Desing of On-Route Charging Infrastructure for EV

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Abstract - **Design and development of 30kW Inductive Power Transfer system for on-route charging of Electric Vehicles is described in the present paper. There are several significant factors that make design of IPT more challenging. Its main purpose is a representation an alternative method of charge. At the same time, provides an opportunity for quick charging of electric vehicle batteries. Modes of charge, which are part of functional properties of the system during motion of electric vehicle. The basic units of the Charging converter are described, the circumstances of their design, advantages and disadvantages.**

Keywords - **IPT, coil, ON-Route, matchingcircuit, air gap.**

I.INTRODUCTION

On route charging of EVs is considered as a dynamic charging mode, with the car being charged while moving along the road. Feasibility of this technology is a big challenge in terms of effective EV integration in urban road system, but thanks to this technology the capacity and the weight of battery packs can be reduce potentially up to 60%. As a result the car is lighter and with improved driving range, so dynamic solution may become more cost effective. Because of the vehicle's motion, transfer of energy from the charging road spot to the EV's batteries can be only contactless and inductive principles are preferable.

II. STATE OF THE ARTS

Today's interest is now focused on the dynamic charging because it allows reducing the volume of the battery potentially up to 60%, and therefore the cost of the electric vehicle. Transmitting part is fixed in the roadway in the direction of the movement, and receiving part is in the EV.

The scale of power supply area is related to the charging speed, recharged volume of battery energy and running speed of vehicle and so on. Supposing it takes 30 minutes to make over 80% power for battery's energy, the length of 6 km in charging area is needed for an electric vehicle with speed of 60km/h to supply dynamically 30% of the battery capacity. If a single overall style primary track is designed for this long charging area, the energy loss is huge, with critical power requirements for every single electrical energy transducer. To avoid these problems, energy emission unit of primary side can take the form of coil array and segmented track – fig.1. The whole charging lane is segmented into several charging section and each section owns independent primary underground and side track or coil arrays. This is not only good for charging energy measurement but also for reducing power level of each power supply device.

Moreover, the copper mass is reduced enormously, as the system only supplies power for these charging sections in which electric vehicles are being charged. What's more, an intelligent admittance mechanism could be built to insure that every EV in the system is identifiable and the system is never overloaded [1-3].

a) Coil array b) Segmented track

Fig. 1. The layout of energy emission unit

Optimal design should be achieved for the structure and the layout of energy emission unit, as the transmission efficiency of whole charging system, the first investment cost, operating cost and operating management are directly influenced by these design aspects.

In the on route charging system, the pick-up unit should get as close as possible to the energy emission unit, which can insure the energy pick-up is adequate and the transmission efficiency of system is high. However, in order to maintain the constant close distance, the pick-up unit should adjust its position automatically, including vertical position and horizontal position, to adapt road condition, position variation of energy emission unit and vehicle. The pick-up unit should be able to detect the position of energy emission unit in real-time, and adjust its position automatically to insure the energy pick-up reliably and safely [1-7].

Configurations of on route inductive power transfer.

A. Long Wire Loop

The long wire loop configuration is presented in Fig. 2. The roadbed loop is long compared to the vehicles and pick-up coils. Due to the short gap between long loops (assumed to be 1m), each car charges at least 95% of the time. Each large loop operates whenever a car is near, and all loops operate almost all the time with steady traffic. Reactive magnetization power is almost two orders of magnitude higher than the real-power output.

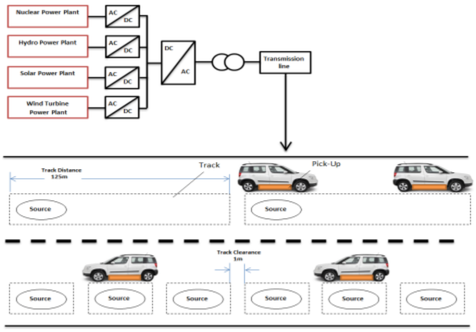

Fig. 2. Long wire loop configuration of EV on route charging.

