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Journal of ELECTRICAL ENGINEERING, VOL 68 (2017), NO3, 235–244

REVIEWS - LETTERS - REPORTS

Technological inductive power transfer systems

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Inductive power transfer is a very fast expanding technology with multiple design principles and practical implementations ranging from charging phones and computers to bionic systems, car chargers and continuous power transfer in technological lines. Only a group of devices working in near magnetic field is considered. This article is devoted to overview of different inductive power transfer (IPT) devices. The review of literature in this area showed that industrial IPT are not much discussed and examined. The authors have experience in design and implementation of several types of IPTs belonging to wireless automotive chargers and to industrial application group. Main attention in the article is paid to principles and design of technological IPTs

Keywords: inductive power transfer, technological IPT, magnetic coupling, magnetic field lines, matching

1 Introduction

An idea of contactless power transfer using electric, magnetic or electromagnetic fields very early stage of practical use of electrical energy. The main pioneering contributions were made by N. Tesla who invented and demonstrated power transfer systems (1888–1890) using electric field and even more important, resonant inductive coupling in near zones [1, 2]. The later operating principle is being widely used at present time, *eg* it is deployed in Qi power transfer systems, passive RFID tags and contactless smart cards. It lays also behind the newer wireless power transfer systems with a range up to 2 meters, such as WiTricity [15].

An impressive demonstration of power signal transfer was made by Indian scientist J.C. Bose. In November 1894 in Kolkata, he ignited gunpowder and rang a bell at a distance using microwaves (millimeter range). Signal transfer using electromagnetic waves became a foundation for all radio communication and related technologies and industries. However power (energy) transfer did not attract much attention till the second half of 20th century.

At present time near field IPT attracts more and more attention due to dramatic progress in power generation and conversion on one side and, on other side, huge increase in types and numbers of electric and electronic devices, higher demand for convenience, reliability, productivity and environment protection. The early applications of IPTs relate mainly to transportation. For example, an IPT system was developed in St. Petersburg, Russia, around 1940 for a vehicle receiving energy inductively from two cables. In 1950s similar systems were used in coal mines with explosive atmosphere and other hazardous environments. At present time the use of IPT systems expanded to residential and communication devices, electric vehicles, aerospace, biomedical, robotic and high speed technological applications. The frequency used in these systems ranges from several kilohertz to several megahertz and power from few milliwatts to several tens of kilowatts and even more.

From electrical point of view a near field IPT device is inherently a transformer, which transfers electrical energy from the primary block to the secondary due to magnetic coupling. There is no energy transfer due to electric contacts of these two components or electromagnetic radiation. Use of IPT eliminates problems caused by electrical contacts (space, arcing, sparking, wearing, corrosion and erosion). The difference between IPT and normal transformers is that at least one part of device is moving (linear movement or rotation) or is movable, and therefore the magnetic circuit isn't completely closed. Movement may be rather fast, up to 40000 rpm in rotation and up to 20 m/sec or even more in linear devices.

The main advantages of IPT systems are

- no need for sockets, cables and moving contacts;
- improved safety level due to absence of exposed live parts and "loose" wires or cables;
- galvanic separation of live parts of the power supply and those of the load;
- high reliability compared to sliding contacts;
- no pollution of the environment with wearing debris;
- low service demand;
- user friendliness, especially for electronic and low power devices.

These advantages of the IPT systems are very important for boosting the consumer's interest and acceptance, which leads to an increased demand on the market.

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DOI: 10.1515/jee-2017–0035, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

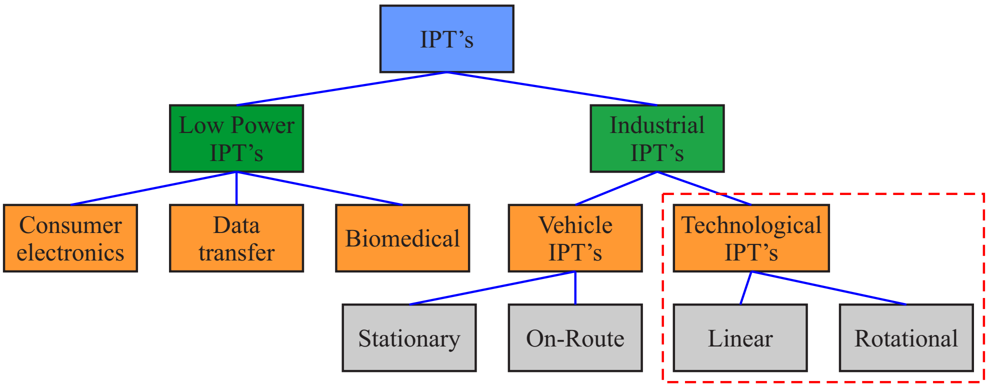


Fig. 1. Different groups of IPTs

There are some drawbacks of IPTs:

- higher price than conductive power transfer;
- sensitivity to mutual positioning of primary and secondary parts (transmitter and receiver);
- lower efficiency due to additional losses in IPT device, especially when the size of receiving part is significantly shorter than the transmitting part and the "coupling gap" is not small.

Depending upon application, IPTs can have very different design and they may be attributed to different groups — Fig. 1.

A wide variety of IPTs for charging phones and other electronic devices, as well as charging implants and diverse tools may be conventionally attributed to Low power group. They can have different number of degrees of freedom according to possible mutual positioning of transmitter and receiver, up to 6 (coordinates x-y-z and 3 Euler angles).

