# Gradient Driver with Digital Control

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## INTRODUCTION

Gradient amplifier technology has evolved to be able to provide gradient field amplitudes and slew rates limited only by physiological constraints, such as peripheral nerve stimulation [1,2]. The big challenges at this power levels are, achieving high fidelity on reproducing the required PSDs, and capability of driving almost arbitrary shape current waveforms to accommodate new fast imaging techniques and operate with oblique angles. The new driver addresses these problems with a digital controller, high switching frequency for bandwidth and optimum filtering design, and an innovative filter design. The digital controller regulates with great accuracy the commanded current waveforms, using a combination of feed-forward and feedback methods, and compensating any non-idealities on the power stage and coil. An innovative new filtering technique for the pulse width modulated (PWM) voltage waveform allows high control bandwidth by providing the required attenuation at the ripple frequency without adding any significant phase delay at frequencies below the switching frequency. We will introduce the new driver architecture and describe the digital control design and implementation.

## AMPLIFIER POWER STAGE

The topology proposed consists of four bridges implemented with IGBTs, Fig. 1. The overall structure consists of three stacked elements: Two bridges supplied with $V_{high}$ with interleaved gating to maximize ripple frequency, and two bridges in parallel operated with interleaved gating also, supplied with $V_{low}$. The combined output provides a ripple frequency of at least 125kHz. The two parallel bridges provide the high bandwidth for the regulation of the output current and the other bridges are employed when higher voltage is required [2]. In order to share the current correctly and minimize any circulating currents, balance inductors are connected between these two bridges in parallel [3,4]. The resulting topology offers high reliability when driving large currents.

Key to providing a ripple free gradient coil current and fast response is the ripple cancellation technique used to filter the PWM voltages and eliminate the ripple in the output current. This circuit requires only passive components, and the overall size is much smaller than a conventional 2nd order LC filter for the same level of attenuation [5].

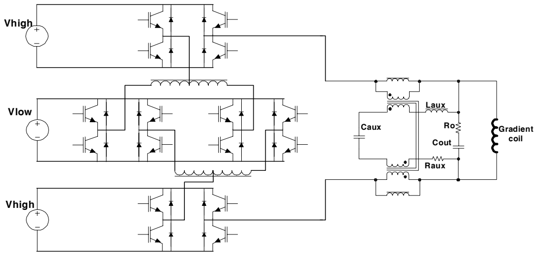

**Fig. 1: Topology used for the gradient amplifier.**

## DIGITAL CONTROL

The system performance of the amplifier greatly depends on the selected control strategy. The option selected here maximizes the bandwidth and can precisely reproduce arbitrarily shaped waveforms. The command for the bridges is generated by the coil current feedback loop with a PII compensator and a feed-forward path that calculates a voltage command using the reference current, the gradient coil impedance model, and the bridges input voltage, Fig. 2. Additional non-idealities such as device lock out time and device voltage drop are compensated in the feed-forward path. The accuracy of the gradient coil model taking into consideration the frequency dependence of its inductance and resistance greatly reduces the control effort required from the feedback loop. Low effort in the control loop directly translates into low instantaneous integral current errors, which is critical for the image quality, and fast imaging applications.

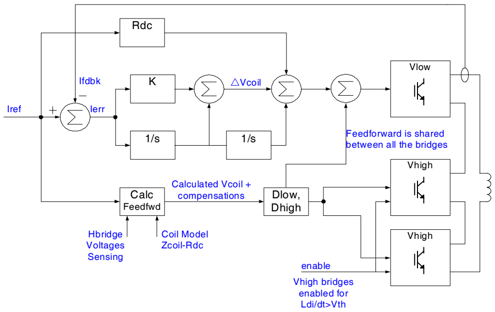

**Fig. 2: Control block diagram.**

The control is implemented with a DSP and an FPGA. This implementation uses the FPGA to relieve the DSP from controlling the required I/O devices, providing protective logic, and generating precise timing of the IGBTs gating signals. The control algorithm is executed in less than 4µsec. The coil current sensing and digitization are specially demanding because of the accuracy and bandwidth requirements. A current transducer with a bandwidth between dc and 100kHz provides the feedback digitized with a fast A/D (20 Msamples/sec). The samples are processed in the FPGA to provide a value every sampling interval, which provides increased resolution as well as excellent rejection of switching noise.

## EXPERIMENTAL RESULTS

The prototype was tested with the different types of waveforms used in MRI systems. Figure 3 shows a trapezoidal current with a slew rate of 1.5 A/µsec, the voltage across the coil and the error. The integral of the current error that in this control is a digital variable was displayed in the oscilloscope using a fast D/A converter to match the error with specific features in the voltage and current waveforms during the development of the system. The maximum error observed is less than 15 µAsec. Figure 4 shows a "spiral" waveform with frequency and amplitude varying with time, in this case showing current errors, which are below 0.5A for most of the waveform. The peak integral current error is lower than the trapezoidal case.

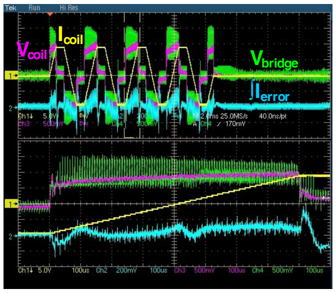

**Fig. 3: Trapezoidal waveform of ±600A amplitude and 1.5 A/µsec slew rate.** (Scale: Voltages = 500V/div, $\int I_{error}$ = 10µAsec/div, $I_{coil}$ = 160A/div)

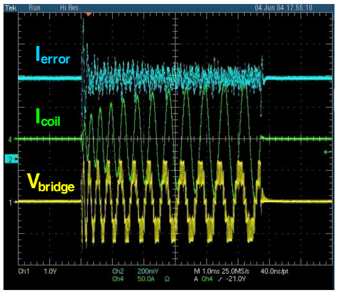

**Fig. 4: Spiral waveform, ±100A max.** (Scale: Voltage= 1000V/div, $I_{error}$ =0.8A/div, $I_{coil}$ =50A/div)

## CONCLUSIONS

The proposed new architecture for the gradient coil driver provides the high power required and operates at a switching frequency that enables high bandwidth control. An innovative filter design minimizes filter size without compromising the bandwidth. The digital control provides maximum bandwidth with a combination of feedback and coil model based feed-forward, and non-idealities compensation. The control implementation with the control algorithm partitioned between a DSP and an FPGA execute the control functions at 250kHz sampling rates. The integral of the current error is kept below a few µAsec, reproducing a variety of possible waveforms. The experimental results show the design validity for the gradient coil driver system.

## REFERENCES

[1] Steigerwald, R et al, Proc. IEEE PESC 2000, pp. 643-647; [2] Sabate, J., *et al*, *Proc. IEEE PESC 2004, pp.261-266*; [3] Sabate, J., *et al*, Proc. *IEEE IPEMC 2004, pp*. 1563-1567*;* [4] Watanabe, S., *et al*, *Proc. IEEE PESC 1999*, pp.909-913; [5] Sabate, J., *et al*, Proc. *IEEE APEC 2004, pp.792-796;*