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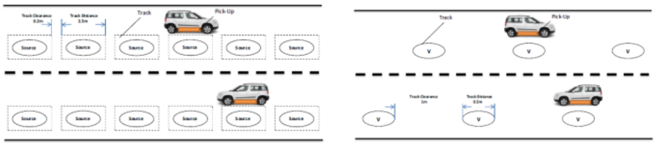
B. Sectioned Wire Loop (Car-size Section)

The sectioned loop configuration is shown in Fig. 3a). The length of the loop is about the size of an EV. The gaps between the loops are assumed to be smaller (0.2m). The source loop in this case supplies only one car at a time, and the loop operates only when a car interacts with it. The coupling coefficient is larger than the long wire loop because the area that does not contribute directly to magnetic power transfer is reduced.



a) Sectional wire loop b) Spaced loop

Fig. 3. Sectioned loop configuration

C. Spaced Loop (Small Loop)

The spaced loop configuration is shown in Fig. 3b). The loop (0.5 m) is much smaller than a car. Hence, the interval during a car interacts with the road coil is much smaller than for the other loop configurations. It may be possible to operate more than one loop per car, or to have a pickup coil larger than the source loop. The gaps between the loops are large (1m). However, the flux is more confined within the air gap, so external stray fields are substantially lower.

Numerous international teams [2,4,6] are currently working on the development and improvement of technology for dynamic EV charge and in particular on the efficiency of energy transfer during the movement and the possibility of transmission of more energy in a shortest distance of EV movement. This activity can be divided into two main groups - market products produced and developed by firms and companies and-experimental development of university teams.

Table 1 shows the technical parameters of the leading companies' achievements in this field. The main conclusion that arises is that the average efficiency achieved with this method is between 85 and 90%.

Table I. Leading companies achievements in the field of contactless charging

Company	***Application and rated power***	***Type IPT***	***Air gap , mm***	***Web site***
Conductix Wampfler	*Industrial – $10^1 \div 10^2$kW Car, Bus*	*Static and dynamic*	*$10^1 \div 10^2$*	*conductix.com*
Primove	*Railway Transport – 400kW* *Bus – 200kW* *EV – 10kW*	*Static and dynamic*	*200÷300*	*primove.bombardier.com*
OLEV Technologies	*Bus– 100kW, 20kHz,85% eff.*	*Static and dynamic*	*200*	*olevtech.com*

As a conclusion, it can be underline that companies' practical solutions are currently preferably oriented to the big public vehicles, like buses and trains. Dynamic on route charging solution for mini-buses and passenger cars are still subject of development and investigation. For this target group of vehicles is very important that the new developed technical products must be identical for static and dynamic charging mode and interoperable..

III. DESIGN OF ELECTRONIC MODULES FOR ON ROUTE CHARGING

The designed mock-up of charging station contains electrical and mechanical parts. The main components of electrical part are: 3 phase AC/DC rectifier, input C filter and five dual IGBT modules that compose four full bridge IGBT inverter circuits; control circuit and distribution board. The mechanical parts are heat sink and supporting sheet metal construction. In [6] detailed analysis of electromagnetic processes is made and on this basis electrical parameters of each electronic element, passive and active, are selected.

Electrical circuit of investigated modules, inverter and compensation capacitors and transformers, for on route charging mode are shown in figure 4.

