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Research of the main electromagnetic parameters during the operation of an AC charging station for electric vehicles

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Annotation. Problem. *The increasing popularity of electric cars worldwide is also seen in Ukraine, leading to a growing need for more charging stations. Studies show that 80% of electric car charging happens at home. This home charging usually occurs either through the standard AC power grid or through dedicated AC charging stations. This raises concerns about the safety of these charging stations and their potential interference with other electrical and electronic devices nearby.* ***Goal.*** *The goal of this work is to determine the main electromagnetic parameters in the connection cable during the operation of an AC electric vehicle charging station.* ***Methodology.*** *To achieve this goal, it is necessary to study the electromagnetic parameters of the charging station connection cable when AC flows through it and to identify the electromagnetic parameters of the interference that occurs during the operation of the AC charging station. Classical electrophysical methods for calculating electric and magnetic fields and methods for determining the parameters of quadrupoles from the theoretical foundations of electrical engineering are used.* ***Results.*** *The main electromagnetic parameters in the connection cable during the operation of the AC electric vehicle charging station have been identified. Formulas for calculating the current strength and magnetic field strength have been obtained.* ***Originality.*** *New formulas for calculating the electromotive force of interference generated during the operation of the electric vehicle charging station, when AC flows through the charging cable, have been developed. Parameters of capacitive and magnetic coupling between two conductors in a common bundle have been identified. Formulas for determining the current induced by these parasitic connections have been obtained.* ***Practical value.*** *Accurately determining and calculating these parameters allows for the design of a charging station that operates reliably over a long period without causing interference with nearby electrical and electronic systems or devices.*

Key words: *energy source, charging station, electric car, energy efficiency, traction battery, electromotive force, solar panels, capacitive coupling, magnetic coupling.*

Introduction

The modern world is entering a new phase of energy use. Specifically, the automotive industry is transforming towards a more eco-friendly and efficient type of energy: electric power. Those who are ready to follow this trend often ask: how do I choose a charging station for my electric vehicle?

The answer can be found by looking at Norway's experience. Norway has the fastest-growing electric vehicle market in Europe. Statistics show a significant increase in electric vehicle sales, reaching a record high of 82.4 % of the total new car market in 2023, up from 79.3 % in 2022. In total, 126,953 new cars were sold in Norway in 2023, with over 104,600 of them being electric vehicles [1]. Based on the experience of this Scandinavian country, we can predict how the electric vehicle market and its charging infrastructure will develop in other European countries, including Ukraine.

When designing the charging infrastructure, it is important to rely on the experience of countries that are leaders in the introduction of electric vehicles. The results of research on the distribution of charging sessions presented in [2] are interesting. These studies showed that 80 % of electric vehicle charging takes place at home, the remaining 20 % – at work or in places of free access with appropriate equipment, or at paid charging stations. From these statistics it is clear that the installation of a home station is more convenient, more in demand and more common.

Charging of an electric car at home takes place either directly from the general AC power supply network, or from special AC charging stations [3-5]. Therefore, the question naturally arises as to how safe it is to use such charging stations and whether they will not affect other electrical and electronic devices that can beat located nearby.

Analysis of publications

Works [6-8] present the results of research into the operation of fast charging of electric vehicles at DC charging stations. The studies show how these charging stations affect the quality of electricity in the network. For reference purposes, the results of AC slow charging measurements were evaluated. The researchers also proposed a working model for fast DC charging in the Matlab/Simulink software environment. Technological gaps in fast charging stations were identified. According to the researchers, this will help pave the way for joint efforts to develop charging station infrastructure.

Fast DC charging requires large amounts of electricity in a short time to speed up the charging process. This, in turn, can lead to negative consequences for the power grid, including problems with stability, reliability and efficiency. The authors of the study [9] evaluate fast charging stations with the aim of reducing peak energy consumption during charging sessions. They propose an energy management algorithm that, using dynamic data, ensures more efficient and reliable operation of such systems.

