Single-phase vs. Three-phase
High Power High Frequency Transformers

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Abstract

This thesis proposes one comparison methodology for single and three-phase high power high frequency transformers in power conversion systems. The objective is to compare the volume of the transformers. And single and three-phase Dual Active Bridge Converter (DAB1 and DAB3) topologies with single and three-phase isolating transformers are selected for the transformer comparison. Design optimization of power transformer has been studied and simplified models have been built for the single and three-phase transformer design optimization in this work, including assumptions for core shapes, materials, winding structures and thermal model. Two design methods have been proposed according to different design constraints, named T – B Method and J – B Method separately. T – B Method is based on feature of the core, which has the major limits of maximum flux density and temperature rise. The flux density should not reach the saturation value of the core, and temperature rise should meet specifications in different applications to assure the performance of the core (permeability, saturation flux density, and core loss) and the insulation of the wire. And J – B Method starts from the comparison of area product in conventional design method. The relationship between area product of transformer cores and the flux and current of the transformer in design is analyzed. There is specified relationship between area product of single and three-phase transformers if flux and
current densities are specified for both. Thus J – B Method is proposed with the design constraints of specified current and flux density. Both design methods include both single and three-phase transformer design.

One example case for single and three-phase transformer comparison is selected as high power high frequency DAB conversion system. Operation principles are studied for both DAB1 and DAB3 based on previous work. And transformer design based on the T – B and J – B Methods are carried out and transformer volumes are compared. And results show that three-phase transformer has little benefit in volume or thermal than single-phase transformer, when they are utilized in single-phase DAB and three-phase DAB converters separately. Scaled-down single and three-phase DAB systems have been built and volume and thermal tests have been carried out.
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Chapter 1. INTRODUCTION

1.1. Thesis Background

Transformer is widely used in power conversion systems because of its function of isolation and voltage regulation. And considering the big core needed to avoid flux saturation, low frequency (<100 Hz) transformers often dominate the volume and weight of the power system. In recent years, with the development of power systems on vehicles, ships and airplanes, (as shown in Figure 1-1) power density of the power system has become more and more important.

![Figure 1-1 Illustration of an All-electric Ship Power System](image)

To make the whole power converter smaller and lighter, transformer is one big problem. As one effective solution, the concept of power density improvement has been raised in recent years as solid-state power transformer, as shown below in Figure 1-2:

![Figure 1-2 Solid-state Power Transformer](image)
One example of the detailed circuit of the solid state power transformer is shown in the following Figure 1-3:[1-1]

![Figure 1-3 Detailed Circuit of a Solid State Power Transformer Example](image)

In it, solid-state devices help improve the operating frequency of the transformer from 50/60 Hz to tens or even hundreds of kilo Hz, which greatly decreases the flux density going thru the core of the transformer. And as a result, the volume and weight of the transformer can be reduced greatly, which improves the power density of the whole system.

1.2. Single and Three-phase Dual Active Bridge Converter

Based on the concept of solid-state power transformer, different topologies of the circuits have been proposed to further improve the power density of the power conversion system. [1-2][1-3][1-4]

The single-phase DAB topology shown in Figure 1-4 is first introduced in the 1980s. It has two full bridges on the two sides of a transformer. The leakage inductance of the transformer is used as energy storage and transfer component. It operates at a fixed frequency. Each full bridge generates a 50% duty cycle square
wave with certain phase shift. The energy flows from the leading side to the lagging side. The amount of energy is controlled by the phase shift angle. With this modulation scheme, the topology has a nature ZVS capability for both bridges. But it suffers hard switching while operating at very light load condition.

In 1989, one three-phase topology of dual active bridge (DAB) DC-DC converter has been proposed in [1-5] and compared with single-phase DAB topology.

Similarly, as shown in Figure 1-5 the leakage inductance of the three-phase transformer is used as energy storage and transfer component in the three-phase DAB converter. It also operates at a fixed frequency. The difference is at the bridge. There are three phase legs in three-phase DAB converter. And same with single-phase DAB converter, the upper and bottom switch each works at complementary 50% duty cycle.
There is a constant 120° phase shift angle between each of the three phase legs. The energy flows from the leading side to the lagging side. The amount of energy is controlled by the phase shift angle between the two sides. With this modulation scheme, the three-phase topology also has a nature ZVS capability for both bridges. And it also suffers hard switch while operating at very light load condition.

In [1-5], three-phase transformer is stated to have smaller apparent power, which is one key parameter representing the volume of the transformer, than single-phase transformer, when applied to same power rating cases. And later on, similar three or multi-phase transformer topologies have been raised with different kinds of modulation schemes, and compared with single-phase ones. [1-6][1-7]. Although in these works, three-phase solid-state power transformer design in DC/DC converter has been studied and verified with experiments in different topologies, work focusing on comparison of size of single and three-phase transformer based on the utilization benefit mentioned in [1-2] is quite limited. In [1-8][1-9], some tradeoff analysis of single and three-phase transformer has been carried out, but still the conclusion about volume comparison is not clearly claimed.

1.3. Thesis Objective and Outline

This thesis proposes a methodology for comparing the power density of single and three-phase high power high frequency transformers. To make the comparison fair, the thesis focuses on the optimization of the design of both single and three-phase at same application. And considering the difference in topologies for single and
three-phase transformers, attentions are paid on the equivalent comparison criteria in the operating point selection of the circuits.

Chapter 1 of this thesis details the application and motivations of this work while Chapter 2 focuses on the volume optimization methods for both single and three-phase transformer design, and Chapter 3 concentrates on a comparing example based on single and three-phase dual active bridge converters in high power high frequency applications. Chapter 4 describes the prototype experiments setup and some results for the comparison verifications. Finally, the conclusion and future work is summarized in Chapter 5.
Reference


Chapter 2. POWER TRANSFORMER DESIGN OPTIMIZATION

2.1. Introduction

2.1.1. Transformer Conventional Design

Transformer design includes the determination of a number of variables (core dimensions, wire gauge and turns number) and constraints from different aspects (electrical, magnetic, thermal and geometry). Traditionally, in conventional design, the first step is to select the core meeting the electrical, magnetic and geometric requirement of the design. Usually this requirement is quantified thru different constraints of the design, and related to one geometric factor of the core, like the $K_{gfe}$ method introduced in [2-1] and $K_e$ approach introduced in [2-2].

For example, in the $K_{gfe}$ method mentioned in [2-1], according to the optimum loss calculation, the minimum loss of the transformer can be expressed by the following equation, with both core geometric parameters and electrical / magnetic parameters:

$$P_{\text{tot}} \geq [A_c m K_{fe}] \left( \frac{2}{\beta+2} \right) \left[ \frac{\rho A_c^2 I_{\text{tot}}^2 (MLT)}{4 K_u W_A A_c^2} \right] \left( \frac{\beta}{\beta+2} \right) \left( \frac{\beta}{\beta+2} \right) + \left( \frac{\beta}{2} \right)^{2}$$

(2-1)

And by regrouping the equation, the geometric factor $K_{gfe}$ can be got from the inequality as below:

$$K_{gfe} = \frac{W_A (A_c)^{(2(\beta-1)/\beta)}}{(MLT)_{m}^{(2/\beta)}} \left[ \left( \frac{\beta}{2} \right)^{2} \right. + \left. \left( \frac{\beta}{2} \right)^{2} \right]$$

(2-2)

In the equation, $W_A$ is the window area of the core, and $A_c$ is the cross sectional
area of the core. \( MLT \) stands for the mean length per turn and \( l_m \) is the average length of the main flux path. They are all dimensional parameters of the core. \( \beta \) is the parameter of core loss calculation, which is simplified as 2.7 for most core materials. As a result, it is shown that \( K_{gfe} \) is one inherent parameter of the core and every core has its own \( K_{gfe} \).

And according to the minimum total loss calculation, this \( K_{gfe} \) should meet the following requirement:

\[
K_{gfe} \geq \frac{\rho \lambda_1^2 l_{tot}^2 K_{fe}^{2/\beta}}{4K_v \left( P_{tot} \right)^{(2+2)/\beta}} \tag{2-3}
\]

In transformer design, cores are selected according to this \( K_{gfe} \) value. Different \( K_{gfe} \)s of different cores are compared with the minimum required value, and the cores whose \( K_{gfe} \) meets the requirement are selected. When core is selected, winding turns number and wire sizes can all be determined, and with these values decided, the draft design of one transformer is completed.

The general procedure of the traditional design method is shown as below in Figure 2-1:
These traditional design methods are mainly for the initial design of a transformer. Since the core selection is based on one inequality, there is still room to further improve its power density by optimizing the core to hit the limit of the requirement thru design iteration.

In this work, single and three-phase transformer should be compared in equal conditions, which means the design of both single and three-phase transformers should be optimized equally. Thus a design optimization procedure is needed for both single and three-phase transformer.
2.1.2. Computer Aided Power Transformer Design Optimization

The iteration work of the core selection after the initial design is mainly traversal, which is time-consuming. Computer aided design method can be utilized in this case instead of working by hand. By using optimization techniques, the number of iteration can be reduced and there might be a better understanding of the tradeoff of variables.

The first utilization of digital computer in power transformer design and optimization is carried out in May, 1953, in Schenectady, N. Y. and then in Pittsfield, Mass., with IBM 701 and later IBM 706. [2-3]

The main idea of the optimization is to simplify the design of the transformer into one mathematic model. In the model, optimization objectives, design variables, design constraints, and specified boundaries for the variables should be involved.

The optimization objective of transformer design is decided by the application of the power transformer and specification of the design. Usually it can be the weight [2-12, 22, 28] and volume [2-6, 11, 13, 16, 18, 25] of the transformer, or the cost [2-7, 8, 14, 17, 19, 20, 23, 41], or sometimes the minimum loss [2-5, 10, 15, 27], or the combination of any of them [2-26, 29].

And the design constraints are from the limit of the magnetic, electrical and mechanical properties of the materials used in transformers. Usually the constraints include the maximum flux density, maximum allowable temperature rise and sometimes current density. From geometry view, there should be enough space for wires to be put in the window of the core, thus window area is always one constraint in optimization design. With different constraints, there will be different optimization
results for the transformer design.

The origin of design variables is the values to be determined in transformer design, for example the dimensions, shape and materials of the core, and winding size and arrangement. In design optimization, these values should be quantified and sometimes transformed into variables that are directly related to optimization objectives and constraints. Commonly, for volume, weight and cost optimization, the dimensions of the core and the number of turns are chosen as design variables [2-8, 11, 42], since it is straightforward that the objective can be easily expressed by these variables. Whatever variables are selected, the basic requirement is that they can involve all the design information of the transformer, which means that after deciding the variables with optimization calculation, with the selected variables, the transformer design can be completed.