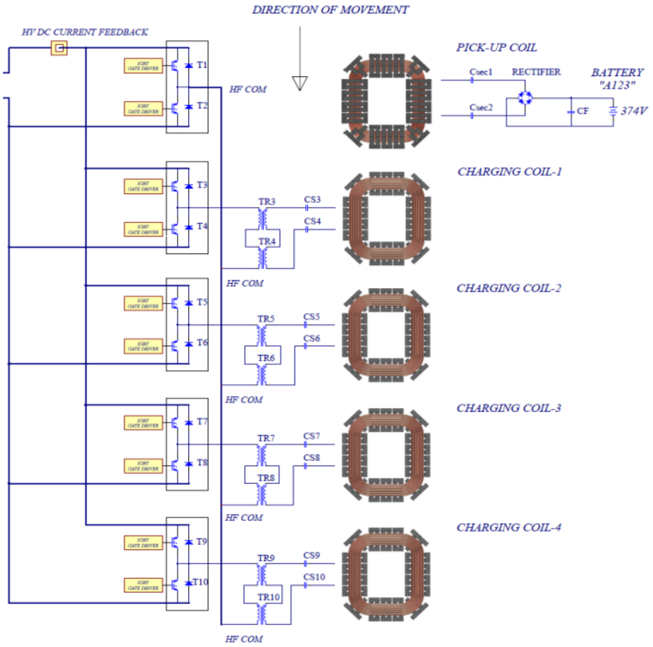


Fig. 4. Electrical circuit of investigated modules

The inductive power transfer (IPT) device is inherently a transformer, which transfers electrical energy from the primary to the secondary without direct contact between the two components. Due to inevitable air gap, parameters of such transformer are lower than for a normal transformer and the main challenge of the development was to make a system with good efficiency low sensitivity to the load parameters and air gap variation. Compared to charging system without IPT, the developed system (with IPT) has much higher reactive power and therefore is more sensitive to parameter variation. It has more reactive components as well, which can result in additional partial resonances in the range of frequency used for the generator scanning [2,4,6].The IPT primary and secondary parameters (figure 4) are shown in table 2.

Table II. IPT parameters

Element	CS3÷CS10	Csec 1,2	CF	T1÷T10
Value	2.4μF	2.4μF	550μF	200A/1200V
Transformers TR3,4÷TR9,10	Connection of primary windings - series Connection of secondary windings - series Trafo ratio - 9:5 Primary current : I1 = 60A/20kHz Secondary current : I2 = 120A/20kHz Trafo core : 4 xE100/60/28, material 3C90			
IPT primary	Weight ≈ 33kg Dimensions : 812x712x100mm Turns number: 7 LITZ cross section: 60mm^2			
IPT secondary	Weight: 25kg Dimensions: 760 x660x52mm Turns number: 7 LITZ cross section: 30mm^2			

One of the most important features for effective transfer of energy is magnetic coupling factor K. This is why influence of the misalignment between coils in direction X,Y,Z on the coupling factor has been investigated. For specified dimensions of the coils, 800mm/700mm/90mm (including winding aluminium shielding construction) the coupling factor K>0,25-0,3 is preferable. The main outputs of this investigation is that to realize on route charging is necessary to have information of misalignment between primary and secondary coils in direction X (in direction where the car is moving). The above results show that "X" misalignment up to 20 cm can be used as a threshold value for switching ON and OFF the transmitting windings - fig.5.

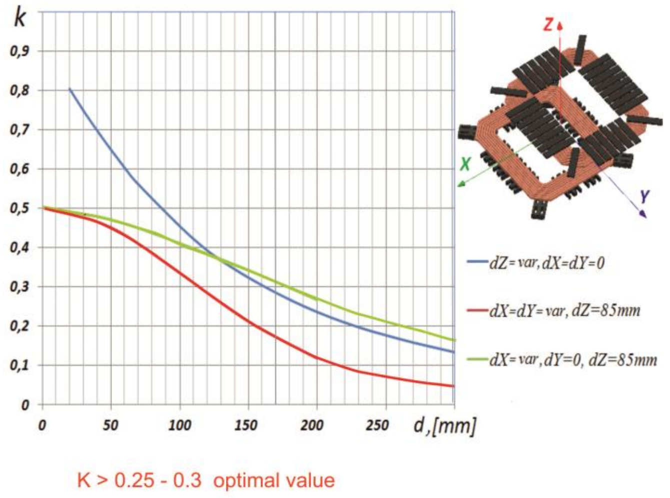


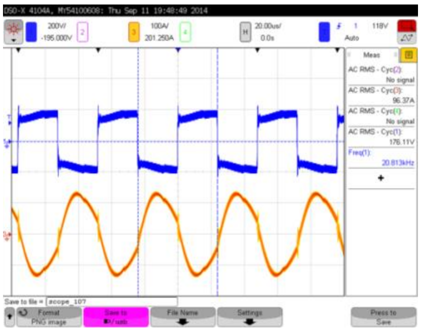
Fig. 5. Coupling factor K Vs. misalignment in X,Y,Z

The next step of testing and measurement of the whole power transfer electronic system with real battery load was optimization of charging station operating mode. The final outputs are presented in table 3.

