43	2
TS 15	91	5
TS 14	24	1
TS 13	11	1
TS 12	50	3
TS 11	3	1
TS 10	73	4
TS 9	48	2
TS 7	16	1
TS 8	26	1
TS 6	7	1
TS 5	72	4
TS 4	49	2
TS 3	113	6
TS 2	148	7
TS 1	38	2

Figure 13 shows the consumption on the observed feeder for July 18, 2023, with EV charging stations connected. The consumption increases from 6:00 PM to 11:00 PM, with the highest increase of 45% compared to the same period in the initial state. The consumption curve, compared to the previous case without charging stations, shows a greater spike between 6:00 PM and 11:00 PM, resulting from the EV charging.

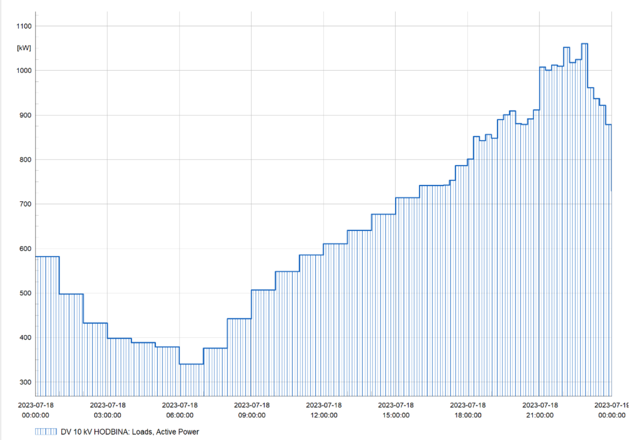

Figure 13: Consumption of the 10 kV feeder - second scenario

With the connection of charging stations, the maximum losses in the network increased from 12 kW to 19.8 kW, representing a 65% increase compared to the initial state.

Table V: Network losses - second scenario

Name	Losses, P, range [kW]	Losses, P, min. [kW]	Losses, P, max. [kW]	Losses, P, average [kW]
Grid	17.1	2.7	19.8	8.0

Table VI: Voltage conditions on 0.4 kV busbars – second scenario

Busbar [0.4 kV]	Ul, Value, min. [p.u.]	Ul, Value, max. [p.u.]	Ul, Value, average [p.u.]	Ul, Value, range [p.u.]
TS 16 0.4 kV	0.992	1.003	0.998	0.010
TS 15 0.4 kV	0.982	1.001	0.996	0.020
TS 14 0.4 kV	0.991	1.003	0.997	0.012
TS 13 0.4 kV	0.997	1.005	1.002	0.008
TS 12 0.4 kV	0.991	1.003	0.999	0.012
TS 11 0.4 kV	1.002	1.006	1.004	0.004
TS 10 0.4 kV	0.981	1.001	0.993	0.020
TS 9 0.4 kV	0.992	1.003	0.999	0.011
TS 8 0.4 kV	0.997	1.004	1.001	0.007
TS 7 0.4 kV	0.995	1.003	1	0.008
TS 6 0.4 kV	0.996	1.004	1.001	0.008
TS 5 0.4 kV	0.983	0.999	0.992	0.016
TS 4 0.4 kV	0.99	1.003	0.998	0.013
TS 3 0.4 kV	0.984	0.999	0.992	0.015
TS 2 0.4 kV	0.98	0.998	0.992	0.018
TS 1 0.4 kV	0.992	1.004	1	0.012

With the connection of EV charging stations, the maximum load on the most heavily loaded transformer in the relevant part of the network, TS 5 160 kVA, increased by 17% compared to the initial state.

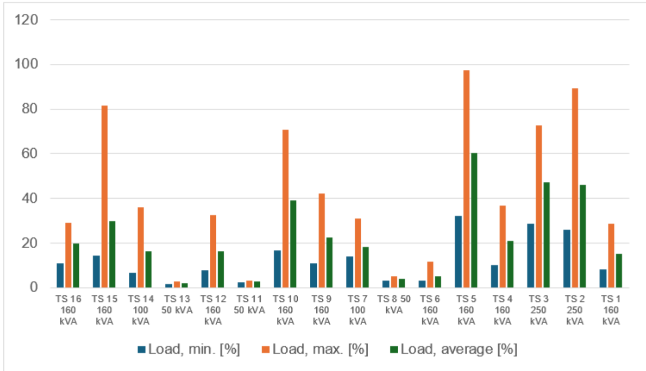

Figure 14: Transformers load - second scenario

Figure 15 shows the load on the TS 15 substation with five connected EV charging stations. In the initial case, the maximum load of TS 15 was 47.2%, and it has now increased to 81.6%. The reason for this increase in load is the rapid charging of EVs, which occurs between 5:00 PM and 11:00 PM, with each vehicle being charged at a power of 11 kW.

