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Modeling of Fast-Switching Transformers for Voltage Stability Studies in Python

MASTER THESIS

by

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Contents

1 Introduction

Some blibla as introduction. [1]

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Research Interests

Here are gaps and possible extension of knowledge.

Here are the research objectives and questions.

- Influence of OLTC control on possible operational uses: Short-term voltage stability, long-term voltage stability;
- Can a increased dynamic regulation help machine recovery?
- Does the increased tap ratio gradient harm transient stability of machines? Does it help or harm CCT of machines or machine groups?
- Transformers act as big low-pass filters: Can this behavior be beneficial as well for the interactions of inverters in the grid on AC side (in the sense of Harmonic Stability)? **[Quelle]**

Research question of this thesis

How do different control types and characteristics of Tap Changing transformers influence the voltage stability?

Therefore following questions/steps can be imagined as supportive:

1. How can Voltage stability of a system be classified and be looked at? Which indices, measurements, etc.
2. Which transformer model has to be considered to show influences?
3. Which additional load models, source models, transmission model have to be modeled for an adequate assessment?
4. Which systems are useful to consider in showing effects? Which circumstances lead to a stability support, which to a decrease? Where can limits be drawn?

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 Power System Modeling

2.1.1 General and Existing Model

2.1.2 Transformer Electric Model and Behavior

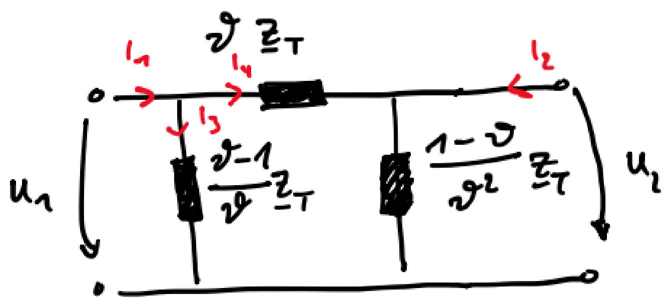

Figure 2.1: Π-representative circuit of a transformer with a longitudinal tap changer; own figure after [1], [2]

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

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

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.

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

Another way of writing down the admittance matrix is shown in Equation 2.3. It is considering, that the matrix can be split up in a symmetric, constant part, and a variable current injection part. The latter is not symmetrical and depends on the tap position of the transformer. Therefore in some simulation algorithms the static part is used in the admittance matrix, and the variable part is considered in the current injection vector. [1]

$$\begin{bmatrix} \underline{I}_1 \\ -\underline{I}_2 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{\mathrm{T}} & -\underline{Y}_{\mathrm{T}} \\ -\underline{Y}_{\mathrm{T}} & \underline{Y}_{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} - \begin{bmatrix} \Delta\underline{I}_1 \\ \Delta\underline{I}_2 \end{bmatrix} \text{, where}$$

$$\begin{bmatrix} \Delta\underline{I}_1 \\ \Delta\underline{I}_2 \end{bmatrix} = \begin{bmatrix} \underline{0} & (\underline{\vartheta}-1)\underline{Y}_{\mathrm{T}} \\ -(\underline{\vartheta}^{*}+1)\underline{Y}_{\mathrm{T}} & (\underline{\vartheta}^{*}\underline{\vartheta}+1)\underline{Y}_{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} \text{ leading to}$$

$$\underline{\mathbf{Y}}_{\Pi,\mathrm{T}} = \begin{bmatrix} \underline{Y}_{\mathrm{T}} & -\underline{Y}_{\mathrm{T}} \\ -\underline{Y}_{\mathrm{T}} & \underline{Y}_{\mathrm{T}} \end{bmatrix} - \begin{bmatrix} \underline{0} & (\underline{\vartheta}-1)\underline{Y}_{\mathrm{T}} \\ -(\underline{\vartheta}^{*}+1)\underline{Y}_{\mathrm{T}} & (\underline{\vartheta}^{*}\underline{\vartheta}+1)\underline{Y}_{\mathrm{T}} \end{bmatrix} \tag{2.3}$$

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.

$$\underline{Y}_{\mathrm{T}} = \frac{1}{r_{\mathrm{T}} + x_{\mathrm{T}} \cdot j} \cdot \frac{b_{\mathrm{T}} \cdot j}{2}$$

$$\underline{Y}_{\mathrm{T,\ sim}} = \underline{Y}_{\mathrm{T}} \cdot \frac{S_{\mathrm{n}}}{S_{\mathrm{n,\ sim}}} \tag{2.4}$$

$$\underline{U}_{\mathrm{whatever,\ sim}} = \underline{U}_{\mathrm{whatever}} \cdot \frac{S_{\mathrm{n}}}{S_{\mathrm{n,\ sim}}} \tag{2.5}$$

Displayed like in Equation 2.4, the characteristic of the operational unit is referred to the simulation base value. Here, the admittance of the transformer is multiplied with its own rated apparent power, then devided by the apparent power of the simulation system. Similar, the voltages are calculated via Equation 2.5. This specialities are considered in the tap changer modeling, thus further information is given in [1], Appendix A.

