Design of monophasic pulsed magnetic fields for use in low bias fields

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Abstract
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Disciplines
Controls and Control Theory | Electromagnetics and Photonics | Electronic Devices and Semiconductor Manufacturing | Industrial and Product Design

Comments
This article is published as Prabhu-Gaunkar, N., Theh, W., Weber, R.J., Mina, M., Design of monophasic pulsed magnetic fields for use in low bias fields. AIP Advances, 2020 10(2); 025032. Doi: 10.1063/1.5130438.

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Cite as: AIP Advances 10, 025032 (2020); https://doi.org/10.1063/1.5130438
Submitted: 03 October 2019 . Accepted: 26 November 2019 . Published Online: 21 February 2020

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COLLECTIONS

Paper published as part of the special topic on 64th Annual Conference on Magnetism and Magnetic Materials
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ABSTRACT

In this work, the design of a pulsed magnetic field generator, with user-selective pulsed modulation frequency is described. The ability to operate at various frequencies (single-frequency below 10 MHz) makes the system valuable to several areas such as medical treatments and pulsed switching systems. In this work, the pulsed magnetic field generator is designed to create localized field effects in portable magnetic resonance systems. Users may operate at a Larmor precession frequency between 100 kHz - 10 MHz and can achieve high currents through the load. Certain tunability can also be obtained by varying the load inductance or switching device conditions. In summary, this paper will describe the design considerations and challenges for portable monophasic pulsed magnetic field systems.

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I. INTRODUCTION

Pulsed electromagnetic fields have been used in a variety of applications including medical therapy, radar, magnetic resonance imaging, motors and magnetic switching. Based on the scale of operation, in each application, the pulsed magnetic field is used to transmit a sudden impulse of energy for a short duration. In most cases, rapid switching pulsed magnetic fields are created by a capacitive discharge through an inductor implying that high voltage sources or transformers are essential for charging the capacitors. However, it must be noted that inductors (>500 nH) bring a limit to the maximum switched pulsed field produced due to high load impedance.

There are some applications that also require small, localized pulsed fields for creating minor perturbations or torques within magnetic materials. For such applications, the design of high voltage pulsed field generators needs to be modified to cater to creation of localized pulsed fields at varying field strengths and operational frequencies. Correspondingly, in this work, a monophasic, low external bias field, portable pulsed field system is designed and examined. For this work, high currents (upto 10 A) are obtained by controlling the load inductance (<500 nH), rise time of switching device and drain voltage. The design stages and challenges along with the experimental operations and results will be presented and discussed.

A. Role of pulsed fields in magnetic resonance

In magnetic resonance applications, pulsed fields are required to initiate the process of resonance and to realign magnetic moments during resonance. Initially, a static magnetic field is used to align the magnetic moments. The presence of the static field, $B_0$ also causes precession of the magnetic moments at the Larmor precession frequency, $\omega_0$.

$$\omega_0 = \gamma B_0$$  \hspace{1cm} (1)

Here, $\gamma$ is the gyromagnetic ratio and it depends on the nuclei under investigation. The pulsed field is then applied at the precession frequency to initiate magnetic resonance. During resonance, magnetic moments undergo transitions from lower energy to higher energy states and revert back once the pulsed field is removed. Since the applied field is at the precession frequency of the magnetic moments,
the strength of the pulsed magnetic field, $B_1$ can be lower than the static magnetic field, $B_0$. Additionally, the pulse duration can be used to control the orientation of the magnetic moments. Generally, the rotation angle $\theta$ is controlled to obtain $90^\circ$ or $180^\circ$ rotations to detect different relaxation rates. The rotation angle also depends on the pulsed field strength and the pulse duration $\tau$.

$$\theta = 2\pi \gamma \tau B_1$$  \hspace{1cm} (2)

The rotation of the magnetic moments is necessary to maximize the signals detected by the coils, particularly from the magnetic moments undergoing magnetic resonance.

II. DESIGN CONSIDERATIONS

For every pulsed field application, AC or pulsed currents are needed to energize an inductor/antenna for creation of (radiating) pulsed fields. Thereafter, even for localized systems, it is necessary to examine methods of creating pulsed currents based on the switching mechanism, the inductor and frequency of operation. Independent of the switching device and/or the load, the two major design consideration for any pulsed field generation system are:

i. Operational frequency

ii. Maximal current

For the application of magnetic resonance in low static fields, the desired pulsed field strength, $B_1$, and operational frequency is dictated by the static field strength, $B_0$. Typically, for a static field strength, $B_0$ between 0.1 - 0.2 T, the operational frequency would vary between 4 - 8 MHz for detection of magnetic resonance from a proton. Moreover, a higher operational frequency relates to a higher signal to noise ratio. In this design, based on the external static field, a pulsed operational frequency of 5 MHz was selected and a peak current of 10 A was desired. To ensure signal integrity at the operational frequency, an operational amplifier (opamp) with a high gain bandwidth product (approximately 100 MHz or more) was used. To obtain high currents, proper biasing conditions were maintained at the gate and drain of the switching device.

III. PROPOSED DESIGN

Several prior designs have demonstrated the utility of switching field effect transistors (FET’s) in obtaining pulsed fields through coils. Extending these existing designs for operations at higher frequencies (MHz) remains a challenge. This is due to multiple reasons such as inductive loading of the switching device, switching device response time, impedance mismatch between the pulse shaping and switching stages and limitations to rapid switching of large inductors. To combat some of these challenges, in the design described here, reliable pulsed currents are obtained using feedback control between an opamp and a switching device at a frequency of 5 MHz.

