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RESEARCH ARTICLE

Magnetic Signature Reduction by Converter Switching Frequency Modulation in Degaussing Systems

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ABSTRACT Ships can avoid to be detected by magnetic mines by reducing their magnetic signature with degaussing coils. Degaussing currents are provided by switched mode power supplies which impose a current ripple on top of the degaussing current. The ripple might be visible in the magnetic signature which would increase the detectability of the ship. A way to reduce the ripple in the magnetic field is to use a switching modulation scheme in the degaussing power supplies. In this paper, a magnetic model of a ship with degaussing coils is described. It is used to find the magnitude of the ripple in the magnetic signature. Also the effect of reducing the current ripple by frequency modulation is investigated. Several modulation schemes are modelled. It is found that the ripple in the magnetic signature is often, but not always, negligible due to attenuation by the ship's hull. For low frequency switching applications, like high temperature superconductor degaussing systems, the ripple is visible in the magnetic signature. It is found that switching frequency modulation is a very effective technique to reduce the ripple of degaussing currents. Of the tested schemes, random lead lag and random switching frequency are the most effective.

INDEX TERMS Attenuation, current ripple, degaussing, HTS, magnetic signature, switching frequency modulation.

I. INTRODUCTION

On-board safety is vital in the shipping industry. It can be disastrous for a ship to be detected by a sea mine. Magnetically triggered sea mines are able to sense a small distortion in Earth's magnetic field when a ship passes by and therefore detect the ship. The ferromagnetic hull of the ship influences the magnetic flux density around the ship. Ships can reduce their magnetic signature by several methods. One of the methods is to compensate for the magnetic signature by degaussing the ship [1]–[3].

A degaussing system consists of a set of on-board coils which generate a magnetic field that opposes the magnetic signature. Ideally, the magnetic signature is completely cancelled by the magnetic field caused by the degaussing system. Degaussing systems have already been developed in World War II, but nowadays there is a renewed interest in the topic. Closed loop degaussing is being developed for a more accurate control of the degaussing systems [4]. High temperature superconductive coils are investigated as a replacement of copper coils in degaussing systems [5]–[8]. The use of superconductors can drastically improve the efficiency of degaussing systems.

In the past, degaussing coils were powered with a low voltage motor-generator set, where the motor was connected to the AC bus of the ship. In case of a DC ship, the degaussing coils could be powered from the DC bus and the currents were controlled by rheostats [9]. Nowadays, degaussing coils

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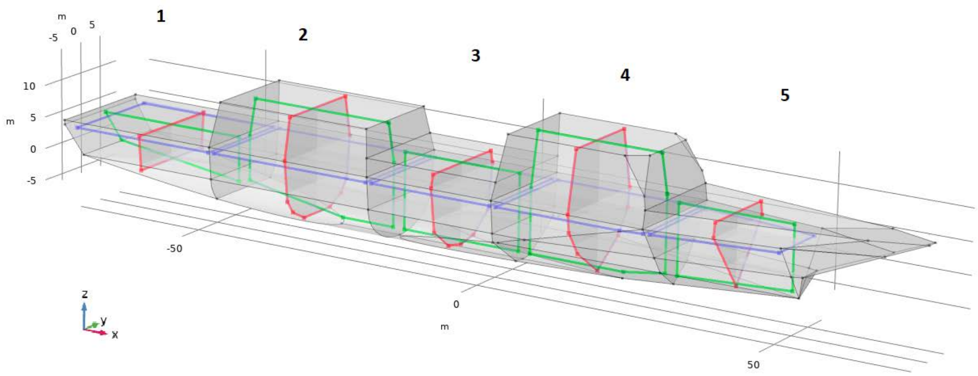

FIGURE 1. Ship geometry with 5 M (main), 5 L (longitudinal) and 5 A (athwart ship) degaussing coils depicted in blue, red and green respectively.

are powered by switched-mode power supplies. This is done for energy efficiency and system compactness. However, switched-mode power supplies inherently impose a current ripple on top of the degaussing current. A concern is that the degaussing current ripple will be seen in the magnetic signature of the ship as well. A Fast Fourier Transform of the magnetic signature will then show clear peaks at the converter switching frequency and its harmonics. Moreover, with the use of ultra-sensitive SQUID magnetic sensors, the detection of very low magnetic fields with a large bandwidth is already possible [10].

