Multithreading Analysis of Properties and Electromagnetic Interference in Inductive Contactless Power Supply System with Bidirectional Energy Flow— Part 1: Topology System for Electric Vehicles

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Abstract Inductive Contactless Energy Transfer systems (ICET) are becoming commonplace in electrical and electronics equipment. Increased growth of interest in electric vehicles (EV) and renewable energy sources, significantly changed the approach to vehicle. EV battery pack is no longer just a vehicle for the drive tank, but it is also a distributed storage for energy from the power grid. To ensure the automation of the flow of energy best fits is inductive contactless power supply system with bidirectional energy flow. These systems are based on inductively coupled resonant circuits and offer many properties that affect the high-efficiency energy transfer. The paper presents selection and simulation studies ICET system in use for EV with power $P = 100$ kW.

1 Introduction

Inductive Contactless Energy Transfer systems (ICET), are becoming an everyday reality in electrical and consumer electronics. A wide range of applications and transmitted power in many areas by medicine to the vehicles and transport

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equipment [1, 3], causes the design of the system is selected for a particular application. One of the concepts of applying the ICET system is battery chargers for electric vehicles (EV). The idea of a fully automated battery charging is one of the important technical problems since the resumption of work on the vehicles EV. The current trend in European countries, promoting EV and renewable energy from the renewable energy sources has created a new concept of contactless power supply system. Assuming that the battery EV during his stopover can provide energy storage for the power grid, and the energy produced from RES is unevenly over time, then these batteries can become distributed storage for energy extracted from RES.

For this application perfectly fit ICET systems with bidirectional energy flow.

The most important advantage of this system is to automate the process flow of energy charge and return it to the grid. Block diagram of the inductive contactless energy transfer system with bidirectional energy flow is shown in Fig. 1.

The ICET system consists of two main parts: the stationary-located at the charging station and the mobile part associated with energy receiver. The main elements of the stationary part are the primary winding of the transformer, the compensation circuit elements, and the inverter responsible for the power system or to enable the return of energy to the grid. The work of the components of the system controls the master controller responsible for the maintenance and billing functions with the operator of the electricity system. The movable part, similar to the stationary, comprises a secondary coil system, the compensation circuit elements, and converters. The main task of controllers of lower and higher levels is to ensure optimal charging process or the return energy to the grid and maintain the longest possible battery life. In the process control ICET system with bidirectional energy transfer, the information about currents, voltages and the direction of energy flow are exchanged between drivers using wireless communication modules, Bluetooth or others. The CET systems based on inductive coupling require selection of multiple elements, such as construction of a transformer, resonant compensating circuits, and power supply converter, etc. The article presents the genesis of contactless energy transfer systems, selection, and description of the properties the transformer circuit with a resonant compensation circuit in the application for EV.
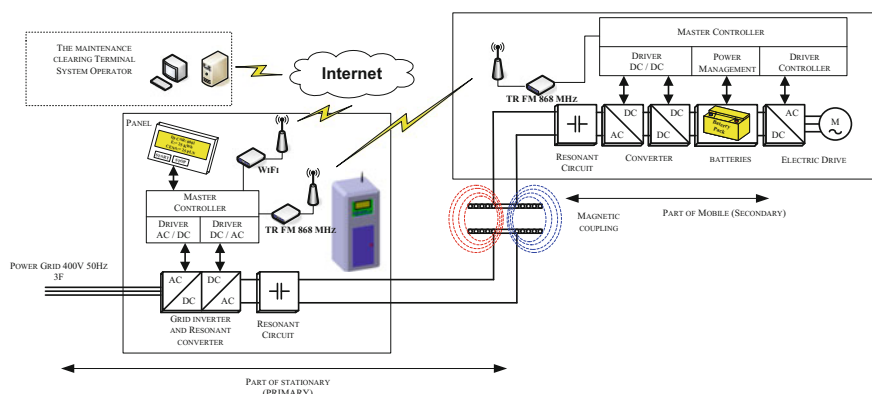

Fig. 1 Block diagram of the inductive contactless energy transfer system with bidirectional energy flow

Presents the methodology of ICET with bidirectional energy flow control converters and the results of simulation for a system with rated power $P = 100$ kW.

