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Preliminary Design of a Mid-Range Superconducting Wireless Power Transfer System for Magnetic Levitation Vehicles: Application to the MagLev-Cobra

Cláudio Mendes
NOVA School of Science and Technology (FCT NOVA)
Caparica, Portugal
cab.mendes@campus.fct.unl.pt

Luís Romba Jorge
NOVA School of Science and Technology (FCT NOVA)
Caparica, Portugal
romba.jorge@gmail.com

Roberto Oliveira
UNINOVA – Instituto de Desenvolvimento de Novas Tecnologias
Caparica, Portugal
r.oliveira@uninova.pt

João Murta-Pina
NOVA School of Science and Technology (FCT NOVA)
CTS – Centre of Technology and Systems (UNINOVA)
Caparica, Portugal
jmmp@fct.unl.pt

Richard Magdalena Stephan
Federal University of Rio de Janeiro (UFRJ)
Rio de Janeiro, Brasil
richard@dee.ufrj.br

Stanimir Valtchev
NOVA School of Science and Technology (FCT NOVA)
CTS – Centre of Technology and Systems (UNINOVA)
Caparica, Portugal
ssv@fct.unl.pt

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***Abstract*—This work presents a mid-range wireless power transfer (WPT) system that uses a high-temperature superconducting coil in the transmitter circuit to increase the efficiency of the system. The presented system is foreseen to provide energy to superconducting magnetic levitation vehicles and is intended to be implemented in the Brazilian MagLev-Cobra. The developed concept is based on an Inductive Power Transfer (IPT) system, using magnetic core reactors (MCR) to tune the resonant frequency under load variations, which arise in the charging process of the vehicle. Based on this architecture, the proof of concept was demonstrated in a laboratory-scale system, namely by assessing the performance as a function of the distance between the receiver and the transmitter coils, as well as its misalignment.**

Keywords*—high-temperature superconductors (HTS), inductive power transfer (IPT), magnetic core reactor (MCR), wireless power transfer (WPT)

I. INTRODUCTION

Mid-range Wireless Power Transfer (WPT) is based on a time-varying magnetic field linking two resonant circuits, a transmitter and a receiver [1]. There are two different processes to transmit power without wires, namely strong magnetic coupling (SMC) and inductive power transfer (IPT). In the latter, focused on this work, the transmitter unit is built of the transmitter source directly connected to its resonant circuit. Similarly, in the receiver unit, the load is directly connected to the corresponding resonant circuit.

In WPT, changes in the load have a direct impact on the tuning circuit, which implies a loss of efficiency. This problem is minimized if the SMC process is used. Here, the resonant circuits are not galvanically connected to the generating source and the load. Yet, the connection is established magnetically, making this circuit less prone to load variations. However, the SMC circuit is more complex than IPT, as it uses, e.g., more coils to implement the magnetic connection. Another possibility, while maintaining an IPT circuit, is the use of a Magnetic Core Reactor (MCR) to tune the frequency under load variations.

An MCR is a device with the ability to correct matching deviations of the resonance frequency. It allows for adjusting frequency, in the emitter as well in the receiver circuits, which may occur, as mentioned, due to load variations [2]. These arise in the charging process of the, e.g., batteries, as later mentioned, connected to the WPT system.

In this work, a WPT system for Magnetically Levitated (MagLev) vehicles is proposed. It is aimed at MagLevs using superconducting-based levitation. Since these already have cryogenic systems available, required for superconducting materials to operate, these materials are also proposed in the WPT system. Materials that enter superconductivity above liquid nitrogen temperature (77 K), called High-Temperature Superconductors (HTS) are used, e.g., for the sake of cost-effectiveness when comparing to other, low temperature, materials.

The preliminary design of a WPT, with one HTS coil in the transmitter, for MagLev-Cobra, a MagLev vehicle developed at the Federal University of Rio de Janeiro, Brazil, is presented in this paper. A proof-of-concept of the system, in a laboratory-scale prototype, is also described. It is based on an IPT circuit with an MCR to tune the frequency under load variations. The transmitter coil is made of HTS Y-Ba-Cu-O (YBCO) tape, immersed in liquid nitrogen, and the receiver coil is made of copper, both in pancake configuration.