In modeling the transformer, according to previous work, the main effort is on building up the relationship between variables and constraints, especially thermal and loss constraints.

For thermal model, empirical equations are utilized in [2-8, 23, 32, 37, 41]. And thermal models with detailed thermal resistances have been built in [2-6, 10, 11, 13, 22, 28, 29, 34].

Considering the core loss calculation, curve fitting from testing results and manufacturer’s datasheets is the main method. Different core material and operation conditions make the curve fitting equations different.

The accuracy of the winding or copper loss calculation is based on the estimation
of the AC resistance of the winding. Skin and proximity effects need to be considered for modeling. [2-5, 42]

With an already built transformer model, different algorithms can be utilized to find the best design among the alternatives. Classic gradient based algorithms are used in [2-6, 41]. And generic algorithms are more and more used in recent years, including [2-17, 21, 24, 30, 31, 33, 36, 38, 41]. One improved Particle Swarm Optimization method is used in [2-40]. And simulated annealing algorithm is used in [35].

To sum up, the design optimization of the power transformer can be generalized as below:

![Diagram of Computer Aided Power Transformer Design Optimization](image)

Figure 2-2 Computer Aided Power Transformer Design Optimization
As a sum of the models and algorithms, software has been built for power transformer design optimization as shown in [2-9, 14, 39].

2.1.3. Optimization Method in Present Work

For the present work, the volume is the optimization objective, and according to [2-42] and [2-8], the design variables are selected as the dimensions of the core and turns number. And for the calculation of the core loss, iGSE [2-43] is utilized for Ferrite material and WcSE [2-44] for nanocrystalline material. In the winding loss calculation, [2-45] is used. For the thermal model, a simplified one is utilized thru [2-2].

And since this work does not focus on the algorithm comparison, one classic gradient algorithm is utilized in MATLAB Tool box. It is called “trust-region-reflective” or “large-scale” [2-46].

In this chapter, effort is mainly on the modeling of the transformer for optimization design. Single and three-phase core type transformers are selected as an example. For single-phase transformer, two U cores are selected and combined with no air gap between the two cores. For each leg of the U core, half of the primary winding and half of the secondary winding are winded. And for three-phase transformer, two pieces of customized E cores are selected. In the customized E cores, the center posts are processed carefully to make sure all three legs have same width, as the main path of flux for each phase. And the primary and secondary windings of each phase are winded on each leg. The structure of the transformer is shown as
Two transformer design optimization models are described in detail, including the design variables, constraints and objectives, and boundaries of the transformer variables. One is set with the constraints of maximum temperature rise and flux density, named as T–B Method. And the other has the constraints of specified flux and current density, which can be called J–B Method.

2.2. T–B Design Method

One optimal design method with the constraints of maximum temperature rise and flux density is introduced. And considering its constraints T and B, this method is named T-B method in short. To minimize the volume, some assumptions are made to simplify the volume model of the transformer.

Firstly, the windings are assumed to be fully filled in the window area of the core, since whenever there is still room left in the window, the core size can be further decreased, so is the total volume of the transformer.

Secondly, to simplify the volume model of the transformer, assumptions are made
to simplify the arrangement of the winding as solid coil, as shown in the following two figures, for both single and three-phase transformers.

![Figure 2-5 Single-phase Transformer Simplified Volume Model](image)

Thus, as a result of the above assumptions, we can find that whenever the core is selected, the volume of the transformer can be determined. Here we define the four key parameters of the core as a, b, d and h, which separately stand for the width of the main flux path, the width of the window, the thickness of the core and half the height of the window of the transformer. The following figures show how these parameters are defined in single (U Cores) and three-phase transformer (E Cores).

![Figure 2-6 Dimension Variables Definition for Single-phase Transformer](image)  
![Figure 2-7 Dimensional Variables Definition for Three-phase Transformer](image)

Then, the volume of the transformer, together with the core and windings of both single and three-phase transformer can be expressed with these four parameters as
shown in the following table:

**Table 2-1 Single and Three-phase Transformer Dimension Characterization**

<table>
<thead>
<tr>
<th>Core Type Transformer</th>
<th>Single-phase</th>
<th>Three-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Sectional Area</td>
<td>( A_c = ad )</td>
<td>( A_c = ad )</td>
</tr>
<tr>
<td>Window area</td>
<td>( A_w = 2bh )</td>
<td>( A_w = 2bh )</td>
</tr>
<tr>
<td>Mean Length per Turn</td>
<td>( l_0 = 2(a + b + d) )</td>
<td>( l_0 = 2(a + b + d) )</td>
</tr>
<tr>
<td>Transformer width</td>
<td>( l_1 = 2a + 2b )</td>
<td>( l_1 = 3a + 3b )</td>
</tr>
<tr>
<td>Transformer thickness</td>
<td>( l_2 = d + b )</td>
<td>( l_2 = d + b )</td>
</tr>
<tr>
<td>Transformer height</td>
<td>( l_3 = 2a + 2h )</td>
<td>( l_3 = 2a + 2h )</td>
</tr>
<tr>
<td>Transformer volume</td>
<td>( V = l_1 \times l_2 \times l_3 )</td>
<td>( V = l_1 \times l_2 \times l_3 )</td>
</tr>
<tr>
<td>Core volume</td>
<td>( V_c = (2a + b)(2a + 2h)d - 2hbd )</td>
<td>( V_c = (3a + 2b)(2a + 2h)d - 4hbd )</td>
</tr>
<tr>
<td>Transformer thermal area</td>
<td>( A_t = 2(l_1l_2 + l_1l_3 + l_2l_3) )</td>
<td>( A_t = 2(l_1l_2 + l_1l_3 + l_2l_3) )</td>
</tr>
</tbody>
</table>

And the flux density of the core can be expressed as below:

\[
B_{\text{max}} = \frac{\sum V \times t}{N A_c} = \frac{V_{in}}{k_1 f N A_c} = \frac{V_{in}}{k_1 f N ad} \tag{2-4}
\]

The value of \( k_1 \) in the above equation is decided by the waveform of the voltage applied on the transformer. As a result, the flux density constraint can be expressed by the dimensional variables \( a, d \) and turns number, which can be simplified as:

\[
B_{\text{max}} = B(a, b, d, h, N) \tag{2-5}
\]

For the calculation of the core loss, considering both iGSE for Ferrite materials and WcSE for nanocrystalline materials, the expression of core loss can be generalized as below:
In the equation, B and Vcore can be expressed by the four dimensional variables a, b, d and h as well as turns number N. And K, α, β are core loss parameters from Steimetz Equation which can be found in core material datasheet. $k_2$ here stands for the waveform coefficient of the flux density. In iGSE, the core loss of each flux density waveform has one constant ratio against sinusoidal waveform value got from original Steinmetz Equation. In sum, the expression of core loss has only variables of a, b, d, h and N, which can also be simplified as:

$$P_{core} = P_{core}(a, b, d, h, N)$$  \[(2-7)\]

Similarly, the winding loss of the transformer can be modeled with the following equation:

$$P_{winding} = k_{AC} \times k_m \times \rho \frac{Nl_0}{W_A/Nk_w} = k_{AC}k_mk_w\rho N^2 \frac{l_0}{W_A}$$  \[(2-8)\]

In the equation, $k_{AC}$ is the AC resistance coefficient, which is a constant when frequency is set. $k_m$ stands for the coil numbers in the transformer, for single-phase transformer, the value is 2 and for three-phase, it is 6. $k_w$ is the fill factor of the window area. To make sure there is enough space for wires in the window, margins of fill factor are left and here $k_w$ is set to be 0.1 in the design. And $\rho$ in the equation means the electrical resistivity of copper wire, which is $23 \times 10^{-9} \Omega \cdot m$ at 100°C. According to the previous table, the mean length per turn of the winding and the window area can both be expressed by the dimensional variables a, b, d and h. As a result, the whole winding loss can be simplified as below:
According to the simplified thermal model mentioned in [2-2], the average temperature rise of the transformer can be expressed as below:

\[ T_{\text{rise}} = 450 \times \left( \frac{P_{\text{core}} + P_{\text{winding}}}{A_t} \right)^{0.826} \]  \hspace{1cm} (2-10)

Since the surface area is also one function of the dimensional variables a, b, d and h, the temperature rise can be summarized as below:

\[ T_{\text{rise}} = T_{\text{rise}}(a,b,d,h,N) \]  \hspace{1cm} (2-11)

As a result, the two constraints of the design, temperature rise and flux density can both be written as functions of the five common variables a, b, d, h and N. They should not exceed certain specified values as the maximum allowed temperature rise and flux density.

\[
\begin{cases}
B_{\text{max}} = B(a,b,d,h,N) \\
T_{\text{rise}} = T_{\text{rise}}(a,b,d,h,N)
\end{cases}
\]  \hspace{1cm} (2-12)

And the optimization objective volume is also the function of a, b, d and h.

\[ Volume = Volume(a,b,d,h) \]  \hspace{1cm} (2-13)

Thus the optimization function can be summarized as below:
Table 2-2 T – B Model for Transformer Design Optimization

<table>
<thead>
<tr>
<th>Optimization variables:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a, b, d, h, \text{ and } N)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimization Object:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization:</td>
</tr>
<tr>
<td>(V_{1\phi} = (2a + 2b)(d + b)(2a + 2h))</td>
</tr>
<tr>
<td>(V_{3\phi} = (3a + 3b)(d + b)(2a + 2h))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Constraints:</th>
</tr>
</thead>
</table>
| \(\begin{align*} 
B_{1\phi} &< B_{\text{max}} \\
T_{1\phi} &< T_{\text{max}} \\
B_{3\phi} &< B_{\text{max}} \\
T_{3\phi} &< T_{\text{max}}
\end{align*} \) |

Also to avoid the case like negative core flux path width in the optimization calculation, the dimensional variables \(a, b, d\) and \(h\) are set to be positive values. And considering the winding of turns, \(N\) is set to be positive integer. Besides, considering the shape of the core not to be too significant in one dimension, constraints are set to limit the ratios between the four dimensional variables. The following table collects all available E cores dimensions from MAGNETICS. And from the table, we can get the minimum and maximum values for the ratio among \(a, b, d\) and \(h\), which are shown as below:
Table 2-3 Core Dimensional Constraints

<table>
<thead>
<tr>
<th></th>
<th>Single-phase (UU)</th>
<th>Three-phase (EE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a/b)</td>
<td>[0.2, 0.9]</td>
<td>[0.9, 2.1]</td>
</tr>
<tr>
<td>(a/d)</td>
<td>[0.2, 1.8]</td>
<td>[0.4, 1.4]</td>
</tr>
<tr>
<td>(a/h)</td>
<td>[0.4, 1.1]</td>
<td>[0.4, 1.3]</td>
</tr>
<tr>
<td>(b/d)</td>
<td>[1, 3.5]</td>
<td>[0.4, 1.1]</td>
</tr>
<tr>
<td>(b/h)</td>
<td>[0.6, 3.2]</td>
<td>[0.3, 1.1]</td>
</tr>
<tr>
<td>(d/h)</td>
<td>[0.3, 2.9]</td>
<td>[0.5, 2]</td>
</tr>
</tbody>
</table>

With all the variables, constraints, and optimization objectives, the design can be solved thru math software like MATHWORK MATLAB optimization toolbox.