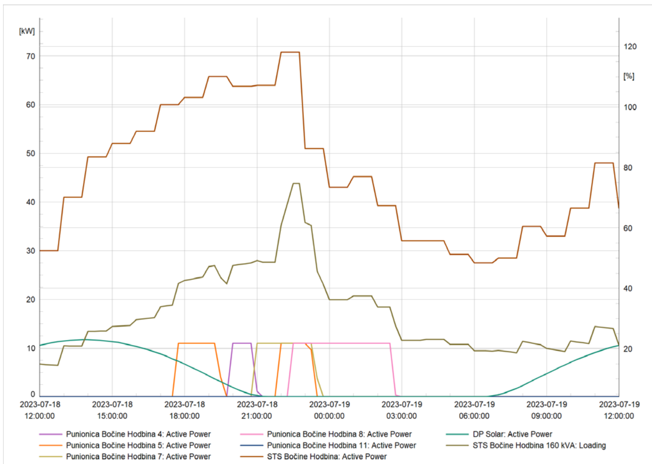

Figure 15: Load on TS 5 - second scenario

3.2.3. Analysis Results for the Third Scenario

In the third scenario, the number of home charging stations increases to 15% of the total number of consumers per metering point, and the network state is analyzed after their connection. The charging takes place on July 18, 2023 (Tuesday), and consumers begin charging their EVs between 5:00 PM and 11:00 PM. The number of connected charging stations per substation is shown in Table VII.

B&H Electrical Engineering, Volume 20, Issue 1, 2026
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0001

Table VII: Number of connected charging stations at substations (15% of the total number of consumers)

Transformer	Total number of consumers	Number of charging stations at substation
TS 16	43	6
TS 15	91	14
TS 14	24	4
TS 13	11	2
TS 12	50	8
TS 11	3	1
TS 10	73	11
TS 9	48	7
TS 7	16	2
TS 8	26	4
TS 6	7	1
TS 5	72	11
TS 4	49	7
TS 3	113	17
TS 2	148	22
TS 1	38	6

Figure 16 shows the consumption with the connection of 15% of EV charging stations from the total number of consumers per substation charging their EVs. The consumption increased by approximately 110% compared to the initial state during peak hours. The consumption curve rises because all the EVs are charged during the same period, which places additional load on the system and can cause instability in the network.

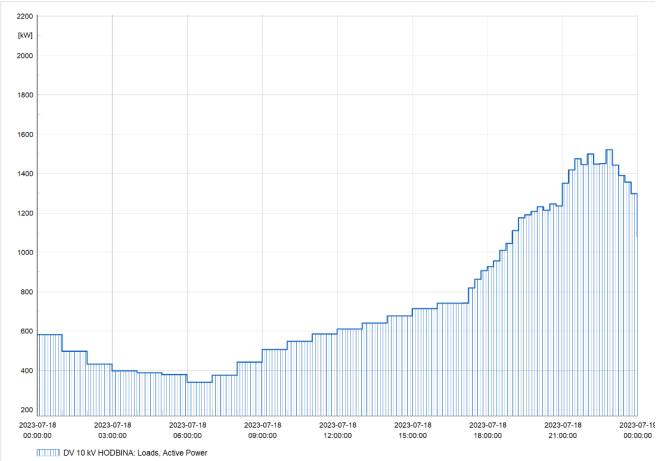

Figure 16: Consumption of the 10 kV feeder - third scenario

Table VIII shows the losses in the network after connecting 15% of EV charging stations from the total number of consumers per substation. Considering that the maximum losses in the initial state were 12 kW, and they are now 39.2 kW, this represents an increase of approximately 225%.

Table VIII: Network losses - third scenario

Name	Losses, P, range [kW]	Losses, P, min. [kW]	Losses, P, max. [kW]	Losses, P, average [kW]
Grid	36.5	2.7	39.2	11.4

The voltage conditions on the 0.4 kV busbars remain within the allowed limits, as shown in Table IX.

Table IX: Voltage conditions on 0.4 kV busbars – third scenario

Busbar [0.4 kV]	Ul, Value, min. [p.u.]	Ul, Value, max. [p.u.]	Ul, Value, average [p.u.]	Ul, Value, range [p.u.]
TS 16 0.4 kV	0.984	1.003	0.996	0.019
TS 15 0.4 kV	0.974	1.001	0.993	0.028
TS 14 0.4 kV	0.979	1.003	0.995	0.024
TS 13 0.4 kV	0.993	1.005	1.001	0.012
TS 12 0.4 kV	0.984	1.003	0.997	0.019
TS 11 0.4 kV	1	1.006	1.004	0.006
TS 10 0.4 kV	0.973	1.001	0.991	0.028
TS 9 0.4 kV	0.986	1.003	0.997	0.017
TS 8 0.4 kV	0.993	1.004	1	0.011
TS 7 0.4 kV	0.991	1.005	1	0.015
TS 6 0.4 kV	0.992	1.004	1	0.012
TS 5 0.4 kV	0.976	0.999	0.99	0.024
TS 4 0.4 kV	0.983	1.003	0.996	0.019
TS 3 0.4 kV	0.972	0.999	0.99	0.027
TS 2 0.4 kV	0.973	0.998	0.989	0.025
TS 1 0.4 kV	0.985	1.004	0.998	0.019

The transformer loads are higher than in the previous scenario, and on five transformers, the maximum load nearly exceeds 100%, as shown in Figure 17. Short-term overloading of transformers should not cause significant damage, while prolonged overloading can lead to various issues such as reduced efficiency, insulation damage, shortened lifespan, voltage surges in the network, and accelerated aging due to increased temperature.

