DEFINICIJA AMPERA JE ZBUNJUJUĆA
THE DEFINITION OF AMPERE IS CONFUSING

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SI jedinica amper definirana je pomoću magnetskih sila između dva paralelna vodiča protjecana strujom. Pritom se ne spominje električna sila suprotnoga smjera, koja također postoji među vodičima. Zbog toga postojeća definicija zbunjuje studente, jer ih navodi na pomisao da se njome amper u laboratoriju i praktično ostvaruje. Provedena analiza sila pokazuje da je u određenim uvjetima električna sila mnogo manja od magnetske, ali ta činjenica ipak mijenja fizikalnu sliku postavljene definicije. Električna se sila može kompenzirati, što bi pri navođenju definicije ampera u udžbenicima valjalo i napomenuti, ili navesti da se on praktično ostvaruje strujnom vagom.

SI unit of ampere is defined by means of magnetic force between two parallel conductors through which current flows. However, no mention is made of electric force in the opposite direction, which also exists between conductors. For that reason the existing definition is confusing for students, because it leads them to assume that by means of it ampere is also practically realized in laboratory. An analysis of forces shows that under certain conditions the electric force is much smaller than the magnetic force, but that fact still changes the physical picture of the propounded definition. The electric force can be compensated, which should be stated in textbooks when it comes to the definition of ampere, or else mention that ampere is practically realized by the current balance.

Ključne riječi: definicija ampera, strujna vaga
Key words: ampere definition, current balance

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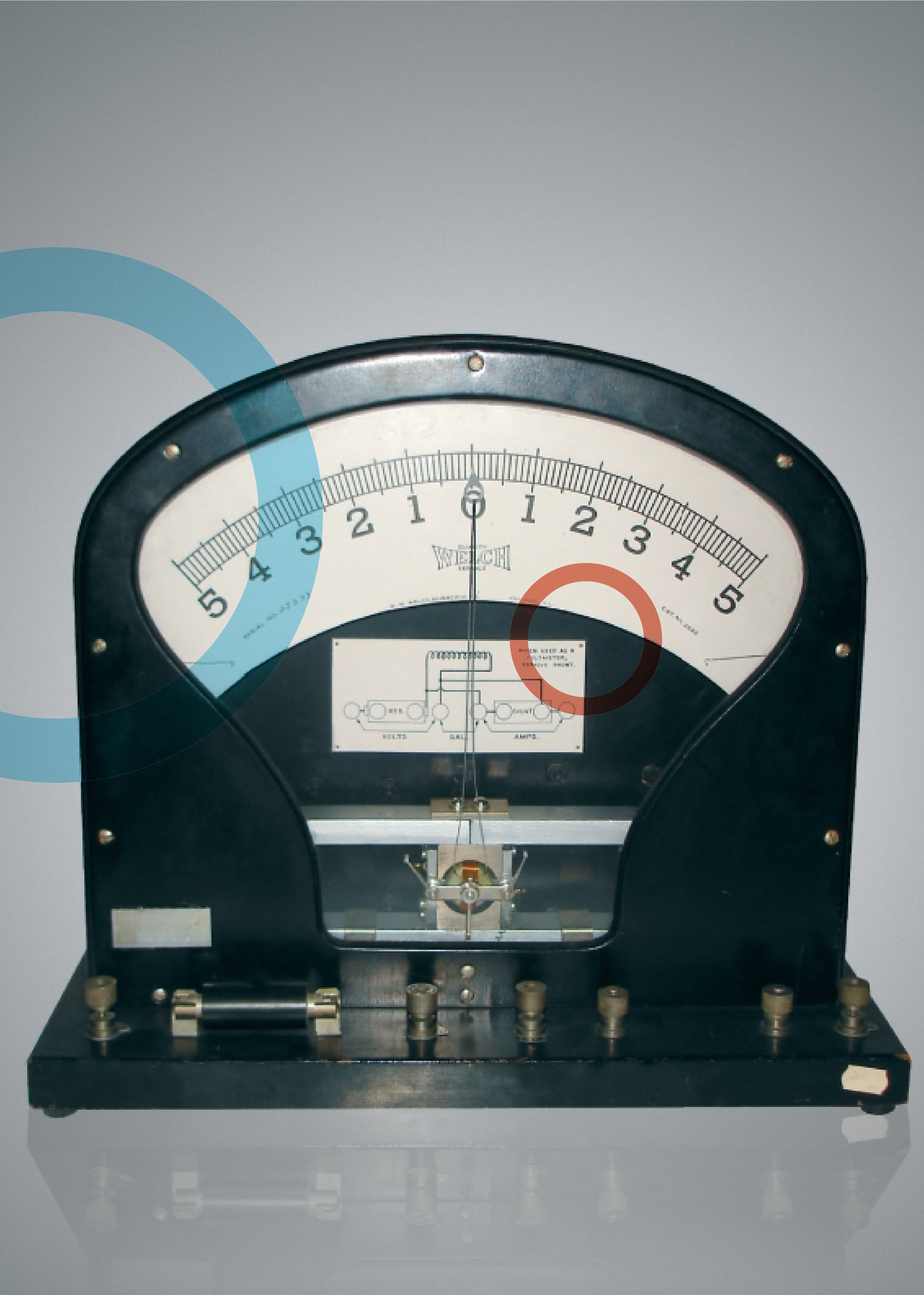