The optimization calculation leads to one optimal group of the turns number and four dimensional variables \(a, b, d\) and \(h\), which define the core, and which makes the volume of the transformer to be minimum. To complete the design of the transformer, what is left is the selection of the wire. The gauge of the wire is decided by the depth of the skin effect and the paralleling strands number is determined by the available window area of the core. The depth of the skin effect can be calculated as below:

\[
\delta = \sqrt{\frac{\rho}{\pi \mu \mu_0}}
\]  \hspace{1cm} (2-14)

In the equation, \(\rho\) is the resistivity of the conductor materials at operating temperature, copper or aluminum for example. And \(\mu\) stands for the permeability, for copper conductor,

\[
\mu = \mu_0 = 4\pi \times 10^{-7}
\]  \hspace{1cm} (2-15)

The radius of the wire should be no more than \(\delta\).
And when the wire is selected, and assume that the cross sectional area to be $s$. The paralleling strands number should be

$$x = \frac{k_u W_A}{k_m N_s}$$  \hspace{1cm} (2-16)

Then the transformer optimal design based on T – B Method is finished. The following figure shows the design result.

### 2.3. J – B Design Method

Similar with the T – B Design Method, here one other optimal design method for power transformer is introduced as J – B Design Method. The main difference of this method is the constraints settings. As previous section shows about conventional transformer design method, the area product often decides the size of the core, and if assuming the transformer volume can be defined by core size as assumed in T – B Method, that product directly decides the volume of the transformer. And the J – B Method is based on the comparison of the area product of the single and three-phase transformers. For single-phase transformer, the area product is defined as below:

$$A_{p1} = A_{s1} \times W_{Ai}$$  \hspace{1cm} (2-17)

And according to the handbook of transformer and inductor design, since there are two window areas and three cross sectional areas, the area product of three-phase core type transformer is defined as below:

$$A_{p3} = \frac{3}{2} \times A_{s3} \times W_{A3}$$  \hspace{1cm} (2-18)

Thus the comparison of single and three-phase transformer size can be referred to
the ratio of area product as below:

\[
\frac{A_{p1}}{A_{p3}} = \frac{A_{c1} \times W_{A1}}{\frac{3}{2} \times A_{c3} \times W_{A3}} \quad (2-19)
\]

Considering the relationship between flux density and cross sectional area, cross sectional area of single and three-phase transformer cores can be replaced by flux density in the above equation.

\[
B_{\text{max}} = \sum \frac{V \times t}{NA_c} = \frac{V_{\text{max}}}{k_1 fNA_c} \quad (2-20)
\]

Similarly, window area of the transformer can be represented by current density of the winding as the following equation shows:

\[
J_{\text{max}} = \frac{k_n NI}{k_n W_A} \quad (2-21)
\]

Then the product of flux and current density can be simplified as below:

\[
B_{\text{max}} J_{\text{max}} = \frac{k_n V_{\text{max}} l}{k_n k_1 f A_c W_A} = \frac{k}{A_c W_A} \quad (2-22)
\]

Thus the area product comparison for single and three-phase transformer can be changed into density product comparison as the following equation shows:

\[
\frac{A_{p1}}{A_{p3}} = \frac{A_{c1} \times W_{A1}}{\frac{3}{2} \times A_{c3} \times W_{A3}} = \frac{k_1}{B_{\text{max1}} J_{\text{max1}}} \times \frac{3}{2} \times \frac{k_3}{B_{\text{max3}} J_{\text{max3}}} = \frac{2}{3} \frac{k_1}{k_3} \frac{B_{\text{max3}} J_{\text{max3}}}{B_{\text{max1}} J_{\text{max1}}} \quad (2-23)
\]

Hence, we can find the volume comparison results of the single and three-phase transformer when the area product of the two transformers are set as we define the value of flux and current density for single and three-phase transformers. And the J – B Method is developed base on this idea. When flux and current densities are set as strict specifications for single and three-phase transformers, transformer volume can
be compared with the reference of area product comparison.

Similarly, the flux and current densities of the transformer are then expressed by the dimensional variables $a$, $b$, $d$, $h$ and turns number $N$. And the values of flux and current density should be equal to specified values. The optimization function can be summarized as below:

<table>
<thead>
<tr>
<th>Optimization variables:</th>
<th>$a$, $b$, $d$, $h$, and $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization Object:</td>
<td>Min.: $V_{1\phi} = (2a + 2b) \times (d + b) \times (2a + 2h)$ $V_{3\phi} = (3a + 3b) \times (d + b) \times (2a + 2h)$</td>
</tr>
<tr>
<td>Design Constraints:</td>
<td>$B_{1\phi} = \frac{V_{in}}{k_1 f N_1 A_{c1}} = B_{max1}$ $J_{1\phi} = \frac{k_m 1 N_1 I}{k_w A_{1}} = J_{max1}$ $B_{3\phi} = \frac{V_{in}}{k_3 f N_3 A_{c3}} = B_{max3}$ $J_{3\phi} = \frac{k_m 3 N_3 I}{k_w A_{3}} = J_{max3}$</td>
</tr>
</tbody>
</table>

And additional constraints also include the positive value of $a$, $b$, $d$, and $h$, the positive integer requirement of turns number and the relationship between the four dimensional variables to limit the shape of the core.

Further design also includes the selection of wire gauge and paralleling strand numbers. And in the J – B Method, after the design, the temperature rise of the transformer can also be checked.
Reference


Chapter 3. Single and Three-Phase Transformer Comparison in Dual Active Bridge Converters

3.1. Comparison Introduction

Dual Active Bridge Converter (DAB) is selected here for the comparison of single and three-phase transformer volume. In this chapter, the single and three-phase DAB are introduced firstly. Then, transformer comparison criteria for single and three-phase DAB are analyzed. And after that optimized single and three-phase transformers utilized in single and three-phase DAB converters are design and compared, with different methods mentioned in previous chapter.

3.2. Single-phase DAB Converter Analysis [3-1]

The single-phase DAB topology shown in Figure 3-1 is first introduced in the 1980s. It has two full bridges on the two sides of a transformer. The leakage inductance of the transformer is used as energy storage and transfer component. It operates at a fixed frequency. Each full bridge generates a 50% duty cycle square wave with certain phase shift. The energy flows from the leading side to the lagging side. The amount of energy is controlled by the phase shift angle. With this modulation scheme, the topology has a nature ZVS capability for both bridges. But it suffers hard switching while operating at very light load condition.
By referring the secondary side of the converter to the primary one, the simplified equivalent circuit can be found in Figure 3-2. In it, the transformer is replaced with its leakage inductance and the output voltage is \( V_o' = \frac{N_1}{N_2} V_o \). And according to this simplified circuit, the operating procedure of the circuit in one period can be divided into six steps in the waveforms of primary and secondary voltage, leakage inductance current and DC bus current in Figure 3-3, separated by different color plates. And Figure 3-4 shows the simulation result at 5000V, 20kHz, 250kW when primary and secondary resistances of the transformer can be neglected and the turns-ratio is 1:1. And the simulation circuit in Synopsis Saber is shown in Figure 3-5.
And the detailed six steps of operating are shown in the following circuits:
Step 1

Step 2

Step 3

Step 4

Step 5

Step 6

Figure 3-6 Detailed Six Steps of Single-phase DAB Operation Procedure

The positive directions of the primary and secondary currents are denoted red arrows. And according to Figure 3-6 we can get the circuit condition of every step in the following table:
Table 3-1 Circuit Conditions in Six Steps

<table>
<thead>
<tr>
<th>Conducting</th>
<th>Triggered</th>
<th>$L_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1, D_4, D_2', D_3'$</td>
<td>$T_1, T_4, T_2', T_3'$</td>
<td>Discharge</td>
</tr>
<tr>
<td>$T_1, T_4, T_2', T_3'$</td>
<td>$T_1, T_4, T_2', T_3'$</td>
<td>Charge</td>
</tr>
<tr>
<td>$T_1, T_4, D_1', D_4'$</td>
<td>$T_1, T_4, T_1', T_4'$</td>
<td>Charge</td>
</tr>
<tr>
<td>$D_2, D_3, D_1', D_4'$</td>
<td>$T_2, T_3, T_1', T_4'$</td>
<td>Charge</td>
</tr>
<tr>
<td>$T_2, T_3, T_1', T_4'$</td>
<td>$T_2, T_3, T_1', T_4'$</td>
<td>Discharge</td>
</tr>
<tr>
<td>$T_2, T_3, D_2', D_3'$</td>
<td>$T_2, T_3, T_1', T_4'$</td>
<td>Discharge</td>
</tr>
</tbody>
</table>

With the analysis above, we can get the expression of the leakage current as following: [3-1]

When $0 \leq \theta \leq \phi$

$$i(\theta) = i(0) + \frac{V_i(1+d)}{\omega L} \theta \tag{3-1}$$

In the equation, $\phi$ is the phase-shift angle between the two sides of the transformer, $L$ is the leakage inductance, and $d$ is the primary referred voltage gain which can be expressed as $d = \frac{V_2'}{V_i} = \frac{N_1}{N_2} \frac{V_2}{V_i}$.

When $\phi \leq \theta \leq \pi$

$$i(\theta) = i(\phi) + \frac{V_i(1-d)}{\omega L} (\theta - \phi) \tag{3-2}$$

And with $i(0) = -i(\pi)$, we can get

$$i(0) = \frac{V_i}{2\omega L} (\pi d - 2d\phi - \pi) \tag{3-3}$$

Assuming the transformer is ideal, which means the resistance is zero, we can get the output power
And the transformer apparent power can be written as:

\[
kVA_{r} = \frac{1}{2} (V_{pri}I_{pri} + V_{sec}I_{sec}) = V_{i}(d + 1)I_{rms}
\]  

(3-5)

To reach soft-switching mode of primary bridge, \(I(0)\) needs to be negative so that the leakage current can go thru anti-paralleling diodes for ZVS. And similarly, for the secondary bridge, \(I(\Phi)\) needs to be positive so that diodes are conducting when corresponding switches are triggered on. As a result, we can get the soft-switching boundary of the circuit as below:

\[
\begin{align*}
\phi &> \frac{\pi}{2}(1-d), d \leq 1 \\
\phi &> \frac{\pi}{2}(d-1), d > 1
\end{align*}
\]  

(3-6)

From the above equations, we find that the phase shift angle \(\phi\), leakage inductance \(L\), and the primary referred voltage gain \(d\) are the three important parameters to decide the operating points of the converter. And considering the output power equation, when the rated output power and operating frequency of the converter has been specified, the minimum leakage inductance needed for soft-switching can be expressed by the other two parameters \(\phi\), and \(d\) as shown below:

\[
L = \frac{V_{i}^{2}}{\omega P_{o}} d\phi[1-\frac{\phi}{\pi}]
\]  

(3-7)

Thus transformer apparent power, leakage inductance current and DC bus capacitor ripple current RMS values can all be expressed by the two variables of \(\phi\), and \(d\). The distribution of these values can be plotted as shown in the following
figures at the case when output power is 250kW, operating frequency is 20kHz, and both input and load voltage is 5000V.

