International Journal on Magnetic Particle Imaging
Vol 8, No 1, Suppl 1, Article ID 2203014, 3 Pages

Infinite Science Publishing

Proceedings Article

Heat it up: Thermal stabilization by active heating to reduce impedance drifts in capacitive matched networks

Florian Thieben [1,2,*] · Fynn Foerger [1,2] · Fabian Mohn [1,2] · Florian Sevecke [2,3,4] · Tobias Knopp [1,2] · Matthias Graeser [1,2,3,4]

[1]Section for Biomedical Imaging, University Medical Center Hamburg-Eppendorf, Hamburg, Germany
[2]Institute for Biomedical Imaging, Hamburg University of Technology, Hamburg, Germany
[3]Fraunhofer Research Institute for Individualized and Cell-based Medicine, Lübeck, Germany
[4]Institute for Medical Engineering, University of Lübeck, Lübeck, Germany
[*]Corresponding author, email: f.thieben@uke.de

Abstract

The achievable sensitivity in Magnetic Particle Imaging is not only limited by noise, but also depends on the stability of the system. Thermal dependencies of the current carrying components lead to drive-field distortions in amplitude and phase, causing drifting background signals. In this work, an active capacitor heating system is developed that allows for thermal stabilization and trimming a resonance circuit to the desired frequency.

I. Introduction

Magnetic Particle Imaging (MPI) is currently developing from small-animal to clinical size with various research groups working on upscaling of the instrumentation [1, 2]. Upscaling MPI systems leads to three main challenges. First, a different coil design is needed as the larger cross section of the bore leads to large inductance compared with small size coil designs. This large inductance would require high voltages to drive the current for the required magnetic field, which is undesirable next to the patient. Therefore different coil designs using larger wire cross sections are required [3]. Second, as the field is coupled to the current density in the coil, the larger cross section results in high currents in all connecting components. In the case of the human scale imager in Hamburg [1] this leads to currents of up to 340 A in the coil. While this does not necessarily change the power dissipation in the coil itself, the third point is that all other components in the high current circuit have to handle the same current. The high currents lead to impedance drifts, especially in the capacitors, due to the temperature increase. The result is a drift in phase and amplitude in the drive field and the receiver circuits, limiting the stability of the systems background [4] and consequently the achievable signal-to-noise ratio and resolution [5, 6].

Typical strategies to handle thermal heating in the system include active water or oil cooling, combined with a heat exchange to the surrounding air or cooling water from local infrastructure. This typically requires extensive construction, flow control and complicates the maintenance of the system. In this paper, a different approach is taken by actively heating the capacitor assembly to amplify the heat transfer to surrounding air. The thermal energy is provided by a heating cartridge which is connected to a simple temperature control board. This solution only requires electrical connections without any need of a liquid coolant. We demonstrate the stability of the system and show that the temperature dependency can even be exploited to trim the resonance circuit to the desired frequency.

II. Methods and materials

All measurements are taken with the human brain imaging system at the University Medical Center in Hamburg [1]. The high current circuit is shown in Figure 1. The drive field generator (DFG) is matched by two capacitor banks to be resonant at $f_r = 26.042\,\mathrm{kHz}$ (resonance 2). In series to the capacitor banks, a second toroidal coil is made resonant (resonance 1), forming an air coil resonant transformer which provides a potential barrier and an impedance matching network [7]. This inductive coupling network (ICN) is driven by a primary winding along the toroids surface, which couples energy into the high current circuit [8]. The total rated current in the circuit is 340 A.

To control the temperature within the capacitors banks, a copper construction serves as a thermal distribution unit (Figure 1). The construction is insulated with 50 µm Kapton foil avoiding electrical shorts. A total number of 16 heating cartridges, two for each capacitor bank, is used to provide a maximum heating power of 1440 W to achieve a fast heat-up of the system. Within the steady state of the system, the power is only around 60 % of the maximum heating power. Each capacitor bank is controlled by a simple threshold controller which uses a K-type temperature sensor inside the copper construction. In addition, the temperature of the capacitors itself is observed by a PT100 sensor.

In order for the entire system to resonate at f_r, at a target specific temperature, all installed capacitors have to be at the rated temperature during the trimming process. For the presented device a target temperature of 50 °C was chosen. The system was roughly trimmed to be resonant at the desired frequency and then fine tuning was provided by temperature adaptation of a few degrees.

