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Rectifier Transformer Modelling
Using SABER

Francis CALMON (CERN CN-CE-AE)
Francis.Calmon@cern.ch

Knud DAHLERUP-PETERSEN (CERN SL-PC)
Knud.Petersen@macmail.cern.ch
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1. Three-phase rectifier transformer modelling

1.1. Introduction

This grid-frequency (50 Hz), high-power, rectifier transformer model provides the means to simulate accurately the magnetising steady state currents, the inrush currents (transformer turn-on phase) and the short-circuit impedance \( \left( Z_{sc} \right) \) in a bridge circuit configuration.

Based on the geometrical description of the transformer (Figure 1) and the properties of the magnetic core material (manufacturer’s data sheets), an equivalent model is built for the SABER software (Figure 2) based on reference [4]. Each magnetic element of the transformer is described with an associated magnetic core. Air cores in series may be added to take into account the air gaps between the limbs and the yokes (Figure 1). Such air gaps are either deliberately introduced or represent imperfection in the joints. The flux leakage during the saturation of the magnetic material (when \( \mu_r \rightarrow 1 \)) is simulated with additional air cores in parallel with the cores of the magnetic material (Figure 2). These air cores represent the different flux paths between the windings and the limbs.

The transformer model includes electrical and magnetic variables. The template \textit{wind.sin} (already available in SABER) provides the connection between these variables (Table 1) [6]. This winding template has two electrical pins and two magnetic pins.

<table>
<thead>
<tr>
<th>Number of pins and type</th>
<th>Magnetic variables</th>
<th>Electrical variables</th>
<th>Basic relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{wind.sin}</td>
<td>mmf : magnetomotive force</td>
<td>v : voltage</td>
<td>mmf = i*n</td>
</tr>
<tr>
<td>\textit{core.sin}</td>
<td>mmf : magnetomotive force</td>
<td>i : current</td>
<td>(n number of turns)</td>
</tr>
<tr>
<td>(magnetic material core)</td>
<td>f : flux</td>
<td>v = d(n<em>f)/dt + r</em>i</td>
<td>( r : ) winding resistance</td>
</tr>
<tr>
<td></td>
<td>f : flux</td>
<td>none</td>
<td>mmf = H*length</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(H : magnetic excitation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B = \mu_0<em>mu_r</em>H</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(B : induction, \mu_0*mu_r : magnetic permeability)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>f = B*area</td>
</tr>
</tbody>
</table>

![Figure 1: Transformer cross section](image)

Table 1: Electrical and magnetic variables in \textit{wind.sin} and \textit{core.sin}

The linear air core template \textit{core.sin} with \( \mu_r = \text{constant} = 1 \) is already available in the SABER library [7]. The main part of our work consisted in creating the magnetic material core template (a non-linear model). Depending on the simulated phenomena, the user chooses the appropriate magnetic material core model (Table 2). The magnetic material properties are represented by the B (induction) versus H (magnetising force) curve. In order to simulate the steady state magnetising currents, the hysteresis cycle must be taken into account.
1.2. **Non-linear core model**

Table 2 presents the choice of the appropriate magnetic material core model. The simulation of the steady state magnetising currents of the transformer requires an accurate model of the magnetic properties of the non-linear cores. In this case, the core model must include the hysteresis effect (see §1.2.1.). This can be ignored while simulating the inrush currents (during the turn-on of the transformer) and the transformer behaviour when connected to a full bridge (see §1.2.2.).

<table>
<thead>
<tr>
<th>Simulation of:</th>
<th>Appropriate core model:</th>
<th>Remark about the transformer model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state magnetising currents</td>
<td>B-H curves with hysteresis.</td>
<td>The flux flows completely through the magnetic material =&gt; no need of parallel air core, except series air cores representing air gaps between the limbs and the yokes (Figure 2).</td>
</tr>
<tr>
<td>Inrush currents</td>
<td>B-H curves without hysteresis. Available core models for the materials: Orsi 97, Orsi 111, M 5, 27zh95.</td>
<td>Need a full description of the transformer: magnetic cores and parallel air cores (flux leakage between the windings and the core during magnetic material saturation)</td>
</tr>
<tr>
<td>Bridge</td>
<td>B-H curves without hysteresis. Available core models for the material: Orsi 97, Orsi 111, M 5, 27zh95.</td>
<td>As for inrush currents. Need a full description of the transformer</td>
</tr>
</tbody>
</table>

Table 2: Transformer modelling methodology
1.2.1. Core model with hysteresis effect

The magnetic properties of the material are described by the B (induction) versus H (magnetisation force) curve. In this section we present two non-linear core models including the hysteresis cycle.

