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Laboratory model of charger for electric vehicle based upon the principle of energy transfer by air

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***Abstract* — The wireless energy transfer is known for over hundred years and it is method for transferring electric energy over long distances without the use of any conductive medium. Because of lack of conductive element, the major disadvantage of such system lies in low efficiency. This paper presents analysis of such system for electric vehicle. The simulation model created in COMSOL Multiphysics is presented. Two coils are placed in close proximity and theoretical efficiency of energy transfer between coils is estimated. Laboratory model of such system for radio controlled (RC) model of car is developed. Experimental measurements are compared with simulation results and necessary steps are summarized that are needed in designing of such system.**

***Keywords* — battery chargers, energy conversion, magnetic field, magnetic flux, electromagnetic field, electric vehicle, energy transfer**

I. INTRODUCTION

Global warming as well as limitation of fossil fuels and increased rate of social problems leads to efforts to reduce the dependency on finite energy sources. One of the solutions lies in introduction of ecologically harmless vehicles into real life. Electric vehicle (EV) is such type of harmless vehicle. Its operation however brings the complications, like the inability of fast, comfortable and smooth charging of accumulators, which are essential for EV´s operation. In present, several charging possibilities exist. From the broad-spectrum view, these are however not suitable for mass commercial utilization, because of price, time, or availability. These disadvantages can be removed by utilizing the proposed high-speed charger which utilizes the directed energy transfer by air. This solution provides the end user with comfortable, wireless and fast way of accumulator charging.

Energy transfer by air is a long known topic. So far, no significant results applicable to real life were obtained. The most significant problem lies in great energy loss, which leads to inefficient energy utilization. This, as well as other problems is solved by the method of proposed solution, where the knowledge of energy transfer theory is combined with modern methods, technology and thinking.

II. ENERGY TRANSFER BY AIR

The wireless transfer of picture, sound or data is a common thing. It is possible to connect any two electrical devices without a cable. The problem is that none of them will operate more, than few hours without the mains connection. Therefore, the wireless energy transfer is considered more and more in the last years. The wireless transfer of electrical energy is in the present, the most perspective direction of development. It is only a matter of time, when this technology will be mass commercially utilized.

The basic idea of the wireless energy transfer is very simple. Energy is wirelessly transmitted into the vehicle´s battery by transmitting coil installed in the road or parking place and receiving coil installed in bottom part of the vehicle. When the vehicle parks above the transmitting coil, the energy is transmitted without physical contact to the receiving coil mounted in the vehicle. In the transmitting coil, the variable magnetic field is excited, which leads to induced voltage on the receiving coil. The induced voltage is the reason of current formation, as soon as the receiving coil is connected to the load, in this case the accumulation element. But before that, the transmitted alternating signal is rectified. The principle of wireless charging of electric vehicle is shown in Fig. 1.

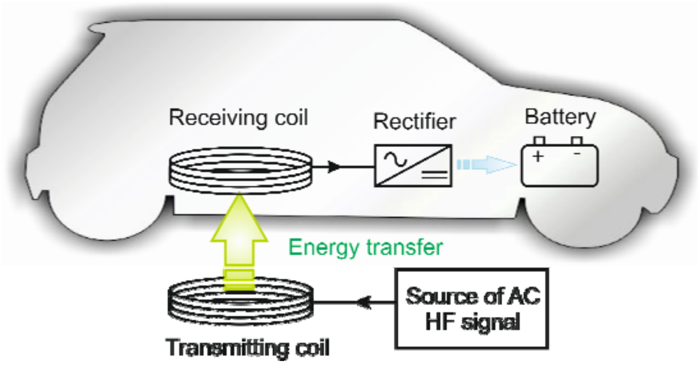

Fig. 1. Principle of wireless charging of electric vehicle

Our proposed model for energy transfer consists of two coils shown in Fig. 2 and Fig. 3. One of them is the transmitting (A) coil, the second one is the receiving (B) coil. The coils are part of electrical circuit. In order to examine the system behavior, the mathematical model of such system was created.

