The Influence of Electric Vehicle Charging Stations on the Quality of Power Supply to the Consumer in Novosibirsk 10/0.4 KV Electrical Networks

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Abstract — **Currently, there is a massive use of electric vehicles in the world. This is due to the ever-increasing importance and severity of the environmental safety issue. Now, there is no more convenient, affordable, popular and at the same time less harmful alternative to road transport. The annual global emissions are more than 25 million tons of pollutants of various origins, which are extremely dangerous for nature in general. On average, they increase by 3% every year. The transport sector accounts for 23% of all greenhouse gas emissions in the world. Electric vehicles can contribute enormously to the reduction in greenhouse gas emissions. In 2025, sales of electric vehicles are expected to increase to 100 000 units. By 2030, the number of electric vehicles will reach 1.5 million units. However, widespread adoption of electric vehicles will cause an increase in electricity consumption. In addition, an appropriate charging infrastructure is required to power electric vehicles. It is worth noting that the market for electric vehicles and charging stations is developing dynamically with an annual growth rate up to 80%. The main barriers to the development of electric vehicles in Russia are their high cost and underdeveloped network of charging stations. The relevance of the problem is confirmed by an order signed by Prime Minister Mikhail Mishustin in March 2022 to allocate about 1.37 billion rubles for the creation of charging infrastructure for electric vehicles in Russia. As for incentives, there are many of them. This is the need to solve the environmental problem in large cities, achieve the goal of reducing CO2 emissions and pursue industrial policy, including the policy of innovative development of the country. Another way of increasing the payback of charging stations is the employment of smart services, which can reduce the cost of technological connection through dynamic power distribution between the main facility and the charging station. There are other, more advanced solutions, which are currently being piloted, such as optimization of investment in network infrastructure, including an operator of a regional public charging infrastructure. This study focuses on the development of a power supply system to connect an electric vehicle charging station to a substation in Novosibirsk. The connected electric vehicle charger, being a non-linear load, can not only increase the load on the power grid infrastructure, but also cause a deterioration in the power quality due to the generation of harmonic distortions. Therefore, special attention is paid to the analysis of the power supply quality during the operation of the charging station by using the model developed in the MATLAB Simulink software for the analysis of harmonics.**

Index Terms: **Charging station, electric vehicles, mathematical modeling, non-linear load, harmonics.**

I Introduction

One of the effective tools to prevent climate warming on Earth is the large-scale introduction of an electric vehicle (EV), especially in metropolises. Over the past few years, the demand for electric vehicles has grown. For comparison, the number of electric vehicles in China has exceeded one million units and there are already more than 167 000 charging stations, whereas in Russia, there are about 1 000 electric vehicles and approximately 150 public charging stations. The number of individual (home) charging stations is unknown. Electric vehicles release half as much CO_2 emissions as internal combustion engine vehicles on average. In addition, an important incentive for the introduction of electric transport is support for industrial policy, including the policy of innovative development of the country.

According to [1], 2021 saw a sharp increase in the

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share of electric vehicles sold globally. That year marked a turning point for the entire electric vehicle industry as sales more than doubled compared to 2020 and made up 9% of the global car sales, which is a serious bid for the future dominance of "green" transport.

The large-scale adoption of electric vehicles, however, will increase electricity consumption. It is also necessary to establish an appropriate charging infrastructure to power electric vehicles. All this will require commissioning the additional power capacities and changing the electric load curve. It is worth noting that the market for electric vehicles and charging stations is developing dynamically with an annual growth rate of up to 80%.

The main barriers to the development of electric vehicles in Russia are their high cost and a poorly developed network of charging stations. The urgency of the problem is confirmed by an order signed by Prime Minister Mikhail Mishustin in March 2022 to allocate about 1.37 billion rubles to create the charging infrastructure for electric vehicles in Russia.

Smart services could increase the payback of charging stations, primarily by reducing the cost of technological connection through dynamic power distribution between the main facility and the charging station. There are other, more advanced solutions, such as optimizing investment in network infrastructure, for example, for the operator of a regional public charging infrastructure.

Vehicle-to-Grid (V2G) technology seems promising (it allows connecting a car to a common power grid for timely recharging it or returning excess electricity back).

Today private charging infrastructure prevails in the world, when the owner of an electric car buys a charging station, installs it in their private house, underground parking, or near the house. The same trend is observed in Russia. It is also clear that with an increase in the number of budget proposals for electric vehicles, it is necessary to competitively develop public charging infrastructure near shopping and business centers and residential complexes.

Modern trends in transport infrastructure are reflected in a growing number of vehicles that switch to electric traction motors. Instead of an internal combustion engine, such cars are equipped with an electric motor (EM), which receives energy from batteries. These batteries can be charged from the mains or from other electrical energy sources (for example, from an induction transformer located under the roadbed). The main automakers have begun to actively introduce a new generation of electric vehicles with the improved battery technology (lithium-titanate batteries), increased energy intensity, and lower production costs. It has led to the demand for modern electrical equipment that provides both fast battery charging and conversion of electrical energy stored in the battery for the needs of the final electrical equipment. New electronic components emerge as electronics develops and new opportunities appear for creating power electrical equipment with improved characteristics.

Battery life is a defining factor to be given special attention to, as the energy efficiency of a vehicle depends on it. Today, the world's infrastructure of charging stations operating from the electrical network is developing at a fairly high pace. The study on the enhancement of battery life and economic efficiency is relevant today because it aims to improve consumer properties and the availability of electric vehicles for the end consumer [2–4].

This paper aims to design a power supply system for a charging station considered as a load of the power grid and analyze its impact on the quality of electricity in the grid on the example of the Teatralnaya substation in Novosibirsk.

This can be achieved by:

- Analyzing the operational principles of the charging stations and battery swapping stations for electric vehicles;
- Analyzing the main types of charging stations, namely charging stations for trucks, electric buses, cars; and their location for megacities (on long highways outside the city), for private use (own), in terms of maximizing the life and improving the performance of the vehicle;
- Designing a power supply scheme for connecting EV charging stations;
- Analyzing the harmonics during the charging station operation in the MATLAB Simulink software for the quality of power supply.

II Implementation of Electric Vehicle Charging Stations

According to the Federal Law of November 23, 2009, No. 261-FL "On Energy conservation, energy efficiency enhancement, and amendment to some legislative acts of the Russian Federation," the development of electric vehicles is a significant direction, which requires state regulation and support.

Now, the model range of the automotive manufacturer of electric cars consists of four cars that are different not only in their appearance but also in their functions and purposes: TeslaModelS hatchback, TeslaModel X crossover, TeslaModel3 budget electric car, and new off-road vehicle TeslaCyberTruck [5–7].

