CHAPTER 5

ANALYSIS, DESIGN OF HIGH VOLTAGE FERRITE CORE TRANSFORMER AND OZONE TUBE STRUCTURE

5.1 INTRODUCTION

Transformers generally contain two or more electrical circuits, primary and secondary windings, consisting of multi turn coils of electrical conductors that are interlinked by means of one or more magnetic circuits or cores. Cores typically consist of a plurality of ferromagnetic laminations that are stacked together to form a closed loop, surrounding and coupling magnetically the primary and secondary windings. Cores may be manufactured either mutually overlapping or abutting individual laminations or from a continuous strip of magnetic sheet material wound around a mandrel to form a closed circuit. The magnetic and electric circuits are combined either by assembling the cores around pre-wound primary and secondary coils are by winding the conductor coils around one or more legs of the closed magnetic circuit.

The ferrite cores are best suited for high frequency applications and steel laminations are best suited for low frequency applications (George Orenchak 1997). Both materials are available in a variety of grades, each best suited for different applicants. Ferrites are dense, homogeneous ceramic structures made by mixing iron oxide with oxides or carbonates of one or more metals such as manganese, zinc, nickel, or magnesium.
In specific operating conditions, ordinary laminated core made of steel lamination can be employed only to the working frequency range within 50 to 70 Hz (Prasopchokhothongkham et al 2010). For high frequency in the range of kHz, the laminated core cannot be used and only the core made of ferrite materials must be used.

For most ferrite materials used in SMPS applications, hysteresis losses dominate up to 300 kHz. At high frequencies eddy current losses take over, because they tend to vary with frequency squared. In order to overcome these losses the ferrite core is made of laminated metal alloy and powered metal cores are used (Mulder 1995).

The common core used for the transformer is E42 type (Chryssis 1989). The number of turns in the primary and secondary is limited to the size of the core (Yu Du Seunghun Baek et al 2010). The number of turns in the primary and secondary side of the transformer is determined by the standard wire gauge of the conductor to be used. The core is specifically designed for frequency capability. Ferrite is the best choice in high frequency transformer except for mechanical ruggedness. Frequency has become a strategic variable. Switching power supplies have become so popular because of their ability to operate at high frequencies, thus increasing their efficiency. A switching power supply that supplies the same performance requirements of a linear power supply can be many times smaller in size. Since the induced voltage in a transformer is dependent upon the changing magnetic flux, the more you change the flux (higher frequency), the smaller and more efficient, the transformer becomes.

With higher frequencies however, different considerations come into play. With lower frequencies, core material selection is driven by core saturation considerations. The eddy current losses are low so steel laminations can be considered. With higher frequencies, core material selection is driven
by core loss considerations as eddy currents can be significant. Here ferrites are commonly used because their high electrical resistivity minimizes eddy current losses (Bhattacharya et al. 2010). However, there is a price to be paid for the reduced core losses. Ferrites have lower saturation and permeability values.

The choice of magnetic material will be influenced by several factors:

1. Circuit topology used, usually chosen to yield the best combination of minimum power transistor off voltage and peak current stresses. Cost and component count must also be taken into account.
2. Operating frequency of the circuit.
3. Power requirements.
4. Regulation needed.
5. Cost.
7. Input/output voltages.
8. Permissible temperature rise.

Some of the drawbacks in other transformers like Fly Back Transformers or Line Output Transformers compared with the ferrite core transformers are:

1. Current is limited and the transformer winding may not burn away or blow a fuse.
2. The normal operating current output of FBTs are very low, in the low milliamps range.
3. The high frequencies required make it necessary to build a more complicated control circuit.
4. These reasons render FBTs unsuitable for a power supply application for this project.