Additionally to consider:

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

2.1.3 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.

Table 2.1: Voltage instability types and different time frames with examples; after **[Quelle]**

No	Type	Cause of incident	Time frames
1	Long-term	Slowly use up of reactive reserves and no outage	Several minutes to several hours
2	Classical	Key outage leads to reactive power shortage	One to five minutes
3	Short-term	Induction motor stalling leads to reactive power shortage	Five to fifteen seconds

2.2 Voltage stability basics

2.2.1 Voltage stability definitions, classifications, and conditions

A Practical introduction to voltage stability assessment, methods and indices is given in the standard and extending literature of Rueda-Torres, Annakage, Vournas, *et al.* [3], Danish [4], and Cutsem and Vournas [5].

Interesting to note/implement here: Basic classification, definitions, and the nature or conditions of voltage stability. Such as

- Short term vs. long term
- Static vs. dynamic
- Transmission driven vs. load driven vs. generation driven; stability/instability, and/or contributions
- Influence OLTC: Restoring voltage level, but not adding reactive capacities; hence adding risk of voltage collapses
- Load vs. transmission aspects
- Example mechanism: **Collapse effect of the nordic test system** [5], [6]

2.2.2 Stability Indices

One easy idea for obtaining a stable operation is looking at the Jacobian Matrix. If this matrix is getting singular, the System will not remain in a stable operation. Singularity of matrices is checked by follwing two hypothesis tests:

$$\det(\mathbf{J}) = 0 \tag{2.6}$$

$$J \times J^{-1} \uparrow \tag{2.7}$$

The Jacobian Matrix is defined as:

$$\mathbf{J} = \begin{bmatrix} \Delta\mathbf{P} \\ \Delta\mathbf{Q} \end{bmatrix} = \left[\begin{array}{c|c} \mathbf{H} & \mathbf{M'} \\ \hline \mathbf{N} & \mathbf{K'} \end{array}\right] \cdot \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix}$$

$$\left[\begin{array}{c} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \hline \Delta Q_1 \\ \vdots \\ \Delta Q_n \end{array}\right] = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & V_1\frac{\partial P_1}{\partial V_1} & \cdots & V_n\frac{\partial P_1}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & V_1\frac{\partial P_n}{\partial V_1} & \cdots & V_n\frac{\partial P_n}{\partial V_n} \\ \hline \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & V_1\frac{\partial Q_1}{\partial V_1} & \cdots & V_n\frac{\partial Q_1}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \delta_1} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & V_1\frac{\partial Q_n}{\partial V_1} & \cdots & V_n\frac{\partial Q_n}{\partial V_n} \end{array}\right] \cdot \left[\begin{array}{c} \Delta \delta_1 \\ \vdots \\ \Delta \delta_n \\ \hline \Delta V_1/V_1 \\ \vdots \\ \Delta V_n/V_n \end{array}\right] \tag{2.8}$$

Although this method seems easy to implement, there are some numerical problems realted to that. Checking if a Matrix is singular with numerical mathods, can only be realised as a probablilty expression. A result could be, that the determinant of the matrix is below a certain threshold. The algorithm would propose, that the matrix is probabilistic singular. [QUELLE] This problem leads to the necessity of applying other methods or indices for stability assessment. Danish [4] is proposing a few other indices, that are based on the Jacobian Matrix, and shows comparitive characteristics between Jacobian Matrix and system variable based voltage stability indices. These Jacobian Matrix based indices are listed and further described in section A.2, while the comparative characteristics are described in section A.3.

2.2.3 Assessment methods

2.2.4 Analytical stability calculation of static power systems

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]**

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]**

2.3.2 Dynamic voltage stability

Can I really express this as „Controller theory"?

2.3.3 Bifurcations and Chaos theory control

Is this necessary or already out of scope?

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.