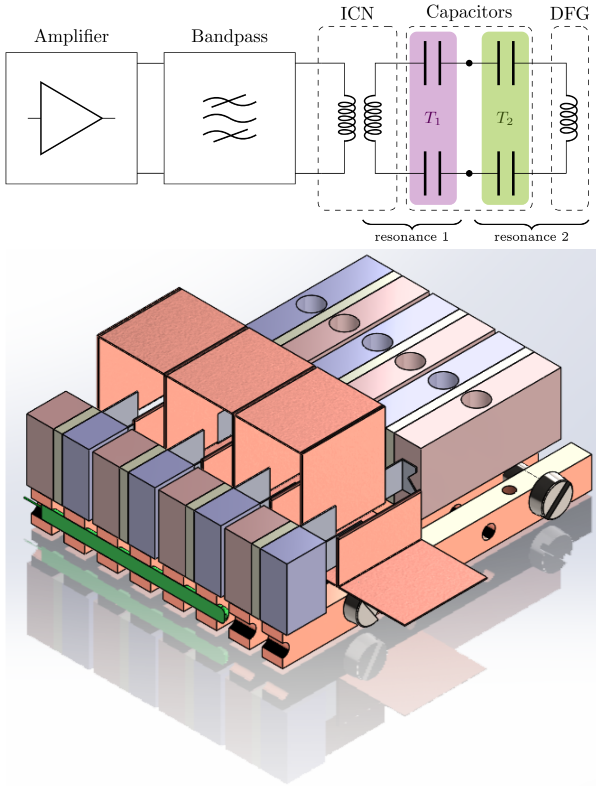

Figure 1: Measurement setup with temperature controlled capacitor banks for impedance matching. On top, the measurement circuit is depicted. It contains an amplifier, a bandpass filter, the ICN, temperature controlled capacitors and the DFG. With the temperature setting T1 of the capacitors highlighted in purple, resonance 1 is tuned. Analog, the temperature setting T2 of capacitors highlighted in green tune the resonance 2, with the DFG. Below is a section through a CAD rendering of a capacitor bank with seven capacitors mounted on insulated copper bars. The capacitor bank is heated by two heating cartridges (green) centered below the capacitors.

III. Experiments

The complex impedance of the system at f_r seen from the primary side of the ICN was measured by an LCR meter (E4980A/AL, Keysight Technologies, Inc.) during the heat up process. To test the reproduceability of the desired frequency, the system was repetitively heated up and cooled down to see if there is any deviation between heating cycles. Last, the temperature stability and its impact on the impedance were observed over a steady state controlling period.

IV. Results

Figure 2 shows the slope of the impedance during the heating process, starting at room temperature (16 °C) and with an impedance of $|Z(f_r)| = 16\,\Omega$, $\mathrm{phase}(Z(f_r)) = -48°$. In the heating experiment, with T_1 set to 47.2 °C and T_2 set to 52.5 °C the target resonance was reached after 41 min with an appropriate phase of $\pm 2°$. In several heating tests with the same temperature setting and different room temperatures, the resonance was reliably tuned again to the desired frequency. The temperature and impedance of a measured steady state controlling period over 1 h is shown in Figure 3. When controlling the temperature of the capacitor banks, an average positive phase angle of $(1 \pm 0.4)°$ of the impedance was achieved.

V. Conclusion

By active heating of current carrying components, we demonstrated a method to stabilize and trim the systems impedance simultaneously. The resonant circuit reaches thermal equilibrium state at the desired temperature if the total heat radiation due to the additional heating exceeds the power converted into heat by ohmic losses.

10.18416/ijmpi.2022.2203014

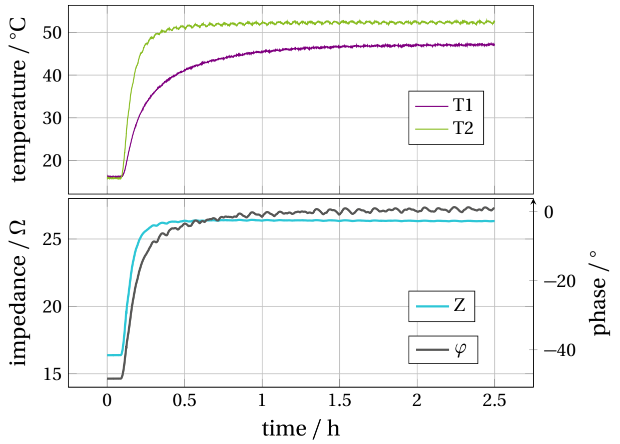

Figure 2: Measured complex impedance and tracked temperatures during heating experiment. On top, the temperature curves for sensors T1 and T2 are shown, starting at room temperature. Plotted below is the temperature dependent impedance in magnitude and phase.

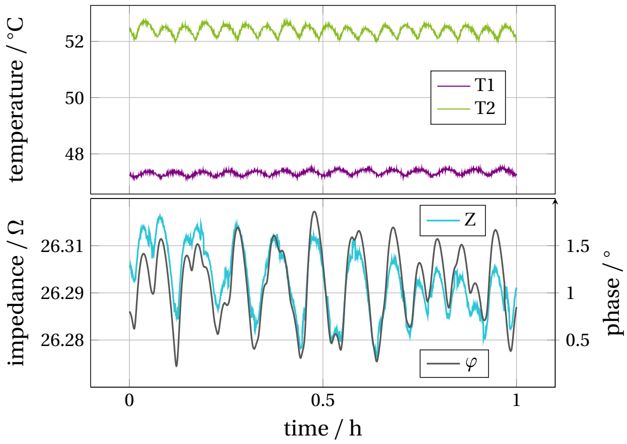

Figure 3: Measured complex impedance and tracked temperatures during steady state controlling period. On top, the slightly oscillating temperature curves for sensors T1 and T2 are shown. Below, the impedance in magnitude and phase is plotted.

Utilising this technique, the system can be held at resonance even for long imaging times. The long heatup time can be addressed by a better control circuit, including the known behaviour of the system and thus compensating the overdamped behaviour of the threshold controller used so far. This easy-to-implement method replaces a lot of infrastructure, that would be required for an active water or oil cooling system for medium power dissipation parts.

Author's statement

Research funding: The authors thankfully acknowledge the financial support by the German Research Foundation (DFG, grant number KN 1108/7-1 and GR 5287/2-1) The Fraunhofer IMTE is supported by the EU (EFRE) and the State Schleswig-Holstein, Germany (Project: IMTE – Grant: 124 20 002 / LPW-E1.1.1/1536. Conflict of interest: Authors state no conflict of interest.

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