5.2 FERRITE CORE TRANSFORMER

The magnetic field distribution in the single phase core is analyzed in this section. The main reason for a core is to provide a return path for harmonic flux. However, the problem introduced by this construction is that the actual flux paths are uncertain. The uncertainty of the flux paths is due to the fact that the yokes are not large enough to carry the whole flux from the core. Although the natural tendency for the flux is to follow the pattern, the yokes saturate and force excess flux to “spill over” into the outer legs. For this reason, it is a good practice to design the flux density in the core in the lower region than the saturation knee, to avoid saturation. Leakage inductance delays the transfer of current between switches and rectifiers during switching transitions. These delays, proportional to load current, are the main cause of regulation and cross regulation problems.

The energy losses in a transformer appear as heat in the core and coils. This heat must be dissipated without allowing the windings to reach a temperature which will cause excessive deterioration of the insulation. One of the challenges of high frequency design is the heat dissipation and effective cooling surfaces. The main cooling method for these transformer designs is natural convection that is the heat generated from core and coils get transfer to air through effective cooling surface area. Alternately, cooling fans may be needed for higher loss designs. The temperature limits for conductor and core are 120°C respectively (Ronan et al 2000). The design temperatures for each component should be around 100°C and allow 20°C for localizing hotspot temperature.
5.2.1 Basic Design Equation

The relation of the transformer with the turn’s ratio to the voltage and current is given by

\[
\frac{V_1}{V_2} = \frac{l_2}{l_1} = \frac{n_1}{n_2} \quad (5.1)
\]

The following equation shows how the various design variables can be manipulated to achieve the desired outputs.

\[
E = 4.44 \cdot B \cdot N \cdot A_c \cdot f \cdot 10^8 \quad (5.2)
\]

where \(E\) is induced voltage in volts, \(B\) is maximum induction in gauss, \(N\) is number of turns in winding, \(A_c\) is cross section of the magnetic material in \(\text{cm}^2\), and \(f\) is frequency in Hz. From the equation, we can see how the parameters interact with each other. In most transformer design situations, \(E\) is already set. The following cases show what happens when one variable is changed and how it affects the other variable; again, holding \(E\) constant for the sine wave condition.
If B increases, the turns would decrease, reducing copper losses. However, increasing B increases core losses resulting in higher core temperatures.

If N increases, B would decrease, reducing core losses. Increasing N leads to higher copper losses and requires extra room for more windings. Higher copper losses means higher winding temperatures and reduced efficiencies. Extra room for windings means a larger component.

If \( A_c \) increases, B would be decreased yielding lower core loss per unit weight; however, the weight would increase offsetting some of that gain. An increased area means longer lengths of wire, increasing copper losses. This would result in a larger and heavier transformer. Excessive core heating may reduce the B value thus reducing the efficiency.

If \( f \) increases, B would decrease, possibly resulting in lower core losses. However, moving to higher frequencies, core losses could become more significant. A switch to ferrite will minimize these losses but at a cost of decreased B.

However, the efficiency gains from a higher frequency will more than offset the lower B. The higher frequency would also allow for a smaller transformer, N and/or \( A_c \) would decrease.
5.2.2 Selection of Ferrite Core Material

The ferrite core is selected and is composed of 50-80% of NiFe, and at room temperature has a saturation magnetization of 1.56 T. The core loss can be 70%-80% less than silicon steel material. Ferrite core has a wide range of high frequencies and hot-spot temperatures up to 120 °C (Namihira T et al 2007). Its thermal limit is close to that of winding conductor’s thermal limit (120 °C), so the thermal design of the transformer can be best optimized. Its high saturation flux density range can add flexibility when designing the number of turns between the primary and secondary windings (Ketkaew et al 2002). The core cross-sectional area can also reduce to the minimum by increasing the flux density within the thermal limits. Because of its high performance characteristics, E core material as shown in Figure 5.2 is chosen for the 300 Hz to 20 kHz transformer design. The analysis flow chart using SOLIDWORKS is shown in Figure 5.3. Effective core parameters designed are shown in Table 5.1. The methodology for the same is explained in Appendix: 5.

These are the most common cores used in power applications. They are cost effective, allow for simple bobbin winding, and are easy to assemble. E cores do not, however, offer self-shielding.