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1 UVOD

Definicija osnovne jedinice SI za jakost električne struje, u svom izvornom obliku na engleskom jeziku, onako kako je određena Rezolucijom 2 Međunarodnog odbora za mjere i utege (CIPM) 1946. godine, glasi: *The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to* 2×10^{-7} *newton per metre of length*. Na hrvatskom jeziku to znači: amper je ona stalna struja koja tekući dvama ravnim, usporednim i neizmjerno dugačkim vodičima, zanemarivo malog kružnog presjeka, razmaknutim 1 metar u vakuumu, proizvodi među njima silu od 2×10^{-7} njutna po metru duljine.

Pri praktičnom određivanju jakosti električne struje (do sredine 60-ih godina 20. stoljeća) strujnom ili Rayleighovom vagom rabi se načelo slično definicijskom, a mjerenje se struje svodi na mjerenje sila između vodiča protjecanih strujom. Budući da njezini svici preuzimaju ulogu vodiča, razumljivo je da ta metoda načelno odstupa od navedene definicije ampera. Novijim izvedbama strujnih, odnosno učinskih ili vatnih vaga (engl. *Watt Balance*) u NPL-u i NIST-u sredinom 80-ih godina 20. stoljeća postižu se nesigurnosti manje od jedne milijuntinke. Stoga se posljednjih dvadesetak godina intenzivno radi na zamjeni postojeće definicije kilograma, ako bi se takvim vagama u dogledno vrijeme postigle bolje točnosti. Tada je moguće očekivati da bi među osnovnim jedinicama SI sustava amper i vat mogli vrlo skoro zamijeniti svoje uloge.

Druga je mogućnost primjene metode transportiranja i brojenja ioniziranih čestica (jednu po jednu) električkim postupcima elektromagnetskog ozračivanja dvaju labavo vezanih (supra)vodiča, smještenih u kriostat s radnom temperaturom bliskom apsolutnoj nuli (engl. *Single electron tunneling*, SET). Pritom je struja određena izrazom $I = e \cdot f$, razmjerna umnošku jediničnog naboja e naelektriziranih čestica (elektrona) transportiranih preko tunelirajućeg spoja u ritmu ozračivanja elektromagnetskim poljem frekvencije f [1]. Ako bi se ovaj postupak primijenio za novo definiranje ampera, time bi se zatvorio nobelovski kvantni mjeriteljski trokut U - I - f, poznat u suvremenom mjeriteljskom svijetu pod nazivom *Quantum Metrology Triangle*, odnosno započela bi primjena novog mjeriteljskog područja znanog kao *Quantum Metrology*. Elektronska crpka, kao osnovni dio SET-a, sastoji se od tri ili više tunelirajućih spojeva, a na svako je spojno mjesto preko pripadajućih kapacitivnih vratiju spojen upravljački napon.