Articles [10-16] show that electric vehicles (EVs) will dominate the automotive industry in the next few years. One of the problems that their owners have already faced is the charging infrastructure for EVs. The authors of these works propose a scheme that will allow EV charging in a hybrid way. Such hybrid charging stations for EVs are powered by solar panels and the general power grid, and in emergencies, when both sources are unavailable, it uses backup batteries. The integration of charging stations into the electrical network leads to large losses and voltage drops that lead to damage to electrical and electronic equipment. On the other hand, the installation of solar panels, in addition to the advantage of energy production, improves the profile of the electrical network in terms of voltage drops [12].

Analysis of research results [17] shows that the proposed hybrid charging stations are able to provide constant and environmentally friendly energy for EVs, minimizing dependence on hydrocarbon fuel. The authors come to these conclusions after analyzing the modulation results in the Matlab/Simulink application package.

The article [18] investigates the impact of charging stations for EVs on the quality of electricity in the distribution network, analyzes the topology of charging stations for EVs. The charging stations are connected to the distribution network as charging piles, and the influence of EV charging stations of different topologies on the harmonics and voltage deviations of the distribution network is simulated and compared. These studies provide a reference for suppressing distribution network power quality problems caused by the charging station.

In the work [19], a charging station for EVs with power quality improvement functions is also proposed.The positive sequence components of the grid voltages are estimated for the calculation of the unit templates in case of unbalanced or distorted grid voltages for improving the grid power quality.

The article [20] analyzes the impact of electric vehicles on the power grid. Electric cars have non-linear elements of electrical circuits in their design. Therefore, they are a source of harmonic current in the power supply network. Accordingly, the authors of the study show that charging EVs negatively affect the quality of electricity in the power grid.

The analysis of publications on the topic of the study showed that the problem of determining the main electromagnetic parameters during the operation of a charging station for electric vehicles is relevant and requires further resolution.

Goal and tasks

The goal of this work is to determine the main electromagnetic parameters in the connection cable during the operation of an AC electric vehicle charging station.

To achieve the goal, the following tasks need to be addressed:

− investigate the electromagnetic parameters of the cable connecting the charging station when alternating charging current flows through it;

− determine the electromotive force of interference generated during the operation of the ac electric vehicle charging station;

– determine the capacitive coupling parameters between two conductors;

– determine the magnetic coupling parameters between two conductors.

Electromagnetic parameters of the charging station connection cable

We will conduct research and determine the main electrical parameters in the connection cable during the operation of the AC EV charging station. Essentially, these are indicators of electromagnetic interference generated during the operation of the charging station, which can affect the performance of electrical and electronic devices and systems, both within the charging infrastructure and the vehicles themselves.

The charging of EV traction batteries and the powering of their charging infrastructure occurs through electrical cables (conductors) with a relatively large cross-section, allowing for the flow of a significant current. We will refer to these conductors as "massive" conductors. To simplify the calculation of the inductance of a "massive" conductor with finite size, we will assume that the loop has a rectangular shape (see Fig. 1) with a length of (l+m) and a height of (m-r).

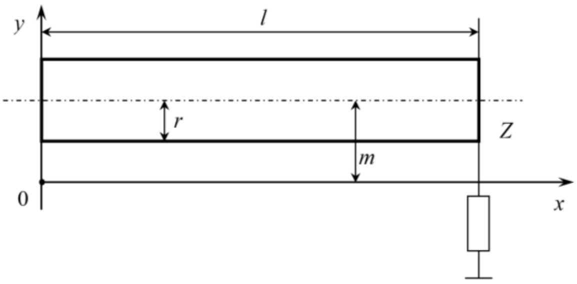


Fig. 1. Technical characteristics of the "massive" conductor

The inductance of the other part of the circuit can be neglected, bearing in mind that the magnetic field reaches its greatest value at the surface of the "massive" conductor. The current $i(t)$ in the time interval τ varies linearly (Fig. 2) [21].

In accordance with the full current law, the value of the magnetic field strength H at a distance y from the center of the "massive" conductor can be found from the equation:

$$i(t)= 2H\cdot\pi\cdot y, \tag{1}$$

where $i(t)$ is the current flowing through the "massive" conductor, A; H – magnetic field strength, A/m; y is the distance from the center of the "massive" conductor to the point under consideration.

