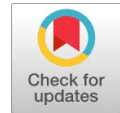# Electrical Energy Transmission Systems at Elevated Frequency

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Abstract: *The article presents information about the composition of the equipment of resonant power transmission systems. The resonant systems of electrical energy transmission by single-wire cable or overhead lines at elevated frequency include frequency conversion devices, power transmission lines, and devices for the reverse transformation of electrical energy to the voltage required by the consumer. In contrast to traditional systems of electrical power transmission, resonant systems are being operated on an elevated frequency of 5-15 kHz, a power transmission line voltage is 1-10 kV. In this case resonant transformers are used. The frequency of the power transmission system is set by the resonant transmitting transformer; the receiving transformer is a wideband step-down one.The main components of the resonant transmitting transformer are a power resonant circuit and a step-up/step-down winding. The maximum output power of the converter depends on the voltage supplied to the circuit, circuit voltage, circuit capacitance, frequency, and other parameters. One can change the transmitted power by changing the transmission frequency, for example, for lighting systems.Due to the fact that resonant power transmission systems operating at elevated frequency are less demanding on the grounding quality, they are more efficient compared to single wire ground return line operating at a constant current and an alternating current of commercial frequency.*

Index Terms: *resonant single-wire system, electrical power transmission, frequency converter, resonant circuit.*

I. INTRODUCTION

The resonant systems of electrical energy transmission by single-wire cable or overhead lines at elevated frequency include frequency conversion devices, power transmission lines, and devices for the reverse transformation of electrical energy to the voltage required by the consumer. In contrast to traditional systems of electrical power transmission, resonant systems are being operated on an elevated frequency of 5-15 kHz, a power transmission line voltage is 1-10 kV. In this case resonant transformers are used. The frequency of the power transmission system is set by the resonant transmitting transformer; the receiving transformer is a wideband step-down one. At that, grounding is used as the second wire, or the transformer windings are connected to the capacitances C3 and C4, made of a conductive material and having a sufficient size to transmit electrical energy. In the case where there are dielectric layers of soil between the transmitting and receiving units, these capacitances can serve the plates of a single capacitor.

II. METHODS

A. Electrical diagram

The main components of the resonant transmitting transformer include a power resonant circuit *C2L1* (Fig. 1) and a step-up/step-down winding *L2* [1], [2]. The receiving transformers do not affect the resonant frequency of the power transmission system, therefore they may be connected to the power line in any quantity, the total power should not exceed the power of the transmitting voltage converter.
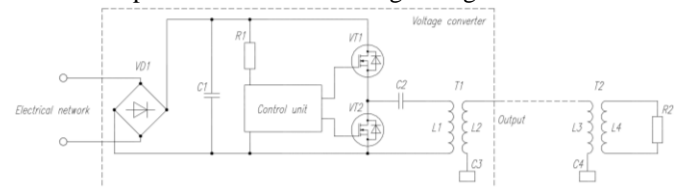

Fig. 1. Electrical diagram of the resonant power transmission system

The resonant converter consists of the control unit *CU*, power keys *K1, K2*, and a resonant transformer, which includes transformer capacitance *C2* and windings *L1* and *L2* (Fig. 1). The parameters of the *C2L1* determine the resonant frequency. The frequency is influenced also by the capacitance of a transmission line, which lowers the natural resonance frequency of the circuit *C2L1*.

The maximum output power of the resonant converter is determined by the voltage supplied to the circuit, circuit voltage, circuit capacitance, frequency, and other parameters. The maximum output power of the resonant circuit is calculated based on the loaded Q-factor formula [1], [3]:

$$P_{out} = \frac{U_{out}^{\,2}}{R} = R(U_{in}\omega C)^2 / 1.69 = \left(\frac{U_{in}\sqrt{L/C}}{r + \frac{\left(\sqrt{L/C}\right)^2}{R}} \right)^2 / R, \; W,$$

where U_{out} is the circuit voltage, V; U_{in} is the input circuit voltage (output voltage of the frequency converter), V; R is the circuit load resistance, Ohm; C is the circuit capacitance, F; L is the primary winding inductance; r is the internal resistance of the circuit. The transmitted power can be changed by changing the frequency. These power transmission systems significantly reduce the capital costs of electrification of buildings and territories.

B. Algorithm

Electrical energy transmission in resonant systems occurs at elevated voltage and elevated frequency in the resonant mode. The elevated voltage allows reducing losses at energy transmission, while the elevated frequency allows reducing the weight and dimensions of electric equipment.

A transmission transducer with the anti-resonant circuit is installed at the inlet of the power line, which allows pumping electrical energy into the power line due to the reactive power of the resonant circuit. Automation stabilizes the voltage in the power line regardless of its frequency, so that the voltage is not changed because of the load. The end of the power line is equipped with the inverse converter with a broadband transformer, which transforms electrical energy, including harmonics, into the electrical energy of the secondary winding, to which the inverter is connected, with a standard output voltage of AC 220 or 380 V. With such a power transmission system, the voltage is converted first in the transmission transducer, and then in the inverse converter with the total loss of electrical energy of about 10-12%. While comparing single-wire power transmission systems, the high-frequency resonant single-wire system has the maximum efficiency among single-wire power lines of all types. Single wire ground return systems of 50-60 Hz (low-frequency power line, > 300 kVA, >80 kV, >200 km) [4], used for many decades, are effective only for good conductive soils and at high-quality grounding (for example extra deepening of dry soils in Australia). In single-wire DC power transmission systems (constant current line), the grounding requirements are even higher: cathode should be made of copper, while anode must be made of graphite or titanium. The use of such technologies still does not allow obtaining high efficiency of power transmission through low-conductive soil layers due to the low frequency of power transmission. Thus it is known, that with a rise in frequency, the resistance of dielectrics falls down.
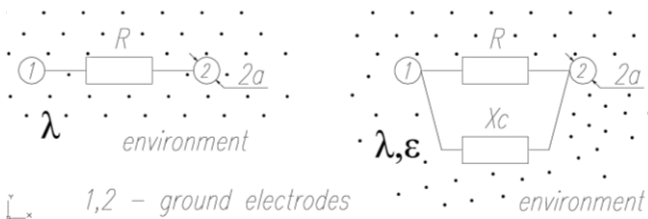

Fig. 2. The electrical resistance of the ground for low-frequency and high-frequency currents

The classical formula [5] to determine the medium resistance between two sparking balls of radius a, immersed in a boundless homogeneous medium with a specific conductance λ (Fig. 2), shows that the resistance is independent of the distance between the electrodes even for direct current.

$$R = \frac{U}{i} = \frac{1}{2\pi a \lambda},$$

where a is the radius of the spark balls.

In reality, this is impossible because of the presence in the earth of powerful dielectric layers with $\lambda=0$, such as gravel, sand, granite, just dry soil, etc. That is why for low-frequency power and constant current systems one faces problems associated with soil specific conductance λ and grounding quality. In resonant power lines, resistance ceases to depend on the λ and the grounding quality with increasing frequency.

Both active and reactive resistances operate at elevated frequencies because the actual medium has non-zero active and reactive conductivities. It becomes possible to use in addition to the standard deep grounding, also surface areal grounding, for example, of alpine lakes. This is a possible solution to energy transmission in rock massifs.

The X-reactance between the two ground electrodes of the power transmission line is determined as:

$$Xc = \frac{1}{4\pi^2 a f \varepsilon \varepsilon_0},$$

where f is the frequency, ε is the dielectric permittivity of the soil, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ is the electric constant.

The resulting resistance between the two grounding electrodes of the power transmission line is

$$X = \left(\frac{1}{R} + \frac{1}{Xc}\right)^{-1} = \frac{RXc}{R + Xc}.$$

Due to the fact that at elevated frequency bias currents have a significant value, this allows transmitting energy by bias currents. The principle of work is like in an electric capacitor: there are two plates; one of them is a conductive soil layer on the energy transmission side, the second plate is a conductive layer on the receiver side. Between the plates there is a dielectric component – a nonconductive soil layer. Therefore, transmission at elevated frequency may be carried out through groundings with a lower quality [6],[7],[8]. The reduction of grounding losses can be achieved by increasing the operating frequency.

III. RESULTS AND DISCUSSION

In 2012, All-Russian Institute of Electrification of Agriculture together with All-Russian Research Institute of Railway Transport JSC with the participation of representatives of the Department of Technical Policy of Russian Railways JSC (RZHD) and the Main Department of Electrification and Power Supply of the Central Directorate of infrastructure of Russian Railways JSC and Promavtomatika LLC conducted research and testing of resonant single-wire transmission system of electrical energy of 3 kW, which (Fig. 2) consisted of (from left to right): device controlling energy use parameters, transmitting voltage converter (TC), receiving (inverse) voltage converter (RC), additional load unit (voltage limiter), and inverter with standard output voltage of 220 V, 50 Hz.

Fig. 3. A set of equipment for electrical energy transmission in resonant mode

The developed equipment has a resonant frequency of 7-9 kHz and an output voltage of 980 V in the transmission line. The set of equipment is transmitting electrical energy with a power of up to 3000 W at a distance of up to 2000 m.

Additional load unit (Fig. 3) removes some energy from the power transmission line when operating the system without load. In case when load appears, this unit automatically shuts off.

Tests of the set of equipment for electrical energy transmission by the single-wire system in a resonant mode were carried out by the staff of the Institute of Railway Transport at the Experimental Ring Shcherbinka test site on June 29, 2012.

Table I. Measurement results of the main performance specifications of the resonant power transmission system at idle and at maximum load using an overhead power transmission line

Load option	Voltage of TC(out)/RC (in), V	Consumed power of TC, W	The output voltage of RC, V	Output current of RC, A	Frequency, kHz	The inverter output voltage, V	Power output, W
XX with limiter	950	488	-	-	6.88	-	-
6 tens 500 W each + 2 lights 100 W each	950/890	3,100	185	14	7.2	219	2,590

The conducted tests have shown that the total efficiency when transmitting power of 2,590 W through a single-wire line was 83%.

Table II. The effect of the grounding quality of the receiving transducer on the maximum transmitted power

Grounding option	The output voltage of the transmitting unit, V	Consumed power of TC, W	The input voltage of the receiving unit, V	The output voltage of RC, V	Output current of RC, A	Frequency, kHz	Power output, W
Standard grounding, 4 Ohm	950	3,100	890	185	14	7,2	2,590
Buried wire 2-4 m long	940	2,990	830	176	11.4	7.14	2,007
Buried wire 0.2 m long	960	1,800	750	174	5.6	7.0	974
No grounding	920	290	50	15	0.62	7.0	9.4

From this experiment, it can be seen that even with minimum grounding of the receiving transducer, it is possible to transmit one kilowatt of electrical energy.

In the course of the experiment, the effect of the grounding quality of the receiving transducer on the maximum transmitted power was determined. From the conducted experiment, it was determined that even with minimum grounding of the receiving transducer, in the form of a wire 2-4 m long buried in the ground, the difference in the transmitted power was small, and even with grounding by means of a piece of wire 0.2 m long, it was possible to transmit one kilowatt of electrical energy.

IV. CONCLUSION

1. Single-wire power transmission systems operating at elevated frequencies are more efficient than single-wire ground return lines operating at direct current and alternating current of commercial frequency.

2. It is shown that electrical energy can be transmitted by a single wire using nonconducting media between the transmitting and receiving devices as grounding.

3. It is shown that electrical energy with power of 3,000 W can be transmitted by a single wire using individual grounding of the receiving transducer, at that, the maximum transmission distance can reach 5,000 m.

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