![Figure 5.2 Schematic of EE Core](image)
Table 5.1 Effective Core Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma (VA)$</td>
<td>Core factor (C1)</td>
<td>0.894</td>
<td></td>
</tr>
<tr>
<td>$H_y$</td>
<td>Height of yoke</td>
<td>5/16</td>
<td>mm</td>
</tr>
<tr>
<td>$D_y$</td>
<td>Diameter yoke</td>
<td>5/16</td>
<td>mm</td>
</tr>
<tr>
<td>$W$</td>
<td>Length of yoke</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of frame</td>
<td>2(1/4)</td>
<td>mm</td>
</tr>
<tr>
<td>$A$</td>
<td>Area of window</td>
<td>0.46</td>
<td>mm²</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass of core</td>
<td>16</td>
<td>gm</td>
</tr>
</tbody>
</table>

Figure 5.3 Flow chart for Analysis of High voltage, High frequency Transformer using SOLIDWORKS
5.3 BLOCK DIAGRAM FOR CONTROL CIRCUIT OF THE FERRITE CORE TRANSFORMER

The proposed high voltage variable frequency power supply consists of rectifier for conversion, variable frequency, driver circuit for control and to produce pulse wave, auto transformer for the variation of input voltage for the required output variation as shown in Figure 5.4. The snubber circuit is for overvoltage protection and reduce spike wave, then finally the ferrite core transformer is to step up the output voltage based on the DBD tuber requirement.

Figure 5.4 Block Diagram for Control Circuit of the Ferrite Core Transformer

5.4 CIRCUIT FOR FIXED AND VARIABLE FREQUENCY

By using the boost converter the voltage can be varied up to 10 kV of the required voltage, the frequency variation takes place in the high voltage switching frequency circuit (Ordiz et al 2008). The frequency can be varied to obtain the maximum efficiency of ozone gas.
There are several improvements that may be expected from the adoption of high frequency switched mode operation:

1. High frequency switching operation will allow much more precise control over the operating parameters such as output voltage level, current level, voltage rise times and response to variations in load demand.

2. High frequency switching will allow a significant reduction in the size and weight of the high voltage transformer. This reduction in size and weight leads to a compact design, which minimizes the installation and maintenance costs.

3. High frequency switching will allow the reactance of the transformer core to be much lower and hence the efficiency of the power supply can be improved.

4. In some applications the ability to pulse the DC output voltage of the converter from one level to another at a specific and programmable magnitude, time duration and period has substantial benefits, e.g., in electrostatic precipitators this method may improve dust/gas particle charging and collection.

   By varying the frequency we might obtain different values of ozone concentration.
5.5 CIRCUIT SIMULATION FOR FREQUENCY WAVEFORM

5.5.1 Fixed Frequency Waveform

In the simulation, a model circuit is designed for fixed frequency with discrete PWM generator as shown in Figure 5.5. The input voltage is about 180 V of AC supply and using converter it is converted to DC voltage. Capacitor acts as filter and MOSFET is operated at fixed frequency. To obtain the waveform of square wave, filter is used. The wave form is shown in Figure 5.6.
5.5.2 Variable Frequency Waveform

In the simulation, a model circuit is designed for variable frequency with triggering pulse generator as shown in Figure 5.5. The input voltage applied is 180 V of AC supply and using converter it is converted into DC voltage. Capacitor acts as filter and MOSFET is operated with variable frequency. By using the counter, which is applied five variable frequencies. To obtain the pure waveform, wave filter are used. The waveform is shown in Figure 5.7.
5.6 ANALYSIS AND CALCULATED RESULTS OF THE FERRITE CORE TRANSFORMER

It describes certain analysis ideas stair by stair applied to the ferrite core transformer to accomplish substantial reductions in volume, weight and losses, with improved reliability and better accuracy compared with other transformers. The ferrite core transformer has been designed and built which is novel in its combination of high voltage (5 kV), high frequency (5 kHz) and power (720 VA) specifications. The design technique utilized a spread sheet approach which facilitated an iterative design procedure as shown in Figure 5.8 and 5.9. The transformer used a NiFe for the best choice of frequency about (300 Hz – 20 kHz). Probably, for the analysis of the transformer being carried out by SOLIDWORKS, in which magnetic flux density, applied current density, total current density, thermal loss and temperature distribution can be scrutinised. Some of the results such as
inductance, flux linkage, leakage inductance and loss can be viewed in the SOLIDWORKS. Finally, some of the calculations have been worked out for intact design of the transformer.