1 INTRODUCTION

Ampere as an SI base unit of electric current is originally defined in Resolution 2 of the International Bureau of Weights and Measures (CIPM) 1946 as follows: *The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to* 2×10^{-7} *newton per metre of length*.

In practical determination of the rate of electric current (by mid-60-ties of the last century) by means of the current balance, or Rayleigh balance, a principle is applied similar to the definition, whereas the measurement of current is reduced to the measurement of forces between the conductors through which the current flows. As its coils assume the role of conductors, it is understandable that this method in principle deviates from the above given definition of ampere. More recent designs of current or watt balances in NPL and NIST in mid-80-ties of the last century have an uncertainty of less than one millionth. That is why in the past twenty years intensive work is under way to replace the existing definition of kilogram, in case that even higher precision is achieved with such balances. It could then be expected that among the SI base units ampere and watt may very soon exchange their roles.

The alternative is to apply the method of transporting and counting ionised particles (one by one) by electromagnetic radiation of two loosely connected (super)conductors placed in a cryostat maintaining a working temperature close to absolute zero (*Single electron tunnelling*, SET). Current is defined by the expression $I = e \cdot f$, proportional to the product of unit charge e of electrons transported over the tunnelling connection in the radiation rhythm of the electromagnetic field frequency f [1]. If this procedure were to be applied to a new definition of ampere, the Nobel quantum metrology triangle U - I - f, known in modern metrology under the name of *Quantum Metrology Triangle*, would thereby be closed and the application of a new metrological area known as *Quantum Metrology* would be started. The electronic pump, as the main part of SET, consists of three or more tunnelling connections, with control voltage connected to each connection point via pertaining capacitive port. If in a static operating point, when the electrons from the transmitter element cannot pass, alternating and phase-shifted high-frequency (HF) appear at the port, then a single-electron transport will start during each HF signal period, i.e., current $I = e \cdot f$ will flow in the circuit. With a 5-connection electronic pump at the Japanese Electrotechnical

Ako se u statičkoj radnoj točki, kad elektroni iz odašiljačkog elementa ne mogu prolaziti, na vratima pojave izmjenični i fazno pomaknuti visokofrekvencijski (VF) upravljački naponi, tad će započeti prijenos po jednog elektrona za svake periode VF signala, odnosno krugom će teći struja $I = e \cdot f$. U japanskom Elektrotehničkom laboratoriju (ETL) elektronskom crpkom s 5 spojeva, u zadnjem desetljeću 20. stoljeća ostvarili su nesigurnost mjerenja manju od $0{,}5 \cdot 10^{-6}$ [2], pa se danas istražuju mogućnosti izrade *kvantnog strujnog etalona* primjerene točnosti s devet i više spojeva. Kao alternativno rješenje SET-u postoje studije o tunelirajućem mikroskopu (engl. *Scanning Tunneling Microscope*, STM), kojim bi se pri istoj frekvenciji dobila desetorostruko veća struja nego kod SET-a.

Usprkos napretku praktičnog određivanja struje, na snazi je i dalje teorijska definicija jedinice amper. Međutim, u udžbenicima elektrotehnike i fizike još uvijek se nailazi na pomalo zbunjujuću gore navedenu definiciju, uz koju autori obično ne spomenu da se njom izravno ne može u praksi ostvariti amper. U njoj se govori isključivo o magnetskoj sili između dva beskonačno duga, ravna i paralelna vodiča, dok se električne sile među njima ne spominju. Oni studenti koji znaju da postoji i električna sila, pitaju svoje nastavnike da li električna sila utječe na točnost definicije. Pozabavit ćemo se postojećom definicijom i provesti analizu sila kod paralelnih vodiča protjecanih strujom. Time će se pokazati da se izravnim pokusom na osnovi definicije, u realnim uvjetima ne može postići zadovoljavajuća točnost.