1.2.1.1. Jiles-Atherton model

SABER already includes a physical model of the magnetic material properties based on the work of D. C. Jiles & D. L. Atherton [2][8]. There are two ways to implement the parameters of this model: the user can directly specify the physical parameters of the Jiles-Atherton model \( (M_m, H_m, M_r, \alpha) \), or SABER will calculate a set of parameters from the measurable hysteresis cycle \( (u_i, u_{hc}, b_{max}, h_{max}, b_{sat}, h_{sat}, b_r, h_c) \). The second method appears to be more useful because the hysteresis cycle characteristics are available from the manufacturer’s data sheets. However, SABER may have some difficulties in extracting the correct set of physical parameters [5].

![Figure 3: Hysteresis cycle from Jiles-Atherton model and J. H. Chan model](image)

1.2.1.2. J. H. Chan model

We propose an alternative method using a behavioural model. This new core template `chan_core.sin` built from the data given in reference [3] is very useful because the user has to specify only three parameters:
- \( b_r \): remanence,
- \( b_{sat} \): saturation,
- \( H_c \): coercive force.

The B-H cycle is calculated using two hyperbolic functions (one for the upper branch and one for the lower branch, Equations 1 & 2).
The set of parameters \{parl, par2, par6, const1, const3\} depends on the magnetic material.

Figure 4: Part of the core template \((m27zh95\_core.sin)\): analytical expression \(B\) versus \(H\)

\[
B' = \frac{B'_+(H) + B'_-(H)}{2}
\]

The final induction \(B\) is calculated using the equation 3:

\[
B = B' + \mu_0 H
\]

The anhysteretic curve (1\(^{n}\) magnetisation) is calculated as follows (Equation 4):

\[
B_1 = B'_+(H) + B'_-(H)
\]

Remark: The J. H. Chan core model cannot be used in the simulation of the inrush currents because it is not accurate for these large excitation values.

1.2.2. Core model without hysteresis effect

From the DC magnetising curve provided by the manufacturer, several models have been built using the MAST language from the SABER simulator. The different magnetic materials are Orsi 97, Orsi 111, M 5 and 27ZH95.

We propose two possibilities:

1/ The core model reads the couples of values \([H, B]\) in a table from an existing file and the model calls a C-language routine. This method works well, but is time consuming, and the simulation time increases drastically when the transformer model contains several cores (as in the case of a three-phase transformer).

2/ For more complex cores, it seems easier to use an analytical expression of \(B\) versus \(H\). We choose an hyperbolic tangent function (Equation 5) with at least six parameters (par1, par2 ... par6). These can be determined using PAW [9] or MATHCAD.

\[
B = par1*\text{tanh} \left( \frac{par2*H^{par3}}{par4+par5*H^{par6}} \right)
\]

In addition, we add to the previous equation some terms to fit the analytical curve for large values of the magnetising force, \(H\) (see Figure 4).

```c
if (h>0) {sign=1; else if (h<0) {sign=-1; else sign=0; if (abs(h)<25) {modul=0; else modul=1; if (abs(h)<80) {modul0=0; else modul0=1; if (abs(h)<850) {modul12=0; else modul12=1; int = par2*sign*(abs(h))**par3/(par4+par5*(abs(h))**par6)); b = par1*tanh(int) +4*\text{math}_p1*1e-7*h -sign*modul*const1*(log(abs(h))-log(25)) -sign*modul*const2*(log(abs(h))-log(80)) -sign*modul*const3*(log(abs(h))-log(850))}
```

Figure 4: Part of the core template \((m27zh95\_core.sin)\): analytical expression \(B\) versus \(H\)

The set of parameters \{par1, par2 ... par6, const1 ... const3\} depends on the magnetic material.
Figure 5 presents the B-H curves obtained with the data table (m27zh95_core_tbl.sin template) and with the analytical expression (m27zh95_core_sin template).

