FERROMAGNETIC COILS FOR WIRELESS POWER TRANSFER

Aigars Laizans[1], Ainars Galins[1], Vitalijs Osadcuks[1], Aldis Pecka[1], Aivars Rubenis[2]
[1]Latvia University of Agriculture; [2]TransfoElectric, Latvia
aigars.laizans@llu.lv, ainars.galins@llu.lv, vitalijs.osadcuks@llu.lv, aldis.pecka@llu.lv,
aivars.rubenis@ivorygroup.eu

Abstract. The research paper deals with the investigation results of ferromagnetic wire use for wireless power transfer (WPT). Two groups of coils with a different size, winding material (copper and iron), and conductor cross-sectional areas were developed. Resistance and inductance of coils was evaluated, taking into account that iron is a ferromagnetic material, but copper – a diamagnetic material. It was found that there is substantial increase in coil inductance the when iron wire was used – by almost 20 % at 20 kHz, and by 7 % at 150 kHz, in comparison with the same type copper coil operating at the same frequency. A trend of impedance increase with increase of operation frequency was observed for both types of coils, but for the ferromagnetic material coil it was much more substantial – by more than 9 % when the frequency increased from 20 kHz to 150 kHz. Signs of Giant Magnetic Impedance (GMI) were observed there also - with current increase through the windings, impedance and inductance of the ferromagnetic coil increased, but for the diamagnetic coil – decreased. The research results indicate that further investigation of ferromagnetic material use in wireless energy transfer coils is necessary, as this could allow increasing the coil inductance in WET resonance circuits, thus decreasing the requirements for the capacitance and potentially increasing the power transfer intensity.

Keywords: ferromagnetic wire, coil, wireless energy, inductance, skin effect, resonance.

Introduction

Wireless energy transfer systems are becoming more and more popular in everyday life. Different electric energy transfer principles were used and tested, but the most developed by now is the magnetic resonant coil coupling [1; 2]. The system using this principle typically consists of four coils referred to as driving, transmitting, receiving and load coils [1]. The driving coil and transmitting coil, as well as the load coil and receiving coil are coupled inductively, but the transmitting and receiving coils are coupled magnetically at resonant frequency. The driving coil is supplying energy to the transmitting coil inductively (usually via magnetic link – intermediary transformer). The system is operating at the frequency, which is the transmitting coil resonance frequency.

The transmitting system is developed as *LC* resonance contour with relatively small resistance R, and the current and voltage in this system are substantially higher than in the driving coil because of the resonance. Industrial partners developing wireless power transfer systems for cars have agreed on the two basic frequencies to be used – 20 kHz for trucks and lorries, and 85 kHz for other cars [3]. Research is going on 150 kHz system development as well [3]. Choosing optimal *LC* parameters for such frequencies as resonance frequencies is becoming a challenge, taking into account limitations for the design – the transmitting and receiving coil radius less than 25 cm, possibly minimal height, potentially high voltage due to high WPT power levels – 30..50 kW and more (requesting special design of core wiring and capacitance allowing up to 3500 V operating alternating current (AC) voltage), and minimal parasitic losses in the surrounding environment [3].

Traditional WPT transmitting coils are designed as loop antennas [4] with one or few (3..7) turns of copper wire with a substantial cross section in order to minimize *R*, and Litz wire is being used also in order to reduce resistive losses due to the skin effect [5]. Inductance of such coil is rather small (10…20 μH), and to obtain the resonance for such coil at 85 kHz it is necessary to use the capacitance *C* = 350..175 nF [5]. Any increase in coil inductance could decrease capacitance – the WPT element, which has limitations as to break-through voltage. Capacitors with high break-through voltage usually are having low capacitance, and the prices are increasing drastically when capacity is increasing. Ferrite core is being used to increase the inductance, but this solution is delivering the weight increase, and the thickness of antennas becomes substantially bigger, which is not acceptable for the production as the costs increase substantially.