It is known that there are several other relevant AC components in the magnetic signature [1]. The impressed current cathodic protection (ICCP), for example, is a system which actively pumps an electric current through the sea water to prevent corrosion of the hull. This current is provided by switch mode power supplies as well [11]. Also the use of HTS for degaussing systems can add to the ripple. To our knowledge, there is no publication known about how large the ripple in the magnetic signature is due the the current ripple in degaussing systems.

A potential way to reduce the ripple caused by the switching power supplies is to use a frequency modulation switching scheme in the converters. With such a scheme the switching frequency changes over time. Instead that all the power is concentrated in one switching frequency, the power of the ripple is spread over a frequency band. This technique is already used to reduce EMI in microchips and power converters [12]. It is also used to reduce acoustic noise in electrical machines [13]. It has not been seen in degaussing systems yet.

In order to evaluate the need for the use of switching frequency modulation, the amount of ripple in the magnetic signature needs to be determined. The first aim of this paper is to estimate the contribution of the ripple to the magnetic signature due to the degaussing system. After that, the possibility to reduce the ripple in the magnetic signature by means of frequency modulation is explored. The second aim of this paper is to estimate by how much the ripple can be reduced by means of switching frequency modulation.

The organization of this paper is as follows. Section II describes the model to find the magnetic signature of a ship with degaussing coils supplied by switched-mode power supplies. This model is validated by experiments and the results of the model are discussed. Section III presents an overview of the switching modulation schemes which can be implemented in the converter. The modulation schemes are modelled and applied to a degaussing case. The results are discussed. Finally, in section IV a conclusion is drawn.

II. MODEL DESCRIPTION

In order to find the influence of the degaussing current ripple on the magnetic signature, a model is developed. The model is split into two parts, the static and the dynamic model. The first one is used to calculate the static magnetic signature. From this model, the nominal degaussing currents, coil inductances and coil resistances are determined. The degaussing currents are optimised in such a way so that the magnetic signature is minimised. The dynamic model determines the waveform and magnitude of the current ripple on top of the degaussing currents. This is incorporated in the magnetic model to determine how the current ripple translates to the magnetic signature. Finally, the models give the magnetic signature at any point in space as a function of current, switching frequency and externally applied magnetic flux density.

A. STATIC MODEL

A simplified geometry of a modern sized frigate has been created. Degaussing coils are usually placed in such a way that the magnetic field can be altered in three dimensions. In this model, the ship is divided into five compartments, each having a coil positioned perpendicular to the longitudinal (L), athwart ship (A) and main (M) direction, highlighted in red, green and blue respectively in figure 1.