IPTs for charging car batteries have 3 main degrees of freedom (x-y-z), though a yawing angle can have certain influence, which depends upon the system design. For a fixed distance z a number of degrees of freedom drops to 2, which makes easier optimization and standardization. It is important that only few (one or two) degrees of freedom are typically essential for the energy transfer. Other degrees, such as tilting and rolling angles, can play a role of "perturbing" factors with small effect on coupling coefficient of the receiver and transmitter and respectively, on the transferred power level and efficiency. The IPT secondary side contains a device which controls battery charging voltage and power. Through the industrial Wi-Fi feedback it sends signals to the HF generator on the primary IPT side in order to regulate the battery charging parameters. There are many not considered in this paper.

2 Technological IPT systems

Technological IPTs have several specific features compared to small power and vehicle IPT chargers:

- fewer degrees of freedom, usually one or two;
- high duty cycles, up to 100 %, which requires accurate analysis of the IPT and related equipment temperature;
- big variety of the secondary loads, from motors and actuators to resistive or inductive heaters or ultrasonic tools with complex equivalent electrical circuit;
- demand for high stability and repeatability of parameters;
- in majority cases, there is no special feedback link and the only way to control the load parameters is an analysis of the IPT input parameters;
- gaps between primary and secondary blocks are usually small (millimeters or even less), which allows to design very efficient devices;
- special environment (explosive, aggressive, vacuum, underwater, clean or aseptic).

Technological applications require transfer of relatively high powers, from hundreds watts to tens or even hundreds kilowatts. Stability and high efficiency are the main requirements to technological IPTs, which must be provided by careful design and advanced control system. To improve efficiency and provide better matching and control, in some cases it is reasonable and possible to install on the secondary side of IPT additional components, usually capacitors. In many systems, such as packaging machines [6], one IPT supplies one after another multiple inductors, mounted on a chain. It is obvious that parameters of these inductors may be slightly different, mainly due to variation in parameters of the packaging material. Though these differences are small, they can cause significant impact on quality of the package seam. In this case matching due to careful setup of the system is insufficient and additional channels of regulation are necessary. The main additional control of matching is made by means of frequency sweeping at low signal when each new inductor with its own receiving block "coupled" to IPT primary, and power is activated. A control system of the power source analyses impedance, select optimal frequency and deliver a pulse of technologically required power. When necessary, an additional correction of matching setup may be performed automatically by connection of parallel capacitors on the IPT primary by means of electronic switches — Fig. 2 [7].

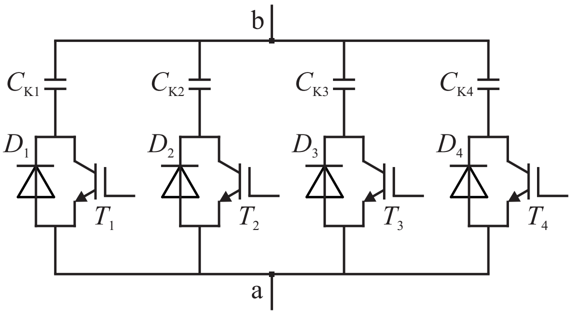


Fig. 2. Four positional electronic switches

A wide range of linear and rotating IPTs for various technological applications has been proposed and used in industry [3, 4, 8, 9, 12]. Some examples of technological applications are shown below.

Clean factory automation – IPT systems are used in the factories for automatic manufacturing flat panel displays, computer CPU's and other Integrated Circuits (IC's) under stringently clean conditions [16] — Fig. 3(a).

Dynamic and static battery charging of industrial transport units, so called intelligent transport devices. In this application IPT systems are usually supply up to 5 kW of power per each unit at a relatively small and almost constant distance of several millimeters [17]. Due to controlled trajectory, lateral displacements can be small. These systems are used for transporting and storing in multiple manufacturing plants including car manufacturing lines, *eg* in engine and gearbox assembly lines (Fig. 3(b))

Power transfer in high-tech automated systems [9, 15], [17] – in this case high speed IPT systems transmit energy to linear or rotary moving equipment — Fig. 3(c). A load, connected to the IPT, can have R-L impedance (HF inductor or motor) or R-L-C impedance (US transducer with a complex character of impedance)

Traffic control [9, 16] – IPTs are used for signal systems for traffic control. For example, to separate two traffic lanes in tunnels, illuminated pointers mounted on the roadway — Fig. 3(d). In this application there are many disadvantages associated with contact power supply: cables, need for junction box for each signal light, contact links and others. With contactless power transfer to each signal light can avoid these disadvantages with an additional advantage of easy assembling and position change.

Induction heating [10] – in non-rotational induction heating of crankshafts and camshafts the common problem is non-reliable electrical contacts between two parts of the "clamshell" induction coil. As an alternative, the induction coil may be made of two parts for simultaneous heating of two pins or cams. A "stationary" part is connected to power source. The second part is "removable" and connected to the primary one by means of magnetic coupler — Fig. 4. Coupler has very small gap and high permeability of materials and the induced current in the "passive" part of the coil is almost equal to the primary current

3 Rotational IPT systems

Rotational (rotary) IPTs are being used in several technological processes such as Rotary Ultrasonic Machining (RUM). Piezoelectric ultrasonic transducer is incorporated in a rotating spindle that drives a hard alloy