The aim of the research was to find a non-traditional way of inductance increase. Observation of recent developments in magnetic systems revealed that ferromagnetic materials are used rather more intensively, especially for designing magnetic sensors using the ferromagnetic resonance and employing the Giant Magnetic Impedance effect [7]. It was decided to study the ferromagnetic wire coil electromagnetic properties and to compare them with the results from similar design diamagnetic material (copper) coils, and evaluate the feasibility of the ferromagnetic coil use in WPT.

Coil Design Impact on Wireless Power Transfer

The main aim for the designer of WTP coil systems, especially the ones which are devoted to electrical transport accumulator charging, is to maximize the power transfer efficiency, at the same time to minimize the coil size, thus reducing the material costs.

When the transmitting coil excitation current effective value is constant, the maximum output power P on the load can be calculated using the following equation [1]:

$$P = P_{su} Q_s = \omega_0 I_p^2 \frac{M^2}{L_s} Q_s , \tag{1}$$

where P_{su} – power supplied to the coil system, VA,
Q_S – receiver circuit quality factor;
ω_0 – angular resonant frequency of the coil system, rad·s^{-1};
Ip – effective value of the coil current, A;
M – mutual inductance between the transmitting and the receiving coil, H;
L_s – inductance of the receiver coil, H.

Quality factor Q is an important element describing the wireless energy transfer quality. If series compensation of the receiver coil is used, Q is frequency dependent and can be calculated using the following equation [1]:

$$Q = \frac{\omega_0 L_s}{R_L + R_S} , \tag{2}$$

where R_L – resistance of the coil, ohms,
R_S – resistance of the load, ohms;
ω_0 – angular resonant frequency of the coil system, rad·s^{-1};
L_s – inductance of the receiver coil, H.

Inductance L_s of the receiving coil depends on the coil design and materials used. Mutual inductance M of the coil system depends on coil positioning and inductances of both coils. A widely used approach to inductance L phenomena explanation is that it is some kind of coefficient, and does not depend on outside factors like magnetic fields applied and current intensity through the conductor. The approach of inductance calculation usually is static, using the basic formulas, e.g., the following formula is being used for simple solenoid inductance calculation:

$$L = \frac{N\Phi}{i} = \mu_0 \frac{N^2 A}{l} , \tag{3}$$

where N – number of turns of the wire;
Φ – magnetic flux through the solenoid, Wb;
i – current through the conducting wire, A;
μ_0 – magnetic constant, $\mu_0 = 4\pi \cdot 10^{-7}$ H·m^{-1};
l – length of the solenoid coil, m;
A– cross section area of the solenoid, m^{-2}.

Applying (2) and (3) equations in equation (1), series system maximum output power equation is developed:

$$P = \omega_0 \frac{\Phi^2}{L_s} Q_s = \omega_0^2 \frac{\Phi^2}{R_L + R_S} = \omega_0^2 \frac{L^2 i^2}{N(R_L + R_S)} . \tag{4}$$

Resonance frequency of the receiving coil using series compensation can be calculated using the following equation:

$$\omega = \frac{1}{\sqrt{LC}}, \quad (5)$$

where ω – angular resonant frequency of the system, rad·s^{-1};
L – system coil inductance, H;
C – system capacitor capacitance, F.

Assuming that $\omega = \omega_0$, the series system maximum output power equation derived from (1), (2), (3) and (4) equation, becomes the following:

$$P = \omega_0^2 \frac{\Phi^2}{R_L + R_S} = \omega_0^2 \frac{L^2 i^2}{N(R_L + R_S)} = \left(\frac{1}{\sqrt{LC}}\right)^2 \frac{L^2 i^2}{N(R_L + R_S)} = \frac{L i^2}{CN(R_L + R_S)}. \quad (6)$$

The developed equation (5) shows that to achieve maximum power transfer under resonance frequency the designer has to increase inductance of the coil L, but keep minimal number of turns N, at the same time decrease capacitance C. The most usual solution for such systems is ferromagnetic core use in both coils, as wiring usually is made from copper.

