Experimental Investigation of a Naval Propulsion Drive Model With the PWM-Based Attenuation of the Acoustic and Electromagnetic Noise

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***Abstract*—An extensive experimental investigation of a 40-hp ac drive was conducted with the focus on mitigation of the acoustic and electromagnetic noise, and vibration, by means of random pulsewidth modulation (RPWM) employed in the drive's inverter. The drive was a laboratory model of an electric propulsion system for naval vessels, particularly electric submarines, in which the noise mitigation is crucial for survivability. Three PWM methods were compared: 1) the classic deterministic PWM, characterized by a constant switching period equal to the sampling period of the digital modulator; 2) the known RPWM technique, referred to as RPWM I, in which the switching and sampling periods are varied simultaneously in a random manner; and 3) a novel RPWM method, referred to as RPWM II, with a constant sampling period and the switching periods randomly varied around an average value equal to the sampling period. The experimental results have confirmed the mitigating properties of RPWM with respect to the acoustic and electromagnetic noise, and vibration. Because of the fixed sampling frequency, the RPWM II technique is technically more convenient than the classic RPWM I method and only marginally less effective in flattening the peaks of noise spectra. Importantly, conclusions drawn from the described study are valid for ac drives in general.**

***Index Terms*—Acoustic- and electromagnetic-noise mitigation, naval ac drives, random pulsewidth modulation (RPWM).**

I. Introduction

ARGUABLY, of all the branches of the U.S. armed forces, it is the Navy that is most committed to research and development of adjustable-speed drives (although the Army and Air Force have been pursuing this technology as well). Various concepts of electric ships and submarines have been under consideration. Electric drives of propelling screws can significantly improve maneuverability and survivability of a naval vessel. In place of a single screw (or a pair of screws) driven by the main engine via a shaft (or shafts), multiple screws can be employed, each driven by an independently supplied and controlled electric motor. This makes the propulsion system more flexible and less vulnerable to enemy fire. Other applications of adjustable-speed drives in naval warfare are also of interest.

A naval-propulsion drive must be designed for high levels of power and torque density, robustness, efficiency, and controllability. It should also be quiet to hamper detection, with low emitted electromagnetic noise so as not to disturb the operation of the sensitive electronic equipment aboard. The maximum speed is relatively low (100–200 r/min) and, because of the progressive torque–speed characteristic of the screw, field weakening is not needed. A torque-dense permanent-magnet synchronous motor is the leading candidate for such drives, although the induction motor has its advantages too. In either case, a pulsewidth-modulated voltage-source inverter would be employed to supply a high-quality current to the stator.

The fixed switching frequency used today in commercial inverters results in tonal sounds being emitted by the motor. This is due to the ripple of stator current, which is reflected in a similar ripple of forces of magnetic attraction between the stator and rotor. The resultant acoustic noise is generated mostly in the stator shell acting as a membrane. The mitigation of this noise and accompanying vibration would improve stealth performance of naval vessels. Although underwater sound gets progressively attenuated as the frequency increases, modern hydrophones are sufficiently sensitive to detect tonal acoustic emissions, especially at close quarters. Therefore, a simple increase in the switching frequency, even if feasible in a high-power inverter, may prove to be insufficient.

Inverter-generated noise intensity increases with the size and power of the motor. Tonality of the noise is a direct consequence of the harmonic clusters that appear in the frequency spectra of the voltages and currents of the motor. These clusters are located about multiples of the switching frequency. The random variation of the switching period results in a transfer of most of the harmonic power (watts) into continuous power density (watts/hertz). This well-known idea of random pulse modulation (RPWM) has been shown to significantly flatten the voltage and current spectra, resulting in atonal noise [1]–[3]. Such noise can be expected to blend with the ambient sea noise, or, in the case of an industrial drive, with the noise of the factory floor.

The fundamentals of spectral analysis of the voltages and currents produced in RPWM inverters have already been developed. However, the derived closed-form equations are too