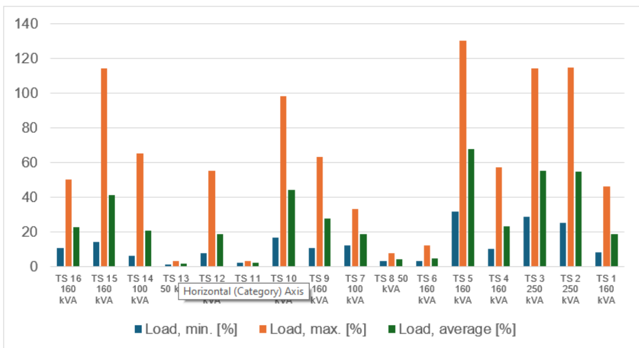

Figure 17: Transformers load - third scenario

Figure 18 shows the condition of the TS 15 transformer with 14 connected EV charging stations. The transformer load is shown from 12:00 PM on July 18 to 12:00 PM on July 19, 2023. In the previous case with 5 charging stations, the maximum load on TS 15 was 81.6%, while now it is 114.1%. The figure shows that the peak consumption occurs between 10:00 PM and 11:00 PM, and the charging of EVs at this time only further impacts system instability. Since consumption and transformer load decrease after midnight, shifting the EV charging time would significantly help mitigate transformer overloading and improve system stability.

Figure 19 shows the condition of the TS 5 transformer with 11 connected EV charging stations. The transformer load is shown from 12:00 PM on July 18 to 12:00 PM on July 19, 2023. In the first scenario, the maximum load of the substation was 80.5%. In the previous case with 5% charging stations, the maximum load was 97.5%, and now it is 130.1%. The decrease in consumption occurs after midnight the following day, and it is recommended to shift the EV charging at this time, which would flatten the consumption curve and stabilize the system.

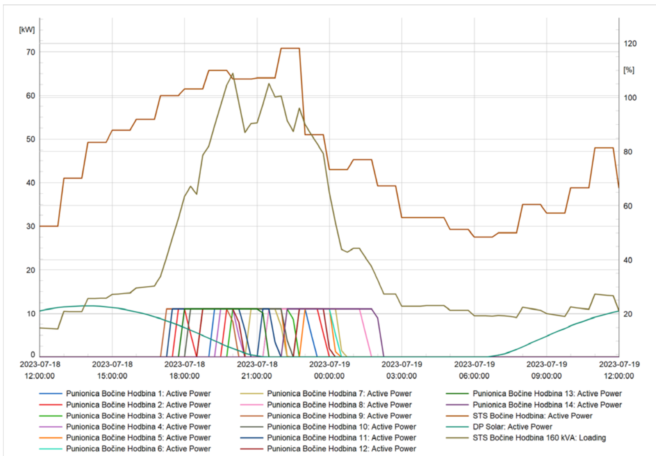

Figure 18: Load on TS 15 - third scenario

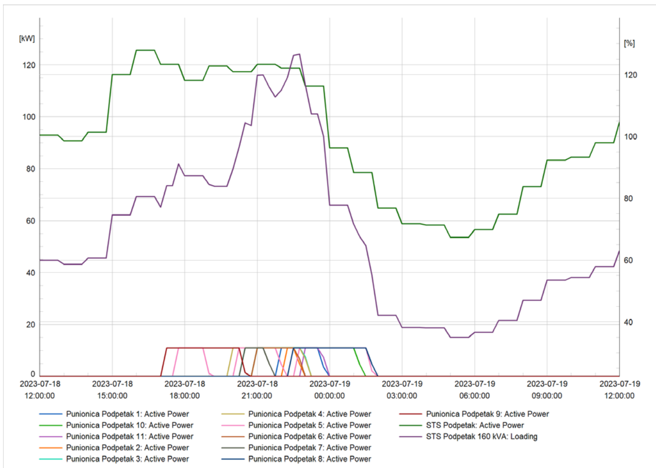

Figure 19: Load on TS 5 - third scenario

Figure 20 illustrates the load during charging at TS 10 from 12:00 PM on July 18 to 12:00 PM on July 19, 2023. In the first scenario, the substation's maximum load was 51.1%, and it has now increased to 98.5%. It is evident that peak consumption and EV charging occur during the same time of day, and shifting the charging times could help balance the consumption curve.

