# Current Control System for Coupled Coil Arrays in MPI

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Magnetic Particle Imaging (MPI), a novel biomedical imaging technique, maps the spatial distribution of superparamagnetic tracers. One challenge in upsizing the imaging systems from small animal to human-size is the power consumption. An energy-efficient topology for selection and focus field generators was presented using coupled multi-coil arrays. A trivial, cost-intensive solution to drive these arrays is the usage of separate 4-quadrant amplifiers for each coil. In this paper a cost-efficient and scalable alternative is presented. A current controlled design achieves currents of up to 30 A with frequencies up to 10 Hz and suppresses the inductive coupling within the arrays.

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## I Introduction

MPI is a novel real time capable biomedical imaging technique that was invented at the Philips Research Laboratories in Hamburg, Germany [1]. MPI systems utilize the combination of different magnetic fields to image the spatial distribution of the SuperParamagnetic Iron Oxide Nanoparticles (SPIONs): a quasi-static magnetic gradient field with a Field Free Region (FFR), and alternating drive fields for signal generation by SPIONs. The gradient field creating the FFR is shaped by the Selection and Focus field generator (SeFo). Only in the vicinity of this FFR the SPIONs can be excited following their nonlinear magnetization curve by the drive field. Those SPIONs induce a signal in a receive coil, which can be used to reconstruct the spatial distribution. SPIONs located away from the FFR are in saturation and thus not excited by the drive field [1].

A challenge in upscaling MPI scanners to human-size is the increase in power consumption. A new SeFo topology was introduced by Foerger et al.. Simulations have shown its energy efficiency [2]. The downside of this topology is the need to control the current in each of the 18 coils individually to move the FFR on a specific trajectory within the region of interest. 4-quadrant amplifier for each coil is a trivial but cost-intensive solution.

In this paper a modular, cost-effective alternative electrical circuit design is presented to drive a coupled multi-coil setup and suppress unwanted coil coupling [3].

## II Requirements of the control system

The developed SeFo consists of two coil arrays with 9 coils each, see Figure 1. Preceding simulations have shown that the SeFo coils need to be driven with sinusoidal currents of up to 30 A peak to achieve the desired gradient field strength with a frequency of up to 10 Hz. They steer the FFR in the region of interest, making the system real time imaging capable. With the flexibility of the SeFo it should also be able to apply forces and torques onto magnetic devices and nanoparticles [4,5]. Furthermore, as the coils of each array reside on the same soft-iron core the inductive coupling of the coils has to be suppressed.

**Figure 1: Developed SeFo by Foerger et al. [3], coil array (left), top view of aligned setup with both arays (right)**

## III Technical realization

To distribute the current to the individual coils, commercially available motor drivers Dimension Engineering LLC Sabertooth Dual 60A were chosen.

These motor drivers do not have a current controlled mode, but act as a H-bridge Voltage Source Inverters (VSI), an analogue PID-controller board was developed to control the currents.

The main component of these boards is a LEM LAH-50P current transducer, which measures the current in each coil. The measured current is scaled and subtracted from the set point provided by a Red Pitaya STEMlab 125-14 stack [6]. A tuneable, discrete analogue PID-controller supplies the control variable to the motor driver and the control loop is closed.

As the coils consist of massive soft iron cores, eddy currents occur at the switching frequency of the VSI at 24 kHz. Measurements with an LCR meter were conducted at 20Hz and 25kHz showing a significant reduction of the average inductance of all 18 coils from 865 µH to 41.7 µH (-95,18%). To reduce the occurring ripple currents due to the switching frequency of the VSI, a LC-low-pass filter (Tamura NAC-20, Nichicon PHC1255100KJ) with an attenuation of ~20dB at 24Khz was introduced into the circuit.

The H-bridges are configured in the lock anti-phase mode, therefore excess energy of the coils is fed back into its power supply. A regenerative approach is introduced to further improve the energy-efficiency of the setup. A capacitor bank was designed to take up the excess energy of the coils which can be resupplied. The size of the capacitors was chosen to be able to supply the maximum possible ripple current from the VSI, as well as to be able to take up the maximum energy of the coils and keep the input voltage to the rated voltage of the motor drivers. The total capacity of the capacity bank is 92.8mF (24x2200 µF type Vishay MAL213660222E3 and 4x10000 µF type Kemet ALC70A103EH100).

An input diode (IXYS DSS2X121-0045B) prevents the return of energy to the DC sources. The total system current is supplied by two Delta Electronica SM52-AR-60 DC sources. They supply up to 120 A to the SeFo driving circuit system. A functional diagram of the setup can be seen in Figure 2.