Copper is the major material used in coil design because of high electric conductivity ($\sigma = 5.96 \cdot 10^7$ S·m^{-1}), and by occasion it is also diamagnetic, with relative permeability $\mu = 0.999994$ – very close to 1. Copper wires are being used in DC systems low frequency solutions and in applications, where minimal inductance is necessary. Magnetic systems, on the other hand, are using ferromagnetic materials, which have relative permeability $\mu = 20...1000$ (for ferrite) to 5000 (for 99.8 % pure iron), but with substantially smaller electric conductivity ($\sigma = 1 \cdot 10^7$ S·m^{-1}).

The hypothesis driven from the theoretical analysis made is the following: ferromagnetic material use for the WPT coil can increase the series coil inductance, and reduce the capacity required, thus increasing the series system maximum output power.

Limitation which should be taken into account – the impact of the wire magnetic properties on energy transfer through the conductor, when AC is applied, is known as the skin effect, which results in substantial increase in wire impedance, when AC frequency is increasing. This could reduce the expected result of ferromagnetic material use.

Internal inductance L_{int} of the wire created by the skin effect can be calculated using the formula:

$$L_{int} = \frac{1}{2\pi r}\sqrt{\frac{\mu}{2\sigma\omega}}, \quad (7)$$

where r – coil wire radius, m;
σ – electric conductivity, S·m^{-1};
μ – magnetic permeability, H·m^{-1};
ω – angular frequency, rad·s^{-1}.

The equation (7) states that L_{int} increases with magnetic permeability increase (e.g., ferromagnetic material use) and decreases, when angular frequency of the signal is increasing.

On the other hand, if ferromagnetic resonance and GMI effect in ferromagnetic materials could be initiated at lower frequencies, this could reduce the skin effect impact.

Materials and methods

The experimental research was done in order to evaluate the impact of frequency on coil inductance (impedance) and to measure the impact of current on coil inductance (impedance), when two magnetically substantially different types of wire materials – diamagnetic (copper) and ferromagnetic (iron) are used. Six air core coils were made (see Fig. 1, Table 1).

Coils were wound on ABS plastic tubes. Two types of wire material were used: copper alloy wire type PEV1.2 and PEV0.3 and uncoated iron wire type SV08, 1.2 mm. The configuration of the coil was chosen so that iron coils of two diameters are as close as possible to copper coils in DC resistance (coil pairs 2-3 and 5-6) and in external diameter (coil pairs 1-2 and 4-5).

The measurements were performed in two steps: using LCR bridge in order to evaluate the impact of frequency on coil inductance (impedance) and by measuring the phase angle using an oscilloscope – to measure the impact of current on coil inductance (impedance).