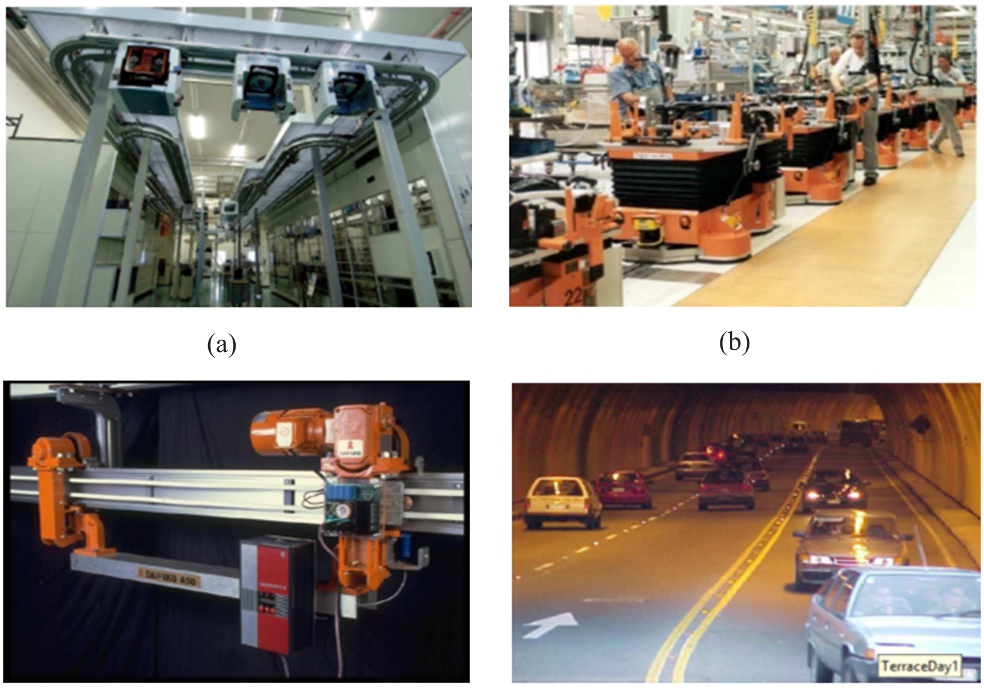
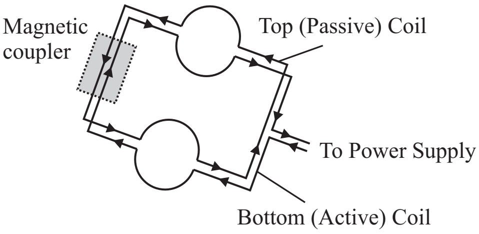

(a)
(b)

Fig. 3. Various industrial applications of IPTs: (a) – clean factory automation, (b) – dynamic and static battery charging of intelligent transport devices, (c) – industrial automation system, and (d) – traffic control



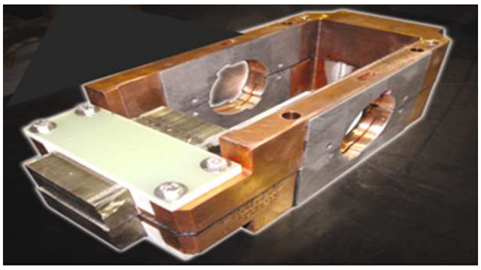


Fig. 4. Scheme of induction coil with magnetic coupling (left) and assembled coil (right), design of inductoheat [10]

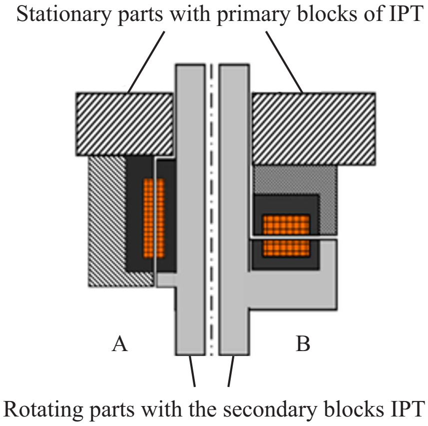


Fig. 5. Rotary IPT devices – no magnetic tensile stress distribution in the (a) – axial IPT and (b) – radial IPT

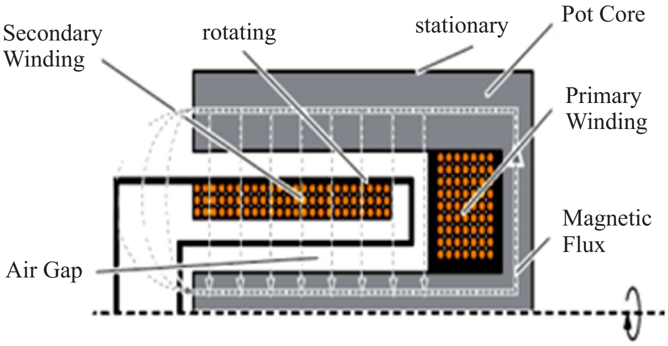


Fig. 6. Design of IPT without rotation of magnetic cores [11]

or diamond tool. Combination of rotation and US vibration provide higher speed of machining (drilling, milling) and better tolerances [4, 5, 11]. Tough the principle of this technology is known for many years, its industrial application started mainly in 2000s for machining rocks, hard ceramics, silicon and special alloys. Significant research works are being conducted at present time on this advanced technology [9].

Figure 5 shows two designs of rotary IPTs – with axial and radial positions of windings. Two factors leads to good IPT performance in RUM applications: small and stable coupling gaps compared to linear IPTs and capacitive reaction of US transducer impedance. Frequency must be precisely selected and adjusted for good matching of transducers with highly resonant characteristics. Typically frequency is in a range 20–30 kHz. Special attention must be paid to significant stresses in IPT components (windings and cores) caused by fast rotation, up to 10.10^5 rpm. An example of design without rotation of magnetic cores (only the secondary winding is rotating) is presented in Figure 6. However this design has low electromagnetic parameters: big magnetization current and stray flux.

