A typology for magnetic field generator technologies

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I. INTRODUCTION
Magnetic field generator (MFG) systems are ubiquitously used in a wide variety of applications. Some applications areas include magnetic/optical switching, pulsed resonance, power converters, radar and medical therapy.1–8,11–13 The ubiquitous nature of such systems implies that several attributes or performance parameters may be shared though there might be application specific variations. In this work we aim to examine the distinctions that may exist in MFG systems and identify overall characteristics and unifying factors. Such unification or classifications could serve as a standard protocol for creating basic field generation systems. All magnetic field generators are based on the same concept aiming to create a large current pulse to energize a solenoid or inductive system. While the idea is straightforward there are clear distinctions in the challenges, design and their output operations. The main operating characteristics of a magnetic field generator are linearity/nonlinearity, power efficiency and output. One method used to distinguish the electrical characteristics of different types of magnetic field generators is by “class.” In this work, magnetic field generators will be classified according to their circuit configuration and method of operation. MFG classes will also encompass the magnetic field strength produced at the load. The classification of magnetic field generators ranges from entirely linear operation with very low efficiency, to entirely non-linear operation but with a much higher efficiency, while others are a compromise between the two. Magnetic field generator classes are mainly assembled into two groups. The first set of magnetic field generators are switching magnetic field generators of class I and II. The active device used in this case acts as an ideal switch where the signal goes ON and OFF. The second are controlled magnetic field generator classes of III and IV which are defined by the length of their conduction state over some portion of the output waveform, such that the magnetic field generator operation lies between ON and OFF.

II. CLASSES OF MAGNETIC FIELD GENERATOR
The design of new magnetic field generators and the expansion of existing MFGs technologies are required for future innovations. However due to the design complexity very few designers are familiar with the complete process that allows these technologies to be successfully completed. This research/paper highlights the major issues associated with these designs and provides an understanding of the types of issues that must be addressed during the design process. Each magnetic field generator has a related type of
functionality to perform, and for each functionality a type of response. There are two classes, conduction period based and device based. Different classes of magnetic field generators exhibit different responses when they are conducting current through the entire swing of the driving signal. According to the system specifications, the classification (shown in Figure 1) encompasses a variety of parameters: input and output variables, level of voltage, supplied power, required magnetic field strength, frequency range, monophasic or biphasic, and application need. However, some devices have better functionality in practical linearity, which allows variations in power efficiency and performance parameters. Similar to amplifiers which are commonly used circuit devices, magnetic field generators can also be described based on their characteristics and performance with particular magnetic field strength generated via the coil, current, and the pulse shape (monophasic or biphasic). Figure 1 shows a list of different classes. Each class defines each magnetic field generator in terms of the enumerated characteristics.

A. Class I magnetic field generator (monophasic)

Magnetic field generators of Class I (see Figure 2: Option A or B) are based on the most common type of topology using one output switching transistor (Bipolar, MOSFET or IGBT) within their design. The output stage reproduces the input signal (sinusoidal or pulse) to its entirety in terms of amplitude or current or shape. The transistor of a magnetic field generator conducts for the entire cycle of the input signal while using the transistor as current source. The bias current is sufficient to ensure the device continuously conducts, while the device remains in the transconductance area. It is also capable of supplying the maximum current required to create a high magnetic strength.

B. Class II magnetic field generator (biphasic)

Magnetic field generators of class II (see Figure 2: Option C) require the use of two switching transistors (Bipolar, MOSFET or IGBT) to produce a complete output waveform. One transistor is used to create the positive half cycle of the input signal while the second is used to create the negative half-cycle. The advantage of this configuration is each transistor dissipates low power. The class II magnetic field generator configuration uses a symmetry, and it is extremely important that the two transistors are perfectly matched and synchronized so that the positive and negative portions of the output is a complete waveform. While an input signal is applied,

| Classification of Magnetic Field Generator |
|------------------------------------------|
| Parameter                  | Frequency of operation | Class I | Class II | Class III | Class IV |
| Input Voltage              |                          |        |          |          |          |
| Input Current              |                          |        |          |          |          |
| Output Monophasic          | <= 100KHz                |        |          |          |          |
| Output Biphasic            | >= 500KHz                |        |          |          |          |
| Transistor Type BJT        |                          |        |          |          |          |
| Transistor Type MOSFET     |                          |        |          |          |          |
| Transistor Type IGBT       |                          |        |          |          |          |
| Field Strength             | 0.05 - 0.05T             |        | 0.05 - 0.5T | 0.5 - 1T | Varies   |