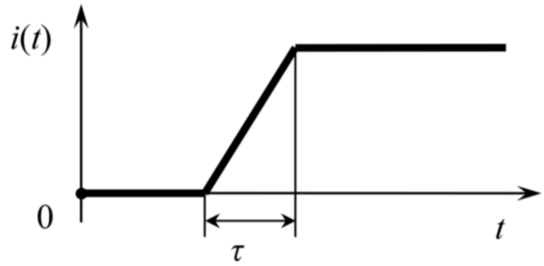


Fig. 2. The law of current change in a "massive" conductor in time intervals τ

The intensity of the magnetic field H is defined as $H = i(t)/2\pi y$, and its induction is B:

$$B = \mu_0 H = \mu_0 \frac{i(t)}{2\pi y}. \tag{2}$$

The coupling flux Φ with the circuit is determined as:

$$\begin{aligned}\Phi &= \frac{\mu_0 i(t)}{2\pi}\int_r^m \int_0^{(l+m)} \frac{dy}{t}\,dx = \frac{\mu_0 i(t)}{2\pi}(l+m)\int_r^m \frac{dy}{y} = \\ &= \frac{\mu_0 i(t)(l+m)}{2\pi}\ln y\Big|_r^m = \\ &= \frac{\mu_0 i(t)(l+m)}{2\pi}(\ln m - \ln r) = \\ &= \frac{\mu_0 i(t)(l+m)}{2\pi}\ln\frac{m}{r}.\end{aligned} \tag{3}$$

Let's determine the electromotive force (EMF) of the interference generated during the operation of a charging station for alternating current electric vehicles:

$$e_{AC} = -\frac{d\Phi}{dt} = -\frac{\mu_0 (l+m)}{2\pi}\ln\frac{m}{r}\cdot\frac{di(t)}{dt};$$

$$\frac{di(t)}{dt} = \frac{I}{\tau}; \quad e_{AC} = -\frac{\mu_0 (l+m)}{2\pi}\frac{I}{\tau}\ln\frac{m}{r}\cdot\frac{di(t)}{dt};$$

$$e_{AC} = -L\frac{di(t)}{dt}; \quad L = \frac{e_{AC}}{I/\tau} = \frac{e_{AC}\tau}{I}; \tag{4}$$

$$e_{AC} = -\frac{\mu_0(l+m)}{2\pi}\ln\frac{m}{r}, \tag{5}$$

where μ_0 is the magnetic constant, Hn/m; m is the distance from the ground to the central axis of the conductor, m; r is the radius of the conductor, m; l is the length of the conductor, m; $i(t)$ is the current flowing through the "massive" conductor, A; y is the distance from the center of the "massive" conductor to the point under consideration, m; Φ is the engagement flow, Vb; τ is the time interval, s; e_{AC} is the electromotive force generated during the operation of a charging station for alternating current electric vehicles, V; L is the induction of the "massive" conductor, Tl.

The proposed method of assessing the main electromagnetic parameters during the operation of a charging station for alternating current electric vehicles assumes that it works in its nominal mode of operation. However, it should be noted that electromagnetic disturbances are also formed during various transient impulse processes, which act either randomly or in accordance with the algorithm of the given charging station.

Table 1 shows typical values of the parameters of impulse disturbances that occur during transient processes from various sources [21].

Table 1 – Parameters of pulsed electromagnetic disturbances

Source of interference	Repetition frequency, s^{-1}	Pulse duration, s
1	2	3
Fluorescent lamps	10^2	10^{-7}
Ignition systems: - at idle - in working mode	 10^2 10^3	 10^{-8} 10^{-8}
Relays and solenoids	10^3	10^7
Collector engines	10^3	10^{-8}
Switches: - wall - machine tools	 10^{-4} 10^{-3}	 10^{-6} 10^{-7}

Capacitive and magnetic connection between conductors

All power cables and wires are usually laid in a separate tunnel where they are located next to each other. Therefore, there is a need to determine and calculate the possibility of their joint work.