II. CASE STUDY: THE MAGLEV-COBRA

The MagLev-Cobra, shown in Fig. 1, is a superconducting magnetic levitating (SML) vehicle [3], built by four modules, with six cryostats per module, which provide a total of 36 kN levitating force. The thrust force is developed by a three-phase linear induction motor (LIM) whose armature or primary is placed in the vehicle, while the rail acts as secondary (short-primary LIM). This is typical in urban low-speed MagLevs, which is the case of the MagLev-Cobra [4].

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Fig. 1. The MagLev-Cobra.

The MagLev-Cobra is currently on a 200 m test rail, and to energize the LIM the vehicle has collector brushes connected to a 550 V DC bus that goes along the whole rail.

The current solution is not feasible for commercial applications, and this paper proposes a WPT system that can provide energy to such MagLev vehicles, where Cobra is used as a case study. The system is developed considering a receiver coil in the vehicle and transmitter coils in the stations. The vehicle is thus charged in the stations, storing the energy to feed the LIM during the trip to the next station. The storage system can be either Lithium-ion (Li-ion) batteries or a hybrid system built of Li-ion batteries and supercapacitors, although this is not addressed in this work.

To define the power rating of the WPT system, the energy demand of the MagLev-Cobra must be assessed. The vehicle currently connects two stations, named CT1 and CT2, 200 m apart, thus performing a 400 m round trip. Cobra departs from CT1, travels to CT2, and returns to CT1. The induction motor demand is extremely low due to the absence of mechanical friction with the rails (only air friction exists) and a practically flat trajectory. Prior simulations showed that a fully loaded vehicle (3030 kg) would require only around 140 Wh for the round trip. This LIM demand is negligible when considering the air-conditioning power consumption, which is around 50,000 BTU/h or 14.65 kW. This is the average demand considered in the next calculations.

Therefore, consumption is dictated by the air-conditioning system, which operates all the time, even when the vehicle is stopped. The total amount of energy required in one round trip or cycle is thus dependent on the headway, i.e., the interval between Cobra leaving from CT1 and the next departure time, after having returned from CT2. The total energy required per cycle as a function of the headway, shown in Fig. 2, is given by

$$E = P_{ml} \frac{H}{3600} = 4.07 \times 10^{-3} H \tag{1}$$

where E is the energy (kWh), P_{ml} is the average power of 14.65 kW, and H is the headway (s). The traveling time between two stations, independent of the direction, is around 100 s. So, for instance, $H = 240$ s means a total stopping time of 40 s, which can be split differently among CT1 and CT2, thus affecting the total energy that should be transferred by the WPT system at each station.

It is assumed that the energy transfer in CT1 and CT2 is equally performed since the receiving coil is always the same. Therefore, neglecting recovery due to braking, energy is transferred in a total time given by $H - 200$, as 200 s is the total traveling time. The power of the WPT system, P_{WPT}, is thus given by

$$P_{WPT} = E \frac{3600}{H-2} = P_{ml} \frac{H}{H-200} \tag{2}$$

This equation is represented in Fig. 3. As an example, considering $H = 1020$ s, the required energy for a cycle is 4.15 kWh $(= 14.65 \times 1020/3600)$. This should be transferred in a total time of 820 s, split among CT1 and CT2, which means a minimum power $P_{ml} = 18.22$ kW.

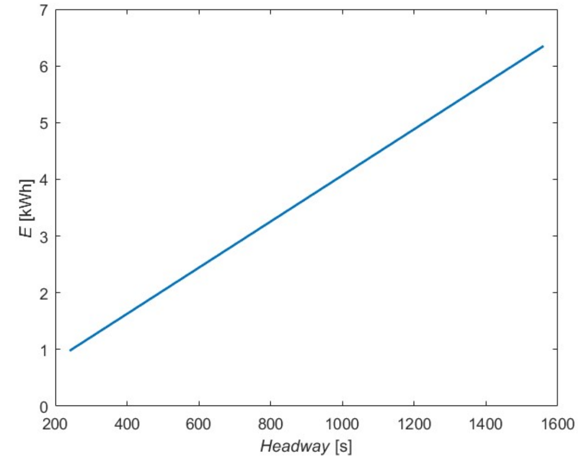

Fig. 2. Dependence of the energy required by MagLev-Cobra in an operation cycle and the headway.

