SIXTH INTERNATIONAL SYMPOSIUM NIKOLA TESLA
October 18 – 20, 2006, Belgrade, SASA, Serbia

Nikola Tesla and Future of Electric Power Engineering

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***Abstract* –If an electric engineer* had studied classical electrotechnics during three semesters and works in the field of high-power electric networks, it is rather difficult for him to accept, that an alternative electrotechnics exists, which is characterized by the following features:A closed circuit containing two conductors between the generator and the load is not necessary to obtain an electric current flow.**

The current can flow through a single-wire circuit, like the water flows through a pipe from the upper basin to the lower one, or like the heat flows from a hot end of a metal bar to its cold end. (W. Thomson was first to point to the analogy between thermal conduction and electrostatics, while J. Maxwell was first to show the analogy between hydrodynamics and electrodynamics).

In a coil containing a single-layer wire winding, the phase velocity of the electromagnetic wave along the coil axes can be hundreds times lower, than in an overhead transmission line (or than the light speed in the free space).

The current varies along the line length, in different winds of a coil, or in different sections of a single-conductor line, it can have any local value, including zero. Furthermore, the current in different segments of a single-wire circuit can flow in opposite directions.

***Keywords* – Nikola Tesla, high-power electric networks, Tesla's coil**

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I. INTRODUCTION

However, such exotic behavior of the current (from the viewpoint of a classical electric engineer) does not seem strange to a radio engineer, because a beam antenna and a single-conductor waveguide are classical examples of single-conductor lines for him [1–3]. Standing waves and traveling waves of the current (and voltage) exist in such lines, and the circuit is closed by displacement currents in the space surrounding the single-conductor line. J. Maxwell wrote: "Extraordinary difficulty of coordinating the electromagnetism laws with the existence of unclosed electric currents is one of the reasons (among many other), why we must admit the existence of currents created by displacement variation". At a high frequency, the single-layer electric coil is transformed from a classical induction coil (in different application conditions) to a slow-wave structure or electromagnetic-wave delay line, to a helical waveguide, helical antenna or electric resonator with distributed parameters, which can not be determined using the classical electric circuit theory.

All the considered phenomena in a single-conductor line and in a spiral coils exist also at frequencies of 1 to 100 kHz, and they can be used for electric power transmission. Furthermore, the specified frequency range is most suitable for electric power transmission along a single-conductor waveguide in connection with limitations imposed by the radiation loss caused by the antenna effect. Unfortunately, the radio engineers have little interest in this frequency range, while the electric engineers are insufficiently prepared for working at the interface of electrotechnics and radiotechnics.

The electric power transmission along a single-conductor line at a higher frequency has been first proposed and realized by N. Tesla more than 100 years ago [4]. N. Tesla considered a resonant single-conductor system for electric power transmission as an alternative to a dc power transmission system proposed by T. Edison. The competition between dc and ac power transmission systems continues at present, however it takes place in the context of classical single-phase (double-wire) and three-phase (triple-wire) closed transmission lines.

We have shown experimentally, that a single-conductor line with a high-frequency resonant Tesla transformer at the line end can transmit electric power at any frequency, including zero frequency (i.e. using rectified current). The single-conductor resonant systems (see Fig.1, 2) offer possibilities for designing super-long cable lines and replacing (in future) the existing overhead lines with cable single-conductor lines [5]. In this way one of major electrification problems: increasing the reliability of electric power supply will be solved.

The open-ended line shown in Fig. 1, whose length is $l = (2n + 1)\,\lambda/4$, $n = 0, 1, 2, 3, \ldots$, has a current loop and a voltage node at the generator terminals; in case of $l = n\,\lambda/2$, it is a voltage loop and a current node. In both cases the line is equivalent to a resonant oscillatory circuit.

The standing waves in the open-ended single-conductor line (see Fig. 3) arise as a result of superposing the incident and the reflected waves having equal amplitudes. The voltage and current phase values demonstrate no displacement along the line, while the phase shift between the current and the voltage is equal to 90°. The line cross-sections with voltage loops contain current nodes, while voltage nodes correspond to current loops. The mean power delivered by the generator into the open-ended single-conductor lossless line (or into a line, loaded with a capacitor) is equal to zero [2].