2 Inductive Coupling: The Genesis of Contactless Energy Transfer

The inductive coupling (transformer air) is a phenomenon that occurs when you have two or more coils coupled magnetically. A characteristic feature of such a circuit is low, magnetic coupling factor k. The flow of alternating current in the coil produces an alternating magnetic field and thus the magnetic flux. The only part of this flow mediates in energy transfer. The rest of the stream called dissipation or leakage flux causes the induction voltage opposite to the voltage forcing, which strongly limits the energy transfer. A simplified equivalent circuit of the ICET transformer and vector diagram are shown in Figs. 2 and 3.

When L_p, L_s—the windings self-inductances, L_{rp}, L_{rs}—leakage inductances, L_m—mutual inductance, N_p, N_s—number of the windings coils.

The equation for output voltage is as follows:

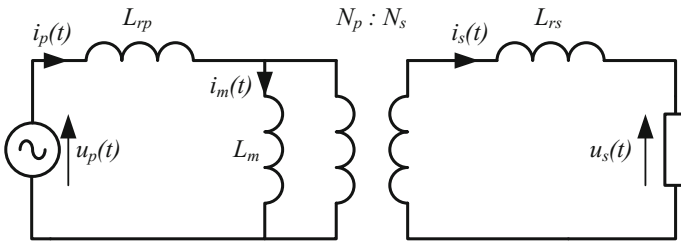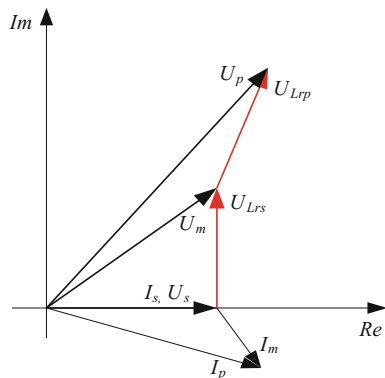$$u_s(t) = u_p(t) - u_{L_{rp}}(t) - u_{L_{rs}}(t) \tag{1}$$

Fig. 2 Equivalent circuit of the ICET transformer

Fig. 3 Vector diagram in the ICET transformer

In order to make energy transfer in ICET transformer possible with high efficiency, you need to compensate for voltage drops in the leakage inductances. For this purpose to primary and secondary terminals of both transformer sides, capacitors are included. Figure 4 shown the general case as it looks like a compensation voltage drop on the leakage inductance. Blue indicator shows the system after compensation.

Then the output voltage u_s is almost equal the supply forcing voltage u_p taking into account the voltage drops on the resistances of passive components. Additionally, satisfying a condition of $R < \omega L_m$ the currents and voltages in the circuit are in phase. This case makes the efficiency of energy transfer grows with increasing load. The distribution of magnetic field strength for this state is shown in Fig. 5.
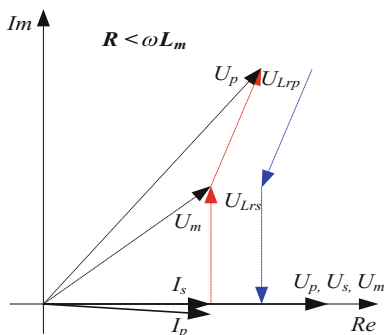

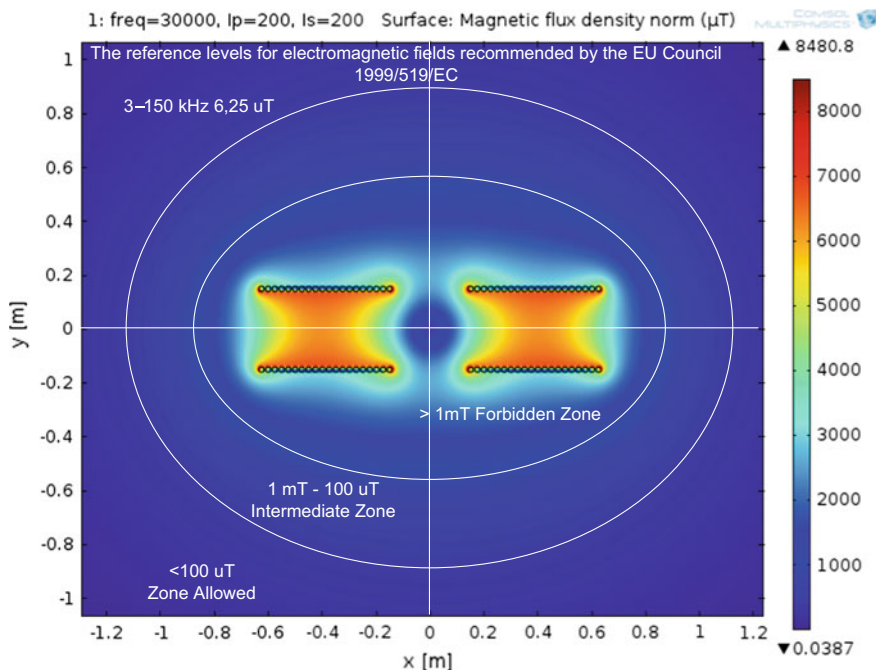**Fig. 4** Vector diagram of the compensated ICET system

