Influence of operating frequency on design of power electronic transformers

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Abstract. The influence of operating frequency on parameters of power electronic transformers is investigated. An improved fast design algorithm is used to calculate competitive transformer designs based on ferrite cores and round wires under the same input parameters, while varying the operating frequency in a wide range (25 kHz to 400 kHz). Two sets of designs are compared: for a 400W and a 1200W full bridge converter. Specific optimization approaches are proposed to decrease eddy current losses in wires by interleaving windings.

1. Introduction
The paper investigates the influence of operating frequency on parameters of power electronic transformers with ferrite cores and windings realized using round wires.

2. Design Algorithm
Calculation of losses in ferrites [1], [2] and eddy current losses in wires [3] including skin and proximity effects is decisive for the accuracy of the design.

The design algorithm applied in the paper consists of 15 steps [4]. The design starts with calculating a proper core size based on heat transfer capability under natural convection [5]:

\[ a_{ch} = \left( \frac{S_{tot}}{A} \right)^{1/\gamma} \]

where \( a_{ch} \) is the largest dimension of the component, used as a scaling parameter;

\( A \) is a coefficient, for ferrites, \( A = (5\text{–}25) \times 10^6 \) if \( a_{ch} \) is in (m), [4];

\( \gamma \) is an exponent, characterizing the material and shape of the core, \( \gamma = 3 \);

\( S_{tot} \) is the total volt-amp rating of the component.

Then, the allowable power losses of the component are obtained. The losses are equally assigned to the core and the windings. When having their values, the peak induction is found using manufacturer's graphs. Having \( B_{ac,\text{peak}} \) value, the necessary turns for the primary and secondary windings are calculated, followed by choosing the appropriate conductors' diameters and winding arrangements. Real power losses are found. Finally, according to the values of coefficients \( k_{\text{eddy}} \) and \( k_{\text{cup}} \), if necessary a next available (smaller or bigger) core size is chosen and the algorithm is proceeded with that core. The coefficient \( k_{\text{eddy}} \) gives the ratio between eddy current losses and ohmic losses and \( k_{\text{cup}} \) is copper filling factor.
3. Winding Loss Calculations

Winding losses are calculated using an approach [4], based on a global loss factor $k_w$, which represents the ratio between the eddy current losses and the losses in the ohmic resistance:

$$P_{\text{eddy}} = (R_0 I_{\text{ac}}^2) k_w \left( m, f_{\text{op}}, d, \eta, \lambda \right)$$

(2)

where $m$ is an equivalent layer, $f_{\text{op}}$ - operating frequency, $d$ - wire diameter, $\eta$ - relative filling between the conductors and $\lambda$ - relative filling between layers.

4. Design Results Comparison

Ten designs of power transformers are calculated based on EE ferrite cores (N87) using the 15-step algorithm [4]. Input design parameters: $V_{\text{prim,rms}}=300$ V, $V_{\text{sec,rms}}=100$ V, $I_{\text{sec,rms}}=12$ A; $I_{\text{sec,rms}}=4$ A, $f_{\text{op}}=25$ kHz-400 kHz. The comparative study focuses only on using round wires. Remarks:

- Possible improvements applied are interleaving windings and using a few wires in parallel.
- The wire diameters are chosen so that the whole winding width is filled for both primary and secondary windings, the results are shown in Table 1.

Table 1. Design results for transformers with input design parameters: $V_{\text{prim,rms}}=300$ V, $V_{\text{sec,rms}}=100$ V, $I_{\text{sec,rms}}=12$ A; $I_{\text{sec,rms}}=4$ A, $f_{\text{op}}=25$ kHz-400 kHz, interleaving is used to decrease the losses in windings.