Electric vehicles however have disadvantages, the main of which are the battery capacity for their long-term operation and the operating temperature range, which is especially significant for Russia. Although electric buses that can withstand temperatures down to –40ºC for 12 hours have recently appeared in Moscow, St. Petersburg and Volgograd, they encounter temporary difficulties, including an underdeveloped infrastructure of charging stations inside the megacities, which is the subject of this paper.

A charging station is an electrical device equipped with connectors necessary to plug in electric vehicles, which charges electric vehicles in various conditions [8–10]. Figure 1 shows grid connection options for the charging stations [11].

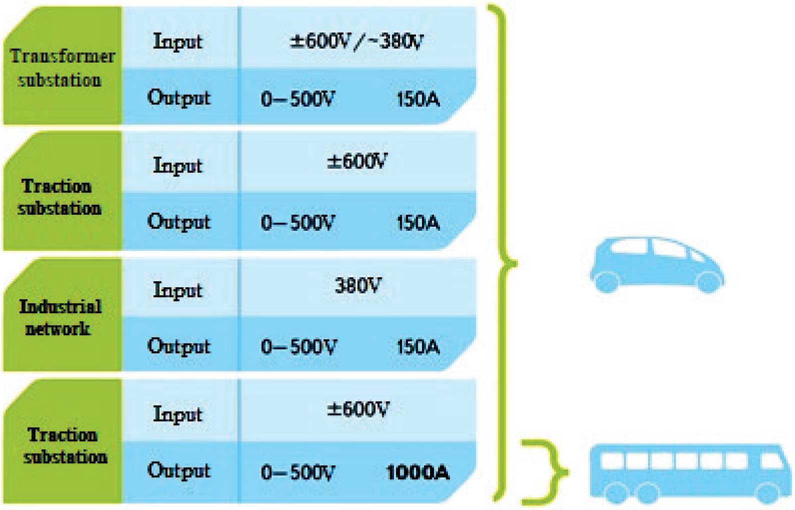


Fig. 1. Options for the connection of charging stations to the grid.

Table 1. Comparison of Charging Station Concepts

Charging stations powered from the buses of DC traction substation	Charging stations powered from the buses of AC 10 kV traction substation	Remarks and explanations
Installed capacity of traction substation does not change	Installed capacity of traction substation should be changed	New technical conditions for power connection
No additional 10 kV switchgear, MV transformer (100 kVA), the ATS system are required	It is necessary to install a 10 kV switchgear, a MV transformer (100 kVA), an ATS system	Additional 3 chambers with high-voltage circuit breaker and at least 1 chamber with AT + ATS on the 10 kV side are required
Charger cost is lower, no rectifier is required	Charger cost is higher because of converter cost	A rectifier is used in the option of power supply from AC bus bars
Charger dimensions are smaller	Charger dimensions are larger	Because no rectifier, switchgear 10, ATS system, 10 kV transformer are required
No power corrector for the charging station is required	Power corrector is required for the charging station	If charging stations are considered separately
There is no need to obtain new specifications for connection	New specifications for connection are required	

A wide range of developed charging stations provides fast charging from the traction substation network, industrial network and by currents up to 1000 A for charging electric buses.

Design of charging stations should factor in the requirements of State Standards (GOSTs), for example, such as EN-61851-1, IEC 62196. Permissible charging modes are described in section 1 of the IEC 62196 standard, which defines the main options.

To date, there has been a developed infrastructure of charging stations for electric vehicles in large cities of Russia (Moscow, St. Petersburg, Samara, Kazan, etc.). In the context of growing fleet of electrical vehicles, the design and establishment of power supply systems for charging stations in megacities becomes a relevant issue for Russia.

Table 1 indicates possible options for charging stations, including those for megacities, remote routes, individual use; for electric buses, cars, and trucks.

Some countries are developing and testing the so-called "smart road" or induction road. In the future, Russia may follow this experience, when electric vehicles gain popularity in the Russian market.

The mass use of electric vehicles will:

- significantly enhance the efficiency of application and design of electrical distribution networks due to controlled distributed load;
- increase the useful supply to the network by the inverter mode;
- level the night-time valley of the load in the power system;
- consider electric vehicles as distributed energy storage devices to cover the peak loads of the power system when introducing the latest technologies (Vehicle-To-Grid (V2G);
- significantly boost the efficiency of the electrical distribution networks and increase productive supply;
- reduce emissions of harmful substances, which will improve the environmental situation in the world.

Moreover, since the main generating sources of energy

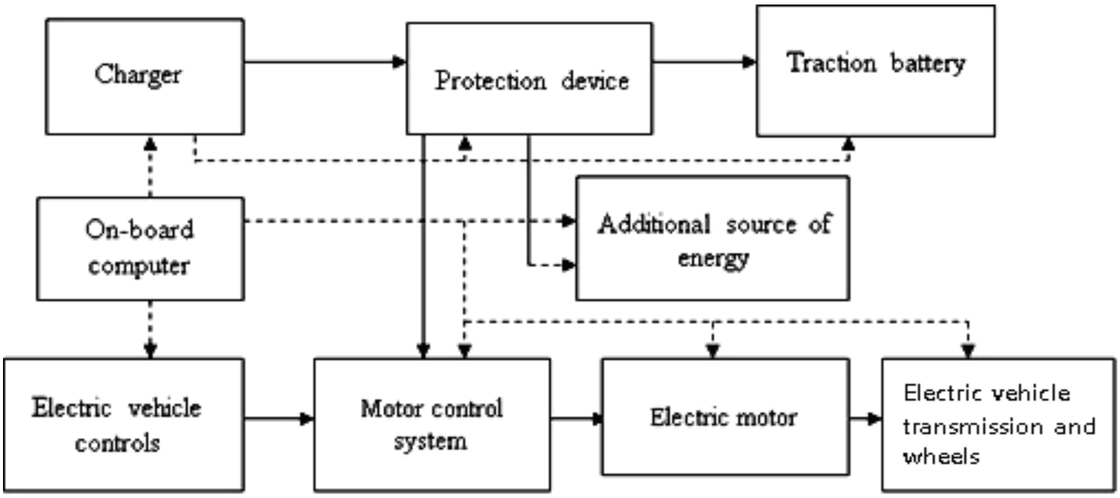


Fig. 2. Block diagram of an electric vehicle.