Fig. 5 The distribution of magnetic field strength

The distribution of magnetic field strength shown in Fig. 5, proves that shaping/control of the phase shifts voltage (voltage resonance) by a resonant circuit, brings together the main stream within the working field coils to minimize its leakage dispersion, despite the absence of the magnetic core (the magnetic core of the transformer). ICET systems allow to the construction of any structure or require a transformer. In the use of EV best fits the design of transformer windings flat (planar). This is because of less sensitivity to the windings displacement relative to each other and the flat structure which allows easy installation on the vehicle, etc.

3 Compensating Circuit Topologies and their Properties

Hig-efficiency ICET systems require the use of resonant circuits compensating voltage drops on leakage inductances [2, 4]. Their distribution is shown in Fig. 6.

They are divided into two groups: simple and complex. Nomenclature of individual circuits has adopted the method of connecting the capacitors to the transformer terminals. The second division is the possibility of bidirectional energy flow. For ICET systems with bidirectional energy flow check up a few circuits compensation methods.
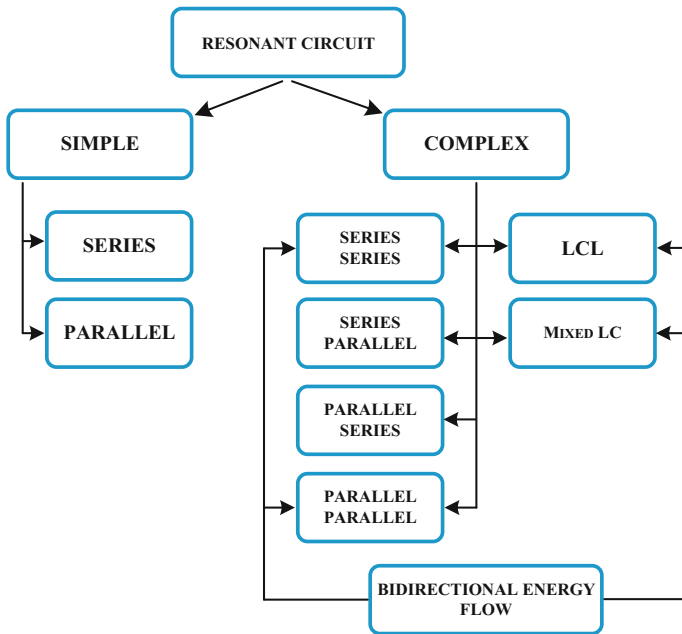

Fig. 6 Division of resonance compensation circuit
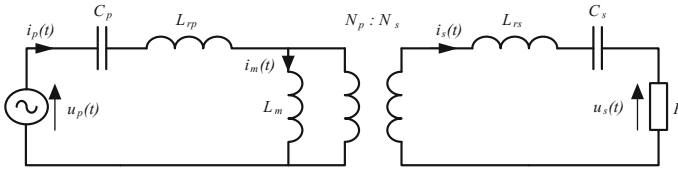
Fig. 7 Equivalent circuit with series–series compensation

The basic criteria for the selection of the compensation circuit are type of power supply—voltage or current inverter, the acceptable sensitivity of the system to changes in magnetic coupling factor, and also on the parameters of the circuit, allowable susceptibility to a change load. For systems with parallel–parallel compensation and fed up from the current inverter, the system shows a high sensitivity to change of the load parameter, and each time required the selection of the LC elements according to magnetic coupling coefficient.

The systems with mixed and LCL compensation circuits supply from voltage inverter, operating in a limited range of changing magnetic coupling coefficients. The basic characteristics of serial–serial compensation circuit are: fed up from voltage inverter, low sensitivity to changes in the magnetic coupling, and a single choice of LC elements. This feature mainly determines the use of series compensated ICET system with bidirectional energy flow for EV. The equivalent circuit is shown in Fig. 7.

Solving the system of equations created on the basis of the equivalent circuit diagram, Fig. 7, we can determine the three basic characteristics, which are complex numbers defining the properties and behavior of the system.

