On the calculation of fluxlinkage/current-characteristics for Δ-coupled transformer windings

Nicola Chiesa                     Dept. of Electrical Engineering / NTNU
NTNU, Norway                      N-7491, Trondheim, Norway
chiesa@stud.ntnu.no

Hans K. Hoidalen                  Dept. of Electrical Engineering / NTNU
NTNU, Norway                      N-7491, Trondheim, Norway
hans.hoidalen@elkraft.ntnu.no

Abstract - This paper concerns the modelling of the transformers magnetization curve. A new SATURA-like routine has been developed. It is called “rms2peak” and calculates the λ/i values of the magnetizing curve from \( U_{\text{rms}}/I_{\text{rms}} \) values taking the type of winding coupling into account (Y or Δ). The new approach gives improvement in the case of delta coupling. A study case is analyzed and the results for the two methods are compared. The “rms2peak” routine can gives accurate results when a proper set of data is known. This routine has been written for the new ATPDraw component “XFMR”.

Keywords: transformers, SATURA, rms2peak, magnetization curve, XFMR, coupling.

1 Introduction

The core nonlinearities of a transformer are represented by the magnetization curve. In ATP-EMTP the magnetization curve can be obtained using the “SATURA” routine [1]. This routine converts the measured \( U_{\text{rms}}-I_{\text{rms}} \) test report values into the \( \lambda-i \) (fluxlinked-current) characteristic. The issue here is how to handle 3-phase transformers and the relation between line and phase currents. Traditionally it is assumed that the phase current for a Δ-connected winding is equal to the line current divided by \( \sqrt{3} \). This is however a doubtful assumption since the involved currents are not sinusoidal.

![Figure 1: Definition of line and phase current for Δ and Y coupling.](image)

The solution proposed in this paper deals directly with the phase currents. A new routine called “rms2peak” has been developed and used for the new ATPDraw component “XFMR”, see [4]. The efficiency of the new routine is tested in this paper and its results are compared with the ones obtained with the standard “SATURA” routine.
2 The “rms2peak” routines

The nonlinear magnetization characteristic relates the flux linkage to the phase current. Such curves can be derived using RMS voltage-current readings. With an impressed sinusoidal voltage, an RMS reading of the line non-sinusoidal current is obtained. The user inputs the RMS measured values of the v-i curve as a sequence of points, assuming linear interpolation between the values. The output λ-i curve (peak values) is piecewise-linear. Transformer open-circuit test-report gives the RMS line values of voltage and current. However, the “SATURA” routine requires as input the phase values of voltage and current, see [1], [2]. In case of wye coupling the line current is equal to the phase current, so no

![Diagram of SATURA routine](image1)

**Figure 2:** Fundamentals of the “SATURA” routine.

![Diagram of rms2peak routine](image2)

**Figure 3:** Fundamentals of the “rms2peak” routine.
conversion is needed. The factor \( \sqrt{3} \) is used to obtain the phase voltage due to an impressed sinusoidal voltage. The case of delta coupling requires more considerations: it is assumed that the phase current for a \( \Delta \)-connected winding is equal to the line current divided by \( \sqrt{3} \). This is a doubtful assumption since the involved current is not sinusoidal and all the harmonics results neglected.

The “rms2peak” routine answers to this problem avoiding the conversion of the line current in the phase values. In case of wye coupling the procedure is analogous to the one used in “SATURA” routine. The innovative aspect concerns the case of delta coupling.

Figure 2 and Figure 3 show the fundamentals of and compare “SATURA” and “rms2peak” routines for the case of delta coupling. The doubtful use of \( \sqrt{3} \) is avoided in the “rms2peak” routine, where measured and simulated line currents are directly compared. The rms2peak routine can be summarized in three steps:

1) Conversion of the RMS line voltage in the phase peak flux-leakage for all the points of the RMS V-I characteristic:

\[
\lambda_{\text{peak}}(n) = \frac{\sqrt{2} \cdot V_{\text{line-RMS}}(n)}{k \cdot \omega} \quad \text{with} \quad k = \begin{cases} \sqrt{3} & \Delta \text{-coupling} \\ 1 & \text{Y-coupling} \end{cases}
\]  

(1)

2) Estimation of peak current of the first point of the magnetization characteristic as:

\[i_{\text{peak}}(1) = \sqrt{2} \cdot I_{\text{RMS}}(1)\]  

(2)

3) Calculation of the other points of the magnetization characteristic with an iterative, numerical procedure that fits each peak current such as:

\[I_{\text{line-RMS,calc}}(n) = I_{\text{line-RMS,calc}}(n)\]  

(3)

Figure 4 shows the process for calculating the nonlinear phase current from the sinusoidal flux basing on the magnetization characteristic. Once the phase current is known, the line current is:

- for wye connected winding:

\[I_{\text{line}}(t) = I_{\text{ph-\(\Delta\)}}(t)\]  

(4)

- for delta connected winding:

\[I_{\text{line}}(t) = I_{\text{ph-\(\Delta\)}}(t) - I_{\text{ph-\(\Phi\)}}(t)\]  

(5)

where \( I_{\text{ph-\(\Delta\)}}(t) \) is the phase current waveform, and \( I_{\text{ph-\(\Phi\)}}(t) \) is the same current waveform but shifted by \( \frac{2}{3} \pi \), as represented in Figure 3.
3 Open-circuit simulation

Simulations are performed on a three-phase 290 MVA transformer with delta coupling on the low voltage side. The data is taken from [3] and Table 1 gives the transformer test report.