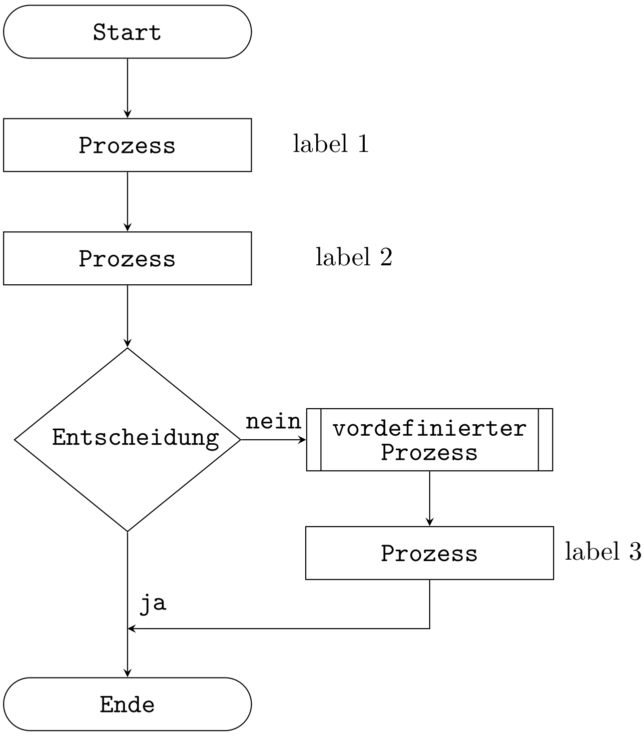

Figure 3.1: Program plan proposal for determining the Critical Clearing Time (CCT) t_{cc}, critical power angle δ_{cc} and the Time Domain Solution (TDS) of the Single Machine Infinite Bus (SMIB)-model; including the associated main function name

3.1 Advancing the Transformer Model

3.1.1 Model Demands and Changes in the Framework

- What is the current implementation?
- First model: Admittance Matrix manipulations
- Second model: Current Injection Model

3.1.2 Considering Load Flow Dependent Control

- How can I change the transformer control setpoints to be load flow dependent?
- How can I ensure, utilization of the transformer is not $> S_\mathrm{n}$?

3.2 Tap Changer Control Modeling

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

3.2.1 Discrete Control Loop

This control method represents the currently most used and thus representative control scheme for OLTCs. With the mechanic nature of the switching mechanism, the control look can only access discrete ratios within time frames of around a few seconds. Such a discrete control loop is described by Milano [7], [8]. A scheme of this control loop is shown in Figure 3.2.

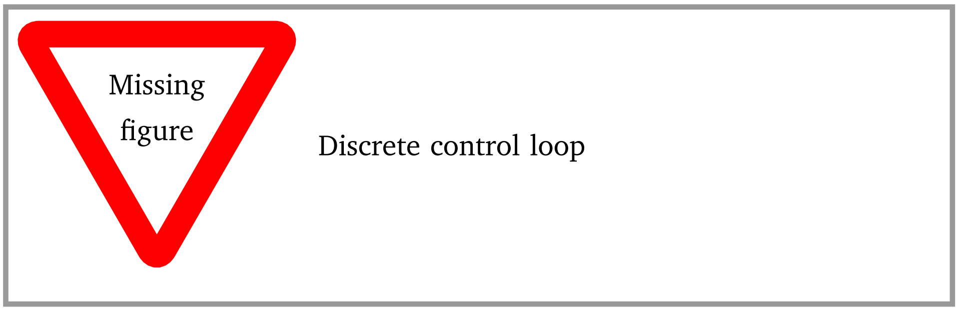

Figure 3.2: Discrete control loop of an OLTC; scheme based on Milano [7]

This control loop type is beneficial due to its accurate representability of current OLTC abilities. It gains access to assess stability within simulation environments, as analytical methods are not suited.

A negative aspect of a discrete control loop is the missing opportunity of generating a transfer function. This blocks the stability assessment with standard control engineering methods. Further, popular analysis methods like eigenvalue analysis is not possible, due to the lack of possibility to form derivatives.

```python
def get_output(self, vbb=None):
    if vbb is None:
        try:
            # get current bus bar voltage
            vbb = self.trafo.to_voltage
        except:
            raise ValueError('No access to instantaneous bus voltage.')

    self.v_diff = (torch.abs(vbb) - torch.abs(self.v_ref)) * torch.ones
        ((self.parallel_sims, 1), dtype=torch.float64)
```

```
    v_dead_prev = self.v_dead

    self.v_dead = self.deadband.get_output(self.v_diff)

    # reset the integrator, if the v_diff falls under the deadband (could as well be == 0)
    # OR if the sign suddenly changing
    if torch.abs(self.v_dead) == torch.zeros_like(self.v_dead):
        self.integrator.reset()
    elif torch.sign(self.v_dead) != torch.sign(v_dead_prev):
        self.integrator.reset()

    self.integ = self.integrator.get_output(torch.abs(torch.sign(self.v_diff))) # or v_dead/self.v_diff for variable gain

    if (self.integ > self.t_1):
        # reset the integrator after the switching operation mandatory for remaining operatbility of t_1 s window
        # if the deadband is continously overstepped for more than t_1 s, switching operation is triggered
        self.m = self.switching(self.v_diff)
        self.integrator.reset()
        self.u_l += self.delta_m * self.m

    return self.u_l
```