The input impedance Z_{we}, current gain G_i and voltage gain G_v can be expressed by following equations:

$$z_{we} = \frac{U_p}{I_p} = j\omega L_{rp} - j\frac{1}{\omega C_p} + \frac{\frac{L_m}{C_s} - \omega^2 L_{rs} L_m + j\omega L_m R}{R + j\left(\omega L_{rs} - \frac{1}{\omega C_s} + \omega L_m\right)} \tag{2}$$

$$G_I = \frac{I_s}{I_p} = \frac{\omega L_m C_s}{\omega^2 C_s (L_m + L_{rs}) - 1 - j\omega C_s R} \tag{3}$$

$$G_V = \frac{U_s}{U_p} = R\frac{G_I}{Z_{we}} \tag{4}$$

From the above equations, we can determine the frequency characteristics of the module and phase. In order to the presentation of the properties of series–series compensation system is sufficient: the module voltage gain |Gv|, phase impedance and phase current gain. The characteristics shown in Figs. 8, 9 and 10 presenting the behavior of the circuit to changes in the magnetic coupling factor and the load resistance changes.
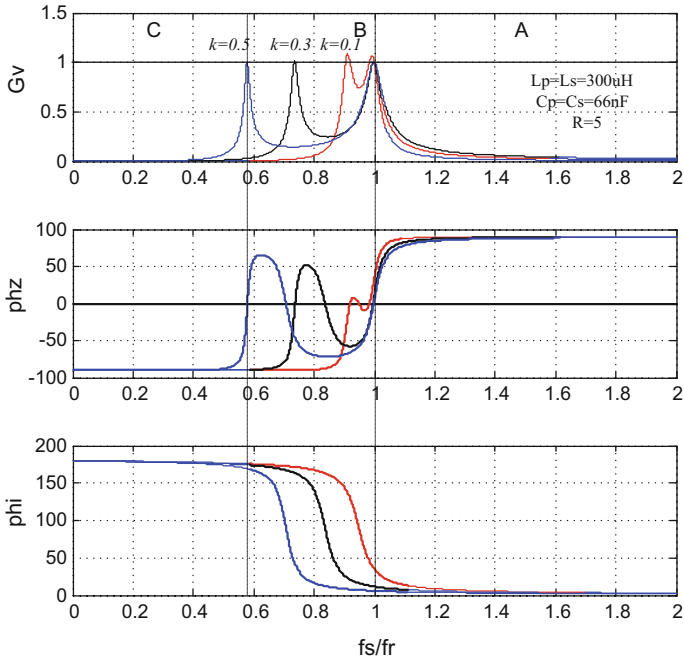
Fig. 8 Frequency characteristics of series–series compensation circuit as a function of changes in the magnetic coupling coefficient *k*
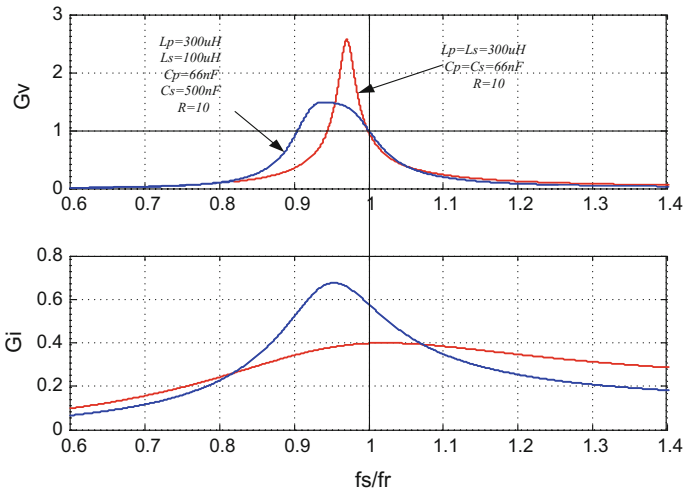