2 SILE IZMEĐU DVA PARALELNA VODIČA PROTJECANA STRUJOM

Spojem prema slici 1, gdje su dva paralelna ravna vodiča protjecana strujama I_1 i I_2 u neovisnim strujnim krugovima, ostvarena je privlačna magnetska sila F_m, a zbog istoimenog linijskog naboja i odbojna električna sila F_e.

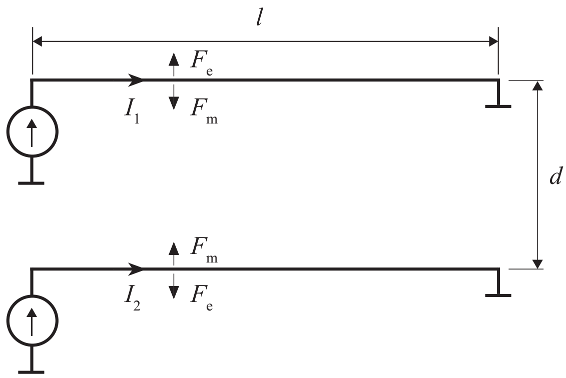
Laboratory (ETL), in the last decade of the last century they achieved measurement uncertainty below $0{,}5 \cdot 10^{-6}$ [2], and now they are exploring the possibility of making a *quantum current standard* with nine or more connections. As alternatives to SET there are studies in the *Scanning Tunnelling Microscope* (STM), which at the same frequency would yield current tenfold compared with SET.

In spite of the progress made in the practical definition of current, the theoretical definition of unit ampere is still in force. However, in the textbook of electrical engineering and physics we can still find the somewhat confusing above quoted definition, where the authors usually fail to note that by means of the definition it is impossible to realize the ampere in practice. The definition mentions only a magnetic force between two straight parallel conductors of infinite length, whereas no reference is made to electric forces between them. Those students who know that an electric force also exists there tend to ask their teachers whether or not the accuracy of the definition is influenced by the electric force. We shall discuss the existing definition and make an analysis of forces occurring in parallel conductors in which current is maintained. We shall show that by means of a direct experiment based on the definition it is impossible to achieve satisfactory accuracy in real conditions.

2 FORCES BETWEEN TWO PARALLEL CONDUCTORS IN WHICH CURRENT IS MAINTAINED

With the connection according to Figure 1, where in two parallel straight conductors currents I_1 and I_2 are maintained in independent circuits, an attractive magnetic force F_m is achieved, as well as a repulsive electric force F_e due to the same-character line charge.

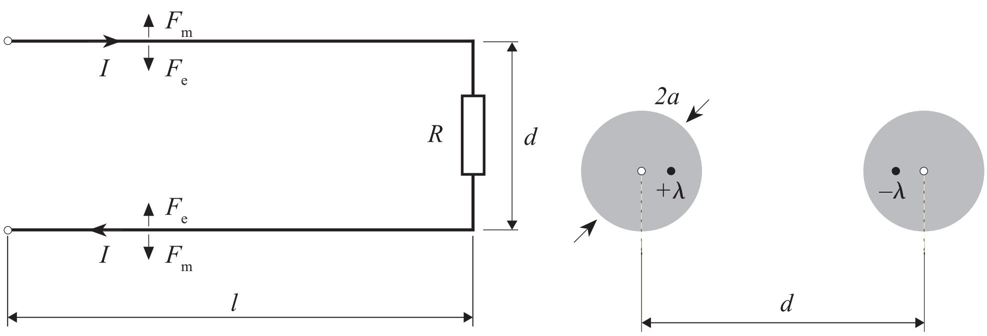
Slika 1
Magnetska i električna sila između vodiča spojenih u zasebne strujne krugove
Figure 1
Magnetic and electric forces between conductors connected into separate circuits



Međutim, kako je u praksi gotovo nemoguće postići jednakost struja, analizira se odnos magnetske i električne sile kod dva paralelna ravna vodiča priključena na napon U, čije je spojište zaključeno otporom R (slika 2a).