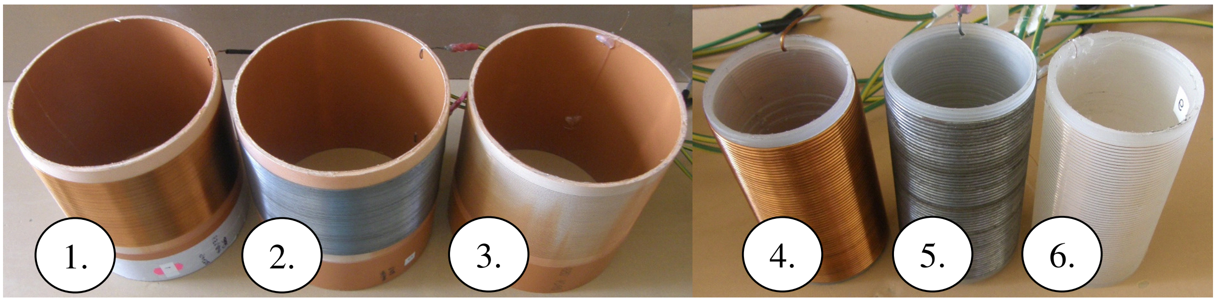

Fig. 1. **Coils used in the experiment**

Table 1

Main physical parameters of coils

Coil No.	C1	C2	C3	C4	C5	C6
Wire material	Cu	Fe	Cu	Cu	Fe	Cu
Wire diameter, mm	1.30	1.15	0.30	1.30	1.15	0.30
Coil external diameter, mm	159.2	159.6	158.4	55.5	55.9	54.5
Coil length, mm	90					
Windings	60					

Initially HIOKI 3532-50 LCR HiTester measurement bridge was used to determine the inductance and active resistance to frequency relation of coils. L and R parameters were measured for series equivalent model and the LCR bridge was set to constant voltage output 1 V with current limit to 20 mA. The measurements were made at the following frequencies: 20, 50, 80, 100, 120 and 150 kHz.

Then the measuring circuit was developed, using the function generator G1, power amplifier and oscilloscope in order to evaluate the coil performance, when changing current (see block diagram in Fig. 1).

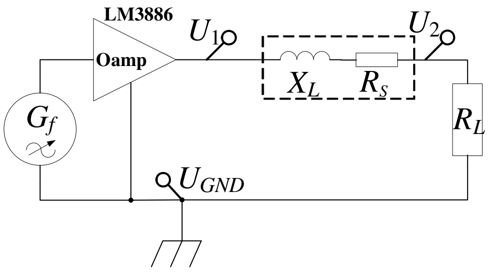

Fig. 2. **Block diagram of experimental setup**

Power amplifier supplies voltage U_1 to LR circuit, U_2 is the voltage on load resistance R_L, which is used for the current measurement.

The device Keysight InfiniiVision MSO-X 2024A was used as the oscilloscope and function generator. LM3886 integral audio power amplifier was used to amplify function generator signals. Measurements of the current effect were carried out using 1 kHz sinusoidal signal. The measurements were automated using PC. The time range of the oscilloscope was automatically set to cover two full periods of sinusoidal waveform. Voltage ranges were kept constant over entire measurement for each individual coil. To minimize the noise, ease the phase measurement and increase the accuracy by oversampling, each acquired waveform was averaged from 4096 measurements. Beginning of the waveform was marked with a trigger source from the waveform generator.

Phase angle between the input voltage U_1 and load resistance voltage U_2 was determined by finding zero crossing points of interpolated lines between two acquired waveform points with different signs for each voltage. Inductance of coils in this case was calculated using (8).

$$L = \frac{x_L}{\omega} = \frac{R\,\mathrm{tg}\,\varphi}{2\pi f} = \frac{(R_s + R_L)\,\mathrm{tg}\left(\frac{\tau_{zc}}{360}\right)}{2\pi f} \cdot 10^6, \quad (8)$$

where L – inductance, μH;
x_L – inductive reactance, Ω;
φ – phase angle, degrees;
f – frequency, Hz;
ω – angular frequency, rad·s^{-1};
τ_{zc} – zero crossing time of U_2 signal relative to U_1 zero crossing.

Coil current $\bar{I}_c$ was calculated as RMS value from voltage drop on the known active resistance R_L. DC series resistances of coils, R_L and total DC resistance of the experimental circuit were measured using the U-I method (both instruments Fluke 87). The DC series resistances of coils, shunts R_L and the experimental setup as well as the measurement ranges used in the tests are summarized in Table 2. For each coil one waveform with given test parameters was acquired.