Fig. 9 Frequency characteristics of series–series compensation circuit as a function of changes in the inductance of the windings
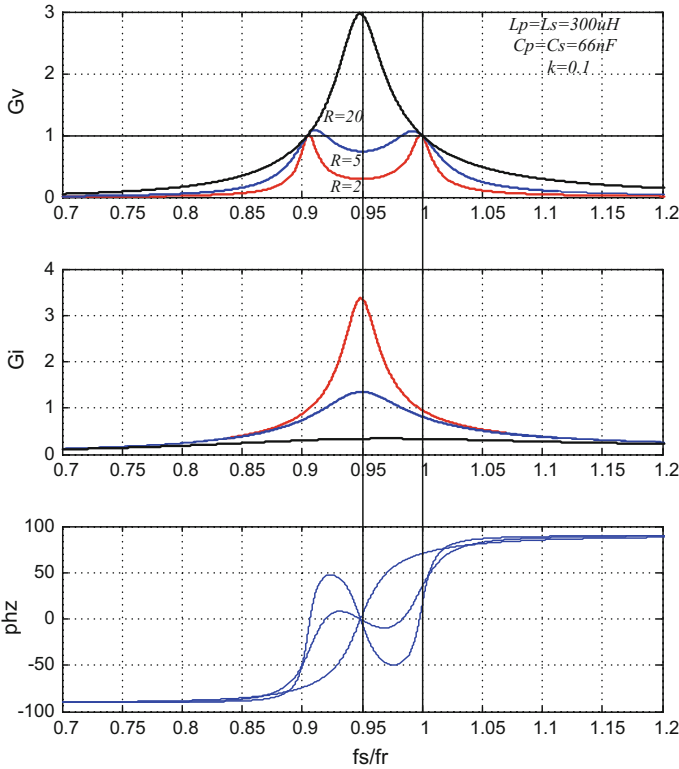
Fig. 10 Frequency characteristics of series–series compensation circuit as a function of load resistance changes

On the basis of the above characteristics can be specified many properties of the above circuit. The first feature is the elimination of the concept of helical gears by the resonant circuit. When the system operated at the resonant frequency regardless of changes in the number of coils (the self-inductance) or the capacitance $C_s = (L_p/L_s) C_p$ the voltage gain is a unit, this state is shown in Fig. 9.

If the resistance $R < \omega L_m$, we can distinguish three frequency operating ranges A, B, and C. Zone A and C are characterized by a monotonic decrease in gain. Zone B is unstable as a function of changes in the resistance. Zero phase shift and separate voltage gain are obtained for the resonant frequency of a particular relationship according to Eq. (6).

$$f_r = \frac{1}{2\pi\sqrt{L_{rp}C_p}} \tag{6}$$

In case of $R > \omega L_m$ the zero phase shift is obtained for frequencies (7)

$$f_r = \frac{1}{2\pi\sqrt{L_p C_p}} \tag{7}$$

and a discussed system has a voltage boost.

Higher load resistance causes greater voltage gain. The frequency characteristics illustrate the output voltage regulation. The first method is to tune and maintenance the system operation at the resonant frequency. The adjustment is made by changing the amplitude of supply voltage. The second method is to change the frequency of the supply voltage, regulate the output voltage by changing the frequency of the supply voltage. The third method is not directly resulting from the above analysis, it is the integration method [1]. It involves zero voltage switching vector forcing for a period equal to a multiple of the current half-cycles whose amplitude exceeds the set point. It uses here the phenomenon of attenuation of current amplitude. Then the output voltage varies in amplitude by a number of {Up, Up/2, Up/3, …, Up/n}.

4   The Simulation Model of the ICET System with Bidirectional Energy Flow for Electric Vehicle

The system is based on the planar transformer with series–series compensation circuit voltage drops across the leakage inductances. To control the inverter it uses a method which combines the integration with the phase shift method. The main aim of this type of control is to stabilize the output voltage regardless of the direction of energy flow. Rated power of the analyzed system is $P = 100$ kW. The parameters of the simulation model of ICET system are presented in Table 1.

Because the system operates as a symmetric, voltage and current waveforms are shown only for one of the directions of energy transfer, Figs. 11, 12 and 13. The study was carried out for the magnetic coupling coefficient $k = 0.1$.