FIG. 1. Classification of Magnetic field generator (MFG), three possible circuit configurations (Low-side load switch (A), High-side load switch (B), Half-bridge setup (C)) and example of response from MFG system.
one of the transistors being the opposite type, the transistor will conduct on opposite half-cycles of the input. The NPN transistor conducts during the positive half-cycle, with a resulting half-cycle of signal at the output load. During the negative half-cycle of signal, the PNP transistor conducts. For a complete cycle of the input, a complete cycle of output signal is developed across the coil. One disadvantage of the circuit is the need for two separate voltage supplies. In addition, a crossover distortion can occur in the output signal (see Figure 1: Biphasic response). Crossover distortion occurs when during the signal crossover from positive to negative or vice versa, there is some nonlinearity in the output signal. This results from the non-exact switching of one transistor off and the other on at the zero-voltage condition which can cause unstable current levels at the load.

C. Class III magnetic field generator (monophasic or biphasic)

Magnetic field generators of class III use switching transistors (Bipolar, MOSFET or IGBT) to produce a magnetic strength with a high current level ranging in thousands of amps, high efficiency, and low distortion.

D. Class IV magnetic field generator (monophasic or biphasic)

Magnetic field generators of class IV are based on switching transistors (Bipolar, MOSFET or IGBT) to produce current to energize an inductor. They are composed of a signal generation stage, pulse shaping or tuning stage, switching stage, and the inductive load. Some magnetic field generators of class IV may be identical to magnetic field generators of class I, II except that the active device or transistor is similar to a control switch. Thus, it alternates between high conductivity (“switch closed”) and high impedance (switch “open”). The input signal of the class IV magnetic field generator is generated by mixing a pulse with required waveforms, performing appropriate pulse shaping or tuning and applying the waveform to the gate of the switching device. The tuning is performed by simply designing a load network with purely reactive impedances at a specific harmonic impedance.

III. DESIGN FRAMEWORK FOR MAGNETIC FIELD GENERATOR TECHNOLOGIES

Magnetic field generator technologies are circuits that are used for magnetic field production. The input signal to a magnetic field generator will be a current or voltage and the output will be an amplified/tuned version of the input signal. The magnetic field depends on the current through the load/coil. Magnetic field generators are circuits that are based on a switching scheme. In order to design a magnetic field generator (MFG), several different factors must be considered. The overall goal is to obtain response after the application of magnetic fields, but modeling is undoubtedly not precise due to non-reciprocity of the circuitry. However, by understanding how the magnetic field interacts with the load, parameters can be optimized to achieve fast and stable switching. Giving the designer the key information regarding device suitability, (Table I) describes

| Device characteristic | BJT | MOSFET | IGBT |
|-----------------------|-----|--------|------|
| Voltage rating        | High <1000V | High <1000V | Very high >1000V |
| Current rating        | High <500A | Low <200A | High >500A |
| Input drive impedance | Current | Voltage | Voltage |
| Low                   | Low  | High  | High |
| Output impedance      | Low  | Medium | Low |
| Switching speed       | Slow (uS) | Fast (nS) | Medium |
| Cost                  | Low  | Medium | High |
A. Choice of the switching device

There is a considerable overlap in application areas for the major types of high-power semiconductors. How does the designer determine whether to use a BJT, IGBT or MOSFET? The application area (power supply, magnetic switching, motor control, etc.) influences the decision including the load power modulation technique (linear or switching) and operating frequency. Defining the design criteria based on electric characteristics (Table II) and approach first, then the following: Magnitude of current for the load, the desired voltage to be applied across the load to achieve the current, and the maximum rate of change of current (dI/dt) and voltage (dV/dt). Having defined the load characteristic with the following parameters:

- Maximum voltage and current
- Maximum frequency of operation
- Reactive parameters of the load (load inductance and load capacitance)
- DC characteristics or bias
- Switching losses
- Waveform constraints

will allow to explore the plethora of choices for driving the load. Table II represents a list of common parameters found on switching device datasheet which is used to determine whether it would be suitable in a particular application.

| Parameter              | BJT | IGBT | MOSFET |
|------------------------|-----|------|--------|
| Breakdown voltage      | $V_{CEO}$ | $V_{CES}$ | $V_{DSS}$ |
| Continuous current rating | $I_c$ | $I_c$ | $I_D$ |
| Threshold voltage      | $V_{GE(th)}$ | $V_{GS}$ |
| Current gain           | $h_{FE}$ | $I_{DS}$ |
| On-voltage             | $V_{CE(sat)}$ | $V_{CE(sat)}$ | $V_{DS}$ |
| On-resistance          | $R_{DS(OFF)}$ |
| Turn off time           | $t_{f} + t_{r}$ | $t_{f(OFF)} + t_{r}$ | $t_{f(OFF)} + t_{r}$ |

Table II. Parameters comparison from datasheet.

are sometimes capable of operating at high frequency, however the complexities of providing a base drive current in a switching application typically limits the use to 100kHz or less. Conversely, MOSFET designed for high power transistors will have high current and low voltage. Switching frequencies can be up to 500kHz. An advantage of MOSFETs is that circuitry required to drive the gate is simple and low power. Interestingly, IGBTs are designed with the aim of combining both high current and high voltage. While they can handle current higher than 1000A with several thousand volts, they have limitations in switching speed which can range from 50kHz.

B. Choice of configurations based on performance and output characteristic

This section examines the factors influencing the performance of the magnetic field generator, in order to build up a comprehensive picture in addition to four possible layouts: high-side load switch, low-side load switch, half-bridge setup. Configuration (C and class II) were used in several cases (medical therapy and optical switching) yielded magnetic strength ranging from (0.05 – 0.5T) while configuration (A and class I) were used in optical switching. In all topologies, an input signal (pulse or waveform) with adjustable width is provided by a microcontroller or by signal generator (Figure 1: Example of response from an MFG system). A monophasic (pulse or waveform) is obtained by turning on and off one of the switches (BJTs, IGBTs or MOSFETs). When turning on or off, the load (coil) is connected to one of the discharge systems that allow a magnetic field to be generated. A biphasic (waveform) is obtained by activating both switching devices while avoiding a cross distortion during their pulse durations. The output must also be protected from numerous issue: excessive current flow in the transistor, undervoltage, transistor turn-on timing, etc.

IV. EXPERIMENTAL SETUP

Figure 3 shows a designed magnetic field generator circuit (a variant of configuration C and class I) to produce a monophasic pulse based on the framework and classification from Section III of the document. The circuit has an NMOS transistor which is used to supply a positive voltage from the DC source of 30V to the coil L1. The current flowing through the coil generates required magnetic field. The capacitors C2 (640 μF) is used during the fast charge and discharge phase of the coil. Figure 3 shows the experimental setup. The current flow through the resistor and is monitored by measuring the voltage differential between two nodes. The combination of CI(3.3μF), R3(0.66Ω), D1, D2(1N40016) form the RC snubber which is used to suppress high-frequency oscillations associated with reverse recovery effects in power semiconductor applications. Two optimal gate resistors (R4 and R5) were chosen to increase the switching speed of the switching device by reducing a surge voltage at the gate of the MOSFET(U1(TPH3212PS), U2 (TPH13212PS)). Both resistors act according to the following: Gate resistor for turn-on: R4, gate resistors for turn-off: R4 and R5 in parallel.