III. Simulation Model

On a macroscopic level the problem of electromagnetic analysis is that of solving Maxwell's subject to certain boundary condition. Maxwell's equations are set of equations, written in integral or differential form, describing the electromagnetic field. In this case, the interest of analysis is only magnetic field. For that purpose the Magnetic fields interface in COMSOL Multiphysics was used.

For general time-varying fields, Maxwell's equations are

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

$$\nabla . \mathbf{D} = \rho \tag{3}$$

$$\nabla . \mathbf{B} = 0 \tag{4}$$

where **E** is electric field intensity, **D** is electric flux density, **H** magnetic field intensity, **B** magnetic flux density, **J** is current density, and ρ is electric charge density. To obtain a closed system, the constitutive relationships describing macroscopic properties of the medium are needed

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \tag{5}$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \tag{6}$$

$$\mathbf{J} = \sigma \mathbf{E} \tag{7}$$

where ε_0 is the permittivity of vacuum, μ_0 is the permeability of vacuum, σ is the electric conductivity, **P** the electric polarization vector, and **M** is magnetization vector.

To derive time harmonic equation this interface solves Ampere's law including displacement current as these do not involve any extra computational cost in frequency domain.

$$\nabla \times \mathbf{H} = J + \frac{\partial \mathbf{D}}{\partial t} = \sigma \mathbf{E} + \sigma \mathbf{v} \times \mathbf{B} + \mathbf{J}^{e} + \frac{\partial \mathbf{D}}{\partial t} \tag{8}$$

Now assume time-harmonic fields and use the definitions of the fields

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{9}$$

$$\mathbf{E} = -j\omega \mathbf{A} \tag{10}$$

and combine them with constitutive relationships (5), (6) the Ampere's law can be rewritten as

$$(j\omega\sigma - \omega^2 \varepsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) = \mathbf{J}^{e} \tag{11}$$

Both coils are present in the analyzed magnetic field. The coils are made from copper and whole model is placed into air in order to display the magnetic field, Fig. 2. The primary coil will excite the magnetic field, which will induce the voltage in the secondary coil. The current will flow through the coil, which size relies upon the load and coil impedance.

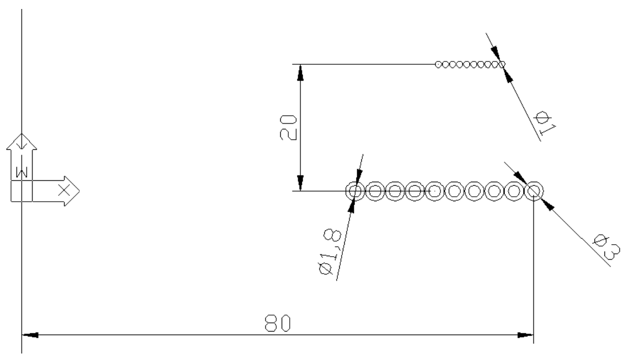

Fig. 2. Construction detail of simulated circuit with dimensions in millimeters and car scaling factor 1:10

IV. Simulation Results

The most important factor which affects the transfer efficiency is the mutual distance of coils, their shape and position. This factor can be expressed by coefficient of mutual magnetic coupling, which can be obtained by series of simulation analysis shown in Fig. 3, Fig. 4, and Fig. 5. The simulation conditions are: peak to peak value of the current that flows through the transmitting coil is ±10 A, 25 kHz frequency and a scale of the model of 1:10.