Let's determine the induced voltage in the circuit through capacitive coupling for an unshielded conductor. In Fig. 3 presents a model of capacitive coupling between two conductors, where the electrical parameters of conductor 1 affect conductor 2 through capacitive coupling. The model and its replacement scheme are marked:

$$C_{12} = \frac{\pi\varepsilon'}{\ln\left(\frac{d}{a}\right)} \tag{6}$$

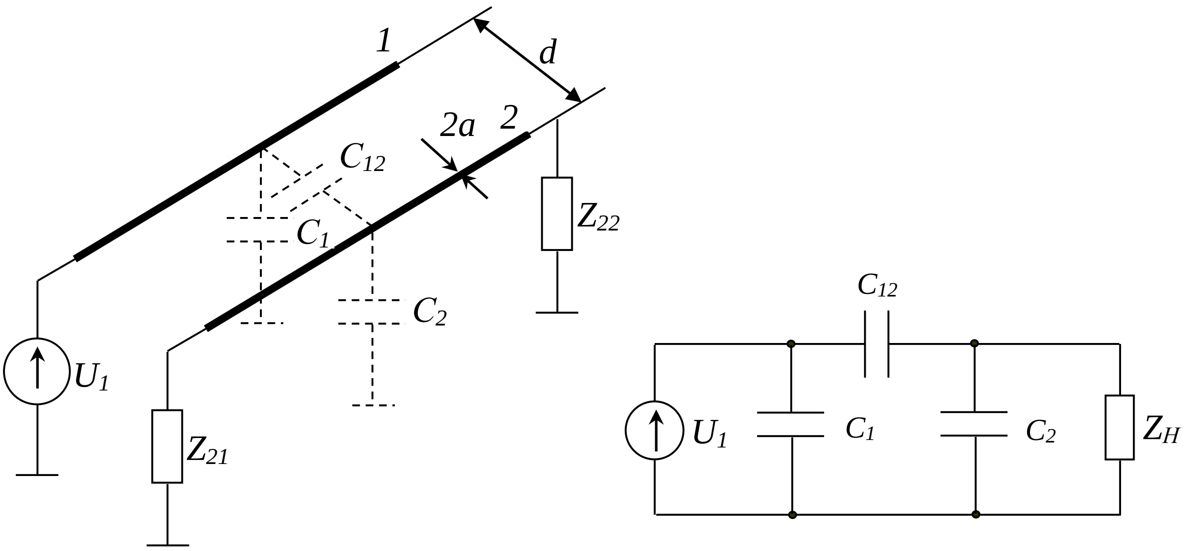
where C_{12} is the capacitance between conductors 1 and 2, F; ε′ is the dielectric constant of the medium around the conductors; C_1 and C_2 is the capacitances of the conductors in relation to the "earth", F; Z_H is the total resistance of wire 2 in relation to "earth", which is not a parasitic element, but is the working resistance of the circuit, Ohm.

The capacity C_1 can be neglected, since it does not affect the electrical connection of the conductors, because the sources that cause capacitive interference are connected in parallel. The voltage relative to the "ground" of conductor 2, due to capacitive coupling, can be deduced from the quadrupole equation.

Using the equivalent substitution scheme of Fig. 3,b can be written:

$$\left.\begin{aligned} \dot{U}_1 &= \underline{A}\dot{U}_2 + \underline{B}\dot{I}_2; \\ \dot{I}_2 &= \frac{\dot{U}_2}{Z_H}. \end{aligned}\right\} \tag{7}$$

where $\underline{A}$ and $\underline{B}$ are complex values of the four-pole constants.



a b

Fig. 3. Model of capacitive coupling between conductors: a – the physical model; b – an equivalent substitution scheme

Let's define $\dot{U}_2$:

$$\dot{U}_1 = \underline{A}\dot{U}_2 + \underline{B}\frac{\dot{U}_2}{Z_H} = \underline{A} + \frac{\underline{B}}{Z_H} = \frac{\underline{A}Z_H + \underline{B}}{Z_H}; \qquad (8)$$

$$\dot{U}_2 = \dot{U}_1 \frac{Z_H}{\underline{A}Z_H + \underline{B}}. \qquad (9)$$

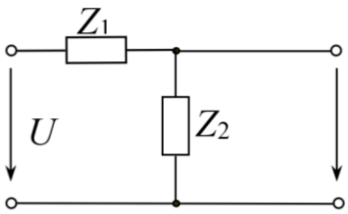
Based on the physical processes, it is obvious that the capacity C_1 can be neglected, then the equivalent circuit of the replacement of Fig. 3, b will correspond to the L-shaped circuit of the four-pole, which is presented in Fig. 4, a and transformed into the calculation circuit, which is shown in Fig. 4, b.