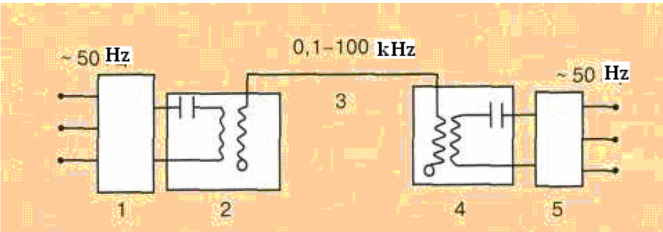

Fig. 1. Resonant system for electric power transmission *1*-converter; *2*, *4* – resonant high-frequency Tesla transformers; *3* – single-conductor high-voltage line connecting the transformers; *5* – inverter

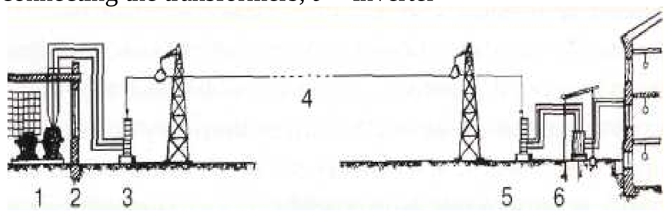

Fig. 2. Single-conductor resonant power transmission system
1 – electric generator, 50 Hz (1 to 100 kHz); *2* – frequency converter 50 Hz / 1 to 100 kHz (absent, if the generator frequency is 1 to 100 kHz); *3* – high-frequency step-up transformer 0.4 kV / 10 to 500 kV; *4* – single-conductor line 10 to 500 kV; *5* – high-frequency step-down transformer 10 to 500 kV / 0.4 kV; *6* – inverter 1 to 100 kHz / 50 Hz

If the line operates in the standing-wave regime, its input impedance is reactive. If the line is lossy, a certain traveling wave from the generator compensates for the loss. If traveling and standing waves are present in the line, its input impedance contains both reactive and active components.

The single-conductor resonant line, open at the load end (or loaded with a capacitor) is shown in Fig. 4,*a*; the current and voltage distribution for the open-ended line is plotted in Fig. 4,*b* [2, 6].

$n = 0$; $f = 5$ kHz; $\lambda = 60$ km; $l = \lambda/4 = 15$ km

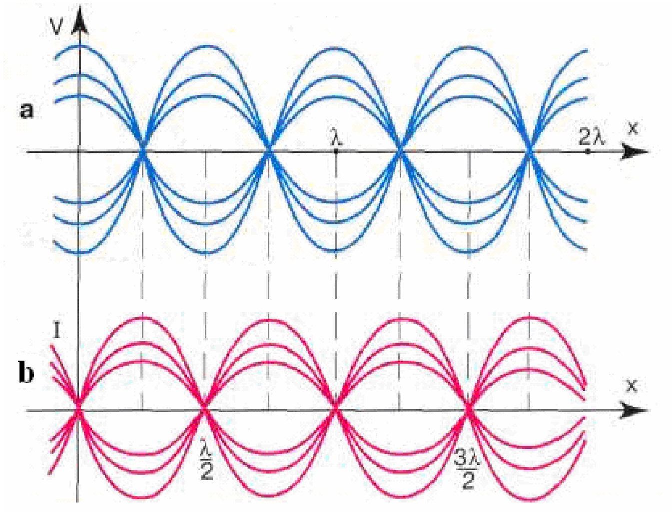

Fig. 3. Standing waves in an open-ended line at various time points
a – voltage; *b* – current