Listing 3.1: Output Function of the discrete OLTC controller

- Describe implementation
- Describe benefits / drawbacks
- Control scheme
- Switching logic and behavior (voltage tracking)

```
def get_output(self, vbb=None):
    if vbb is None:
        try:
            # get current bus bar voltage
            vbb = self.trafo.to_voltage
        except:
            raise ValueError('No access to instantaneous bus voltage.')

    self.v_diff = (torch.abs(vbb) - torch.abs(self.v_ref)) * torch.ones((self.parallel_sims, 1), dtype=torch.float64)

    v_dead_prev = self.v_dead

    self.v_dead = self.deadband.get_output(self.v_diff)

    # reset the integrator, if the v_diff falls under the deadband (could as well be == 0)
    # OR if the sign suddenly changing
    if torch.abs(self.v_dead) == torch.zeros_like(self.v_dead):
        self.integrator.reset()
    elif torch.sign(self.v_dead) != torch.sign(v_dead_prev):
        self.integrator.reset()
```

```
    self.integ = self.integrator.get_output(torch.abs(torch.sign(self.
        v_diff))) # or v_dead/self.v_diff for variable gain

    if (self.integ > self.t_1):
        # reset the integrator after the switching operation mandatory
            for remaining operatbility of t_1 s window
        # if the deadband is continously overstepped for more than t_1 s
            , switching operation is triggered
        self.m = self.switching(self.v_diff)
        self.integrator.reset()
        self.u_l += self.delta_m * self.m

    return self.u_l
```

Listing 3.2: Output Function of the discrete OLTC controller 2

3.2.2 Continous Control Loop

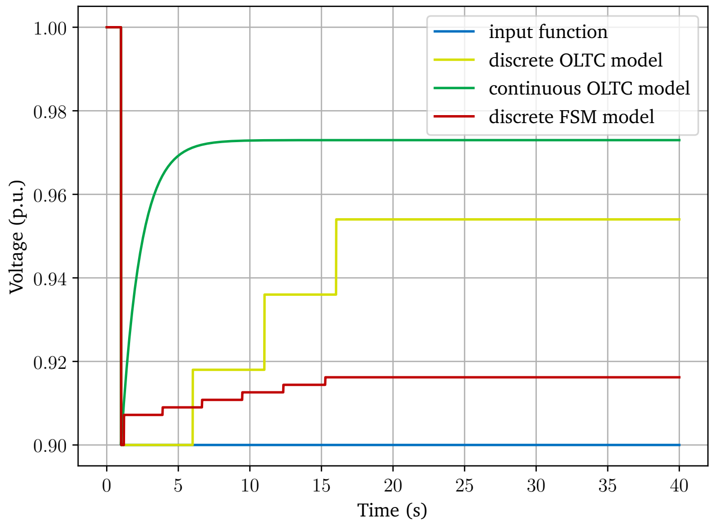

Figure 3.3: Characterization of the OLTC control loop; the input function simulates the to be regulated voltage, the output functions are characterized by $o(t) = i(t) \cdot \underline{\vartheta}_{\text{trafo}}$

3.2.3 Control Schemes for the Fast Switching module

Discrete Control Loop as most Representative

A continous control loop for a FSM is presented within Burlakin, Scheiner, Mehlmann, *et al.* [2], [9]. Similar to the solely OLTC loop, it represents the real behavior best, but is obstructive for stability assessments. The scheme of the logic is shown in Figure 3.4.

Continuous Control Loop for best Stability Assessment

3.3 Transformer Model and Control Validation

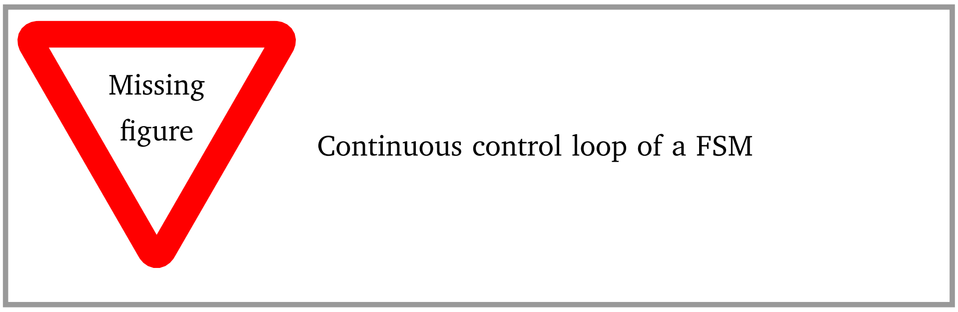

Figure 3.4: Continuous control loop of a FSM; scheme based on Burlakin, Scheiner, Mehlmann, *et al.* [2]

4 Supplementary Modeling and Advancements

As the python framework is currently missing some representations of components, this chapter aims to describe the implementation of those. Mainly focussing on source and load models, as the later considered test, benchmark, and use case networks require alternative behaviors.