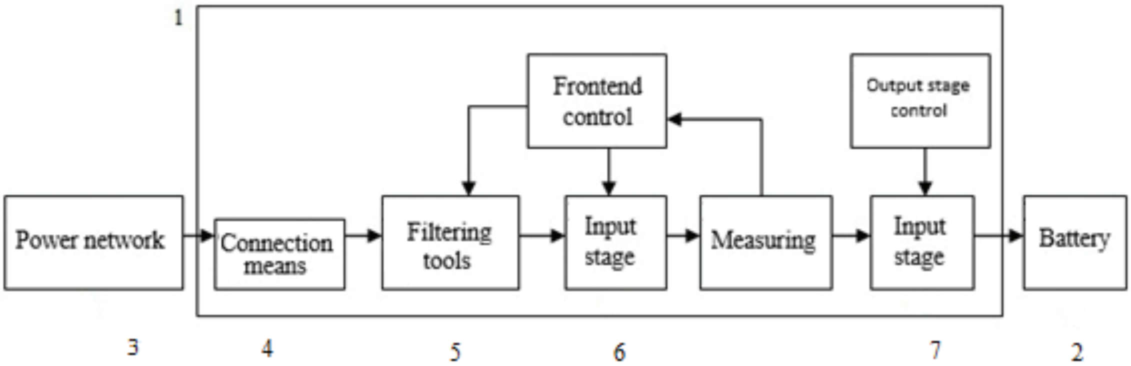


Fig. 3. Diagram of an electric vehicle battery charger.

and other industries are located within the boundaries of large metropolitan areas, the most relevant direction for the development of charging stations are megacities.

A Description of the electric vehicle layout

Unlike a car with an internal combustion engine, an electric car has a simpler design, including a minimum number of moving parts, and is therefore more reliable [14–17]. The block diagram of the electric vehicle is shown in Fig. 2.

Charger converts the AC voltage of the external network to DC to charge the traction and auxiliary batteries. *Protection device* (relay and fuse box) consists of switches, relays, and fuses. When a fault occurs, the AC circuit and batteries are disconnected. *Traction battery* provides energy to the motor of an electric vehicle. *On-board computer* monitors the condition of the main functional components and on-board systems of the electric vehicle, and initiates protective measures if necessary. *Additional power source* (usually a 12 V auxiliary battery) ensures the operation of lighting devices, instrument panel, power windows, wipers, etc. *Electronic motor controller* forms the required type of supply voltage and controls the number of revolutions and the traction moment on the shaft by the driver's commands or automatically. Electric motor drives the wheels of an electric vehicle directly or through a transmission.

The main battery is charged from a charger located either on board the electric vehicle or outside it. It aims to provide the required current in the shortest period of time in compliance with the battery charging algorithm recommended by the manufacturer.

Features of electric vehicle engines. The electric motor includes a stator and a rotor. The rotating magnetic field in the stator acts on the rotor winding and induces an induction current in it, a torque occurs that sets the rotor in motion. The electrical energy supplied to the motor windings is converted into mechanical rotational energy.

AC electric motors are divided into groups. The two types of electric motors most often used in the modern production cars with electric traction [18–20] are asynchronous, where the rotation speed of the stator magnetic field is higher than the rotor speed, and synchronous, for which the rotation speed of the stator and rotor magnetic field are the same.

Structural diagrams of chargers. One of the main weaknesses of electric vehicles is their low availability for work. In practice, when the battery is depleted, the electric

Table 2. Calculation of the Charging Station Loads.

Group	cos φ	tg φ	P_P, kW	Q_P, kvar	S_P, kVA
Charging station (CS) TeslaSuperCharger	0.89	0.51	250.00	127.5	280.6
Power supply to Business center	0.87	0.56	282.70	158.31	324.94
Business center auxiliaries	0.90	0.50	42.65	21.25	47.65
Total			575.35	307.06	653.19

vehicle remains inoperable and if a complete discharge of the battery occurs far from the charging station, it will lead to difficulties in getting to the charger.

It is known that in order to reduce the battery recharge time, it is necessary to increase the charging power by boosting the current consumed from the network. It is also proposed to draw this current from a three-phase network, and not from a single-phase one. In the case of a three-phase power supply network, the charging power is increased.

Thus, the charger is completely built into the car and does not require an additional output inverting stage, since the inverting stage is already in the car. Therefore, it is possible to provide charging points in the infrastructure, where the charging points are simply output sockets of the power supply network, which reduces the cost. In addition, the infrastructure network cost goes down, which enables an increase in the number of charging sites to provide charging services to a greater number of car users [21–24].

A battery charger (1) consists of an input rectifier stage (6) configured to be connected to the power supply network (3) and an output inverting stage (7) configured to be connected to the battery (2). There is a device for regulating the average value of the current received from the input stage (6) relative to the value of the current obtained based on the maximum current supplied by the power supply network (3) and in accordance with a factor that is at least equal to the ratio of the maximum voltage rectified by the input stage (6) to the battery voltage (2). The charger may include filters built into the vehicle to filter the current drawn by the charger from the supply mains.

The paper discusses the design of an electric vehicle charging station on the example of the 10/0.4 kV Teatralnaya substation in Novosibirsk (Table 2).

B Analysis of network transfer capability for establishing charging stations

The network assessment is required by reason of the need to correctly calculate and select the capacity of the electrical network components and consider the main conditions for choosing the network components (wire cross-section, location of the TP, power transformer, switches, and others).

The loads were calculated using the data of the terms of reference in accordance with RM-2696 "Instructions for the calculation of electrical loads" [12] and in accordance with SP 31-110-2003 "Design and installation of electrical plants of residential and public buildings" given the discrepancy between the maximum loads of the premises and buildings belonging to the same complex.

Since the load is given by the installed capacity and the number of individual power receivers, the electrical

Table 3. Purposes and Functions of the Wired Interface Components and Signals for Charging Station Systems of Type A.

