COMPARISONS OF HIGH FREQUENCY MAGNETIC CORE LOSSES
UNDER TWO DIFFERENT DRIVING CONDITIONS:
A SINUSOIDAL VOLTAGE AND A SQUARE-WAVE VOLTAGE

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ABSTRACT

It is observed that for the same peak flux density and the same operating frequency, the core loss induced by a square-wave voltage drive is less than the loss induced by a sinusoidal voltage drive, which is contrary to what one would normally anticipate. To the best of the author's knowledge, there is no theory that predicts the loss difference observed.

INTRODUCTION

In recent years, applications of power electronics have enjoyed a rapid growth. In most of the applications, the efficiency and the size of the power circuitry are often of primary concern. In order to achieve high circuit efficiency and small component size, the power devices of the circuit are normally operated at high frequency switching mode. Because of such operation, a high frequency square-wave (or quasi-square) voltage is typical of the voltage waveform applied across the magnetic components of the power circuit. There are magnetic materials and core structures suited for high frequency operation, such as thin tape-wound alloys, ferrites and recently, amorphous alloys.(1) However, such magnetic materials or cores are normally characterized under sinusoidal driving condition. Little work has been done to investigate the material characteristics under square-wave driving condition.(2) The primary purpose of this paper is to bring out the common misconception about the magnetic core losses under the two different driving conditions, that is, for the same peak flux density and the same operating frequency, one normally anticipates higher core loss under a square-wave driving condition than under a sinusoidal voltage. Power loss measuring schemes are described and several observations of the measurement results are presented. An attempt to explain the observations is also included. The operating frequency of interest is in the 10-100 kHz range.

HIGH FREQUENCY SQUARE-WAVE POWER GENERATOR AND LOSS MEASUREMENT SCHEMES

High Frequency Square-Wave Generator

A half bridge square-wave inverter is used to drive the sample core for square-wave loss measurement. Figure 1 shows the circuit diagram of the inverter, in which the two transistors switch alternatively and the voltage across the inductor is square-wave. The two diodes are for commutating purpose. Figure 2 shows typical waveforms of the voltage and current of a ferrite core inductor in the inverter. The squareness of the voltage waveform depends on the frequency of operation, the magnitude of inductor peak current and capacitor size. For the present measurement, half bridge inverter is preferred to the parallel inverter for the following two reasons:

1. There are problems associated with "Flux walking" in the parallel inverter configuration because of unbalance of volt-second resulting from unmatching of the two power transistors. This problem is eliminated in the half bridge configuration because the circuit automatically balances the volt-second even if the two transistors are not matched or the duty cycle is unsymmetrical.(3)

2. In the parallel inverter configuration, the inevitable leakage between the two windings on the core, even though it can be made small, causes ringings and spikes in the waveform, which may confuse the measurement. In the half-bridge configuration, however, there is only one winding on the core and clean waveforms can be obtained.

Phase Error in a Loss Measurement

Power loss of an electrical component can be calculated according to the relationship $P_{loss} = \frac{1}{T}\int_T i\cdot v\,dt$. For a linear circuit driven by a sinusoidal source, the loss can be calculated by $P_{loss} = Im\cdot Vm \cos\phi$, where Im, Vm and ϕ are defined in Fig. 3. For a highly reactive component, ϕ is nearly $\pi/2$. Let $\theta \triangleq \pi/2 - \phi$, then $P_{loss} = Im\cdot Vm \sin\theta$. Expanding $\sin\theta$ into series terms,

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} + \dots + \frac{\theta^{(2n-1)}}{(2n-1)!}$$

For $\theta << 1$, $\sin\theta = \theta$. Therefore, $P_{loss} = ImVm\theta$. For a highly reactive component, θ is a very small value and therefore, a small phase error introduced in the amplifier and the multiplier of a wattmeter would cause a large measurement error. For example, for a typical low loss core for power application, θ is typically in the range of 0.1 to 0.05 depending on frequency and flux density of operation, 1° phase error would result in 18% to 85% of loss measurement

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error. 1° phase error is not too difficult to have, considering the frequency response of the amplifier and the multiplier of an electronic wattmeter at high frequency. This is especially true for the case of highly nonsinusoidal waveform such as a square-wave voltage.