The system design stages, as seen in Fig. 1, includes input pulse generation, switch, delay line followed by the opamp, output switching device and the inductive load. Since the selection of the opamp and the feedback loop determine the stability of the switching device, our focus in this work was on the highlighted block in Fig. 1. For the input pulse generation, a system similar to prior designs was used. The highlighted block which includes the opamp, output switching device, inductive load and feedback mechanism is seen in Fig. 2.

Here, a FET-based switch was selected for rapid switching and energy transfer to the inductor. A coil of 100 nH was connected as the inductive load at the drain terminal of the FET. In order to achieve activation of the FET, the gate terminal of the FET was controlled through the output of an opamp. The multiple feedback paths between the opamp and the source terminal of the FET are needed to eliminate occurrences of spurious oscillations, maintain opamp stability and to obtain stable repetitive switching. On solving for the feedback voltage, the voltage at the output of the opamp is

$$V_0 = 1.65V_+ + 2.95$$  \hspace{1cm} (3)
Finally, as per the device specifications, it was expected that the FET switch could operate in a frequency range of 100 kHz - 10 MHz. However, the maximum operational frequency is dictated by the gain bandwidth product of the opamp and the slew rate controls the maximum switching rate.

A. Relation between frequency and current

In order to switch magnetic fields at a frequency of 5 MHz, a fast switching FET (nanoseconds) was selected. It was essential that the self-resonant frequency of the load did not match with the operational frequency, since the opamp loop’s stability would be impacted. Additionally, a higher inductance would lead to a longer response time. Thus, an inductor of approximately 100 nH was selected. Besides the load and the switching device, it was observed that the opamp should have a high slew rate to obtain switching at the desired frequency. Three different operational amplifiers, LM 6152 (unity gain bandwidth: 75 MHz), LM 6171 (unity gain bandwidth: 100 MHz) and LM 7171 (unity gain bandwidth: 200 MHz), with different slew rates were compared at an operational frequency of 5 MHz, Fig. 3. It was observed that the opamp with the lowest slew rate, LM6152 was unable to respond at the rapid switching rate. This is observed from the gate voltage at the switching FET, Fig. 3a.

Another consideration for the operational frequency is the maximum attainable current. As seen in Fig. 3b, simulation results reveal that with an increase in operational frequency, the peak pulsed current amplitude reduces. This is primarily due to the signal rise time of the switching device and the slew rate of the selected opamp. Besides using better switching devices, one method of overcoming this effect is reduction in the pulse width or duty cycle of the applied pulse. However, in magnetic resonance applications, the pulse width controls the angle of rotation of the magnetic moments and user flexibility on the duty cycle may be limited.

IV. RESULTS AND DISCUSSION

Simulations and experimental measurements were performed at varied operational frequencies. The simulations were performed with a continuous sinusoidal waveform instead of a pulsed sinusoidal input at the opamp due to software limitations. A coherent sinusoidal input was applied at the input of the opamp to minimize occurrence of spurious signals. As observed in Fig. 3a, simulation results reveal that modifications in the operational amplifier’s slew rate affect the maximum operational frequency of the pulsed field generator.

Fig. 4a represents voltage measured at the drain terminal of the switching device for varied operational frequencies. Measurements show that the measured signal amplitude is significantly affected by ringing at lower frequencies though it reduces at higher operational frequencies. This effect is apparent at all the other terminals of the switching device and is attributed to impedance mismatch and phase delays from the feedback loop. Other possible sources of ringing are currently under study.

The load current measured at different frequencies is shown in Fig. 4b. Here, three pulse cycles were applied at the input of the switching device and it is observed that these appear at the load. The ringing observed in the drain voltage is significantly reduced in the measured current implying that the system can reliably generate pulsed magnetic fields. The maximum current that may be obtained also depends on the current sense resistor connected at the source terminal. Thus, in Fig. 4b, the units for the measured current are arbitrary.

Finally, assuming the load to be a solenoid with 10 turns, length of 0.01 m and a current of 10 A, \( B_1 \) of 0.01 T can be obtained. As per Eq. (2), the pulse duration can be controlled to obtain sufficient rotation of magnetic moments.
V. CONCLUSIONS

In this work the design, development, challenges and operation of a pulsed magnetic field generator system was demonstrated. The design reveals the importance of appropriate feedback mechanisms, switching devices and loads to obtain stable pulsed currents and correspondingly magnetic fields. With an increase in operational frequency, the maximum current in the load decreases though this might be compensated for in experiments by tuning the pulse width and use of faster switching devices. This version of the designed circuit can be used to obtain upto 10 A current through a 100 nH load at operational frequencies upto 10 MHz. Ringing or other non-linear effects may occur due to impedance mismatches, phase effects or improper biasing of switching device. Such conditions can be controlled by maintaining appropriate bias parameters and utilizing appropriate energy dissipation methods. By using the designed circuit and careful control of the feedback system a high frequency stable pulsed field can be generated in contrast to the prior FET based field generator.

VI. FUTURE DIRECTIONS

In this work, a method of designing portable pulsed field systems, producing approximately 0.01 T, for varied operational frequencies is presented. Pulsed field generator systems, as described in this work can be used for creating portable pulsed magnetic fields. Design improvements may be obtained for adaptation to
varied applications. Improvements to the design of the coil and switching device would assist in operations at varied frequencies, pulsed field strengths and for different distances. Improved mechanisms are needed to ensure bias conditions for the switching device and to minimize impedance loading between adjacent design stages. Preliminary simulations reveal that use of gate-driver systems may eliminate high initial rise time limitations. These improvements will be considered for design of future magnetic field generators.

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