Magnetic Field Analisys of a Delta-Connected Autotransformer Based 18 Pulse AC-DC Converters

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Abstract—To improve the total harmonic distortions (THD) of input line currents, the authors present the design of the Delta-connected three phase autotransformer based 18 pulse AC-DC converter. The proposed work takes account the magnetic core topology and the winding position. Moreover, advanced numerical techniques, based on the two-dimensional (2D) and three-dimensional (3D) finite element method (FEM), have been applied for the magnetic field analysis of power transformer (the flux density, the field density, the current density and flux lines). Experimental validation of the proposed methodology is also provided.

Keywords—autotransformer; Design; 2D, 3D finite element modeling.

I. INTRODUCTION

The thyristor AC-DC converter structure 6-pulse is widely used in industry for various applications. The total harmonic distortions (THD) of input line currents of the six-pulse rectifier can reach 31%. In order to meet the harmonic requirement set by IEEE standard 519-1992 [1], the multipulse rectifiers 12, 18 and 24 are adopted to insure that any individual harmonics should not be more than 5% and total harmonic distortion (THD) should not be more than 5%. In order to eliminate 5th, 7th harmonics in the network side, the 12 pulse rectifier is realized by a serial connection of two 6-pulse rectifier [3]-[5], the first rectifier is fed by an YY connected transformer, while the second rectifier is fed by an Δ-Y connected transformer to introduce the 30° phase shift. The AC-DC 18 pulse rectifier is realized with three 6-pulse rectifier in order to eliminate the 5th, 7th, 11th and 13th harmonics. The 18 pulse structure requires the design of autotransformer with special couplings. Various configurations of auto-connected transformers for an 18-pulse AC-DC converter are proposed [2]-[6]. This paper is organized as follow; section II gives a mathematical description of the various winding current, voltages and capacity delta-connected autotransformer-based 18-pulse AC-DC converter with 40° phase shifting of reduced harmonic. Section III gives magnetic field analysis and geometry design of the proposed autotransformer. Moreover, section IV gives an advanced numerical technique, based on 2D and 3D finite element method (FEM) using Maxwell ANSYS, for the magnetic field analysis of power transformer (the flux density, the field density, the current density and flux lines) and the mesh operations [7]-[12]. Finally in section V the simulation results of the topology of 18-pulse are discussed and validated in experimental realization.

II. ANALYSIS AND DESIGN OF THE PROPOSED AUTOTRANSFORMER

The Delta-connected autotransformer is designed where it is supplied by three-phase input voltage (V_a, V_b, V_c) displaced at 120° with respect to each other, it produces from sets of balanced three-phase voltages, namely (V_11, V_12, V_13) and (V_21, V_22, V_23), all displaced through an angle +40° and -40° desired for the 18-pulse converter operation shown in Fig.1.

\[ V_{11} = V_a - K_1, V_{ac} - K_2, V_{bc} \]  \hfill (1)

\[ V_{21} = V_a - K_1, V_{ab} + K_2, V_{bc} \]  \hfill (2)

K_1, K_2 and K_3 are the measures of turn’s ratios of the various windings of the auto-connected transformer. Assume the following set of voltages:

\[ V_1 = V[0°], V_2 = V[-120°], V_2 = V[120°] \]  \hfill (3)

\[ V_{11} = V[40°], V_{12} = V[-80°], V_{13} = V[160°] \]  \hfill (4)

\[ V_{21} = V[-40°], V_{22} = V[-160°], V_{23} = V[80°] \]  \hfill (5)

Where:

K_1=0.1559, K_2=0.293 and K_3=0.6882

Under the assumption of idealized circuit conditions, ideal transformers and the constant current I_ac, the systems solution can acquire from Kirchhoff’s law current and the balance conditions of the amper-turns of each transformer limbs.