![Figure 3-7 Transformer kVA at Different Points](image1)

![Figure 3-8 Leakage Current at Different Points](image2)

![Figure 3-9 Sum of DC Bus Cap Currents](image3)

![Figure 3-10 Soft-switching Boundaries](image4)

### 3.3. Three-phase DAB Converter Analysis [3-1]

Similarly, as shown in Figure 3-11 the leakage inductance of the three-phase transformer is used as energy storage and transfer component in the three-phase DAB converter. It also operates at a fixed frequency. The difference is at the bridge. There are three phase legs in three-phase DAB converter. And same with single-phase DAB converter, the upper and bottom switch each works at complementary 50% duty cycle.
There is a constant 120° phase shift angle between each of the three phase legs. The energy flows from the leading side to the lagging side. The amount of energy is controlled by the phase shift angle between the two sides. With this modulation scheme, the three-phase topology also has a nature ZVS capability for both bridges. And it also suffers hard switch while operating at very light load condition.

Similar with single-phase DAB converter, by referring the secondary side of the converter to the primary one, the simplified equivalent circuit can be found in Figure 3-12. In it, the transformer is replaced with its leakage inductance and the output voltage is \( V'_o = \frac{N}{N_2} V_o \). And according to this simplified circuit, the operating procedure of the circuit in one period can also be divided into steps. But there is a difference in waveforms when phase shift angle is below and above 60°. With the same assumption that the primary and secondary resistances of the transformer can be neglected, in Figure 3-13, it is obvious that the waveforms of the leakage inductance current and DC bus current are different when \( \phi < 60^\circ \) and when \( \phi > 60^\circ \) because of the different overlap of primary and secondary voltage waveform. Simulation has been carried out using Synopsis SABER and similar results are found in the following
figure. As an example, the DAB works at 250kW, 20kHz and 5kV. The phase shift angle is 31.8° and 76.5° separately.

Figure 3-13 Waveforms of Three-phase DAB
The detailed 18 steps when $\phi < 60^\circ$ are shown in the following circuits in the following figures.
The positive directions of the primary and secondary currents are denoted with colorful arrows. And according to Figure 3-15, we can get the circuit condition of every step in the following table:
### Table 3-2 Circuit Conditions in 18 Steps

<table>
<thead>
<tr>
<th>( I_A )</th>
<th>( I_B )</th>
<th>( I_C )</th>
<th>( I_i )</th>
<th>( I_o' )</th>
<th>Conducting</th>
<th>Triggered</th>
<th>Charge</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>( I_A + I_C )</td>
<td>( I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C )</td>
<td>( L_A, L_B )</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>( I_A + I_C )</td>
<td>( I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_A )</td>
<td>( L_B )</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>( I_A + I_C )</td>
<td>( I_A + I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_A )</td>
<td>( L_B )</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>( I_A )</td>
<td>( I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_A )</td>
<td>( L_B )</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>( I_A )</td>
<td>( I_A + I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A )</td>
<td>( L_C, L_B )</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>( I_A )</td>
<td>( I_A )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A )</td>
<td>( L_C, L_B )</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>( I_A + I_B )</td>
<td>( I_A )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A )</td>
<td>( L_C, L_B )</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>( I_A + I_B )</td>
<td>( I_A )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A, L_B )</td>
<td>( L_C )</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>( I_A + I_B )</td>
<td>( I_A + I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A, L_B )</td>
<td>( L_C )</td>
</tr>
<tr>
<td>10</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>( I_B )</td>
<td>( I_A + I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_A, L_B )</td>
<td>( L_C )</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>( I_B )</td>
<td>( I_A + I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_B )</td>
<td>( L_A, L_C )</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>( I_B )</td>
<td>( I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_B )</td>
<td>( L_A, L_C )</td>
</tr>
<tr>
<td>13</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>( I_B + I_C )</td>
<td>( I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_B )</td>
<td>( L_A, L_C )</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>( I_B + I_C )</td>
<td>( I_B )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_B )</td>
<td>( L_A )</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>( I_B + I_C )</td>
<td>( I_B + I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_B )</td>
<td>( L_A )</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>( I_C )</td>
<td>( I_B + I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C, L_B )</td>
<td>( L_A )</td>
</tr>
<tr>
<td>17</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>( I_C )</td>
<td>( I_B + I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C )</td>
<td>( L_A, L_B )</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>( I_C )</td>
<td>( I_C )</td>
<td>( T_1, T_3, T_5, T_2', T_4', T_5' )</td>
<td>( L_C )</td>
<td>( L_A, L_B )</td>
</tr>
</tbody>
</table>
According to the equivalent circuit in Figure 3-12 and the waveforms in Figure 3-13 and Figure 3-14, we can get the expression of the leakage current as following [3-1]:

Mode 1: \(0 < \phi < \frac{\pi}{3}\)

When \(0 < \theta < \phi\)

\[
I_{a1}(\theta) = \frac{(1+d)V_i}{3\omega L}(\theta + i(0))
\] (3-8)

When \(\phi < \theta < \frac{\pi}{3}\)

\[
I_{a2}(\theta) = \frac{(1-d)V_i}{3\omega L}(\theta - \phi) + i(\phi)
\] (3-9)

When \(\frac{\pi}{3} < \theta < \frac{\pi}{3} + \phi\)

\[
I_{a3}(\theta) = \frac{(2-d)V_i}{3\omega L}(\theta - \frac{\pi}{3}) + i(\frac{\pi}{3})
\] (3-10)

When \(\frac{\pi}{3} + \phi < \theta < \frac{2\pi}{3}\)

\[
I_{a4}(\theta) = \frac{(2-d)V_i}{3\omega L}(\theta - \frac{\pi}{3} - \phi) + i(\frac{\pi}{3} + \phi)
\] (3-11)

When \(\frac{2\pi}{3} < \theta < \frac{2\pi}{3} + \phi\)

\[
I_{a5}(\theta) = \frac{(1-2d)V_i}{3\omega L}(\theta - \frac{2\pi}{3}) + i(\frac{2\pi}{3})
\] (3-12)

When \(\frac{2\pi}{3} + \phi < \theta < \pi\)

\[
I_{a6}(\theta) = \frac{(1-d)V_i}{3\omega L}(\theta - \frac{2\pi}{3} - \phi) + i(\frac{2\pi}{3} + \phi)
\] (3-13)
And with \( i(\pi) = -i(0) \), we can get the output power expression as:

\[
P_o = \frac{V_i^2}{\omega L} d\phi \left[ \frac{2}{3} - \frac{\phi}{2\pi} \right]
\]

Mode 2: \( \frac{\pi}{3} < \phi < \frac{\pi}{2} \)

When \( 0 < \theta < \phi - \frac{\pi}{3} \)

\[
I_{a1}(\theta) = \frac{(1 + 2d)V_i}{3\omega L} \theta + I_a(0)
\]

(3-15)

When \( \phi - \frac{\pi}{3} < \theta < \frac{\pi}{3} \)

\[
I_{a2}(\theta) = \frac{(1 + d)V_i}{3\omega L} (\theta - \phi + \frac{\pi}{3}) + i(\phi - \frac{\pi}{3})
\]

(3-16)

When \( \frac{\pi}{3} < \theta < \phi \)

\[
I_{a3}(\theta) = \frac{(2 + d)V_i}{3\omega L} (\theta - \frac{\pi}{3}) + i(\frac{\pi}{3})
\]

(3-17)

When \( \phi < \theta < \frac{2\pi}{3} \)

\[
I_{a4}(\theta) = \frac{(2 - d)V_i}{3\omega L} (\theta - \phi) + i(\phi)
\]

(3-18)

When \( \frac{2\pi}{3} < \theta < \frac{\pi}{3} + \phi \)

\[
I_{a5}(\theta) = \frac{(1 - d)V_i}{3\omega L} (\theta - \frac{2\pi}{3}) + i(\frac{2\pi}{3})
\]

(3-19)

When \( \frac{\pi}{3} + \phi < \theta < \pi \)
\[I_{a6}(\theta) = \frac{(1-2d)V_i}{3\omega L}(\theta - \frac{\pi}{3} - \phi) + i(\frac{\pi}{3} + \phi) \quad (3-20)\]

And with \(i(\pi) = -i(0)\), we can get the output power expression as:

\[P_o = \frac{V^2}{\omega L}d[\phi - \frac{\pi}{18} - \frac{\phi^2}{\pi}] \quad (3-21)\]

And the 3\(\Phi\) transformer apparent power can be written as

\[kVA_r = \frac{1}{2}(V_{pri}I_{pri} + V_{sec}I_{sec}) = \frac{V_i(d + 1)I_{rms}}{\sqrt{2}} \quad (3-22)\]

To reach soft-switching mode of primary bridge, \(I(0)\) needs to be negative so that the leakage current can go thru anti-parallel diodes for ZVS. And similarly, for the secondary bridge, \(I(\phi)\) needs to be positive so that diodes are conducting when corresponding switches are triggered on. As a result, we can get the soft-switching boundary of the circuit as below:

When in Mode 1 \(0 < \phi < \frac{\pi}{3}\):

\[1 - \frac{3\phi}{2\pi} < d < \frac{1}{1 - \frac{3\phi}{2\pi}} \quad (3-23)\]

When in Mode 2 \(\frac{\pi}{3} < \phi < \frac{\pi}{2}\):

\[\frac{3}{2} - \frac{3\phi}{\pi} < d < \frac{1}{\frac{3}{2} - \frac{3\phi}{\pi}} \quad (3-24)\]

Similar with the single-phase case, we can also define the three variables: phase shift angle \(\phi\), leakage inductance \(L\), and the primary referred voltage gain \(d\) to demonstrate all possible operating points of the three-phase DAB converter. And considering the following equation, when the phase shift angle is below 60°, we have:
\[ L = \frac{V_i^2}{\omega P_o} \, d\phi \left[ \frac{2}{3} - \frac{\phi}{2\pi} \right] \]  \hspace{1cm} (3-25)

And when the phase shift angle is over 60°, we have:

\[ L = \frac{V_i^2}{\omega P_o} \, d\left[ \phi - \frac{\pi}{18} - \frac{\phi^2}{\pi} \right] \]  \hspace{1cm} (3-26)

Thus the three-phase transformer apparent power, leakage inductance current and DC bus capacitor ripple current RMS values can all be expressed by the two variables of \( \phi \) and \( d \). The distribution of these values can be plotted as shown in the following figures at the case when output power is 250kW, operating frequency is 20kHz, and both input and load voltage is 5000V.