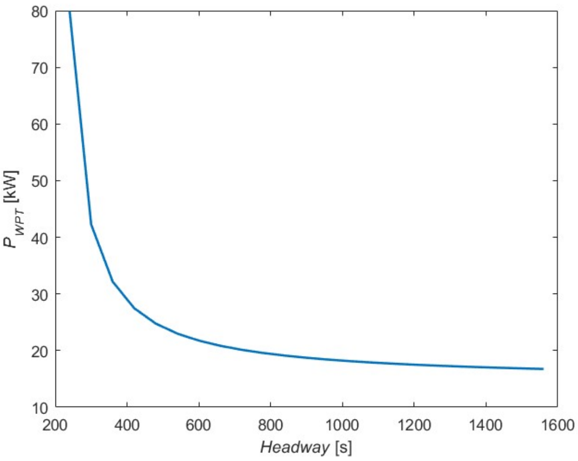

Fig. 3. Power of the WPT systems as a function of the headway.

III. HTS WIRELESS POWER TRANSMISSION SYSTEM FOR THE MAGLEV-COBRA

The proposed WPT system for MagLev-Cobra includes an HTS coil in the transmitter. At the receiver, a copper coil is used. Below are some formulas that are important in the design of a WPT system.

The coupling factor, k, indicates the quality of the magnetic connection between the receiving and transmission coils and depends on the distance between both [5], and is given by

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{3}$$

where M is the mutual inductance between the transmitter and receiver coils, and L_1 and L_2 are their respective self-inductances. The mutual inductance can be obtained experimentally using [6]

$$M = \frac{U_{OC}}{\omega I_1} \tag{4}$$

where I_1 is the transmitting circuit current, U_{OC} is the receiving circuit open voltage and ω is the angular frequency.

The transmission efficiency, η, of a WPT system is given by

$$\eta = \frac{P_{out}}{P_{in}} \tag{5}$$

where P_{out} is the receiving circuit power and P_{in} is the transmitting circuit power.

For an RLC circuit, with inductance L_c and capacitance C, to be in resonance, its inductive and capacitive reactances, X_L and X_L, respectively, must be equal (Fig. 4).

This leads to a resonance frequency, f_r, given by

$$f_r = \frac{1}{2\pi\sqrt{L_c C}} \tag{6}$$

To obtain the desired resonance frequency, the presence of capacitors in the transmitting and receiving circuits is necessary. Considering that the circuit under analysis has compensation (coil, MCR, and capacitor in series), as shown in Fig. 5, the rationale to be adopted is described below.

It is necessary to calculate the series of impedance parallels related to the MCR and the coil, of the transmitter or receiver, depending on the case, considering their distributed capacities. It should be noted that each coil has also an internal resistance, but this is neglected. Thus, the impedance of a generic parallel LC branch, X_{eq}, with general inductance L and capacitance C, is just

$$X_{eq} = -\frac{\omega L}{(\omega^2 LC - 1)} \tag{7}$$

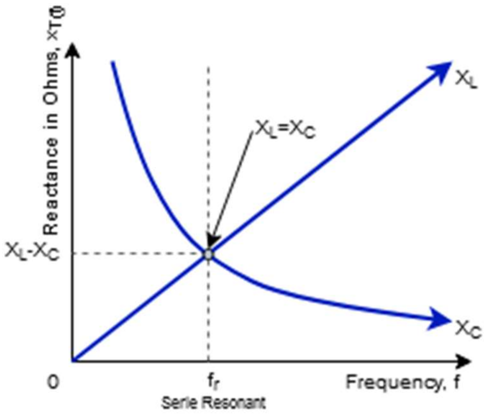

Fig. 4. The intersection of capacitive and inductive reactance in a series RLC circuit.