In the connection depicted in Fig. 1 and Fig.2, Kirchhoff’s current law can be written as follows [6]:

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For phase $V_a$:

\[
i_{V1a} = i_{V0a} + i_{K1Va}
i_{K1Va} = i_{K1V11} + i_{K1V21}
i_{K1V11} = i_{V11} + i_{K3Va}i_{K1V21} = i_{V22} - i_{K3Vb}
\]

For phase $V_b$:

\[
i_{Vb} = i_{V0b} + i_{K1Vb}\]

\[
i_{K1Vb} = i_{K1V12} + i_{K1V22}
\]

For phase $V_c$:

\[
i_{K1V12} = i_{V12} + i_{K3Vb}
i_{K1V22} = i_{V22} - i_{K3Vc}
\]

The ampere-turns equations of the autotransformer are expressed as follows:

\[
K_2(i_{V11} - i_{V21}) + K_1(i_{K1V22} - i_{K1V13}) - K_3i_{K3Va} = 0
\]

\[
K_2(i_{V12} - i_{V22}) + K_1(i_{K1V23} - i_{K1V11}) - K_3i_{K3Vb} = 0
\]

The currents, $i_{V0a}$, $i_{V11}$, $i_{V21}$, $i_{V0b}$, $i_{V12}$, $i_{V22}$ and $i_{V0c}$, $i_{V13}$, $i_{V23}$ are obtained from the conduction conditions of the corresponding thyristor. The solutions of current related phase $V_a$ are expressed as follows:

\[
i_{K3Va} = K_2(i_{V12} - i_{V22}) + K_1(i_{V23} - i_{V11})
\]

\[
i_{K3Vb} = K_2(i_{V11} - i_{V21}) + K_1(i_{V21} - i_{V12})
\]

\[
i_{K3Vc} = K_2(i_{V11} - i_{V21}) + K_1(i_{V22} - i_{V13})
\]

The total autotransformer capacity is expressed by:

\[
S_T = 6K_2V_1i_{V11} + 6K_1V_1i_{K1V11} + 3K_3V_1i_{K3Va}
\]
The autotransformer total equivalent capacity is defined by

$$S_{t,\text{equiv}} = \frac{1}{2} V_{ac} I_{dc}$$

(25)

Where $V_I$ is the rms value of the line-to-line voltage of the power source, $V_{ac}$ and $I_{dc}$ are the average values of the dc output voltage and current, respectively.

The rms values of currents are given by

$$I_{K1A} = \sqrt{\frac{2}{3}} I_{DC} \sqrt{(K_2 - K_1)^2 + K_2^2 + K_1^2}$$

(26)

$$I_{K1I1} = \frac{I_{DC}}{3} \sqrt{1 + K_2 - K_1)^2 + 2K_2^2 + (K_2 - K_1)^2 + b^2 + (1 - K_1)^2}$$

(27)

$$I_{K11} = \frac{\sqrt{3}}{2} I_{DC}$$

(28)

$$I_{V11} = 0.711 I_{DC}$$

$$I_{V11} = 0.866 I_{DC}$$

The THD current is calculated by the relationship between the rms value of line current and the effective value of the fundamental frequency component of the line current. These values are obtained by analyzing the waveform of the current

$$I_{Va} = \frac{1}{2\pi} \int_{0}^{2\pi} I_{va}(t)^2 \, dt$$

(29)

$$I_{vat} = \frac{1}{2\pi} \int_{0}^{2\pi} I_{vat1}(t)^2 \, dt$$

(30)

$$THD = \frac{\sqrt{I_{va}^2 - I_{vat}^2}}{I_{vat}}$$

(31)

III. MAGNETIC FIELD ANALYSIS

Finite Element modelling (FEM) is a highly accurate method of calculating the transformer parameters. The FEM formation makes use of the fact that partial-differential equation is satisfied when total magnetic energy function is a minimum [7].

The geometry to solve (which is basically the core and set of transformer winding represented simple as rectangular blocks) can be drawn using the Maxwell ANSYS when we do a cross section. The appellations of coils shown in Fig. 3 are Coil_A1, Coil_A2, Coil_A3, Coil_A4, Coil_A5 (n=1:5) respectively for the phase A, phase B and phase C. Each limb has five concentrates coils to improve the magnetic coupling between the coils. The design of the limbs and core considered phase A are shown in Fig. 4. The Table 1 and Table 2 shows respectively the geometrical parameters of core and coils.

