Development, Analysis and Experimental Investigation of Superconducting Wireless Power Transfer System Operating in Kilohertz Range

1st Pawel Lasek
Dep. of Power Electronics, Electrical Drives and Robotics
Faculty of Electrical Engineering
Silesian University of Technology
pawel.lasek@polsl.pl

2nd Mariusz Stepien
Dep. of Power Electronics, Electrical Drives and Robotics
Faculty of Electrical Engineering
Silesian University of Technology
mariusz.stepien@polsl.pl

***Abstract*—High-temperature superconducting (HTS) coils are potentially alternative for replacement of copper coils, thanks to high Q-factor and high current capabilities. In the following paper, the HTS coils for transmitter and receiver are designed, analyzed and measured to ensure high performance and good coupling between coils. The presented wireless power transfer (WPT) system operates at 30 kHz with resonance at the receiver coil and with triangle current waveform on the transmitter coil. The coils are analyzed using finite-element method to establish the operating point of HTS.**

***Keywords*—high-temperature superconductors, wireless power transmission, finite element analysis, critical current, type-II superconductors**

I. Introduction

In pursuit of high efficiency and high quality factors of power transferring devices the reduction of losses is required. This is done mainly by utilization of higher cross-section area of wires and litz wires with multiple strands for high frequency applications. High-temperature superconductors (HTS) are promising candidates to replace copper wires in coils due to outstanding capabilities of conducting high current with almost no losses due to superconducting effect occurring at low temperatures i.e. 77 K. Up to this date the main focus of researchers are DC applications, where very thin films of superconductor material can conduct hundreds of amperes without any losses. There are also low frequency applications (50 Hz and 60 Hz), mainly for devices operating in power grid, such as power transformers, current limiters, electric motors and generators. High frequency applications are generally avoided due to increase of losses inside superconductors and other parts of superconducting tapes which are limiting transport current due to increased local temperature [1] [2].

where critical current I_c occurs when reaching voltage drop of $U_c = 1\ \mu\mathrm{Vcm}^{-1}$. The value of power n shows how steep the transition is and typically ranges from $10 - 30$, but may change depending on setup. In this case, the critical current $I_c = 95$ A when tape is cooled with liquid nitrogen (LN2) at a temperature of 77 K at atmospheric pressure. For the following tape, the power $n = 30.72$.

II. System design

A. Structure of the Circuit

The first step in designing a superconducting wireless power transfer system is deciding on circuit design for transmitter and receiver sides to establish operating conditions of HTS coils. The receiving side will operate in series resonance of capacitance C_s (1) and self inductance of receiver coil with resistive load R as shown at Fig. 1.

$$C_s = \frac{1}{\omega^2 L_{\sigma 2}} \tag{1}$$

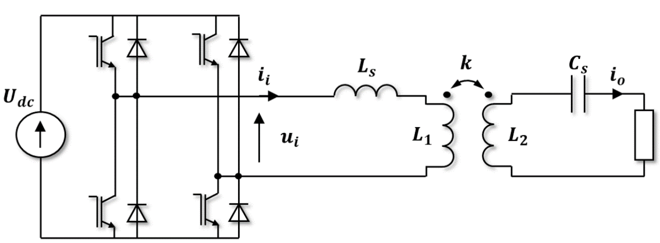

Fig. 1. Lumped circuit model of HTS wireless power transmission system.

Operating in series resonance should provide best power transfer capability. For the transmitter side, it was decided to use full bridge inverter with frequency of 30 kHz. The current waveform will be formed by using series inductance L_s to create triangular current waveform shown in Fig. 2 This is not the typical approach when designing a power transfer system that will operate eventually in resonance. Usually, the current waveform of transmitter would be a sine-wave, created by either resonance (with series or parallel capacitance) or utilization of L or LC filter with pulsed-width modulation

(PWM). The PWM requires switching frequency of at least 10 to 20 times higher than operating frequency - in this case 300 kHz - 600 kHz which will create a lot of challenges when designing inverter and will create a lot of losses along the way.

