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Modelling of tranformers with on-load tap-changers (OLTC) in Python

MASTER THESIS

by

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Contents

> *All models are wrong, but some are useful.*
>
> **— Albert Einstein**

1 Introduction

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Research interests

Here are gaps and possible extension of knowledge.

Here are the research objectives and questions.

Construction of the thesis

This leads to the following structure for the paper:

- **Chapter 2,**
  some description about chapter 2;
- **Chapter 3,**
  some description about chapter 3;
- **Chapter 4,**
  some description about chapter 4.

2 Fundamentals

Following chapter shall introduce the basics for implementing an OLTC equipped transformer into a existing PSS framework. This is considering the already existing surrounding, more detailed the electric behavior of the transformer itself and some control engineering theory for the corrosponding OLTC. Thus its main goal is increasing voltage stability [1], main indices and assessment methods are considered as well.

2.1 Voltage stability basics

2.1.1 Stability indices

2.1.2 Assessment methods

2.1.3 Analytical stability calculation of static power systems

2.2 Power System Modeling

2.2.1 General and existing model

2.2.2 Transformer electric model and behavior

$$\underline{I} = \underline{\mathbf{Y}} \cdot \underline{U}$$

$$\begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} \\ \underline{Y}_{21} & \underline{Y}_{22} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} \tag{2.1}$$

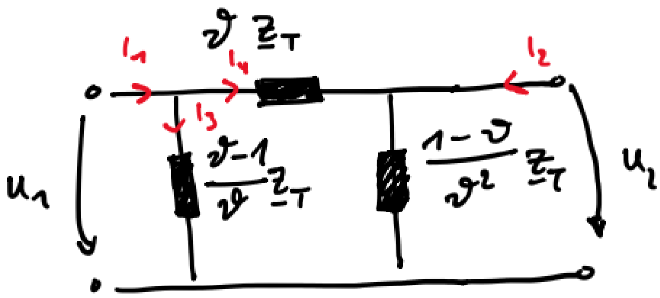

Figure 2.1: Π-representative circuit of a transformer with a longitudinal tap changer; own figure after [1], [2]

The admittance matrix of a two port network can be expressed after Machowski, Lubosny, Bialek, *et al.* [1] as Equation 2.1. For the Π-model of an OLTC transformer it is leading to Equation 2.2.

$$\underline{\mathbf{Y}}_{\Pi,\mathrm{T}} = \begin{bmatrix} \underline{Y}_\mathrm{T} & -\underline{\vartheta}\underline{Y}_\mathrm{T} \\ \underline{\vartheta}^*\underline{Y}_\mathrm{T} & -\underline{\vartheta}^*\underline{\vartheta}\underline{Y}_\mathrm{T} \end{bmatrix} \tag{2.2}$$

Per unit system specialities

Reactances and resistances are referred to the base voltage and apparent power of the operational unit, such as the transformer. The power system simulation uses its own base voltage and base apparent power, enabling the use of one single calculation domain. This is done to simplify the calculation and to make the results easily comparable to each other. Hence, the reffered values have to be transformed from the equipment based values to the simulation based values. The relations and conversions are defined as follows.

Additionally to consider:

- D-q transformations,
- Frequency domains: reactances and inductances are dependent and can change with the base frequency,
- Torque and power relations.

This specialities are considered in the tap changer modeling, thus further information is given in [1], Appendix A.

2.2.3 Open-Source Power System Simulation tools

Some information about other open source python power system simulation tools, such as:

- Pandapower,
- TOPS,
- ... .

Build up like a scan (see Georg's thesis).

BUT: As well including the there used implementation of transformers mathematical background and complexity.

2.3 Control engineering theory

2.3.1 Commonly used on-load tap changer control

A few basics are in the interest, understanding differences between real world beahavior, or possible ways of building up a OLTC transformer control. This control theory difference can be limiting as well for the results and objectives compared to the actual possible control in the field.

Typical presets are manually set

The target voltage is typically set from the control room of the grid operator, coming from pre-calculated load flow analysis. This can be set hours before, or even day-ahead with the estimated loads of the grid. This value is set locally for each operating unit subsequently. The control is then operating locally and without further involvement of the grid operator.