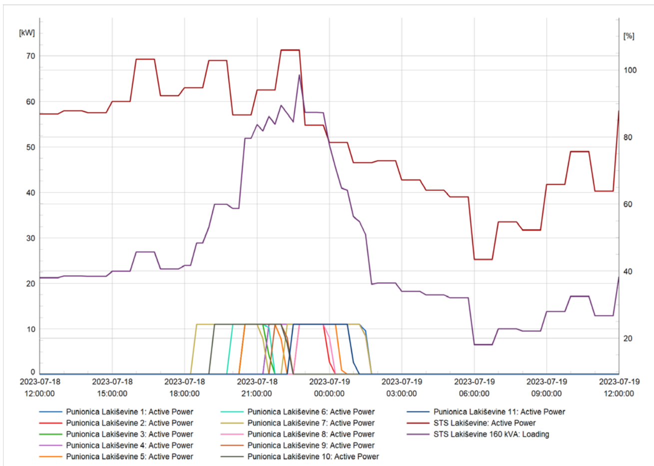

Figure 20: Load on TS 10 - third scenario

Figure 21 illustrates the load on the TS 2 substation with 22 connected EV charging stations. In the first scenario, the substation load was 62.6%; in the second scenario, it was 89.2%, and now it stands at 115%. The overloading results from the large number of EVs charging simultaneously.

Figure 22 depicts the load on the TS 3 substation during charging. In the first scenario, the substation load was 61.9%; in the second scenario, it was 72.6%, and now it is 114.1%. Adjusting the timing of EV charging is the only solution to alleviate the transformer overload.

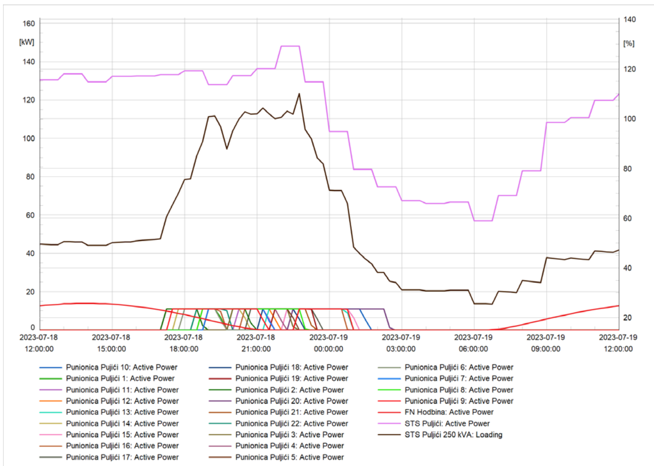

Figure 21: Load on TS 2 - third scenario

ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0001

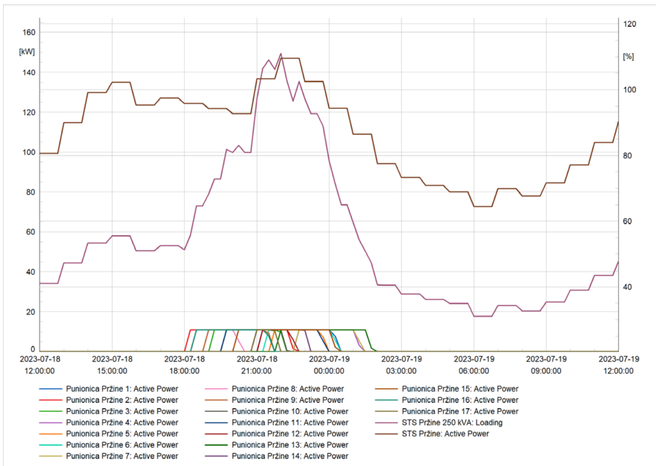

Figure 22: Load on TS 3 - third scenario

3.2.4. Analysis Results for the Fourth Scenario

In the fourth scenario, the number of home charging stations remains the same, at 15% of the total number of consumers per metering point.

Charging takes place in such a way that 50% of consumers with charging stations connected to the overload TS, participate in demand response by shifting the charging time of their EV. By postponed charging, the original sessions are moved to specific time intervals, thereby better aligning with the targeted consumption profile. [5] In other words, the second peak of the consumption curve is reduced, contributing to grid stability and decreasing the need for additional capacity and network resizing.

In the settings of the quasi-dynamic EV model, the parameters EarliestArrival and LatestArrival will be shifted from the initial times of 5:00 PM and 11:00 PM to 1:00 AM and 2:00 AM, meaning that vehicles will charge the following day between 1:00 AM and 2:00 AM when transformer loads are lower.

Figure 23 shows a decrease in consumption between 6:00 PM and midnight, compared to the previous scenario where consumption increased until 11:00 PM, peaking at around 1500 kW at 11:00 PM. In this case, the peak occurs at 6:00 PM, reaching about 1370 kW.