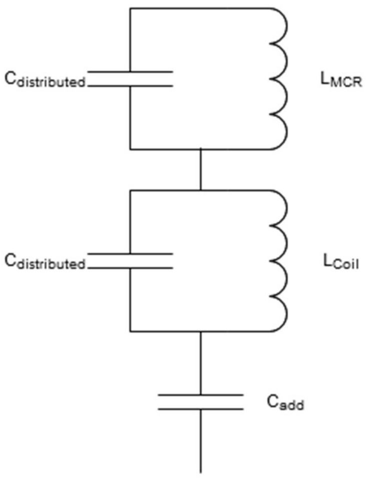

Fig. 5. Equivalent circuit allowing obtaining the capacitance needed to add, C_{add}, to obtain resonance. The (transmitter or receiver) coil is modeled by a distributed capacitance (represented as $C_{distributed}$) and an inductance (L_{Coil}). The MCR is also represented by a distributed capacitance and an inductance (L_{MCR}).

After calculating the reactance of each parallel branch, the following equation needs to be solved,

$$C_{add} = \omega\left(X_{eq,MCR} + X_{eq,coil}\right) \tag{8}$$

where $X_{eq,MCR}$ and $X_{eq,coil}$ are the equivalent reactances of the MCR and the corresponding transmitter or receiving coil.

The copper coil, used in the receiving circuit, with inductance L_{Cu}, is shown in Fig. 6. The HTS coil, with inductance L_{HTS}, shown in Fig. 7, used in the transmitter circuit, is made of 4 mm wide YBCO tape from the SuperOx Company. Prior calculations lead to a coil inductance, L_{HTS}, of around 1.6 mH. It was designed using a classical equation for planar coils [7],

Fig. 6. The copper coil of the receiver circuit.

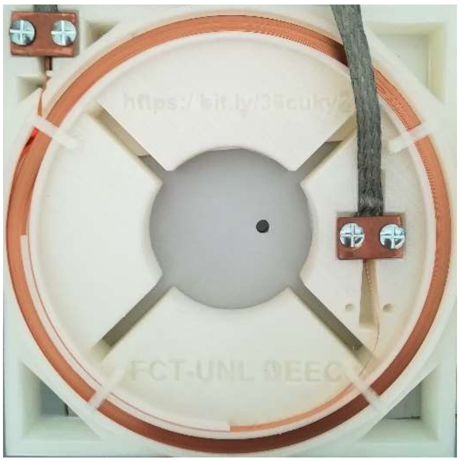

Fig. 7. HTS coil of the transmitter circuit.

$$L_{HTS} = 0.0315\,\frac{a^2N^2}{6a+9b+10c} \qquad (9)$$

The parameters in (8) are shown in Fig. 8, where N is the number of turns of the HTS planar coil, with internal radius r_i, made of superconducting tape with thickness ε. Thus, $a = r_i + \frac{c}{2}$, $c = N\varepsilon$, and b is the width of the tape. For the present HTS tape, $b = 4$ mm and $\varepsilon = 0.11$ mm. The specifications of both coils are shown in Table I.

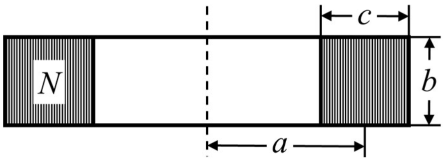

Fig. 8. Geometric parameters, a, b, and c, of a planar coil with N turns.

TABLE I. SPECIFICATIONS OF THE COILS USED IN THE WPT SYSTEM

Parameter	**Value**	
	Copper Coil	***HTS Coil***
Inductance (mH)	0.15	1.6
Number of turns	34	60
Outer diameter (cm)	24.0	20.3
Inner diameter (cm)	5.0	19.0

The MCR, whose detailed operation can be found in [2], and is shown in Fig. 9, is used, as mentioned before, to correct variations in the resonance frequency that occur due to load changes. A DC current allows controlling the inductance of the device since it operates in the nonlinear region of the ferromagnetic core that builds the MCR. In this case, the DC current range is 0 to 3 A. As an example, the resonance frequency in the receiver circuit as a function of the DC current in the MCR is shown in Fig. 10.

