New technology of electric power transmission

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ABSTRACT: Low cost and low losses single-wire electric power system (SWEPS) was developed. The new technology of electric power transmission uses idle operation regime of the transmission line and reactive capacitive current for transmission of active electric power. Three different SWEPS were constructed and tested: 230 V, 10 kV and 100 kV each is of one kilowatt capacity. Resonance mode of oscillation with frequency from 3 to 30 kHz was used to provide the most efficient power transmission. Frequency converter and modified Tesla transformer are applied at the generator site to generate high frequency reactive capacitive current. Reversal Tesla transformer and standard rectifier and invertor were used at the user's end to convert the reactive high frequency electric power to standard 50–60 Hz electricity. It was experimentally proved that SWEPS has quasi-superconductive properties for reactive capacitive current flow along the line even at high operation temperature of the electric conductor. SWEPS has no resistance losses for following tested conductor materials of the line: copper, aluminum, steel, tungsten, carbon, water, damp soil. The result of theoretical calculation and experimental study shows that SWEPS can be applied both for the energy transmission from renewable powerful generation site to a large energy system and for transmission lines for connecting different parts of renewable energy system.

Keywords: energy system; electric power transmission; high frequency conductor

Implementation of renewable-based technologies for rural electrification would contribute to the social and economic growth of the rural communities and would serve sustainable progress of the remote regions.

The electric grid faces specific problems of non-efficient operations, including transmission losses and the high cost of grid extension in remote sparsely populated areas (STREBKOV 1994). For example off-shore wind turbines, micro-hydro or geothermal generators are often located far from the consumer and require costly installation of long distance transmission lines which usually have from 6% to 10% electric losses.

Hybrid system, with jointly operating small power generators of equal capacity, faces the problem of joint electromagnetic operation stability during renewable energy potential or electric load variation.

We have made computer simulation of solar power system, consisting of three or more solar power plants of equal capacity connected by superconducting electric transmission lines. One solar power plant is located in Spain, another solar plant is installed in Far East region of Russia, the third one is situated in Astrakhan region near Caspian Sea.

The computer simulation shows that this distributed Europe-Asia solar power system is generating electricity 24 hours per day 6 months a year and it does not require electric accumulator or back up generator during the night. In winter season solar electricity should be transmitted from Africa, India and Australia and for this United Solar Electric Power System new low cost and low losses electric power transmission technology should be applied.

The objective of this paper is to introduce the low cost and low losses single-wire electric power system (SWEPS) for electric grid instead of three phase network.

THREE PHASE NETWORK FOR ELECTRIC POWER TRANSMISSION

It is known that the total transmitted power over electric transmission line

$$S = \sqrt{P^2 + Q^2} \tag{1}$$

where: P and Q – active and reactive powers.

The important parameter of transmission line affecting the energy transmission capability is surplus reactive capacity, which is depending on the regime of energy transmission. When the line operates in the idle regime its surplus reactive capacity is equal to the capacity of electrical the field of the line (ALEXANDROV, SMOLOVIC 1999):

$$P = 0 \qquad S = Q = P_n \cdot l_\lambda \tag{2}$$

where: P_n – natural power which is equal to the surge impedance Z loading of the line.

$$Z = \sqrt{\frac{L_0}{C_0}} = vL_0 \tag{3}$$

L_0 and C_0 are the specific inductance and capacitance of the line.

l_λ – wavelength of the line, which is equal to the variation of wave phase during the wave propagation along line of length l

$$l_\lambda = \frac{\omega}{v} l = \beta l \qquad (4)$$

where: $\omega = 2\pi f$,
f – frequency of generator,
β – the phase variation coefficient of the electromagnetic wave,
v – the velocity of electromagnetic wave propagation.

No-load operation mode is dangerous for electric power transmission because of voltage rise due to electromagnetic wave oscillation. When the generator frequency is equal to the resonance frequency of the line the overvoltage has maximum value. The voltage coefficient of the line

$$K_V = \frac{|\dot{U}_{\max}|}{|\dot{E}|} = q \cdot |\dot{E}| \qquad (5)$$

where: $|\dot{E}|$ – a generator voltage and q is the quality factor of the line.

In natural (nominal) regime of active electrical power transmission the magnetic field of the line completely compensates the electric field of the line and surplus reactive line capacity is equal to zero. In this ideal case reactive current and reactive power are equal to zero.

The angle Θ between vectors of voltage at the beginning of the line $\dot{u}(o)$ and at the end of the line $\dot{u}(l)$ is equal to wave length of the line, $\Theta = \beta l$.

The voltage is stable along the line $|\dot{u}(o)| = |\dot{u}(l)|$.

The active current and the active power transmission are controlled by variation of angle Θ and voltage along the line.

When a transmitted power is decreased and varies the compensation of electric field is not complete, the voltage will become higher and for its limitation shunt reactors are used to compensate the surplus reactive capacity of the line.

The equivalent circuit of this line is similar to series connection of active resistance and inductive impedance and such line has no wave and resonance characteristics.

Flexible alternative current transmission systems with fast acting shunt reactors and series capacitate compensation control system allows providing the stable energy transmission over the line length 1,000–3,000 km. The transmitted power is limited by resistance losses and by electrical isolation of the air. The installation cost of the 10–35 kV aerial transmission line is 10,000–25,000 US$/km.

A three phase a.c. 1.2 MV, 10 GW, 1,000 km long extra-high-voltage power transmission line costs 1.31×10^6 US$/km, and the whole power transmission system including transformer's substations and other electrical equipment has the installation cost 5.1×10^6 US$/km (MOGILLIS 1991).

Very costly direct current transmission lines for longer distance (7,000 km) and higher transmission capability (up to 70 GW) are proposed.

The installation cost of 10 GW, 1,000 km, ± 600 kv bipolar d.c. transmission line is 5.8×10^6 US$/km, and designed wasted power is 443 MW (4.43%). In future direct current transmission will provide even higher capability using advanced superconducting technology. The general conclusion regarding widely applied power transmission systems is that reactive power should be completely limited and compensated in order to provide stability of power transmission, to avoid the dangerous overvoltage and to secure the oscillation damping.

NEW TECHNOLOGY FOR ELECTRIC POWER TRANSMISSION

In this paper we consider new technology for electrical power transmission using idle operation regime and wattless capacitive circulating power for transmission of active power to the user's end of the line. In the open-ended line the active current and the magnetic field of the line are equal to zero, while the electric field has maximum value and it is created by the reactive displacement current which is charging the capacitance of the line. The angle Θ between voltage vectors at the beginning and at the end of the line is equal to zero.

Practically because we use the open-circuit line we offer one-pole single-wire electric power system (SWEPS) instead of three-phase network (AVRAMENKO 1997, 1998).

The most important problems, which are to be solved:

1. How to provide the high density reactive capacitive current at the beginning point of the line;
2. How to convert the reactive capacitance current and reactive power to active power and heat at the user's end of the line.

Schematic circuit of SWEPS is shown in Fig.1. Because the traditional three phase 50–60 Hz generators and other a.c. electrical equipment are widely used we offer electrical devices (black boxes), which can be installed at the beginning, and at the end of transmission line and can provide electromagnetic compatibility of new technology with standard a.c. electricity. Frequency converter and modified Tesla transformer with ferrite corn were applied at the generator site to generate high voltage and high frequency reactive electromagnetic power. Reversal Tesla transformer and standard rectifier and inverter were used at the consumer's end of high voltage SWEPS to decrease the voltage and to convert the reactive high frequency electric power to standard three phase 50 Hz electric power.

For proper operation of SWEPS it is necessary to connect the neutral primary voltage terminal of reversal Tesla transformer to artificial natural capacitance like an insulated metallic sphere or the frame of equipment.

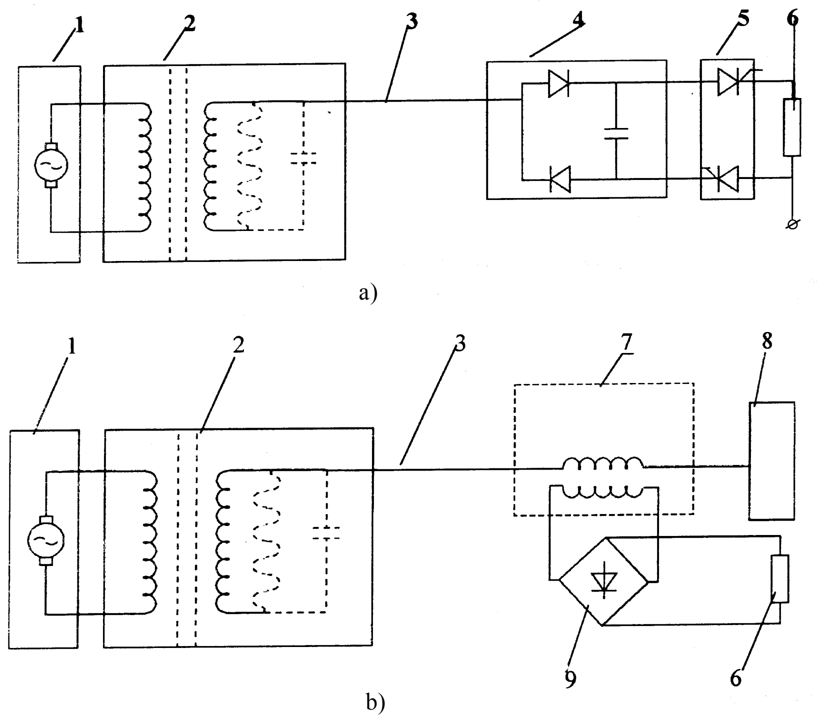

Fig. 1a. Low voltage single-wire line 10–1,000 V
1b. High voltage single-wire line 1–1,000 kV
1 – High frequency converter
2 – Step-up high frequency Tesla transformer
3 – Single-wire line 1–300 kHz
4 – Diode-capacitor block
5 – Thyristor electronic key
6 – Electric load
7 – Step-down Tesla transformer
8 – Electric capacitance
9 – Rectifier

A reactive capacitive current flows trough Tesla transformer and provide resonance overvoltage on its inductance impedance.

Another technique of conversion of capacitive reactive power to active power is application of diode-capacitor device which is usually used in d. c. voltage doubling circuit in low voltage SWEPS (Fig. 1b).

CALCULATION OF SWEPS PARAMETERS

In order to increase the transmitted power the operating frequency was significantly increased due to well-known equation for reactive power.

$Q = 2\pi f c U^2$

The quality factor, q at frequency 10 kHz is increased by 200 times comparing with 50 Hz power system. The upper value of frequency 100–300 kHz is limited by irradiation of electromagnetic power. Effective radiated power Pir of the unloaded line can be calculated using known formula for transmitter's antenna

$$Pir = 80\pi^2 I^2 \left(\frac{l}{\lambda}\right)^2 \qquad (6)$$

For I = 100 A, λ= 30,000 m, l = 100 m, f = 10 kHz, $Pir = 8 \times 10^{-3}$W

Consequently the radiated power is low at this frequency.

Let us consider a single-wire capacitive-inductive series resonant circuit without corona losses connected to the Tesla transformer without the magnetic shunt (Figs. 2, 3). As the line is open-ended the conduction current is equal to zero (Fig. 3). The Tesla transformer generates capacitive current, which is charging the capacitance of the line. For standard 50 Hz 500 kV line the capacitive current is 1.13 A/km, and reactive capacitive power is 0.98 MVAR/km. A single-wire overhead line capacitance is defined under the known formula:

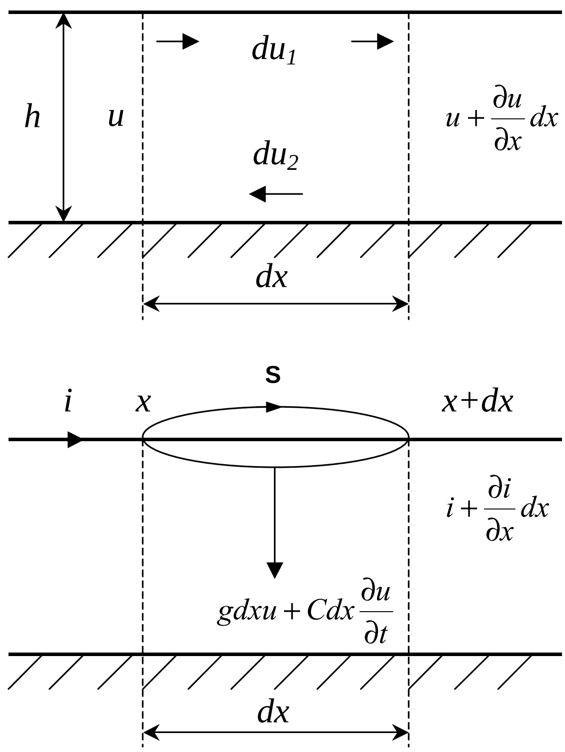

Fig. 2. Currents and voltage drops in single-wire line

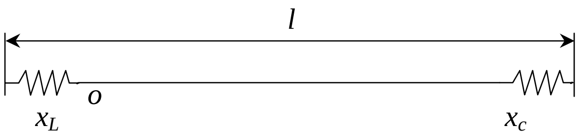

Fig. 3. Equivalent circuit of SWEPS
X_L – inductactive impedance of Tesla transformers and single-wire line
X_c – capacitance of the line and the load

$$C_o = \frac{l}{2\,ln\frac{4h}{d}} \qquad (7)$$

where: l – the length of the line,
d – diameter of a conductor,
h – distance between the earth and conductor.

For l = 1 km, d = 0.1 cm, h = 6 m, Co = 15,505 mμF.

The open line is grounded through leakage current and displacement current, which are distributed on all space, enclosing a conductor. The displacement current and voltage depends on time and on coordinate.

The equation of continuity for current

$$(-i) + (i + \frac{\partial i}{\partial x}dx) + (gdxu + Cdx\frac{\partial u}{\partial t}) = 0 \qquad (8)$$

where: $gdxu$ – leakage current,
g – conductance of air.

$Cdx\frac{\partial u}{\partial t}$ – displacement current.

The equation for voltages:

$$(-u + u + \frac{\partial u}{\partial x}dx) + Ldx\frac{\partial i}{\partial t} = 0 \qquad (9)$$

where: $Ldx\frac{\partial i}{\partial t}$

We obtain a set of equations for calculation of parameters of single-wire line.

$$-\frac{\partial u}{\partial x} = L\frac{\partial i}{\partial t}$$ – voltage drop across an inductive resistance.

$$-\frac{\partial i}{\partial x} = gu + C\frac{\partial u}{\partial t} \qquad (10)$$

These equations differ from known (RASEVICH 1976) the ohmic voltage drops across resistance being equal to zero and the specific parameters g, L and C having been considered for one conductor in relation to the ground but not for two-wire or three-wire lines.

The solutions of the equations for operating complex voltages and currents:

$$\dot{u}(o) = \dot{u}(l) \times ch\dot{\gamma}l$$
$$\dot{i}(o) = \frac{\dot{u}(l)}{z} \times sh\dot{\gamma}l \qquad (11)$$

u (o) and u (l) – voltage at the beginning and at the end of the line.

As the line is open-ended the current $i(l) = 0$
γ – coefficient of electromagnetic wave propagation
$\gamma = \alpha + i\beta$
α – damping factor

$$\alpha = \frac{r}{2\sqrt{\frac{L}{C}}} \qquad (12)$$

At high frequencies $\omega C > g,\ \omega L > r$

$$\alpha = 0 \quad \gamma = i\beta \qquad \beta = \omega\sqrt{LC} \qquad Z = \sqrt{\frac{L}{C}}$$

$$\dot{U}(o) = \dot{u}(l)\cos\beta x$$
$$\dot{I}(o) = j\frac{\dot{u}(l)}{z}\sin\beta x \qquad (13)$$

The maximum voltage is equal

$$U(l) = \frac{4}{\pi}qE \qquad (14)$$

where: E – a voltage of Tesla transformer.

The capacitive current $Ic = 2\pi fCU$

Assuming $u(o) = E$ = 10 kV, q = 10, f = 5 kHz, C = 0.1 μF, $u(l$ = 15 km) = 127.25 kV

The capacitive current Ic = 39.75 A

The reactive power $Q = 2\pi fCu^2$ = 5.08 MVAR

Energy stored by the capacitor 0.1 μF.

$$E_c = \frac{Cu^2}{2} = 0.809kJ$$

Takeoff active power from capacitor transmitted through electronic key with switching frequency fo = 1 kHz $P = Ec \times fo$ = 0.809 MW

EXPERIMENTAL RESULTS

Three different types of SWEPS were designed and tested: 230 V, 10 kV and 100 kV, each one being of one-kilowatt capacity. Tesla transformer has C-type unclosed magnetic circuit with ferrite core of 40–50 mm diameter. Secondary high voltage bobbin coil is wound upon ferrite core and it has 4–6 thousand of winding turns. One terminal of the secondary coil is in the center of secondary coil and from this terminal the current is taken to single-wire line. External neutral terminal of the secondary coil has a zero potential in relation to the ground. This neutral terminal is isolated.

Primary coil is wound around in proximity to the secondary coil. Primary coil has 40–50 winding turns. The terminals of primary coil are connected to frequency converter. SWEPS comprises two Tesla transformers, connected by single-wire line. Reversal step-down Tesla transformer at the user's end has the same structure of coils as a step-up Tesla transformer (Tesla 1900).

As a material of conductor copper, aluminum, steel, and tungsten were used. The diameter of wire is 5–100 microns. The transmitted power is 1 kW at voltage from 230 V to 100 kV. Diode-capacitor block comprises 0.25 μF, 16 kV capacitor. As a conductor also non-metallic conductive media were used, like carbon wire of 100m/km diameter with resistivity 100 Ohm/m, plastic water tube of 10 mm diameter, plastic saucer with 10 mm layer of damp soil, ITO conductive film on glass substrate. Conductive film has a resistivity 30 Ohm/m and a thickness of 0.3 microns.

The current, voltage and power of SWEPS were measured by standard 50 Hz devices at the beginning of the line.

As electric load appliances a.c. motors and filament lamp were used. The parameters of the load are measured by standard a.c. electric meters.

Single-wire circuit was tuned by frequency variation. At resonance mode the capacity of the load is at its maximum. The experiments showed that in resonance mode the current transiting to the load through set-down Tesla transformer in ten times exceeds a current transiting through the secondary coil and charging the natural capacitance. Transmitted power does not vary at any diameter and material of a single-wire circuit. The wire room temperature does not increase after several hours of power transmission. The powerful electric oscillation produces stationary waves in unloaded single-wire line.

The wavelength is defined by frequency of generator or frequency converter. But when the electric load is switched on, traveling waves appear. The reactive power transmission is carried out by electromagnetic field propagation along the line which one executes a role of guiding system.

Transmitted power of single-line-to-ground short is equal to zero because of a detuned circuit.

Resonant frequency is dependent on distributed capacitance and inductance of the Tesla transformer, the line and the load. At removal of ferrite core the resonant frequency was augmented by 2–3 times.

The Tesla coil generates also electromagnetic waves of 4–5 cm length, which is equal to diameter of secondary coil of a setup Tesla transformer. These waves were observed by connecting several series connected fluorescent lamps to the inner terminal of secondary coil. In the loaded line the transversal dark and light areas displaced. The size of each area was 2–3 cm. So the secondary coil of set-up Tesla transformer plays a role of spiral antenna, emitting electromagnetic waves. The wavelength is defined by the diameter of the resonator and waveguide, the functions of which are executed by secondary Tesla coil.

SWEPS includes mono-polar low loss single-wire line. In a spark-gap of loaded single-wire line there was a plasma discharge of reactive power. We called this reactive plasma as cold plasma. There is a great difference between cold plasma discharge of reactive power and arcing short discharge of two-wire line transmitting an active power.

If a water layer is included as part of the loaded single-wire line and a spark-gap is created between the conductor and the surface of water, the cold plasma discharge between conductor and water is initiated. This cold plasma discharge does not change the temperature of water and does not evaporate water during 30 minutes of operation of line. We use spring water as well as sea water and water seems to be an ideal superconducting material for capacitive reactive power transmission.

When arcing short was created by an active power in a spark-gap between water and standard 50 Hz two-wire line we could observe splashes and evaporation of water. The industrial electrode boiler is a good illustration of effective electric power conversion to heat.

The plasma discharge in spark-gap of unloaded single-wire line decreases and depends on natural capacitance of a body. Using this property of one pole single-wire line we develop cold plasma coagulator for application in medicine and chemistry (AVRAMENKO, STUPIN 1997).

DISCUSSION

The electrostatic analogy is one of the visual arguments of operation principles of SWEPS.

Transversal electromagnetic waves are propagated along the line and these waves can have any frequency, including zero. The structure of wave field in a transversal plane is identical to electrostatic field and stationary magnetic field. The step-up Tesla transformer generates during half-cycle the charges of high density and high electrostatic potential. The free charges are moving along the line from generator site with high potential to the user's end with small potential and this capacitive charging current is stipulated by Coulomb forces. These charges are moving on the surface of wire and this current is not affected by Joule's rule. So Tesla transformer is operating during one half-cycle as electrostatic generator continuously generating free charges and supporting high potential at the generator site. In the following half-cycle there is a change of the sign of charges, which are recharging the line capacitance but the potential difference between the generator and the end of the line is saved and charges of the other sign are moving along the line to the load.

A displacement current in the space surrounding the wire corresponds to change of an electric field strength. The displacement current as well as capacitive charging current is not affected by Joule's rule.

Another component of displacement current takes into account moving charges and polarization in dielectric surrounding a wire. Polarization losses can be used for direct conversion of idle power to heat. But this effect has quite different nature than Joule losses physics. We found out the very high temperature increase of fresh wood when we use it as a conductor material for loaded single-wire line.

This simple method can be used for fast wood drying and one can find a lot of materials, which can be used to provide heat from reactive electric power using polarization losses mechanism.

One hundred years ago Nicola Tesla has developed his apparatus for transmission of electric energy using single-wire technology (Tesla 1956). In 1900 there was no photovoltaic industry, radio engineering, laser technology and superconductivity. Now we better understand the theory and application possibilities of SWEPS. Nicola Tesla considered that one terminal of secondary and primary coil of step-up and step-down transformers must be connected to the earth. That means that single-wire line can be applied only to the power transmission along the earth.

Now we know that electric power can be transmitted to any body, not connected to the earth, for example, to air balloon, plane or even to satellite. We even do not need to apply a step-down transformer for single-wire power transmission (Fig. 1a) and we can use for power transmission non-metallic conducting media, like isolated water tubes, cables made from carbon or conducting oxides on glass etc. We developed SWEPS using laser beam as a single-wire line (STREBKOV et al. 1999a). Laser beam creates ionized conducting channel in the air with ionic concentration $10^{15}/cm^3$. Step-up frequency Tesla transformer generates high voltage (more than 1,000 kV) potential and traveling electromagnetic waves which flow along this conducting channel. At the voltage level of 1,000 kV the transmitted power may reach the value of 1,000 MW, depending on the frequency and capacitance of the load.

Another field of SWEPS application is the electric transport. We offer electric transport systems using hybrid electric car and public transport: bus, tram, trolleybus, metro, electric train using single trolley line, isolated from the earth (STREBKOV et al. 1999b). 5 W 12 V experimental model of single-trolley car was constructed and tested.

New principles of electric power transmission, using capacitive and displacement current in single-wire one pole circuit in future can be applied for construction of United Global Solar Electric Power System for the world.

CONCLUSIONS

– Single-wire electric power system for electric grid can be applied instead of three-phase network. SWEPS uses one pole single-wire open-tuned circuit, capacitive and displacement current for transmission of active power. Modified step-up Tesla transformer was applied at the generator site to generate high frequency reactive capacitive current. Reversal step-down Tesla transformer or diode-capacitor block was used at the user's end to convert high frequency reactive power to standard a.c. 50 Hz or d.c. electricity.

– Three different 1 kW capacity SWEPS were tested: 230 V, 10 kV and 100 kV. Resonance mode of oscillation with frequency from 5 to 15 kHz was used to provide the most efficient power transmission. The transmitted active power is proportionate to the frequency, capacitance of the load and quadrate of the load voltage. SWEPS and three-phase transmission line have the same parameter affecting energy transmission capability and this parameter is surplus reactive capacity of the line, which is equal to the capacity of the line's electrical field. So both lines have the same transmission capabilities in the range from 1 W to 10 GW. Both the predicted and observed electric losses of single-wire line are considerably less than the losses predicted for three-phase network. It is known from the theory of electricity that capacitive and displacement currents are not affected by Joule's rule. It was experimentally proved that SWEPS has quasisuperconducting property for capacitive and displacement current. SWEPS has insignificant resistance losses for following tested conducting materials: copper, aluminum, steel, tungsten, carbon, conducting ITO oxides on glass, isolated water tubes, damp soil. Conducting channel in the air ionized by laser beam was offered as a single-wire line for SWEPS.

– SWEPS is one of the most promising electric power transmission technologies for renewable-based electric grid. This technology may be recommended both for the power transmission from a powerful generation site to electric grid and for transmission line for joining together different parts of energy system. The computer simulation of distributed solar power system, consisting of several solar power plants installed in Spain, in European part of Russia and Far East of Russia, connected by low loss transmission line, resulted that this power system is generating electricity 24 hours a day 6 months a year and does not require electric accumulator or back-up generator during the night.

Another promising possibilities include single-trolley electric transport, isolated from earth and powered by solar power system, solar driven cold plasma generator and compact extra high voltage equipment.

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Nová technologie přenosu elektrického výkonu

ABSTRAKT: Byl vyvinut SWEPS, jednodrátový elektrický systém (elektrického výkonu) s nízkými náklady a ztrátami. Nová technologie přenosu elektrického výkonu používá režim přenosového vedení běhu naprázdno a jalový kapacitní proud pro převod činného elektrického výkonu. Byly zkonstruovány a otestovány tři různé SWEPS: 230 V, 10 kV a 1 000 kV jednotlivě s kapacitou 1 kW. Rezonanční vid oscilace s frekvencí od 3 do 30 kHz se použil pro maximálně účinný převod výkonu. U polohy generátoru pro výrobu vysokofrekvenčního proudu jalového výkonu byly použity frekvenční konvertor a modifikovaný transformátor Tesla. Na konci uživatele ke konverzi vysokofrekvenčního jalového elektrického výkonu na standard 50–60 Hz elektřiny byly použity reverzní transformátor Tesla, standardní rektifikátor a inventor. Bylo experimentálně dokázáno, že SWEPS má kvazisuperkonduktivní vlastnosti pro tok jalového kapacitního proudu ve vedení (elektrickém) rovněž při vysokých pracovních teplotách elektrického vodiče. SWEPS nemá ohmické ztráty pro následující testované vodičové materiály ve vedení: měď, hliník, ocel, wolfram, uhlík, voda, vlhká půda. Výsledek teoretických výpočtů a experimentální studie ukazuje, že SWEPS se může aplikovat jak pro přenos energie ze sítě produkce energie z obnovitelných zdrojů na větší energetické systémy, tak v přenosovém vedení pro spojení různých částí energetického systému s obnovitelnými zdroji.

Klíčová slova: energetický systém; přenos elektrického výkonu; vysokofrekvenční vodič

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