Experimental study of wireless inductive system for electric vehicles batteries charging

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***Abstract*- This article presents created experimental stand for wireless inductive system for electric vehicles (EV) batteries charging and investigation of the main problems for moduls integration in the system for effectivnes energy transfer in the large exigenses of the batteries for electric vehicles. Flexible control of the high frequency (HF) inverter limited from resonant conditions of the flexible load with differents transmitters and differents parameters of the batteries was in the scops.A control system with capabilities for large diapazon of charging voltage and curent is proposed as a possible solution of the main problematic issues related to EV charging.An optimization problems are defined and solved for transmitters dimentions, bobbine's inductans and for distance from sender and receiver.**

***Keywords:* wireless, contactless, energy, converters, transmitter, electric vehicle, battery charging**

I. INTRODUCTION

The Distributed Energy Resources (DER) is the most important elements that constitute actual Smart Energy Networks [1]. Electric vehicles batteries chargers [2] are essential to develop Smart Energy Networks in order to accept the challenge of new scenarios at European level. Concepts, capacities and methods for testing EV systems and their interoperability are presented in working document and publication [2]. Wireless charging of batteries can be used to easily associate electric vehicles (EV) with the smart grid [3]. Many articles are published in the field of Wireless Energy transfer (WET) , aimed to verify the efficient operation [4,10,11], developing tendency [6,7,8], converters design [7,11,12] , stability of converter operation for different circuit of coupling of converter and transmitter [9]. Different configuration of transmitters with small dimensions and distances between "sender and receiver" are presented [13], an approach for dynamic inductive system for power transfer is showing [14] in relation with [15]. All this publication presents the data for one selected frequency 20 (50) kHz and distances no more 10 cm. The relation between frequency, distance, efficiency and real load is not presented.

On the basis of WET publications and the self-maid experiment based on induction heating equipment presented in [16, 17] for frequency 100-500kHz the author created the experimental stand with full system for EV batteries charging for investigation the efficiency of the inductively coupled set of transmitter "sender/receiver" depending on distance, ,loads, resonance frequency and mode of coupling and operation.The objectives of this work includ the design of the transmitters, the proper choice of the resonant capacitors, the definition of the power for the experiments, the reconfiguration of the system of coupling, the necessary measurements and analyses of the obtained parameters.

II. WIRELESS TRANSFER OF ENERGY STAND for EV batteries charging

The main blocks of WET stand are voltage rectifier DC/DC switch, HF resonant frequency inverter - suppliers of "sender", HF impulsive rectifier loaded from "receiver" and filter related to EV storage. The resistors are included for experimentation. The realized configuration of the stand is shown in the Fig.1.

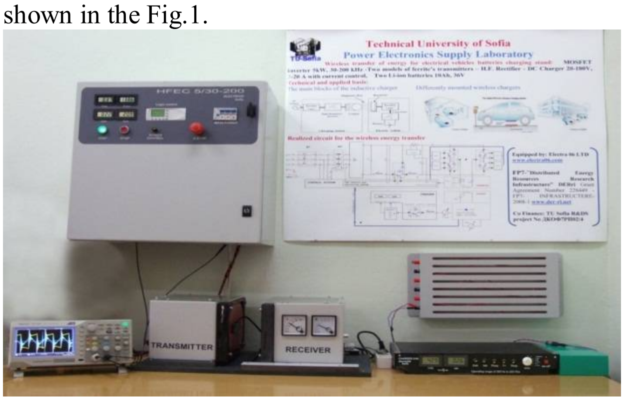

Fig.1 Realized stand during charging regime of operation

Following parameters are accepted for this complex system:

- Rectifier DC/DC Switch k=t/T=0,25-0.9
- HF inverter 5kW, 30-200 kHz
- Ferrite's Sender- Receiver with 50-150 mm distance
- HF Rectifier
- DC charger 20-180V, 2- 20 A with current control
- Load resistors 5-150 Ω
- Two li-ion batteries 10Ah, 36V
- Current of charge 5-20A

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Fig.2 presents front panel of supply. The inverter is series resonant with sinusoidal current in exit circuit and rectangular voltage. The control is “Zero Voltage Switching” with minimalized losses of MOSFET switches and high efficiency. The synchronization of the inverter control is realized with measurement of current and voltage phases in the limits of nanosecond.

Fig.2 Inverter with indicators and control

Fig.3 presents front panel of charger. Each case of batteries charging start from set of parameters of the concrete battery-voltage and maximum current of charger. The voltage of the exit of the receiver must to be 20-25% higher from expected voltage of charge. The control system of the charger is related to DC/DC converter observe the voltage requirement value in the limit for current charge value.

