Comparison of Audible Noise Caused by Magnetic Components in Switch-Mode Power Supplies Operating in Burst Mode and Frequency-Foldback Mode

Laszlo Huber and Milan M. Jovanović
Delta Products Corporation
P.O. Box 12173
5101 Davis Drive
Research Triangle Park, NC 27709, USA

Abstract – In this paper, it is shown that operation of switch-mode power supplies in burst mode (BM) results in lower audible noise than operation in frequency-foldback mode (FFM). However, the selection of the switching frequency in a burst package can have a significant impact on the audible noise. In both BM and FFM, the audible noise can be reduced by decreasing the peak value of current pulses and proportionally increasing the burst frequency in BM and the switching frequency in FFM. In BM, the audible noise can be further reduced if instead of increasing the burst frequency, the number of burst pulses is increased without changing the burst frequency. The presented BM and FFM audible noise analysis is experimentally verified on a dc-dc boost test circuit.

I. INTRODUCTION

To meet the challenging efficiency requirements of today’s power supplies in the entire load range [1], [2], the switching frequency at light loads and no load needs to be reduced. This can be achieved by employing cycle skipping, also called burst-mode (BM) operation, or by continuously decreasing the switching frequency as the load decreases, also called frequency-foldback mode (FFM) operation. However, reducing the switching frequency in bursts in burst mode may cause audible noise if the switching frequency or the burst frequency falls in the audible range (20 Hz - 20 kHz).

The main sources of audible noise in switched-mode power supplies are cooling fans and magnetic components such as transformers, input-filter inductors, and power-factor-correction (PFC) chokes. In today’s power supplies that employ fan speed control, the fan noise caused by the air turbulence generated by the fins is dominant at heavy and medium loads, i.e., at loads above approximately 20-40% of full load. As a result, the noise generated by magnetic components is not a concern at these loads. However, at lighter loads, with a reduced fan speed, the noise generated by magnetic components may become a design issue.

Generally, audible noise produced by magnetic components can be attributed to three different excitation mechanisms, as described in [3], [4]. In magnetic components with an air gap, the dominant source of the audible noise is the Maxwell force in the air gap, which is proportional to the square of the magnetic flux density [3]. The second most dominant part of the noise is caused by magnetization of the core, assumed to arise from magnetostriction, where the core dimensions change when subjected to an applied magnetic field. Magnetostriction can cause a mechanical interaction between the core and the windings that leads to vibrations [4]. The magnetostrictive forces are also proportional to the square of the magnetic flux density. The third part of the magnetic component noise is caused by electromagnetic forces created by the magnetic field of the currents in the component’s windings (Lorentz forces) [4].

Methods for reducing the magnetic-components-related audible noise in switch-mode converters can be divided into mechanical and electrical methods. The mechanical approaches are based on techniques that prevent or damp vibrations by mechanical means such as varnishing, gluing, and potting. While these methods are successful in some applications, generally, they are undesirable since they involve extra manufacturing steps and, therefore, increase the cost. Electrical methods of controlling audible noise are preferred since they are more successful and cost effective.

Different electrical methods for audible-noise reduction in switch-mode converters caused by magnetic components are available in the literature for both operation in BM [5]-[7] and operation in FFM [8], [9]. However, a comparison of the audible noise caused by operation in BM and operation in FFM is not available yet.

In this paper, it is shown that operation in BM results in lower audible noise than operation in FFM. In both BM and FFM, audible noise can be reduced by decreasing the peak value of the current pulses and proportionally increasing the burst frequency in BM and the switching frequency in FFM. In BM, the audible noise can be further reduced if instead of increasing the burst frequency, the number of burst pulses is increased without changing the burst frequency. Audible noise measurements were obtained on a dc-dc boost test circuit.

II. COMPARISON METHODOLOGY

The audible noise study of BM and FFM operations was carried out on a dc-dc boost converter test circuit shown in Fig. 1. However, it should be noted that conclusions of this study can be extended to any other non-isolated or isolated topology.

Because the audible noise produced by magnetic components is proportional to the square of the magnetic flux density, as explained in the Introduction, the comparison of audible noise in BM and FFM operations is performed by analyzing the frequency spectrum of the square of the magnetic flux density in the inductor core. Recognizing that at light loads the inductor current is discontinuous and that the magnetic flux density is proportional to the current, the
magnetic flux density in the inductor core is triangular. Figures 2(a) and (b) show typical magnetic flux densities for the BM and FFM operations, respectively. To perform the comparison at the same current (power) levels, the magnitudes and frequencies of the triangular waveforms in Figs. 2(a) and (b) are selected so that their average values over the shown burst period of $T_{\text{Burst}} = 2.5\, \text{ms}$ are the same, i.e., the total area of the triangles in BM and FFM operations were adjusted to be the same. The frequency spectra of the square value of the triangular magnetic flux densities in Figs. 2(a) and (b) are shown in Figs. 3(a) and (b), respectively. As can be seen from Fig. 3(a), the five-pulse BM spectrum exhibits frequency bands of 5 kHz, i.e.,