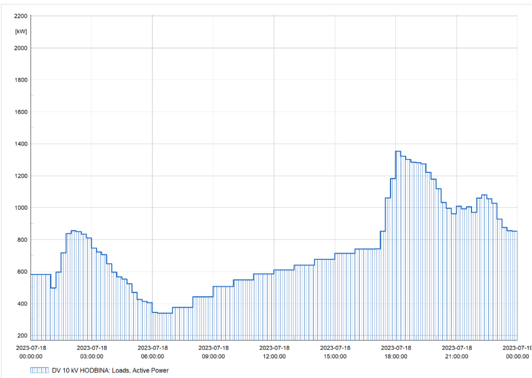

Figure 23: Consumption of the 10 kV feeder - fourth scenario

The maximum losses, range, and average have decreased compared to the previous scenario. In the previous third scenario, when there was no demand response on overloaded transformers, the maximum losses were 39.2 kW. Now, they have decreased to 28.7 kW, which represents a reduction of about 27%.

Table X: Network losses - fourth scenario

Name	Losses, P, range [kW]	Losses, P, min. [kW]	Losses, P, max. [kW]	Losses, P, average [kW]
Grid	26.0	2.7	28.7	10.3

All voltage values on the 0.4 kV busbars remain within the allowed limits.

Table XI: Voltage conditions on 0.4 kV busbars – fourth scenario

Busbar [0.4 kV]	Ul, Value, min. [p.u.]	Ul, Value, max. [p.u.]	Ul, Value, average [p.u.]	Ul, Value, range [p.u.]
TS 16 0.4 kV	0.985	1.003	0.997	0.018
TS 15 0.4 kV	0.982	1.001	0.994	0.020
TS 14 0.4 kV	0.981	1.003	0.995	0.022
TS 13 0.4 kV	0.994	1.005	1.001	0.011
TS 12 0.4 kV	0.984	1.003	0.997	0.019
TS 11 0.4 kV	1.001	1.006	1.004	0.005
TS 10 0.4 kV	0.979	1.001	0.991	0.022
TS 9 0.4 kV	0.987	1.003	0.998	0.016
TS 8 0.4 kV	0.995	1.004	1	0.009
TS 7 0.4 kV	0.993	1.003	1	0.010
TS 6 0.4 kV	0.994	1.004	1	0.010
TS 5 0.4 kV	0.982	0.999	0.991	0.017
TS 4 0.4 kV	0.984	1.003	0.996	0.019
TS 3 0.4 kV	0.979	0.999	0.991	0.020
TS 2 0.4 kV	0.977	0.998	0.990	0.022
TS 1 0.4 kV	0.985	1.004	0.998	0.019

Figure 24 shows the loads on the observed transformers during charging with 15% of EV charging stations connected to the total number of consumers per

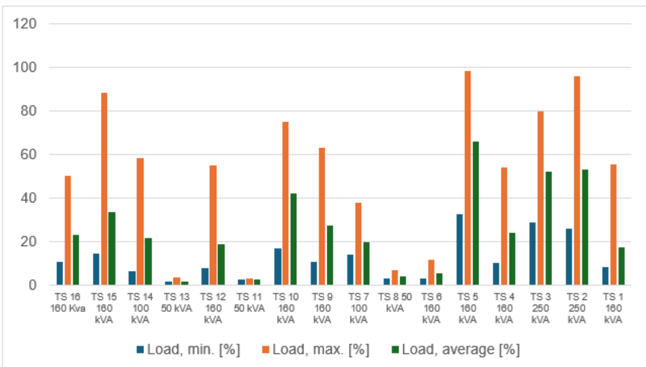

Figure 24: Transformers load - fourth scenario

substation, where 50% of consumers on overloaded transformers participate in demand response.

Table XII shows the loads on the observed transformers in the third and fourth scenarios. According to the obtained data with 15% of charging stations connected by the total number of consumers, and with 50% of consumers on overloaded substations participating in demand response, it is evident that the maximum transformer load has decreased.

The maximum load on TS 15 decreased by 25.5%. A reduction in the maximum load was also observed on TS 10, with a decrease of 23.3%, TS 5 with a reduction of 31.8%, TS 3 with a 34.1% decrease, and TS 2, where the load decreased by 19.1%. No transformer exceeds a load of 100%. The maximum loads have been reduced by shifting consumption away from peak hours, thereby eliminating the need for additional capacity and network resizing.

Table XII: Comparison of maximum transformer load

Transformer	Maximum load at third scenario [%]	Maximum load at fourth scenario [%]
TS 15 160 kVA	114.1	88.6
TS 10 160 kVA	98.5	75.2
TS 5 160 kVA	130.1	98.3
TS 3 250 kVA	114.1	80
TS 2 250 kVA	115	95.9

Figure 25 shows the load on the TS 5 substation during demand response. Unlike in Scenario 3, the consumption curve has stabilized, and the maximum transformer load has decreased by 31.8%. This was achieved by shifting the charging of half of the EVs to the following day, between 1:00 AM and 2:00 AM.