Figure 5.8 Analysis Results for Flux Linkage

Figure 5.9 Analysis Results for Leakage Linkage
5.6.1 Transformer Analysis with EMS Post-Processing

Magnetic flux density can be viewed enough by ISO clipping of the B field can be animated by varying the phase angle. In which applied current density can be shown using stress of vectors as shown in Figure 5.10.

In total current density, inside the transformer can be analysed using section clipping, multi section in which clipping can be applied (Treutpicharan et al 1996).

Figure 5.10 Analysis of Applied Current Density by Stress Vector
In the temperature analysis, thermal radial and heat flux in temperature distribution can be analysed with more gradient of heat flux as shown in Figure 5.11. Thermal plot can be manipulated from electrical orbits which can be ISO clipping, section clipping and shapes can be viewed.

Figure 5.11 Analysis of Temperature Gradient for Thermal Radial and Heat Flux

Table 5.2 shows a ferrite core transformer designed with an output voltage of 5 kV, rating of 720VA, switching frequency of 5 kHz. The design and analysis have been verified using SOLIDWORKS. Total efficiency is approximately about 92% and the hot spot temperature on the surface at 100°C.
The main features of the high frequency transformer are

1. High resistivity with low eddy current loss and high usable frequency range.

2. High magnetic permeability with high induction in minimal space.

3. Versatility of core shapes which satisfies magnetic requirements in minimal space.

4. Light density due to winding core of light weight.

5. Low cost relative to alternate materials.

<table>
<thead>
<tr>
<th>Core material</th>
<th>Ferrite core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core type / Stamping No.</td>
<td>EE42 / 41</td>
</tr>
<tr>
<td>Operating freq</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Rating</td>
<td>720 VA</td>
</tr>
<tr>
<td>Primary Voltage</td>
<td>230V</td>
</tr>
<tr>
<td>Secondary Voltage</td>
<td>5000V</td>
</tr>
<tr>
<td>Primary Amp</td>
<td>3.4A</td>
</tr>
<tr>
<td>Secondary Amp</td>
<td>144mA</td>
</tr>
<tr>
<td>Turns ratio[n₁:n₂]</td>
<td>1:21.7</td>
</tr>
<tr>
<td>Standard wire gauge of primary turns</td>
<td>17 SWG</td>
</tr>
<tr>
<td>Standard wire gauge of secondary turns</td>
<td>32 SWG</td>
</tr>
<tr>
<td>Inductance</td>
<td>3mH</td>
</tr>
<tr>
<td>Efficiency</td>
<td>92%</td>
</tr>
<tr>
<td>Flux of core</td>
<td>265 µ Wb</td>
</tr>
<tr>
<td>Net core area</td>
<td>26.5 mm²</td>
</tr>
<tr>
<td>Width of window</td>
<td>0.665 inch</td>
</tr>
<tr>
<td>Height of window</td>
<td>0.107 inch</td>
</tr>
<tr>
<td>Area of window</td>
<td>0.0711 sq. inch</td>
</tr>
</tbody>
</table>
5.7 ANALYSIS, DESIGN OF OZONE TUBE STRUCTURE USING SOLIDWORKS