4 Typical designs of linear IPT systems

Majority of technological IPT devices belong to linear systems with the much longer primary blocks than the secondary. As a result, the "empty" portions of the primary block create additional inductance and resistance causing additional losses and voltage drop. For high frequency applications these factors are especially important and must be seriously addressed during optimal development process. Individual design and optimization are required for each application. In general, all IPT devices consist of the following 4 basic components or their groups: primary winding and magnetic core, secondary winding and magnetic core. Depending on positioning and movement of these parts there are three basic mechanical concepts for the IPT device.

Type 1: moving secondary and partial or complete moving of primary – this is more similar to a traditional transformer, just with both components moving in concert with one another. This is the best solution in terms of all electrical parameters. The main complication is related to mechanical motion of the primary and how the primary cables and connections would hold up under service conditions. This solution is a reasonable choice for low speed applications

Type 2: moving secondary, stationary primary – this type is different from traditional transformers in that the primary should be significantly longer than the secondary. Due to this, there will be inherently high stray flux in the system, which leads to a relatively low power factor and low coupling of the primary and secondary blocks. This concept is typical for high speed applications.

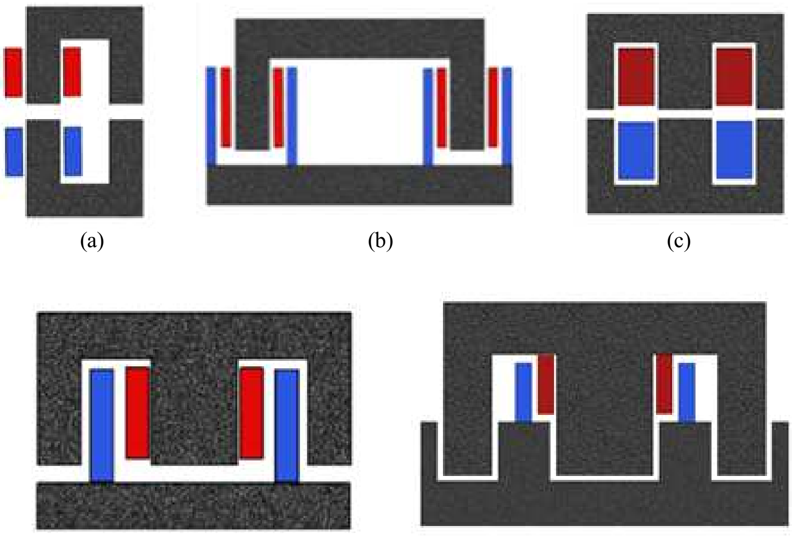


Fig. 7. Main configurations of linear IPT devices: (a) – C-shaped to C-shaped core, (b) – flat core to C-core, (c) – E-core to E-core, (d) – flat core to E-core, (e) – inverted E-core to E-core

Type 3: moving secondary, stationary primary with switching active zone. It is a solution that tries to reduce the stray flux for Type 2 without adding the mechanical complexity of Type 1. This solution could have the best potential for real world performance for machines that require a very long primary (dynamic charging of electrical vehicles, *etc*)

Required power, frequency and multiple mechanical demands and limitations define the system type and configuration of active parts. Main versions of IPT cross-sections are presented in Fig. 7.

(a) C-shaped core to C-shaped core

An advantage of this design is simplicity and small required space. If solid copper is used for the primary and/or the secondary, the current will flow along the outer face of the secondary and primary copper due to the concentrator effect and copper losses will be high. Another drawback is high sensitivity of ITP parameters to variation of coupling gap.

(b) Flat core to C-shaped core

There are two main advantages of this design compared to the E-shaped Core to E-shaped Core. The first is that in this design with popped-up primary winding the stray flux of the ”passive portion of primary is significantly lower than for design a). The second advantage is good “coupling” between the windings and low losses in copper because of large surface provided for high frequency currents to flow. The windings may be connected in series or in parallel, which is favourable for matching. Main disadvantage is high sensitivity to coupling gap variation and strong requirements to side displacements of the secondary.

(c) E-shaped core to E-shaped core

This configuration is close to traditional transformers. The advantages of this design are low external magnetic field and good space available for copper and losses in windings if Litz wire is used for them. For solid conductors losses are high. There are two main disadvantages of this design: inherently high stray flux in “passive” zones and high sensitivity to vertical displacement of the secondary.

(d) E-shaped core to Flat core

This design provides low copper losses and low stray flux in “passive” portion of primary. Compared to version (b), it is more compact and has more simple connection of leads. High sensitivity to vertical displacement of the secondary is the main drawback.

(e) Inverted E-shaped core to E-shaped core

This design has advantages of case d) with much improved magnetic coupling of cores, which strongly reduces sensitivity to gap variation. Simulation and experiments proved effectiveness of this design for high speed machines with high demand to stability of power transfer. In this paper main attention is paid to this design.

Computer assisted study and experimental validation showed that a difference in IPT performance (efficiency, reactive power, power limit) can be very large for different types of system [6]. For example, in evaluated case the input reactive power of IPT with design (c) was almost

3 times higher than with design (e) for the same active power at the IPT output.

5 Winding and cores

5.1 Winding design and materials

The secondary winding goes around the magnetic core and must have leads for connection to the load busswork. This winding has a good mechanical support and can be made as one or several turns of copper strip or as multiturn block from Litz wire for any configuration of IPT device.