Some real measurements are presented in figure 6. From these time charts is visible (see IPT primary current, IPT secondary current, IGBT voltage) that charging station operating mode is totally acceptable from electrical and safety point of view.

Table III. Electrical parameters of primary and secondary IPT coils

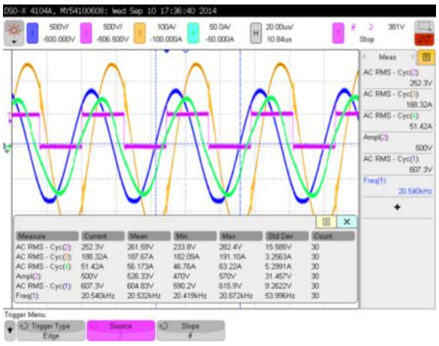
LOAD	**Battery – A123 system**
IPT ratio	$W_1 : W_2 = 7:7$
Air gap	70 ÷ 90mm
Frequency	f = 18 ÷ 22 kHz
IGBT current	I_{BRIDGE} = 60A rms @ 20kHz
Secondary matching trafos voltage TR3,4÷TR9,10	$U2_{TR3} + U2_{TR4} \approx U_{DC} : 1.8 \approx 300$ V
Primary IPT capacitor voltage CS3 (4,5, etc.)	U_{CS} = 600V rms @ 20kHz
IPT primary current	$I_{TX\ coil} = I_{CS} = I2_{TR} = 1.8 \times I1_{TRprim} = 110A$
IPT primary voltage	U_{TX} = 1200V rms @ 20kHz
IPT secondary current	$I_{RX\ coil} = I_{LOAD}$ = 75A rms
IPT secondary voltage	U_{TX} = 1100V rms @ 20kHz
Secondary IPT capacitor voltage C_{sec}	U_{sec} = 550V rms @ 20kHz



AC RMS - Cyc(2): No signal
AC RMS - Cyc(3): 96.37A
AC RMS - Cyc(4): No signal
AC RMS - Cyc(1): 176.11V
Freq(1): 20.813kHz

IPT primary Current (orange) 96,37 A and voltage on the secondary winding of matching trafo (blue) 176,11V at power 28.5 kW and frequency 20.81 kHz. No misalignment

a)



AC RMS - Cyc(2): 252.3V
AC RMS - Cyc(3): 188.32A
AC RMS - Cyc(4): 51.42A
Ampl(2): 500V
AC RMS - Cyc(1): 607.3V
Freq(1): 20.540kHz

Measure	Current	Mean	Min	Max	Std Dev	Count
AC RMS - Cyc(2):	252.3V	261.59V	233.8V	282.4V	15.585V	30
AC RMS - Cyc(3):	188.32A	187.67A	182.09A	191.10A	3.2563A	30
AC RMS - Cyc(4):	51.42A	56.173A	46.76A	63.22A	5.2991A	30
Ampl(2):	500V	526.33V	470V	570V	31.457V	30
AC RMS - Cyc(1):	607.3V	604.83V	590.2V	615.9V	9.2622V	30
Freq(1):	20.540kHz	20.532kHz	20.419kHz	20.672kHz	53.996Hz	30

IPT primary current (orange) 188.32A; Matching capacitors voltage CS3-CS10 (blue) 607.3V; IPT secondary current (green) 51.42A; IGBT voltage (pink) 500V at misalignment dx=150mm, power 18.7 kW, frequency 20.54 kHz

b)

Fig. 6. Electrical tests - time charts

The optimized operating modes of all elements (currents and voltages) are in accordance with their catalogue electrical data.