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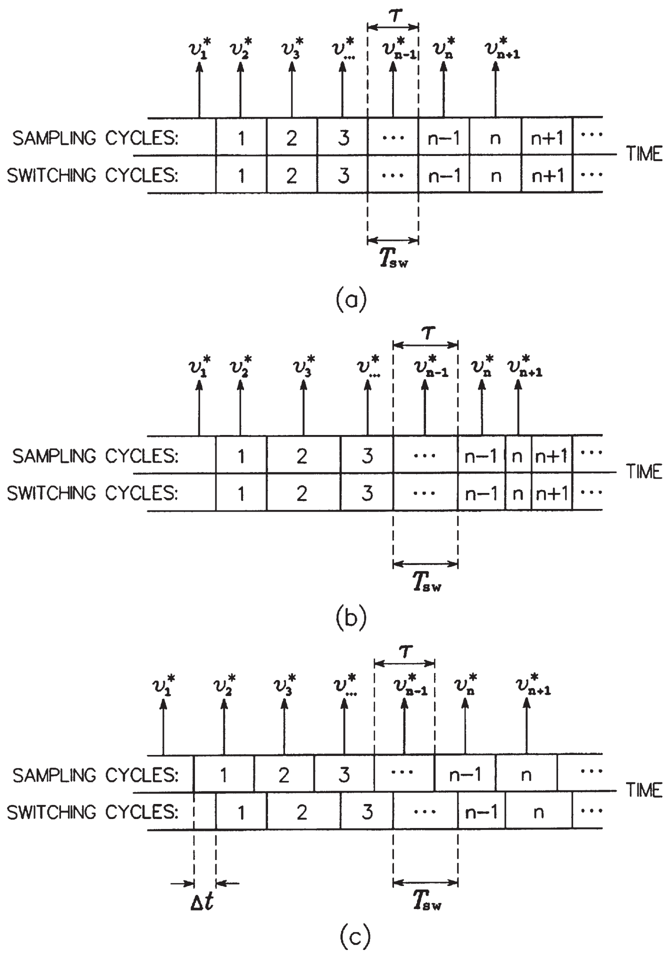

Fig. 1. Illustration of PWM techniques used in the study. (a) DPWM. (b) RPWM I. (c) RPWM II.

complex and too general to be practical, except for some very basic PWM strategies [4]. Therefore, especially with respect to such phenomena as noise and vibration, practical experiments remain the best source of reliable information. In this paper, results of an experimental investigation of a 40-hp laboratory model of a marine drive are described. For comparative analysis, three different PWM techniques, one deterministic and two random, all based on the same space-vector principles, were employed in the inverter feeding the ac motor. Because of the standard structure (power line, rectifier, dc link, voltage-source inverter, induction motor) of the experimental drive, the results can be extended on the whole class of such drives, not necessarily those for naval propulsion.

II. Random PWM Techniques

Simultaneous variations of both the switching and sampling periods is a major disadvantage of the known RPWM technique, subsequently referred to as the RPWM I method. Typically, the modulator constitutes only a small part of the overall control system of a drive. Many tasks are simultaneously performed by the system, such as acquisition of the operator and sensor signals, speed, torque, and flux control, field orientation, fault detection, etc. The fixed sampling frequency represents a tradeoff between the various corresponding bandwidth requirements. If the control system is based on a single digital processor with high information-processing capacity, the PWM can just be one of its operating tasks. Even when the modulator function is realized in a separate processor, its operation must be synchronized with the control system. Therefore, a novel RPWM technique, named RPWM II, has been developed. It is characterized by a constant sampling frequency and a varying switching period T_{sw} realized by random changes of the delay of switching cycles with respect to the corresponding sampling cycles.

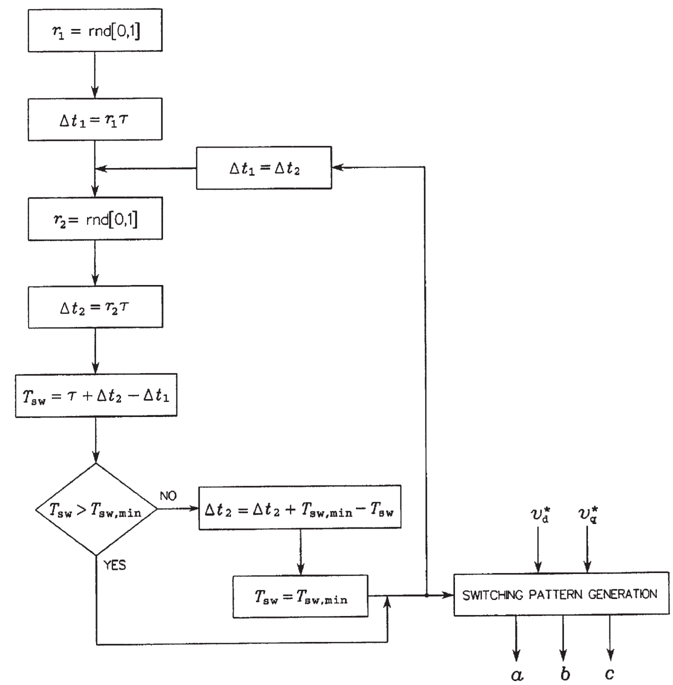

Fig. 2. Flowchart of the RPWM II technique.

The deterministic PWM (DPWM), RPWM I, and RPWM II techniques are illustrated in Fig. 1. Subscripts of the reference voltage vectors v_i^*, $i = 1, 2, \ldots$, indicate switching cycles in which corresponding vectors of the actual output voltage are generated. In the RPWM I technique, the range of switching periods is $xT_{\mathrm{sw,ave}}$ to $(2-x)T_{\mathrm{sw,ave}}$, where $T_{\mathrm{sw,ave}}$ is the average switching period and x is an arbitrary fractional number. In the RPWM II method, the random delay Δt acquires values between zero and the sampling period τ with uniform probability distribution. If a long delay in one sampling cycle is followed by a short delay in the next cycle, the resultant switching period may turn out to be too short; that is, shorter than its minimum allowable value $T_{\mathrm{sw,min}}$. In such case, the switching period is set to that value. As a result, the length of the switching cycle varies between $T_{\mathrm{sw,min}}$ and 2τ. A flowchart of the variable-delay technique is shown in Fig. 2. Clearly, the number of switching cycles is the same as that of sampling cycles; that is, the reciprocal of the average switching period equals the fixed sampling frequency. Note that setting Δt to zero transforms the RPMW II into DPWM.