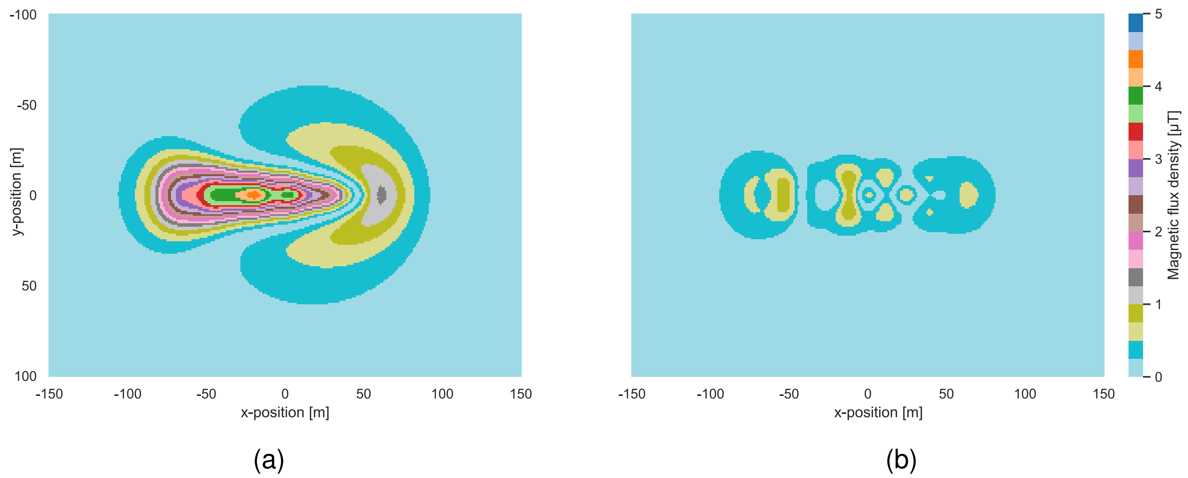

FIGURE 2. **The magnetic signature of the ship in a horizontal plane 15 m under sea level. (a) Magnetic signature without degaussing. (b) Reduced magnetic signature with degaussing.**

TABLE 1. **Magnetic model parameters.**

Symbol	Description	Value	Unit
l	ship length	150	m
w	ship width	12	m
h	ship height	20	m
t	hull thickness	25	mm
μ_r	relative permeability hull	320	
$\hat{B}_{\text{Earth}}$	Earth's magnetic field	46.1	µT

The parameters used for the modelling of the ship are shown in table 1. It is assumed that the magnetic permeability is linear and frequency independent.

The simulations are set out using the commercial finite element modelling software COMSOL. The thickness of the hull is relatively small compared to the size of the ship which makes it difficult to generate a mesh. The model could be made by creating an extremely fine mesh, but then the simulations would take a long time to finish. A better way is to model the hull using the magnetic shielding node in COMSOL. This node describes a thin layer of permeable material with an adjustable thickness and permeability. The degaussing currents are modelled as edge currents along a 2D plane. This way of simulating the magnetic signature of a steel object with degaussing coils has been experimentally verified in previous works [7], [8], [14]. The total vector field of the magnetic flux density around the ship, $\vec{B}$, can then be found by adding the magnetic signature of the hull to the magnetic signature from each degaussing coil as follows:

$$\vec{B} = \vec{B}_{\text{sig}}(\vec{B}_{\text{Earth}}) + \sum_{i=1}^{N} \frac{I_i}{I_0} \vec{B}_i(I_0) + \vec{B}_{\text{Earth}}, \tag{1}$$

where $\vec{B}_{\text{sig}}$ is the magnetic signature of the ship due to Earth's magnetic field $\vec{B}_{\text{Earth}}$, N is the number of degaussing coils, I_i is the current through degaussing coil i and $\vec{B}_i$ is the magnetic field due to current I_0 through degaussing coil i.

By adjusting the degaussing currents I_i in equation 1, the difference between magnetic flux density around the ship, $\vec{B}$, and Earth's magnetic field, $\vec{B}_{\text{Earth}}$, can be minimised. An optimisation loop is used to minimise the highest peak of the magnetic flux density in the horizontal plane at 15 m below the water line with the degaussing currents as optimisation variables. Figure 2 shows the absolute value of the magnetic flux density in this plane. Earth's magnetic field is subtracted in the figure so that only the magnetic signature and the reduced magnetic signature remain.

The plot in figure 2a shows the magnetic signature of the steel hull of the ship due to Earth's magnetic field. The plot in figure 2b shows the magnetic signature with the optimised degaussing currents through the coils. Although the magnetic signature is reduced, there is still a distortion in the magnetic field. This can be minimised even further by increasing the number of degaussing coils and by optimising the position of the coils.