Charging station, EV, conductors and signals	Symbol	Explanation
Charging station	d1	Control signal (CP) to control the charging start/stop signals from the station to EV
	d2	CP to control the charging start/stop signals from the station to EV
	j	Signal reader to detect if EV is ready/not ready to receive power
	+V DC	DC power supply to EV contactors
Electric vehicle (EV)	C1, C2	Disconnect switch for DC power lines (EV contactors)
	e	Relay for switching on EV contactors
	f	Signal reader for determining status of d1
	g	Signal reader for determining status of d2
	h	Signal reader to detect EV connection/disconnection
	k	Switch to start/stop charging
Conductors and signals	DC+	DC power supply (positive)
	DC-	DC power supply (negative)
	CP	Control signal indicating the start/stop status of the station
	CP2	Control signal indicating the start/stop status of the station
	CS	Control signal indicating the connection status of the EV connector
	CP3	Control signal confirming the EV readiness for charging
	COM1 COM2	Signal line pair for digital communications
	PE	Protective wire between the station and the EV for detecting the first DC earth fault

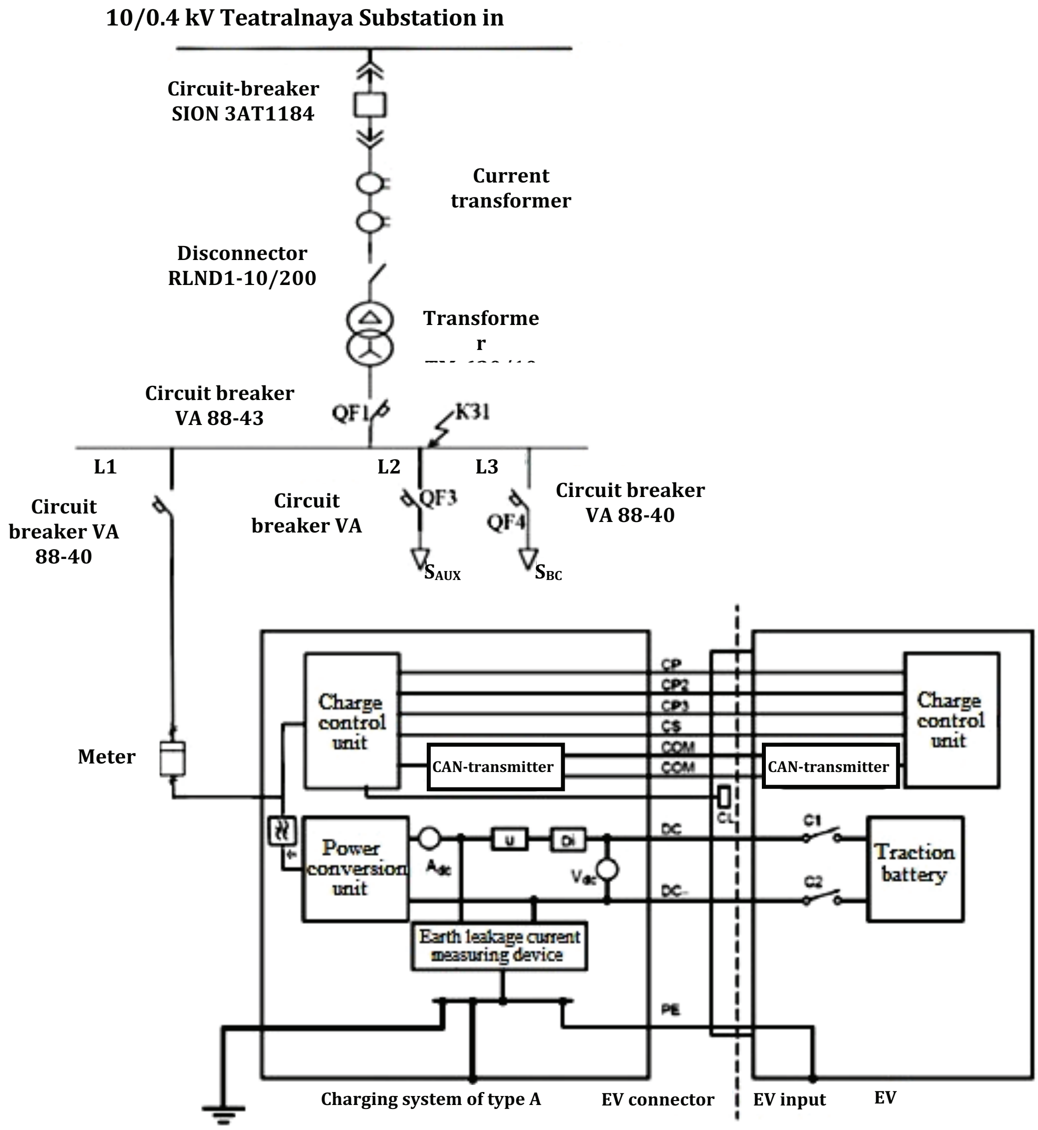


Fig. 4. Scheme of electrical connections of complete TS.

loads are calculated using the demand factor method. We took the load of the business center auxiliaries S_{aux} in the amount of 10% of the rated power.

Choice of power supply scheme. The operation of power supply systems, their reliability and quality are determined by the reliability of their constituent components. The choice of a single-line complete transformer substation scheme is made following the basic requirements [25–27]:

- The reliability of power supply to consumers in normal, repair, and post-emergency conditions;
- The scheme should be as simple, visual, and economical as possible.

Since the power supply system (PSS) under consideration belongs to the 3rd category of power supply, we assume one transformer substation (TS).

The notations and roles of the wired interface components and signals for charging station system of type A are shown in Table 3.

The developed power supply scheme is shown in Fig. 4.

The sequence of digital data exchange during the operation of the charging station is shown in the diagram below (Fig. 5).

All selected equipment meets the modern short-circuit current requirements.

III Analysis of the Influence of EV Charging Stations on the Quality of Power Supply to the Consumer in Novosibirsk 10/0.4 kV Electrical Networks

The power quality (PQ) in power supply systems is currently one of the most acute issues in the energy sector, since PQ is a significant factor affecting the performance of the power system and consumers, especially in the era of the “capricious consumer.” The quality of electricity is determined by the reliable and stable power transmission.