It should also be noted that the constant x in RPWM I is so selected as to make the shortest switching period $xT_{\mathrm{sw,ave}}$ not shorter than $T_{\mathrm{sw,min}}$, and that in RPWM II, $T_{\mathrm{sw,ave}} = \tau$. This allows comparing ranges of switching periods for the two

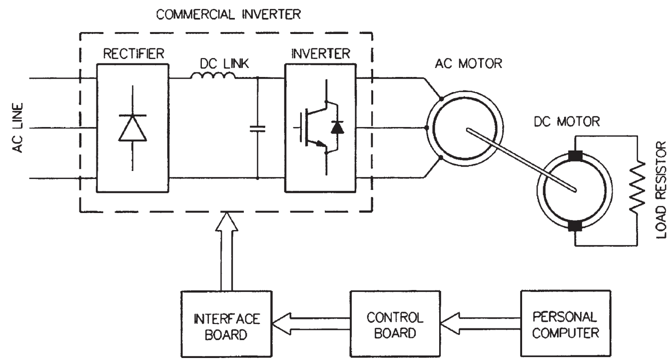

Fig. 3. Block diagram of the investigated model of naval-propulsion drive.

random PWM techniques described. This range for RPWM I is $T_{\mathrm{sw,min}}$ to $(2-x)\tau$, while it is $T_{\mathrm{sw,min}}$ to 2τ in RPWM II. Clearly, the range is greater for RPWM II, which partially compensates for the reduced randomness of this technique due to the loose synchronization of switching and sampling cycles. On the other hand, experience gathered from previous studies of random PWM indicates that: 1) for a flat spectrum of output voltage, it is sufficient for the maximum switching period to be three times longer than the minimum one, and 2) further increases of that multiple do not tend to yield noticeable advantages. This condition, with x set to 0.5, was satisfied in the experimental system described below.

III. Experimental Setup

Although certain experiments with RPWM have already been published, e.g., in [5]–[8], all the drives investigated were of low power, and the extent of the studies was narrow. Typically, apart from the spectra of inverter output voltage and current, only the acoustic noise was measured. A few pilot studies were focused on the conducted electromagnetic interference (EMI) [9]–[11]. The experimental investigation described in this paper was wider in scope, and the drive was much larger than those in the other studies (although still much smaller than the planned megawatt-range naval-propulsion drives). A commercial induction motor was used in the project. This machine has the same type of stator as the PMSM. Therefore, assuming similar stator–rotor interactions, the investigated effects are expected to be not much different from those in the latter motor.

A block diagram of the experimental setup is shown in Fig. 3. A 40-hp 230-V 60-Hz six-pole induction motor drove a 40-hp 240-V 1750-r/min dc generator with a resistive load. Both machines were placed in an anechoic chamber. Power was supplied to the motor from a commercial 40-hp 230-V inverter (Danfoss VLT5032). The original control system of the inverter was bypassed with an external TMS320F243 digital signal processor, controlled from a personal computer and linked with the inverter via an interface board. The protection circuits of the inverter were left intact.

The motor was operated in the constant-volts/hertz control mode. Measurements were made of the stator voltage and current, current noise conducted to the grid, acoustic noise sensed by microphones, and vibration detected by an accelerometer

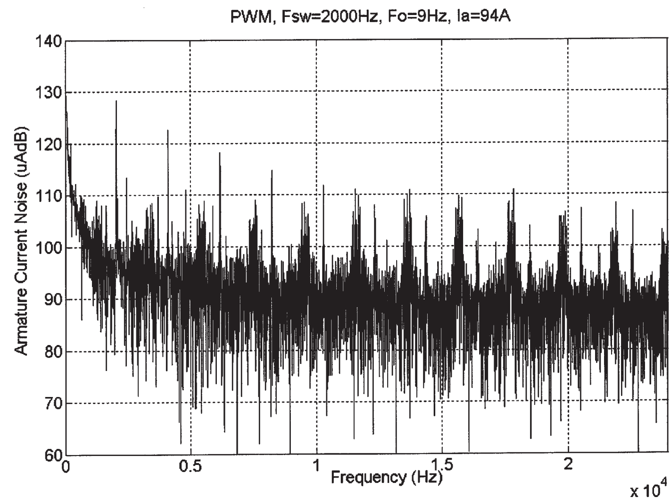

Fig. 4. Frequency spectrum of armature-current ripple: DPWM.