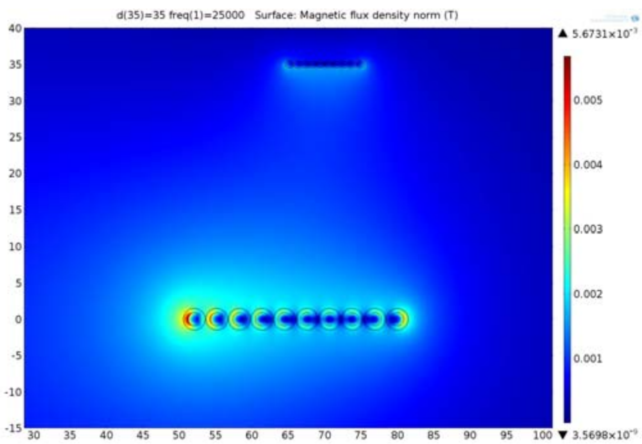

Fig. 3. Magnetic field distribution for distance of 35 mm between coils

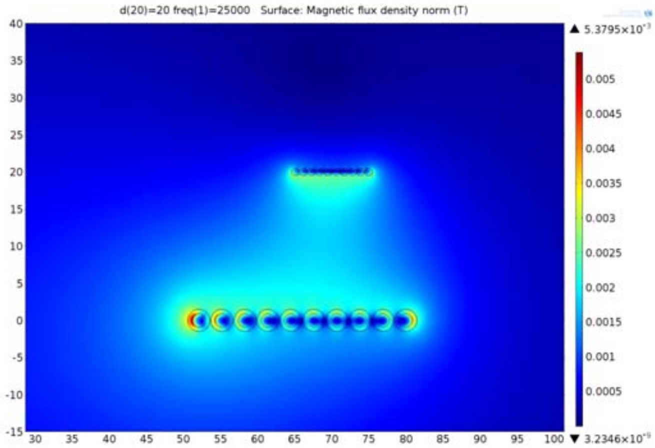

Fig. 4. Magnetic field distribution for distance of 20 mm between coils

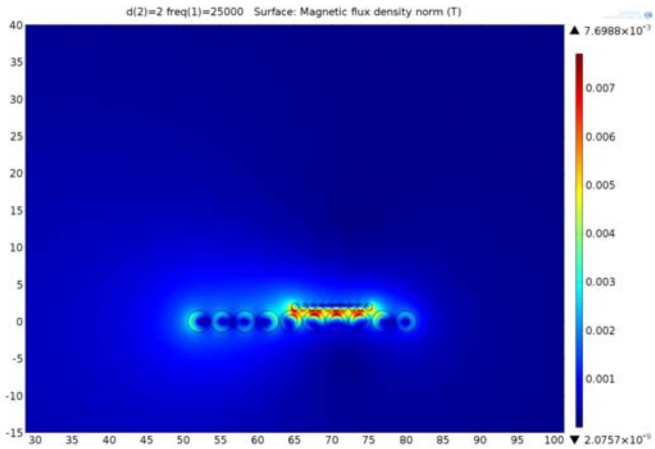

Fig. 5. Magnetic field distribution for distance of 2 mm between coils

The coefficient of magnetic coupling can be obtained from the ratio of magnetic fields between transmitting and receiving coils. The coupling coefficient is the expression of maximum theoretical efficiency of energy transfer between transmitting and receiving coils for the distance level.

The curve deformation on small distances was caused by inaccuracy of numerical calculation of magnetic field size in the simulation model. Due to small distance, only a limited calculating network can be generated.

As we can see from Fig. 6 the theoretical efficiency of energy transfer decreases with distance between coils. It is worth noting, that this efficiency is dependent only upon the arrangement of coils,

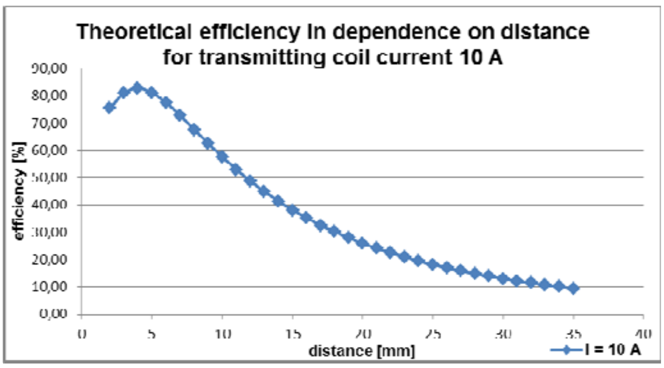

Fig. 6. Theoretical efficiency in dependence on distance for transmitting coil current 10 A

their size, material properties of the environment between them and frequency of exciting signal, which generates the field. It is however not dependent upon its size. By affecting these parameters, the efficiency can be changed. The simplest way of efficiency increase is to lower the distance between the coils. By this, it is possible to obtain the wireless transfer efficiency value near 83%. From the graph, it is evident, that the energy transfer in our 1:10 scale model (with estimated distance 20 mm between coils), is possible to obtain the 25.93 % efficiency.