Expressions for the four-pole constants through the elements of the substitution scheme (Fig. 4a):

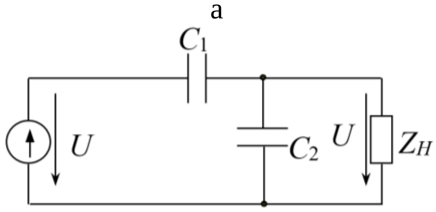
$$\left.\begin{aligned} \underline{A} &= 1 + \underline{Z}_1\underline{Y}_2; \\ \underline{B} &= \underline{Z}_1; \end{aligned}\right\} \qquad (10)$$

Then the constants of the quadrupole are determined:

$$\left.\begin{aligned} \underline{A} &= 1 + \frac{C_2 \cdot j\omega}{j\omega \cdot C_{12}} = \frac{1 + C_2}{C_{12}}; \\ \underline{B} &= \frac{1}{j\omega \cdot C_{12}}; \ \underline{Z}_1 = \frac{1}{j\omega \cdot C_{12}}; \\ \underline{Y}_2 &= \frac{1}{\underline{Z}_2} = \frac{1}{\dfrac{1}{j\omega \cdot C_2}} = j\omega C_2. \end{aligned}\right\} \qquad (11)$$



a



b

Fig. 4. L-shaped circuit of a four-pole circuit: a – a substitution scheme; b – calculation scheme

Now let's substitute the values of the coefficients in formula (8):

$$\dot U_2=\dot U_1\cdot\frac{Z_H}{(\frac{1+C_2}{C_{12}})\cdot Z_H+\frac{1}{j\omega C_{12}}}=\dot U_1\cdot\frac{Z_H}{(\frac{C_{12}+C_2}{C_{12}})\cdot Z_H+\frac{1}{j\omega C_{12}}}\cdot\frac{\frac{C_{12}}{(C_2+C_{12})\cdot Z_H}}{\frac{C_{12}}{(C_2+C_{12})\cdot Z_H}}=$$

$$=\dot U_1\cdot\frac{Z_H\cdot\frac{C_{12}}{(C_2+C_{12})\cdot Z_H}}{\frac{(C_{12}+C_2)\cdot Z_H}{C_{12}}\cdot\frac{C_{12}}{(C_2+C_{12})\cdot Z_H}+\frac{C_{12}}{j\omega C_{12}\cdot(C_2+C_{12})\cdot Z_H}}=$$

$$=\dot U_1\frac{\frac{C_{12}}{C_2+C_{12}}}{1+\frac{C_{12}}{j\omega C_{12}\cdot(C_2+C_{12})\cdot Z_H}}\cdot\frac{j\omega}{j\omega}=\dot U_1\frac{j\omega\cdot\frac{C_{12}}{C_2+C_{12}}}{j\omega+\frac{C_{12}\cdot j\omega}{j\omega C_{12}\cdot(C_2+C_{12})\cdot Z_H}}=\dot U_1\frac{j\omega\cdot\frac{C_{12}}{C_2+C_{12}}}{j\omega+\frac{1}{(C_2+C_{12})\cdot Z_H}}.$$

Thus, the values of $\dot U_1$ and $\dot U_2$ are related by the expression:

$$\dot U_2=\dot U_1\frac{j\omega\frac{C_{12}}{C_{12}+C_2}}{j\omega+\frac{1}{Z_H(C_{12}+C_2)}}. \qquad (12)$$