Figure 3-16 Transformer kVA at Different Points
Figure 3-17 Leakage Current at Different Points
Figure 3-18 Sum of Bus Cap Currents
Figure 3-19 Soft-switching Boundaries
### 3.4. Single and Three-phase Transformer Comparison Criteria

As a summary of the single and three-phase DAB converter, the following table is built:

Table 3-3 Single and Three-phase DAB Converter Operating Principles Comparison

<table>
<thead>
<tr>
<th></th>
<th>1Φ DAB</th>
<th>3Φ DAB (0°&lt;Φ&lt;60°)</th>
<th>3Φ DAB (60°&lt;Φ&lt;90°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_o )</td>
<td>( P_o = V_o I_o = V I_0 \frac{V^2}{\omega L} \left[ 1 - \frac{\phi}{\pi} \right] )</td>
<td>( P_o = \frac{V^2}{\omega L} \left( \frac{2}{3} - \frac{\phi}{2\pi} \right) )</td>
<td>( P_o = \frac{V^2}{\omega L} \left[ \phi - \frac{\pi}{18} \frac{\phi^2}{\pi} \right] )</td>
</tr>
<tr>
<td>( I_o )</td>
<td>( i(\theta) = i(0) + \frac{V(1+d)}{\omega L} \theta )</td>
<td>( I_{o1}(\theta) = \frac{(1+d)V}{3\omega L} \theta + I_o(0) )</td>
<td>( I_{o1}(\theta) = \frac{(1+d)V}{3\omega L} \theta + I_o(0) )</td>
</tr>
<tr>
<td>( I_L )</td>
<td>( i(\phi) + \frac{V(1-d)}{\omega L} (\theta - \phi) )</td>
<td>( I_{o2}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o2}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
</tr>
<tr>
<td>( I_{o1}(\theta) = \frac{(1+d)V}{3\omega L} \theta + i(\phi) )</td>
<td>( I_{o2}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o2}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td></td>
</tr>
<tr>
<td>( I_{o3}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o3}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o3}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td></td>
</tr>
<tr>
<td>( I_{o4}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o4}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td>( I_{o4}(\theta) = \frac{(1-d)V}{3\omega L} (\theta - \phi) + i(\phi) )</td>
<td></td>
</tr>
</tbody>
</table>

To get transformer of single and three-phase DAB circuit fairly compared, equivalent operating points for these two topologies should be found. According to the basic application of DAB circuits and high efficient operating criteria, assumptions have been made as below:

1) Same transferred power, and same operating frequency, input and load voltage;

2) Both converters work in soft-switching area;

3) Same working efficiency when transformer loss is not considered.
Due to ZVS turn on and near zero current turn off [3-3] for high efficiency operating, switching loss can be neglected in the comparison. Thus the efficiency of the circuit is totally decided by conducting loss of the switches. Here, from the cost view, we assume both single and three-phase DAB converter having same total amount of die in their switching devices. Since the input and load voltages are the same for both two circuits, the thickness of the die should be the same. As a result of the different device numbers, the cross sectional area of the die in single-phase DAB converter should be 1/3 larger than the three-phase one, as shown below, in which switches are replaced by modular devices with same die area. [3-2]

Thus with this assumption, the turn-on resistance of the switches in these two topologies can be compared as below:
\[
\begin{align*}
R_{1\phi} &= \rho \frac{l}{S_{1\phi}} \\
R_{3\phi} &= \rho \frac{l}{S_{3\phi}} = \rho \frac{2}{3} \frac{l}{S_{1\phi}} = \frac{3}{2} R_{1\phi}
\end{align*}
\] (3-27)

And the conducting loss of the two topologies can be shown as below:

\[
\begin{align*}
P_{1\phi} &= I_{1\phi}^2 R_{1\phi} \times 8 \\
P_{3\phi} &= I_{3\phi}^2 R_{3\phi} \times 12 = I_{3\phi}^2 R_{1\phi} \times \frac{3}{2} \times 12 = I_{3\phi}^2 R_{1\phi} \times 18
\end{align*}
\] (3-28)

With the assumption \( P_{1\phi} = P_{3\phi} \) we can get the ratio of the switching current of the two topologies:

\[
\frac{I_{1\phi}}{I_{3\phi}} = \frac{3}{2}
\] (3-29)

From the operating point’s distribution study, we find that the relatively high power density and high efficiency working conditions are gathering around the area when \( d=1 \) and phase shift angle is around 30° to 40°. The red circle areas in the following zooming in Figure 3-22 and Figure 3-23 show the preferred working area for both the single and three-phase DAB converters.

As a result, with the above assumptions of \( d, \phi \) and current ratio, we can get comparable operating point for three-phase DAB converter when single-phase point is selected, and vice versa. For example, when the output power is 250kW and operating frequency is 20kHz, we can firstly select one operating point for the single-phase DAB converter, in the area of the red circle, as shown below:
And at that point, the phase shift angle $\phi$ is 30.6°, the primary referred voltage gain is 1, and the leakage inductance current is 56.72A. From the above equation about single-phase DAB output power, we can get the leakage inductance as
352.75µH. Thus the current of the three-phase DAB converter should be 37.81A. And with a 2% revolution, we can get those red spots as the points when the current is OK. And further selecting the point when $d=1$, we can get the corresponding three-phase operating point as Figure 3-25. The operating points of the two topologies can be shown in the following Table 3-4 and the summary of topology comparison criteria is shown in Table 3-5.

Table 3-4 Case Study for Single and Three-phase DAB Comparison

<table>
<thead>
<tr>
<th></th>
<th>DAB1</th>
<th>DAB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_o$</td>
<td>250kW</td>
<td>250kW</td>
</tr>
<tr>
<td>$F$</td>
<td>20kHz</td>
<td>20kHz</td>
</tr>
<tr>
<td>$V_i$</td>
<td>5000V</td>
<td>5000V</td>
</tr>
<tr>
<td>$V_o$</td>
<td>5000V</td>
<td>5000V</td>
</tr>
<tr>
<td>$I_{L_{rms}}$</td>
<td>56.72A</td>
<td>37.81A</td>
</tr>
<tr>
<td>$N_1:N_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_{lk}$</td>
<td>352.75µH</td>
<td>255.43µH</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>30.6°</td>
<td>31.8°</td>
</tr>
</tbody>
</table>

Table 3-5 Topology Comparison Assumptions Summary

\[
\begin{array}{|c|c|c|}
\hline
0^\circ<\Phi_{\text{DAB3}}<60^\circ & 60^\circ<\Phi_{\text{DAB3}}<90^\circ \\
\hline
P_o & \left(\frac{V_i^2}{\omega L} \cdot \left(1 - \frac{\phi}{\pi}\right)\right)_{1g} = \left(\frac{V_i^2}{\omega L} \cdot \left(1 - \frac{\phi}{\pi}\right)\right)_{3g} = \left(\frac{V_i^2}{\omega L} \cdot \left(1 - \frac{\phi}{\pi}\right)\right)_{3g} = \left(\frac{V_i^2}{\omega L} \cdot \left(1 - \frac{\phi}{\pi}\right)\right)_{3g} \\
I_{L_{rms,1g}} & I_{L_{rms,3g}} = \frac{1}{3} \\
& \frac{N_{1,3g}}{N_{2,3g}} = \frac{V_i}{V_o} = 1 \\
& I_{L_{rms,1g}} / I_{L_{rms,3g}} = 3/2 \\
\hline
\end{array}
\]
From previous analysis, as shown in Figure 3-3 and Figure 3-4, the voltage applied on the two terminals of the single-phase transformer is a square waveform. And for three-phase DAB converter in our study, the transformer is Y-Y connected as shown in Figure 3-24. And the voltage waveforms in Figure 3-13 and Figure 3-14 are the voltage between the mid-point of each phase leg and the neutral point.

![Figure 3-24 Three-phase Y-Y Connection](image)

According to the waveforms of single and three-phase DAB converter, we can get the voltage RMS value applied on transformers in single and three-phase transformer as:

\[
\frac{V_{i\phi}}{V_{3\phi}} = \frac{3}{\sqrt{2}}
\]  

(3-30)

And based on the equation that \( \frac{I_{1\phi}}{I_{3\phi}} = \frac{3}{2} \), for the comparison of apparent power applied on transformers, we get:
\[
\frac{kVA_{1\Phi}}{kVA_{3\Phi}} = \frac{V_{1\Phi} \times I_{1\Phi}}{3 \times V_{3\Phi} \times I_{3\Phi}} = \frac{3}{2\sqrt{2}} \approx 1.06
\]  
(3-31)

From kVA view, three-phase transformer is a little bit smaller than single-phase one, about 6%, if the apparent power of the transformer can generally stand for the volume, as experience goes. This is the benefit of applying three-phase DAB converter and transformer, from topology comparison view.

3.5. Transformer Comparison with T – B Method Design

Case study has also been carried out at 20kHz, 250kW, 5000V. And the maximum allowed temperature is 100°C while the maximum allowed flux density is 0.5T. The design results can be found below:

Table 3-6 20 kHz, 250 kW, 5 kV T-B Model Design Results - Temperature Rise Limit

<table>
<thead>
<tr>
<th></th>
<th>1Φ</th>
<th>3Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume (inch³)</strong></td>
<td>720.2</td>
<td>634.3</td>
</tr>
<tr>
<td><strong>B_{max} (T)</strong></td>
<td>0.2773</td>
<td>0.3234</td>
</tr>
<tr>
<td><strong>J_{max} (A/cm²)</strong></td>
<td>427.1</td>
<td>425.5</td>
</tr>
<tr>
<td><strong>Temp. Rise (°C)</strong></td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Core Loss (W)</strong></td>
<td>284.8</td>
<td>251.3</td>
</tr>
<tr>
<td><strong>Winding Loss (W)</strong></td>
<td>282.2</td>
<td>249</td>
</tr>
<tr>
<td><strong>Total Loss (W)</strong></td>
<td>567</td>
<td>500.3</td>
</tr>
<tr>
<td><strong>Turns Number</strong></td>
<td>33</td>
<td>53</td>
</tr>
<tr>
<td><strong>a (mm)</strong></td>
<td>52.8</td>
<td>57.1</td>
</tr>
<tr>
<td><strong>b (mm)</strong></td>
<td>58.6</td>
<td>64.7</td>
</tr>
<tr>
<td><strong>d (mm)</strong></td>
<td>58.6</td>
<td>64.7</td>
</tr>
<tr>
<td><strong>h (mm)</strong></td>
<td>97.7</td>
<td>107.8</td>
</tr>
</tbody>
</table>
From the table we find that the three-phase transformer is more bulky than single-phase one at the condition when the temperature rise has reached the limit but the flux density not.