Situation with the primary winding is more complicated. In linear IPT systems the primary winding, covering full length of the core, must not obstruct the motion of the secondary magnetic circuit. This factor gives advantage to windings submerged into the core material, which allows is favourable to making multi-turn winding of Litz wire. However, as it was discussed earlier, submerged windings lead to high stray flux in "passive" portion of the device, especially when winding is made of Litz. The most efficient are designs Figs. 7(b), (d) and (e) with “popped-up” primaries. These windings must be mechanically strong for “self-support” and must have the bending zone. It gives advantages to winding made of few turns of strip, with one turn the most desirable from mechanical and electrical points of view. Losses in solid primary winding and especially losses in bending zones can be significant and can lead to overheating of this component and reduction of the IPT efficiency. Selection of turn number is very important because it defines the level of voltage, at which IPT must operate. In turn, voltage and frequency define the core cross-sections and dimensions. In specific cases of high load voltage, which for ultrasonic transducers can exceed 1000 Vrms, it is reasonable to install a step-down transformer on the entrance of IPT with a single turn primary winding. High output voltage can be obtained by using multiturn secondary winding.

In rotary IPT it is natural to make both primary and secondary windings as multiturn blocks of Litz wire. In order to minimize losses in copper, Litz wire gauge must be optimal for a given working frequency and selected winding design.

5.2 Magnetic circuit materials

Selection of magnetic material for the primary and secondary cores is very important. Ideally, in an active zone both cores must have as high permeability as possible. In “passive” zone situation is opposite: low permeability of the core is desirable, especially for designs (a) and (c) in Fig. 7. High core permeability in this zone leads to big voltage drop and increased losses. It means that different materials can be ideally used for primary and secondary cores.

It is natural to evaluate use of standard E-shaped ferrite for the secondary core in designs (c), (d) and (e), see Fig. 7. Ferrites have high permeability and low losses at high frequency if properly selected. Well-known drawbacks of ferrites, such as relatively low saturation flux density and low Curie temperature, usually aren't important in HF IPTs. More essential are relatively big dimensional tolerances of large standard pieces. This factor can be prohibitive in IPTs with small coupling gaps between the cores, which can be as small as 1 mm. Possible dimensional selection (sorting) or machining of ferrites pieces are expensive. Assembling of cores from individual pieces by gluing does not give reliable construction. Increase of air gaps is not desirable due to reduction in electrical efficiency and lower repeatability from one cycle to another.

Another group of magnetic materials for high frequency IPTs is Soft Magnetic Composites (SMC) presented on the induction market mainly by Fluxtrol products [14]. Fluxtrol materials can be used in a wide range of frequencies, from line frequency to several megahertz and have permeability from 18 to 100 depending on type. Materials have excellent machinability and are produced in wide range of dimensions with plates up to 216×165 mm. Therefore, for the primary magnetic circuit a machinable SMC material should be considered. The secondary magnetic core can be made from SMC or ferrite, depending of application. Lower permeability of SMC compared to ferrites in majority cases does not cause significant adverse effect on the performance of the IPT due to presence of air gaps in the magnetic circuit. It is important that SMC are quasi-linear materials, *ie* their permeability does not vary much in a wide range of magnetic inductions, especially for HF materials such as Ferrotron 559H [14]. Quasi-linearity is a positive feature for stable performance of IPT.

Iron-based SMC can rust in oxidizing atmosphere and must be protected by Teflon or other coating to prevent possible rusting and to meet the process environmental requirements.

6 Optimal design of IPT

Optimal design of IPT must be developed on the following multi-factor basis

- required power, frequency and duty cycle;
- type and parameters of the load;
- available space on the machine;
- weight and mechanical strength of device;
- magnetic saturation and losses in the cores and winding;
- service environment (temperature, atmosphere, water or air cooling, *etc*;
- acceptable air gaps defining magnetic coupling between the primary and secondary cores.

The analysis of the IPT is similar to methods used with the high-frequency transformers. The equivalent magnetic circuit has three main components – magnetomotive force MMF, magnetic core reluctance – R_{fer1} and R_{fer2}

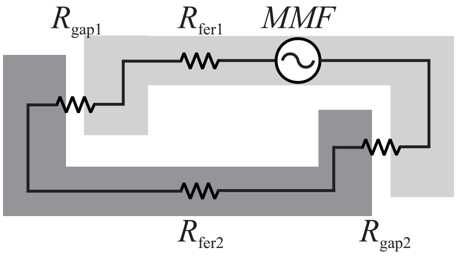


Fig. 8. IPT magnetic circuit

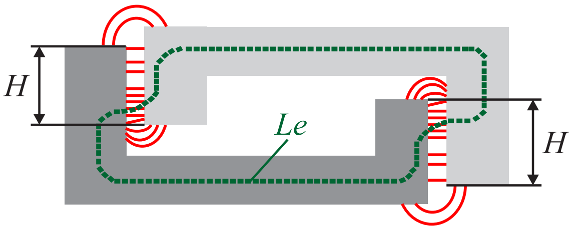


Fig. 9. Effect of core overlapping

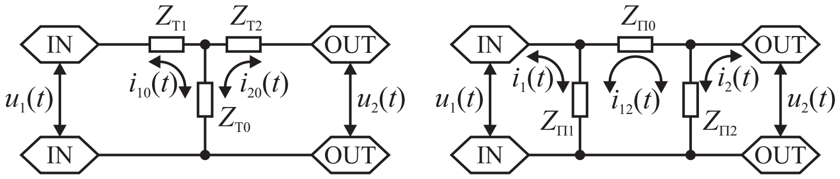


Fig. 10. IPT equivalent circuit (a) – T-scheme, and (b) – Π - scheme

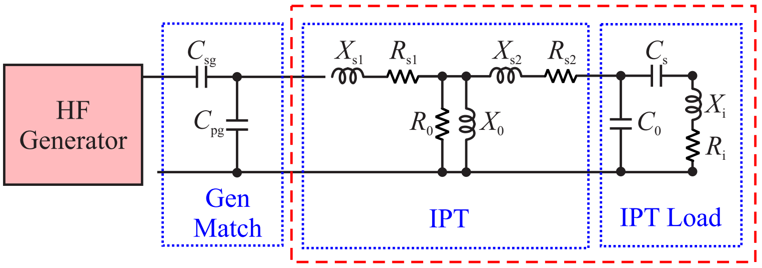


Fig. 11. Equivalent circuit of ipt with matching capacitors

and air gap reluctance – R_{gap1} and R_{gap2} (Fig. 8). In order to simplify the calculations the two magnetic cores reluctances and the two air gap reluctances are combined