This problem is especially pressing in low-voltage

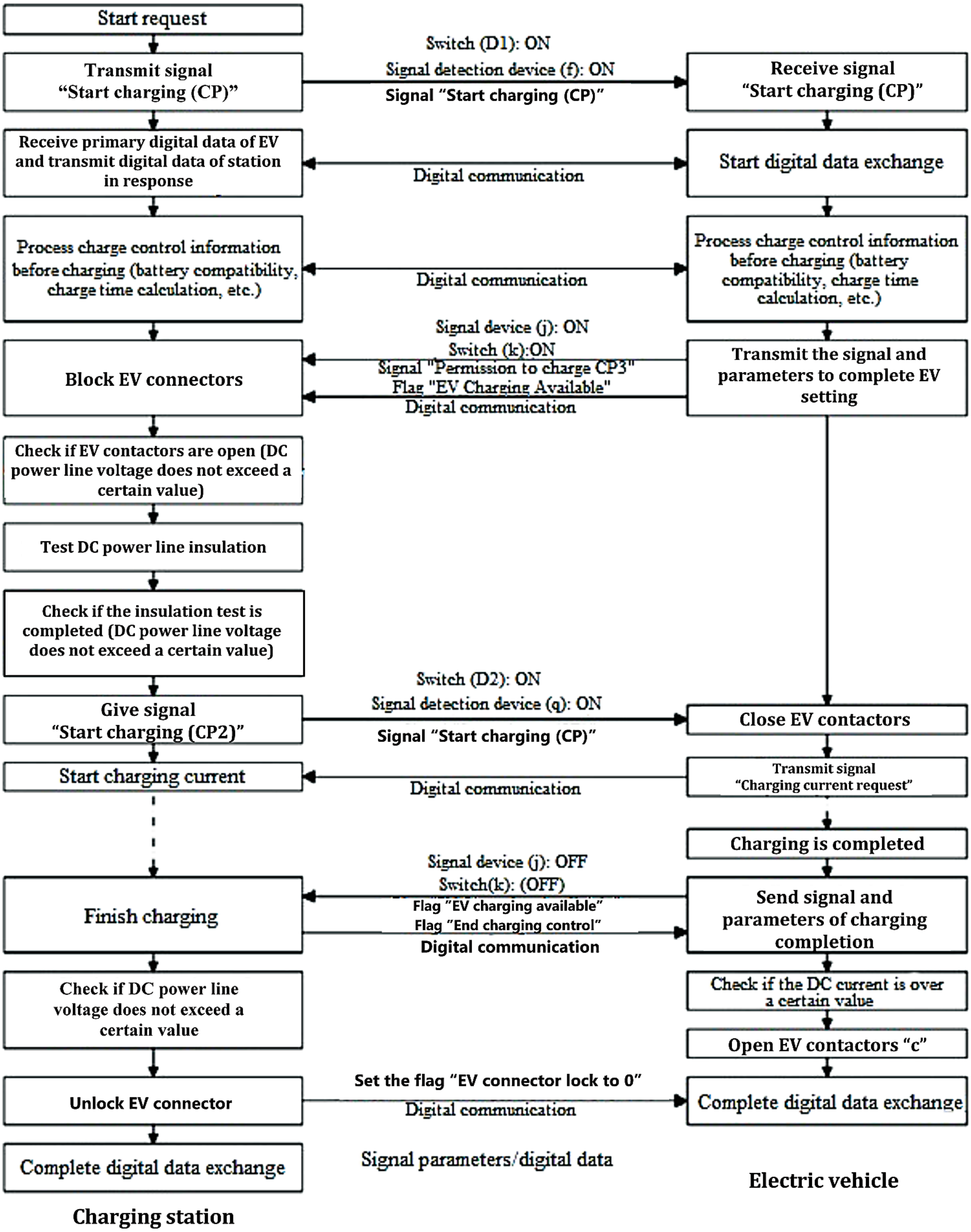


Fig. 5. The sequence of actions for digital data exchange during the operation of the charging station.

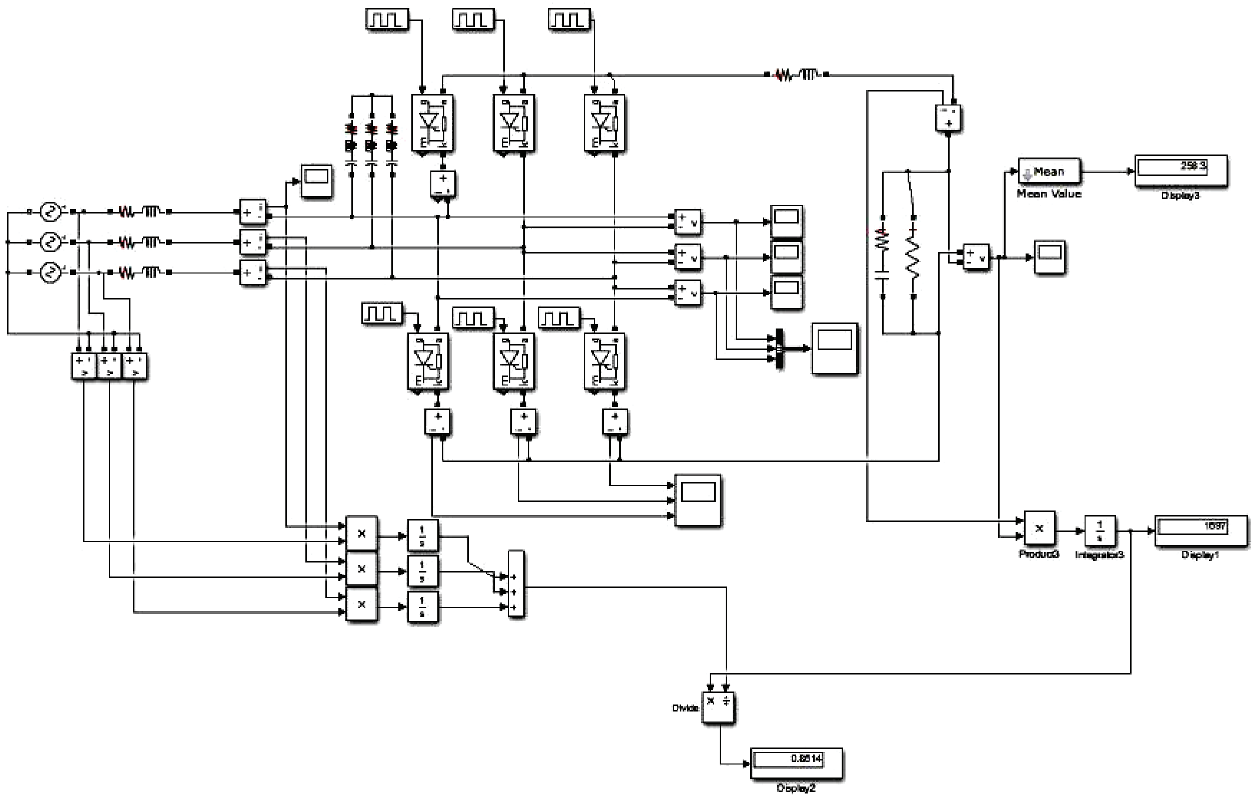


Fig. 6. Model of a three-phase bridge rectifier with filter.