1.3. Example 1: A three-phase model for a dry type transformer

Figure 6 presents the template of a 342 kVA, water-cooled, cast-resin rectifier transformer used in a LHC pre-studies converter (see Appendix 1 for transformer characteristics). Its equivalent circuit is presented in Figure 2.
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```plaintext
# Inside diameter of primary delta portion winding
number pd_inside_diam=0.221
# Outside diameter of primary delta portion winding
number pd_outside_diam=0.243
# Inside diameter of primary extended delta portion winding
number px_inside_diam=0.267
# Outside diameter of primary extended delta portion winding
number px_outside_diam=0.289
# Inside diameter of secondary winding
number s_inside_diam=0.329
# Outside diameter of secondary winding
number s_outside_diam=0.359
# Height of the windings (< h)
number winding_height=0.56
# Length of each air gap (2 per limbs)
number len_air_gap=5e-4

<consts.sin

********************************************************************** electrical netlist **********************************************************************

# primary coupling in extended delta

# delta part of primary windings
wind.p3 em:int1 ep:int2 mm:m2 mp:m3 = rs, nspd # primary windig 1st
wind.p3 em:int2 ep:int3 mm:m1 mp:m6 = rs, nsxd # primary winding 2nd
wind.p3 em:int3 ep:int1 mm:m9 mp:m8 = rs, nspd # primary winding 3rd

# extended delta part of primary windings
wind.p3 em:int2 ep:int1 mm:m22 mp:m22 = rs, nspx, nspx # primary winding 1st
wind.p3 em:int3 ep:int2 mm:m11 mp:m11 = rs, nspx, nspx # primary winding 2nd
wind.p3 em:int1 ep:int3 mm:m99 mp:m99 = rs, nspx, nspx # primary winding 3rd

# secondary coupling in Y
wind.s1 em:gd ep:op1 mm:mm22 mp:mm22 = rs, nsx, nsp # secondary windig 1st
wind.s2 em:gd ep:op2 mm:mm11 mp:mm11 = rs, nsx, nsp # secondary windig 2nd
wind.s3 em:gd ep:op3 mm:mm99 mp:mm99 = rs, nsx, nsp # secondary windig 3rd

r.int1 int:0 0 = 100meg # electrical reference
r.int2 int:0 0 = 100meg # electrical reference
r.int3 int:0 0 = 100meg # electrical reference

********************************************************************** magnetic netlist **********************************************************************

# Parallel air cores

# between primary delta portion winding and limb
number len_r1=limb_length
number area_r1=math_pi*(pd_inside_diam-pd_outside_diam)/4)**2

- limb_area
  core.R11 mm:m3 pm:m3 = area-area_r1, len=len_r1, ur=1
  core.R12 mm:m6 pm:m6 = area-area_r1, len=len_r1, ur=1
  core.R13 mm:m8 pm:m8 = area-area_r1, len=len_r1, ur=1

# between primary x portion and primary delta portion windings
number len_r2=limb_length
number area_r2=math_pi*((px_inside_diam+px_outside_diam)/4)**2

- limb_area
  core.R21 mm:m22 pm:m3 = area-area_r2, len=len_r2, ur=1, geo_units=micrometer
  core.R22 mm:m11 pm:m6 = area-area_r2, len=len_r2, ur=1, geo_units=micrometer
  core.R23 mm:m99 pm:m88 = area-area_r2, len=len_r2, ur=1, geo_units=micrometer

# between secondary winding and primary x portion winding
number len_r3=limb_length
number area_r3=math_pi*(s_inside_diam+s_outside_diam)/4)**2

- limb_area
  core.R31 mm:m222 pm:m33 = area-area_r3, len=len_r3, ur=1, geo_units=micrometer
  core.R32 mm:m111 pm:m66 = area-area_r3, len=len_r3, ur=1, geo_units=micrometer
  core.R33 mm:m999 pm:m888 = area-area_r3, len=len_r3, ur=1, geo_units=micrometer