One way to avoid the problem associated with the phase error described is to add a silver mica tuning capacitor in the measurement as shown in Fig. 4. Since the capacitor loss is negligible, the core loss can be calculated as $P_{loss} = VmImcos\phi$, where ϕ is zero at resonance. From series expansion of $\cos\phi$, it can be proved that $\cos\phi = 1$ when $\phi << 1$. Therefore, it is concluded that using this method, the loss measurement error resulting from a small phase error or a slight mistuning is much reduced. However, this technique is not applicable to the loss measurement in the case of square-wave drive since resonance can only be obtained at single frequency and the magnitude of higher harmonics of a square-wave waveform is significant as compared with the fundamental.

Core Loss Measurement Schemes

As described above, an electronic wattmeter is not suited for high frequency highly reactive power loss measurement especially when the waveforms involved are highly nonsinusoidal. Two improved techniques used for such measurements will be described. Core losses measured using these two techniques agree within seven percent of error.

Liquid Calorimeter

A relatively simple calorimeter, consisting of a vacuum bottle, a thermometer, a stirring mechanism and mineral oil, can be used for reasonably accurate loss measurement. The whole set-up is calibrated by using a power resistor driven by known input power, and the core loss can then be determined by measuring the liquid temperature rising rate. It should be cautioned that in designing a calorimeter for high frequency loss measurement, one should be aware of the possibility of induction heating on the set-up due to stray flux. While this is not a particular concern in the loss measurement of a toroidal sample cores, it has been observed, in attempting to measure the loss of a leakage transformer, that induction heating on the mercury of the thermometer and the silver coating of the vacuum bottle caused a large measurement error.

Digital Computation

The other technique used for loss measurement is to integrate the waveform of voltage-current product with respect to time using digital computation techniques. A Techtronix computer-based digital scope was used for taking the waveforms which are then processed by the associated minicomputer to give the measurement result. This technique gets around the problem associated with phase error of the multiplier in an electronic wattmeter. Attention must be given to make sure that the current probe does not introduce significant time delay. If a significant time delay is observed in the current probe, it should be corrected in the computer program.

RESULTS OF CORE LOSS COMPARISONS

Several magnetic materials were investigated, including ferrite, silicon iron, nickel iron and amorphous metal. The criterion of comparison is that the core flux density under both the sinusoidal and the square-wave driving condition is of the same peak value and of the same frequency. The frequency of interest is in the range of 10 kHz to 100 kHz, and the core peak flux density investigated is between 10% to 60% of the core saturation flux density. All the comparisons were made for the case where the hysteresis loop is symmetrical.

The comparison shows somewhat surprising results, that is, for the same peak flux density and the same operating frequency, the core loss under a square-wave driving condition tends to be lower than that under a sinusoidal driving condition. This observation is contrary to one's intuition that a square-wave driving voltage should induce more loss because of higher eddy current loss due to higher frequency harmonics. Figure 5 shows the hysteresis loops for ferrite core under the two driving conditions. The difference of core loss observed is 7% in one case and is 12% in the other, all in favor of square-wave drive. Figures 6 and 7 show two other examples, one for amorphous alloy and the other for nickel iron. The loss differences observed are in the range of 20%. Figure 8 shows the hysteresis loops of a 12 mil thick silicon iron at 20 kHz, 2000 Gauss, and the loss difference observed is 30%. As can be seen from these figures, the difference in the shape of the hysteresis loops between the two driving conditions is less pronounced for ferrite cores than that observed for metal cores.

Discussions on Comparison Results

From limited data taken, several observations are summarized as follows:

1. For the same peak flux density, the higher the operating frequency, the more pronounced the difference in loss between square wave and sinusoidal operation.
2. For the same operating frequency, the lower the flux density, the more pronounced the loss difference is;
3. The lower the material resistivity, the more pronounced the loss difference is.

All the three observations tend to suggest that the difference in core losses between a sinusoidally driven core and a square-wave driven one depends on the ratio of eddy current loss to hysteresis loss of a core. The difference between the effect of the two different driving source on core loss is primarily in the eddy current loss. For the same peak flux density, the higher the frequency, the higher the percentage of the total loss the eddy current loss becomes, and therefore the loss difference is more pronounced. (This explains Observation #1.) For the same frequency, the lower the flux density, the higher the percentage of the total loss the eddy current loss becomes, and therefore, the loss difference observed is more pronounced. (This explains Observation #2.) For ferrite, the major loss is hysteresis loss, and therefore, the loss difference observed is less pronounced. (This explains Observation #3.)

In recent years, it has been common to interpret the core losses in terms of domain wall motion. Various models have been proposed using domain wall theory to explain the eddy current loss.[4] While such models provide useful insight into the loss mechanism, to the best of author's knowledge, they do not estimate the loss accurately nor do they explain the loss reported in the present paper. However, it can be proved from simple arguments to follow that a square-wave voltage does not necessarily induce more core loss than a sinusoidal voltage as one may anticipate. Figure 9 shows voltage and flux waveforms of a sinusoidal voltage and a square-wave voltage. For the same peak flux, the magnitude of the two voltage waveforms must be such that the area under each half cycle is the same, which leads to the condition $V_{m,sin} = (\pi/2)V_{m,sq}$. Therefore, the sinusoidal voltage is larger than the square-wave voltage in magnitude in the central portion of each half cycle and is less in the rest portion of the cycle. The eddy current loss of a core depends on the rate of domain wall motion, which in turn is determined by an instantaneous voltage. The eddy current loss induced by the sinusoidal voltage is therefore higher than the loss induced by the square wave voltage in the central portion of each half cycle and is the opposite in the rest portion of the cycle. It is therefore concluded that for the same peak flux density and the same frequency, a square-wave voltage does not necessarily induce more core loss than a sinusoidal voltage does. To predict how much the loss difference is, it is required to know the functional dependence of eddy current loss on applied voltage.

It was reported in literature that a correction factor for eddy current loss has been established for the case in which the flux waveform is a sinusoidal fundamental plus a single harmonic component, using a purely sinusoidal flux of the same peak value and the same frequency as the baseline.[5] Correction factors have been established for the odd harmonics up to the 11th of varying contents and varying phase angles (with respect to the fundamental) for 25 mil thick silicon iron at 60 Hz. It is interesting to note that the value of the correction factor established is greater than unity for most cases except in the case of 3rd harmonic of 180° phase angle, in which the correction factor is about 0.9. A Fourier expansion of a triangular flux waveform (square-wave voltage), neglecting harmonics above 5th order, indicates that a triangular waveform would fall into the exceptional case in which a purely sinusoidal flux induces more eddy current loss than a flux containing fundamental plus a single harmonic component. In this sense, this result agrees with the observation reported in the present paper.

CONCLUSIONS

In conclusion, it is observed that for the same peak flux density and the same operating frequency, the core loss induced by a square-wave voltage drive is less than the loss induced by a sinusoidal drive, which is contrary to what one normally would anticipate. The loss difference observed depends on the frequency of operation, the operating flux density and material resistivity, and could be significant in some cases. To the least, the observation presented in this paper suggests that a square-wave voltage drive is no worse than a sinusoidal one as far as core loss is concerned, and the core loss data obtained under a sinusoidal driving condition should serve as conservative guidelines.

It is important to note, however, that this observation does not imply that for transforming the power, a square-wave voltage is the better choice of the two. It can be shown that to transform the same amount of power, the core peak flux density has to be $\pi/2\sqrt{2}$ times higher in the square-wave case than in the sinusoidal case, which is not the criterion the above observation is based on.

To the best of author's knowledge, there is no adequate microscopic model or theory that explains or predicts the loss difference observed. Extensive measurements are required to develop a mathematical model to predict the loss difference. It is not the intention of the present paper to present extensive measurement data. The primary purpose of this paper is, rather, to bring out the subject and the observation and hope to stimulate further interest in this area.

ACKNOWLEDGMENTS

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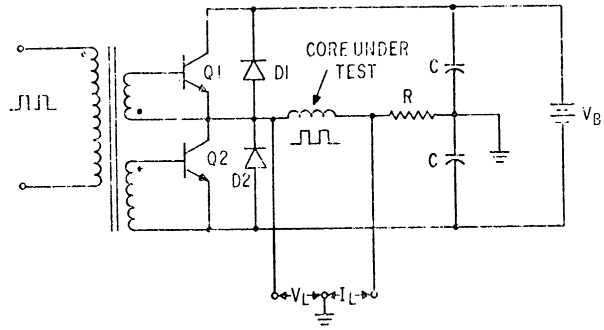


Fig. 1. Half Bridge Inverter Circuit

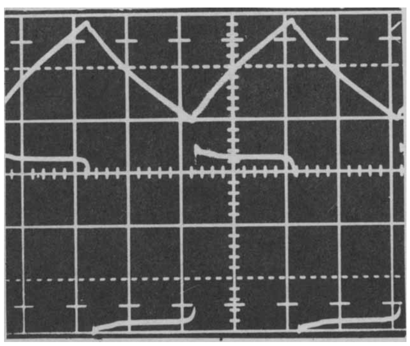


Fig. 2. Voltage and Current Waveforms of a Ferrite Core Inductor in a Half Bridge Inverter
V: 30V/Div; I: 0.2A/Div; t: 10μ.S/Div.

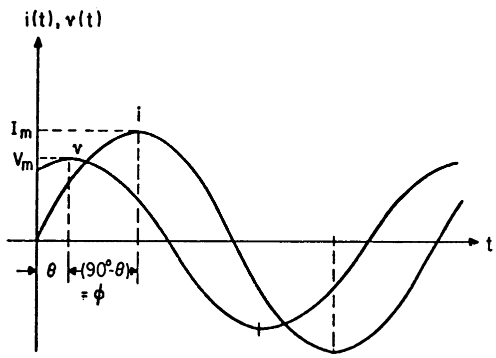


Fig. 3. Inductor Voltage and Current Time Relationship Under a Sinusoidal Driving Condition

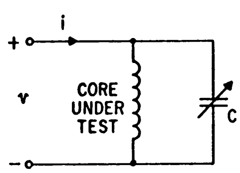
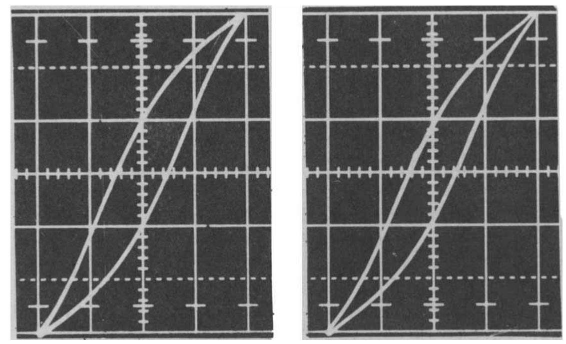
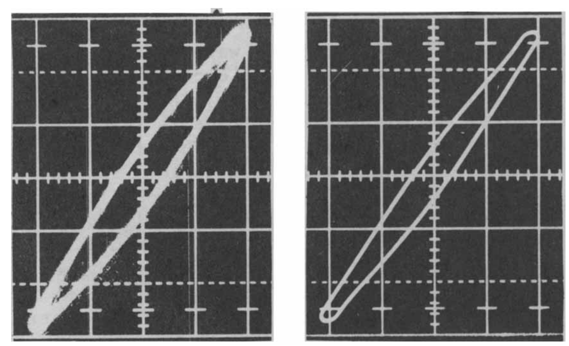


Fig. 4. Loss Measurement Using a Tuning Capacitor



Sinusoidal Drive Square-Wave Drive

(a)

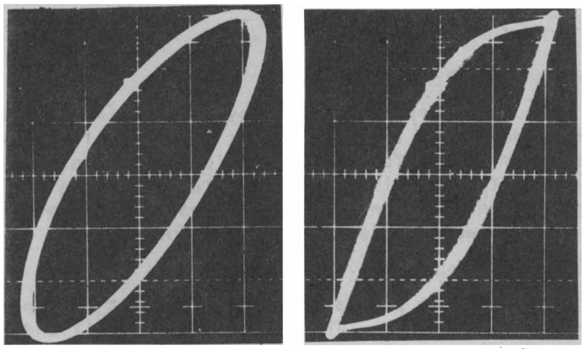


Sinusoidal Drive Square-Wave Drive

(b)

Fig. 5.

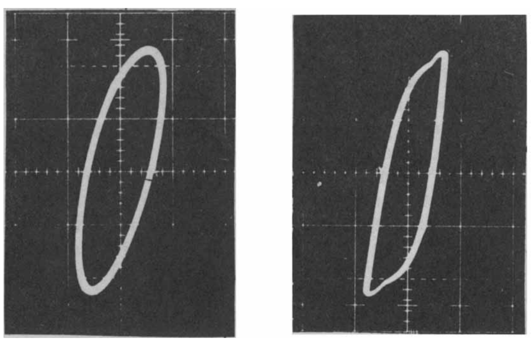
Hysteresis Loops of Ferrite Core (Stackpole 24B) Under Two Different Driving Conditions
(a) (2000 Gauss, 25 kHz, 50°C);
Loss Ratio $\triangleq$ Psin/Psq. = 1.07
(b) (1000 Gauss, 75 kHz, 50°C);
Loss Ratio = 1.12



Sinusoidal Drive Square-Wave Drive

Fig. 6.

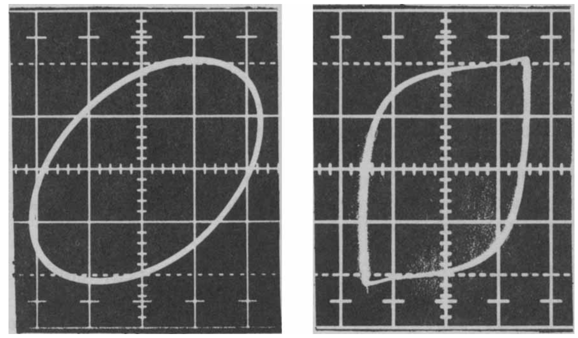
Hysteresis Loops of 2 mil Thick Amorphous Metal (Allied Chemical Metglass 2826) (1000 Gauss, 10 kHz); Loss Ratio $\triangleq$ Psin/Psq. = 1.20



Sinusoidal Drive Square-Wave Drive

Fig. 7.

Hysteresis Loops of 2 mil Thick Nickel Iron (Round Permalloy 80) (800 Gauss, 50 kHz); Loss Ratio $\triangleq$ Psin/Psq. = 1.24



Sinusoidal Drive Square-Wave Drive

Fig. 8.

Hysteresis Loops of 12 mil Thick Silicon Iron Under Two Different Driving Conditions (2000 Gauss, 20 kHz); Psin/Psq. = 1.30

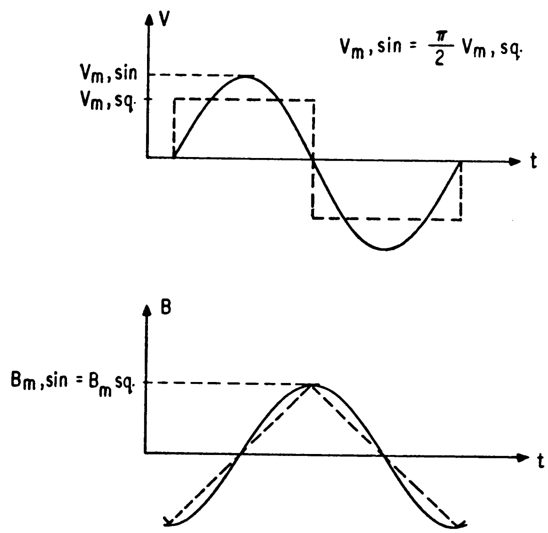


Fig. 9. Voltage and Flux Waveforms of a Sinusoidal Voltage and a Square-Wave Voltage