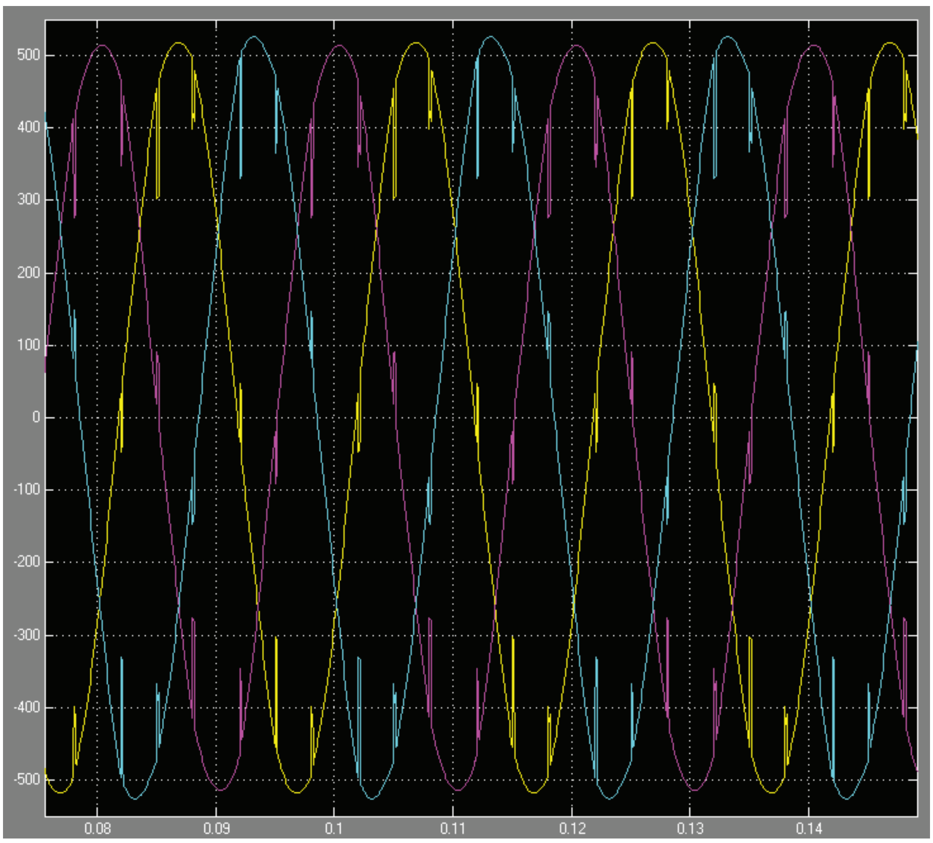
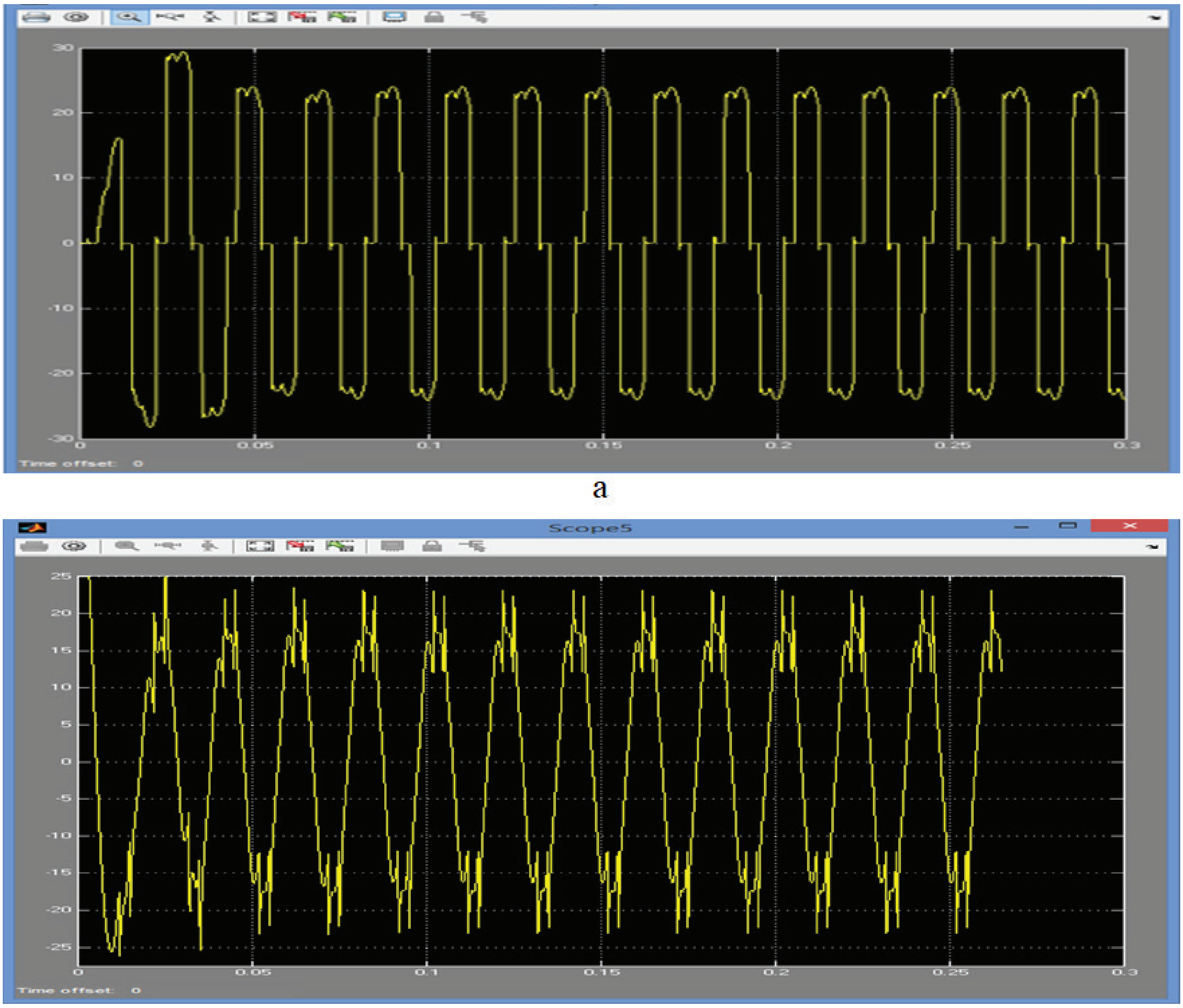


Fig. 7. Thyristor voltage graphs.



a

b

Fig. 8. Oscillograms of currents without (a) and with (b) filter.

networks, since the number of small non-linear electrical consumers (computer equipment, television equipment, audio and video equipment, household appliances, chargers, and others) is increasing at a fast pace. One of the reasons for the decline in power quality is non-linear loads that generate electromagnetic interference, which distorts the sinusoidal current and voltage curves, thereby reducing the power quality.