# parallel to the limbs (leakage return path)
number len_r4=h # or winding_height
number area_r4=area
# arbitrary choice
core.R41 mm:m4 pm:m4 = area-area_r4, len=len_r4, ur=1, geo_units=micrometer
core.R42 mm:m5 pm:m5 = area-area_r4, len=len_r4, ur=1, geo_units=micrometer
core.R43 mm:m6 pm:7 = area-area_r4, len=len_r4, ur=1, geo_units=micrometer
```

---

8
Figure 6: Template of the cast-resin transformer

The primary windings are \texttt{wind.p1d}, \texttt{wind.p2d} and \texttt{wind.p3d} (delta parts) and \texttt{wind.p1x}, \texttt{wind.p2x} and \texttt{wind.p3x} (extension parts). The secondary windings are \texttt{wind.s1}, \texttt{wind.s2} and \texttt{wind.s3} (coupling in star). The magnetic material is described with 5 elements: \texttt{m27zh95.core.R11} (limb 1), \texttt{m27zh95.core.R12} (limb 2), \texttt{m27zh95.core.R13} (limb 3), \texttt{m27zh95.core.Ruly} (upper left yoke), \texttt{m27zh95.core.Rury} (upper right yoke), \texttt{m27zh95.core.Rlly} (lower left yoke), \texttt{m27zh95.core.Rryl} (lower right yoke). The transformer contains 2 deliberately introduced air gaps per limb. They are represented by \texttt{core.Rag1} and \texttt{core.Rag4} (limb 1), \texttt{core.Rag2} and \texttt{core.Rag5} (limb 2), \texttt{core.Rag3} and \texttt{core.Rag6} (limb 3). To take into account the flux leakage during magnetic material saturation, additional air cores in parallel with the limbs are introduced (\texttt{n} is the limb number 1, 2 or 3): \texttt{core.R1n} (leakage between primary delta portion winding and limb core), \texttt{core.R2n} (leakage between primary extended delta portion winding and primary delta portion winding), \texttt{core.R3n} (leakage between secondary winding and primary extended delta portion winding), \texttt{core.R4n} (leakage return path). The areas and length of the air cores are calculated from the geometrical description of the transformer, as given by the manufacturer.

2. Simulation of the steady state magnetising currents

The down-transformer TR 1/2 of the LEP Klystron converters has been modelled. A previous study has been made of this unit, including the theoretical calculations of the magnetising currents (see reference [1]). The magnetic circuit of the transformer is subdivided: each magnetic core part is described by a non-linear model (i.e., the limbs and half of the yokes). The simulations of the steady state magnetising currents concern only the magnetic material. The flux flows entirely through the magnetic material, the flux leakage through the air being negligible.

The simulations of the steady state magnetising currents require an accurate description of the magnetic material characteristic \(B\) versus \(H\). We need to take into account the hysteresis cycle. We can use either the Jiles-Atherton model (§ 1.2.1.1.) or the J. H. Chan model (§ 1.2.1.2.).

The circuit includes only 3 sinusoidal sources connected to the primary of the transformer via 3 impedances limiting the apparent power of the net. The secondary of the transformer is opened. To avoid large inrush currents, the applied voltage to the transformer primary was slowly increased from zero to the nominal value with a rise time of about 200 ms.

Figure 7 presents the simulated steady state magnetising currents which are in agreement with a previous study [1].
3. Simulation of the inrush currents

This section is illustrated with data from the 342 kVA cast-resin transformer. We need here to describe the magnetic material and also the flux leakage through the air (insertion of parallel air cores). The B-H curve of the magnetic material must be available for a large range of H values and hysteresis effects may be ignored (Table 2). The test circuit is similar to that used in the previous chapter, but with full nominal voltage applied to the transformer primary at turn-on. Simulated results are compared with available measurements [12].