Table 2

Parameter summary for tests

Coil No.	C1	C2	C3	C4	C5	C6
DC series resistance R_s, Ω	0.47	9.67	10.83	0.17	3.32	3.70
Load shunt DC resistance R_L, Ω	0.100					
Total setup DC resistance (excluding R_s) , Ω	0.119					
Voltage range U_1, V·div^{-1}	5	5	5	0.5	2	5
Voltage range U_2, mV·div^{-1}	100	50	50	100	100	100
Time range, ms·div^{-1}	0.2					

Results and discussion

The measurement results of all six coil inductances are presented in Fig. 3.

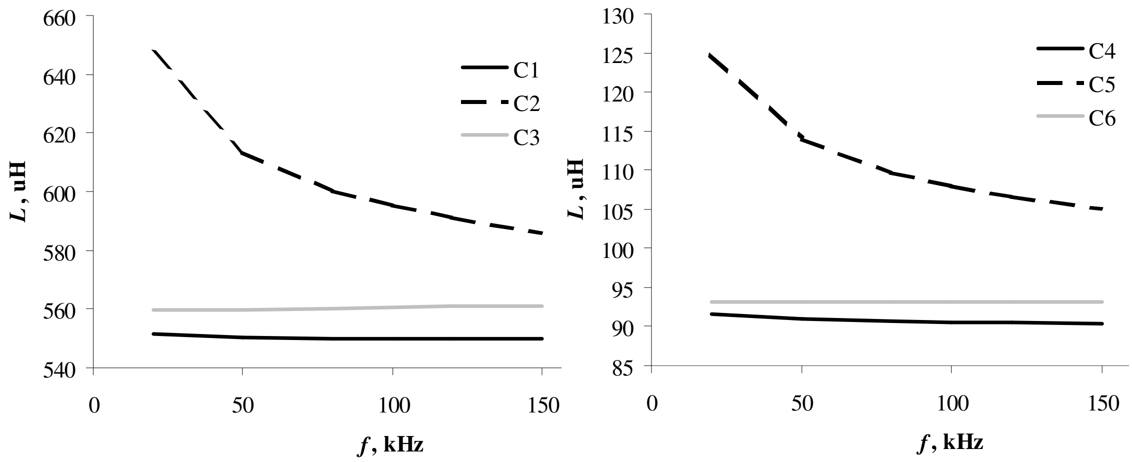

Fig. 3. **Inductance *L* of coils in relation to frequency**

Although equation (4) states that inductance directly depends on the coil cross section, analysis of the measurements shows substantial discrepancy – inductance of coils with a larger diameter has 5.5..6 times higher inductance, – inductance is 5.5 to 6 times higher, but it should be in average 8.2 times higher (small and large coil cross section difference). There is no direct explanation for this discrepancy, and further research should be done there.

Inductance of coils with the ferromagnetic wire show substantially higher values for both sizes of coils – it is 17.35 % higher at 20 kHz, and 6.45 % higher at 150 kHz for larger coils, and 36.3 % higher at 20 kHz, decreasing to 16.3 % at 150 kHz for small coils. As the inductance formula includes magnetic permeability (equation (3)), this could be due to ferromagnetic material permeability larger than 1, but this directly does not explain the next trend visualized from the graphs in Fig. 3 – inductance of the ferromagnetic coil shows strong dependence on the frequency – it decreases with the frequency increase from 650 µH at 20 kHz to 586 µH at 150 kHz for large coils, and the trend line is nonlinear. A similar trend was observed also for the small ferromagnetic material coil - inductance decreased with the frequency increase from 125 µH at 20 kHz to 105 µH at 150 kHz. The reason for this could lie in substantially stronger impact of internal inductance created by the skin effect (equation (7)), which is inversely proportional to frequency. The coils with the diamagnetic material wire did not show substantial inductance dependence on frequency, as their permeability is rather small, and internal inductance is much smaller in comparison with the inductance created by the coil design.

The resistance measurement results of all six coils are presented in Fig. 4.