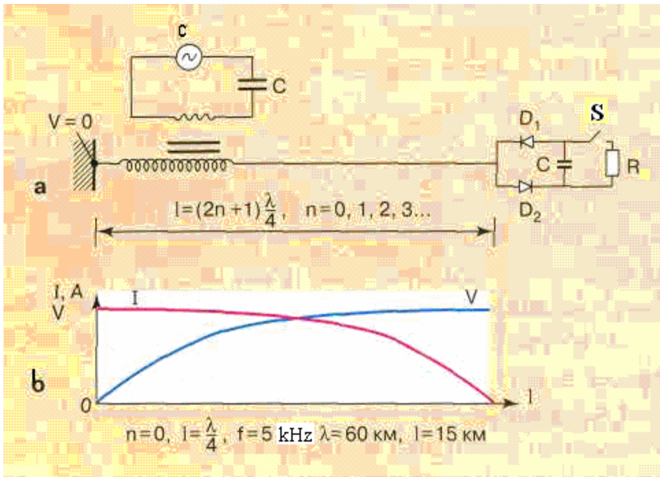

Fig.4. Circuit representation for a single-conductor resonant line, open at the load end or loaded with a capacitor (*a*); current and voltage distribution (*b*)

G – generator; C_0 – capacitance of the resonant circuit; D_1 and D_2 – diode unit;
C – load capacitance; *S* – electronic switch; *R* – load resistance

$n = 1$; $f = 10$ kHz; $\lambda = 30$ km; $l = \lambda/2 = 15$ km

The current and voltage distribution in a single-conductor line shorted to the ground at both ends is shown in Fig.5 [5]. The classical electric engineer (mentioned at the beginning of this section) would say, looking at Fig.5,*a*,*b*, that it is a closed double-conductor transmission line using the ground as the second conductor, with the conductance current in the closed circuit. The radio engineer would give a correct explanation: it is a conventional waveguide characterized by 90° phase shift between the current and the voltage, fastened to grounded metal supports, which are connected to the line at the voltage node points. The line grounding at the voltage node points does not change the waveguide parameters and does not effect the transmitted power value.

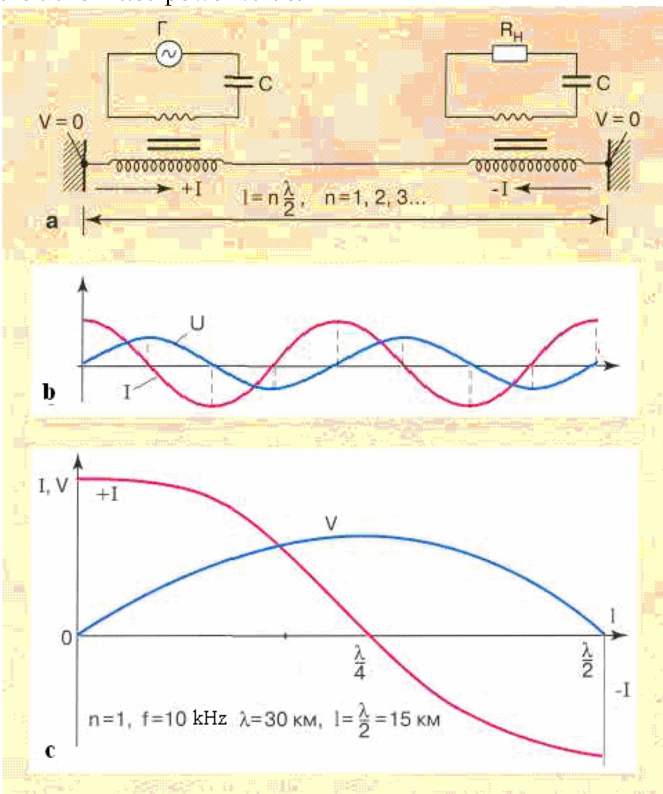

Fig.5. Current and voltage distribution in a single-conductor line shorted to the ground at both ends

a – circuit representation (*G* – high-frequency generator, R_l-load resistance, *C* – capacitance of the resonant circuit);
b – current and voltage standing wave distribution along a single-conductor line;
c – current and voltage distribution in a half-wave single-conductor line