As it was already mentioned, another factor which can affect the efficiency of the transfer is the frequency of exciting current. By using the same procedure like in the previous case, the information about coefficient size depending upon the frequency can be obtained. The multiple simulation of magnetic field distribution between the 20 mm distant coils was realized. The transmitting coil is fed by alternating current with 10 A amplitude, but its frequency was changed. The results of the simulation can be seen in the Table 1.

Table 1
Magnetic Field Energy and Magnetic Coupling Values of Coils Depending on Frequency of Exciting Current

Frequency [Hz]	Coil B magnetic field energy [J]	Coil A magnetic field energy [J]	Ideal energy transfer [%]
100	4.34E-07	8.49E-06	5.11
500	1.01E-06	8.24E-06	12.21
1000	1.42E-06	8.05E-06	17.60
5000	1.69E-06	7.79E-06	21.69
10000	1.68E-06	7.43E-06	22.60
25000	1.57E-06	6.21E-06	25.34
50000	1.40E-06	4.82E-06	28.95
100000	1.17E-06	3.57E-06	32.66
200000	9.28E-07	2.62E-06	35.40
300000	8.03E-07	2.18E-06	36.90
400000	7.23E-07	1.90E-06	38.05
500000	6.65E-07	1.70E-06	39.09

The graphical representation of efficiency depending on frequency in case of 20 mm distance between coils is shown in Fig. 7.

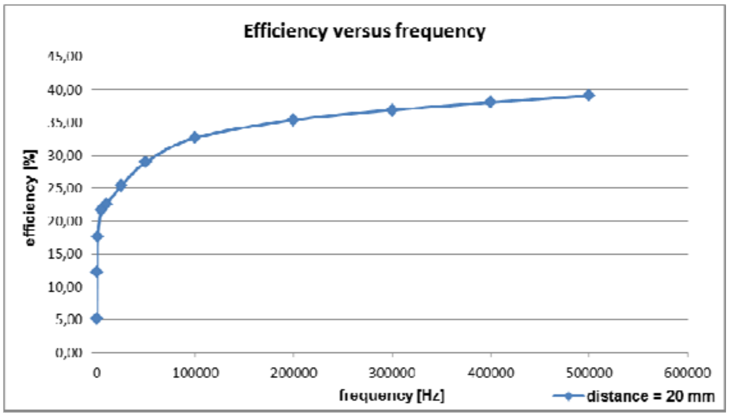

Fig. 7. Energy transfer efficiency in dependence on frequency for model 1:10 and distance 20 mm

From the Fig. 7 can be seen, that the threshold for maximum theoretical efficiency energy transfer in our model reaches 40%, however only with frequencies higher than 500 kHz. The field distribution for the specified efficiency and frequency is shown in Fig. 8.

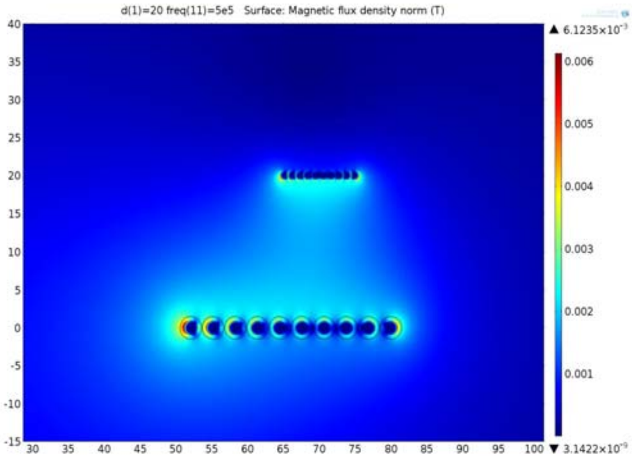

Fig. 8. Magnetic field distribution for coil's distance 35 mm and frequency of primary current 500 kHz

V. Transmission System

In order to charge the accumulating elements of the electric vehicle, the output signal of the receiving coil has to be rectified and regulated. For this purpose, the regulator and rectifier are present. Fig. 9 shows the proposed model of a transfer system (system which transfers the energy by air). The transfer model consists of voltage inverter, transmitting coil, receiving coil and rectifier. After the rectifier, there is a switched regulating element, because the charging current of the used accumulator has to be respected.