The charger of an electric vehicle is a non-linear load and, in addition to increase in the load on the power grid infrastructure, can deteriorate the quality of electricity through harmonic distortions, which is why it is necessary to analyze the effect of electric vehicles on the quality of power supply to consumers according to State Standard (GOST) 32144-2013.

Harmonic distortion leads to an increase in power consumption and a decrease in power quality. The harmonic current of the electrical network causes some consequences, including:

- additional power losses in distribution transformers and wires [17, 20];
- interference that affects the normal functioning of the connected equipment [13];
- reduction in the service life and transfer capability of the electrical network [28];
- increase in the danger at hazardous production facilities [29].

Thus, any electrical network has always harmonic currents of frequencies that are multiples of 50 Hz. During the day, the total harmonic factor varies within 0.9–1.4% (the highest maximum permissible value of the harmonic factor according to GOST 32144-2013 is 5%). The main sources of harmonics in low-voltage networks are power consumers, including a rectifier with a powerful capacitive filter.

A controlled rectifier, which on an industrial scale

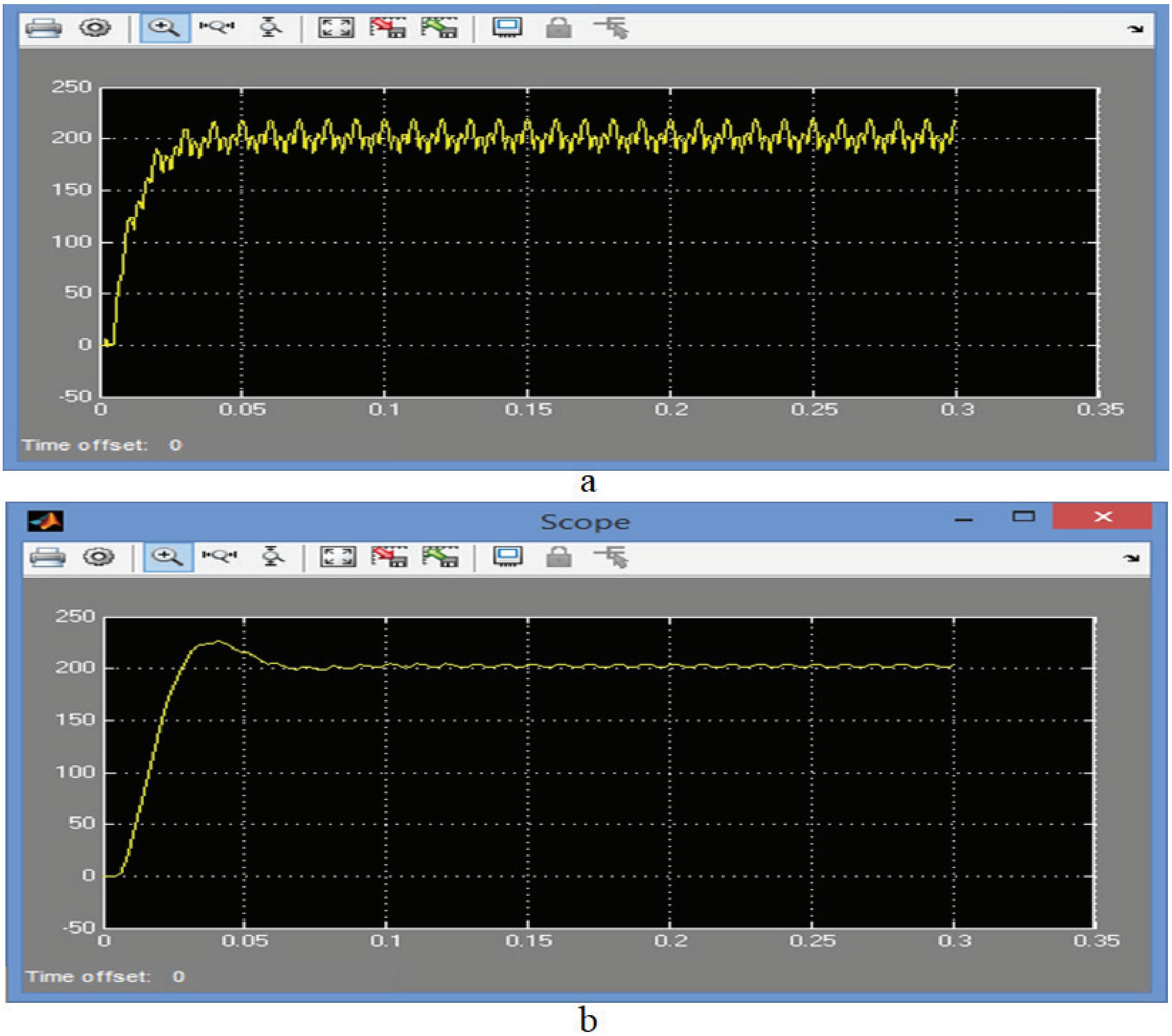


Fig. 9. Graph of the rectified voltage without (a) and with (b) filter.

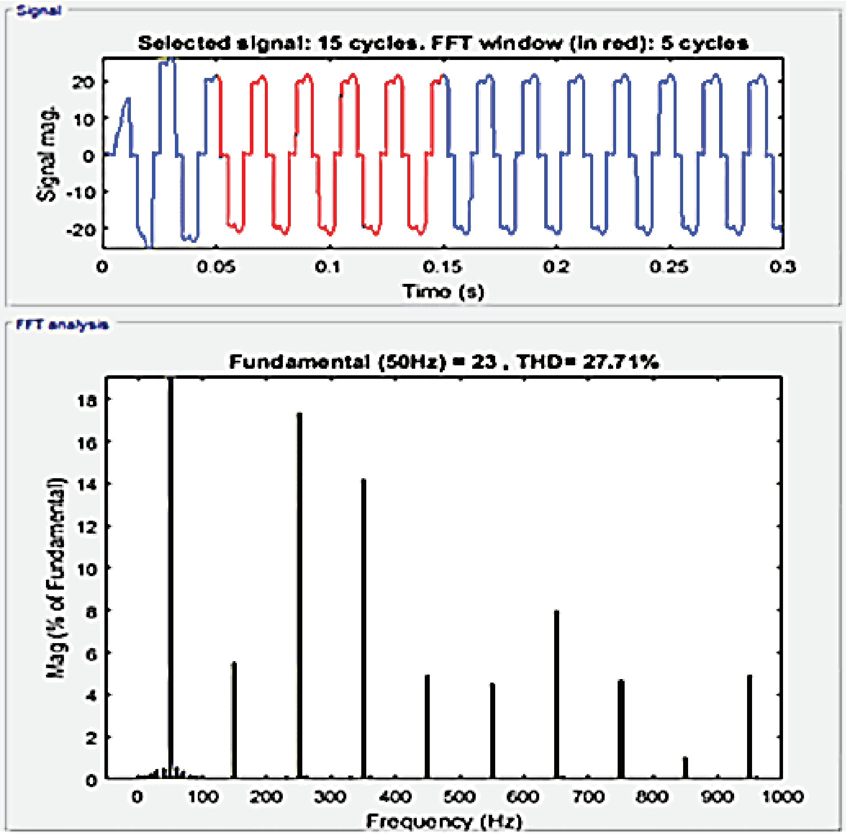
relies on a three-phase bridge circuit, is required to charge the batteries (Fig. 6). The operation of this device causes harmonics. Therefore, it is necessary to analyze the impact of the charging station on the quality of the power supply to the consumer for the presence of harmonic current and voltage, since it is this indicator that has the most significant impact on power losses in networks up to 1000 V. Consider the model of a three-phase bridge voltage rectifier made in the MATLAB program (Fig. 6).