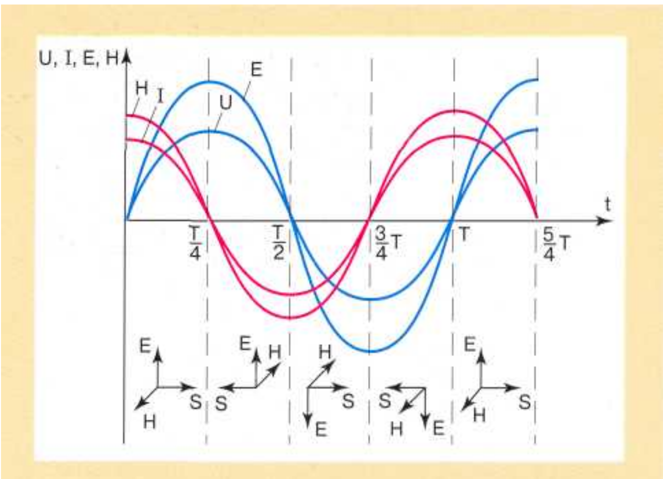

Fig.6. Direction of the Poynting vector $\bar{S}$ along the single-conductor line in the standing-wave regime *I*, *H* – waves of the current and the magnetic field strength; *V*, *E* – waves of the voltage and the electric field strength

When the line operates in the standing-wave regime, the direction of the Poynting vector $\bar{S}$ is inverted every quarter of the time period: it is directed from the generator to the load or back (see Fig.6). This phenomenon is explained in the following way. The phase shift between the voltage and the current in the line (and consequently between the values of the electric and magnetic field strength) is equal to 90°; as a result, the direction of one of the vectors: $\bar{E}$ or $\bar{H}$ is inverted every quarter of the period. This consideration confirms, that the generator spends no energy to produce standing waves in the line [2].

For the electric engineer, the stationary or standing waves shown in Fig.6 illustrate a phenomenon, which has no real physical basis, because the length of transmission lines does not usually exceed 1000 km, while the current and voltage wavelength at a frequency of 50 Hz equals to 6000 km. A half-wave line (see Fig.5,*c*), 1000 km in length, can be obtained at a frequency of 150 Hz, and in this case even a conventional single-phase or three-phase line will transmit considerably more power, than at a frequency of 50 Hz. However conventional transmission lines reveal resonant properties only in an emergency condition (for example, in case of line break at the consumer). In order to understand N. Tesla works and develop his ideas on resonant electrotechnics, the classical course for electric engineers shall be supplemented by a special course containing information on high-frequency resonant lines, principles of single-conductor and helical waveguides, methods for designing electric circuits with distributed components, main scientific and practical results in the field of resonant electric technologies and prospects for their application.

Several application fields for resonant single-conductor electric systems are considered below.

A 20-kW, 1-kHz resonant transmission line based on a single-conductor cable, 1.2 km in length, has been successfully developed and tested at the VIESH (Fig. 7) [6].

Fig.7. 20 kW, 1 kHZ resonant electric power transmission system

Application of various conducting mediums in the resonant systems for transmitting electric power has been illustrated using an electric boat model, which receives electric power from a water basin with alive fish (Fig 8, 9).

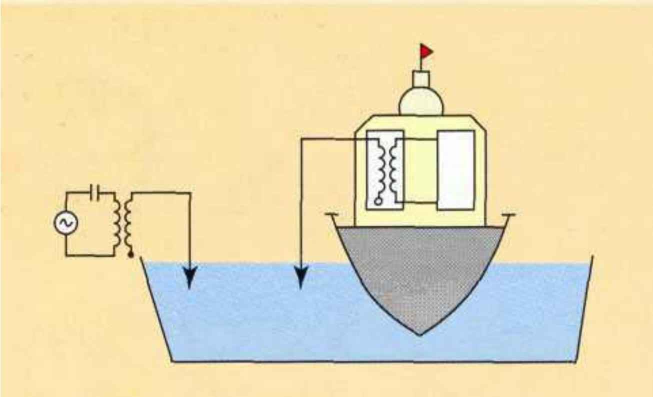

Fig. 8. Electric power transmission using water as conducting media

Fig. 9. Electric boat model receiving electric power trough the water

A wind power station, a solar battery, etc can be used as a source of electric power in a resonant electric system.