V. RESULTS AND DISCUSSION

Experimental measurements were performed at varied operational input gate voltages. Appropriate signals were applied to the
gate drivers of the NMOS and the desired output was achieved (Figure 3). For the NMOS driver circuit, applying 10V to the gate driver results in an output pulse with an amplitude of approximately 20A, for 200us, a load resistance of 500mΩ and 100A for a load resistance of 50mΩ. Using a current of 90A, we were able to generate a magnetic field approximately 0.03T using a hand wound coil (a 7-turn, 4.4 mm long coil with a radius of 11mm) at the center of the coil.

VI. CONCLUSION

This paper presented a new method/classification for magnetic field generators with adjustable parameters for various applications. The design framework and functionality of the system was introduced, in addition the operational functionalities were discussed. The classifications were used to validate the functionality while showing the practical limits. These characteristics include devices parameters, topologies and control of waveform output.

AUTHORS’ CONTRIBUTIONS

All authors contributed equally to this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1. G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, “A survey on OFDM-based elastic core optical networking,” IEEE Commun. Surveys Tuts. 15(1), 65–87 (2013).

2. N. P. Gaunkar, J. Selvaraj, W.-S. Theh, R. Weber, and M. Mina, “Pulsed magnetic field generation suited for low-field unilateral nuclear magnetic resonance systems,” AIP Advances 8(5), 056814 (2018).

3. Q. Wu, J. Ruan, Z. Weng, and S. Lin, “A novel magneto-optic switch based on nanosecond pulse,” in Proceedings of the Asia Communications and Photonics Conference (ACP), Shanghai, China, 2009, pp. 1–8.

4. J. Selvaraj, P. Rastogi, N. Prabhu Gaunkar, R. L. Hadimani, and M. Mina, “Transcranial magnetic stimulation: Design of a stimulator and a focused coil for the application of small animals,” IEEE Trans. Magn. 54, 1–5 (2018).

5. N. R. Bouda, M. Mina, and R. J. Weber, “High current magnetic field generator for transcranial magnetic stimulation applications,” IEEE Trans. Magn. 50(11), 1–4 (2014).

6. N. Prabhu Gaunkar, J. Selvaraj, L. Bauer, M. Mina, R. Weber, and D. Jiles, “Design and experimental implementation of a low frequency pulsed magnetic field generator,” IEEE Trans. Magn. 53(11), 1–4 (2017).

7. A. V. Peterchev, K. D’Ostilio, J. C. Rothwell, and D. L. Murphy, “Controllable pulse parameter transcranial magnetic stimulator with enhanced circuit topology and pulse shaping,” Journal of Neural Engineering 11(5), 056023 (2014).

8. P. Hu, G.-Y. Hu, Y.-L. Wang, H.-B. Tang, Z.-C. Zhang, and J. Zheng, “Pulsed magnetic field device for laser plasma experiments at Shenguang-II laser facility,” Rev. Sci. Instrum. 91(1), 014703 (2020).

9. S. Kemmet, M. Mina, and R. J. Weber, “Magnetic pulse generation for high-speed magneto-optic switching,” J. Appl. Phys. 109, 07E333-1–07E333-3 (2011).

10. R. V. Shapovalov, G. Brent, R. Mosher, M. Shoup, R. B. Spielman, and P.-A. Gourdain, “Design of 30-T pulsed magnetic field generator for magnetized high-energy-density plasma experiments,” Physical Review Accelerators and Beams 22, 080401 (2019).

11. S. Ponmalar and S. Sundaravadivelu, “Design of high speed optical switches for intelligent optical networks,” in Proceedings of the International Conference on Communication, Computing and Networking, ICCCN, 2008, pp. 1–4.

12. S. J. B. Yoo, “Optical packet and burst switching technologies for the future photonic internet,” J. Lightw. Technol. 24(12), 4469–4492 (2006).

13. L. Peng, C.-H. Youn, W. Tang, and C. Qiao, “A novel approach to optical switching for intradacenter networking,” J. Lightw. Technol. 30(2), 252–266 (2012).