The magnetic reluctance of air gap and magnetic core are

$$\begin{aligned} R_{\mathrm{gap}} &= l_{\mathrm{gap}}/(\mu_0 A_{\mathrm{g}})\,, \\ R_{\mathrm{fer}} &= l_{\mathrm{fer}}/(\mu_0 \mu_r A_{\mathrm{fer}})\,, \end{aligned} \tag{1}$$

where A_{g} and A_{fer} are cross section of air gap and magnetic core and l_{gap}, l_{fer} – their length.

The expression of the air gap reluctance is corrected by a factor K_A, which is used for adjustments due to the increased equivalent cross section in the air gap zone

$$R'_{\mathrm{gap}} = l_{\mathrm{gap}}/(\mu_0 A_{\mathrm{fer}} K_A)\,, \tag{2}$$

where $K_A < A_{\mathrm{gap}}/A_{\mathrm{fer}}$.

It can be noted that K_A is a coefficient, which is analogous to the magnetic permeability of the magnetic core and its influence grows when the ratio of μ_r/K_A decreases, *ie* for cases with low magnetic permeability of the material and/or large equivalent air gap cross section.

The equivalent magnetic permeability of the equivalent magnetic circuit is adjusted with respect to the cores overlapping effect (Fig. 9) using (2):

$$\mu_e = \frac{\mu_T}{1 + (R'_{\mathrm{gap}}/R_{\mathrm{fer}})}. \tag{3}$$

The individual inductances of the primary and the secondary are determined with the equivalent magnetic permeability μ_e and turns number N:

$$L = 1.257 \mu_e N^2 A_{\mathrm{fer}} \times 10^{-8}/L_{\mathrm{fer}}\,. \tag{4}$$

The value of the mutual inductance M can be calculated as

$$M = k\sqrt{L_1 L_2}\,. \tag{5}$$

where k is the magnetic coupling coefficient.

It is not an easy task to determine the values of the coefficient k analytically, because it depends on many parameters including the transformer geometry, misalignment of the windings, magnetic way and *etc.* However, its real value can be measured using open circuit and short circuit configurations

$$L_{\mathrm{oc}\text{-}n} = (1-k)L_n\,;\; L_{\mathrm{sc}\text{-}n} = (1-k^2)L_n \tag{6}$$

where $L_{\mathrm{oc}\text{-}n}$, $L_{\mathrm{sc}\text{-}n}$ – windings inductances, measured with open circuit and short circuit configurations.

The magnetization current of the IPT as a function of the flux density (at sinusoidal voltage) is presented analytically with

$$\begin{aligned} I_{\mathrm{magn}} &= \frac{BA_{\mathrm{fer}}}{N}(R_{\mathrm{gap}} + R_{\mathrm{fer}}) \\ \text{where}\quad B &= \frac{U \times 10^8}{4.44 A_{\mathrm{fer}} N f}. \end{aligned} \tag{7}$$

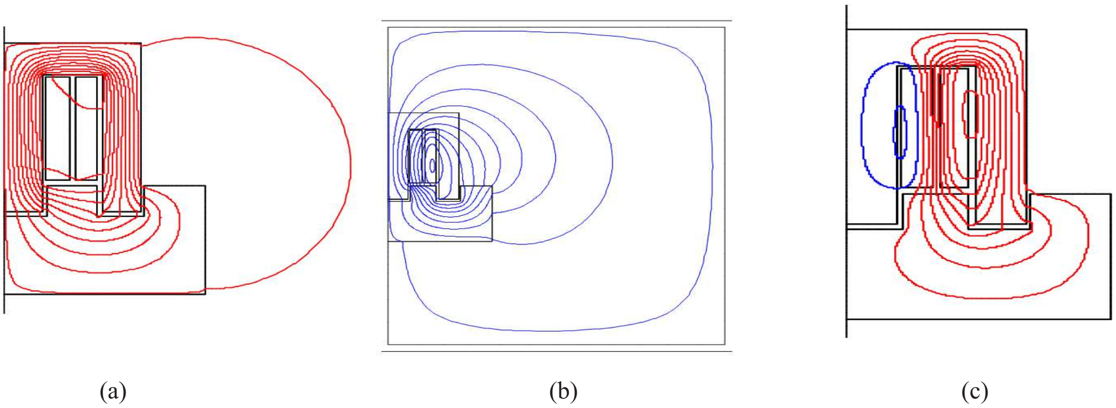


Fig. 12. Magnetic field lines for the "active" and "rails" zones of IPT with 1 mm gap: (a) – active zone with open secondary; (b) – rail zone (secondary core and winding described as air), (c) – active zone with short-circuited secondary

The next step after determination the IPT parameters is matching with HF generator and load. The best matching is when IPT is transparent to the high frequency and the generator "seen" directly load. The IPT device can be considered as quasi-linear quadripole and may be presented in the form of T equivalent circuit (Fig. 9(a)) with Z_{T1} – impedance of primary winding; Z_{T2} – impedance of the secondary winding, Z_{T0} – impedance of coupling, depending on quality of magnetic circuit. Another substitution scheme has Π-shape, where $Z_{\Pi 1}$ and $Z_{\Pi 2}$ – input and output parallel impedances and $Z_{\Pi 0}$ – "coupling" impedance (Fig. 9(b)). All impedances must be referred to the same turn number (primary or secondary).

