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A contactless battery power supply system with bidirectional energy transfer

Abstract. *The article presents the contactless battery power supply system with bidirectional energy transfer based on the resonant series-parallel SP-LCLC energy converter providing output power of several watts. In order to improve the power system performance an innovative integrated reactance module was developed, that contains all the elements of a high current inductive resonant circuit and allows to shape the distribution of magnetic induction to increase the power transfer efficiency. (**Bezstykowy układ bateryjnego zasilania z systemem dwukierunkowego przesyłu energii elektrycznej**).*

Streszczenie. *W artykule zaprezentowano bezstykowy układ bateryjnego zasilania z systemem dwukierunkowego przesyłu energii elektrycznej oparty o rezonansowy szeregowo-równoległy SP-LCLC układ przetwarzania energii o mocy rzędu kilku watów. W celu poprawy właściwości układu zasilania opracowano nowatorski zintegrowany moduł reaktancyjny, który zawiera wszystkie silnoprądowe elementy indukcyjne obwodu rezonansowego oraz pozwala kształtować rozkład indukcji magnetycznej tak, aby zwiększyć sprawność energetyczną transferu energii elektrycznej.*

Słowa kluczowe: bateria bezstykowa, zintegrowany element magnetyczny, szeregowo-równoległa LCLC przetwornica rezonansowa, dwukierunkowy przesył energii.
Keywords: contactless battery, integrated magnetics, series-parallel LCLC resonant power converter, bidirectional energy transfer.

Introduction

Power supply units with contactless energy transfer are currently a hot topic in top research institutes and electronic producers [1, 2]. Such devices do not require galvanic connection with load, which is a great advantage in applications where electrical connections are prone to corrosive or even explosive atmospheres, vibration, humidity etc. This technology is employed to a wide range of devices, from RFID transponders consuming several micro watts of power, through consumer electronic devices such as phones and laptops requiring several watts to electrical vehicle battery chargers needing several kilowatts and up to several hundred watts in Maglev trains. The common thing about such power supply units is the use of inductive coupling between an energy source and load, and also resonant methods of forcing currents and voltages in power circuits. This is why magnetic field modelling techniques are often used in research on contactless energy transfer to find spatial distribution of field that provides high energy transfer efficiency [1, 3]. Detailed analysis is also conducted on the geometry of inductive elements windings, shape and parameters of magnetic materials used, and thermal properties of the whole element [1, 3]. Another important aspect of a contactless power supply unit is the configuration of a resonant circuit forcing sinusoidal currents and voltages.

The following chapters describe a unique rechargeable and removable battery solution with bidirectional contactless energy transfer, designed for safe and easy operation in harsh environmental conditions. In the proposed solution the battery is charged at the charger and discharged at the load in a contactless way, thus the energy is transferred in both directions without using wires. There are many advantages of such solution:

- no mechanical contacts, fully hermetic enclosure provides full water resistance and ability to operate in high humidity or even underwater, in chemically aggressive environment, dust, etc.;
- suited to operation and charging in potentially explosive atmospheres (coal mines, chemical and petrochemical industry, silos);
- easier ways to achieve ATEX boundary power supply parameters (power/voltage/current);
- ability to power equipment with moving parts;
- easy battery replacement, even under harsh environmental conditions.

The main disadvantage is a more complicated and expensive construction and a possible increase in EMC disturbances.

Contactless battery system

The proposed contactless battery power supply system with bidirectional energy transfer has been designed chiefly for mobile radio-communication devices operated in explosive atmospheres (underground coal mines) but may also prove useful in other applications (i.e. underwater) [4]. The system consists of three devices: the contactless battery, the receiver - load mounted in the powered device, and a contactless battery charger (fig.1). In this solution the battery is charged and discharged in a contactless way - the energy is transferred in both directions without wires.

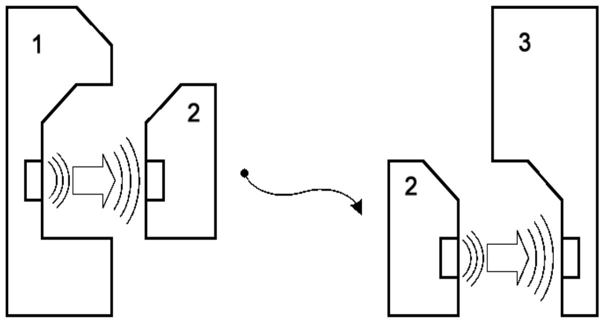

Fig.1. Elements of the contactless battery power supply system: 1 – charger, 2 – battery, 3 – powered device with energy receiver

The main elements of the bidirectional energy transfer circuit, presented in fig. 2 are the resonant serial-parallel power converter (SP-LCLC) with quality factor limiter and the integrated reactance module (IRM).

Resonant SP-LCLC power converter with quality factor limiter

Fig. 2A shows the schematic of a half-bridge structure of a resonant SP-LCLC power converter with quality factor limiter (L3, D3) and bidirectional energy transfer. The presented version operating at medium frequency (typically 50-60 kHz), consists of two inductances L1, L2 and two capacitive elements C1, C2 in the main resonant circuit.

