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Equation-Based Modeling of Three-Winding and Regulating Transformers using Modelica

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Abstract—The simulation of power transformer models is a critical for analyzing the dynamic behavior of power systems, in particular, when considering voltage magnitude or phase regulation controls. This paper reports results of extending the library of transformers in the iTesla Modelica Power Systems Library. Three transformer models have been implemented: a three-winding transformer, an under-load tap changing transformer (ULTC) and a phase shifting transformer (PST). A simple power system test model was also implemented, both in Modelica and PSAT, to assess the performance of the models. Software-to-software validation is carried out against PSAT.

Index terms – Modelica, PSAT, Power Transformer, Simulation Software, Power System Simulation.

I. EXTENDED ABSTRACT

Adequate modeling of conventional and controllable power transformers allows studying the dynamic behavior of power network under certain different operating conditions. In the literature, classical transformer models are studied [1]. Different transformer models have been developed, each focusing on a particular application or to represent specific physical phenomena. Generally, transformer models are classified according to their application: lightning overvoltage studies or the purpose of elements of the model, e.g., models based on leakage inductance, transmission line modeling, etc.

From the models above, those used in phasor time-domain simulations can be easily implemented using equation-based modeling languages. This kind of languages allows engineers to implement models directly using mathematical equations. The Modelica equation-based modeling language is object-oriented and open-source, which allows model implementation directly from mathematical equations. This is an important characteristic, which implicitly decouples the model from the mathematical solver, thus providing unambiguous simulation results among different tools [2]. The attractive features of this language have been successfully applied in different areas such as the automotive and aerospace industry [3].

European transmission system security is becoming a challenge due to the growing complexities of the pan-European power network. To overcome these complexities, the FP7 iTESLA (Innovative Tools for Electrical System Security within Large Areas) project was initiated to develop a toolbox that will support the operation of the European transmission network [4]. The iTesla project has adopted the Modelica language for modeling of power system dynamic components, and a Modelica library compatible with Modelica tools has been developed.

The purpose of this work is to improve this Power System Library with the implementation of new Modelica models of conventional power system components (Transformers) for Phasor Time-Domain Simulation. To implement these models the PSAT implementation is taken as reference [5]. Finally, to prove that Modelica models of transformers have the expected behavior, a software-to-software validation is performed, taken PSAT as a software reference for this validation.

II. IMPLEMENTATION OF TRANSFORMER MODELS

This work reports the implementation and validation of Modelica models for two regulating transformers and a Three Winding Transformer. The regulating transformers considered herein are: Under Load Tap Changing (ULTC) and Phase Shifting Transformer (PST) transformers. The mathematical description in [5] is taken as reference for model implementation. Due to space limitations, only one model and a summary of the rest of the work are provided in this abstract.

Figure 1: Secondary voltage control scheme of ULTC [14].
A. ULTC (Under Load Tap Changer)

ULTC is a regulating transformer that regulates the voltage or reactive power at the secondary side of the transformer. The regulator used to control the secondary voltage shown in Fig.1. The ULTC transformer is modeled as an equivalent PI circuit as depicted in Fig. 2.

\[
\begin{align*}
\frac{1}{m^2} & - \frac{1}{m} & - \frac{1}{1} \quad & \text{(1)}
\end{align*}
\]

where, \( y \) is the series admittance, \( m \) is the off nominal tap ratio. The tap ratio \( m \) is the output of the regulator shown in Fig. 1. The tap ratio step \( \Delta m \) is taken as zero, from where \( \bar{m} = m \).

B. ULTC in Modelica

The Modelica implementation of the ULTC uses the connector class PwPin [6]. First the parameters are defined, as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SystemBase</td>
<td>100</td>
</tr>
<tr>
<td>Vbus1</td>
<td>400000</td>
</tr>
<tr>
<td>Vbus2</td>
<td>100000</td>
</tr>
<tr>
<td>Sn</td>
<td>100</td>
</tr>
<tr>
<td>Vn</td>
<td>400000</td>
</tr>
<tr>
<td>fn</td>
<td>50</td>
</tr>
<tr>
<td>kT</td>
<td>4</td>
</tr>
<tr>
<td>H</td>
<td>0.001</td>
</tr>
<tr>
<td>K</td>
<td>0.10</td>
</tr>
<tr>
<td>m_max</td>
<td>0.98</td>
</tr>
<tr>
<td>d</td>
<td>0.05</td>
</tr>
<tr>
<td>vm0</td>
<td>1.008959700699460</td>
</tr>
<tr>
<td>m0</td>
<td>0.98</td>
</tr>
<tr>
<td>v_ref</td>
<td>1.0</td>
</tr>
<tr>
<td>xT</td>
<td>0.001</td>
</tr>
<tr>
<td>rT</td>
<td>0.1</td>
</tr>
<tr>
<td>deltam</td>
<td>0</td>
</tr>
<tr>
<td>v_ref</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Then, equations (1) and (3) are added to complete the model:

\[
\begin{align*}
R*p.ir-X*p.ii &= (1/m^2)*p.vr- (1/m)*n.vr; \\
R*p.ii+X*p.ir &= (1/m^2)*p.vi- (1/m)*n.vi; \\
R*n.ir-X*n.ii &= n.vr- (1/m)*p.vr; \\
X*n.ii+R*n.ii &= n.vi- (1/m)*p.vi; \\
der (m) &= -(H*m)+K*(vm-vref);
\end{align*}
\]

III. VALIDATION OF THE ULTC MODEL

Having the Modelica implementation of the ULTC, a small test power system was implemented both in Modelica and PSAT to perform software-to-software validation.

A. Test System

Fig. 3 shows the Modelica implementation of a three bus test system. The same test system was implemented in PSAT. Initial guess values for algebraic and state variables in the Modelica test system were taken from the power flow solution calculated in PSAT.

B. Validation Case: Perturbations

To test the dynamic behavior of the ULTC, perturbations are applied introduced in the test system. The perturbations are applied in such a way that the limits of the ULTC controller are reached. The perturbations applied in this test system are:

- **Synchronous Machine: Sinusoidal oscillation.** 0.001 * \( \sin(2\pi * 0.2 * t) \) in the field voltage \( (v_f) \) of the generator from time 0s to 5s.
PQ Load: +0.05 per unit (pu) reactive power load is added, from 5s to 8s, and -0.05 (pu) reactive power load is added from 8s to 12s.

C. Simulation and Results

Simulations were performed both with Modelica and PSAT. The outputs of both the software tools match with negligible variation (see Fig. 4).

REFERENCES

[6]. D 5.2: Proof of concept for an open simulation and model sharing framework validated on a medium size power system. [Online]: http://fp7-pegase.com/

Figure 4: Software-to-Software validation results