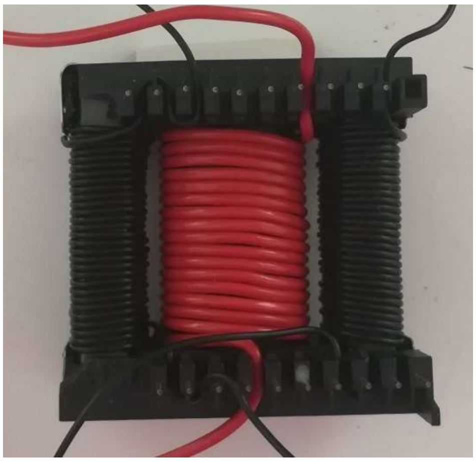

Fig. 9. The magnetic core reactor. The DC current is injected into the coil of the central leg. The coils in the outer legs are connected in series, with opposite orientations, and connect to the external circuit.

IV. RESULTS AND DISCUSSION

In this section, the results of simulations and experiments are described and discussed.

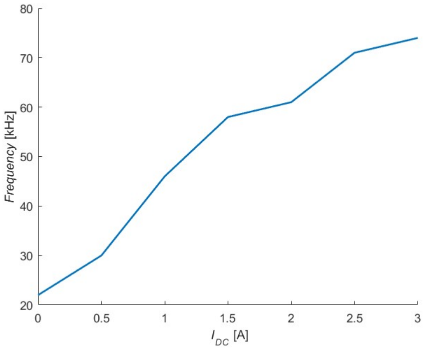

Fig. 10. Resonance frequency as a function of the DC current in the MCR in the receiver circuit.

A. Simulations

Fig. 11 illustrates the WPT system implemented in the Matlab/Simulink environment. An inverter controlled by a Pulse Width Modulation (PWM) generator supplies the resonant system. Energy is transferred from the transmitter to the receiver system. A simple RL circuit is used as a load. The parameters of the circuits are shown in Table II.

Simulations resulted in an efficiency of the WPT system of around 73% for a load level of 100%. The results for the different load levels are shown in Table III.

B. Laboratory Tests: Preliminary Approach

Due to the reduced power provided by the signal generator, a variation of the current I_{DC} in the MCRs did not influence the resonance frequency of the WPT system. Therefore, I_{DC} was not used in the emitter circuit. The laboratory assembly of the WPT circuit is shown in Fig. 12.

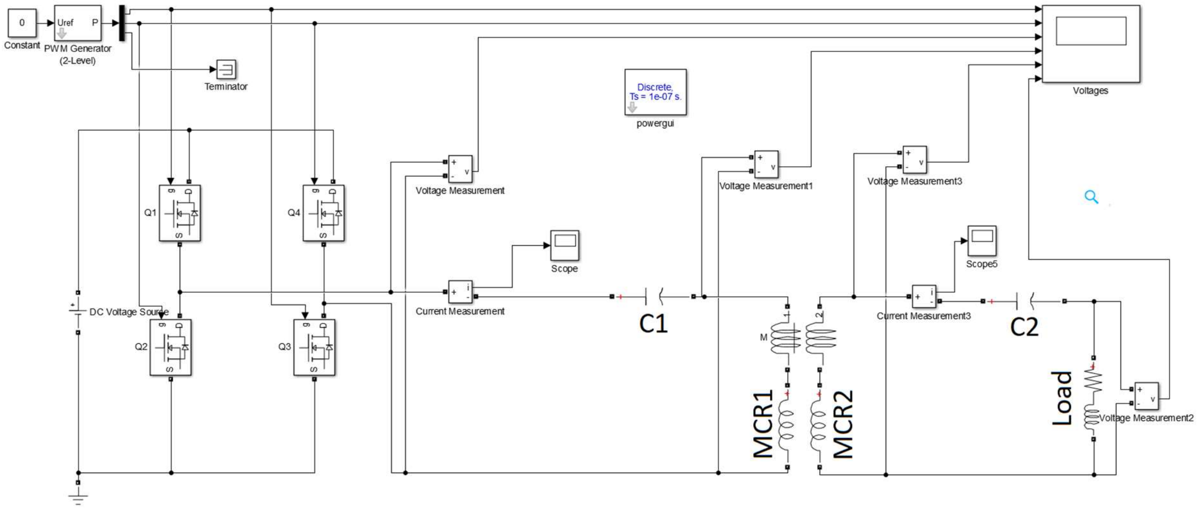

Fig. 11. Simulation circuit of the WPT system, implemented in Matlab/Simulink.