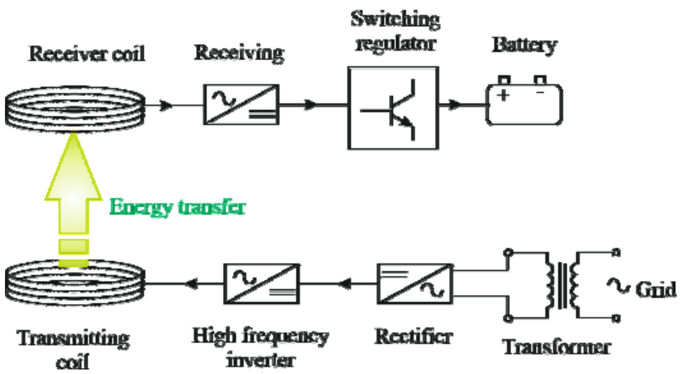

Fig. 9. Overview of transmission system - block diagram

In order to transfer the energy by air with the two coil system, (one transmitting and one receiving) it is essential to generate the high-frequency (HF) signal. In this case the half-bridge inverter shown in Fig. 10 was used. This inverter serves as source of such signal, where the transmitting coil is

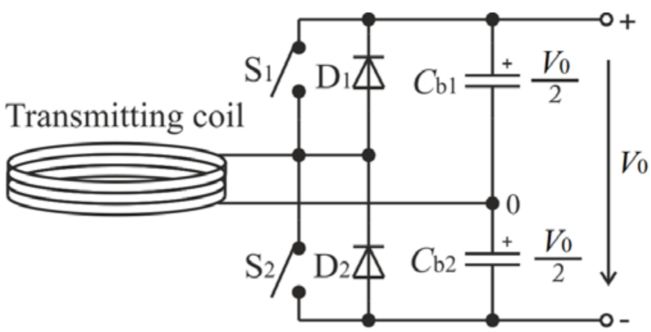

Fig. 10. Principle topology of inverter for transmitting coil feeding

connected to its output. The HF signal excites the HF magnetic field which cuts through the receiving coil. These are two inductive coupled circuits.

To verify the theoretical assumptions, the simulation model of inverter for transmitting coil was created in the OrCAD Capture CSI software as it is shown in Fig. 11. In order to approach the reality with simulations, the resistors representing the real technical coils, the series resistance of a voltage source and the parasitic resistance of a wire were added into the circuits.

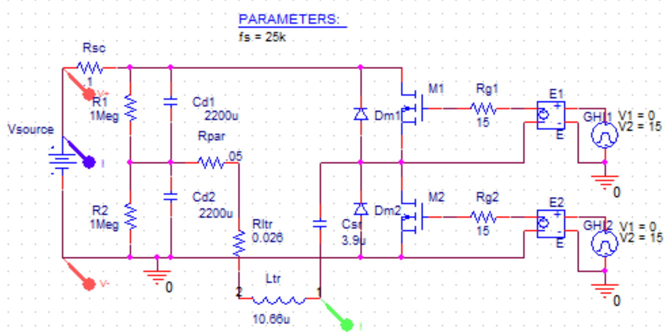

Fig. 11. Simulation model of inverter with transmitting coil – serial resonance circuit