The line impedances $Z$ between the transformer and the sinusoidal voltage sources are related to the apparent power of the net with the following expression:

$$Z = \frac{U_{ph-ph}^2}{S}$$

with $U_{ph-ph}$ being the r.m.s. voltage (phase to phase) and $S$ the apparent power of the net in VA.

The line impedances $Z$ are important since they have a strong impact on the maximum inrush current level (1st peak). Furthermore, the inrush current damping is lower when the impedance is mainly inductive (worst case). In reference [12], the measurements of the inrush currents have been performed with a net power of 35 MVA, giving $Z = 4.5$ mΩ. We assume that the line impedance is 100% inductive (14.4 μH).
4. Simulation with a six-pulse thyristor converter

The circuit is presented in Figure 9. The transformer model again refers to the 342 kVA cast-resin transformer. The thyristor model used was developed by A. COURTAY [10].

The transformer short-circuit impedance $\varepsilon_s$ (in %) is related to the winding inductance as follows:

$$X = 2.\pi f L = U_{ph-ph} \frac{\varepsilon_s \text{ (in %)}}{100 \sqrt{3} I_n}$$  \hspace{1cm} (7)

with $f$ : frequency, $L$ : winding inductance, $I_n$ : nominal current.

Normally the load current passes through 2 thyristors (one in each half of the bridge). When the current is switched from one thyristor to another (in each half bridge) there is a brief moment of short-circuit between 2 phases [11]. The total inductance (i.e. the sum of the short-circuit inductance of the transformer plus the line inductance) determines the current decrease ($\text{di/dt}$) when one thyristor turns off and the following thyristor turns on (Figure 10). The duration of the overlap, during which the current is switched from one thyristor to another, is proportional to the total inductance. Therefore, the efficiency of the bridge depends on the inductance of the transformer. If the inductance is large, the thyristor switching phases are slow and the filtered voltage at the output of the bridge decreases (Figure 11). In order to keep a given current in the load, the user has to increase the size of the transformer.

From measurements $\varepsilon_s$ is about 5.7 % to 6 %. The output voltage is the sinusoidal part of a six-phase system (Figure 11).
Figure 9: Rectifier transformer connected to a three-phase bridge

Figure 10: Thyristor switching phases (simulation without line inductance)
5. TR 8 transformer modelling

TR 8 is a 6.68 MVA oil-immersed rectifier transformer for the Main Bend converters of LEP2. Its geometrical and electrical characteristics are presented in Appendix 1. Appendix 2 presents the user note of the `transformer_1b.sin` template which corresponds to the TR 8 transformer. The table below shows the comparisons between measurements and simulations.

<table>
<thead>
<tr>
<th>Magnitude of inrush current (worst case)</th>
<th>Short-circuit behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured 1100 A</td>
<td>6.6 % / 24 µH</td>
</tr>
<tr>
<td>simulated 1350 A</td>
<td>5.5 % / 20 µH</td>
</tr>
</tbody>
</table>

Table 3: TR 8 simulation

6. Summary of developed models

The following models are available at CERN:
- `transformer_1.sin`: generic power transformer model, primary: extended delta (inside), secondary: star (outside),
- `transformer_1b.sin`: generic power transformer model, primary: extended delta (outside), secondary: star (inside),
- `transformer_2.sin`: generic power transformer model, primary: delta (outside), secondary: star (inside),
- `tr8.sin`: TR 8 transformer model (6.68 MVA, oil-immersed),
- `dthg400.sin`: RAMP transformer model (342 kVA, cast-resin type, water-cooled secondary),
- `m5_core.sin`: core model without hysteresis, material M 5.
7. Conclusion