4.1 Load Models

4.1.1 ZIP Load Models

Why important?

Mostly, a polynomial load model is used. It is called ZIP-model, as there are individual contributions to constant impedance $\underline{Z}$, constant current $\underline{I}$, and constant power P, or respectively Q, are considered. The model is described by *IEEE Guide for Load Modeling and Simulations for Power Systems* [10]. Either two ways of mathematical description are considered valid, dependent on the allowed influence of the frequency deviation. The use of periodized phasor representation, typical for a RMS simulation, is missing or often neglecting this frequency information. Therefore the set of Equation 4.1 and Equation 4.2 is considered sufficient and implemented in the Python framework.

$$P = P_n \cdot \left[p_1 \left(\frac{U}{U_n} \right)^2 + p_2 \left(\frac{U}{U_n} \right) + p_3 \right] \tag{4.1}$$

$$Q = Q_n \cdot \left[q_1 \left(\frac{U}{U_n} \right)^2 + q_2 \left(\frac{U}{U_n} \right) + q_3 \right] \tag{4.2}$$

with $\quad p_i \in [0, 1] \quad$ and $\quad q_i \in [0, 1]$

Characteristics?

How does it look like in the simulation environment?

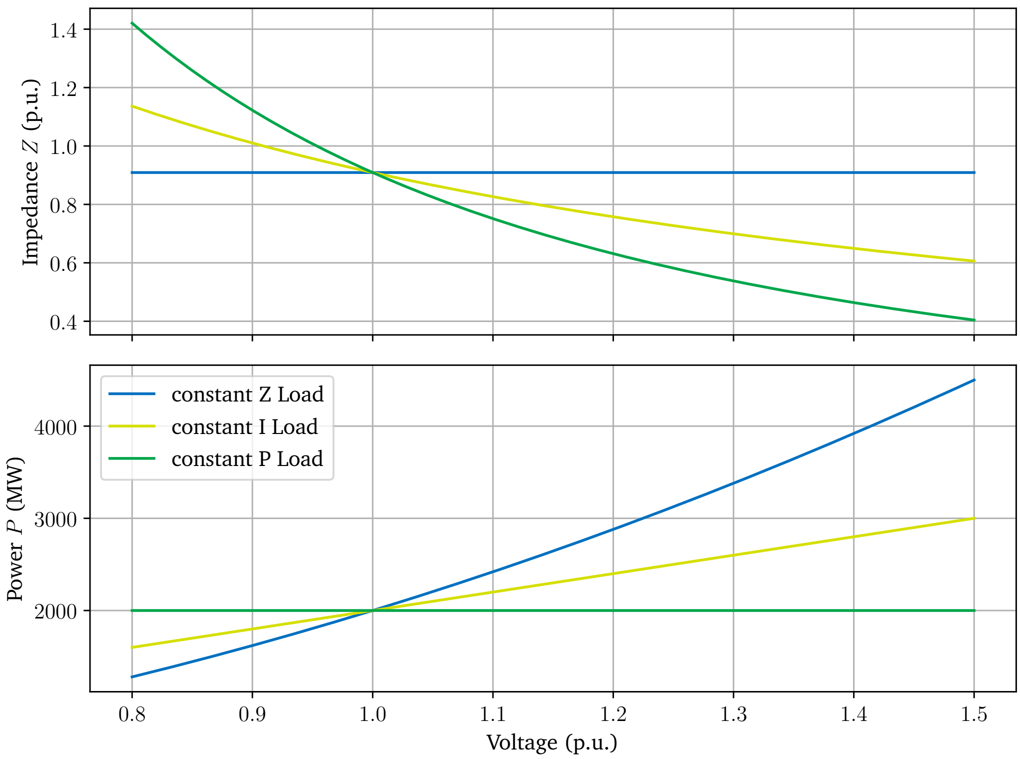

Figure 4.1: Characterization of the ZIP load model; with (upper) the result of the impedances dependent on the voltage at the connected bus, and (lower) the resulting power consumption of the different models, representative only the real power P

$$P = P_n \cdot \left[p_1 \left(\frac{U}{U_n} \right)^2 + p_2 \left(\frac{U}{U_n} \right) + p_3 \right] \cdot (1 + k_{pf} \Delta f) \tag{4.3}$$

$$Q = Q_n \cdot \left[q_1 \left(\frac{U}{U_n} \right)^2 + q_2 \left(\frac{U}{U_n} \right) + q_3 \right] \cdot (1 + k_{qf} \Delta f) \tag{4.4}$$

$$\text{with} \quad \sum_{i=1}^{3} p_i = 1 \quad \text{and} \quad \sum_{i=1}^{3} q_i = 1$$