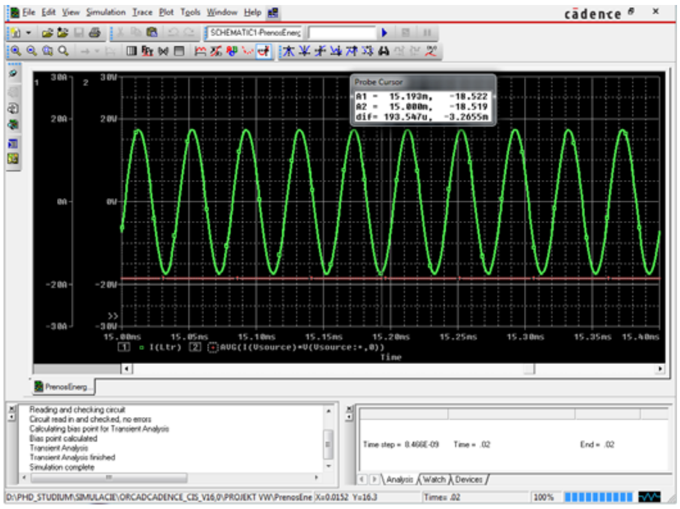

Fig. 12. Simulation results - *RLC* circuit in series (R_Z = 26 mΩ, L_Z = 10.66 μH, C_Z = 3.9 μF), P_I = -18.6 W

As was mentioned above, in order to charge the accumulating elements of the electric vehicle, the output signal of the receiving coil has to be regulated and rectified. For this purpose, the regulator and rectifier are present. Fig. 13 shows the simulation model of a transfer system. The simulation transfer

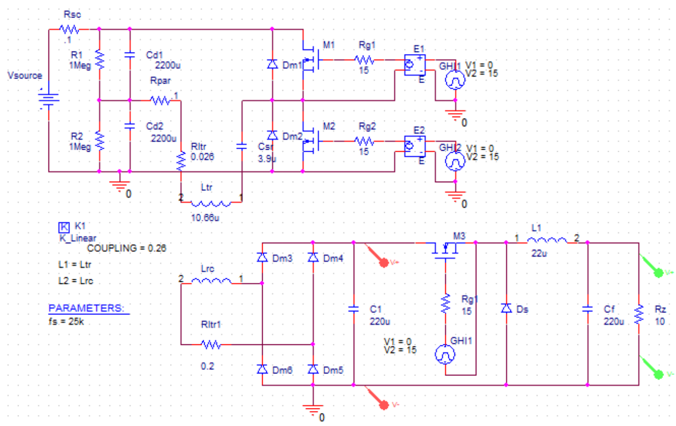

Fig. 13. Simulation model of transmission system

model consists of voltage inverter, transmitting coil, receiving coil and rectifier. After the rectifier, there is a switched regulating element, in this case the buck converter, because the charging current of the used accumulator has to be respected according to the type of battery. The simulation result is shown in Fig. 14.

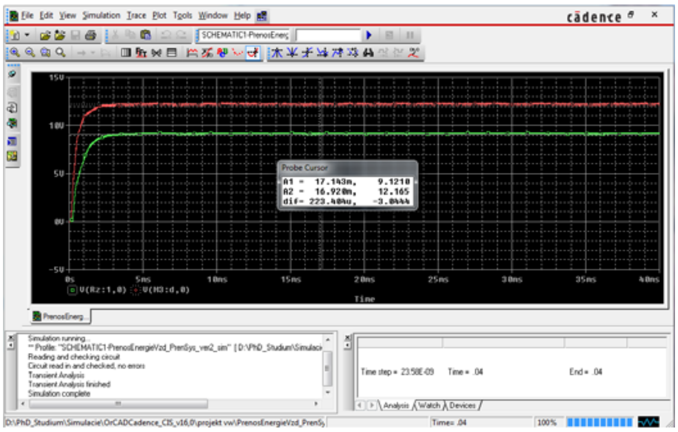

Fig. 14. Simulation model of inverter with transmitting coil

VI. Experimental Results

The connection with results shown in Fig. 13 was realized as a functional sample and verification measurements were realized. The progress of transmitting coil current with input voltage V_{IN} = 44 V, is shown in Fig. 15. The progress of transmitting coil current with input voltage V_{IN} = 22 V, is shown in Fig. 16.