The modelling of grid-frequency (50 Hz) high-power rectifier transformers has been presented. Each transformer magnetic element is described with an associated magnetic core. The main part of our work consisted in creating the magnetic material core models for the most commonly used materials. Simulation results including magnetising and inrush currents as well as operation with a 6-pulse thyristor give satisfactory comparison with measured data.

8. Acknowledgments

The authors would like to thank Messrs. H. Mattausch and V. Richter of the company "Starkstrom Gerätebau" Regensburg FRG for supplying the detailed transformer data which were not already available at CERN. Thanks are also given to C. Eck, R. Zürbuchen and J. Evans from the CN-CE Group.

9. References


[12] Inrush currents measurements of the RAMP Rectifier Transformer, Company "Starkstrom Gerätebau", Regensburg, FRG.

10. Appendix 1 : Description of TR 1/2, TR 3/4, Cast-resin RAMP transformer & TR 8

<table>
<thead>
<tr>
<th>TR 1/2</th>
<th>TR 3/4</th>
<th>Cast-resin RAMP trfo</th>
<th>TR 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Starkstrom</td>
<td>Starkstrom</td>
<td>Starkstrom</td>
</tr>
<tr>
<td>Magnetic material</td>
<td>M5</td>
<td>M5</td>
<td>Starkstrom</td>
</tr>
<tr>
<td>Power</td>
<td>2 x 2945 kVA</td>
<td>2 x 2945 kVA</td>
<td>342 kVA</td>
</tr>
<tr>
<td>Primary coupling</td>
<td>extended delta</td>
<td>delta</td>
<td>extended delta</td>
</tr>
<tr>
<td>Secondary coupling</td>
<td>star</td>
<td>star</td>
<td>star</td>
</tr>
<tr>
<td>Primary r.m.s. voltage (phase to phase)</td>
<td>18 kV</td>
<td>1000 V</td>
<td>400 V</td>
</tr>
<tr>
<td>Secondary r.m.s. voltage</td>
<td>1000 V</td>
<td>52 kV</td>
<td>55.2 V</td>
</tr>
<tr>
<td>Primary : number of turns</td>
<td>star = 335</td>
<td>delta = 581</td>
<td>star : 15</td>
</tr>
<tr>
<td>Secondary : number of turns</td>
<td>36</td>
<td>1407</td>
<td>14</td>
</tr>
<tr>
<td>B_n - T</td>
<td>1.493</td>
<td>1.345</td>
<td>1.340 (limb)</td>
</tr>
<tr>
<td>h : height of the limbs - m</td>
<td>1.722</td>
<td>1.915</td>
<td>0.67</td>
</tr>
<tr>
<td>l : length of the yokes - m</td>
<td>0.752</td>
<td>0.625</td>
<td>0.785</td>
</tr>
<tr>
<td>Primary winding resistance - mΩ</td>
<td>320</td>
<td>7.0</td>
<td>320</td>
</tr>
<tr>
<td>Secondary winding resistance - mΩ</td>
<td>1.5</td>
<td>3.2</td>
<td>0.115</td>
</tr>
<tr>
<td>Surface - m²</td>
<td>0.048374</td>
<td>0.071213</td>
<td>0.02675 (limb)</td>
</tr>
<tr>
<td>Air gaps</td>
<td>none</td>
<td>none</td>
<td>2 per limb each one 0.5 mm</td>
</tr>
<tr>
<td>Primary winding diameter (inside / outside) - mm</td>
<td></td>
<td></td>
<td>delta : 221/243</td>
</tr>
<tr>
<td>Secondary winding diameter (inside / outside) - mm</td>
<td></td>
<td></td>
<td>star : 267/289</td>
</tr>
</tbody>
</table>

Table 4 : Geometrical characteristics

<table>
<thead>
<tr>
<th>TR 1/2</th>
<th>TR 3/4</th>
<th>Cast-resin RAMP trfo</th>
<th>TR 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{magmax}} - A$</td>
<td>$i_{m1} = 0.152 A$</td>
<td>$i_{m1} = 1.77 A$</td>
<td>$i_{R} = 0.360 A$</td>
</tr>
<tr>
<td></td>
<td>$i_{m2} = 0.070 A$</td>
<td>$i_{m2} = 1.07 A$</td>
<td>$i_{S} = 0.277 A$</td>
</tr>
<tr>
<td></td>
<td>$i_{m3} = 0.160 A$</td>
<td>$i_{g} = 1.07 A$</td>
<td>$i_{T} = 0.356 A$</td>
</tr>
<tr>
<td>$I_{\text{annih}} - A$</td>
<td>$i_{R} = -230 A$</td>
<td>22560 A</td>
<td>see measurements [12]</td>
</tr>
<tr>
<td></td>
<td>$i_{S} = 683 A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$i_{T} = -453 A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$h_{\text{air}} = 1.21 m$, $B_{n} = 1.494 T$, $A_{\text{m}} = 1486.10^{4}$ m², $A_{\text{w}} = 483.7.10^{4}$ m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon$ (%)</td>
<td>6.9 %</td>
<td>7.1 %</td>
<td>5.7 to 6.0 %</td>
</tr>
</tbody>
</table>

Table 5 : Electrical characteristics
11. Appendix 2 : User note of transformer_1b.sin template

**transformer_1b.sin**  (generic power transformer model)