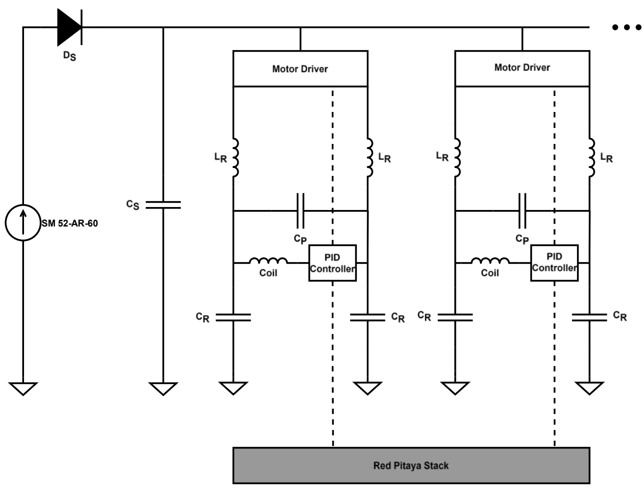


**Figure 2: Functional diagram of the current control system: DC sources SM 52-AR-60 protected by the diode DS, the capacitor bank CS, VSI with the LC low pass (Lr,Cp,Cr), the coils of the SeFo, PID controller and the Red Pitaya Stemlab 125-14 stack., signal lines dashed, power lines solid**

## IV Test setup and results

The used hardware components can be seen in Figure 3. In a first testcase a sinusoidal current with a frequency of 10 Hz and an amplitude of 30 A was supplied as a set point, as specified in the requirements. Rectangular currents were also tested. To test the compensation of inductive coupling two coils were placed seamlessly facing each other. The first coil was excited with a current edge, while the second coil was set to 0A DC. A comparison with an uncontrolled coil was made. The results can be seen in figure 3.

The setup can drive 10 Hz sinusoidal currents with an amplitude of up to 30 A. Inductive coupling of coils on a single coil array is compensated by the PID-controller.

## V Conclusion and outlook

A cost-efficient solution for driving multichannel coil arrays was proposed in this paper. The modularity of this approach allows for expansion or adaption of components. Single quadrant DC sources can be used in this configuration and the stored energy of the magnetic fields can be used regeneratively. The SeFo topology has already shown to be able to generate FFRs [7]. The total system energy efficiency is still to be measured while generating these fields.

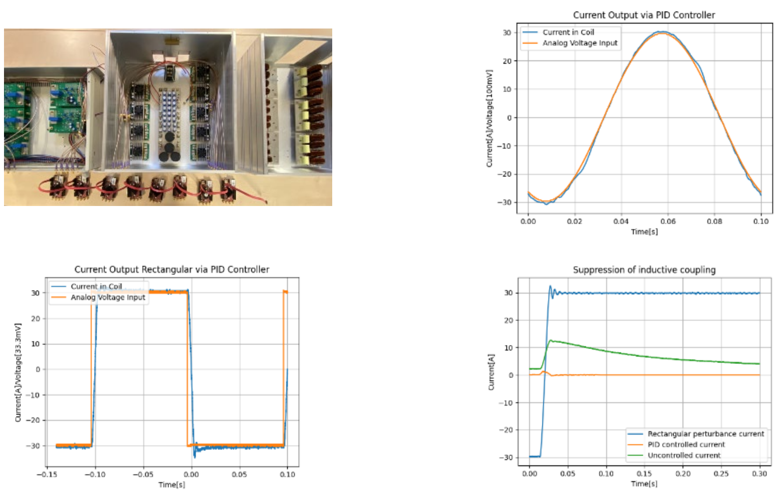


**Figure 3: Top left to bottom right:**
**Full current control setup, left to right: PID controllers, motor drivers, capacitor bank and power diode, output filters, Red Pitaya Stack at bottom.**
**10Hz 30A sinusoidal current, set point orange, measured current in coil blue**
**5Hz 30A rectangular current, set point orange, measured current in coil blue**
**Suppression of inductive coupling, two coil positioned seamlessly face to face, one coil excited by a current edge blue , current in other coil is to be kept at 0A, the PID controlled current orange,the uncontrolled current green.**

A for human head sized scaled up version SeFo with a similar coil array topology is being developed. The current control system based on the presented setup is updated to supply currents of up to 60A to the new SeFo. The modular design allows for easy adaptation to the new requirements. An upscaled capacitance bank is needed as larger inductances must be driven at higher currents. Due to the increased current, an input diode with a higher current rating will be needed. The output filters will be excluded in a first revision as the new coils are manufactured out of laminated electrical steel. The possibility for an external digital controller will be provided.

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