To assess the performance of the system, two types of tests were performed, namely changing the vertical distance and the horizontal alignment (Fig. 13).

Three vertical distances were selected, namely 3, 4, and 7 cm, while the frequency was varied in the range of 80 to 90 kHz. The frequency that led to higher efficiency was set in the horizontal alignment tests, at a vertical distance of 3 cm. In both tests, the load was at 50% of its nominal value.

1) Vertical distance tests: Fig. 14 allows assessing the efficiency of the WPT system. It can be observed that, as expected, the increase in the vertical distance between the coils significantly reduced the efficiency of the system. It is also noted that the resonance frequency of the circuit is located at 86 kHz.

2) Horizontal alignment tests: Fig. 15 allows verifying the influence that a perfect alignment between the transmitter and receiver coils has on the efficiency of the WPT system. For a misalignment of only 5 cm, the efficiency of the system decreases by 50% for a vertical distance of 3 cm.

TABLE II. COMPONENTS IN THE SIMULATION MODEL OF THE WPT SYSTEM

Parameter	**Value**
DC source	400 V
$C1$	2 nF
$C2$	4.7 nF
L_{HTS}	1.6 mH
L_{Cu}	0.15 mH
$MCR1$ (transmitter)	1 mH
$MCR2$ (receiver)	1 mH
M	80 µH

TABLE III. VOLTAGE EFFICIENCY OF THE SIMULATION CIRCUIT FOR DIFFERENT LOAD LEVELS FOR A 68 KHZ FREQUENCY

Load level (%)	**Resistive load level (Ω)**	**Inductive load level (mH)**	**Efficiency (%)**
0	0.8	2.25×10^{-3}	6.3
50	200	0.4	71.3
100	500	0.8	76.3

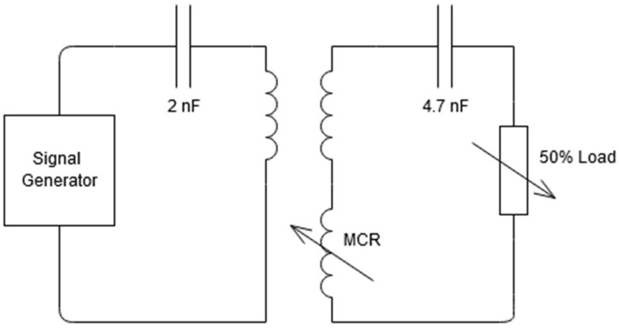

Fig. 12. Diagram of the circuit used in the laboratory tests. The transmitter, on the left, has an HTS coil, while the receiver, on the right, has a copper one.

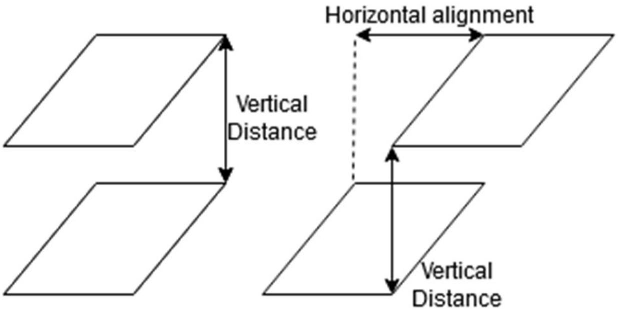

Fig. 13. Two types of tests were performed in laboratory experiments, changing the vertical distance between coils and their horizontal alignment.

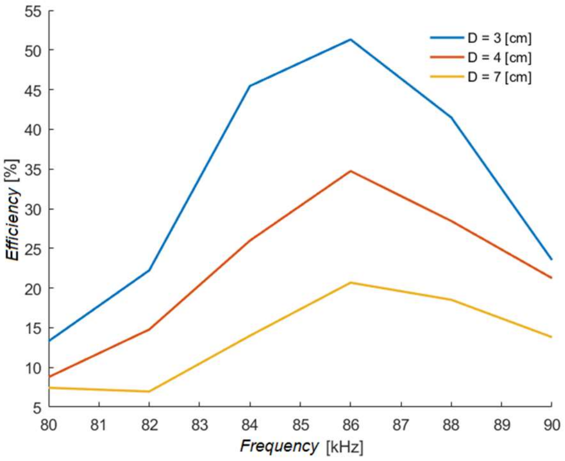

Fig. 14. The efficiency of the WPT system as a function of the frequency and the vertical distance, D.