$$f_{\text{sw}} \frac{N_{\text{Burst}}}{5} = 5\, \text{kHz} \, ,$$

with the 0-5-kHz base band as the most dominant and the 20-25-kHz side band, which is outside the audio frequency range, as the next dominant. The magnitudes of the frequency components between 5 kHz and 20 kHz are significantly smaller than those in the two most dominant bands. On the other hand, the FFM spectrum, shown in Fig. 3(b), is more uniform in magnitude. Specifically, the magnitude of the 20-kHz component is only 27.2% lower than the dc component. As the magnitude of the frequency components of the BM spectrum in Fig. 3(a) is significantly smaller than the magnitude of the frequency components of the FFM spectrum in Fig. 3(b), it can be predicted that operation in burst mode will result in lower audible noise than operation in frequency-foldback mode.

It should be noted in Fig. 3(a) that the selection of the switching frequency can have a significant impact on the audible noise. By selecting $f_{\text{sw}} = 25\, \text{kHz}$, the dominant band around $f_{\text{sw}}$ is completely outside the audible range. However, if, for example, $f_{\text{sw}} = 20\, \text{kHz}$ were selected, the lower half of the dominant band around $f_{\text{sw}}$ would be inside the audible range, as illustrated in Fig. 4, resulting in elevated audible noise.

### III. Audible Noise Measurements

The audible noise is measured as the “A” weighted sound pressure level (SPL) relative to 20 µPa, which is the lower threshold of the human perception of sound [10], i.e.,

$$L_{\text{pA}} [\text{dB(A)}] = 20 \log \frac{p}{20\, \mu\text{Pa}} + L_{\text{wA}} [\text{dB}] \, ,$$

where $p$ is the measured sound pressure in µPa before weighting and $L_{\text{wA}}$ is the transfer function of the “A” weighting network employed to compensate the characteristic of the human ear, which is nonlinearly sensitive to different frequencies. In fact, the transfer function of the “A” weighting network is approximately equal to the inverted equal loudness level contour of the human ear at a lower SPL (40 phon). The measured SPL after “A” weighting is converted into the frequency domain by using Fast-Fourier-Transform (FFT), as shown in Figs. 5(a) and 6(a). Instead of
using the results of the FFT analysis for audible-noise comparison, it is more convenient to use the results of the so-called constant-percentage-bandwidth (CPB) analysis [10], shown in Figs. 5(b) and 6(b). The CPB analysis is performed by dividing the audible range into 1/3-octave bands. In each 1/3-octave band, based on the FFT spectrum, the rms value of the “A” weighted sound pressure is determined and plotted as a function of the band center frequency. In Figs. 5(b) and 6(b), in addition to the measured CPB spectrum, typical audible noise limits for power supplies are also shown. In fact, in the absence of any audible noise agency specifications, many power-supply manufacturing companies have defined their own internal specifications.

The audible noise was measured by using the PULSE 3560C system from Bruel & Kjaer (B&K). The B&K 4190 microphone was used. The measurement was performed in a 45cm x 45cm x 65cm anechoic chamber. The audible noise measurement methods are specified in [11].

The FFT and CPM spectra in Figs. 5 and 6 represent the measured audible noise produced by operation in BM and FFM, respectively, corresponding to Figs. 2(a) and 2(b). It should be noted that the FFT spectrum in Figs. 5(a) and 6(a) is in good agreement with the BM and FFM spectrum in Figs. 3(a) and 3(b), respectively. For example, the four 5-kHz bands inside the audible range in the BM spectrum in Fig. 3(a) can be easily recognized in the corresponding FFT spectrum in Fig. 5(a).

Comparing the magnitude of the frequency components in the FFT spectrum in Figs. 5(a) and 6(a), it can be concluded that the operation in BM results in lower audible noise than
Fig. 5. Measured audible noise produced by operation in BM corresponding to Fig. 2(a): (a) FFT spectrum, (b) CPB spectrum and audible-noise limits

Fig. 6. Measured audible noise produced by operation in FFM corresponding to Fig. 2(b): (a) FFT spectrum, (b) CPB spectrum and audible-noise limits
Fig. 7. Magnetic flux density in (a) BM operation ($f_{sw}=25\text{kHz}, T_r=T_f=10\text{us}, B_{max, norm}=0.5$), (b) FFM operation ($f_{sw}=8\text{kHz}, T_r=T_f=10\text{us}, B_{max, norm}=0.5$), and (c) BM operation ($f_{sw}=25\text{kHz}, T_r=T_f=10\text{us}, f_{Burst}=400\text{ Hz}, N_{Burst}=20, B_{max, norm}=0.5$).