Although the subset of Equation 4.3 and Equation 4.4 would consider a relation to the frequency at the given time, it is not used. The use of periodized phasor representation, typical for a RMS simulation, is missing this information in the framework diffpssi. Therefore the set of Equation 4.1 and Equation 4.2 is implemented in the Python framework. It has to be mentioned, because the comparison tool PowerFactory is using this load model, though in some parts of the simulation results are showing a slightly bigger error.

4.1.2 Induction Machine Models

As one of the most important loads to consider, especially for many load driven instability mechanisms, the Induction Machine (IM) is a crucial component, **[Quelle]**

Just briefly:

- Why is it crucial?
- How do the instability mechanisms work and look like?
- What are the different types of IMs modeling (complete and dynamic, static, ...)

Three main ways of IM modeling are relevant to mention in this section:

1. Static model as introduced in *IEEE Guide for Load Modeling and Simulations for Power Systems* [10],
2. a dynamic 'fixed-speed' IM model, and
3. a doubly fed IM model.

The last ones are mentioned and further described in Machowski, Lubosny, Bialek, *et al.* [1]. Least model requires very detailed information, and shall be suitable for SMIB models for machine behavior studies or similar. The second model is suitable for network analysis and machine behaviors. The first model applies for high perception of IMs in total loading of the network. As referencing to *IEEE Guide for Load Modeling and Simulations for Power Systems* [10], is is similar implemented as the before mentioned ZIP load model, considering characteristic equations for its real power P and reactive power Q. Both models shall be described in the following section.

Static Model of Induction Machines

For this operational unit type is a detailed dynamic modeling possible. With some considerations, it can be sufficient, modeling this equipment just with the The model is described by *IEEE Guide for Load Modeling and Simulations for Power Systems* [10] as formulated in following set of equations.

$$P = \left(R_\mathrm{s} + \frac{R_\mathrm{r}}{s}\right) \cdot \frac{U^2}{\left(R_\mathrm{s} + \frac{R_\mathrm{r}}{S}\right)^2 + (X_{\gamma\mathrm{s}} + X_{\gamma\mathrm{r}})^2} \tag{4.5}$$

$$Q = (X_{\gamma\mathrm{s}} + X_{\gamma\mathrm{r}}) \cdot \frac{U^2}{\left(R_\mathrm{s} + \frac{R_\mathrm{r}}{S}\right)^2 + (X_{\gamma\mathrm{s}} + X_{\gamma\mathrm{r}})^2} + \frac{U^2}{X_\mathrm{s}} \tag{4.6}$$

[MK1]: Is here really a difference between the two s in the equations?

Briefly describe the implementation.

Dynamic 'fixed-speed' Induction Machine model'

From ChatGPT:

The dynamic model of IMs is essential for accurately representing their behavior under various operating conditions. This model includes the differential equations that describe the machine's electrical and mechanical dynamics. The equations are typically derived from the machine's equivalent circuit and can be expressed in the d-q reference frame.

The dynamic model can be represented by the following set of equations:

$$\frac{\mathrm{d}\psi_{\mathrm{d}}}{dt} = v_{\mathrm{d}} - R_{\mathrm{s}} i_{\mathrm{d}} + \omega \psi_{\mathrm{q}} \tag{4.7}$$

$$\frac{\mathrm{d}\psi_{\mathrm{q}}}{dt} = v_{\mathrm{q}} - R_{\mathrm{s}} i_{\mathrm{q}} - \omega \psi_{\mathrm{d}} \tag{4.8}$$

$$\frac{\mathrm{d}\omega}{dt} = \frac{1}{J}(T_m - T_e - B\omega) \tag{4.9}$$

where:

- $\psi_{\mathrm{d}}, \psi_{\mathrm{q}}$ are the d-q axis flux linkages
- $v_{\mathrm{d}}, v_{\mathrm{q}}$ are the d-q axis voltages
- $i_{\mathrm{d}}, i_{\mathrm{q}}$ are the d-q axis currents
- R_{s} is the stator resistance
- ω is the rotor angular velocity
- T_{m} is the mechanical torque
- T_{e} is the electromagnetic torque
- J is the moment of inertia
- B is the damping coefficient

The electromagnetic torque T_e can be calculated as:

$$T_e = \frac{3}{2} p(\psi_d i_q - \psi_q i_d) \tag{4.10}$$

where p is the number of pole pairs.