Another global application for resonant single-conductor electric power transmission systems consists in the opportunity of developing noncontact high-frequency electric transport. The well-known noncontact method for transmitting electric power to a vehicle through an air-core transformer (using the electromagnetic induction method and conventional single-phase power transmission lines) has basic limitations on the transmitted power level, the transmission efficiency and the line length; therefore, it is not used at present [7].

An experimental model of a small electric vehicle developed at the VIESH receives electric power from an isolated single-conductor cable line laid inside the roadway covering (see Fig.10). The works on increasing the noncontact drive power and developing a commercial project of a resonant electric transport system are being carried out now. It is possible to imagine in future a big green city, full of flowers, without exhaust gases and smog. A cable transmission line will be laid in this city under each driving row along main roads, and each vehicle has an electric motor and a noncontact trolley in addition to the combustion engine. The traffic along big highways between cities can be organized in the same way, including possible use of automated vehicles controlled by robots and computers.

Use of an electric noncontact drive in the agricultural energetics opens the prospects for substantial fuel saving and developing pilotless automatic robots controlled by computers with satellite navigation, intended for tillage, cultivation and harvesting agricultural products. In this case the agricultural plants will turn to field factories organized according to the principles of automated industrial enterprises. Thus, three present-day electrification problems can be solved: energy saving, reducing harmful gas ejection and automation of agricultural production process.

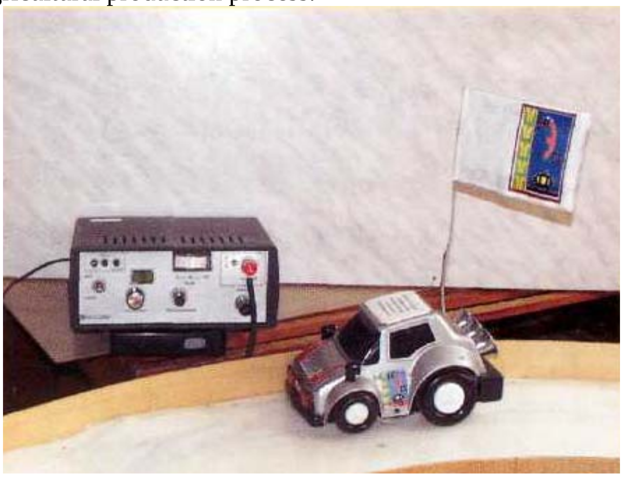

Fig. 10. Contactless high frequency electric vehicle

The third application field for resonant single-conductor systems are plasma medical and technological facilities. They differ from conventional plasmatrons in having not two, but a single electrode, which is the beginning of a resonant single-conductor line, while the capacitance of any body or treated substance is used as a load. A new resonant coagulator developed at the VIESH (see Fig.11) is used in medicine, in veterinary technique and in cosmetology [6]. Technological single-electrode plasmatrons can have pulsed power up to 10^{10} W and continuous power up to 20 MW. They can be used to eliminate weeds (instead of pesticides), to produce liquid biofuel from organic raw material, to manufacture and purify solar-grade silicon, to generate plasma in physical experiments (for example, producing artificial ball lightning [8].

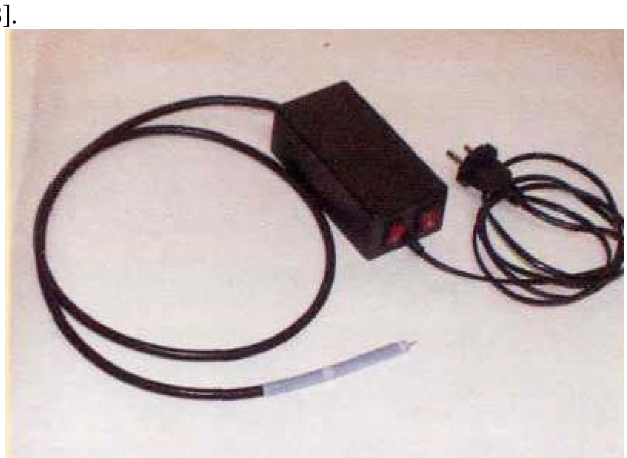

Fig.11. Resonant cold-plasma coagulator developed by Cand. Sci. (Tech.) Veryutin V.I. (VIESH)

The fourth application field for resonant systems is creating global and local information communicating systems using single-conductor lines. Many works by N. Tesla are devoted to this application. The first devices transmitting information signals has been developed by N. Tesla in 1899, they were patented in 1901. In 1943, the Supreme Court of the USA has recognized N. Tesla priority disputed by R. Marconi in long-distant transmission of electric signals.