The L1 inductor, connected in parallel with the C1 capacitor, constitutes the main resonant circuit in which the main portion of the whole circuit energy is stored [5, 6]. The integrated magnetic element concentrates the magnetic flux and transfers energy to load circuits through an insulating spacer. The air gap between the primary and the secondary coil is in the range of several millimetres.

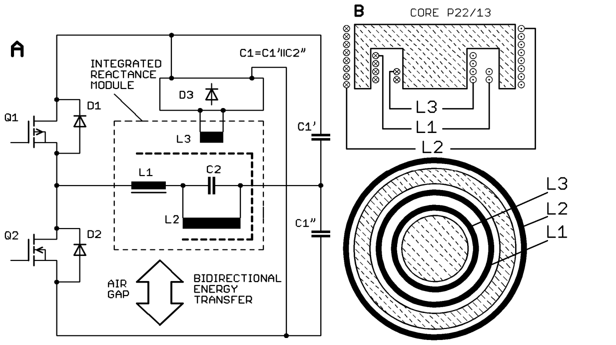

Fig.2. (A) Schematic of a half-bridge resonant series-parallel power converter (SP-LCLC) with Q-factor limiter, where *Q1*,*Q2* transistors are IRF7425 and IRF7456 accordingly, *L1*=47uH, *L2*=27uH, *L3*=5.4uH, *L4*=16uH, *C1'*=*C1"*=100nF, *C2*=670nF. Inductive elements *L1*, *L2*, *L3* are designed as an integrated reactance module. Inductive elements *L2* and *L3* are highly coupled (*k*=0,95) and constitute a quality factor limiter. Other inductive elements are mutually loosely coupled (k<0.2). (B) IRM geometry using P22/13 ferromagnetic core [6, 7]

At the supply voltage of about 7.2V overall energy efficiency is over 75%. Control loop and data transfer between modules are also wireless. This provides reliable communication and voltage output stabilization with good dynamic characteristic under changing load parameters. To optimise the number of inductive elements in power converter they are designed as a single integrated reactance module using one standard P-core. The IRM is shown in fig. 2B. It is utilized in all three elements of the system: the battery, the receiver and the charger. The IRM is built using P22/13 ferromagnetic core made of C90 material. All inductive elements of the energy transfer circuit (*L1*, *L2*, *L3*) are made as winding on this single core. Fig. 3 depicts an oscillogram of the most important voltages and currents in the SP-LCLC converter, operated with 2 lithium-ion batteries connected in series, generating approx. 7.2V, with nominal power output of 3W.

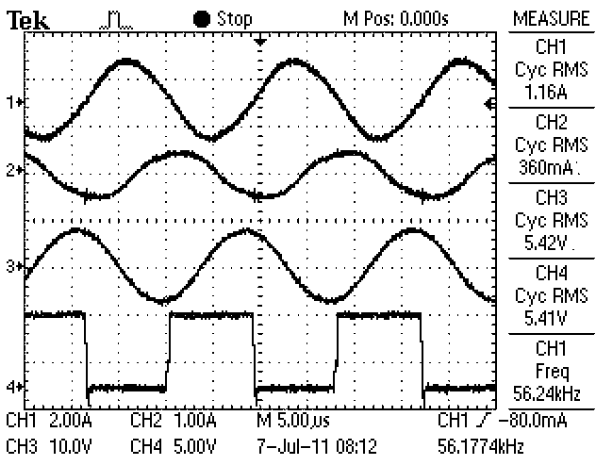

Fig.3. Oscillograms of (top to bottom): current in *L1* inductor, current in *L2* inductor, voltage on the *L2* inductor, voltage on the output of half-bridge SP-LCLC resonant power converter for a case where input voltage is supplied from two lithium-ion batteries connected in series giving 7.2V, and nominal output power is 3W

By selecting proper elements the shapes of voltages and currents may be close to sinusoidal which is desired in order to achieve high efficiency and low EM disturbance emissions.

Integrated reactance module

In order to minimize the number of elements and the final product size, a specialized integrated reactance module was introduced, incorporating all high current inductive elements. A quality factor limiter was added to control overvoltages and overcurrents that may occur in the circuit. The limiter consists of L3 inductor winding and D3 rectifier. It's main function is to return the excessive energy stored in the resonant circuit back to the source. This also guaranties continuous and steady current flow in resonant circuit elements independently on the load, where output can change from short circuit, through nominal to open. This helps to reduce size and cost of the final product, increasing reliability and efficiency, by properly shaping the magnetic flux.

In order to optimise IRM construction, field distribution simulations were conducted using COMSOL environment. Several geometries were studied. The most promising one is shown in fig. 4. The simulation was performed using axial symmetry.