This dynamic model allows for the simulation of the IMs transient response to changes in voltage, frequency, and load conditions. It is particularly useful for studying stability and control strategies in power systems.

Briefly describe the implementation.

4.2 Source Models

4.2.1 PQ Source without Machine Dynamics

Isn't that quite the same as the ZIP load model, but with inversed Power characteristics? Or is there more, for example when looking at a short circuit event. . .

These sections (per module / model) should contain roughly follwing information and / or structure:

1. Why is this model important?
2. How is it implemented?
3. What are the characteristics (show in plots, description, etc.)?
4. How does it look like in the simulation environment? -> Smaller example networks, like the SMIB model; most likely combined with verification data of PowerFactory.

5 Application of Voltage Stability

5.1 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“?)

5.2 Observing the current state of the system

5.2.1 Static and Dynamic Indices

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

5.2.2 Stability Monitoring

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

5.3 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“?

6 Verification setup and results

6.1 Representative Electrical Networks

The following section shall introduce the used power systems in the simulation with the Python framework, considering verification, and also extension meaning the performed case studies in chapter 7. The models are chosen to represent different network sizes and complexities, thus allowing the objective of graded interaction levels of the developed (transformer) model. The models are based on the work of Machowski, Lubosny, Bialek, *et al.* [1], Kundur and Malik [11], *IEEE Guide for Load Modeling and Simulations for Power Systems* [10], and Van Cutsem, Glavic, Rosehart, *et al.* [6].

Single Machine Infinite Bus (SMIB) Model

One very popular and thus powerful electrical network for the verification of power system stability is the SMIB model. It is a compact and simplified model of a power system, allowing easy analytical calculation, verification and development. Mutual influences are comparably simple to understand and calculate, as the infinite bus bus is acting as a fixed grid connection point with a large adjoining grid. The generator is connected to the bus bar via a transmission line and a transformer. The model was largely discussed by Kundur and Malik [11], and is shown in Figure 6.1. The generator and the IBB are represented by synchronous machines, developed and discussed by Kordowich and Jaeger [12]. The specific model details are included in **??**, additionally the simulation setup for verification is described in Table 6.1.

Figure 6.1: Single Machine Infinite Bus (SMIB) model for verification and validation of the Python framework; own figure after [1], [11]

Simple Single Machine Load Model

Follwing model is often recommended **[Quelle]** for easy voltage control studies, in explicit for OLTCs. Similar to the SMIB model, it consists from one synchronous

Table 6.1: Simulation Setup for validation of the Π-modeled transformer; considering a transforming ratio $\underline{\vartheta} \neq 1$ and $\underline{\vartheta} \in \mathbb{C}$

Parameter	**Value**
Generator inertia H	3.5 s
Generator damping D	0.1 p.u.
Generator resistance R	0.01 p.u.
Generator reactance X	0.1 p.u.
Transformer resistance R	0.01 p.u.
Transformer reactance X	0.1 p.u.
Transmission line resistance R	0.01 p.u.
Transmission line reactance X	0.1 p.u.

generator, busses, and lines in a single branch. The IBB is thus removed and changed to a load. This two element type o configuration allows for an easy analytical calculation of voltage stability and control. Although this thesis is focussing on OLTC transformers, the model is extended with one in between. A single line representation is depicted in Figure 6.2.

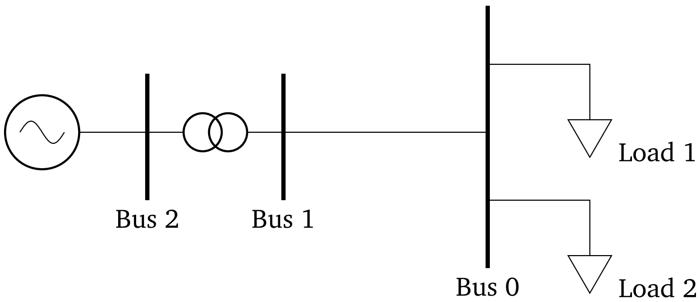

Figure 6.2: Single line representation of a simple single machine load model; own illustration with characterstics from **[Quelle]**

Further details about its configuration and simulation setup are included in **??**. It should be noted, that simple load models are not useful for simulation of this example network. Usually constant Z models are used as loads, therefore simulation results can be misleading and not showing desired effects or voltage instability mechanisms **[Quelle]** . The simulation framework is extended with XX types of load models, to satisfy the requirements of the single machine load model, and a connected stability assessment.