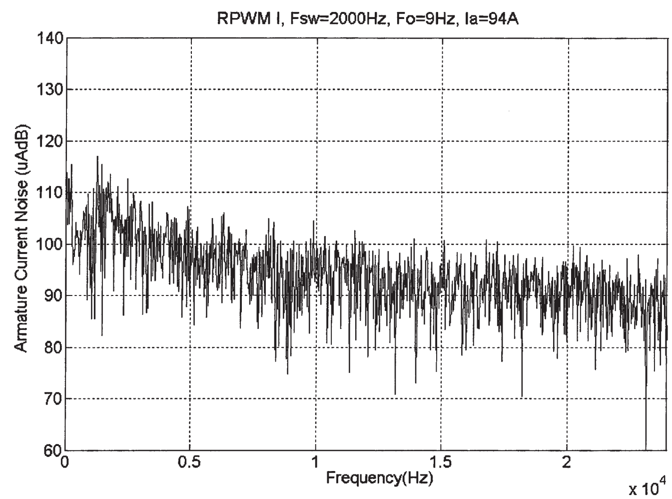

Fig. 5. Frequency spectrum of armature-current ripple: RPWM I.

pressed to the motor surface. Various operating conditions and various average switching frequencies were set up. The DPWM method with fixed sampling and switching frequencies was used as a benchmark for the RPWM I and RPWM II techniques.

IV. Experimental Results

Representative experimental results are illustrated in Figs. 4–15. For the DPWM method, the switching period was 0.5 ms in all cases; that is, the switching frequency was 2 kHz. The same 0.5-ms value was also the average switching period in the RPWM I and RPWM II techniques. The range of switching periods was from 50 to 150% of the average value in RPWM I. In RPWM II, the sampling frequency was the same 2 kHz and the minimum switching period was 0.15 ms. The drive ran on full load, with the armature current of 94 A, and with the supply frequency of 9 Hz, resulting in a speed of about 170 r/min.

Frequency spectra for the armature-current ripple, the major factor in generation of the acoustic noise and vibration, are shown in Figs. 4–6 for the DPWM, RPWM I, and RPWM II, respectively. Harmonic clusters all but disappeared when the

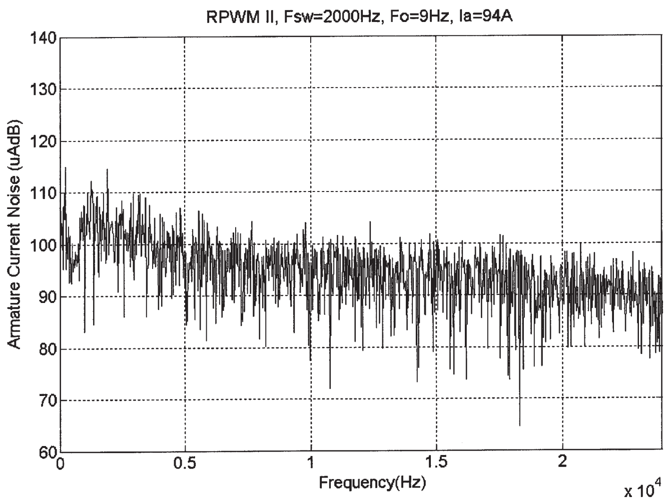

Fig. 6. Frequency spectrum of armature-current ripple: RPWM II.

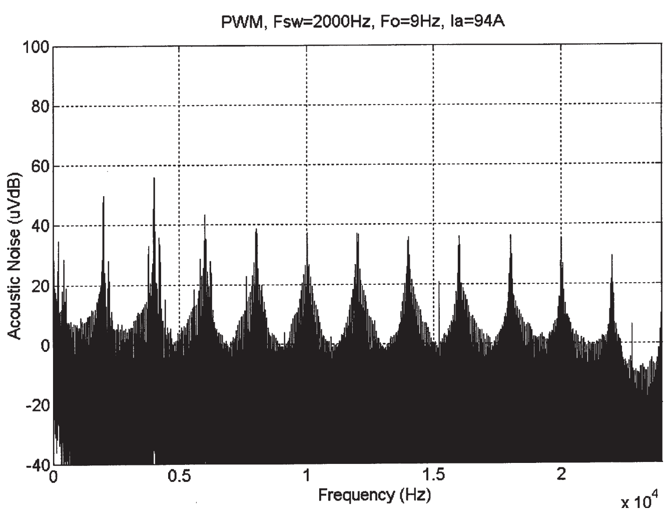

Fig. 7. Frequency spectrum of acoustic noise: DPWM.