Another calculation has also been carried out when setting the allowable flux density to be as small as 0.2T. The result is shown as below:

Table 3-7 20 kHz, 250 kW, 5 kV T-B Model Design Results - Flux Density Limit

<table>
<thead>
<tr>
<th></th>
<th>3Φ</th>
<th>1Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (inch$^3$)</td>
<td>1146.5</td>
<td>1270.6</td>
</tr>
<tr>
<td>$B_{\text{max}}$ (T)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$J_{\text{max}}$ (A/cm$^2$)</td>
<td>359.0</td>
<td>301.9</td>
</tr>
<tr>
<td>Temp. Rise (°C)</td>
<td>72.31</td>
<td>59.37</td>
</tr>
<tr>
<td>Core Loss (W)</td>
<td>255.6</td>
<td>206.4</td>
</tr>
<tr>
<td>Winding Loss (W)</td>
<td>253.3</td>
<td>204.6</td>
</tr>
<tr>
<td>Total Loss (W)</td>
<td>508.9</td>
<td>411</td>
</tr>
<tr>
<td>Turns Number</td>
<td>26.36</td>
<td>43.67</td>
</tr>
<tr>
<td>$a$ (mm)</td>
<td>68.5</td>
<td>80.3</td>
</tr>
<tr>
<td>$b$ (mm)</td>
<td>76.1</td>
<td>89.2</td>
</tr>
<tr>
<td>$d$ (mm)</td>
<td>76.1</td>
<td>89.2</td>
</tr>
<tr>
<td>$h$ (mm)</td>
<td>73.7</td>
<td>92.0</td>
</tr>
</tbody>
</table>

From the table we find that the temperature rise has not reached the limit, but the flux density. In this case, three-phase transformer is smaller than single-phase, but with a higher temperature rise, which is identical with the previous J-B Model result.

Further exploration makes both flux density and temperature rise reach the limit,
which produces the results as below:

Table 3-8 20 kHz, 250 kW, 5 kV T-B Model Design Results - Both Temperature Rise and Flux Density Limit

<table>
<thead>
<tr>
<th></th>
<th>3Φ</th>
<th>1Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (inch$^3$)</td>
<td>810.2</td>
<td>782.9</td>
</tr>
<tr>
<td>$B_{\text{max}}$ (T)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$J_{\text{max}}$ (A/cm$^2$)</td>
<td>506.0</td>
<td>520.6</td>
</tr>
<tr>
<td>Temp. Rise ($°C$)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Core Loss (W)</td>
<td>167.7</td>
<td>120.7</td>
</tr>
<tr>
<td>Winding Loss (W)</td>
<td>445.6</td>
<td>455.8</td>
</tr>
<tr>
<td>Total Loss (W)</td>
<td>613.3</td>
<td>576.5</td>
</tr>
<tr>
<td>Turns Number</td>
<td>41.48</td>
<td>72.88</td>
</tr>
<tr>
<td>$a$ (mm)</td>
<td>54.9</td>
<td>62.1</td>
</tr>
<tr>
<td>$b$ (mm)</td>
<td>61</td>
<td>69</td>
</tr>
<tr>
<td>$d$ (mm)</td>
<td>61</td>
<td>69</td>
</tr>
<tr>
<td>$h$ (mm)</td>
<td>101.7</td>
<td>115</td>
</tr>
</tbody>
</table>

From the table we find that three-phase transformer has almost the same volume with single-phase transformer, only about 2% larger in our example.

3.6. Transformer Comparison with J – B Method Design

After the operation point selection shown in Table 3-9 we select the maximum current density from 100A/cm$^2$ to 500A/cm$^2$, and maximum flux density from 0.3T to 0.7T.
### Table 3-9 Single and Three-phase DAB Operating Point Comparison

<table>
<thead>
<tr>
<th></th>
<th>1Φ DAB</th>
<th>3Φ DAB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input DC Voltage</strong></td>
<td>5000V</td>
<td>5000V</td>
</tr>
<tr>
<td><strong>Output DC Voltage</strong></td>
<td>5000V</td>
<td>5000V</td>
</tr>
<tr>
<td><strong>Turns Ratio</strong></td>
<td>1:1</td>
<td>1:1</td>
</tr>
<tr>
<td><strong>Transformer Input RMS Current</strong></td>
<td>56.72A</td>
<td>37.81A</td>
</tr>
<tr>
<td><strong>Leakage Inductance</strong></td>
<td>352.75uH</td>
<td>255.43uH</td>
</tr>
<tr>
<td><strong>Phase Shift Angle</strong></td>
<td>30.6°</td>
<td>31.8°</td>
</tr>
</tbody>
</table>

The optimization has been conducted at these \((B_{max}, J_{max})\) and the design results are shown as below:

![Figure 3-25 Volume Distribution at J-B Model](image-url)
From Figure 3-25 we find that with the same current and flux density, three-phase transformer is smaller than single-phase one. But at the same time, there will be penalty of higher temperature rise shown in Figure 3-26. The detailed data comparison can be found in the following two bar charts:
This difference in temperature rise might be caused by the different voltage waveforms applied on the two transformers, as shown below:

The quasi-sinusoidal waveform of flux density in three-phase transformer will bring more core loss than triangular waveform in single-phase transformer, according to previous study of core loss prediction.

### 3.7. Transformer Comparison Conclusion

From the J-B Model and T-B Model Design results, we can get a general conclusion that three-phase transformer has little benefit in size comparing with
single-phase transformer, in DAB converter systems. When same boundary of temperature rise has been reached for both single and three-phase transformer, three-phase transformer is larger than single-phase transformer. And when same flux and current density limits have been reached, three-phase transformer is a little smaller, but has higher temperature rise.
Reference

High-Power-Density dc/dc Converter for High-Power Applications”, IEEE


Chapter 4. EXPERIMENTAL VERIFICATION

4.1. Scaled Down Prototype DAB System Design

4.1.1. DAB1 and DAB3 Operating Point Calculation

Considering the available experiment conditions, one scaled down prototype DAB system (300 V, 20 kHz, 1 kW) is built for preliminary verification of the single and three-phase transformer comparison.

According to the operating points selection criteria described in Chapter 3, the single and three-phase DAB converters are designed as below:

<table>
<thead>
<tr>
<th></th>
<th>Single-phase DAB</th>
<th>Three-phase DAB</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Input DC Voltage</em></td>
<td>300V</td>
<td>300V</td>
</tr>
<tr>
<td><em>Output DC Voltage</em></td>
<td>180V</td>
<td>180V</td>
</tr>
<tr>
<td><em>Turns Ratio</em></td>
<td>1:1</td>
<td>1:1</td>
</tr>
<tr>
<td><em>Transformer Input RMS Current</em></td>
<td>2.26A</td>
<td>1.50A</td>
</tr>
<tr>
<td><em>Leakage Inductance</em></td>
<td>580uH</td>
<td>580uH</td>
</tr>
<tr>
<td><em>Phase Shift Angle</em></td>
<td>42°</td>
<td>60°</td>
</tr>
</tbody>
</table>
4.1.2. DAB Converter Power Stage Design

As shown in Figure 4-1, the power stage of the DAB system is based on two integrated IGBT power modules. One XILINX and SHARC ADSP-based “CPES Universal Controller” is used to provide gate signals for the two power modules. In open-loop operation, FPGA generates PWM gate signals and DSP adds constant duty cycle of 50%, 2μs dead time, and constant phase-shift-angle between the two power modules. And one AD Conversion board from CPES is used for protection. The primary and secondary DC currents and DC voltages are sensed, converted into digital signal and sent into Universal Controller for protection. The detailed introduction of the “CPES Universal Controller” and “CPES AD Conversion Board”,

Figure 4-1 System Diagram of Hardware Test
as well as the integrated power module can be found in Appendix. Since there are 6 IGBTs in one power module, this IPM-based system can either be treated as a single-phase DAB system when two phase-legs are activated in either power module or three-phase DAB converter when all three phase-legs are activated in both power modules. For single-phase DAB operation mode, the phase-shift-angle between the two activated phase-legs in one power module is set as 180° from DSP. And for three-phase DAB operation mode, the phase-shift-angle between each two phase-leg of one power module is set as 120°. The DC link capacitor is selected as 0.68µF and the load resistor is set as 90Ω. Since the design and fabrication procedures do not include the leakage inductance, here the 580µF inductance for energy transfer and storage is winded independently with Ferrite cores and solid wires. For single-phase DAB operation, one inductor is in series with the transformer and in three-phase DAB operation, three inductors are in series with the three phases of the transformer. The following picture shows the connection of the power stage without transformers.
4.1.3. Prototype Transformer Design Optimization and Fabrication

With the constraint of the experiment conditions, completely customized cores from design optimization are not available, and as a result, the specified flux and current density requirement in J – B Method cannot be met. Hence, as a preliminary test and verification, focus is on the T – B Method. The optimum design based on T – B Method can be conducted for both single and three-phase transformers. And the available commercial cores which are most close to these two optimized design results are selected as the sample transformers for comparison. And the temperature rise of the two selected sample transformers can be calculated based on the thermal model utilized in the optimum design.