Fig. 8. Frequency spectrum of square value of triangular magnetic flux density in (a) BM operation ($f_{sw}=25\text{kHz}, T_r=T_f=10\text{us}, f_{Burst}=1600\text{ Hz}, N_{Burst}=5, B_{max, norm}=0.5$), (b) FFM operation ($f_{sw}=8\text{kHz}, T_r=T_f=10\text{us}, B_{max, norm}=0.5$), and (c) BM operation ($f_{sw}=25\text{kHz}, T_r=T_f=10\text{us}, f_{Burst}=400\text{ Hz}, N_{Burst}=20, B_{max, norm}=0.5$).
the operation in FFM. A more obvious quantitative comparison can be obtained by comparing the CPB spectrum in Figs. 5(b) and 6(b). In the two worst cases, the magnitude of the CPB spectrum in Fig. 5(b) is above the audible-noise limits by 8 dB(A) at 3.15 kHz and by 7 dB(A) at 12.5 kHz, whereas, the magnitude of the CPB spectrum in Fig. 6(b) is above the audible-noise limits by 12.5 dB(A) at 6.3 kHz and by 16 dB(A) at 12.5 kHz.

In both BM and FFM operations, the audible noise can be reduced by decreasing the peak value of the current pulses, i.e., the peak value of the magnetic flux density, and proportionally increasing the burst frequency in BM and the switching frequency in FFM in order to keep the same average current (power) levels. For example, by decreasing twice the peak value of the magnetic flux density, and increasing four times the burst frequency in BM operation ($f_{\text{Burst}} = 1600$ Hz) and the switching frequency in FFM operation ($f_{sw} = 8$ kHz), as shown in Figs. 7(a) and (b), respectively, the audible noise will be significantly reduced. The frequency spectrum of the square value of the triangular magnetic flux densities in Figs. 7(a) and (b) is shown in Figs. 8(a) and (b), respectively. The corresponding audible noise measurements are presented in Figs. 9(a) and (b). By comparing the BM spectra in Figs. 3(a) and 8(a), it can be seen that the peak magnitude of the frequency components in each 5-kHz band inside the audible range in Fig. 8(a) is approximately one half of the magnitude of the corresponding frequency components in Fig. 3(a). Similarly, by comparing the FFM spectra in Figs. 3(b) and 8(b), it can be seen that the magnitude of the frequency components in Fig. 8(b) is approximately one half of the magnitude of the corresponding frequency components in Fig. 3(b). From these comparisons...
in can be predicted that both BM and FFM operations with decreased peak value of the current pulses and proportionally increased burst frequency in BM and switching frequency in FFM will result in reduced audible noise. Specifically, by comparing the audible noise measurements in BM operation in Figs. 5(b) and 9(a), it can be seen that the CPB spectrum in Fig. 9(a) is below the audible noise limits except at 3.15-kHz, where it is equal to the limit, unlike the CPB spectrum in Fig. 5(b) which is mostly above the audible noise limits in the frequency range above 2-kHz. Similarly, by comparing the audible noise measurements in FFM operation in Figs. 6(b) and 9(b), it can be seen that the CPB spectrum in Fig. 9(b) is below the audible noise limits except at 8-kHz, where it is above the limit by 3.4 dB(A), whereas, the CPB spectrum in Fig. 6(b) is mostly well above the audible noise limits in the frequency range above 3.125 kHz.

In BM operation, the audible noise can be further reduced if instead of increasing the burst frequency, the number of burst pulses is increased without changing the burst frequency. Following the example from above, by increasing the number of burst pulses four times \( N_{\text{burst}} = 20 \), without changing the burst frequency \( f_{\text{burst}} = 400 \text{ Hz} \), as shown in Fig. 7(c), the audible noise is further reduced, as shown in Fig. 9(c) compared to Fig. 9(a). It should be noted that the CPB spectrum of BM operation in Fig. 9(c) meets the audible noise limits with a margin of approximately 10 dB(A). The frequency spectrum of the square value of the triangular magnetic flux density in Fig. 7(c) is shown in Fig. 8(c). It can be easily seen that the magnitude of the frequency components above 1.6 kHz in Fig. 8(a) is significantly larger than the magnitude of the corresponding frequency components in Fig. 8(c).

Finally, it should be noted that a digital implementation of control, which has been increasingly employed in today's switch-mode power supplies, enables easy and precise control of the burst frequency and the number of burst pulses.

**IV. SUMMARY**

In this paper, it is shown that operation of switch-mode power supplies in burst mode (BM) results in lower audible noise than operation in frequency-foldback mode (FFM). However, proper selection of the switching frequency in a burst package is critical for achieving low audible noise.

Because the audible noise produced by magnetic components is proportional to the square of the magnetic flux density, the comparison of audible noise in BM and FMM operations is performed by analyzing the frequency spectrum of the square of the magnetic flux densities.

In both BM and FFM operations, the audible noise can be reduced by decreasing the peak value of the current pulses and proportionally increasing the burst frequency in BM and the switching frequency in FFM. In BM, the audible noise can be further reduced if instead of increasing the burst frequency, the number of burst pulses is increased without changing the burst frequency.

The presented BM and FFM audible noise analysis is experimentally verified on a dc-dc boost test circuit.

**ACKNOWLEDGMENT**

The authors appreciate the help of Mr. Wei Dong from the Delta Shanghai Design Center for performing the audible noise measurements.

**REFERENCES**