5.7.1 Design of Ozone Tube Structure

Corona exists in many forms, including glows and haloes, spots, brushes and streamers. The potential at which corona is found to originate is called corona threshold voltage. Above this voltage, there is a limited region, in which current increases proportionately with voltage. After this region, the current increases more rapidly, leading to the complete breakdown and arcing or sparking at a point called the breakdown potential. Corona discharge is highly dependent on geometry. Electric field intensity is higher around the surface of a charged conductor with higher curvature or lower radii of curvature (Facta et al 2009 ). If \( Q \) is the total charge stored in a conductor and \( r \) is its radius of curvature, the electric field intensity \( E \) is inversely proportional to the radius, as given by the following equation, where \( \varepsilon_0 \) is the permittivity of free space (and air) and is equal to \( 8.852 \times 10^{-12} \) F/m. The Gauss's law for the electric field says that the electric flux through any closed surface is proportional to the amount of electric charge contained within that surface. The electric field of a co-core cylinder of length \( l \) and radius \( r \), \( r_1 \leq r \leq r_2 \), is given by

\[
E(r) = \frac{Q}{2\pi \varepsilon_0 r E} \quad (5.5)
\]

The maximum electric field stress occurs on the inside of cylinder’s surface and is given by:

\[
E_{\text{MAX}} = E(r_i) = \frac{V}{r_i \ln \frac{r_2}{r_1}} \quad (5.6)
\]
5.7.2 Electrode Tube Design and Energy Usage

The principle of ozone tube design relies on an unsmooth electric field for the generation of the ozone gas quantity. Therefore, a two-layer electric insulator is chosen for the electrode design due to the permittivity ($\varepsilon$) differences of the electric insulator (Teranishi et al 2008). It is suitable for the generation of a non-uniform electric field to have variable but close to $\varepsilon$ values of each layer under electric field stress. As shown in Figure 5.13, a two-layer co-core cylinder for ozone tube design is chosen under the following conditions

1. Silica is chosen for the 1$^{\text{st}}$ layer electric insulator due to its effectiveness in generating ozone gas, where $\varepsilon_1 = 4.6$, the diameter is 0.43 cm and the length is 20 cm.
2. Air is chosen for the 2$^{\text{nd}}$ layer electric insulator, where $\varepsilon_2 = 1$.
3. Cathode frilled aluminum (for rubbing pots) in filament coil inside of the silica’s electric insulator is used. The reason is that aluminum has a high conductivity.
4. The anode is a stainless steel cylinder, where the diameter is 1.4 cm and the length is 20 cm.
5.7.3 Calculation of Electric Field (E) and Voltage (V) of Ozone Tube

In Figure 5.10: \( r_1 = 0.43 \) cm, \( r_2 = 1.4 \) cm, \( r_3 = 2.03 \) cm, \( l = 50.8 \) cm. For energies from 5.58 to 7.73 kWh/m\(^3\). If the air is composed of 21\% oxygen (O\(_2\)), the chosen energy range is 1.172 – 1.620 kWh/m\(^3\)

\[
\text{air volume} = \pi (r_2^2 - r_1^2) \times l = 10.053 \text{ cm}^3
\]  

(5.7)

With maximum energy per volume (\( W_{\text{max}} \)) of 1.620 kWh/m\(^3\) and minimum energy per volume (\( W_{\text{min}} \)) of 1.172 kWh/m\(^3\), then (equation 5.7)

\[
W_{\text{max}} = 1.620 \times 10^3 \times 10.053 \times 10^{-6} = 0.016 \text{ Wh},
\]

\[
W_{\text{min}} = 1.172 \times 10^3 \times 10.053 \times 10^{-6} = 0.011 \text{ Wh},
\]

\[
E_{(\text{max, min})} = \frac{2W_{(\text{max, min})}}{\varepsilon \text{Vol}}
\]  

(5.8)

\[
E_{\text{max}} = 39.972 \text{ kV/cm}
\]

\[
E_{\text{min}} = 33.143 \text{ kV/cm}
\]

The average value of the breakdown voltage is

\[
V_{\text{Breakdown (avg)}} = \frac{(E_{\text{max}} + E_{\text{min}})}{10}
\]

\[
= \frac{(73.115)}{10}
\]

\[
= 7.312 \text{ kV}
\]