For the case of low-frequency influence, when formula (12) takes the form:

$$\dot U_2=\dot U_1 j\omega Z_H C_{12}. \qquad (13)$$

If capacitive communication is carried out at a high frequency, when:

$$Z_H=\frac{1}{j\omega(C_{12}+C_2)}, \qquad (14)$$

then:

$$\dot U_2=\dot U_1\frac{C_{12}}{C_{12}+C_2}. \qquad (15)$$

Let's determine the induced voltage in the circuit through inductive coupling. During the flow of the disturbance current in the network, which affects other electrical networks and communication networks, a magnetic field will exist around conductor 1 (Fig. 5), which covers conductor 2 and induces an induced current in it. This current can be determined by the formula of interconnected electrical circuits:

$$i_2(t)=-\frac{M_{12}}{Z_{21}+Z_{22}}\cdot\frac{di_1(t)}{dt}, \qquad (16)$$

where M_{12} is the mutual inductance between conductors 1 and 2, H; $i_1(t)$ is the current in the network as a function of time, A; Z_{21} and Z_{22} are the impedances of the network under influence, Ω.

The mutual inductance is determined by:

$$M_{12}=\frac{\mu l}{2\pi\ln\left(\frac{l}{d}\right)}, \qquad (17)$$

where μ is the magnetic permeability of the space around the conductor, H/m.

If the impedances Z_{21} and Z_{22} are assumed to be purely resistive, the waveform of the induced current in conductor 2 will correspond to the derivative of the current waveform in conductor 1.

When conductor 1 with current $i_1(t)$ influences the "conductor-ground" loop with an area $A=h\cdot l$, and the magnetic field of conductor 1 is perpendicular to the plane of this loop (Fig. 6), the formula (16) can be written as:

$$i_2(t)=\frac{\mu l}{2\pi(Z_{21}+Z_{22})}\ln\left(\frac{d+h}{d}\right)\frac{di(t)}{dt}. \qquad (18)$$

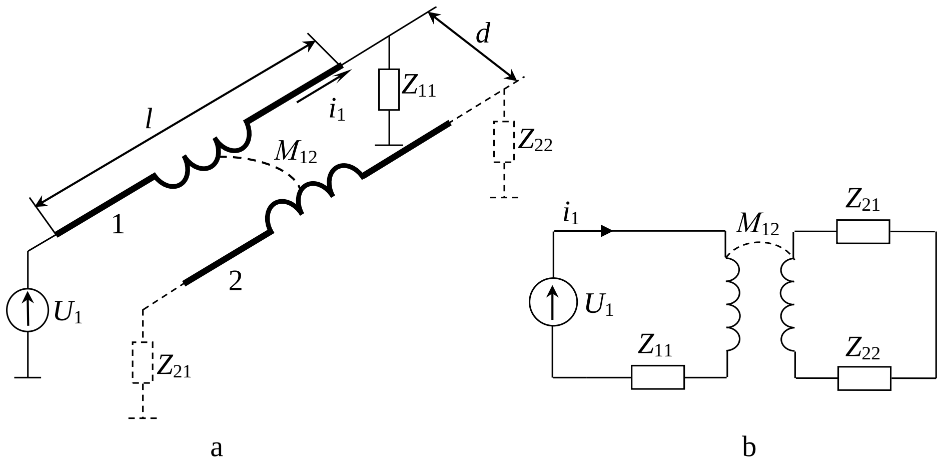


Fig. 5. Magnetic coupling between conductors: a – physical model; b – equivalent circuit diagram

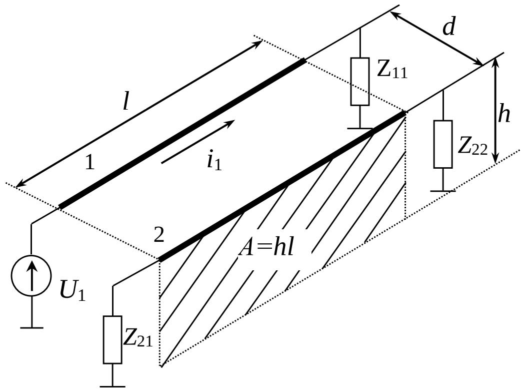


Fig. 6. Magnetic coupling between a current-carrying conductor and the "conductor-ground" loop

From formula (18), it can be seen that if the impedances Z_{21} and Z_{22} are assumed to be purely resistive, the induced current in conductor 2 will have a waveform corresponding to the time derivative of the current in conductor 1.