```
template transformer_1b    ip1, ip2, ip3, op1, op2, op3, gnd =
                          npx, npd, ns, npx, npd, rs, h, l, limb_area, yoke_area, pd_inside_diam,
                          pd_outside_diam, px_inside_diam, px_outside_diam, s_inside_diam,
                          s_outside_diam, winding_height, len_air_gap
```

**Description**

From the geometrical description of the transformer and the magnetic material properties (manufacturer's data sheets), an equivalent model is built for SABER software based on article [1]. Each magnetic element of the transformer is described with an associated magnetic core model. Air cores in series may be added to take into account the air gaps between the limbs and the yokes (see figure below). Such air gaps are either deliberately introduced or represent imperfection in the joints. The flux leakage during the saturation of the magnetic material (when \( \mu_s \rightarrow 1 \)) is simulated with additional air cores in parallel with the magnetic material cores. These air cores represent the different flux paths between the windings and the limbs.

This generic power transformer can be used to simulate the magnetising steady state currents, the inrush currents (transformer turn-on phase). It can also be used in a bridge circuit configuration and presents a satisfactory representation of the short-circuit impedance (\( e_s \)).

The equivalent circuit of the transformer model is presented on the following figure. The coupling of the primary windings is an extended delta (outside) and the coupling of the secondary is a star (inside). The transformer model contains electrical and magnetic variables. The template `wind.sin` (already available in SABER) provides the connection between these variables [2] [3]. This winding template contains two electrical pins and two magnetic pins. The magnetic elements can be linear (air cores). In this case the template `core.sin` (already available in SABER) is used with \( \mu_s = 1 \). The magnetic material properties are non-linear. The table below presents the choice methodology of the magnetic material core model. The simulation of the steady state magnetising currents requires an accurate model of the magnetic properties. We use in this case a core model including the hysteresis effect. Otherwise the simulations of the inrush currents (during the turn-on of the transformer) and the transformer behaviour in a full bridge do not require to take into account the hysteresis effect [3].

More information can be found in the note "Rectifier transformer modelling using SABER" [3]
### Transformer model

(electrical and magnetic equivalent circuits)

<table>
<thead>
<tr>
<th>Simulation of</th>
<th>Choice of the appropriated core model:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inrush currents</strong></td>
<td>B-H curves without hysteresis. Available core models for the materials: Orsi 97, Orsi 111, M 5, 27zh95 (see [3]).</td>
</tr>
<tr>
<td><strong>Bridge</strong></td>
<td>B-H curves without hysteresis. Available core models for the materials: Orsi 97, Orsi 111, M 5, 27zh95 (see [3]).</td>
</tr>
</tbody>
</table>

Transformer modelling methodology

### Connection pins

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ip1</td>
<td>electrical</td>
<td>primary input 1st winding</td>
</tr>
<tr>
<td>ip2</td>
<td>electrical</td>
<td>primary input 2nd winding</td>
</tr>
<tr>
<td>ip3</td>
<td>electrical</td>
<td>primary input 3rd winding</td>
</tr>
<tr>
<td>op1</td>
<td>electrical</td>
<td>secondary output 1st winding</td>
</tr>
<tr>
<td>op2</td>
<td>electrical</td>
<td>secondary output 2nd winding</td>
</tr>
<tr>
<td>op3</td>
<td>electrical</td>
<td>secondary output 3rd winding</td>
</tr>
<tr>
<td>gnd</td>
<td>electrical</td>
<td>common point of the secondary windings</td>
</tr>
</tbody>
</table>

primary: extended delta (outside)

secondary: star (inside)