B. AC SIGNATURE

In order to find the ripple in the magnetic signature, first the current ripple in the degaussing coils needs to be determined. From the static model, the nominal currents, the inductances and the resistances of the degaussing coils are found. The degaussing coils are then modelled as follows:

$$v_i = i_{L_i} R_i + L_i \frac{\mathrm{d}i_{L_i}}{\mathrm{d}t} + \sum_{\substack{j=1 \\ j \neq i}}^{N} M_{ij} \frac{\mathrm{d}i_{L_j}}{\mathrm{d}t}, \tag{2}$$

where v_i is the converter output voltage, i_{L_i} is the current, L_i is the inductance and R_i is the resistance of degaussing coil i. M_{ij} is the mutual inductance between coil i and j. The converter is modelled using the software LTSpice. A buck converter is used as the converter topology. The degaussing coils of each converter are magnetically coupled using the

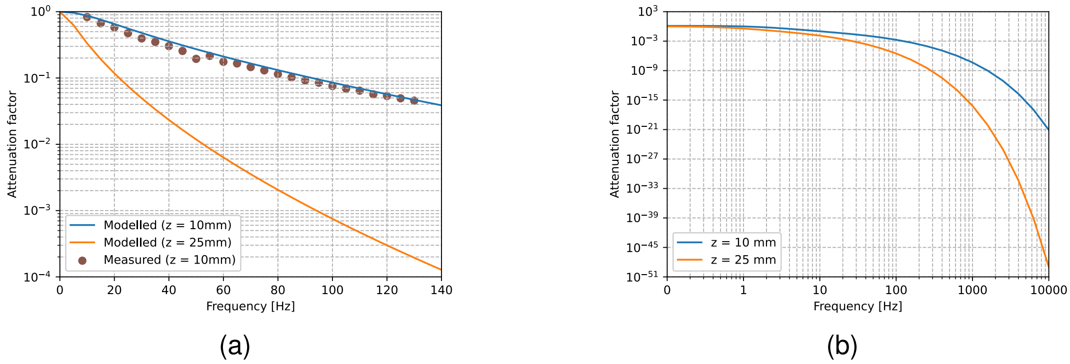

FIGURE 3. Attenuation of the magnetic field in steel as a function of frequency. (a) Measured in a steel pipe. (b) Simulated for full sized ship.

mutual inductances M_{ij}. The ripple in the magnetic signature is then determined using equation 1.

The magnetic field produced by the current ripple will experience attenuation due to induced eddy currents in the steel hull of the ship and in the seawater. Other sources of attenuation, like hysteresis losses are not considered here. In order to quantify the amount of attenuation, the COMSOL model presented in section II-A is used to model the magnetic field in the frequency domain. The magnetic shielding node can not be used for frequency domain analysis. Instead, the transition boundary condition node was used to model the thin metal hull of the ship in the time domain. This node takes the thickness, permeability, permittivity and conductivity of the material into account. This modelling technique was verified by measuring the attenuation of a magnetic field in a metal pipe at several frequencies. The results of this are shown in figure 3.

Figure 3a shows the measured attenuation of the magnetic field compared to the modelled attenuation in a pipe with an outer diameter of 20 cm and a metal thickness of 10 mm. The measured values match with the modelled values. The measurements show a little difference in attenuation with respect to the modelled case. This can be explained by a deviation in the material properties of the pipe. Although the permeability of the material is known, the permittivity and conductivity are an estimation based upon average data for steel. Since the measured results match the simulations, this modelling can also be applied to estimate the attenuation in the full sized ship hull. The ship is assumed to have a hull thickness of 25 mm. For a good comparison, the pipe is also modelled with a thickness of 25 mm. Figure 3b shows the attenuation of one of the degaussing coils on the ship as a function of frequency. The ship is also modelled with a hull thickness of 10 mm so it can be compared to the metal pipe.

C. DISCUSSION

The magnetic signature of a ship is measurable around the ship. It is reduced by applying a magnetic field inside the ship with on-board degaussing coils. The degaussing field translates to the outside of the ship and cancels out the magnetic signature as much as possible. The rate of change of the degaussing field is very low. It only has to change when the ship is moving and it can therefore be considered to be quasi-static. Because of this, it doesn't get attenuated by the hull. The degaussing field also has an alternating component created by the switching of the converter. The attenuation is much higher because of the induced eddy currents in the hull.