Figure 8 and Figure 9 compare the magnetization characteristics obtained with the “SATURA” and “rms2peak” routines, respectively for the wye and delta coupling case. As awaited the result is the same in the case of wye coupling, while for the case of delta coupling the current values estimated with the “rms2peak” routine are higher then the values obtained with the “SATURA” routine, represented in the figure with squared and circular points respectively.

Table 1: Transformer test report, 290 MVA 50 Hz YNd.

<table>
<thead>
<tr>
<th>Main data</th>
<th>[kV]</th>
<th>[MVA]</th>
<th>[A]</th>
<th>Coupling</th>
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<tbody>
<tr>
<td>HS</td>
<td>432</td>
<td>290</td>
<td>388</td>
<td>YNj</td>
</tr>
<tr>
<td>LS</td>
<td>16</td>
<td>290</td>
<td>10465</td>
<td>d5</td>
</tr>
<tr>
<td>Open circuit test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>E0 [kV] (%)</td>
<td>[MVA]</td>
<td>[%]</td>
<td>P0 [kW]</td>
</tr>
<tr>
<td></td>
<td>12 (75)</td>
<td>290</td>
<td>0.05</td>
<td>83.1</td>
</tr>
<tr>
<td></td>
<td>14 (87.5)</td>
<td>290</td>
<td>0.11</td>
<td>118.8</td>
</tr>
<tr>
<td></td>
<td>15 (93.75)</td>
<td>290</td>
<td>0.17</td>
<td>143.6</td>
</tr>
<tr>
<td></td>
<td>16 (100)</td>
<td>290</td>
<td>0.31</td>
<td>178.6</td>
</tr>
<tr>
<td></td>
<td>17 (106.25)</td>
<td>290</td>
<td>0.67</td>
<td>226.5</td>
</tr>
<tr>
<td>Short circuit test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS/LS</td>
<td>432/16</td>
<td>290</td>
<td>14.6, 0.24</td>
<td>Pk [kW]</td>
</tr>
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<td></td>
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<td>704.4</td>
</tr>
</tbody>
</table>
Figure 5: Magnetization characteristics. Wye coupling.

Figure 6: Magnetization characteristics. Delta coupling.

Figure 7: Definition of the currents name.

Figure 8 and Figure 9 show a simulation of the open circuit excitation currents on the low voltage side (delta coupling) at rated voltage. Refers to Figure 7 and to [3] for the clarification of the currents name. Figure 10 shows the measured no-load current of the same transformer. Comparing simulated and measured line currents is observable that the “rms2peak” routine ensures an improved matching and a better estimation of the peaks.

The fitting of the phase currents is unsatisfactory due to a poor accuracy of the measurements. Indeed, it has been possible to measure the phase currents using built-in current transformers, but the rate of these transformers are questionable.
Figure 8: Open circuit currents at nominal voltages. Simulation based on the “SATURA” routine.

Figure 9: Open circuit currents at nominal voltages. Simulation based on the “rms2peak” routine.

Figure 10: Measurement of excitation currents at nominal voltage.
4 Discussion/Conclusion

This paper addresses how to handle $\Delta$-connected magnetization branches 3-phase transformers in EMTP. The “rms2peak” routine has already been implemented in the framework of ATPDraw within the development of the new transformer model “XFMR”. For its improved and tested capability it should replace the “SATURA”-type routine used for the “BCTRAN” and the “Saturable Transformer” components in ATPDraw. The rms2peak routine results in a higher value of the magnetizing current in a $\Delta$-coupled winding than the SATURA routine.

The approach with direct conversion from test report RMS values to a magnetizing characteristic must be used with care when only low levels of excitation are available (<110%). The last segment of the characteristic will be linearly extrapolated and this tends to underestimate the magnetizing current for higher values of excitation than provided by the test report. The new ATPDraw component “XFMR” give an answer to this problem thanks to the deal with an advanced core model.

Finally, assuming a sinusoidal impressed voltage is reasonable, but under some circumstances it cannot be satisfied. In this case the accuracy of the model can decrease due to the inability to reconstruct the proper voltage waveform based only on RMS voltage values, see [4].

5 References