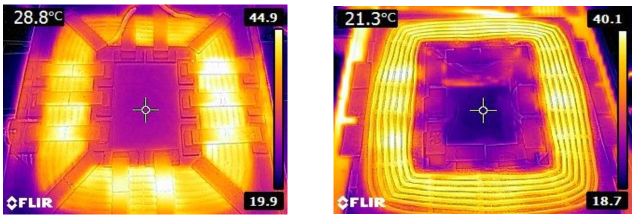
IV. EVALUATION OF HFIPT LOSSES

Table 4 presents the overall IPT ferrite and Litz wire losses, which are acceptable in terms of efficiency and levels of losses. On these bases could be calculated optimal operating temperature, cooling requirements, taking account of environment temperature. Relation between volume and area of the primary and secondary coils allows operating mode of IPT module without additional cooling.

Table IV. Losses in IPT core and Litz wire

IPT		*Air gap 100mm*	
Output power/Output current		*29,7kW / 90A*	
Frequency		*20kHz*	
Winding	*Loses*	P_{loss} *,[W]*	*Plosses/Pout, %*
Transmitting (Tx)	*ferrite core*	*≈ 160W*	*0,54%*
	Litz wire	$I^2R=120^2.0{,}047=677W$	*2,28%*
	Volume and surface area		$363dm^3/133dm^2$
Receiving (Rx)	*Ferrite core*	*≈ 150W*	*0,51%*
	Litz wire	$I^2R=80^2.0{,}085=544W$	*1,83%*
	Volume and surface area		$265dm^3/120dm^2$
Total		*≈1532W*	*5,16%*

To confirm that revised electrical parameters of electrical components guarantee optimal operating mode of each designed module, additional temperature test are implemented. On the figure 7 are shown temperature distributions of IPT module. The test condition during the temperature tests are - 3 min at 90 A and 17 min at 60 A, power 22kW.



IPT primary-max.temp. 44.9°C a)

IPT secondary-max. temp. 40.1°C b)

Fig. 7. IPT temperature tests

The measured maximum temperatures (in red) of the most powered modules at end of test (after 20 minutes) are minimum three times less than permissible catalogue data.

V.DESIGN OF ON ROUTE CHARGING ZONE

In Figure 8 is presented a draft of on route Charging zone with four primary coils, two guidance and one centric lines, that will help the driver to guide the vehicles in the right way with minimum Y misalignment. In front of the first coil, between next three others and after the last one are shown sensors for indication of permissible X misalignment. The green marked sensors are activated when secondary coil covers the corresponding primary coil with dX=200 mm misalignment “before” in the driving direction. Accordingly the corresponding primary coil is switched ON. Similarly, all red sensors are activated when misalignment “after” is again 200mm and they will switch OFF the corresponding primary coil.

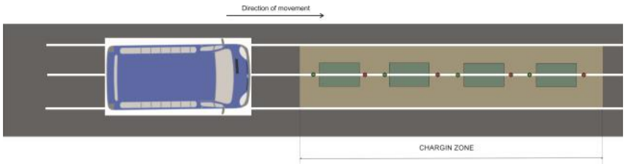


Fig. 8. On route charging zone

Taking into account this principle of activity, it is proposed to choose so called proximity sensors.Sensors will be switched in accordance with 40 mm distance between secondary coil and ground surface, where they have to be built.

VI. DISCUSSION AND CONCLUSIONS

✓Infrastructure on route charging zone is developed.

✓For on route charging, additional investigations of misalignments between primary and secondary coils, especially in X direction (driving direction), were made.

✓For that reason, how the misalignment values influence the permissible magnetic coupling factor has been analyzed and final results have been presented.

✓The currents and voltages of all elements are in accordance with their catalogue electrical data and results of implemented temperature tests have proved that.

✓The analysis of on-route energy distribution and misalignment results has been taken into account to define the distance between primary coils built in a charging zone.

✓It was proved that to realize effective and reliable HF generator operating mode, which correspond to permissible misalignment, the switching sensors have to be used.

VII.REFERENCES

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