

Improving the Efficiency of Digitally Controlled Switching Gradient Amplifiers for Driving Different Gradient Insert Coils

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Introduction: High-performance MRI systems demand the use of digitally controlled switching gradient amplifiers (SGAs) that need complex electronic circuits and control algorithms to achieve not only good image quality but also good power efficiency [1-2]. Moreover, the imaging capabilities of clinical MRI system may be improved by the use of gradient insert coils that achieve gradient amplitudes and slew rates two to twenty times larger than conventional whole-body gradient systems. These high-performance gradient insert coils allow the acquisitions of high-resolution MR images in small animal models that cannot be achieved with stock clinical systems. Current waveform errors, voltage oscillations, and poor energy efficiency are some examples of the problems that users and designers of gradient coils may face. Some of these problems may be associated with a mismatch between the characteristic impedance of the gradient insert coils and the normal load or tuning parameters of the gradient amplifiers. Digitally controlled SGAs offer the flexibility to easily change tuning parameters that affect the behaviour of the control algorithm for different loads, gradient waveforms, current amplitudes and gradient switching requirements. In this work, we present a method to tune SGAs on a clinical MRI system with insertable gradient coils attached, with only limited access to information about the underlying electronic circuits, communication protocol, and control algorithms that govern the SGAs. All that is required is a basic understanding of how the tuning parameters are stored on the gradient processor, and how they are related to the frequency response of a gradient coil, *i.e.* inductance (LC), resistance (RC), and cut-off frequency or roll-off (RO) or to the feedforward and feedback control system, *i.e.* high-frequency gain (HFG), loop gain (LG), and rate feedback (RFB).

Methods: A MATLAB® graphic user interface was developed to change the above-mentioned tuning parameters stored on the SGA control module of a 3T GE Signa clinical system, via serial communication, and to communicate with a 4-channel Tektronix DSA601 digital oscilloscope used to acquire three voltage signals. These signals were associated with a trapezoidal current waveform (Amplitude = 100A, Slew Rate = 1A/μs, flat sections of 1ms) passing through a single gradient coil (I-Coil), the voltage delivered by the gradient amplifier (V-Drive), and the difference between the desired current and the measured current (I-Error). Waveform acquisition was synchronized with the update of each tuning parameter, which were changed sequentially, one at a time, for the coils presented in Table 1. These high-performance coils are used for high-resolution and μMRI of small samples and small animal models ranging in size from small mice up to large rabbits.

The RMS value of I-Error and the RMS value of V-Drive evaluated over the time course of a single waveform were used as cost functions; the first one to minimize gradient field imperfections, and the second one to minimize power losses. For all our experiments, Eddy Current Compensation was disabled and the RMS(I-Error) took precedence over the RMS(V-Drive) to define the final values of the tuning parameters.

Given the number of parameters and the range of values for each one of them, a full search for the global minimum in the multidimensional space would be very time consuming; therefore, a sampled subset of the whole range of values was used and the search was divided into two sections. The first experiment used only those parameters associated with the electrical characteristics of the coil (LC, RC, and RO), keeping the other parameters constant and equal to the default values initially set up by the vendor. The optimal values of LC, RC, and RO found from this three dimensional minimization procedure were then held constant, and a second search for a minimum performed but this time using only the parameters associated with the control algorithm (HFG, LG, and RFB). Based on the results of this two-part minimization strategy, a third search for a global minimum was then performed, changing only the three parameters that produce the most significant reductions of the cost functions and keeping the other parameters constant and equal to the values generating the minimum RMS(I-Error) found by the previous experiments.

Coil Name	S1			S3			T			Low-L
	X	Y	Z	X	Y	Z	X	Y	Z	
Axis										-
Inductance (μH)	920	835	977	840	835	977	1,223	1,198	1,309	239
Resistance (mΩ)	325	301	183	290	301	183	377	400	257	167
Efficiency (mT/m/A)	2.616	2.155	2.181	2.642	2.155	2.181	2.246	1.695	1.648	N.A.
Gmax (G/cm)	83.71	68.96	69.79	84.54	68.96	69.79	71.87	54.24	52.74	N.A.

Table 1. Characteristics of the tested gradient coils driven by the same SGAs of the clinical system.

Results: Table 2 summarizes the improvements in RMS(I-Error) and RMS(V-Drive) obtained with the proposed method with respect to the RMS values obtained without any adjustment of the tuning parameters (*i.e.* using default parameter values). The parameters that have more effect on the two cost functions were, in order of importance, LC, HFG, RC, and RO. However, LG needed to be set within the lower range of values to avoid oscillations and current distortions that prevented the normal operation of the amplifiers. This was most important for the low-inductance coil, which required the use of the lowest possible value of LG in order to be operational. In addition, the effects of RC and RO were minimized when the appropriate values of LC and HFG were chosen, *i.e.* those producing the minimum RMS(I-Error). As expected, the cut-off frequency showed significant differences between the coils constructed with solid copper (Low-L and clinical system) and those constructed with Litz wire (S1, S3, and T coils). Those made with solid copper presented cut-off frequencies in the order of 10-50 kHz whereas the other coils were at the higher end of values (125 KHz).

Coil Name	S1			S3			T		
	X	Y	Z	X	Y	Z	X	Y	Z
Reduction of RMS(I-Error)	58%	69%	57%	78%	66%	50%	12%	14%	23%
Reduction of RMS(V-Drive)	53%	73%	53%	86%	73%	69%	19%	33%	35%

Table 2. Improvements after tuning the SGAs with respect to the RMS values obtained using the default values set up by the vendor.

Discussion: Our results indicate a highly non-linear behaviour of the control system for the different loads and tuning parameters. Even though the minima of both cost functions were not achieved using the same parameter values, they were relatively close to each other and an improvement on RMS(I-Error) also reflected an improvement on RMS(V-Drive). The proposed method allowed the use of the same SGAs over a significant range of coil impedances (inductance in the range of 200 – 1300 μH and cut-off frequencies between 10 – 125 KHz). The method also allowed us to have a deeper understanding of the limitations and capabilities of the SGAs even though detailed information about them was not available from the vendor. Further work is needed to test the method with constant gradient fields, instead of constant currents, and under different (non-trapezoidal) shapes of gradient waveforms. Also, a combination of this method with Magnetic Field Monitoring techniques may certainly improve using gradient insert coils of the type that we are studying, under highly demanding non-Cartesian k-space trajectories. The substantial reduction of RMS(I-Error) that we achieve through our tuning procedure indicates a more accurate coverage of k-space and preliminary results show a slight increase in SNR (3%) for images obtained using the demanding FIESTA pulse sequence with a Cartesian k-space trajectory, comparing default and optimized parameters. However more work is required to define the effects on the MR images as a function of pulse sequence, k-space trajectories, acquisition parameters, or even tissue type.

References: [1] Sabaté J, *et al.* Proceedings of the 20th IEEE APEC 2005, pp1087-1091. [2] Sabaté J, *et al.* Proceedings of the 35th IEEE PESC 2004. pp261-266.