Quelle dafür finden?

Discrete controllers are used in the field

Typically the used controller in the field is a discrete controller, which can change tap positions under load within a time frame of around few seconds. Practical tap steps are around 2 % of the overall transforming ratio. The control is set up with a dead band, to avoid unnecessary tap changes. It is necessecary to note here, that this control and its mathematical caracteristics contains logical elements, blocks, and delays, which cannot be translated in a typical control theory transmission function.

This leads to the missing possibility to easily obtain mathematical stability for the control of the overall considered power system.

Quelle dafür finden?

2.3.2 Dynamic voltage stability

Can I really express this as „Controller theory“?

2.3.3 Bifurcations and Chaos theory control

1. Fuzzy Control mechanisms,
2. Neural Networks,
3. Bifurcations.

3 Transformer Equipment Modeling

Some literature and fundamentals about transformers, control, stability assessment, fast-switching modules, and analysis in Python.

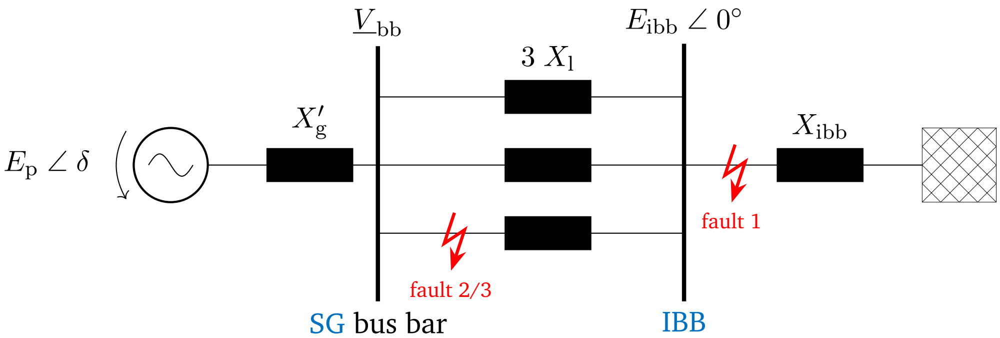

Figure 3.1: Representative circuit of a Single Machine Infinite Bus (SMIB) model with pole wheel voltage $E_{\mathrm{p}} \angle \delta$ and Infinite Bus Bar (IBB) voltage $E_{\mathrm{ibb}} \angle 0°$; positions of considered faults 1 to 3 are marked with red lightning arrows

3.1 Current implementation of transformers

Describe the current implementation of transformers in the Python framework.

3.2 Dynamic behavior of transformers

This is the description of the „new“implementation.

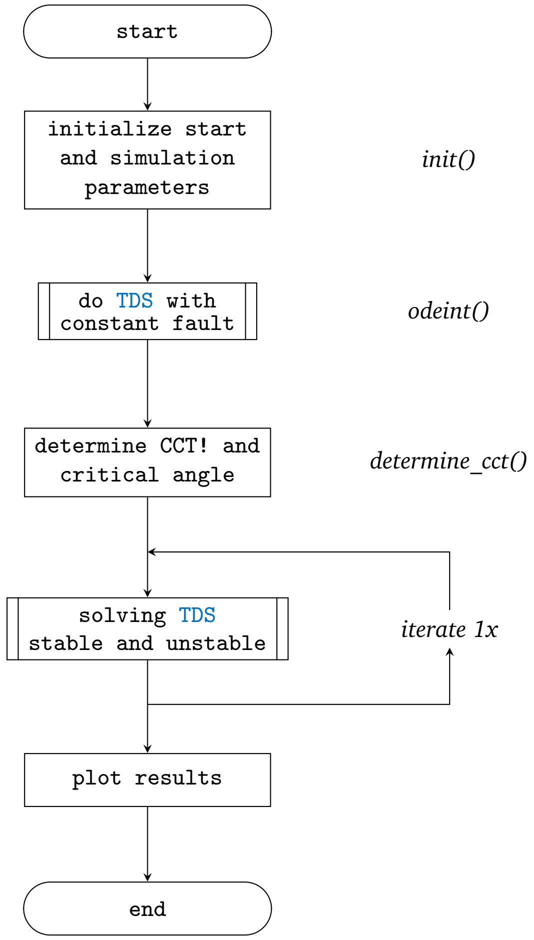

Figure 3.2: Program plan proposal for determining the **CCT!** (**CCT!**) t_{cc}, critical power angle δ_{cc} and the Time Domain Solution (TDS) of the Single Machine Infinite Bus (SMIB)-model; including the associated main function name