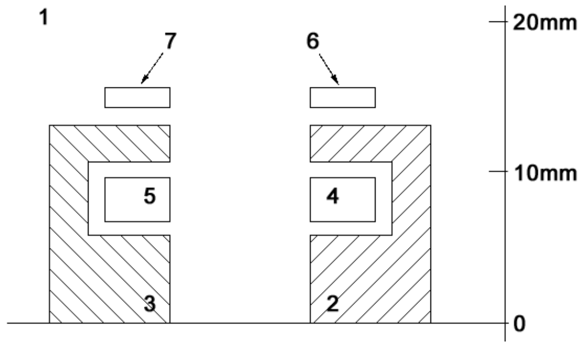

Fig.4. Geometry of the magnetic element used in magnetic flux distribution simulation conducted in COMSOL environment: 1 – surrounding air, 2 – magnetic core of transmitter IRM, 3 – magnetic core of receiver IRM, 4, 6 – innermost windings of *L1* inductors, 6, 7 – outermost windings of *L2* inductors

Fig. 5A shows magnetic flux density with field lines for a case where outer (*L2*) windings do not conduct current while inner (*L1*) windings conduct unity current. Fig. 5B shows the current induced in inner and outer windings of a contactless receiver-load. For air gaps below 15mm the current flowing in inner windings is dominant. Above 15mm outer windings current is more significant.

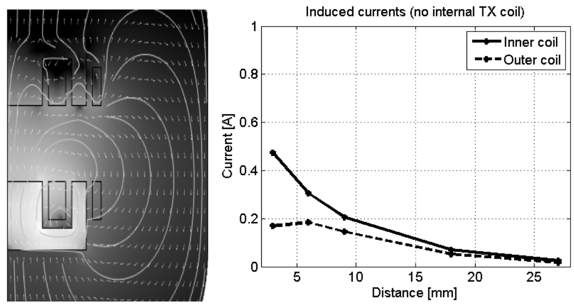

Fig.5. (A) Magnetic flux density with field lines for the case where outer (*L2*) windings do not conduct current while inner (*L1*) windings conduct unity current. The lighter the colour the larger is flux density. (B) Currents induced in outer and inner receiver coils vs. air gap distance

Fig. 6A shows magnetic flux density with field lines for the case where inner (*L1*) windings do not conduct current while outer (*L2*) windings conduct unity current. Fig. 6B shows current induced in inner and outer windings of a contactless receiver-load. Similar to the previous case, the current flowing through inner windings is dominant up to 15mm, above this value the outer windings current is larger. The difference is the coupling factor between inner windings of the transmitter and receiver, which evidently is better for short distances, up to 10mm.

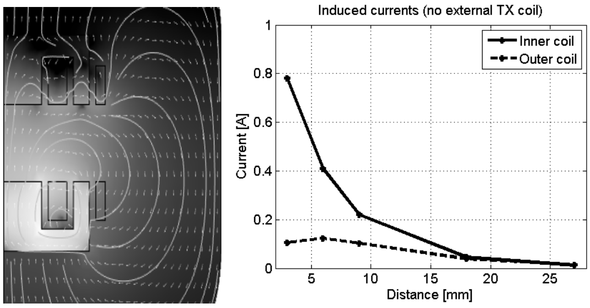

Fig.6. Magnetic flux density with field lines for a case where inner (*L1*) windings do not conduct current while outer (*L2*) windings conduct unity current. The lighter the colour the larger is flux density. (B) Currents induced in outer and inner receiver coils vs. air gap distance

Fig. 7A shows magnetic flux density with field lines for the case where both inner (*L1*) and outer (*L2*) windings conduct unity current. Fig. 7B shows the current induced in inner and outer windings of the receiver-load. Thanks to such currents a superposition of two magnetic fluxes occurs and the coupling factor remains relatively high over the whole distance between the energy transmitter and receiver. Additionally, thanks to reverse winding direction of *L1* and *L2* the flux density in the core outer column is minimized.

Conclusion

The contactless inductive energy transmission technology increases both: the safety and reliability of power supply units. Abandoning any electrical contacts between devices brings new advantages that reduce maintenance effort. No wear and tear on the electrical contacts, no contact resistance, no spark formation and no unprotected voltage-carrying contacts are crucial in many applications. These features are especially important in environments where gas or dust ignition hazard occurs, such as mines, fuel stations and chemical laboratories, as well as those applications where the use of direct connections is impractical, such as moving components or underwater devices. The presented contactless power supply system with bidirectional wireless energy transfer was developed to provide removable and rechargeable battery power supply, that is able to operate in a potentially explosive atmosphere. The designed device is cost-effective and allows construction of highly efficient power supply systems. In the presented solution both: the energy transfer from a battery and the battery charging are contactless.

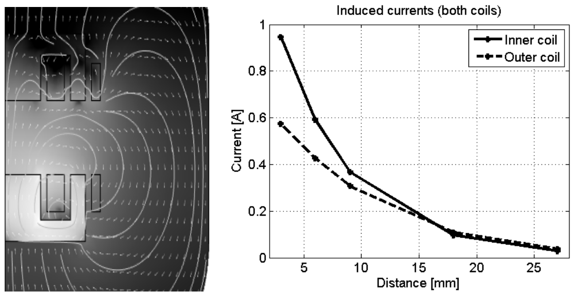

Fig.7. (A) Magnetic flux density with field lines for the case where both inner (*L1*) and outer (*L2*) windings conduct unity current. The lighter the colour the larger is flux density. (B) Currents induced in outer and inner receiver coils vs. air gap distance

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