Physical interpretation of schemes in Fig. 10 is different. In layout of T-scheme impedances Z_{T1} and Z_{T2} describe voltage drop (due to magnetic flux leakage) and Z_{T0} describes magnetization current. Scheme in Fig. 10(b) is dual to the scheme in Fig. 10(a). Impedances $Z_{\Pi 1}$ and $Z_{\Pi 2}$ are responsible for primary and secondary leakage current and $Z_{\Pi 0}$ – for voltage drop. For "good" IPT, Z_{T0} is much larger than Z_{T1} or Z_{T2} and therefore $Z_{\Pi 1}$ and $Z_{\Pi 2}$ are larger than $Z_{\Pi 0}$. Impedance Z_{T0} plays a key role in IPT characteristics and its value theoretically must be as high as possible.

T-circuit is more convenient for technological IPT than a Π-circuit, especially with a large length of the transmitting part, since the impedance of the area not covered by the receiving part is included in the equivalent circuit parameters. It could be conclude the T-scheme is better for clarifying the IPT operating principle and the Π-scheme – to implement the matching. T-equivalent circuit with matching capacitors is shown in Fig. 11.

In case of ultrasonic load capacitors Cs and Co, resistor Ri and reactance Xi describe the parameters of ultrasonic transducer. If the load is inductive, these capacitors can be eliminated from the circuit, or to be used as additional matching elements, necessary at higher frequencies. Capacitors Cpg and Csg can be used to adjust the IPT impedance to the HF generator, especially at dynamic mode, when their values can be changed from cycle to cycle using a high-speed electronic switches [7].

IPT parameters at the design stage can be found by computer simulation. Simultaneous modelling of whole IPT structure requires the use of 3D models and it can be quite difficult because of its large size and the vastly number of components. The process can be greatly simplified by splitting the IPT on specific two-dimensional or quasi-two-dimensional areas. Usually it is sufficient to simulate the working area (wherein the receiving part is magnetically coupled to the transmitting) and the "idle" zone. As an example, Figure 12 shows the magnetic field in the IPT working area at idle and short circuit on the receiving part

Figure 12 shows the magnetic field lines for the "active" length for a 1 mm gap between the primary and secondary magnetic circuits. The picture of Fig. 12(a) shows how magnetic field lines are distributed throughout the gap in the primary and secondary magnetic core. Magnetic lines cross the gap almost uniformly along the whole coupling gap circumference. Deep grooves help to reduce magnetization current and parameter variation with the gap change. Simulation of the rails provides parameters of the non-loaded part of the primary block-Figure 12(b). Three simulation cases of Fig. 12 allowed to calculate the IPT parameters as a 4-pole device for different selected materials and dimensions of the cross-section. The parameters of IPT device whit better accuracy could be obtained by real OC and SC measurements, as the modeling does not account the three-dimensional field in the end, bending zones and *etc.*

Usually IPT devices have a small nonlinearity, so it is relatively easy to create a program for calculating whole HF circuit, using Excel or another program. This allows quickly and precisely to investigate method of matching, including frequency and/or capacitors variation, as well as to determine the system sensitivity by the change of IPT and load parameters

The analytical calculator was developed by company Fluxtrol [14] for IPT performance evaluation and analysis of the whole circuit – HF generator, matching capacitors, IPT and technological load – transducer or inductor – Fig. 11. Using the calculator it is possible to determine loading of the generator (P, Q, U, I) and of all the circuitry

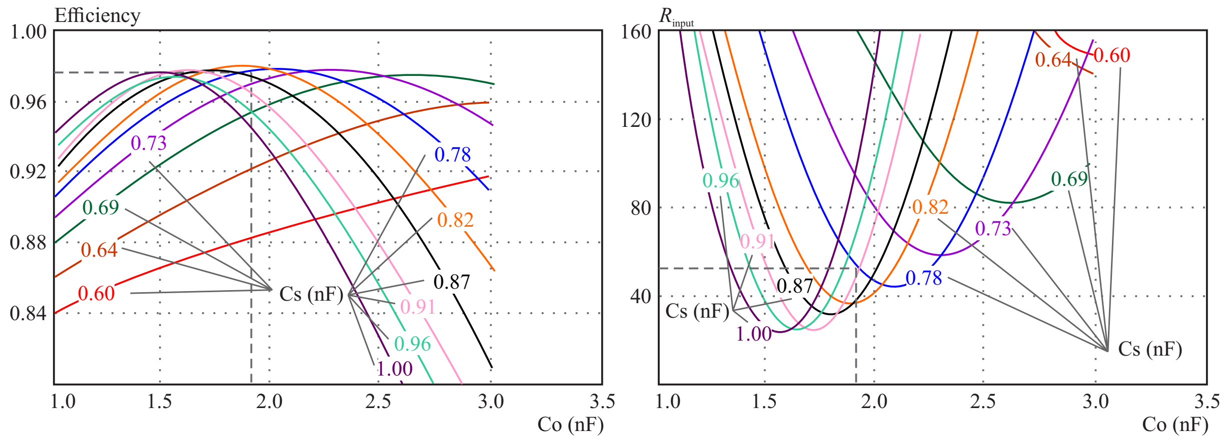


Fig. 13. Graphs for Co = 1.0–3.5 nF and Cs = 0.6–1.0 nF: (a) – of efficiency, and (b) – $\mathrm{R_{input}}$