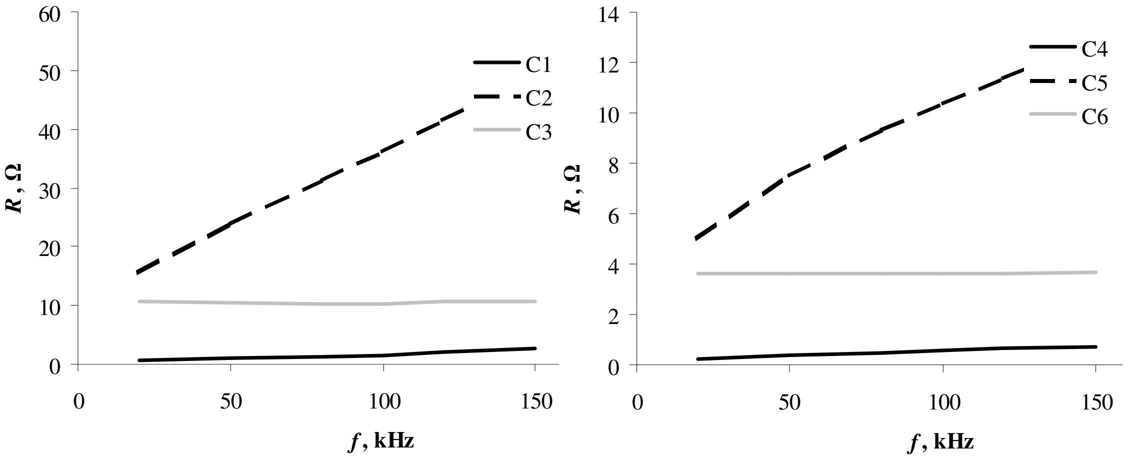

Fig. 4. **Resistance R of coils in relation to frequency**

Resistance of ferromagnetic coil shows strong dependence on frequency – it increases in line with frequency increase from 15 ohms at 20 kHz to 15 ohms at 150 kHz for large coils, showing a rather linear trend line. The same can be found for the small ferromagnetic material coil. The reason for this resistance change could be explained by developing and analyzing the coil resistance formula, which takes into account internal inductance from the skin effect (equation (7)). Coil resistance R_L equation, derived from equation (7), is the following:

$$R_L = R_0 + R_{skin} = \frac{l_w}{A_w\sigma} + 2\pi r\omega l_w L_{int} = \frac{l_w}{\pi r^2\sigma} + 2\pi r\omega l_w \frac{1}{2\pi r}\sqrt{\frac{\mu}{2\sigma\omega}} = l_w\left(\frac{1}{\pi r^2\sigma} + \sqrt{\frac{\mu\omega}{2\sigma}}\right), \quad (9)$$

where A_w – wire cross-section area, m^{-2};
l_w – coil wire length, m;
R_0 – wire DC resistance, ohms;
R_{skin} – wire resistance, created by the skin effect, ohms.

As R_{skin} is proportional to the signal frequency and wire material permeability, it increases in line with them, as it is seen in Fig. 4. Resistance dependence of coils with the diamagnetic material wire on frequency is much smaller, as μ is substantially smaller.

The current related phase angle measurement results for different wire material coils are presented in Fig. 5.

The experiment devoted to inductance and current relationship observation revealed that the coil with the ferromagnetic wire increased the phase angle (and inductance), but the coil with the diamagnetic wire – decreased the phase angle, when current through the coils increased. It seems that the signs of GMI are present, when the ferromagnetic material is used, and inductance increase from current increase can be part of this phenomenon.