Thyristor is used as a non-linear component in this circuit. The graphs of the operation for each of the rectifier arms are shown in Fig. 7. As shown in the Figure, there is a distortion in the shape of pulses, which is a consequence of high-frequency harmonic distortions. This can also be seen in Fig. 7.

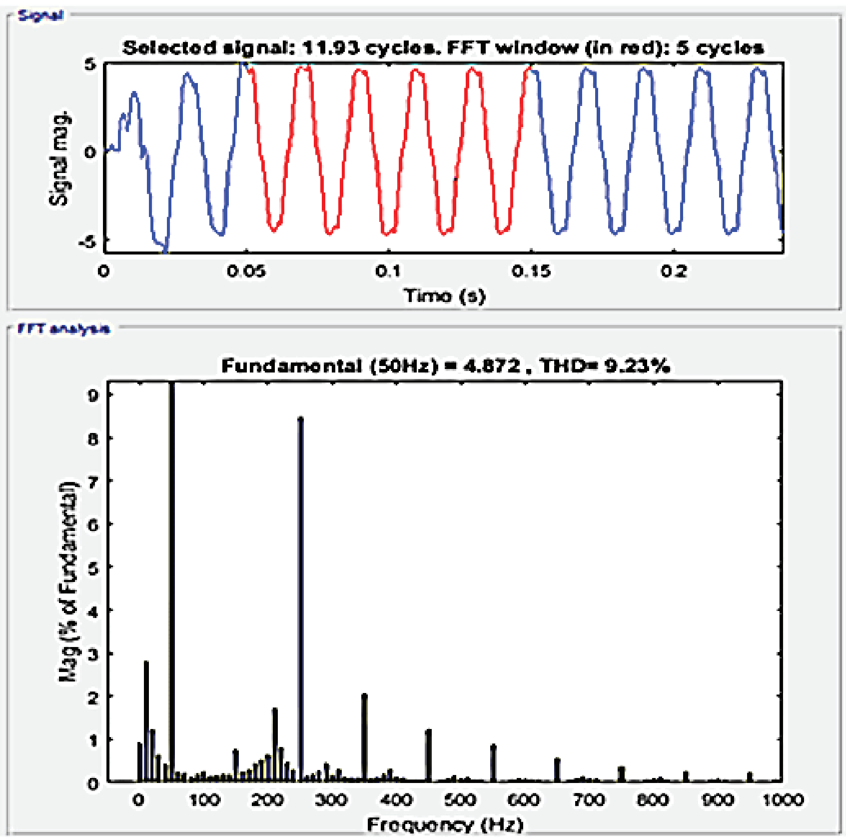
The universal device AFG-0.4-50 UHL 4 was used as a compensation filter. Figure 8 shows the oscillogram of the current at the input of an EV charging station without filter and with it, respectively. As can be seen from the oscillogram, the use of filter made it possible to reduce the harmonic components at the power supply network input. The graph of the rectified voltage is shown in Fig. 8. It is worth noting that the use of filter both at the input and at the output of the power converter is justified. It significantly reduces the ripple of the output voltage (Fig. 9).

The main indicator of the power quality is the total harmonic distortion (THD), which shows how much the signal shape differs from the sinusoidal one. This is also a value for quantifying the nonlinear distortion of a periodic signal. Thus, the primary ways to reduce the level of harmonics in low-voltage electrical networks are to use passive filters, filter compensators, hybrid filters, and active filters. In electrical systems, filters are used to reduce the current or voltage amplitude for one or several fixed frequencies [30].

As the analysis shows, the THD value without filter


Signal
Selected signal: 15 cycles. FFT window (in red): 5 cycles
Signal mag.
Time (s)
FFT analysis
Fundamental (50Hz) = 23 , THD= 27.71%
Mag (% of Fundamental)
Frequency (Hz)

a


Signal
Selected signal: 11.93 cycles. FFT window (in red): 5 cycles
Signal mag.
Time (s)
FFT analysis
Fundamental (50Hz) = 4.872 , THD= 9.23%
Mag (% of Fundamental)
Frequency (Hz)

b

in the case of the charging station is 27.7%, which is unacceptable and indicates the need to use a filter. With the filter compensator used, this value goes down to the value allowed by the State Standard and reaches 9.23% (Fig. 10).

IV Conclusion

The paper is concerned with the installation and design of the charging station for electric vehicles as a load for a power supply system. A detailed calculation and selection of power supply system equipment are made.

- The study examines how the operation of the charging station affects the electrical network and other electricity consumers and if it meets the requirements of State Standard (GOST) 32144-2013 in terms of the non-sinusoidality of the current and voltage curves, which have the greatest impact on power losses in networks up to 10 kV.
- The MATLAB Simulink software was employed to analyze the influence of the charging station on the quality of power supply to consumers. The measures to reduce the harmful effects of harmonics on the electrical network and the neighboring consumer are proposed. The active filter AFG-0.4-50 UHL 4 was chosen as a measure. The THD reached the permissible values and amounted to 9.23% (according to the standards, the permissible THD level is 10%) against the value of 27.7%, which was in the system before the implementation of compensatory measures.

The study shows the effectiveness of the developed power supply scheme for the electric vehicle charging station and indicates the possibility of giving power back to the grid and solving the problem of power shortage in the region. Moreover, the large-scale introduction of EV charging stations in megacities will significantly improve the environmental situation there. All this makes charging stations competitive to traditional energy supply sources in terms of electricity supply to the grid.

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