If we consider that, according to the symbolic method $\frac{di(t)}{dt} = j\omega I$, then expression (18) can be written as:

$$\dot{I} = \frac{\mu l}{2\pi\left(Z_{21}+Z_{22}\right)} \ln\left(\frac{d+h}{d}\right) j\omega I . \quad (19)$$

Given the derived expression for the induced current, it becomes evident that the resistance Z_{21} and Z_{22}, as well as the physical dimensions of the loop, play significant roles in determining the magnitude of the induced current. This insight is crucial for designing charging infrastructure that minimizes electromagnetic interference and ensures reliable operation of both the charging station and nearby electronic devices. By carefully considering these parameters, engineers can enhance the performance and safety of electric vehicle charging systems.

Conclusion

Research has been conducted to determine the main electromagnetic parameters in the connection cable during the operation of an AC electric vehicle charging station. An analysis of publications on the research topic showed that the problem of determining the main electromagnetic parameters during the operation of electric vehicle charging stations is relevant. Identifying and calculating these parameters allows for designing a charging station that can operate reliably for a long time without affecting other electrical and electronic systems and devices that may be located near the station or within it.

The electromagnetic parameters of the charging station connection cable when alternating charging current flows through it have been studied. Calculation formulas for determining the current strength and the induced magnetic field strength are provided.

Formulas for calculating the electromotive force of the interference generated during the operation of the AC electric vehicle charging station, when alternating current flows through the charging cable, have been obtained.

Parameters of capacitive and magnetic coupling between two conductors located in the common bundle of the charging station have been identified. Calculation formulas for determining the current induced by these parasitic couplings have been obtained.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Дослідження основних електромагнітних параметрів при роботі зарядної станції змінного струму для електромобілів

Анотація. Проблема. *Зростання популярності електромобілів у всьому світі також спостерігається в Україні, що призводить до зростаючої потреби у більшій кількості зарядних станцій. Дослідження показують, що 80% зарядок електромобілів відбувається вдома. Це домашнє заряджання зазвичай здійснюється або через стандартну мережу змінного струму, або через спеціальні зарядні станції змінного струму. Це викликає занепокоєння щодо безпеки цих зарядних станцій та їх можливого впливу на інші електричні та електронні пристрої поблизу.* ***Мета.*** *Метою цієї роботи є визначення основних електромагнітних параметрів в кабелі підключення під час роботи зарядної станції змінного струму для електромобілів.* ***Методологія.*** *Для досягнення цієї мети необхідно вивчити електромагнітні параметри кабелю підключення зарядної станції при протіканні по ньому змінного струму і визначити електромагнітні параметри завад, що виникають під час роботи зарядної станції змінного струму. Використовуються класичні електрофізичні методи для розрахунку електричних і магнітних полів, а також методи для визначення параметрів квадруполів з теоретичних основ електротехніки.* ***Результати.*** *Визначено основні електромагнітні параметри в кабелі підключення під час роботи зарядної станції змінного струму для електромобілів. Отримано формули для розрахунку сили струму та напруженості магнітного поля.* ***Оригінальність.*** *Розроблено нові формули для розрахунку електрорушійної сили завад, що утворюються під час роботи зарядної станції для електромобілів, при протіканні по зарядному кабелю змінного струму. Визначено параметри ємнісного та магнітного зв'язку між двома провідниками в загальному жмуті. Отримано формули для визначення струму, індукованого цими паразитними зв'язками.* ***Практична цінність.*** *Точне визначення та розрахунок цих параметрів дозволяє проектувати зарядну станцію, яка надійно працюватиме протягом тривалого часу без спричинення завад іншим електричним та електронним системам чи пристроям поблизу.*

Ключові слова: *джерело енергії, зарядна станція, електромобіль, енергоефективність, тягова батарея, електрорушійна сила, сонячні панелі, ємнісний зв'язок, магнітний зв'язок.*

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