3.2.1 Model demands and changes in the framework

3.2.2 Additional modifications through a Fast Switching module

3.3 Tap Changer Control Modeling

This is the description of the ideas, development, and implementation of a OLTC control scheme.

3.3.1 Control logic and device behavior

3.3.2 Discrete control loop

3.3.3 Continous control loop

4 Application of Voltage Stability

4.1 Influences of other device characteristics

Just look on other mutual influences in the power system (simulation), such as:

- Load characteristics and types of modeling
- Maximum thermal currents of cables and operating components
- Asynchronous machines (or called „induction motors“?)

4.2 Observing the current state of the system

4.2.1 Static and Dynamic Indices

- Which indices can be implemented?
- Which make sense?
- Implementation and calculation of them?

4.2.2 Stability Monitoring

- Index combination and „traffic light“m̃onitoring
- Restauration options and opportunities
- Local mapping
- Weak point identification

4.3 Wide-area control mechanisms

- What influences could an interconnected information system have on curretn „dumb transformer control“?
- Reference voltages usually come from load flow analysis out of the back office (day-ahead); How can this be changed? How can transformers get more „smart“?

5 Verification setup and results

5.1 Representative Electrical Networks

5.2 Results from the Python Framework

5.3 Comparison to Results from PowerFactory

6 Case study

6.1 Scenario setting

6.2 Simulation

6.3 Results

7 Discussion

8 Summary and outlook

Some conclusion.

Some outlook and nice blibla.

Acronyms

IBB	Infinite Bus Bar
OLTC	On-Load Tap Changer
PSS	Power System Simulation
RMS	Root Mean Square
SG	Synchronous Generator
SMIB	Single Machine Infinite Bus
TDS	Time Domain Solution

Symbols

δ	$^\circ$ / deg	power angle (or power angle difference)
$\Delta\omega$	$\frac{1}{\mathrm{s}}$	change of rotor angular speed
$\underline{\theta}$	-	transformer ratio; complex if phase shifting
A	-	acceleration or deceleration area
$\underline{E}$	V	voltage of SG or IBB
H_{gen}	s	inertia constant of a Synchronous Generator (SG)
$\underline{I}$	A	current
P	W	effective power; electrical or mechanical
Q	var	reactive power
R	Ω	ohmic resistance
$\underline{S}$	VA	apparent power
$\underline{V}$	V	voltage
$\underline{X}$	Ω	reactance
$\underline{Y}$	$\frac{1}{\Omega}$ / S	admittance
$\underline{Z}$	Ω	impedance

The different symbols are used with different indices, these are semantic and explained in the surrounding context. Following notation is commonly used for mathematical and physical symbols:

- Phasors or complex quantities are underlined (e.g. $\underline{I}$)
- Arrows on top mark a spatial vector (e.g. $\overrightarrow{F}$)
- Boldface denotes matrices or vectors (e.g. $\boldsymbol{F}$)
- Roman typed symbols are units (e.g. s)
- Lower case symbols denote instantaneous values (e.g. $\underline{i}$)
- Upper case symbols denote RMS or peak values (e.g. $\underline{I}$)
- References to objects are written capitalized Roman (e.g. $\underline{Z}_{\mathrm{TRAFO}}$)
- Subscripts relating to physical quantities or numerical variables are written italic (e.g. $\underline{I}_1$)

In the simulations and calculations the per unit system ($\mathrm{p.u.}$) is preferred, thus normalizing all values with a base value. Where necessary, absolute units are added to indicate the explicit use of the normal unit system. For more information about this per-unit system please refer to Machowski, Lubosny, Bialek, *et al.* [1], specifically Appendix A.1 provides a detailed description and explanation.