| $f_{\text{op}}$ (kHz) | Core (mm) | Volume (mm$^3$) | Component weight (g) | $B_{\text{sec,peak}}$ (T) | Total losses (W) | Copper filling factor | Number of turns P/S | Winding arrangement |
|-----------------------|-----------|-----------------|-----------------------|---------------------------|-----------------|----------------------|-------------------|-------------------|
| **Design 1200W**      |           |                 |                       |                           |                 |                      |                   |                   |
| 25                    | 65/32/27  | 78 650          | 530.200               | 0.212                     | 7.76            | 0.260                | 27/9              | PSP               |
| 50                    | 55/28/21  | 43 900          | 298.305               | 0.167                     | 6.862           | 0.284                | 26/9              | PSP               |
| 100                   | 56/24/19  | 36 400          | 243.782               | 0.123                     | 6.355           | 0.288                | 19/7              | PSP               |
| 200                   | 56/24/19  | 36 400          | 251.179               | 0.078                     | 5.870           | 0.323                | 15/5              | PSP               |
| **Design 400W**       |           |                 |                       |                           |                 |                      |                   |                   |
| 25                    | 42/21/15  | 17 300          | 133.585               | 0.263                     | 3.521           | 0.31                 | 66/22             | PSP               |
| 50                    | 40/16/12  | 11 500          | 80.486                | 0.198                     | 2.965           | 0.273                | 53/18             | PSP               |
| 100                   | 36/18/11  | 9 720           | 85.437                | 0.151                     | 2.287           | 0.426                | 45/15             | PSP               |
| 200                   | 32/16/9   | 6 140           | 55.057                | 0.107                     | 2.062           | 0.484                | 44/15             | PSP               |
| 300                   | 32/16/9   | 6 140           | 57.476                | 0.079                     | 2.03            | 0.531                | 39/13             | PSP               |
| 400                   | 32/16/9   | 6 140           | 49.103                | 0.060                     | 2.147           | 0.369                | 39/13             | PSP               |

4.1. Specifics of 1200W transformers design

For all the 1200W designs, the winding’s realizations follow the same concept — two primary winding’s layers connected in parallel and a secondary winding’s layer sandwiched between them (PSP arrangement), Fig.1,a,b. The turns of the primary winding in each layer consist of a single round wire, whereas the secondary winding’s turns are composed of two round parallel-connected wire.

Note that those designs are still examples. The 1200W designs could have lower losses (or a slightly smaller core) if a PSPPSP arrangement would be used, see 400W designs.

4.2. Specifics of 400W transformers design

The winding arrangement is PSP doubled, i.e. four parallel-connected primary winding’s layers and two parallel-connected secondary winding’s layers. The secondary layers are located between the 1$^{\text{st}}$ and the 2$^{\text{nd}}$, and the 3$^{\text{rd}}$ and the 4$^{\text{th}}$ primary layers, respectively (PSPPSP arrangement), Fig.1,c,d.
Table 2 contains the wire diameters and shows the influence of the eddy currents when increasing the frequency, presented by the coefficient $k_c$ [4]:

$$k_c = P_{\text{eddy}} (R_0 f_{\text{ac}}^2)$$  \hspace{1cm} (3)

| $f_{\text{op}}$ (kHz) | Design 1200W | Design 400W |
|-----------------------|--------------|--------------|
| Diameter of wires (mm)|              |              |
| P                    | 25 | 50 | 100 | 200 | 25 | 50 | 100 | 200 | 300 | 400 |
| 1.25                  | 1.12| 1.12| 1.4 |     | 0.315| 0.280| 0.400| 0.355| 0.400| 0.400 |
| 2x1.6                 |     |     |     |     | 1.000| 0.800| 1.120| 1.120| 1.250| 2x0.63 |
| S                    | 0.88| 1.514| 2.384 | 4.873| 0.005| 0.013| 0.205| 0.385| 0.400| 1.296 |
| 0.192                | 0.404| 0.952| 1.897 |     | 0.041| 0.059| 0.595| 1.331| 1.250| 0.817 |

5. Conclusion
The analysis of the discussed cases leads to the following design considerations:

- Increasing frequency influences strongly eddy currents losses. For example, in 1200W, 50kHz and 1200W, 100kHz designs the same wires are used, but $k_c$ is increased from 1.514 to 2.384 (primary winding) and from 0.404 to 0.9592 (secondary winding).
- At high powers the transformer design become more complicated as the currents are higher and the conductors’ diameters must have larger effective cross-sectional area.
- A way to reduce the eddy current losses is using thinner wires connected in parallel.
- In cases with interleaving, the best approach is all of the turns to fit in a single winding width.
- Interleaving windings provides significant reduction of eddy current and total losses.

References
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