However, as it is virtually impossible in practice to achieve equal currents, we shall analyse the ratio between the magnetic and the electric force with two parallel straight conductors connected to voltage U, the junction of which is terminated by impedance R (Figure 2a).

Slika 2
Geometrija vodiča i sile između vodiča protjecanih jednakom strujom
Figure 2
Geometry of conductors and forces between conductors in which equal current is maintained



a) Sile između vodiča protjecanih jednakom strujom / Forces between conductors in which equal current is maintained

b) Geometrija vodiča / Geometry of conductors

Vodiči duljine l kružnog su presjeka, polumjera a, razmaknuti na udaljenost d (slika 2). Električki je otpor žice:

The conductors of length l have a circular cross-section, radius a, spaced at a distance d (Figure 2). The electrical resistance of the wire:

$$R_V = \rho \cdot \frac{2l+d}{a^2\pi}, \tag{1}$$

pa je struja kroz njih:

so the current through them is:

$$I = \frac{U}{R+R_V}. \tag{2}$$

Pretpostavlja se da je struja jednoliko raspoređena po presjeku vodiča. U tom se slučaju može pokazati da je magnetska sila po metru duljine između strujnih vodiča:

It is assumed that current is evenly distributed on the conductor's cross-section. In that case it can be shown that the magnetic force by metre of length between the current conductors is:

$$F_m' = \mu_0 \cdot \frac{I^2}{2\pi d} \quad , \tag{3}$$

gdje je μ_0 permeabilnosti vakuuma, a njena vrijednost od $4\pi\cdot10^{-7}$ upravo je određena definicijom ampera. Budući da je otpor žice relativno malen, zanemaruje se smanjenje potencijala duž žice i smatra da je statički naboj duž žice jednoliko raspoređen. Taj statički linijski naboj može se prikazati pomoću odslikanog naboja [3] i [4], kako je to prikazano na slici 2b i može se izračunati iz poznate relacije [5] za napon:

where μ_0 is permeability-of-vacuum, and its value of $4\pi\cdot10^{-7}$ is determined in the ampere definition. Since the wire resistance is relatively small, the potential reduction along the wire is ignored and the static charge along the wire is considered evenly distributed. This static line charge can be shown by means of the charge imaging [3] and [4], as in Figure 2b, and can be calculated from the known relation [5] for voltage:

$$U = \frac{\lambda}{\pi\varepsilon_0} \ln\left[\frac{d}{2a} + \sqrt{\left(\frac{d}{2a}\right)^2 - 1}\right], \tag{4}$$

gdje je ε_0 dielektričnost vakuuma. Električna sila između linijskih vodiča po metru duljine je:

where ε_0 is vacuum dielectricity. The electric force between line conductors by metre of length is:

$$F_e' = \lambda \cdot E, \tag{5}$$

gdje je:

where:

$$E = \frac{\lambda}{2\pi\varepsilon_0\sqrt{d^2 - (2a)^2}} \tag{6}$$

jakost električnog polja jednog linijskog naboja na mjestu suprotnog naboja. Pomoću izraza (4) računa se naboj, te se nakon uvrštenja u jednadžbe (5) i (6) dobije za električnu silu:

is the strength of the electric field of one line charge at the place of opposite charge. Charge is calculated by means of expression (4), and after substitution in equations (5) and (6) the following is obtained for the electric force:

$$F_e' = \frac{U^2\pi\varepsilon_0}{2\cdot\sqrt{d^2 - (2a)^2}\cdot \ln^2\left[\frac{d}{2a} + \sqrt{\left(\frac{d}{2a}\right)^2 - 1}\right]}. \tag{7}$$