The magnetic field attenuation increases as the frequency increases. The hull thickness plays an important role in the attenuation of the frequency components of the magnetic signature as well. For a ship with a hull thickness of 10 mm and a converter switching frequency of 10 kHz, the field is already attenuated by a factor 10×10^{-21}. This is so much that it can be considered undetectable. For this reason, it would not be necessary to use a switching frequency modulation scheme in a traditional degaussing system. However, there are also other potential sources of current ripple in the magnetic signature.

High temperature superconductors (HTS) are expected to be a good replacement for copper degaussing coils [7]. When superconductors are used in a degaussing system, the use of a flux pump or a persistent mode current switch arises. Flux pumps could improve the efficiency of a degaussing system significantly compared to switched-mode power supplies. However, they operate at a much lower frequency where the attenuation by the hull is also lower [15]. Besides flux pumps and persistent mode current switches, the use of parallel MOSFET's is also a good possibility for an efficient power supply [16]. Due to the large time constant of the HTS degaussing coil, a low switching frequency can be used. This is even necessary when the MOSFET's are placed inside the coolant. The switching losses then need to be reduced in order to minimize dissipated power in the coolant. This can be done by reducing the switching frequency. Flux pumps operate in the range of $1 - 200$ Hz [15] and a MOSFET based power supply could have a switching frequency as low as 100 mHz [16]. In this frequency range the attenuation by the hull is not sufficient to reduce the peak of the switching frequency in the magnetic signature and the use of switching frequency modulation may be recommendable.

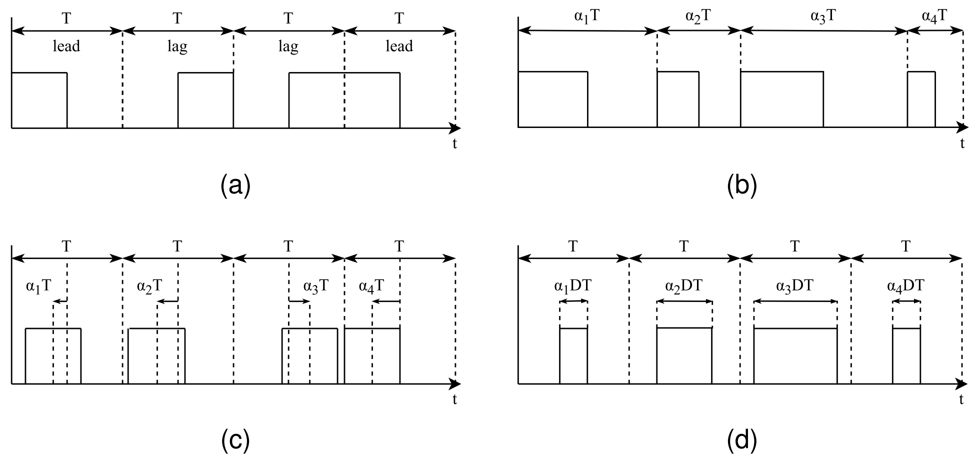

FIGURE 4. **Random switching topologies. (a) Random lead-lag. (b) Random switching frequency. (c) Random center displacement. (d) Random duty cycle.**

Besides degaussing, there are other sources for a current ripple in the magnetic signature. The impressed cathodic corrosion protection (ICCP) system injects a current directly into the seawater. This current, also provided by a switched-mode converter, is not attenuated by the steel hull of the ship, but only by the sea water [11]. Lastly, non-metal ships don't have any attenuation in the hull. On-board switching equipment might be detected by a magnetic sensor. In these cases the attenuation of the ripple is much lower. For these, it might be useful to use a switching modulation scheme. In section III various switching modulation schemes are explored.

III. RIPPLE REDUCTION BY SWITCHING FREQUENCY MODULATION

Several frequency modulation techniques are explored in this section. The first one, Spread Spectrum Frequency Modulation (SSFM), is a deterministic frequency modulation technique which is used for EMI reduction in high frequency digital systems. SSFM can also be used in power converters [12]. Besides deterministic frequency modulation, also stochastic frequency modulation can be used. Random switching frequency modulation techniques are tested for noise reduction in electrical machines [13]. Four stochastic frequency modulation techniques are discussed and tested in this section, namely, Random Lead-Lag Modulation (RLL), Random Center Displacement (RCD), Random Duty Cycle (RDC) and Random Switching Frequency (RS).

A. SPREAD SPECTRUM FREQUENCY MODULATION

When the converter switching frequency is modulated with a constant frequency, each harmonic is spread out over a frequency band. The modulated square wave that drives the switch can be expressed as follows:

$$F(t) = \frac{\text{sgn}\{\sin[2\pi f_s t + \Theta(t)]\} + 1}{2} \tag{3}$$

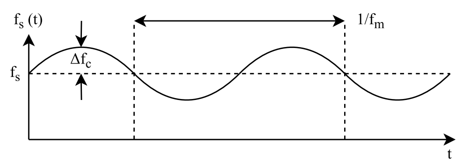

FIGURE 5. **Spread spectrum frequency modulation (SSFM).**

where f_s is the non-modulated switching frequency and $\Theta(t)$ is the phase angle so that:

$$\Theta(t) = \int_0^t k_w sin(2\pi f_m t)\, dt \tag{4}$$

where k_w is a factor that controls the frequency deviation and f_m is the modulation frequency of, in this case, a sinusoidal modulation profile. In this case the duty cycle, D, is set to be 0.5 as a generalization. The modulation profile can be any waveform. SSFM is further illustrated in figure 5.

To control an SSFM switching scheme, the modulation index, m_f, and the modulation ratio, δ, can be used as follows:

$$m_f = \frac{\Delta f_s}{f_m} \quad \text{and} \quad \delta = \frac{\Delta f_s}{f_s} \tag{5}$$

B. RANDOM FREQUENCY MODULATION

The four random switching methods are shown in figure 4. These methods are explained below:

Random lead lag: With RLL modulation the pulse is randomly chosen to be either at the beginning or the end of the switching period. The switching frequency and duty cycle do not vary randomly. This is illustrated in figure 4a.

Random switching frequency: In RSF, shown in figure 4b, a new switching frequency is chosen for every new switching period at random. This is done within a band where the maximum deviation from the switching frequency f_s can be chosen. The random value α needs to be chosen within the

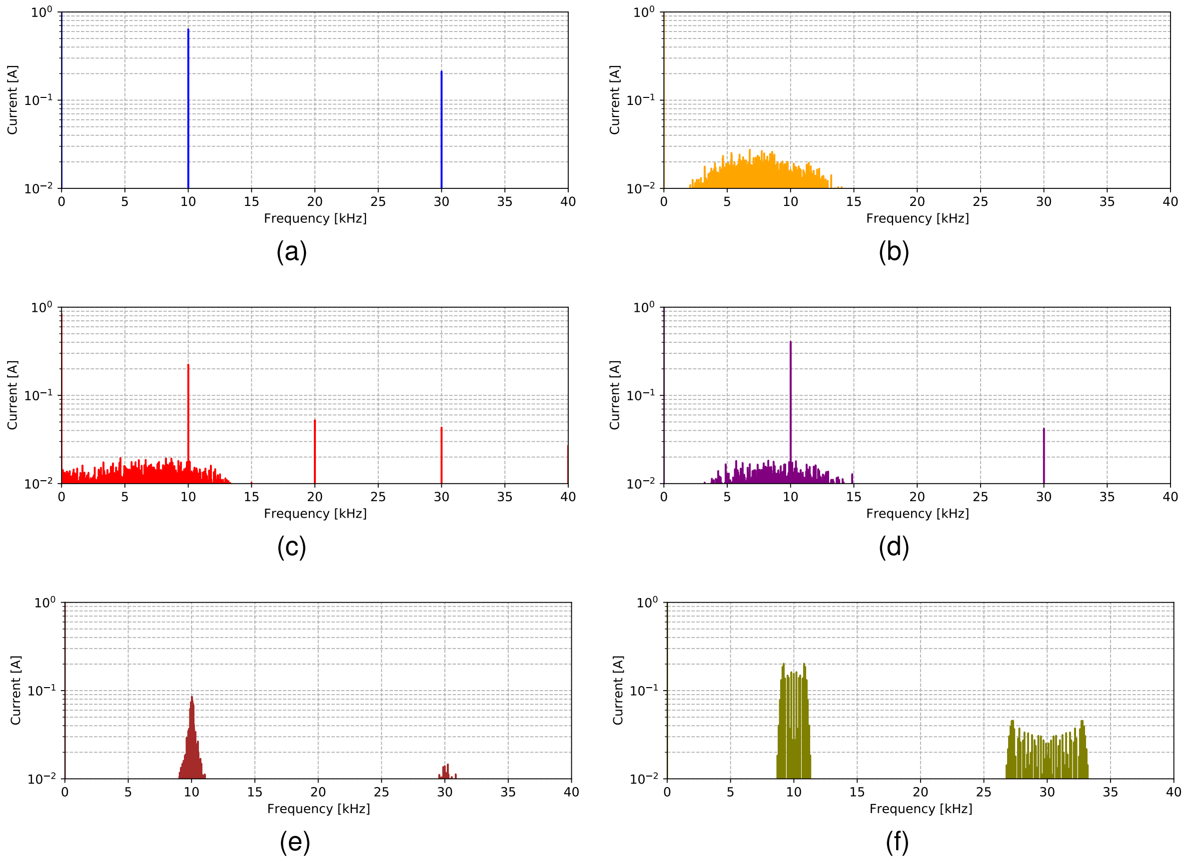

FIGURE 6. Amount of attenuation with (a) no frequency modulation (blue), (b) random lead lag (orange), (c) random duty cycle (red), (d) random center displacement (purple), (e) random switching frequency (brown) and (f) spread spectrum frequency modulation (green).

following boundary:

$$\frac{f_s - \Delta f_s}{f_s} < \alpha < \frac{f_s + \Delta f_s}{f_s} \tag{6}$$

where, for this research, Δf_s is chosen to be 10 % of f_s.

Random center displacement: With RCD the position of the pulse within the switching period is chosen at random. This is illustrated in figure 4c. RCD requires a more extensive control than RLL since the position of the pulse is chosen with more precision. A problem with RCD is that the switching interval between two pulses might become too short when they are placed too close together. The random value α needs to be chosen within the following boundary:

$$-\frac{1}{2}(1-D) < \alpha < \frac{1}{2}(1-D) \tag{7}$$

Random duty cycle: With RDC, the duty cycle is chosen for every switching period at random as shown in figure 4d. The random value α needs to be chosen within the following boundary:

$$2 - \frac{1}{D} < \alpha < \frac{1}{D} \tag{8}$$

In this research, the values for α are randomly sampled from a uniform distribution between boundaries defined by equations (6) to (8). The value for α is generated every switching cycle.

C. RESULTS

The different frequency modulation techniques are tested on the buck converter described in section II-B with a base switching frequency of 10 kHz and a duty cycle D of 0.5. Figure 6 shows the results of the frequency modulation techniques described in this section. They are compared to the case where there is no frequency modulation at all. From the graphs it can be seen that all the modulation schemes reduce the peak at the fundamental switching frequency compared to the use of no modulation scheme. The random frequency modulation techniques introduce some noise around the fundamental frequency. While random center displacement and random pulse width still show a significant peak at the switching frequency, random switching frequency and especially random lead lag show a large reduction of the peak. Spread spectrum frequency modulation spreads the peak into several lower peaks. It seems that random lead lag switching reduces the peak the most and should therefore be the best candidate for switching frequency modulation in our application.

The switching frequency modulation techniques were tested in the lower frequency range where HTS degaussing

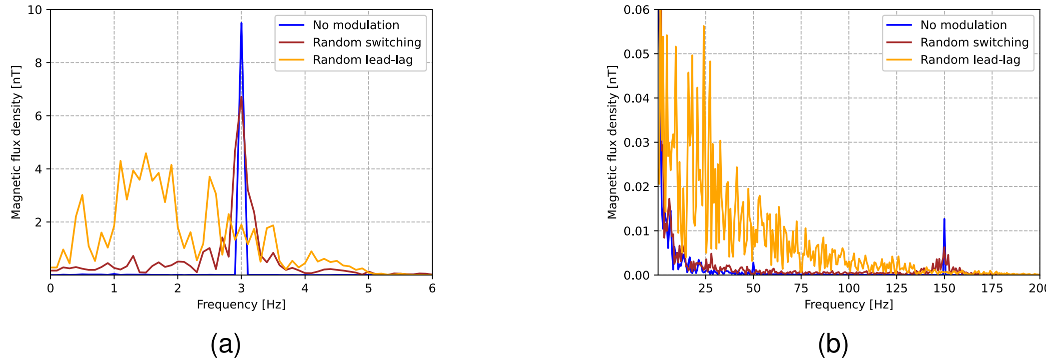

FIGURE 7. **Magnetic signature with switching frequency modulation schemes applied to a degaussing coil with a base switching frequency of (a) 3 and (b) 150 Hertz.**

is expected to operate as described in section II-C. Figure 7 shows two plots of the magnetic signature with the use of random lead lag, random switching frequency and no switching frequency at all. In figure 7a the base switching frequency is set at 3 Hz and in figure 7b the base switching frequency is set at 150 Hz. These plots include the attenuation by the hull of the ship. At 3 Hz, random lead lag reduces the switching frequency peak significantly and therefore the detectability of the magnetic signature. However, there is some noise produced which is not present without using switching frequency modulation. Especially in the lower frequency band where the attenuation is less. Random switching frequency modulation also slightly reduces the peak, at the expense of spreading the frequency content. At 150 Hz, the attenuation by the hull also gets higher. The contribution to the magnetic signature of the switching peak is therefore much lower at higher switching frequencies. The switching modulation techniques still reduce the peak by the same percentage as with lower switching frequencies. However, the noise in the lower frequency band is now relatively more visible. Since random switching produces less noise than random lead-lag, in this case, random switching is the best candidate.

IV. CONCLUSION

The aim of this paper is to analyze the influence of the current ripple in a degaussing system in the magnetic signature of a ship. A magnetic model of a ship has been made which includes the attenuation of time varying magnetic fields. At high switching frequencies, the metal hull of the ship almost completely absorbs the current ripple from the degaussing currents. The attenuation by the hull strongly depends on the thickness of the hull and the switching frequency. It can be concluded that the current ripple of the degaussing coils will not be detectable from outside the ship with a state-of-the-art magnetic sensor if the switching frequency is around 10 kHz and it has a hull thickness of 25 mm. However, in a HTS degaussing system the switching frequency is expected to be much lower. The attenuation of the switching frequency peak produced by the metallic hull of the ship is then not enough.

There are also other contributors to the AC magnetic signature where the implementation of frequency modulation might be useful. The ICCP system, ships with non-metal hulls and the individual degaussing of on-board equipment are all examples that add a frequency component to the magnetic signature and where its detectability can be reduced by using switching frequency modulation.

An option to reduce the switching ripple in the magnetic signature is to increase the switching frequency. With a higher switching frequency the attenuation by the hull increases and the current ripple in the coil will be smaller. However, the switching losses will increase, which can be problematic. In a HTS degaussing system with cryo-cooled MOSFETs, the switching losses should be kept to a minimum in order to reduce heat from entering the coolant.

Switching frequency modulation can be used to reduce the peak in the frequency spectrum of the magnetic signature. Several topologies have been tested. All of them reduce the peak at the switching frequency, but random switching frequency and random lead lag show the most promising results. Especially for a system with a low switching frequency it can be useful to implement switching frequency modulation.

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