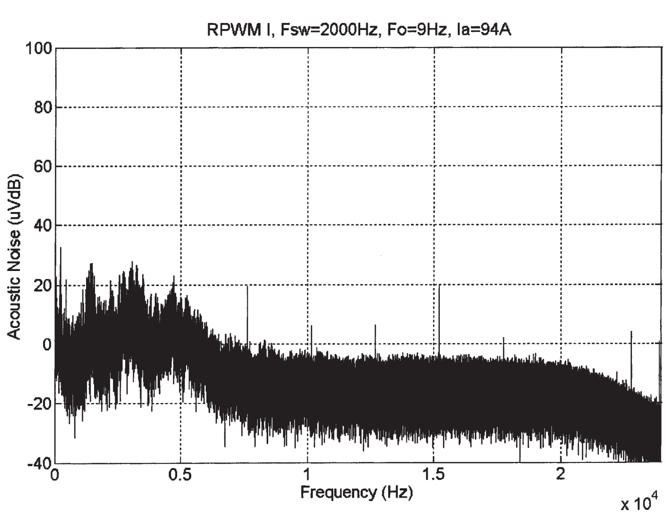

Fig. 8. Frequency spectrum of acoustic noise: RPWM I.

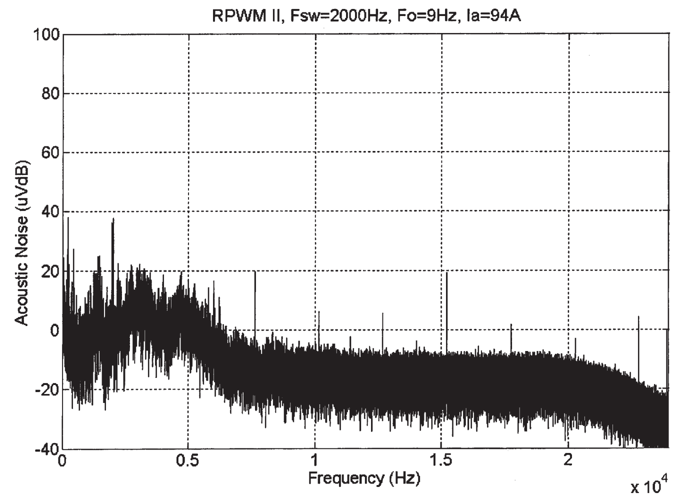

Fig. 9. Frequency spectrum of acoustic noise: RPWM II.

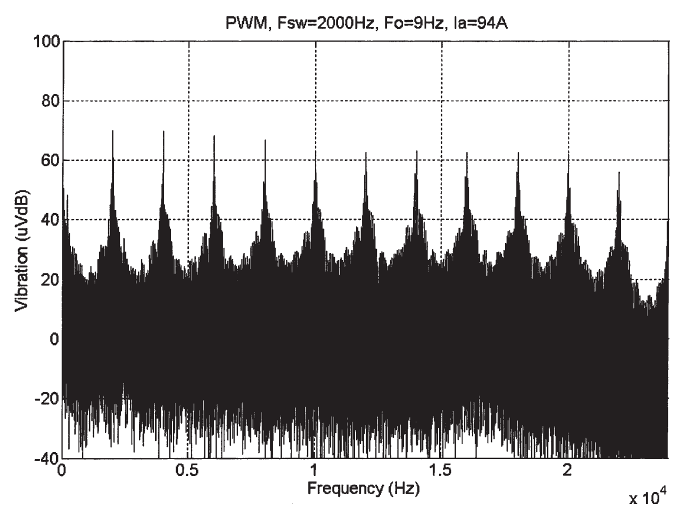

Fig. 10. Frequency spectrum of vibration: DPWM.

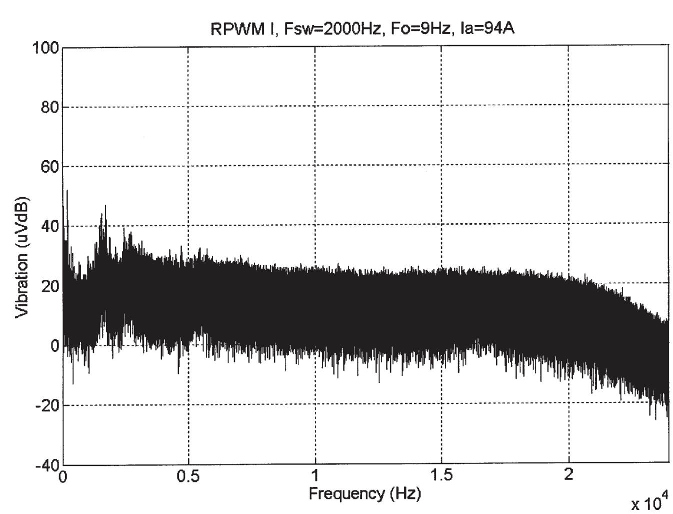

Fig. 11. Frequency spectrum of vibration: RPWM I.

