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High-Frequency Power Source with Constant Output Power

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Abstract

The technical problems treated in the present paper are related to the development of a specific high - frequency power supplies for different applications – induction heating, contactless power transfer systems, ultrasonic devices and etc. They are, in their nature, a hybrid between the achievements in modern microelectronic components - frequency capabilities and low commutational losses, and the latest trends in the development of power conversion circuit manifested in the use of adaptive energy circuits which always maintain the power constant and independent from the load changes [1, 2, 3].
Actually two circuits were investigated and are presented in this paper - a half-bridge circuit and a bridge one, the latter being claimed as a patent by the author. They have their own specific characteristics and in relation to this, specific areas of application determined mainly by their output voltages.

Keywords: constant output power, resonance inverter, electromagnetic coupling, inductive power transfer; impedance matching, zero current, zero voltage.

1. Introduction

A characteristic feature of power source with constant output power is their ability to operate in case of great changes in the load parameters, the power and the operating frequency, preserving good electromagnetic compatibility with the mains. These features are maintained by means of circuit design - use of combinations between series and parallel circuit and suitable controllable components and devices, such as controllable high-frequency transformers and capacitor units. A series-parallel arrangement of capacitors is adopted and optimum mode of operation is proposed [1, 4, 6, 7,11]. In this mode, the inverter is operated at unity power factor by PLL control irrespective of load variations, with maximum times gain, maximum overall system efficiency, and practically no voltage spikes over the transistors at turn-on and off.

The presented in this paper high-frequency power sources with constant output power (COP) offer analogous possibilities. The method in question is best illustrated by means of the half-bridge resonance inverter (RI) and the bridge resonance inverter with COP [2, 3]. The good practical results obtained with the first circuit and the necessity of higher power levels and load voltages have led the author to synthesize the bridge variant as well.

The purpose of the paper is to present the good functional possibilities of a number of circuits - half-bridge (Fig.1) and full-bridge (Fig.2) high-frequency power source with COP with or without reverse diodes of the transistors and on that ground to define the set of technological processes maintained and variations of the load parameters.

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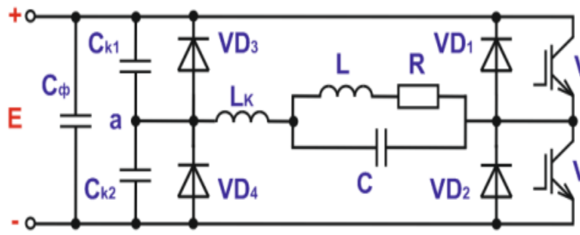

Fig. 1. Half-bridge resonance inverter with constant output power.

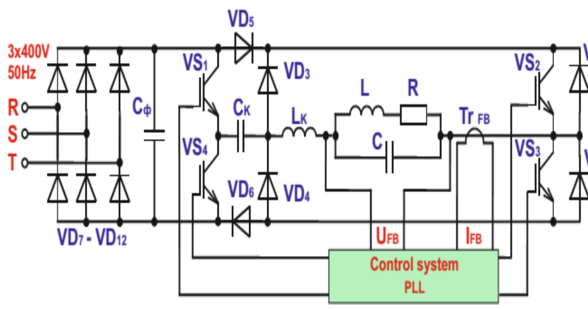

Fig. 2. Full-bridge resonance inverter with constant output power.

2. Matching of the half-bridge and bridge resonance inverters with load at constant output power

Fig.3 presents the time charts of the quantities characterising the operation of the bridge RI with COP in the following order: Fig.3a - the current in *AC* diagonal of inverter; Fig.3b - the voltage of the commutating capacitor C_K; Fig.3c - the voltage of the parallel load circuit.

The operation principle of the circuit becomes obvious from the respective denotations on them. There are two intervals: of energy consumption from the power supply $0\div\varphi_d$ and of the short-circuit of the *AC* circuit over one of the supply lines (positive or negative) - $\varphi_d\div\pi$-t_0.

The flow of electromagnetic processes in the half-bridge variant is analogous, with the only difference that the commutating capacitors are two and the voltage across them is fixed within the limits 0÷E and the current through transistors is two times greater than the full-bridge inverter.