Each single-conductor line has several resonant waves. Therefore, the single-conductor line (as well as a fiber-optic line) may be used to transmit simultaneous different information to several users. A specialized line screening technique allows to reduce the loss in signal amplitude and quality, when it is transmitted over a long distance. N. Tesla has proposed original methods for encoding the information and protecting it against unauthorized access. The information communicating systems and power transmission systems based on modern technologies are now key factors for the social development of the country and progress in the agricultural production.

N. Tesla was an ingenious scientist, who had foreseen the development of the electrotechnics and energetics for hundreds of years. He has produced a voltage of 100 million volts using simple facilities; he has transmitted electric power over tens kilometers, using the ground as the conducting medium; he has tested a boat controlled through the water medium; he has invented the asynchronous electromotor, the multiple-phase current and has made many other inventions. N. Tesla was a brilliant designer of mechanical systems. Magnificent drawings of different mechanisms designed by N. Tesla are stored in Tesla museum in Belgrade. Some of his non-electric inventions are of interest till now: a combustion engine without a piston and a crankshaft, steam and hydraulic turbines without blades, and a mechanical analog for the electric diode (device allowing to a gas or fluid stream to flow in one direction only). In this valveless device, the hydraulic resistance values in the direct and reverse direction differ by factor of 300. Now we can fully repeat and develop Tesla resonant techniques in the field of electric power transmission using single-conductor lines and conducting mediums.

There is little information on N. Tesla works in the field of wireless power transmission methods. His last invention in this field "Device for electric power transmission" has been written in 1902, revised in 1907 and patented in 1914. At a session of the American Institute of Electric Engineers on May 18, 1917, N. Tesla received a reward named after T. Edison. His speech at the session contained the following statement:

"As to power transmission through the space, it is a project, which I consider absolutely successful for a long time. Years ago I could transmit power without wires to any distance without limitation, which was imposed by the physical dimensions of the Earth. In my system, the distance value is of no importance. The transmission efficiency can reach 96 or 97 percents, and there are practically no loss, except for the component, which is inevitable for the device operation. If there is no receiver, there is no power consumption anywhere...

When there is no receivers, the station consumes only a few horsepowers, which is necessary to maintain the electromagnetic oscillations; it is idling, like the Edison station, when the lamps and the motors are switched off...".

The high transmission efficiency may be easily explained, considering the standing waves in the conducting channel (see Fig.6).The journal "Time" wrote on July 23, 1934: "Last week doctor Tesla announced a combination of four inventions, which would make the war absurd. The essence of his idea is connected with deadly rays: a concentrated beam of submicron particles moving with a speed, close to the light speed. According to Tesla, the beam, will defeat the army during flight, causing airplane squadrons to fall down at a distance of 250 miles (400 km). The inventor will launch the rays by using the following: device for reducing the particle delay in the atmosphere to zero;method for producing high potential;procedure for amplifying this potential up to 50 million volts;producing tremendous acting electric force".

II. Conclusion

N. Tesla died on January 7, 1943 in hotel "New Yorker" in Manhattan, in the room 3327 on the 33-rd floor. Immediately after his death, his scientific works disappeared from the room; they were never found. A part of those materials contained an information on the techniques, which could be used for wireless power transmission. Methods for generating and amplifying high potential have been fully described by N. Tesla in [4]. Taking into account the present-day level of the scientific knowledge and progress in electrotechnics, N. Tesla works on resonant methods for electric power transmission give new opportunities for the development of electroenergetics, electric technologies, electric transport and communications.

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