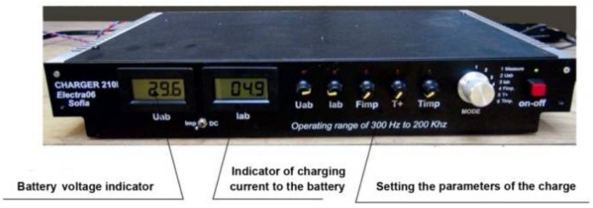

Fig.3 Charger with indicators and control

The development of this wireless charging system will be oriented to relate the regimes of these two converters, with common intelligent control for efficiency optimization for different batteries charging regimes. Analyzing possible circuit [9] for coupling inverter and transmitter for first test case it was choice series connected C_1 with “sender” coil and parallel connected C_2 with “receiver” “series-parallel” (**SP**) resonant circuits - Fig.4.

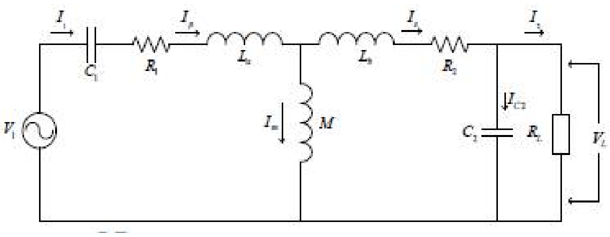

Fig.4 Realized series-parallel resonant circuits

III. TEST CASE 1 – SERIES-PARALEL RESONANT CIRCUITS

1.1 First experiment realized with transmitter №1 shown in the Fig.5

Fig. 5 Transmitter No 1

- Ferrites EE6527 from CF139 in a set
- N1=N2=5 tours, L=10,8 µH, no cooling
- Litz Wire – L = 4,16 µH; R = 43,6 mΩ

  Litz Wire coil with a ferrite L=10,88 µH; R = 23 mΩ
- Distances - Δ = 50 - 200mm

The results from experiment are presented for distance between coils Δ=100mm in Table 1a, в, c for different load resistors. The measurements were made via HF diodes and filters for purpose to minimize the influence of inductance of utilized resistors and for obtained the value of exited power.

Distance „sender/receiver” Δ=100mm

F=109,5KHz; R=30Ω **Table 1a**

Udc_1=70,3 V	Idc_1 =20,8A	Po_1=1462W	η
Udc_2=170V	Idc_2 =6,76A	Po_2=1149W	0,78

F=109KHz; R=60Ω **Table 1b**

Udc_1=112,6 V	Idc_1 =20,7A	Po_1=2330,8W	η
Udc_2=308V	Idc_2 =5,42A	Po_2=1669,4W	0,72

F=109KHz; R=130Ω **Table 1c**

Udc_1=69,5V	Idc_1 =20,9A	Po_1=1452,5W	η
Udc_2=304V	Idc_2 =2,69A	Po_2=817,7W	0,56

Maximum efficiency is obtained for load resistor R=30Ω becouse the resonans of two coupled circuit are relativly near.

1.2 Second experiment: realized with трансмитер №2 shown in the Fig. 6

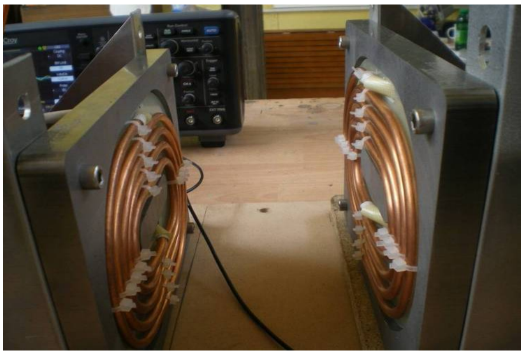

Fig.6 Transmitter №2

The results from experiment are presented for distance between coils Δ=50mm in Table 2a, в, c for different load resistors

Distance"sender/receiver" - Δ=50mm

F=183KHz; R=33Ω **Table 2a**

Udc_1=104V	Idc_1 =21,6A	Po_1=2246W	η
Udc_2=213V	Idc_2 =6,45A	Po_2=1374,8W	0,61

F=183KHz; R=66Ω **Table 2b**

Udc_1=73V	Idc_1 =21,7A	Po_1=1584,1W	η
Udc_2=230V	Idc_2 =3,46A	Po_2=795,8W	0,502

F=183KHz; R=132Ω **Table 2c**

Udc_1=54,4V	Idc_1 =21,8A	Po_1=1185W	η
Udc_2=240V	Idc_2 =1,81A	Po_2=434,4W	0,367

Maximum efficiency is obtained for load resistor R=33Ω becous the resonans of two coupled circuit are near. The resonant frequency is higher , the eficiency is lower for two time shorter distancy.