![Fig. 3 Coil names](image)

![Fig. 4 Three limbs, three phase core and coil type autotransformer](image)

<table>
<thead>
<tr>
<th>Table I</th>
<th>COIL PARAMETERS GEOMETRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry design</td>
<td>H</td>
</tr>
<tr>
<td>200mm</td>
<td>200mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table III</th>
<th>COIL PARAMETERS GEOMETRY</th>
</tr>
</thead>
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<tr>
<td>Geometry design</td>
<td>d_1</td>
</tr>
<tr>
<td>40</td>
<td>47</td>
</tr>
</tbody>
</table>

Selection of steel is important to determine the number of turns of each coil. The magnetic performance of steel is dominated by its Carbene content, for example the steel grade AISI 1010 content less than 0.1% Carbon. According to BH curve Fig.5, the relationship becomes highly nonlinear at B \geq 1.5 Tesla and the material exhibits fully saturable behaviour at
B≥ 2 Tesla. The fully saturated behaviour is reached when the material permeability $\mu = \frac{\Delta B}{\mu_0 \Delta H} \equiv 1$ [8]. Eddy current losses within a transformer are reduced and controlled by reducing the thickness of the steel core. These laminations are insulated from each other by a covering of varnish or paper to increase the resistivity of the core, thus increasing the overall resistance to limit the flow of the eddy currents.

The Turn number of each coil of the autotransformer is calculated using Boucheron theorem as shown in Table 3.

$$N_{\text{coil}} = \frac{V_n \cdot 10^8}{4.44fBS}$$

(32)

Where:

- $V_n$: The rms voltage across a winding.
- $N$: Turn number of the coil.
- $B$: The magnetic field peak amplitude.
- $f$: the voltage frequency applied to the winding.
- $S$: the section of one limb magnetic circuit
- Sheet of steel used in simulation:
  - Steel material used: AISI 1010
  - Coefficients of iron losses in the model Bertotti: $\text{Hysteresis: } KH = 15.45, 10^{-3} [\text{SI}]$.
  - Additional: $KE = 3.2, 10^{-3} [\text{SI}]$.
  - Resistivity: $17.6, 10^6 [\Omega]$.
  - Thickness of sheet metal: $0.5, 10^{-3} [\text{m}]$.
  - Density: $7.85, 10^3 [\text{kg/m}^3]$.

![steel_1010](image)

**Fig. 5 BH Steel 1010 characteristics**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Evaluated Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia Leg</td>
<td>40 mm</td>
<td>40mm</td>
<td>Outer diameter of leg cross section</td>
<td></td>
</tr>
<tr>
<td>Dust Leg</td>
<td>80 mm</td>
<td>80mm</td>
<td>Leg center to center distance</td>
<td></td>
</tr>
<tr>
<td>Dust Yoke</td>
<td>160 mm</td>
<td>160mm</td>
<td>Yoke center to center distance</td>
<td></td>
</tr>
<tr>
<td>Stages</td>
<td>40</td>
<td>40</td>
<td>Number of stages of leg cross-section</td>
<td></td>
</tr>
<tr>
<td>Width Yoke</td>
<td>40 mm</td>
<td>40mm</td>
<td>Yoke width</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE III**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Evaluated Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary winding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil A1</td>
<td>62</td>
<td></td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>Coil A2</td>
<td>338</td>
<td></td>
<td>528</td>
<td></td>
</tr>
<tr>
<td>Coil A3</td>
<td>400</td>
<td></td>
<td>625</td>
<td></td>
</tr>
<tr>
<td>Secondary winding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil A4</td>
<td>117</td>
<td></td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>Coil A5</td>
<td>117</td>
<td></td>
<td>187</td>
<td></td>
</tr>
</tbody>
</table>

**WINDING PARAMETERS AND COILS TURN NUMBER**

- Magnetic field analysis
- Eddy currents and winding stray losses

IV. 2D, 3D MODELING OF THE PROPOSED AUTOTRANSFORMER

In transformers, finite element method can be used to calculate the following quantities [9]:

- Leakage inductance
- Short-circuit impedance

This work present the geometric design for resulting the flux density ‘B’, the field density ‘H’, current density ‘J’ and the flux line ‘A’ in the autotransformer with 40° phase shifting.

A. Geometry Design

Before entering the actual constructing step, the type of analysis should be noted, in this paper we used the transient magnetics problems characteristic magnetic field sizes vary with time. The geometric structure of the model shall be established from a preliminary design by standard methods or existing physical model. Input data (Core size, Coil size) shown in Table 2 and Table 3 may be entered numerically, in which case it follows a fixed pattern, either parametric form, in this case the geometry of the transformer with core simplified in order to reduce the complexity. We can bring the geometries directly and simplified it inside Maxwell. This solution, whereas initially more time-consuming, statement is preferable to a certain configuration optimization. At this step are defined regions that it is to be assigned different material properties [12].