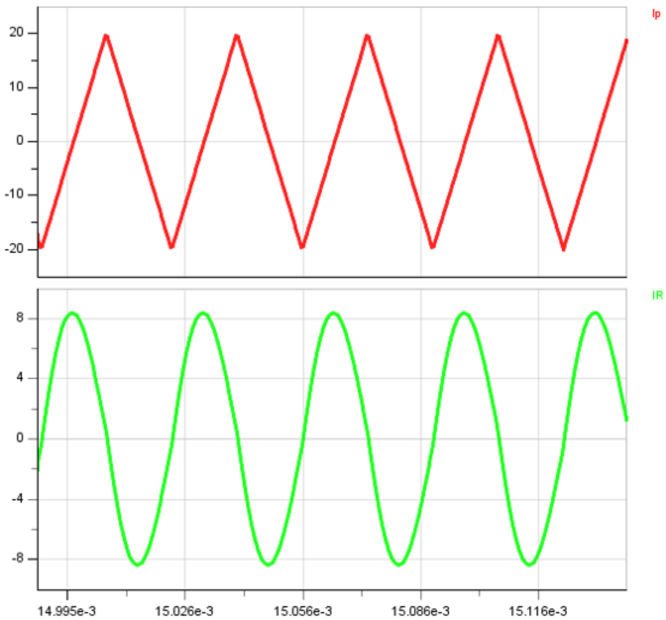

Fig. 2. Current waveforms obtained from lumped circuit model. Current of transmitter (red), and receiver (green).

B. Coil design

First objective of coil design for wireless power transfer is high coupling coefficient to ensure high efficiency of the system. Since the system is based on superconductors, the second objective is ensuring as high as possible critical current I_c. The turns of coil are made of superconducting tape which is prone to damage due to bending or mechanical stress, therefore it is decided that coils will be spirals. The cross-section of setup is shown at Fig. 3. The presence of shield will increase magnetic coupling, but may influence critical current of coils. For that purpose, the finite element method was used to determinate the geometry of a coils to meet both objectives. To simplify and speed-up simulation time the 2D axisymmetric geometry was created shown in Fig. 3, where distance between turns (turn span) was changed by factors of k_1 and k_2 which is the fractions of coil radius r, as well as distance between coils d.

$$\nabla \times \frac{\mathbf{1}}{\mu} \nabla \times \mathbf{A} = \mathbf{J_s} - \frac{\mathbf{1}}{\varrho(\mathbf{J})} \left(\frac{\partial \mathbf{A}}{\partial \mathbf{t}} + \nabla \varphi \right) \tag{2}$$

where: $\mu = \mu_0 = 4\pi \cdot 10^{-7}$ (H/m) - magnetic permeability; ϱ - resistivity of medium; φ - applied electric potential, $\mathbf{A}$ - magnetic vector potential.

Summary and Discussion

The wireless power transfer system based on HTS transmitter and receiver coils was presented. At the design stage,

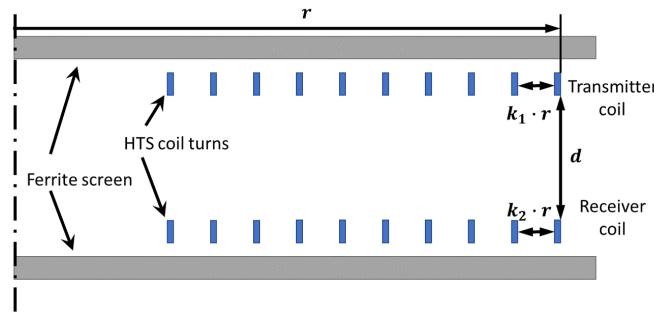

Fig. 3. Finite-element model geometry.

it is necessary to optimize design both for self and mutual inductances of coils as well as critical current density to fully utilize capabilities of high-temperature superconductors. The presence of ferromagnetic shield encapsulates magnetic field, increasing coupling coefficient of WPT system. The shield also shapes magnetic field in proximity of coil in such a way, that flux lines are parallel to coil turns, therefore minimizing diminishing effects on critical current. The designed WPT system utilizes series LC resonance at the receiver and triangle waveform shaped with series inductance at the transmitter.

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