Input parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Default</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>npx</td>
<td>75</td>
<td>-</td>
<td>number of turns of primary windings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(extended delta portion)</td>
</tr>
<tr>
<td>npd</td>
<td>381</td>
<td>-</td>
<td>number of turns of primary windings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(delta portion)</td>
</tr>
<tr>
<td>ns</td>
<td>14</td>
<td>-</td>
<td>number of turns of secondary windings</td>
</tr>
<tr>
<td>rpx</td>
<td>38.4m</td>
<td>Ω</td>
<td>resistance of primary windings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(extended delta portion)</td>
</tr>
<tr>
<td>rpd</td>
<td>347m</td>
<td>Ω</td>
<td>resistance of primary windings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(delta portion)</td>
</tr>
<tr>
<td>rs</td>
<td>0.21m</td>
<td>Ω</td>
<td>resistance of secondary windings</td>
</tr>
<tr>
<td>h</td>
<td>1.08</td>
<td>m</td>
<td>height of the hole between lower and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>upper yokes</td>
</tr>
<tr>
<td>l</td>
<td>1.38</td>
<td>m</td>
<td>total length of the transformer</td>
</tr>
<tr>
<td>limb_area</td>
<td>0.1139</td>
<td>m²</td>
<td>cross section area of the limbs</td>
</tr>
<tr>
<td>yoke_area</td>
<td>0.1139</td>
<td>m²</td>
<td>cross section area of the yokes</td>
</tr>
<tr>
<td>pd_inside_diam</td>
<td>0.570</td>
<td>m</td>
<td>inside diameter of the primary delta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>portion winding</td>
</tr>
<tr>
<td>pd_outside_diam</td>
<td>0.640</td>
<td>m</td>
<td>outside diameter of the primary delta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>portion winding</td>
</tr>
<tr>
<td>px_inside_diam</td>
<td>0.643</td>
<td>m</td>
<td>inside diameter of the primary extended delta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>portion winding</td>
</tr>
<tr>
<td>px_outside_diam</td>
<td>0.647</td>
<td>m</td>
<td>outside diameter of the primary extended delta</td>
</tr>
<tr>
<td></td>
<td>s_inside_diam</td>
<td>0.445</td>
<td>inside diameter of the secondary winding</td>
</tr>
<tr>
<td>s_outside_diam</td>
<td>0.566</td>
<td>m</td>
<td>outside diameter of the secondary winding</td>
</tr>
<tr>
<td>winding_height</td>
<td>1.08</td>
<td>m</td>
<td>height of the windings</td>
</tr>
<tr>
<td>len_air_gap</td>
<td>30μ</td>
<td>m</td>
<td>length of each air gap (2 per limb)</td>
</tr>
</tbody>
</table>

Remark: px_outside_diam > px_inside_diam > pd_outside_diam > pd_inside_diam > s_outside_diam > s_inside_diam

The default parameters correspond to the transformer TR 8 [3]. The default non-linear core corresponds to the magnetic material Orsi 97 (template orsi_97_core.sin).

Post processing informations

The magnetic variables of the non-linear core model are available for post-processing under the grouping name variables. The SABER signal list may be specified as follows:

```
/ /transformer_1b.<name>/orsi_97_core.*/variables or / /.../variables
```

Netlist example

In the netlist below, the transformer is connected to three sine sources through three inductances. This circuit is used to simulate inrush currents.

```
# 3 sine sources (source2.sin template)
#
source2.T out:R ground:0 = v1=0, vh=360, freq=50, retard=240, rise_time=0m
source2.T out:S ground:0 = v1=0, vh=360, freq=50, retard=120, rise_time=0m
source2.R out:T ground:0 = v1=0, vh=360, freq=50, retard=0, rise_time=0m
```

18
Rectifier Transformer Modelling Using SABER

Usage notes

The user can modify the script of the model to replace the non-linear core model. The default model is orsi_97_core.sin, but the user can specify:

- orsi_111_core.sin (material Orsi 111, model without hysteresis),
- m27zh95_core.sin (material 27ZH95, model without hysteresis),
- m5_core.sin (material M 5, model without hysteresis),
- chan_core.sin (generic core model with or without hysteresis [3] [5]),
- coreui.sin (Jiles-Atherton model [2] [4]).

References