The waveforms of current and voltage of inverter – Uinv and Iinv respectively currents of sender and receiver Icoil1 and Icoil2 are presented in Fig.7.

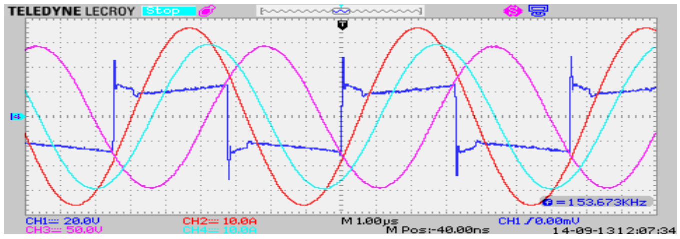

Fig. 7 – Current and Voltage of inverter CH1 - Uinv, CH2 - Iinv, Currents of sender and receiver CH3 – $Icoil_1$, CH4 – $Icoil_2$

IV. TEST CASE 2 – SERIES-SERIES RESONANT CIRCUITS

In order to improve the energy performance it was have created new coils for Transmitter No 1. The circuits for coupling is also modified in order to take advantage of "series-series" (**SS**) resonant circuits, namely - to avoid uncontrolled increase of the output voltage (receiving coil).

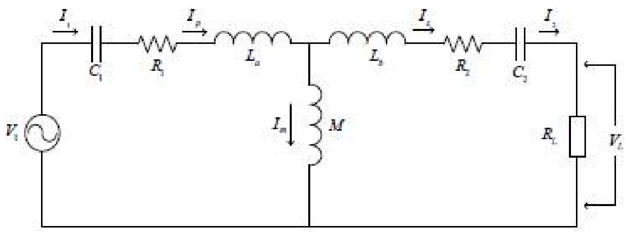

Fig. 8 Realized series-series resonant circuits.

The values of new coils and respectively new capacitors are: L_1= 64µH, L_2 = 30 µH and C_1 =22nF, C2= 47nF.The ferrites are the same of transmitter No 1.

2.1 Experiment realized with SS circuits and new coils for Δ =40mm

The basic parameters are measured and waveforms are presented below for Δ =40mm

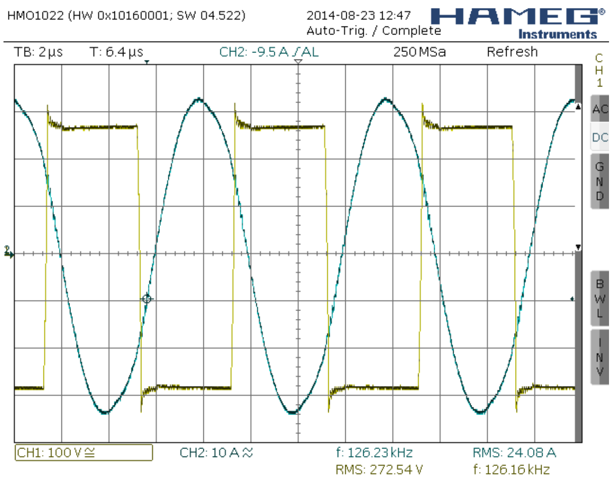

Fig.9 Inverter exit voltage and current for P_{dc2}=5kW and Δ =40mm.

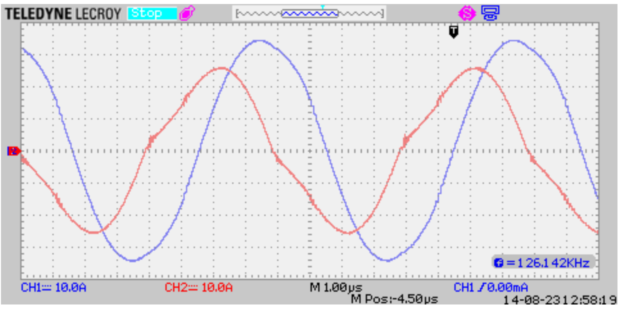

Fig.10 The currents of sender and receiver coils for P_{dc2}=5kW and Δ =40mm

The measured RMS current in sender coil is 24.8 A, RMS current in receiver coil is 17,2 A and inverter power is P_{inv}=5,22kW

The results from experiment are presented for distance between coils Δ=40mm in Table 3a, в, c for different load resistors.

