**System Auto Calibration for the Mutually Coupled Gradient Array Coils in MRI**

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**Synopsis:** Promising capabilities of gradient array systems come with some design and engineering challenges. Driving mutually coupled coils in these systems with desired slew rate is one of these challenges. In this work, an automated method is suggested in order to model the coil parameters such as DC resistance, self- and mutual-inductances of array elements for a single gradient frequency. Good agreement observed between obtained values for these parameters and LCR meter measurements. This work provides practical tool for auto calibration of the gradient array systems and compensation of the mutual inductances between them.

**Introduction:** The gradient array systems have promising applications in MRI(1,2). Flexibilities of these systems come with different design and engineering challenges. In order to achieve desired performance, driving mutually coupled coil elements with required slew rate and precise current is essential. This can be accomplished by modeling the system and its order determines the fidelity of the currents in the coils. Although closed-loop control configurations are used in gradient systems, mutual-inductance compensation in gradient array design can be demanding for a closed-loop control system. Therefore modeling the coils with their DC and AC parameters such as resistance, self- and mutual-inductance (L, M) values results in effective regulation of the coil currents. Utilizing coil model in feed-forward path by measuring the 9 channel coil parameters manually prior to its use with amplifiers has been presented previously (3). Manual measurement of the coil parameters is not practical for high number of array elements in terms of time, accuracy and reliance. Also repeating these measurements is not possible after integrating with amplifiers for dynamic calibration. In this work, a practical method to model the mutually coupled coils using the corresponding amplifiers and gradient current sensors is presented. DC resistances, self- and mutual-inductances of two coupled channels as an example in a 9 channel z-gradient array system(4) is acquired using proposed method. Obtained values are then used to drive the channels with desired current waveforms to validate the model. The algorithm is planned to be implemented in an FPGA, but in this abstract DC and AC coil parameters are obtained using gradient current sensor measurements and known applied DC and AC voltages respectively. Results are then compared with the values measured using an GW Instek LCR-B105G high precision LCR meter (Good Will Instruments, Taiwan). Digital implementation is planned to be finished by ISMRM conference in May 2019.

**Methods:** In proposed method, circuit model determination for a set of mutually coupled coils involves DC and AC characterization for each channel to find DC resistance, self- and mutual-inductance accordingly. This can be done through applying calibration DC voltage to each channel independently and calculate the DC resistance using measured currents of that channel. Self-inductance values of each channel is obtained by driving that channel with a calibration AC voltage and measuring phase and amplitude values of the currents flowing in that channel. The coupling is avoided by leaving the other channels open-circuited. Mutual-inductance between any respective channels is calculated by applying the same calibration AC voltage to one channel and measuring the induced current on the other channel which is short circuited. Above procedures are carried out for all channels to find the complete impedance matrix which can be used in feed-forward path as the model of the system. As a proof of principle, two channels of the home-built gradient array system (Ref?) are evaluated (Fig. 1). The system is composed of two coils connected to their corresponding independent H-bridge amplifiers (40V, 20A) with ripple current reduction one stage LC filter, controlled by an FPGA evaluation board (Spartan-6 SP605). FPGA provides PWM control pulses to the amplifiers for a 5 V DC and (f=1 KHz) V AC voltages at 100 KHz effective switching frequency and determined timings (Fig. 2). Currents for each channel are measured using two current transducers (LEM LAH 100-p). The voltage () and current () relation for set of coils in a single frequency with N number of channels is given in Eq. 1. Main diagonal elements of the impedance matrix are , where , are resistance and self-inductance of each channel respectively. Off-diagonal elements () (m ≠ n) are mutual inductance between the channels. Self- and mutual inductance values assumed to be constant in our working frequency bandwidth (≤10 KHz) and inter-winding capacitors are neglected.

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**Figure 1.** Two channel gradient array system used to implement the proposed method which produces DC and AC calibration voltages for two channels independently and characterizes the whole system using measured currents. This characterization includes H-bridge, filters and cables in addition to the coils. H-bridge and LC filter for channel 2 is not shown here to save space.

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**Figure 2.** Applied calibration voltages to Ch1 (yellow) and Ch2 (green). During self AC and DC characterization of each channel, the other channels are open-circuited in order to avoid coupling. When AC voltage is applied to one channel (Ch1) for mutual coupling characterization with the other channel (Ch2), the respective channel is short-circuited ([25:35] ms). The duration of applied DC and AC voltages are long enough allowing the currents to reach to their steady-states. Discharging intervals for the currents in the coils are placed between successive applied voltages.

**Results:** Measured currents in two channels after applying voltages in Fig. 1 are given in Fig. 3. Calculated values of the coil model are given in Table 1 for two channels using measured DC and AC current values for given voltages. Figure 4 shows the example trapezoidal currents flowing in two channels by applying the acquired system model with proposed method.



**Figure 3.** Measured current waveforms of Ch1 (yellow) and Ch2 (green) by applying the voltages in Fig. 1. Actual current values can be obtained by multiplying the voltage read values by 44.15 and 44.24 [Ω-1] for Ch1 and Ch2 respectively, considering turn ratio of the current transducer and measuring resistors connected to them.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | RDC (Ω) | RAC@1KHz (Ω) | L@1KHz (µH) | M@1KHz (µH) |
| Ch1 | 1.36 | 1.38 | 677 | 300 |
| Ch2 | 1.34 | 1.27 | 622 | 300 |

**Table 1.** DC and AC (at 1 KHz) system parameters measured by proposed method for two mutually coupled coils.

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**Figure 4.** Desired trapezoidal current waveforms applied to the coil using system model acquired with proposed method. Correct rising/falling edges and plateau region value show good AC and DC characterization of the system.

**Discussion and Conclusion:** In this work a practical method for auto calibration of gradient array systems with mutually-coupled coils are presented. Producing desired trapezoidal current waveforms in two channels using the obtained system model verifies that the proposed method meets the feed-forward model requirements. This calibration can be performed fast enough so that it can be applied dynamically throughout the gradient operation to update the system model if it’s required. This is beneficial in terms reducing load for closed-loop control system and better regularization of the current. System characterization in this way includes the switching components in the amplifiers, ripple current filters, cable and connectors as well which results in better approximation of the system model. Although these measurement are performed in a single frequency, system model variations in gradient operation frequency is less than 4% which can be included in the method by doing the calibration in multiple frequencies.

**References:**

1. A z‐gradient array for simultaneous multi‐slice excitation with a single‐band RF pulse

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