RPWM techniques replaced the DPWM method. Similar patterns can be observed for the spectra of acoustic noise and vibration shown, respectively, in Figs. 7–12. The RPWM II algorithm for varying the switching periods is somewhat more restrictive than that in the RPWM I method, causing the existence of certain residual harmonics. Still, the most prominent frequency components of spectra with either of the random

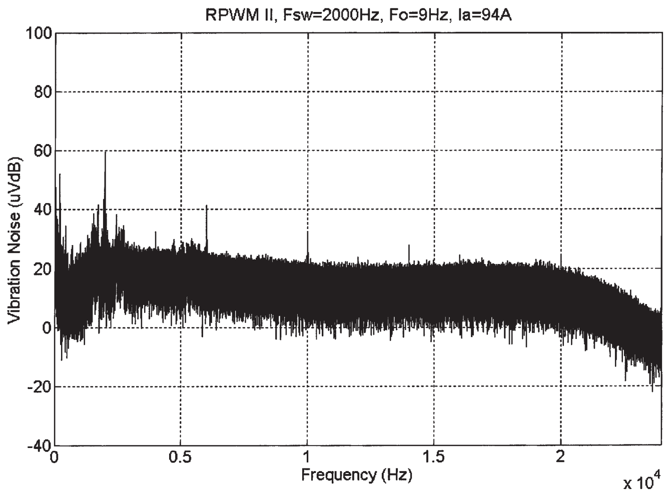

Fig. 12. Frequency spectrum of vibration: RPWM II.

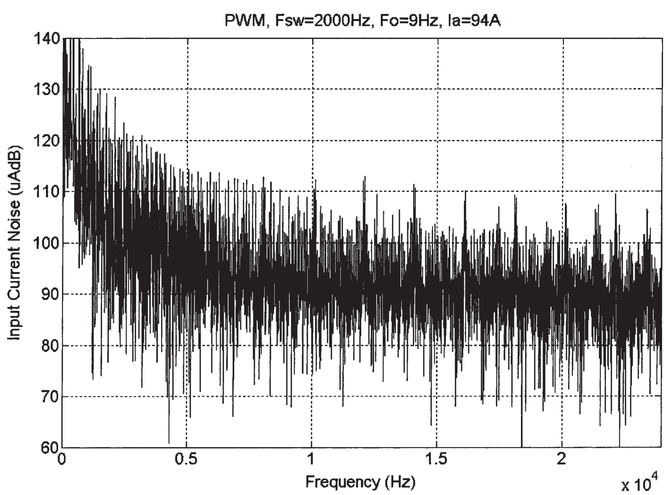

Fig. 13. Frequency spectrum of the input current: DPWM.

PWM techniques tend to be lower by 10–20 dB than those with the deterministic-modulation method. A certain amount of noise is produced by bearings and fans of the motor and generator, which explains the presence of frequency components unrelated to the switching frequency. In the actual naval drives, the motor fan is likely to be disposed of and replaced with a more efficient cooling system, necessary for a power-dense machine.

Frequency spectra of the current noise drawn from the power grid are shown in Figs. 13–15. The inverter is fed from a diode rectifier, which causes the high harmonic content at the low end of the frequency range. Above 5 kHz, the EMI mitigating effect of random modulation is clearly observable. Note that no existing EMI standards cover the frequency range below 9 kHz [12]. Finally, spectra of the vibration and current noise at the lower end of the frequency range are given in Figs. 16–21. It can be seen that in the vicinity of the fundamental output frequency of the inverter, all methods produce similar spectra. Harmonics seen in the vibration spectrum at 180 and 240 Hz seem to be related to the motor speed of 3 r/s, and are most likely caused by imperfections of the shaft's ball bearings and/or minor mechanical resonances.

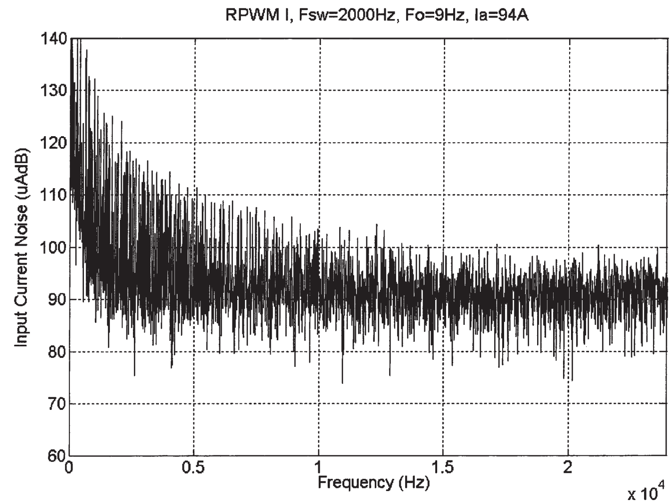

Fig. 14. Frequency spectrum of the input current: RPWM I.