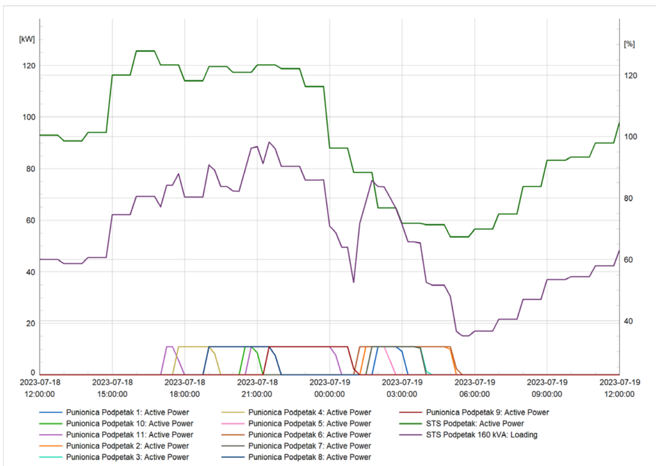

Figure 25: Load on TS 5 – fourth scenario

In the first scenario, the maximum load of TS 15 was 47.2%, in the second scenario it was 81.6%, and in the third scenario, it reached 114.1%. In the fourth scenario, the maximum load of the substation is 88.6%, as shown in Figure 26.

For TS 3, in the first scenario, the maximum load was 61.9%, in the second scenario it was 72.6%, and in the third scenario, it was 114.1%. In the current scenario, the maximum load is 80%, as shown in Figure 27.

For TS 2, in the first scenario, the maximum load was 62.6%, in the second scenario it was 89.2%, and in the third scenario, it was 115%. In the current scenario, with demand response, the maximum load is 95.9%, as shown in Figure 28.

For TS 10, in the first scenario, the maximum load was 51.1%, in the second scenario it was 70.8%, and in the third scenario, it was 98.5%. With demand response, the maximum load is 75.2%, as shown in Figure 29.

Charging EVs outside peak periods, when the network consumption is lower, reduces transformer load.