Table 1 The parameters of the simulation model

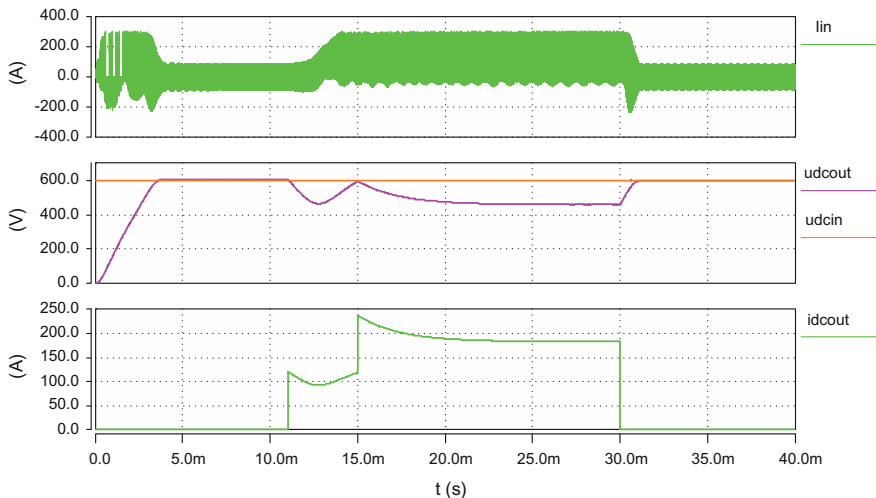| Parameter	Value	Unit
$L_p = L_s$	300	uH
$C_p = C_s$	66	nF
k	0.1	–
U_{in}	600	V
P_{max}	100	kW

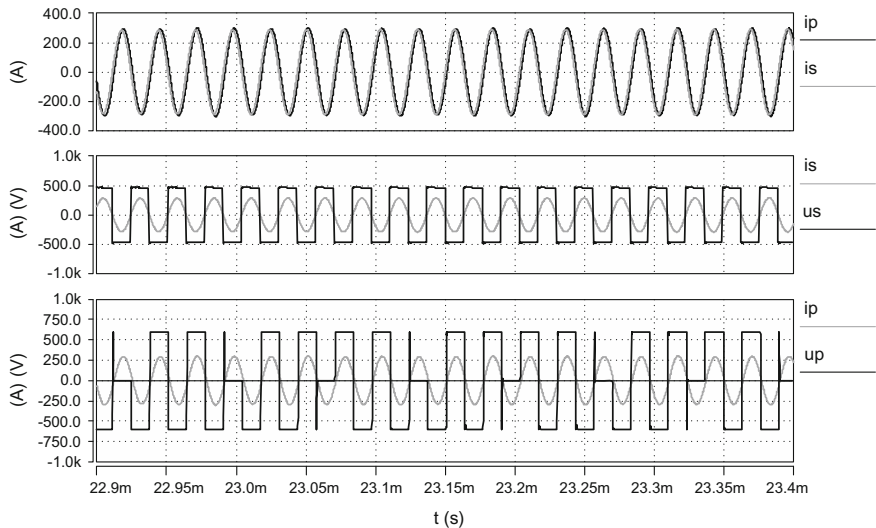**Fig. 11** ICET system response for load jumps

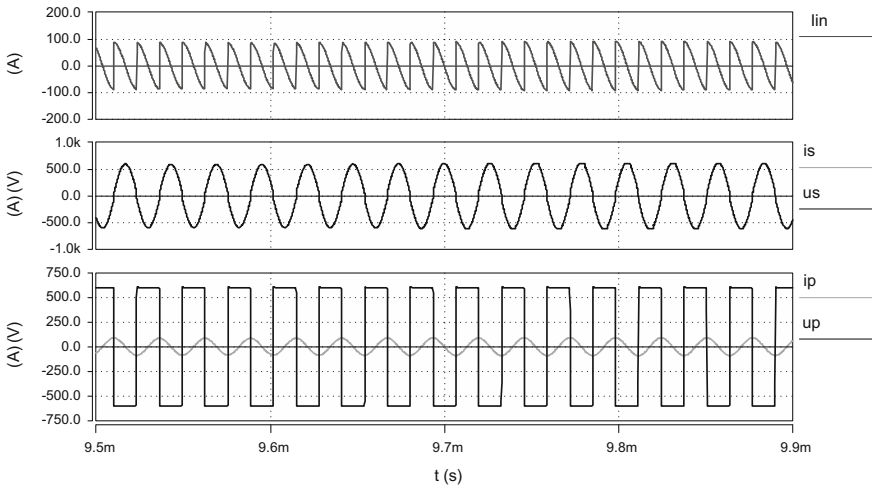**Fig. 12** AC waveforms for the maximum load power $P = 100$ kW

Fig. 13 AC waveforms for minimum power load

5 Discussion and Conclusion

The article presents the contactless energy transfer system ensures:

- Bidirectional energy flow
- The high-efficiency energy transfer
- Universality of application

A wide range of applications ICET systems, their capabilities and value of energy transfer, contributes to their dissemination, together with the development of modern technology. Starting small medical applications ending with all kinds of transport vehicles.

6 Discussion and Conclusions

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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