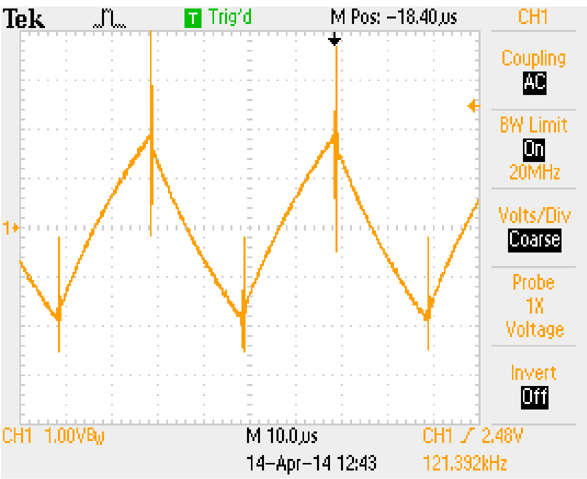

Fig. 15. Transmitting coil A current (V_{IN} = 44 V)

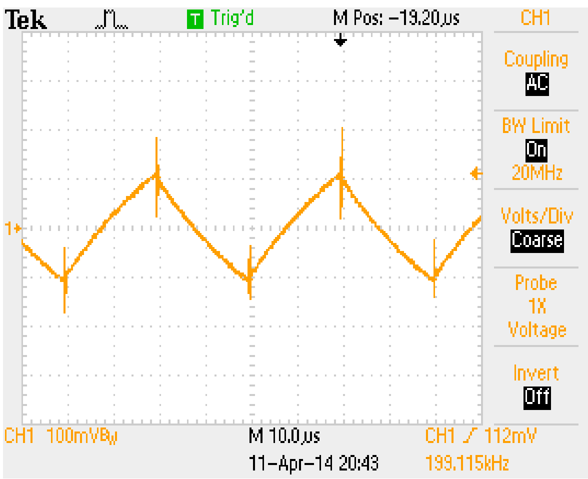

Fig. 16. Transmitting coil A current (V_{IN} = 22 V)

Bypass with resistance value R = 0.1 Ω was used for current screening, therefore from the Fig. 16 can be seen, that the value of current is ±10 A. When compared with progress obtained by simulation, shown in Fig. 12, it can be seen, that the theoretical and practical results are the same. For the efficiency of energy transfer evaluation, the specific connection had been used. The receiving coil was receding at 1mm step from the transmitting coil and the input of inverter and output power of receiving coil had been measured, after the rectification and connection of load resistor R_Z = 1.5 Ω. The measurement had been repeated for 4 different values of inverter feeding voltage, which resulted in 4 different values of transmitting coil current. The measured results are documented in Tab. 2, Tab. 3, Tab. 4, and Tab. 5.

Table 2

Measured Values for Input Voltage Vin = 44 V (Primary Current ± 20 A)

Distance [mm]	V_{IN} [V]	I_{IN} [A]	V_{OUT} [V]	I_{OUT} [A]	P_{IN} [W]	P_{OUT} [W]	Eff. [%]
2	44.24	2.40	6.71	3.90	90.24	26.16	28.99
20	44.49	1.16	3.12	1.74	51.60	5.43	10.52
35	44.53	1.30	1.80	0.98	45.86	1.76	3.84

Table 3
Measured Values for Input Voltage Vin = 31 V (Primary Current ± 15 A)

Distance [mm]	V_{IN} [V]	I_{IN} [A]	V_{OUT} [V]	I_{OUT} [A]	P_{IN} [W]	P_{OUT} [W]	Eff. [%]
2	31.67	1.40	4.58	2.64	44.33	12.09	27.27
20	31.42	0.78	2.07	1.12	24.50	2.32	9.48
35	31.52	0.69	1.14	0.60	21.74	0.68	3.16

Table 4
Measured Values for Input Voltage Vin = 22 V (Primary Current ± 10 A)