Električne su sile privlačne, a magnetske odbojne (slika 2a). Omjer magnetske i električne sile je:

Electric forces are attractive, magnetic forces are repulsive (Figure 2a). The magnetic-electric force ratio is:

$$\frac{F_m'}{F_e'}=\frac{\mu_0}{\varepsilon_0}\sqrt{1-\left(\frac{2a}{d}\right)^2}\left(\frac{a^2\ln\left[\frac{d}{2a}+\sqrt{\left(\frac{d}{2a}\right)^2-1}\right]}{a^2\pi R+\rho(2l+d)}\right)^2 . \tag{8}$$

Analizira se odnos sila za bakrene vodiče (ρ = 0,0175·10^{-6} Ωm) duljine l = 10 m, polumjera presjeka a = 1 mm, razmaknute na udaljenost d = 1 m. Prema (8), sile među vodičima su jednake kada zaključni otpor na kraju voda iznosi R_0 = 829 Ω. Kada je $R > R_0$ postaje $F_m < F_e$, pa je rezultirajuća sila privlačna, dok je u slučaju $R < R_0$ veća magnetska sila ($F_m > F_e$), pa je rezultirajuća sila odbojna. U definiciji ampera očito je potrebno da R bude zanemariv, odnosno da vod na kraju bude kratko spojen.

The ratio of forces is analysed for copper conductors (ρ = 0,0175·10^{-6} Ωm) length l = 10 m, cross-section radius a = 1 mm, spaced at distance d = 1 m. According to (8), the forces between conductors are equal when the termination impedance at the end of the line is R_0 = 829 Ω. If $R > R_0$, then $F_m < F_e$, and the resulting force is attractive, whereas if $R < R_0$, then $F_m > F_e$, and the resulting force is repulsive. Obviously, in the definition of ampere it is necessary that R is negligible, in other words, that the line at the end is short-circuited.

3 ODNOS SILA PRI KRATKOSPOJENOM VODU

Omjer sila (8) ne ovisi samo o vrijednosti zaključnog otpora, već i o izmjerama voda (a, d i l). U slučaju kratkog spoja na kraju voda (R = 0 Ω), električna sila duž voda nije stalna, već linearno opada prema njegovom kraju. Zbog jednostavnosti proračuna uzima se da je ta sila konstantna duž voda. U tom slučaju omjer sila kratkospojenog voda iz prethodnog numeričkog primjera iznosi:

3 RATIO OF FORCES IN A SHORT-CIRCUIT LINE

The ratio of forces (8) depends not only on the value of termination impedance, but also on the line's measures (a, d and l). In case of a short circuit at the end of the line (R = 0 Ω), the electric force along the line is not constant, but is linearly falling towards the line's end. For the sake of simplicity we shall assume that the force is constant along the line. In that case, the ratio of forces of the short-circuit line referred to in the foregoing numerical example is:

$$\frac{F_m'}{F_e'}=50{,}15\cdot 10^6 . \tag{9}$$

Očito je da se u ovom slučaju može zanemariti električna sila. Zanimljivo je da u ovom slučaju omjer količine linijskog naboja (λ_i) i statičkog linijskog naboja λ iznosi:

It is obvious that in this case the electric force can be ignored. In this case, interesting enough, the quantity ratio of the line charge λ_i) and the static line charge λ is:

$$\frac{\lambda_i}{\lambda}=2{,}2\cdot 10^{15} . \tag{10}$$

Omjer magnetske i električne sile u ovom slučaju ipak nije takav da bi se mogla postići zadovoljavajuća točnost mjerene struje. Stoga se razmatra kako omjer sila utječe na izmjere voda. Relacija (8), gdje je R = 0 Ω, izražena je u sljedećem obliku:

The magnetic-electric force ratio in this case is still not such as could reach a satisfactory accuracy of measured current. We shall hence explore how the ratio of forces influences the measures of the line. Relation (8), where R = 0 Ω, will be expressed as follows:

$$\frac{F_m'}{F_e'}\bigg|_{x\neq 0} = \left(\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \frac{d^2}{\rho(2l+d)} \cdot g(x)\right)^2 , \quad (11)$$

gdje je:

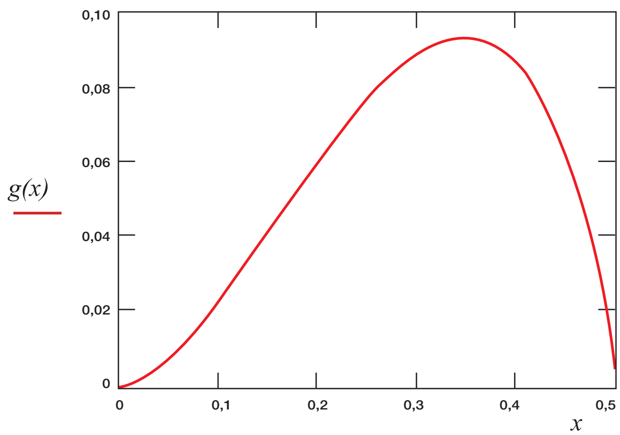
where:

$$g(x)\big|_{x\neq 0} = \sqrt[4]{1-(2x)^2} \cdot x^2 \ln \frac{1+\sqrt{1-(2x)^2}}{2x} , \quad (12)$$

pri čemu je varijabla:

where:

$$x = \frac{a}{d} . \quad (13)$$



Slika 3
Graf funkcije $g(x)$
Figure 3
Function graph $g(x)$

Normirana funkcija $g(x)$ prikazana je na slici 3. Njezin je maksimum dosegnut približno uz x = 0,35. U tom su slučaju vodiči vrlo blizu, pa struja sigurno neće biti jednoliko raspoređena po presjeku vodiča, što svakako unosi dodatnu mjernu nesigurnost. Za promatrani kratkospojeni vod duljine l = 10 m, polovica mu udaljenih na razmak d = 1 m, specifične električne otpornosti ρ = 0,0175·10^{-6} Ωm, omjer sila prema (11) iznosi:

The standardised function $g(x)$ is shown in Figure 3. Its maximum is reached approximately at x = 0,35. In that case the conductors are very close, so current will not be evenly distributed on the conductor's cross-section, which, of course, creates additional measurement uncertainty. For the observed short-circuit line, length l = 10 m, at a mutual distance of d = 1 m between its halves, each having specific resistance ρ = 0,0175·10^{-6} Ωm, the ratio of forces according to (11) is:

$$\frac{F_m'}{F_e'} = (1{,}025 \cdot 10^9 g(x))^2 . \quad (14)$$

Iz danih podataka slijedi da je moguće postići omjer magnetske i električne sile reda 10^{15}. Međutim, točnost struje je tada ograničena sa sedmom znamenkom, što, s obzirom na današnje zahtjeve u pogledu točnosti, nije zadovoljavajuće.

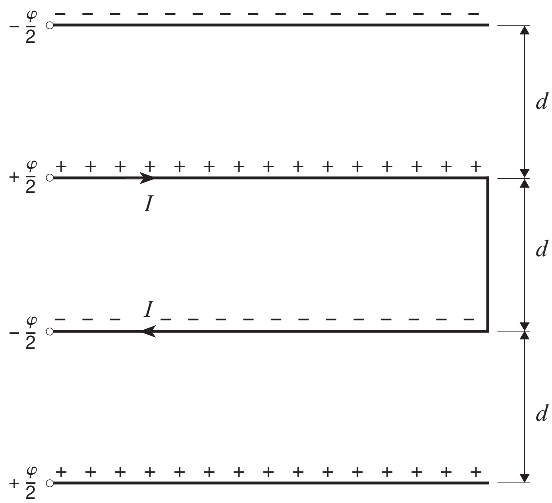
It follows from the given data that it is possible to achieve a magnetic-electric force ratio in the order of 10^{15}. However, the accuracy of current is then limited by the seventh digit, which, considering the present-day accuracy requirements, is not satisfactory.