The following table shows the optimum design based on T – B Method for single and three-phase transformers.
Table 4-2 Test Transformer Design Optimization

<table>
<thead>
<tr>
<th></th>
<th>3Φ</th>
<th>1Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume (inch$^3$)</strong></td>
<td>5.38</td>
<td>5.21</td>
</tr>
<tr>
<td><strong>$B_{max}$ (T)</strong></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>$J_{max}$ (A/cm$^2$)</strong></td>
<td>771.2</td>
<td>791.9</td>
</tr>
<tr>
<td><strong>Temp. Rise (°C)</strong></td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Core Loss (W)</strong></td>
<td>2.49</td>
<td>1.79</td>
</tr>
<tr>
<td><strong>Winding Loss (W)</strong></td>
<td>6.88</td>
<td>7.02</td>
</tr>
<tr>
<td><strong>Total Loss (W)</strong></td>
<td>9.37</td>
<td>8.81</td>
</tr>
<tr>
<td><strong>Turns Number</strong></td>
<td>47</td>
<td>82</td>
</tr>
<tr>
<td><strong>a (mm)</strong></td>
<td>10.3</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>b (mm)</strong></td>
<td>11.5</td>
<td>13.0</td>
</tr>
<tr>
<td><strong>d (mm)</strong></td>
<td>11.5</td>
<td>13.0</td>
</tr>
<tr>
<td><strong>h (mm)</strong></td>
<td>19.1</td>
<td>21.6</td>
</tr>
</tbody>
</table>

And the closest commercial cores for single and three-phase transformers are selected as below:
### Table 4-3 Commercial Design

<table>
<thead>
<tr>
<th></th>
<th>3Φ</th>
<th>1Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core Series No.</strong></td>
<td>0P46016EC</td>
<td>0P44125UC</td>
</tr>
<tr>
<td><strong>Volume (inch³)</strong></td>
<td>5.26</td>
<td>6.42</td>
</tr>
<tr>
<td><strong>$B_{max} (T)$</strong></td>
<td>0.245</td>
<td>0.251</td>
</tr>
<tr>
<td><strong>$J_{max} (A/cm^2)$</strong></td>
<td>364</td>
<td>348</td>
</tr>
<tr>
<td><strong>Temp. Rise (°C)</strong></td>
<td>31.5</td>
<td>28.6</td>
</tr>
<tr>
<td><strong>Core Loss (W)</strong></td>
<td>2.7</td>
<td>2.16</td>
</tr>
<tr>
<td><strong>Winding Loss (W)</strong></td>
<td>2.23</td>
<td>2.84</td>
</tr>
<tr>
<td><strong>Total Loss (W)</strong></td>
<td>4.93</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Turns Number</strong></td>
<td>40</td>
<td>78</td>
</tr>
<tr>
<td><strong>a (mm)</strong></td>
<td>7.7</td>
<td>11.94</td>
</tr>
<tr>
<td><strong>b (mm)</strong></td>
<td>18.34</td>
<td>18.8</td>
</tr>
<tr>
<td><strong>d (mm)</strong></td>
<td>15.62</td>
<td>11.94</td>
</tr>
<tr>
<td><strong>h (mm)</strong></td>
<td>13.8</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Ferrite P material is used for single-phase transformer. The core is 0P44125UC from MAGNETICS®. There are 78 turns of two strands of AWG 22 parallel for both primary and secondary windings. The followings are the pictures of the transformer.
And the impedance of the transformer is shown as below:

According to the tests of the impedance shown above, the fabricated single-phase transformer has the turns ratio of around 1.03:1. And magnetizing inductance is
around 5.3 mH when referred to primary side and 5.0 mH for secondary side. The leakage inductance is around 6 µH, which is negligible comparing with the 580 µH inductor in series with the transformer.

### 4.1.4. Three-phase Transformer

The three-phase transformer also uses Ferrite P material, as 0P46016EC. The center post of the core has been processed symmetrically by ELNA® to have same width with the other legs on the two sides. AWG 20 is used with 40 turns per phase. The pictures of the three-phase transformer are shown as below:

![Figure 4-8 Three-phase Transformer Fabrication](image)

The transformer is Wye Connected by shorting the three output terminals of primary side and the three output terminals of secondary side separately.

By measuring the impedance of the transformer with one side open and shorted, we can get the magnetizing and leakage inductance of each phase, referred to primary side and secondary side, shown as below:
From the above impedance plot, the turns ratio of the Phase A is around 1.07:1, and the leakage inductance is around 10 µH and magnetizing inductance around 4 mH.
From the above impedance plots, the turns ratio of the Phase B is around 1.05:1, and the leakage inductance is around 10 $\mu$H and magnetizing inductance around 4 mH.

Figure 4-12 Leakage and Magnetizing Inductance referred to Secondary Side in Phase B

Figure 4-13 Leakage and Magnetizing Inductance referred to Primary Side in Phase C

Figure 4-14 Leakage and Magnetizing Inductance referred to Secondary Side in Phase C
From the above impedance plots, the turns ratio of the Phase C is around 1.05:1, and the leakage inductance is around 15 µH and magnetizing inductance around 4 mH.

The winding and inductance conditions of the three-phase transformer can be summarized as the table below:

<table>
<thead>
<tr>
<th>Table 4-4 Three-phase Transformer Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn Ratio</td>
</tr>
<tr>
<td>Leakage Inductance (µH)</td>
</tr>
<tr>
<td>Magnetizing Inductance (mH)</td>
</tr>
</tbody>
</table>

From the table, we find that the three phases have the same turns ratio and magnetizing inductance. The leakage inductance of Phase C is higher than Phase A and Phase B, but comparing with the inductor in series with the transformer of 580 µH, the imbalance cannot influence the performance of the transformer.

### 4.2. Prototype DAB System Operation Tests

The single-phase DAB testing equivalent circuit is shown as below:

![Single-phase DAB Testing Circuit](image_url) # Figure 4-15 Single-phase DAB Testing Circuit
And the following photo shows the setup of the single-phase DAB testing platform.

Figure 4-16 Single-phase DAB Testing Setup

And the transformer current, primary IPM output voltage and secondary DC side voltage are tested as below, compared with simulation results:

Figure 4-17 Single-phase DAB Comparison of Test and Simulation Results

And the following table shows the comparison of the experiment and simulation results:
Table 4-5 Single-phase DAB Comparison of Test and Simulation Results

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_L(p-p)$</td>
<td>8.4 A</td>
<td>8 A</td>
</tr>
<tr>
<td>$V_{pri} (p-p)$</td>
<td>600 V</td>
<td>600 V</td>
</tr>
<tr>
<td>$V_o (ave)$</td>
<td>189 V</td>
<td>180 V</td>
</tr>
</tbody>
</table>

In the table, we find that the current and voltage of the test results are a little smaller than simulation results. For the output voltage, the 9 V difference is mainly contributed by the voltage drop on the devices. And the 0.4 A current difference might be caused by device resistance and connecting resistance in the system.

And for three-phase DAB, the equivalent circuit is shown as below:

![Three-phase DAB Testing Circuit](image)

Figure 4-18 Three-phase DAB Testing Circuit

And the following photo shows the setup of the single-phase DAB testing platform.
The primary phase voltage of Phase A, secondary phase voltage of Phase B, the output voltage of secondary side and transformer current of Phase A are tested as below, compared with simulation results.

And the following picture shows the primary three phase voltage waveforms.
In the following table, the testing results and simulation results are compared.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_L(p-p)$</td>
<td>4.4 A</td>
</tr>
<tr>
<td>$V_a (p-p)$</td>
<td>400 V</td>
</tr>
<tr>
<td>$V_o (ave)$</td>
<td>173 V</td>
</tr>
<tr>
<td>$V_b (p-p)$</td>
<td>230V</td>
</tr>
</tbody>
</table>

In the experiment results, we find that there are a lot of ringing in the three-phase voltages and currents. This might be caused by the stray capacitance on the winding of the three-phase transformer. And because of the ringing, the peak to peak value of the primary power module output voltage is higher than the simulation results. For the difference between simulation and test results of secondary Phase B voltage, the turns ratio difference from 1:1 and the device voltage drop may be the main reasons. And this voltage influences the output DC voltage to be lower than simulation result.

Thermocouple from OMEGA® has been placed on the yoke (A) and winding (B) of both single and three-phase transformer as shown in the following pictures for temperature tests.
And the temperature tests results for single and three-phase transformer in single and three-phase DAB operation is shown in the following table:

Table 4-7 Single-phase Transformer Temperature Test Results

<table>
<thead>
<tr>
<th>Volume</th>
<th>6.42 inch³</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>A (Yoke)</td>
</tr>
<tr>
<td>T_{amb}</td>
<td>27.6</td>
</tr>
<tr>
<td>T_{steady}</td>
<td>68</td>
</tr>
<tr>
<td>T_{rise}</td>
<td>40.4</td>
</tr>
<tr>
<td>T_{calc}</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-8 Three-phase Transformer Temperature Test Results

<table>
<thead>
<tr>
<th>Volume</th>
<th>5.26 inch³</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>A (Yoke)</td>
</tr>
<tr>
<td>T_{amb}</td>
<td>29</td>
</tr>
<tr>
<td>T_{steady}</td>
<td>78.4</td>
</tr>
<tr>
<td>T_{rise}</td>
<td>49.4</td>
</tr>
<tr>
<td>T_{calc}</td>
<td></td>
</tr>
</tbody>
</table>
From the table, we find that the test temperature rises of both single and three-phase transformers are higher than the calculated value. And the temperature rise on the yoke is higher than the temperature rise on the winding for both two transformers. The temperature rise of the three-phase transformer is higher than the single-phase transformer for both yoke temperature and wire temperature. Considering the comparison of temperature rise of single and three-phase transformer thru calculation, the testing results have the same trend that three-phase transformer has higher temperature rise.
Chapter 5. CONCLUSION AND FUTURE WORK

5.1. Conclusion

This thesis has presented the methodology for single-phase and three-phase power transformer power density comparison. Optimal design methods for power transformers have been proposed based on the design constraints of maximum allowed flux density, current density and temperature rise.

An example of single and three-phase Dual Active Bridge converter has been studied for the single and three-phase transformer comparison. Optimal designs of single and three-phase power transformers based on the proposed design methods have been conducted for several operating point of the DAB converter. And comparison results show that three-phase transformer has little benefit in size comparing with single-phase transformer. When same boundary of temperature rise has been reached for both single and three-phase transformer, three-phase transformer is larger than single-phase transformer. And when same flux and current density limits have been reached, three-phase transformer is a little smaller, but has higher temperature rise.

5.2. Future work

Firstly, more detailed hardware tests can be carried out based on both T – B and J – B Methods. If possible, customized cores can be built according to the design for both single and three-phase transformers. And detailed 3 – D thermal model can be set
up as estimation of the temperature rise. Previous work has found that the temperatures of different spots are not the same. Thus further work can be carried out to find the hot spot of the whole transformer.

Secondly, more transformer design for DAB converters can be carried out, with different core materials, core shapes and winding arrangements. Also, the influence of operating points of the converter should not be neglected. Different cases of points, from low to high frequency, from low to high power rating and from low to high voltage shall be considered for single and three-phase transformer comparison.

Thirdly, more examples in different topologies might be used as a verification of the comparison methodology. With different applications and design specifications for the transformer, a good view of the applicability of the comparison method will be got.
**APPENDIX HARDWARE IMPLEMENTATION & DSP CODES**

This section describes the setup of the proposed DAB system. The hardware includes the digital controller board, signal-conditioning and A/D sensing board, and the integrated power module as power stage. And the codes of DSP is also attached.

**Universal Controller and A/D Conversion Boards**

**Universal Controller**

The digital controller board selected for the prototype is a universal Controller (UC), which is introduced briefly in this section. UC is produced by Center for Power Electronics Systems in Virginia Polytechnic Institute and State University. It is a topology-free controller board which can implement high-level control for a wide range of power electronic converters and systems using both medium and high power. 