**TABLE II PARAMETERS YOKE**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Evaluated Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia Leg</td>
<td>40</td>
<td>mm</td>
<td>40mm</td>
<td>Outer diameter of leg cross section</td>
</tr>
<tr>
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<td>80</td>
<td>mm</td>
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<td>Leg center to center distance</td>
</tr>
<tr>
<td>Dust Yoke</td>
<td>160</td>
<td>mm</td>
<td>160mm</td>
<td>Yoke center to center distance</td>
</tr>
<tr>
<td>Stages</td>
<td>40</td>
<td></td>
<td>40</td>
<td>Number of stages of leg cross-section</td>
</tr>
<tr>
<td>Width Yoke</td>
<td>40</td>
<td>mm</td>
<td>40mm</td>
<td>Yoke width</td>
</tr>
</tbody>
</table>

**TABLE II PARAMETERS COIL**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Evaluated Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia Leg</td>
<td>80</td>
<td>mm</td>
<td>80mm</td>
<td>Leg center to center distance</td>
</tr>
<tr>
<td>Coil Type</td>
<td>1</td>
<td></td>
<td>1</td>
<td>Coil type: 1 for solenoide coil; 2 for pancake coil</td>
</tr>
<tr>
<td>Width In</td>
<td>41</td>
<td>mm</td>
<td>41mm</td>
<td>Coil width between tow inner sides</td>
</tr>
<tr>
<td>Depth In</td>
<td>41</td>
<td>mm</td>
<td>41mm</td>
<td>Coil depth between two inner ends</td>
</tr>
<tr>
<td>Radius In</td>
<td>30</td>
<td>mm</td>
<td>30mm</td>
<td>Coil inner fillet radius</td>
</tr>
<tr>
<td>Thick Coil</td>
<td>2</td>
<td>mm</td>
<td>2mm</td>
<td>Coil thickness of one side</td>
</tr>
<tr>
<td>High Coil</td>
<td>119</td>
<td>mm</td>
<td>119mm</td>
<td>Coil height</td>
</tr>
</tbody>
</table>

B. Mesh Operations

When the geometry is prepared, it is then divided in to small finite elements [11]. The size of each mesh or element consists in dividing the field of study in geometry characterized by the presence of specific points, called nodes. The most elements geometric used are the triangle nodes are placed in three corners of its Fig. 6.
Usually the meshing operation is automatic, with network generator included in the program.

V. RESULT AND DISCUSSION

The proposed delta connected autotransformer based an 18-pulse converter is modelled and designed for resistive load and validated with an experimental prototype realized in the laboratory MMA shown in Fig. 7.

The topology of 18-pulse ac-dc converters illustrated in Fig. 8 (a) gives an output continuous voltage with fewer ripples in the waveform. Moreover, between 0.02s and 0.04s, means that during 20ms we can view the 18 undulations which is provided by this topology means three times of six pulse configuration. These results are validated by the experimental finding in Fig. 10 (a) which gives an output voltage and an output current closer to the continuous signal.

The waveform of input current shown in Fig. 8 (b) is clear sinusoidal and improves harmonics in network side. Then it’s validated by the experimental outcomes shown in Fig. 10 (b).

The total harmonic distortion “THD” of the input current in network side shown in Fig. 9 is with THD current = 7.98%, then this connection of autotransformer capable to suppress harmonic up to 13th and minimize the THD of the source current.
The uniform flux density ‘B’ distribution in the iron core as shown in Fig. 11(a), represent a healthy magnetic circuit, the color represents the amplitude of the magnetic flux, red being high amplitude. Fig. 11(b) shows the field intensity ‘H’ between primary and secondary windings. The current density ‘J’ is presented in Fig. 11(c). Fig. 11(d) presents the line flux of the autotransformer and is clear that it is completely concentrated in the iron core.

VI. CONCLUSIONS

The simulation results shows that the proposed Delta-connected autotransformer have a great advantage. Indeed this design offers a best quality of output current and voltage compared with the two configurations 6-pulse and 12-pulse. This design proves the elimination of the harmonic with order 5th, 7th, 11th and 13th. Then, the magnetic field analysis (the flux density, the field density, the current density and flux lines) of power transformer are presented using the Maxwell ANSYS 2D and 3D software, the results show the validity of this program and present the healthy magnetic circuit of the proposed autotransformer. Finally, Future works will focus on other simulation for the circuit equivalent calculation (leakage inductance and short circuit impedance), in addition on other topologies who give better THD coefficient such as another design of auto-connected with another special coupling and topologies of 24 pulses.

REFERENCES