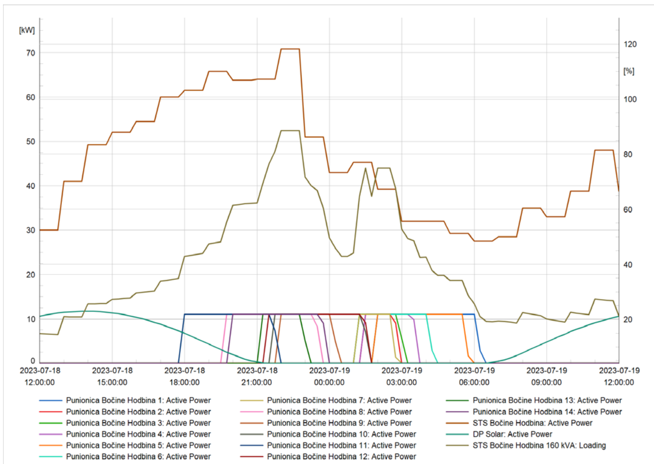

Figure 26: Load on TS 15 - fourth scenario

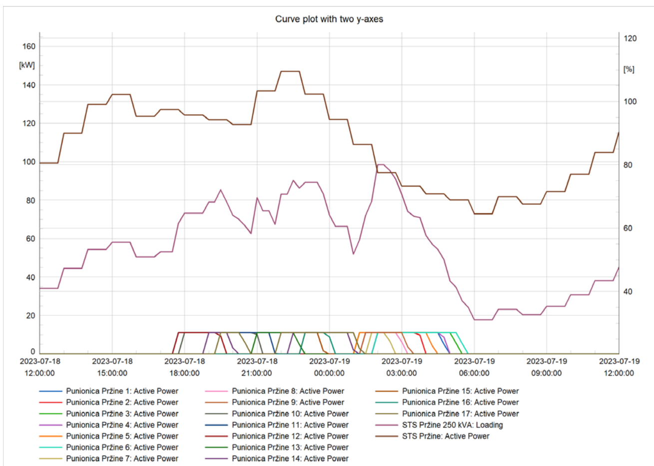

Figure 27: Load on TS 3 - fourth scenario

ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0001

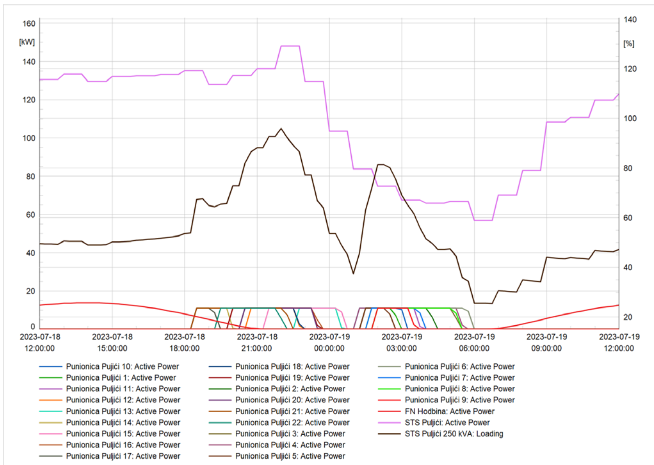

Figure 28: Load on TS 2 - fourth scenario

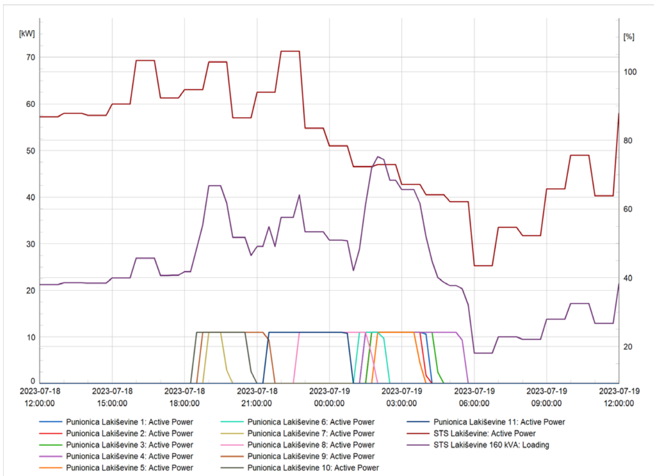

Figure 29: Load on TS 10 - fourth scenario

4. CONCLUSION

The electrical grid currently meets the electricity demand, but the rapid increase in EV adoption could alter this balance. The growing number of vehicles increases the demand for charging stations, which can place additional strain on the power system and distribution network. This study analyzed the integration of household EV charging stations of the rural network in the vicinity of Mostar, with a quasi-dynamic simulation performed for a weekday in the previous year, specifically on July 18, 2023, when the highest consumption on the power line occurred. Simulations for multiple scenarios were conducted using the DISILENT PF software package to assess whether connecting a certain number of charging stations impacts the network.

With the connection of 5% of EV chargers from the total number of consumers at the substations, network losses increase, and overall consumption rises due to EV charging. However, the maximum transformer load remains below 100%. When 15% of EV chargers are connected, losses further increase, consumption rises due to charging, and five transformers in the observed part of the network become overloaded. By implementing charging management, where 50% of consumers at overloaded substations participate in demand response, network losses decrease compared to the previous scenario with 15% EV chargers, voltage levels in the low-voltage network remain within permissible limits, and the maximum load on overloaded transformers is reduced by:

- TS 15 – 25.5%
- TS 10 – 23.4%
- TS 5 – 31.8%
- TS 3 – 34.1%
- TS 2 – 19.1%.

Demand response for EV charging enhances network stability, reduces electricity costs, enables greater integration of renewable energy sources, lowers greenhouse gas emissions, and provides financial savings for EV owners. Previously, power production was always adjusted to consumption, but there is now an increasing expectation of consumers to adapt. This ensures a reliable energy supply and can defer additional investments in the system. Analysis conducted as part of this research demonstrates that smart charging, which includes strategies such as optimizing charging times and balancing load distribution, can effectively reduce peak loads on transformers. By implementing the appropriate technologies and management systems, better stability and flexibility in the power grid can be achieved, the risk of overloads reduced, and the overall efficiency of the distribution system improved.

REFERENCES

[1] International Renewable Energy Agency (IRENA): "Critical material: Batteries for electric vehicles", Abu Dhabi, 2024

[2] J. Suarez, et. al.: "2025 and 2030 CO2 emission targets for Light Duty Vehicles", Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/901734, JRC133502

[3] I. Pavić, et.al.: "Analiza aspekta fleksibilnosti budućeg elektroenergetskog sustava s integriranim električnim vozilima", 13th HRO CIGRE Conference, Šibenik, 2017

[4] Sadeghianpourhamami N, Refa N, Strobbe M, Develder C. Quantitive analysis of electric vehicle flexibility: A data-driven approach. International Journal of Electrical Power and Energy Systems Feb 2018;95:451–62

[5] M. Canigueral, J. Melendez: "Flexibility management of electric vehicles based on user profiles: The Arnhem case study", International Journal of Electrical Power and Energy Systems, Spain, Vol. 133, 2021, 107195, ISSN 0142-0615

[6] L. Kumar, L. Lathwal: "Electric vehicle charging method and impact of charging and discharging on distrution system", International Jurnal of Electric and Hybrid Vehicles, Vol. 14, September 2022

[7] International Energy Agency (IEA): "Global EV Outlook 2024", IEA Publications, April 2024