![Error! Reference source not found.](image)

shows the UC board including its Xilinx FPGA, Sharc DSP, and its communication ports such as I/O pins and fiber optic receiver/transmitters. The I/O pins are utilized to communicate with the A/Ds on the signal conditioning and sensing board and receive the digital sampled signals. They are also used to configure the A/D’s input pins for proper operation [A-1].
The controller architecture consists of two main busses bridged by the FPGA. This approach allows for incremental debugging of the controller without having to worry about every block at once. This also allows for future architectures in which the FPGA could interact with the peripherals without having to know what the DSP is doing. An alternative would be to have a single bus with every peripheral connected to it. The controller architecture is shown in [A-1].

**A/D Conversion Board**

The A/D conversion board includes the sensing circuit, the signal conditioning
circuit, and the A/D conversion circuits as well as the over-limit protection circuit.

Figure A.2 shows the board.

There are two AD7864 AD converters on the board. The AD7864 is a high-speed, low-power, 4-channel simultaneous-sampling 12-bit A/D converter that operates from a single 5V supply [A-2]. The board contains a 1.65us successive approximation ADC, four track/hold amplifiers, a 2.5V reference, an on-chip clock oscillator, signal conditioning circuitry, and a high speed parallel interface. The input signals on the four channels are sampled simultaneously, thus preserving the relative phase
information of the signals on the four analog inputs. The part accepts analog input ranges of +/- 10 V. The time sequence of the signal conversion is shown in Figure A-3.

Before going to the AD7864, the input digital signal first goes through the low pass filter to attenuate the high frequency noise picked up through the environment. The design of the corner frequency of the low pass filter should consider the impact to the controller, since it would introduce phase lag into the data. Additionally, the corner frequency should be much higher than the control bandwidth and should achieve good noise attenuation. The designed corner frequency is 5.25 kHz. The filter configuration is selected as a Butterworth filter as shown in Figure A-4.

The corner frequency of this type of filter is
\[ f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \] (A-1)

The values of the parameters are listed below.

\[
\begin{align*}
R_1 &= 7.15 \text{k}\Omega \\
R_2 &= 7.15 \text{k}\Omega \\
C_1 &= 3\text{nF} \\
C_2 &= 6\text{nF}
\end{align*}
\] (A-2)

**Integrated IGBT Power Module**

In the prototype DAB system, one IGBT-IPM 6MBP20RH060 is selected as the power stage. It is one 600V, 20A power module with 6 IGBT devices integrated in one package. In , the picture of the IPM is shown. [A-3]

![Figure A-5 IGBT-IPM 6MBP20RH060](image_url)

The block diagram of the power module is shown in . The gate drive signal VinU, V, W, X, Y and Z are provided by the Universal Controller mentioned above and one type of optocoupler HCPL4504 [A-4] is utilized for control signal and power stage isolation before the DSP signal going thru the IPM.
Figure A-6 Block Diagram of IGBT-IPM 6MBP20RH060

**DSP Code**

```
///////////////////////////////////////////////////////////////////////////////////////////
//                                                                               /
//   FILE: Single-phase Dual Active Bridge Converter Open-loop Modulation        /
//   March, 6, 2010                                                            /
//   Edited by Jing Xue                                                        /
//                                                                               /
///////////////////////////////////////////////////////////////////////////////////////////
```
//library used in this program
#include <def21160.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "sport.h"
#include <signal.h>
#include <21160.h>
#include "address.h"
#include "variables.h"

void irq1_handler();
//void irq0_handler();

/***********MAIN PROGRAM ************/
void main()
{
  //************** initialize the system register ***********************/
  //========== Setup the relevant register bits for /INT ==============

  *(volatile unsigned int*)(0x08000108) = 0x4c4b4;
  *(volatile unsigned int*)(0x0800010A) = 16000;
  sysreg_bit_clr(sysreg_MODE1, IRPTEN); //enable global interrupt
  sysreg_bit_set(sysreg_MODE2, IRQ0E); //enable /IRQ0
  sysreg_bit_clr(sysreg_IMASK, IRQ0I); //unmask the interrupt/IRQ0 latched in the IRPTL
  sysreg_bit_set(sysreg_MODE2, IRQ1E); //enable /IRQ1
  sysreg_bit_clr(sysreg_IMASK, IRQ1I); //unmask the interrupt/IRQ1 latched in the IRPTL
  interrupt (SIG_IRQ1,irq1_handler); //set the name of ISR for /INT1
  // interrupt (SIG_IRQ0,irq0_handler); //set the name of ISR for /INT0

  //========== Setup variables for PWM ========================

  *reg_ENCLK=0x00000001;
  *reg_PWM_DEADTIME_1=PWM_DEADTIME_1;
  *reg_PWM_DEADTIME_2=PWM_DEADTIME_2;
  *reg_PWM_PER_1 = PWM_PER_1;
  *reg_PWM_PER_2 = PWM_PER_2;
  PSA = PWM_PER_1*65/360;
  PHASE_SHIFT_ANGLE_A1 = 0;
  PHASE_SHIFT_ANGLE_B1 = PWM_PER_1/3;
PHASE_SHIFT_ANGLE_C1 = PWM_PER_1/3*2;
PHASE_SHIFT_ANGLE_A2 = PSA;  // Phase shift angle = 30 deg
PHASE_SHIFT_ANGLE_B2 = PSA+PWM_PER_1/3;  //4000/6+4000*2/3;
PHASE_SHIFT_ANGLE_C2 = PSA+PWM_PER_1/3*2;

*reg_PHASE_SHIFT_ANGLE = PHASE_SHIFT_ANGLE;
*reg_PHASE_SHIFT_ANGLE_A1 = PHASE_SHIFT_ANGLE_A1;
*reg_PHASE_SHIFT_ANGLE_A2 = PHASE_SHIFT_ANGLE_A2;
*reg_PHASE_SHIFT_ANGLE_B1 = PHASE_SHIFT_ANGLE_B1;
*reg_PHASE_SHIFT_ANGLE_B2 = PHASE_SHIFT_ANGLE_B2;
*reg_PHASE_SHIFT_ANGLE_C1 = PHASE_SHIFT_ANGLE_C1;
*reg_PHASE_SHIFT_ANGLE_C2 = PHASE_SHIFT_ANGLE_C2;

ADC_Dealy_1 = 80*22;
ADC_Dealy_2 = ADC_Dealy_1;

*reg_ADC_Dealy_1=ADC_Dealy_1;
*reg_ADC_Dealy_2=ADC_Dealy_2;
*reg_PWM_DIS_1=1;
*reg_PWM_DIS_2=1;

/*** MAIN FUNCTION LOOP***/
while(1);
}

void irq1_handler()
{
    abc=1;
    ADch1=*reg_ADC1CHA;  //Vdc
    ADch2=*reg_ADC1CHB;  //Vab
    ADch3=*reg_ADC1CHC;  //Vbc
    ADch4=*reg_ADC1CHD;  //Ic12
    ADch5=*reg_ADC2CHA;  //Ib1  -2
    ADch6=*reg_ADC2CHB;  //Ia1  -1

    if(ADch1 >= 0x800)
    {
    }
Vdc = (int)(ADch1) - 0x1000;
else
{  
    Vdc = ADch1;
}
Vdc = (Vdc - Offset_ch1) * Inv_Scale_ch1;

if (ADch2 >= 0x800)
{
    Vab = (int)(ADch2) - 0x1000;
}
else
{
    Vab = ADch2;
}
Vab = (Vab - Offset_ch2) * Inv_Scale_ch2;

if (ADch3 >= 0x800)
{
    Vbc = (int)(ADch3) - 0x1000;
}
else
{
    Vbc = ADch3;
}
Vbc = (Vbc - Offset_ch3) * Inv_Scale_ch3;

Vca = -Vab - Vbc;

if (ADch4 >= 0x800)
{
    I_c1[0] = (int)(ADch4) - 0x1000;
}
else
{
    I_c1[0] = ADch4;
}
I_c1[0] = (I_c1[0] - Offset_ch4) * Inv_Scale_ch4;
if (ADch5 >= 0x800)
{
    I_b1[0] = (int)(ADch5) - 0x1000;
}
else
{
    I_b1[0] = ADch5;
}
I_b1[0] = (I_b1[0] - Offset_ch5)*Inv_Scale_ch5;

if (ADch6 >= 0x800)
{
    I_a1[0] = (int)(ADch6) - 0x1000;
}
else
{
    I_a1[0] = ADch6;
}
I_a1[0] = (I_a1[0] - Offset_ch6)*Inv_Scale_ch6;

if (((I_a1[0]>Iin_limit) || (I_b1[0]>Iin_limit) || (I_c1[0]>Iin_limit) || (Vdc>Vdc_limit))
{
    *reg_PWM_DIS_1 = 1;
    *reg_PWM_DIS_2 = 1;
    PWM_DutyA_1 = 0;
    PWM_DutyB_1 = 0;
    PWM_DutyC_1 = 0;
    PWM_DutyA_2 = 0;
    PWM_DutyB_2 = 0;
    PWM_DutyC_2 = 0;
    // interrupt(SIG_IRQ0,SIG_IGN);  //disable interrupt
    interrupt(SIG_IRQ1,SIG_IGN);  //disable interrupt
}

if (I_a1[0]>Iin_limit)
    *g_cpwHEXVAL = 1;
else if (I_b1[0]>Iin_limit)
    *g_cpwHEXVAL = 2;
else if (I_c1[0]>Iin_limit)
    *g_cpwHEXVAL = 3;
else if (Vdc>Vdc_limit)
    *g_cpwHEXVAL = 4;
while (1)  //dead loop
{
    asm("nop;");
    asm("nop;");
}

DutyA_1=0.5;
DutyA_2=0.5;

DutyB_1=0.5;
DutyB_2=0.5;

DutyC_1=0.5;
DutyC_2=0.5;

*reg_PWM_DIS_1 = 0;
*reg_PWM_DIS_2 = 0;

*reg_PWMA_DUTY_1=(1-DutyA_1)*(float)(PWM_PER_1);
*reg_PWMA_DUTY_2=(1-DutyA_2)*(float)(PWM_PER_2);

*reg_PWMB_DUTY_1=(1-DutyB_1)*(float)(PWM_PER_1);
*reg_PWMB_DUTY_2=(1-DutyB_2)*(float)(PWM_PER_2);

*reg_PWMC_DUTY_1=(1-DutyC_1)*(float)(PWM_PER_1);
*reg_PWMC_DUTY_2=(1-DutyC_2)*(float)(PWM_PER_2);

//====================== Send out the Duty Cycle ==============================//
Reference