Distance [mm]	V_{IN} [V]	I_{IN} [A]	V_{OUT} [V]	I_{OUT} [A]	P_{IN} [W]	P_{OUT} [W]	Eff. [%]
2	12.68	0.49	1.50	0.80	6.32	1.48	19.39
20	12.48	0.25	0.48	0.22	3.03	0.10	3.53
35	12.44	0.22	0.08	0.06	2.68	0.01	0.17

Table 5
Measured Values for Input Voltage Vin = 12 V (Primary Current ± 5 A)

Distance [mm]	V_{IN} [V]	I_{IN} [A]	V_{OUT} [V]	I_{OUT} [A]	P_{IN} [W]	P_{OUT} [W]	Eff. [%]
2	22.40	0.94	3.06	1.72	21.05	5.26	25.02
20	22.49	0.53	1.35	0.71	11.97	0.96	8.07
35	22.52	0.47	0.68	0.34	10.44	0.23	2.19

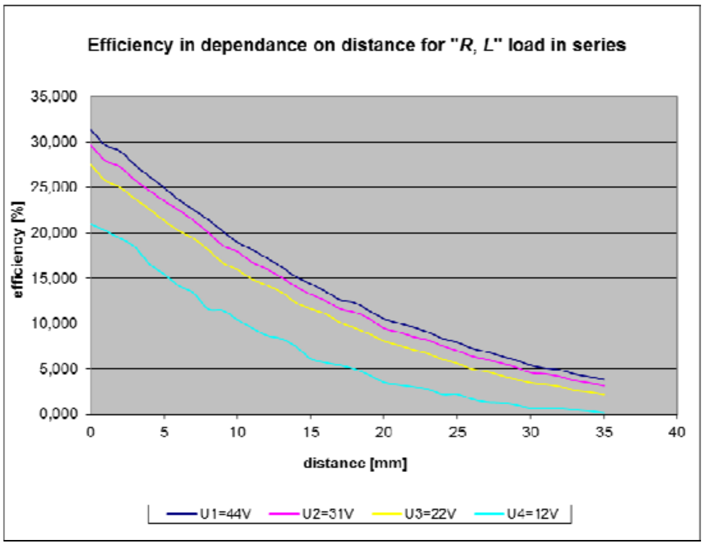

Fig. 17. Efficiency in dependence on distance for *R*, *L* load in series

It can be seen from the obtained results, that for the 1:10 scale model of the automobile charger (20 mm distance between coils), the measured efficiency for input voltage V_{IN} = 22 V is only η = 8.07 %, with the measured input of P_1 = 11.91 W. From the simulation results it can be seen, that for the same conditions, the simulation program (Fig. 13) calculated the input value of P_1 = 15.1 W. The simulation model shows fairly good level of compliance with real measured results.

Fig. 18. Laboratory model of the inverter Fig. 19. Laboratory model of the converter mounted in RC model

Based upon these facts, the theoretical prediction of 1:10 model charger efficiency can be made. The transmitting coil will be connected in serial resonant circuit. The prediction will be based upon the inverter´s input, shown in Fig. 12 (P_I = 18.6 W) and power in Table 2 (P_{OUT} = 5.43 W). The theoretical efficiency is then η = 29.2 %, which is the value near the theoretical maximum transfer efficiency for the specified system, which is 25.34%. With parallel *RLC* connection, the efficiency should be even higher, because in the state of "ideal" parallel resonance, the circuit input should be equal only to withdrawn power.

VII. Conclusion

For correct charger design with the required parameters is necessary to do the next steps:

1. To define required maximal working distance and dimensions of coils,
2. To state the maximal ideal energy transfer in percentage by computer simulation for chosen switching frequency,
3. To realize an inverter with the smallest losses for required output power considering the energy transfer efficiency,
4. Based on required output voltage to calculate the number of coil B turns,
5. To realize the output rectifier and switching regulator.

In order to verify the theoretical and simulation results, the RC model M40S Volkswagen Touareg Dakkar was bought in 1:10 scale. This model was modified, so the simulation results could be verified. The receiving coil was installed to the bottom of the vehicle. The rectifying bridge with regulating element was installed inside the vehicle, too. This element respects the charging properties of the battery used in the M40S Volkswagen Touareg Dakkar model.

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