[8] E. Bićo, J. Bešić, A. Damadžić, N. Harbaš: "Electromobility in BiH", B&H Electrical Engineering, Vol. 17, 33-43, 2023

[9] Privredna/Gospodarska komora FBiH, Udruženje za elektromobilnost, chargerbih.ba – chargerbih.ba, Accessed January 29, 2025

[10] BIHAMK, Informacija o registriranim cestovnim vozilima u Bosni i Hercegovini u periodu siječanj – prosinac 2024

[11] Vlada FBiH, https://fbihvlada.gov.ba/bs/za-poticaje-pri-kupovini-elektricnih-automobila-milion-km, Accessed January 29, 2025

[12] A. Arpadžić, et.al.: "Impacts of Deregulated and Regulated Electric Vehicle Charging in a Distribution Network. Revue Roumaine des Sciences Techniques—Série Électrotechnique Et Énergétique", 67(4), pp.451-456, 2022

[13] F. G. Venegas, M. Petit, Y. Perez: "Active integration of electric vehicles into distribution grids: barriers and frameworks for flexibility services", Renewable and Sustainable Energy Reviews, France, Vol 145, 2021, 111060, ISSN 1364-0321

[14] EA Technology & Southern Electric Power Distribution: "My Electric Avenue Project Close-Down Report", Tech. rep., Issue v2.3., 2016

[15] S. Micari, G. Napoli: "Electric Vehicles for a Flexible Energy System: Challenges and Opportunities", Italy, Energies, 2024, 17, 5614

[16] C. Crozier, et. al.: "Coordinated electric vehicle charging to reduce losses without network impedances", IET Smart Grid, Vol. 3, Issue 5, 2020

[17] Quasi-Dynamic Simulation, https://www.digsilent.de/en/quasi-dynamic-simulation.html, Accessed January 31, 2025

BIOGRAPHY

Mia Previšić was born in 1997 in Mostar. She completed her Bachelor's degree in 2019 and her Master's degree in 2021 in Electrical Engineering, with a specialization in Power Engineering, both at the Faculty of Mechanical Engineering, Computing and Electrical Engineering, University of Mostar. Since May 2022, she has been employed at JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar, within the Development Division, working as an electrical engineer for renewable energy sources. During this time, she successfully passed the professional licensing exam in the field of electrical engineering. Her main areas of interest include the development of renewable energy sources, the application of innovative technologies, and their integration into distribution networks—aiming to contribute to a more sustainable and technologically advanced power system.

Marin Majstorović earned his Master's degree in Electrical Engineering from the University of Mostar in July 2021, becoming the first graduate at that level at the university. He defended his master's thesis titled "Conceptual Design of a Photovoltaic Power Plant Mostarsko Blato." During his studies, he was selected by faculty members to serve as a teaching assistant for the course Power Electronics. As part of his professional development, he completed a two-month internship in designing low-voltage installations, followed by six months of work as a Sales Engineer. Since May 2022, he has been employed at JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar as an Independent Engineer for Distributed Generation. Since October 2022, he has also been engaged as a Laboratory Assistant for the course "Distribution Networks and Distributed Generation" at the Faculty of Mechanical Engineering, Computing, and Electrical Engineering, University of Mostar.

Ivan Šimović holds a Master's degree in Electrical Engineering, obtained in 2021 from the Faculty of Mechanical Engineering, Computing and Electrical Engineering at the University of Mostar. He began his career as a Project Engineer at Violeta d.o.o., where he gained valuable experience in managing technical projects. He is currently employed as an Independent Engineer for Distributed Generation at JP Elektroprivreda HZ HB d.d. Mostar, where he has been working for over two years. His work focuses on the development and implementation of solutions in the field of distributed energy production.

Lucija Medić obtained her Master's degree in Electrical Engineering and Information Technology from the University of Zagreb, Faculty of Electrical Engineering and Computing, in July 2020. Her master's thesis, titled "Application of Gamification in a Knee Rehabilitation System," explored the integration of game design principles in medical rehabilitation technologies. During her studies, she was selected by the university to serve as a teaching assistant for the courses Electronic Circuits and Signals and Systems, demonstrating strong academic performance and commitment to teaching. Since May 2022, she has been employed at JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar as an Independent Engineer for Energy Efficiency, where she is responsible for the assessment, development, and implementation of energy efficiency measures. In addition, since October 2022, she has been engaged as a Laboratory Assistant for the courses Electronic Elements and Circuits and Fundamentals of Electrical Engineering and Electronics at the University of Mostar, Faculty of Mechanical Engineering, Computing, and Electrical Engineering.

Dragana Grabovac earned her Master's degree in Electrical Engineering, specializing in Power Engineering, from the Faculty of Mechanical Engineering, Computing and Electrical Engineering, University of Mostar in October 2024. Since the beginning of 2025, she has been employed as an intern at JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar.