Using a power transformer at a frequency it wasn't designed for

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Power-transformer designs minimize weight and cost based on three assumptions: (1) the power source is a sine wave, (2) the frequency is fixed, and (3) the voltage will not exceed a specified maximum. Given this starting point, an efficient, cost-effective design will set the peak value for magnetic flux density near the limit for the core material at maximum voltage, and the windings will use the least copper consistent with the power and efficiency requirements. Some margin is built in, but a power transformer is narrowly optimized for its application. This doesn't mean the transformer is picky about how it is applied, but it does mean that proper attention is required if the assumptions are changed.

A useful simplified transformer model divides it into a shunt inductor that represents the primary winding followed by an ideal transformer that handles load current, as shown in Figure 1. The transformer's magnetic flux is generated by the current through the shunt inductor, termed excitation current. This can be measured as the current draw of the transformer with no load connected.

When a load is present, total primary current is the vector sum of the excitation and load currents. Primary and secondary load currents circulate in opposite senses, causing their respective magnetic fields to cancel. Hence, only the excitation portion of the total current is responsible for the alternating magnetic field at the heart of transformer operation. Although the currents share the winding, they act as if they are separate. As for any other inductor, excitation current is proportional to driving voltage and inversely proportional to frequency, according to Ohm's Law for inductive reactance. The magnitude is expressed as follows:

\[ I = \frac{V}{2\pi fL} \]

If excitation current exceeds a critical value, the consequence is magnetic saturation of the core. This causes the instantaneous value of \( L \) to drop to the air core value of the winding, resulting in excessive current that can overheat and destroy the transformer. Therefore, if frequency is reduced, the driving voltage must be proportionately reduced to keep excitation current within the core limit.

For a power transformer designed for 115V\(_{\text{RMS}}\) at 400 Hz but used at 60 Hz, the input voltage must not exceed \( 115 \times 60/400 = 17.25 \text{ V}_{\text{RMS}} \), but the transformer will work within this restriction. A
transformer designed specifically for 240V at 60 Hz must not be driven with more than \(240 \times 50/60 = 200\) V at 50 Hz. Obviously, 50/60-Hz-rated transformers are designed for operation at 50 Hz and draw less excitation current at 60 Hz.

It is tempting to conclude that frequency and voltage can be scaled upward. From a magnetic flux viewpoint this is valid, but power dissipation is a second constraint. Notwithstanding that a well-designed transformer can be 98%+ efficient, there are many loss terms. These include hysteresis loss, dielectric loss, magnetostriction, and copper loss from winding resistance, including skin and proximity effects.

To illustrate the importance of loss limits it is sufficient to consider just one major contributor. Assuming that the core is made from thin, stacked laminations stamped from steel alloy, it will have an appearance similar to Figure 2. This is a common type of power transformer construction. Transformer steels, being metal, are conductive. A conductive medium immersed in a varying magnetic field responds with heat-generating eddy currents.

The purpose of laminated construction is to divide the metal mass into thin, electrically insulated layers parallel to the magnetic field. This disrupts eddy-current circulation, greatly reducing this contribution to power loss. Laminations used at 60 Hz are typically around 0.014-in. thick. Higher-frequency designs benefit from thinner laminations but also need less core mass to handle the same amount of power. It is the weight savings possible with 400-Hz power that drives use on aircraft.

Eddy-current loss is described by a classic formula for power dissipation per unit volume of a laminated core (Reference 1). In simplified form, the contribution is expressed as

\[
P_e = K_p f^2 B_{\text{max}}^2 a^2 \sigma^2
\]

or more compactly,

\[
P_e = K_e f^2 B_{\text{max}}^2
\]

where

- \(P_e\) = eddy current power dissipation per unit volume
- \(K_p\) = constant dependent on system of units
- \(K_e\) = combination constant
- \(f\) = frequency
- \(B_{\text{max}}\) = magnetic flux density limit for chosen lamination alloy
- \(a\) = thickness of lamination
- \(\sigma\) = conductivity of lamination alloy

To apply the formula here, the internal parameter \(B_{\text{max}}\) must be related to driving voltage and frequency, since those are what the user controls. A suitable expression can be derived from...
\[ B_{\text{max}} = K_b \Phi_{\text{max}} \]

\[ \Phi_{\text{max}} = L I_{\text{max}} \]

\[ I_{\text{max}} = \frac{\sqrt{2} V_{\text{RMS}}}{2\pi f L} \]

\[ \therefore B_{\text{max}} = \frac{\sqrt{2} K_b V_{\text{RMS}}}{2\pi f} = \frac{K_B V_{\text{RMS}}}{f} \Rightarrow B_{\text{max}}^2 = \frac{K_B^2 V_{\text{RMS}}^2}{f^2} \]

where

\( B_{\text{max}} \) = peak flux density
\( K_b \) = conversion constant dependent on units and construction
\( K_B \) = combined constant
\( \Phi_{\text{max}} \) = peak induction field
\( L \) = primary inductance
\( I_{\text{max}} \) = peak excitation current
\( V_{\text{RMS}} \) = RMS voltage across winding

This result is independent of winding inductance. When inserted into the loss equation, the final result is, on a per-unit volume basis, expressed as

\[ P_e = K_e K_B^2 V_{\text{RMS}}^2 \]

This loss term is independent of frequency because \( B \) decreases by \( 1/f \). The square law effect of \( V_{\text{RMS}} \) is general to other loss terms.

A naive calculation based solely on \( B_{\text{MAX}} \) shows that a 50-Hz transformer driven at 400 Hz could handle up to eight times the rated voltage. However, the \( P_e \) equation shows a corresponding 64-fold increase in eddy-current loss. Perhaps the transformer could be driven this hard on a short-pulse, low-duty-cycle basis, but that doesn't imply that the insulation could withstand the increased voltage. It just means that the transformer is being used at other than the design optimum. The bottom line is that for continuous operation, the rated voltage for a power transformer should be respected for frequencies at or above the design frequency. A 120V-ac, 60-Hz transformer pressed into service at 400 Hz is still a 120V-ac transformer.

Finally, there is the question of wire gauge. For the same power level, lower-frequency transformer windings tend to have more turns of finer wire, while higher-frequency designs generally use fewer turns of thicker wire. From the standpoint of transformer design, winding resistance scales as the inverse square of frequency. Simply put, a 50- or 60-Hz transformer applied at 400 Hz will have disproportionately higher resistance than a purpose-built 400-Hz winding, resulting in degraded voltage regulation under varying loads. It is up to the circuit designer to factor this into the final result.

Note that these results are for power frequencies (Reference 2). The loss equations change if frequency is shifted high enough for parasitic components to affect performance. For example, high-
voltage windings with many turns might have self-resonance low enough to affect operation. In general, it is not useful to push operating frequency beyond an order of magnitude in either direction. Performance should always be tested before commitment to an application.

These observations help us appreciate high-performance audio power transformers, which must handle a bandwidth of 20 Hz to 20 kHz with low losses and low distortion. Special winding techniques and high-performance magnetic materials are required to meet these specifications. Such transformers are of a different kind than line-frequency power transformers optimized for single-frequency, fixed-voltage operation.

References

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