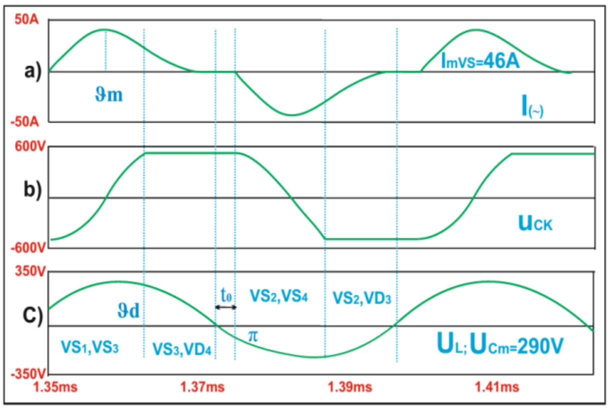

Fig. 3. Basic time charts of full-bridge RI with COP at 15 kW output power: a) - the current in inverter *AC* diagonal; b) - the voltage of the commutating capacitor C_K; c) - the voltage of the parallel load circuit (capacitor C).

The circuits of RI without reverse diodes of the transistors have the same operation but are only capable of functioning in the modes in which the parallel circuit has an equivalent active or active-capacitance character. When the load parameters changes inverter power is always equal to assigned one and zero current switching mode (*ZCS*) without frequency changing necessity is available.

The maintenance of constant power in the inverters discussed is due to the fact that the energy of the power supply is always consumed through the commutating capacitor, the voltage of which is fixed up to the value of the *DC* supply voltage - *E*. Then the power consumed is determined by the following expressions:

- for the bridge variant

$$P = 4C_k E^2 f = EI_0 = \frac{U_{mC}^2 \cos^2\phi}{2R} \qquad (1)$$

- for the half-bridge variant

$$P = (C_{K_1} + C_{K_2})E^2 f = EI_0 = \frac{U_{Cm}^2 \cos^2\phi}{2R} \qquad (2)$$

i.e. when the operating frequency *f*, the supply voltage *E* and the value of the commutating capacitor are constant, the power given up to the load does not depend on its parameters. This is good illustrated at Fig.4 where the output power changing at the load parameters variations is presented for bridge current - fed inverter Fig.4-(1), half - bridge RI Fig.4-(2), RI with COP and reverse diodes Fig.4-(3) and RI with COP without reverse diodes Fig.4-(4) [1, 3, 6, 7].

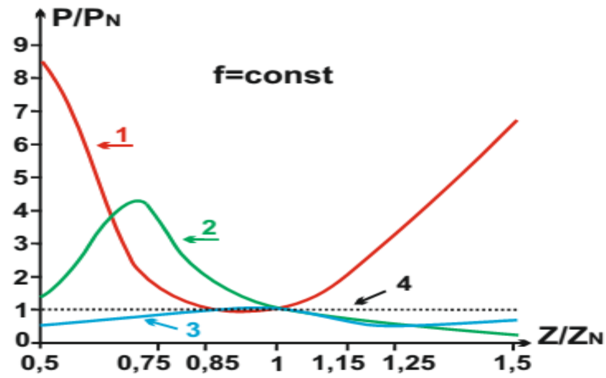

Fig. 4. Comparison of output characteristics P/P_N=f(Z/Z_N) of the current - fed inverter (1), half - bridge RI (2), RI with COP and reverse diodes (3) and RI with COP without reverse diode (4).

Important point here is that the last two characteristics (3 and 4, Fig.4) guarantees practical adaptiviti of the inverter to the load and its changes, due to which it could also operate without regulation when the load changes within the limits stated above.

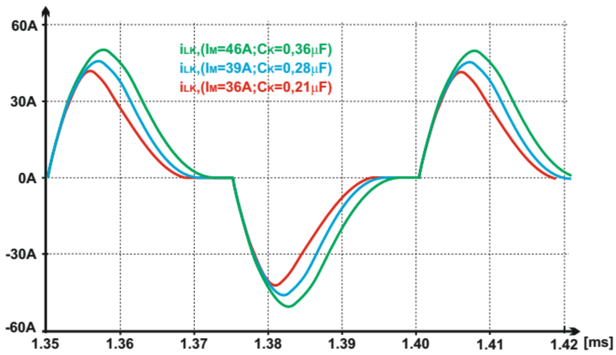

Fig. 5. The current in *AC* diagonal of RI with COP at different commutating capacitor value.

It should be also noted that by changing the commutation capacitor value leads to a proportional change of the output power in accordance with (2). Father more, operating *ZCS* mode of the switches is keeping on – Fig.5.

3. Design procedure of the resonant inverter with constant output power

In accordance with the fact that the electromagnetic processes in the autonomous inverters discussed are identical, a common analysis and design have been carried out for them. The basic analytical dependences have been derived on the basis of the relationships from the harmonic analysis and the postulates of the general theory of autonomous invertors [1, 9, 10].

The following order can be recommended for the RI with COP design:

1. Selection of the relationship ω_{CK}/ω (ω_{CK} and ω - respectively, natural frequency of the *AC* circuit and control frequency). It has been found that in case of a pause between the control pulses t_0=0,1π, the ratio ω_{CK}/ω= 1,2÷1,4.

2. Selection of a phase angle δ in the *AC* circuit, according to the compulsory relationship $tg\delta>\omega_{CK}/\omega$.

3. Determining the maximum value of the voltage across

the capacitor C_K, which is constant in the range $\vartheta_d \div \pi - t_0$ and can be regarded as a sawtooth line cut at the top and bottom on level E, i.e. $U_{Ckm} = (E/2)/\cos[(\pi - \vartheta_d)/2]$. After that the basic phase relationships the electrical quantities and components are determined.

4. A quality factor of the series equivalent circuit:

$$Q = \frac{\omega L_k}{R_e} = \frac{1}{2}\left(\frac{\omega}{\omega_{ck}}\right)^2 \left[tg\delta + \sqrt{tg^2\delta - \left(\frac{\omega_{ck}}{\omega}\right)^2} \right] \tag{3}$$

5. Detuning of the parallel load circuit when it is in resonance on the first harmonic of the alternating current, the real and relative value of its equivalent resistance:

$$\xi_0^2 = \frac{tg\phi + ctg\phi}{tg\phi + tg\psi}, \quad R_e = \frac{1}{\omega C_k tg\delta},$$

$$R_e^I = \frac{\xi_0^2 ctg\phi}{\left(\xi_0^2 - 1\right)^2 + ctg^2\phi} \tag{4}$$

6. The moments: ϑ_d - at which the energy consumption from the power supply stops, ϑ_m - at which the alternating current has maximum value:

$$\vartheta_d = \frac{\pi}{\omega_{ck}/\omega} - \frac{arctg 2Q\omega_{ck}/\omega}{\omega_{ck}/\omega},$$

$$\vartheta_m = \frac{arctg 2Q(\omega_{ck}/\omega)}{(\omega_{ck}/\omega)} \tag{5}$$

7. Values of the circuit elements:

$$C_K = \frac{P}{4E^2 f},$$

$$L_K = \frac{QR_e}{\omega},$$

$$R = ctg\phi . \omega L,$$

$$L = \frac{1}{\xi_0^2 \omega^2 C},$$

$$C = R_E' C_K (tg\delta - tg\psi) \tag{6}$$

8. The average and maximum values of the currents across the transistors and the reverse diodes.

$$I_{mVS_{1\div 4}} = I_{mVD_{7\div 8}} = \frac{E}{\frac{\omega_{ck}}{\omega}\omega L_K} e^{-\frac{\vartheta m}{2Q}} \sin\frac{\omega_{ck}}{\omega}\vartheta_m,$$

$$I_{0VS_{1,4}} = I_{0VD_{7,8}} = \frac{EfC_k}{2} = \frac{I_0}{2},$$

$$I_{0VS_{2\div 3}} = EfC_k\left(1 - e^{-\frac{\pi - t_0}{2Q}}\right),$$

$$I_{mVD_{5,6}} = i(\vartheta_d) = \frac{E}{\frac{\omega_{ck}}{\omega}\omega L_K} e^{-\frac{\vartheta_d}{2Q}} \sin\frac{\omega_{ck}}{\omega}\vartheta_d,$$

$$I_{0VD_{5,6}} = EfC_K e^{-\frac{\lambda}{2Q}},$$

$$I_0 = \frac{1}{\pi}\int_0^{\pi - \vartheta d} i(\vartheta) d\vartheta = EfC_K, \tag{7}$$

The precise determining of the circuit elements has been confirmed by the diverse computer aided and real experiments performed. All those have enabled the prognostication and the setting of the control algorithm, which determines unambiguously the operation mode of the inverter. In order to ensure zero current in turning on and off the switching devices, the following is obligatory: selection of a certain relationship of the frequencies ω_{CK}/ω, maintaining the resonance of the tank circuit and following fixed dephasing of the alternating current and the voltage of the tank circuit. In the research process the last factor has turned into a basic requirement to the control system and has been specified, and this phase should be equal to the pause between two adjacent current pulses of the inverter.

4. Commercial introduction and test result

The experimental research has been performed using transistorized RI with COP, shown in Fig.2, with following technical parameters: P=1-15kW; f=10-50kHz; E=500V.

The investigations have been performed with the three typical technological loads:

- An induction heating for ferrous and non-ferrous metals with coil diameter 100mm and 12 turns – Fiq.8;
- Ultrasonic welding with single head compact transducer that working at frequency around 28 - 29 kHz and provided amplitude of 48 μm peak-to-peak at 100% setting – Fig.6. During the tests of US system –Fig.9, at 5 kN pressure applied to the head, the generator reached power of 4.5 kW [3].
- Contactless charging of electrical vehicles –Fig.10 [5, 8]. The main parameters of contactless charging module, is summarized in Table1.

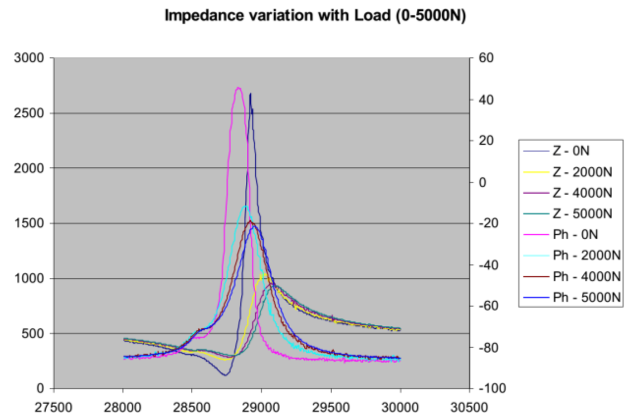

Fig. 6. Impedance and phase angle of the transducer Vs. pressure over the welding material and frequency.

Table 1. Main parameters of the developed and tested contactless charging module.

Transmitting (Tx) and receiving (Rx) coils	
Parameter	Value
Nominal output power	15kW
Efficiency	90-92%
Nominal HF current	60A÷90A HF AC
Max. dimensions of Tx coil	800 x 700 x 90mm
Max. dimensions of Rx coil	800 x 700 x 60mm
Vertical air gap span	dz=75÷100mm
Horizontal misalignment	dx=dy= ±150mm

The inductance L of transmitting (Tx) and receiving (Rx) coils, which are crucial for the equivalent load of RI with COP, depend on vertical distance and horisontal missalligment between coils which are summarized by the coupling coeficient k – Fig.7. Values of k less than 0.2 correspond to the air gap and missalligment out of the range, specified in Table l.

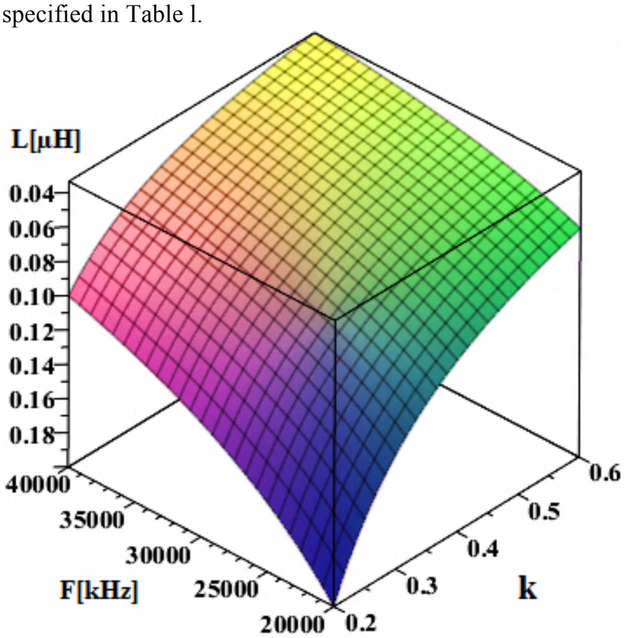

Fig. 7. Inductance of Transmitting (Tx) and receiving (Rx) coils Vs. couling coeficient **k** and friquency.

The power and voltage of the load is according to technological application and therefore the test results are presented with their relative parameters.

The power level is regulated by changing one of the three quantities - E, C_k or operating frequency of the inverter. Actually operating frequency is used for fine tuning and depending on the method of control; the RI with COP has two modes of operation:

- without regulating influence from control system, i.e. with constant operating frequency. It has been found out from the experiments performed that, with the change in the load parameters, the power is kept constant, but the switching on and switching off current of the transistors is different from zero;

- control system of the PLL type maintaining a resonance in the tank circuit. In this way, constant power is guaranteed, as well as zero switching on and switching off currents of the transistors.

In the course of the experiments, the properties of RI with COP were checked when the load parameters are changed in wide range. Operation with different equivalent loads was simulated by different volume of the metal heated - Fig. 8, with different thickness of welding material and pressure over it in range of 0-5000 N – Fig.6, Fig.9 and EV battery state of charge and distance between transmitting and receiving coils (75÷100mm in vertical and ±150mm in horizontal directions) – Fig.7 and Fig.10.

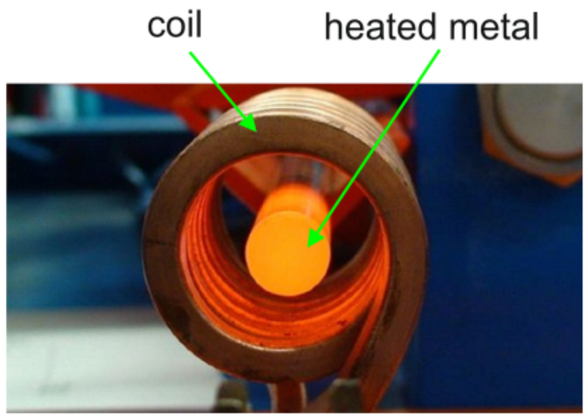

Fig. 8. Induction heating for ferrous and non-ferrous metals as load of RI with COP.

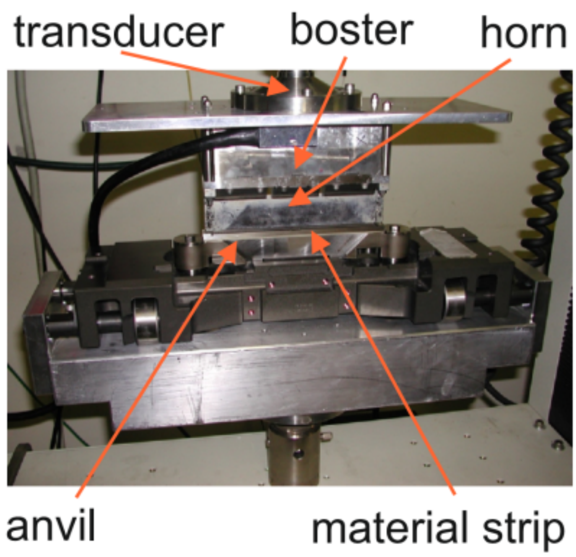

Fig. 9. Mock-up for tests of single head ultrasonic transducer supplied by RI with COP in different welding processes.

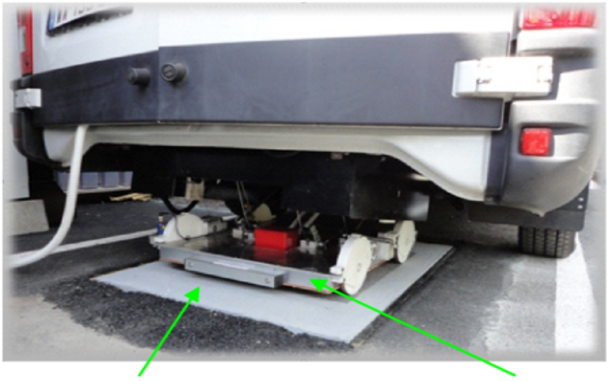

Fig. 10. Investigation of contact less charging system of electrical vehicles supplied by RI with COP at different air gap and horizontal misalignment between coils.

The results obtained in Table 2 have a significant practical value and consist in the following: when load cosφ changes in the range of 0.05 - 0.39, the output voltage changes 1.37 times, keeping P=const. The PLL regulator has changed the operating frequency only 1.1 times, which has helped to maintain the optimal operation of the transistors. The main conclusion that can be drawn is that the power is maintained constant during the investigated technological processes and respectively, wide range of load parameters.

Table 2. Summarized test results.

Parameters	1 nominal load	2	3	4	5	6 idle running
cosφ	0.39	0.35	0.31	0.24	0.2	0.05
f(kHz)	27.65	28.2	28.9	29.6	30	30.4
$I_0^I=I_0/I_{0N}$	1	1.01	1.02	1.02	1	0.33
$U_L^I=U_L/U_{LN}$	1	1.09	1.17	1.3	1.4	1.37
$P_0^I=P_0/P_{0N}$	1	1.01	1.02	1.03	1	0.33

These results have been used to construct the load characteristic of RI with COP - Fig.11.

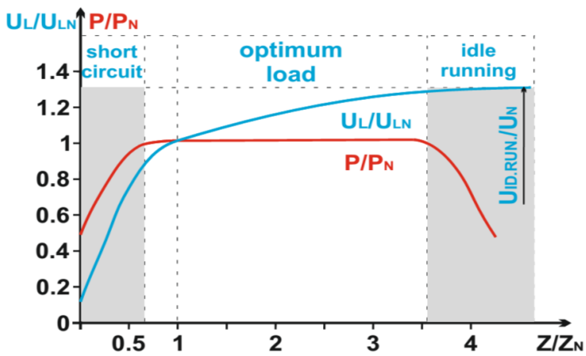

Fig. 11. The load characteristic of RI with COP

This is the main research done on RI with COP. The advantages presented, especially those connected with self-matching, with the possibility of operating in modes close to idle running and short circuit. As well as the easy assignment of power (by means of the Ck value) characterize them as competitive and corresponding to the right tendencies in the development of high frequency power supplies for different technological applications.

5. Conclusion

High-frequency power supply, in the base of RI with COP, was realized and tested with application in electrotechnology and contactless charging station at 1-15 kW power rates and 10-50 kHz frequency range. On the basis of the analysis and the real tests performed the following advantages of the RI with COP can be pointed out:

- Operation with different loads with almost constant power;
- Possibility of operation in modes close to idle running and short circuit;
- Transistors commutation with zero current and zero voltage;
- Easy algorithm of control system operation;
- High power factor in relation to the mains.

The following disadvantages can be pointed out:

- High maximum values of the currents through the transistors and the diodes;
- A large number of passive elements compared to classical half-bridge and full bridge resonant inverters.

The results obtained and the conclusions drawn show that the RI with COP proposed can be used in electrotechnological and industrial contactless applications as sources of high-frequency energy owing to the possibility of working with a wide range of load parameters.

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