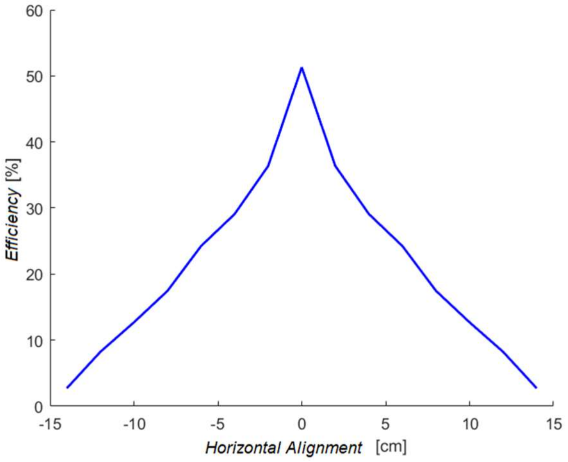

Fig. 15. The efficiency of the WPT system as a function of the frequency and the horizontal alignment.

V. CONCLUSION

A first approach to the WPT system to be designed for the MagLev-Cobra was presented in this paper, using an HTS coil in the transmitter circuit and a copper coil in the receiving circuit. For the laboratory scale system, simulations showed a maximum efficiency of 73%. Concerning experiments, in the case of tests with vertical distance, an efficiency of about 50% was obtained for 3 cm between the transmitter and receiver circuits. For the horizontal alignment test, considering a vertical distance of 3 cm, it was found that for a misalignment of only 5 cm the efficiency of the system decreased by about 50%. Future research involves testing the WPT circuit for significant voltage and current values to analyze the behavior of the circuit with the HTS coil, present in the transmitter circuit.

REFERENCES

[1] W. Zhang and C. C. Mi, “Compensation Topologies of High-Power Wireless Power Transfer Systems,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4768–4778, Jun. 2016, doi: 10.1109/TVT.2015.2454292.

[2] L. F. Romba, S. S. Valtchev, R. Melicio, M. V. Mudrov, and A. M. Ziuzev, “Electric vehicle battery charger controlled by magnetic core reactor to Wireless Power Transfer system,” in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Jun. 2017, pp. 1–6, doi: 10.1109/EEEIC.2017.7977782.

[3] L. S. Mattos, E. Rodriguez, F. Costa, G. G. Sotelo, R. de Andrade, and R. M. Stephan, “MagLev-Cobra Operational Tests,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 1–4, Apr. 2016, doi: 10.1109/TASC.2016.2524473.

[4] R. A. H. de Oliveira, R. M. Stephan, A. C. Ferreira, and J. Murta-Pina, “Design and Innovative Test of a Linear Induction Motor for Urban MagLev Vehicles,” *IEEE Trans. Ind. Appl.*, vol. 56, no. 6, pp. 6949–6956, Nov. 2020, doi: 10.1109/TIA.2020.3023066.

[5] S. Chatterjee, A. Iyer, C. Bharatiraja, I. Vaghasia, and V. Rajesh, “Design Optimisation for an Efficient Wireless Power Transfer System for Electric Vehicles,” *Energy Procedia*, vol. 117, pp. 1015–1023, Jun. 2017, doi: 10.1016/j.egypro.2017.05.223.

[6] K. A. Kalwar, M. Aamir, and S. Mekhilef, “Inductively coupled power transfer (ICPT) for electric vehicle charging – A review,” *Renew. Sustain. Energy Rev.*, vol. 47, pp. 462–475, Jul. 2015, doi: 10.1016/j.rser.2015.03.040.

[7] F. W. Grover, *Inductance Calculations. Working Formulas and Tables*. Instrument Society of America, 1973.