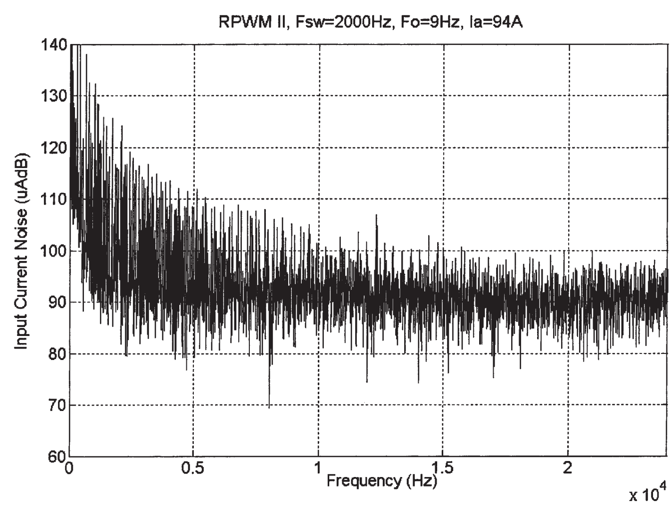

Fig. 15. Frequency spectrum of the input current: RPWM II.

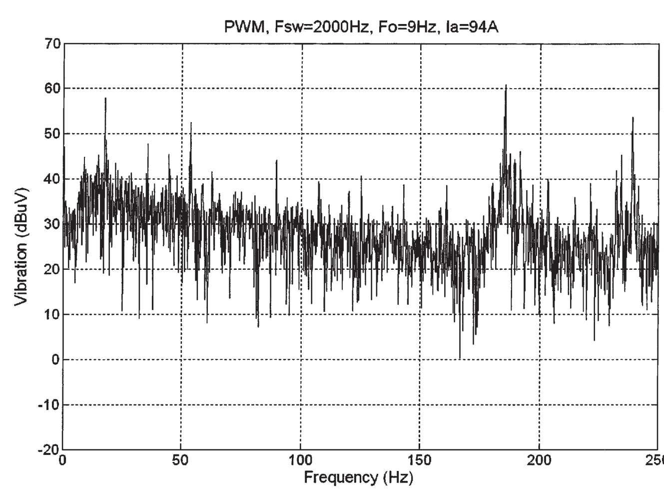

Fig. 16. Narrow-range frequency spectrum of vibration: DPWM.

V. Conclusion

Results of this investigation have decisively confirmed the advantages of random PWM techniques as tools for suppression of harmonics in the spectra of acoustic and electromagnetic

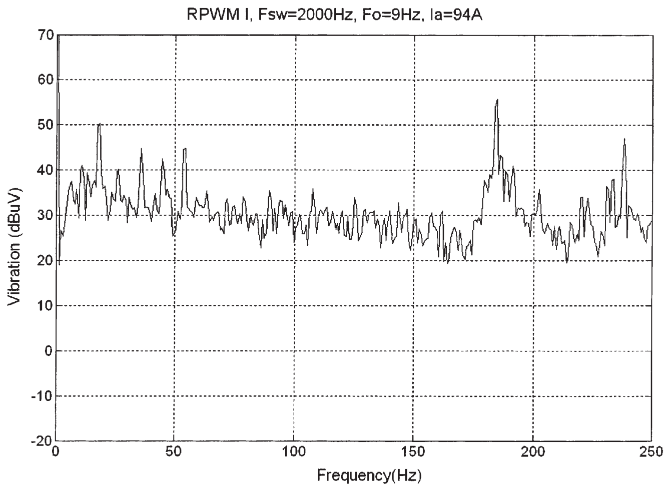

Fig. 17. Narrow-range frequency spectrum of vibration: RPWM I.

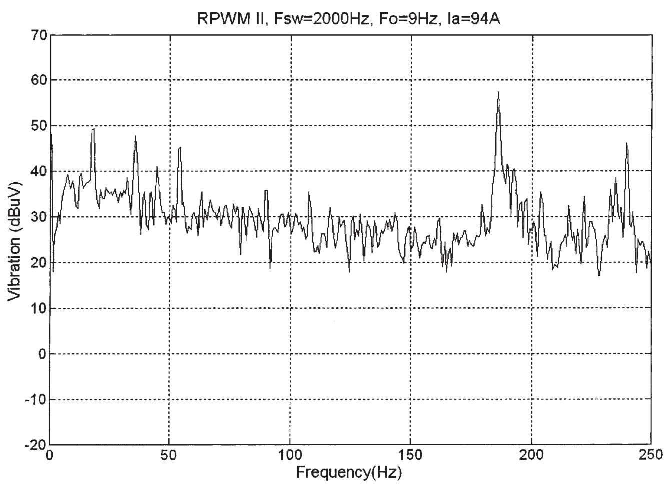

Fig. 18. Narrow-range frequency spectrum of vibration: RPWM II.

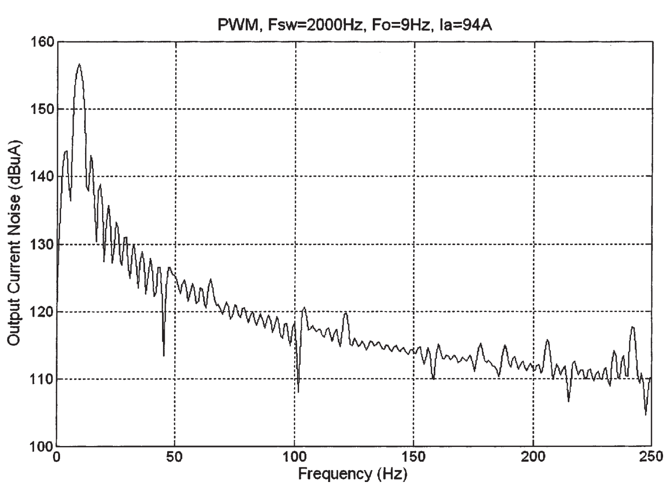

Fig. 19. Narrow-range frequency spectrum of the input current: DPWM.

noise, and mechanical vibration, in drives with PWM converters. In particular, the acoustic noise changes from a shrill tonal sound to rustling "static" resembling the noise of a small waterfall. Spectral components of this noise are reduced by

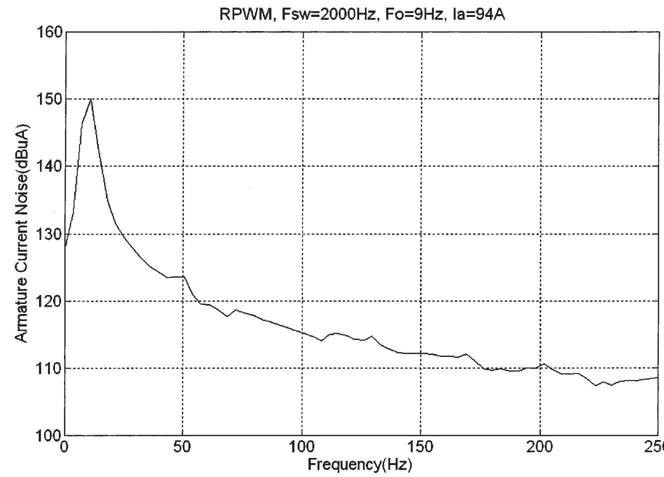

Fig. 20. Narrow-range frequency spectrum of the input current: RPWM I.

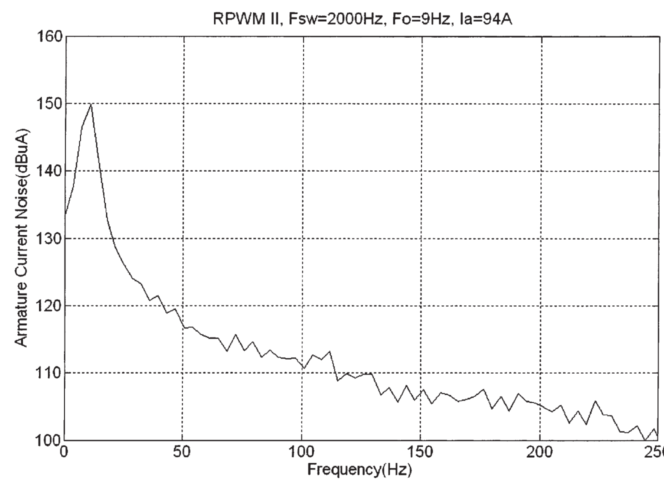

Fig. 21. Narrow-range frequency spectrum of the input current: RPWM II.

an order of 20 dB in comparison with those produced by deterministic modulation.

The novel RPWM II technique has the important and advantageous feature of a constant sampling frequency of the modulator. If the minimum allowable switching period is much smaller than the sampling period, the spectrum-flattening quality of that technique approaches that of the classic RPWM I method. However, if the constant sampling frequency is not an issue, as in low-performance ac drives, RPWM I still remains a technique of choice. As a result of a less constrained operating algorithm (no synchronization with a fixed sampling pattern), its spectral qualities are somewhat superior to these of RPWM II. It can clearly be observed comparing Figs. 11 and 12.

As already mentioned in the Introduction, conclusions drawn from the study are applicable to all inverter-fed ac drives, not only the naval ones. Note that naval-propulsion drives do not require high-performance control of the motor torque. In a ship or a submarine, speed commands rather than torque commands are being issued by the control center of the vessel. Torque transients, highly relevant in such industrial applications as winders or positioning systems, are of no consequence with respect to ship screws operating in water, a highly damping medium. The issue of fixed versus variable sampling frequency is not as important there as in certain high-performance industrial and vehicular drives, in which a constant sampling frequency at an optimal level may be crucial. Thus, in naval drives, the difference between the RPWM I and RPWM II techniques is less essential.

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Dr. Kleppe received the Outstanding Engineer Award from the Northern Nevada Chapter of the IEEE, the Nevada Inventor of the Year Award, the Outstanding Engineering Achievement Award from the Nevada Society of Professional Engineers (twice), and he was awarded a Professional Achievement Award by the University of Nevada, Reno, Alumni Association. He is a Registered Professional Engineer in the States of Nevada and California and a member of the Acoustic Society of America, Eta Kappa Nu, Sigma Tau, and Tau Beta Pi.

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