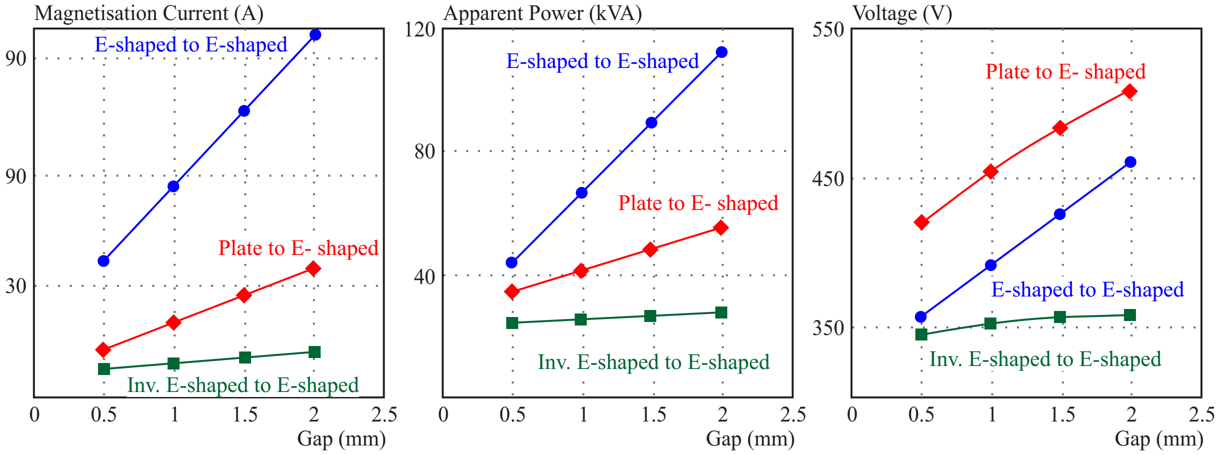


Fig. 14. Magnetizing current, primary apparent power, primary voltage *vs* air gap for different IPT devices

components (U, I and X for all capacitors). The program has an option of automatic building of graphs for the IPT efficiency and parallel equivalent resistor $\mathrm{R_{input}}$ versus $\mathrm{C_O}$ at a fixed set of $\mathrm{C_S}$ and as a result to define the areas of favourable matching.

Resistor $\mathrm{R_{input}}$ represents a parallel active component of the generator loading. It must be in a range 25–75 Ohm for full power delivery for more HF generators [10]. The curves in general help also to investigate an influence of the capacitor tolerances on the results of matching of any particular inductor. In general, matching of the inductors with high quality factors is more sensitive to variation of IPT parameters and capacitor values.

An example of matching for a coil with "difficult" parameters (Xi = 21.7 Ohm, Ri = 1.45 Ohm) is shown in Fig. 3. It is clear that there are multiple areas of good matching (combinations of Co and Cs) and final decision must be made with an account of available capacitor values, their number and influence of tolerances. One of possible points of matching (Co = 1.8 nF; Cs = 0.78 nF) that provides efficiency 97.6 % and $\mathrm{R_{P\,INPUT}}$ = 50 Ohm.

The IPT device must not only have favourable electrical parameters, but it also must have low sensitivity to gap variation. The electrical parameters of the IPT devices were studied at air gaps 0.5, 1.0, 1.5 and 2.0 mm. The parameters of the IPT devices are calculated based upon a total IPT length of 250 mm with the "active" length 45 mm and "Rail" area 205 mm respectively. The secondary current is held constant at 141.5 A at working frequency 500 kHz and power 2 kW. The load impedance is used for simulation with inductance 117 nH and resistance 0.104 Ω. Bending zones and lead areas are not included in these calculations.

In order to compare sensitivity to gap, there are 3 main parameters, which should be considered related to the IPT performance: magnetization current, primary voltage and primary apparent power. Figure 14 shows the how these parameters depend upon the gap for the three different IPT devices studied. The magnetization current describes how much additional current the primary must carry, resulting in higher primary winding loss. The primary voltage gives the core losses in the primary magnetic circuit. The apparent power shows how many kVA the HF power supply must handle or be compensated for by capacitors. Secondary IPT apparent power and voltage do not need to be compared since they will be the same for all cases, because the load parameters are identical.

The magnetization current, the apparent power and the primary voltage are lowest at all gaps for the Inverted E-shaped Core to E-shaped Core. It is also evident from

Fig. 14, that this core has significantly lower sensitivity than the other designs considered.

7 Conclusions

This paper presented a short review of the techniques used for the inductive transmission of electricity and each has their own advantages and disadvantages. The general design and analysis of a technological IPT systems has been introduced. Five linear and two rotating core designs for technological IPT systems are presented and the basic differences between them are demonstrated. It has be shown that the coupling coefficient is an important parameter for IPT systems as it determines the maximum output power and can have great impact on the system efficiency. It's proved that the core design plays an important role when maximizing the coupling coefficient. For this reason, 2D-models of inverted E-core to E-core are created and an analysis of the flux paths is performed showing how the coupling coefficient can be calculated. The coupling coefficient is determined for different scenarios as a consequence of varying frequency, value of matching elements and air gap for inductive and capacitive load. It is shown that the dependence of the air gap is much higher for the E-shaped to E-shaped cores and Plate to E-shaped core than the inverted E-core to E-core. This is an important fact because to achieve maximum power transfer capability the IPT system must be able to transfer its maximum power even in the worst operation point *ie* maximum misalignment. Hence, the selection of the technology is depends upon the number of parameters such required power, shape of the cores, distance, medium, application, complexity and cost.

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Received 30 May 2016

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