F=119KHz; R=60Ω **Table 3a**

Udc_1=104V	Idc_1 =18,5A	Po_1=1924W	η
Udc_2=320V	Idc_2 =5.09A	Po_2=1629W	0,847

F=121KHz; R=30Ω **Table 3b**

Udc_1=177.9V	Idc_1 =18,5A	Po_1=3291W	η
Udc_2=302,5V	Idc_2 =9,67A	Po_2=2935W	0,888

F=121KHz; R=21Ω **Table 3c**

Udc_1=282,7V	Idc_1 =19,4A	Po_1=5484W	η
Udc_2= 321,1V	Idc_2 =15,6A	Po_2=5009W	0,913

2.2 Experiment realized with SS circuits and new coils for Δ =100mm

The basic parameters are measured and waveforms are presented below for **Δ =100mm**

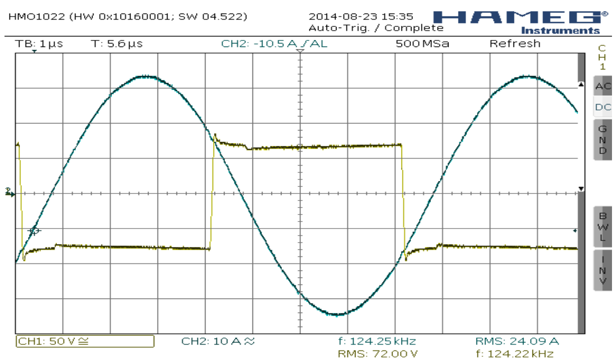

Fig.11 Inverter exit voltage and current for P_{dc2}=1,07kW and Δ =100mm

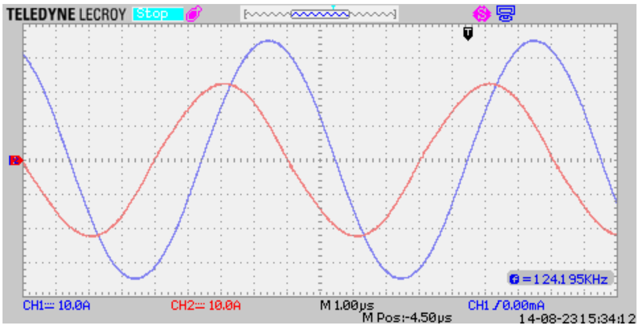

Fig.12 The currents of sender and receiver coils for P_{dc2}=1,07kW and Δ =100mm

The measured RMS current in sender coil is 19,8 A, RMS current in receiver coil is 14,4A and inverter power is P_{inv}=1,37kW. The results from experiment are presented for distance between coils **Δ**=100mm in Table 4a

F=121KHz; R=7,5Ω **Table 4a**

U_{dc1}=75,6V	I_{dc1} =19,8A	P_{o1}=1497W	η
U_{dc2}= 74,6V	I_{dc2} =14,4A	P_{o2}=1074W	0,717

For resistance R=7,5Ω it is measured maximum possible efficiency.

When comparing the results of the measurements, it should be noted that in the above configuration of the Transmitter No 1 with L_1= 64µH, L_2 = 30 µH and C_1 =22nF, C_2= 47nF it is observed opportunity to transfer more power and high levels of efficiency. Given that, irrespective of size, the presence or absence of a load output voltage remains within the range safe for the charging unit.

2.3 Experiment realized with SS circuits and new coils for li-ion battery

Measurement in case direct switch on charger to li-ion battery 10Ah, 40V

- Input of inverter Udc = 40,4V, Idc= 4A, Pdc=161,6W
- Input in Charger (exit of the transmitter) Udc=92V, Idc= 1,43A, Pdc2=132,22W
- Efficiency of the transmitter η=132,22/161,6=0,818
- Entry of the Battery: Udc=42,5V, Idc=2,8A, Pch=119W
- Efficiency only of charger block η=119/132,22=0,9
- Common efficiency η=119/161,6= 0,73

V. CONCLUSIONS

The comparative analysis of the experimental results reveals the complexity of the problems and results:

- The efficiency is related to the relative dimensions of distance between sender/receiver and dimentions of the coils of transmitter. Technical possibility for realization of the larger distance sender/receiver will be the basis of the design of the practical dimensions of the coils of transmitter.
- Frequency of transfer of energy must be resonant frequency of the two electromagnetique related circuits: first is sender-primary capacitor and second receiver-second capacitor including battery resistances. Series-series (SS) resonant circuits will be preferable for stability of the regimes.
- The inverter - series resonant with sinusoidal current and rectangular voltage with frequency control from the resonans of the load is suitable for this WET transfer technology.

The development of presented wireless charging system will be oriented to relate the regimes of two converters MOSFET inverter and DC/DC charger block with common intelligent control for optimization of efficiency depending from different batteries parameters and charging regimes.

For charging the EV batteries regims the 4 mode of operation according standart IEC 6851 [17] and load profil for slow or fast charge must be includet like data base in new inteligent system of control. WET charger [18] is a solution that can achieve a better cooperation between the electric vehicles and the grid.

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