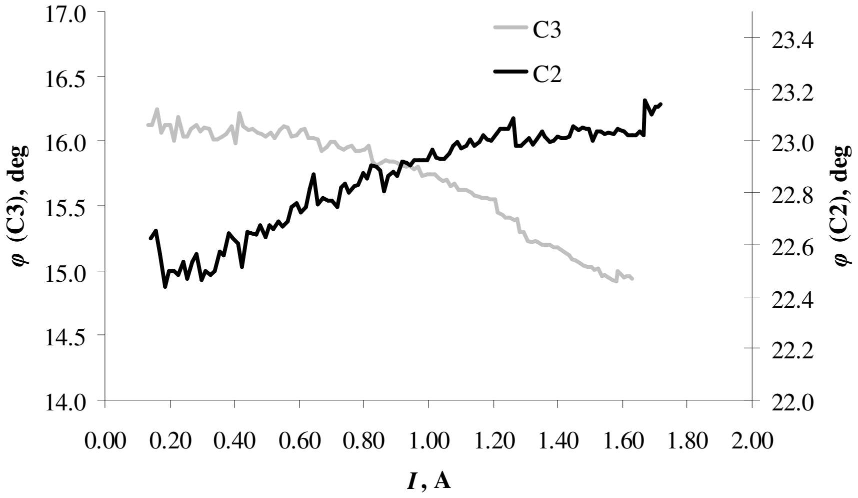

Fig. 5. **Coil phase angle in relation to current (large coils)**

Conclusions

1. The coils with the ferromagnetic wire differ substantially from the coils with the diamagnetic material – their inductance and resistance are substantially higher, and depend substantially on the signal frequency. With frequency increase from 20 kHz to 150 kHz inductance of the ferromagnetic coil decreased by 9.86 %, whereas the copper wire coil inductance did not change.
2. Inductance increases at 20 kHz by 17...36 %, when using the ferromagnetic wire in comparison with the same size coil using the diamagnetic wire in the WPT transmitter coil. This allows to reduce capacitance in the resonance circuit by the same proportion. *L* increase and *C* decrease also lead to higher WPT efficiency, when the series compensation scheme is applied.
3. The ferromagnetic wire resistance is substantially higher than the copper wire resistance, but as copper is more expensive, increased cross section of the ferromagnetic wire could solve the problem, simultaneously not increasing the expenses for the coil production.
4. Investigation of coil with ferromagnetic showed inductance dependence on the current in the coil – inductance increased with current increase. Further investigation is necessary to find the optimal set of frequency and current for the coil design using ferromagnetic material wires in the WPT system.

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References

1. Covic G.A., Boys, J.T. Inductive Power Transfer. Proceedings of the IEEE , Jun2013, Vol. 101 Issue 6, pp. 1276-1289, 14p. Publisher: IEEE.
2. Graurs. I., Vizulis A., Rubenis A., and Laizans A. Wireless Energy Supply to Public Transporation Units with Hybrid Drive – Trends and Challenges. In: Transport and Telecommunication, volume 15, No.1, 67-76, 2014. Transport and Telecommunication Institute, Riga, Latvia. DOI 10.2478/ ttj-2014-0007. ISSN 1407-6160, ISSN 1407-6179
3. Review and Evaluation of Wireless Power Transfer (WPT) for Electric Transit Applications August 2014, FTA Report No. 0060, Federal Transit Administration, prepared by Dr. Aviva Brecher and Mr. David Arthur, P.E, U. S. Department of Transportation, Volpe National Transportation Systems Center. [online][11.01.2015] Available at: http://www.fta.dot.gov /documents/FTA_Report_No._0060.pdf

4. Wang C.W., Keech T. Antenna Models For Electromagnetic Compatibility Analyses, U.S. Departament of Commerce, National Telecommunications and Information Administration, NTIA TM-13-489, October, 2012, [online][11.01.2015] Available at: http://www.ntia.doc.gov/files/ntia/publications/antenna_models_report_tm-13-489.pdf
5. Saltanovs R., Multi-capacitor circuit application for the wireless energy transmission system coils resonant frequency adjustment, 2015 IEEE Wireless Power Transfer Conference (accepted, not yet published, WPTC 2015)
6. Phan M.-H., Peng H.-X., Giant magnetoimpedance materials: fundamentals and applications, Prog Mater Sci, 53 (2) (2008), pp. 323-420.