4 NEUTRALIZACIJA ELEKTRIČNE SILE

Postoje načini da se električna sila neutralizira i postane praktički zanemariva. Na slici 4 je prikazana jedna načelna shema s pomoću koje se može provesti spomenuta neutralizacija. Paralelno osnovnom vodu kroz kojeg teče struja povuku se paralelno dva dodatna vodiča duljine l, jednake duljini osnovnog voda i jednako odmaknuta na udaljenost d. Ti vodiči se priključe na napon polariteta prema slici 4, tako da neutraliziraju električne sile osnovnoga voda.

4 NEUTRALISATION OF THE ELECTRIC FORCE

There are ways to neutralise the electric force and to make it practically negligible. Figure 4 shows a principle diagram with which the said neutralisation can be carried out. Parallel to the main line through which current flows two additional parallel-running lines are drawn, of length l equal to the length of the main line and equally spaced at distance d. These conductors are connected to polarity voltage according to Figure 4, so that they neutralise the electric forces of the main line.



Slika 4 Neutralizacija električne sile osnovnoga voda pomoću dodatnih paralelnih vodiča jednakih potencijala

Figure 4 Neutralisation of the electric force of the main line by means of additional parallel conductors of equal potentials

Na taj je način električna sila neutralizirana, pa preostaje samo magnetska sila između vodiča osnovnoga voda. Ovdje se, naravno, pretpostavlja da nema utjecaja stranih magnetskih polja. Točnost mjerenja bi sada ovisila samo o točnosti mjerenja magnetske sile. Ta točnost nije velika, pa je taj problem u cijelosti riješen gradnjom i primjenom strujnih vaga. Opis postupaka mjerenja strujnim vagama je izvan ove teme, pa se u to nećemo upuštati. Cilj je ovoga rada bio ukazati da tek površno pročitana i doslovno shvaćena definicija jedinice amper može postati nejasna i zbunjujuća.

In this way the electric force is neutralised, so only the magnetic force remains between the main line conductors. The absence of extraneous magnetic fields is, of course, assumed here. The accuracy of measurement would now depend only on the accuracy of magnetic force measurement. This accuracy is not high, so the problem is wholly solved by the construction and application of the current balances. Describing the method of measuring by means of the current balances is outside the scope of the present topic. The aim of this work is to warn that the definition of unit ampere, if superficially read and literally understood, may become vague and confusing.

5 ZAKLJUČAK

Ukoliko je električna sila voda neutralizirana, kao što je to slučaj pri mjerenjima sa strujnim vagama, tada se njezin utjecaj ne mora razmatrati. Kako će do velike revizije definicija osnovnih jedinica SI sustava kilogram i amper proći nesumnjivo još dosta vremena, smatramo da bi u svrhu boljeg razumijevanja postojeće definicije ampera, uvijek pri njenom navođenju trebalo napomenuti da ona nije izravno ostvariva, tj. da je pri praktičnom ostvarenju ampera u laboratoriju njegova definicija samo onoliko točna koliko je kvalitetno vod **neutraliziran**, kao što je to objašnjeno u točki 4. ovoga rada. Tako sročena definicija neće biti zbunjujuća našim budućim najkvalitetnijim studentima elektrotehnike.

5 CONCLUSION

If the electric force of a line is neutralised, as is the case with measurement by means of the current balances, then its effect need not be considered. Since a major revision of the definitions of the base SI units kilogram and ampere will certainly take quite a lot of time, we feel that in the interest of better understanding of the existing definition of ampere it should be noted in every reference to it that it cannot be directly realized, that in the practical realization of ampere in laboratory the definition of ampere is accurate only to a degree in which the line is **neutralised**, as explained in section 4 of this work. A definition thus presented will not be confusing to our best future students of electrical engineering.

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