IEEE nine-bus system

Nordic test system

6.2 Results from the Python Framework

6.3 Comparison to Results from PowerFactory

Single Machine Infinite Bus (SMIB) Model

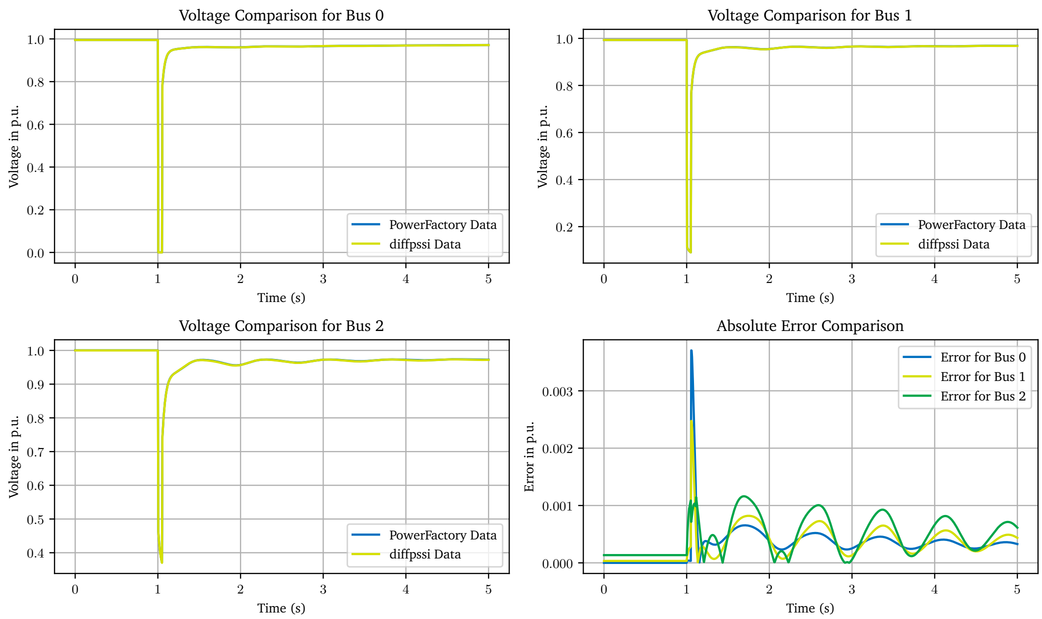

Figure 6.3: Comparison of the Π-modeled transformer in the SMIB model between PowerFactory and the Python framework

Place results here, looking at: off nominal tap ratio, and with off nominal phase shifting (e.g. 110°)

7 Case study

In the interest of investigation / the Case Study are:

- Influence of switching times on stability margin/begin of destabilization,
- Influence of max. ratio change per switching event, and
- Influence on different test systems (destabilization mechanisms).

7.1 Scenario setting

Does it make sense to structure like that?

Or is it a better idea thinking in terms of specific „use cases“ as sections:

- What happens under strong grid conditions? -> Section: Strong grid condition behavior
- What happens under weak grid conditions? -> Section: Weak grid condition behavior
- Strongly interconnected grids
- Widely extended linear string grids
- Section: Use case of Wind farm integration
- Influence on transient stability: SMIB model with and without OLTC

Influence of FSM on Machines and their stability criterions

Thinking of Rotor Angle Stability, maybe considered by an EAC implementation? What does the fast Switching, esp. at up to 8% of the nominal voltage, do to the machines?

Novel Control Strategy FSM

Thinking of fast and slow voltage gradients: fast gradients are compensated by the FSM, slow gradients are compensated by the OLTC. Therefore optimal utilisation of injected damping moment of the FSM.

Also thinking of different presets of the OLTC and FSM, which are tried to keep constant. Different grid operators can utilize for typical grid conditions of over- or undervoltage at PCC.

Following contains:

- Implemetation of different logic
- Testing of presets and switchin logic
- Damping moment beneficial?

Possible Extension for Power Flow congruent Control

Extension in the Control Algorithm to decide which Bus has to be regulated, to avoid contrairy actions of the OLTC and FSM against the power flow. Therefore not decrease of stability, but increase. Possible Application: Grid coupling Transformers, Battery Storage assisted Virtual powerplants, etc.

7.2 Simulation

7.3 Results

8 Discussion of the results

9 Summary and outlook

Some conclusion.

Some outlook and nice blibla.

Acronyms

CCT	Critical Clearing Time
FSM	Fast Switching Module
IBB	Infinite Bus Bar
IM	Induction Machine
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. $\mathbf{F}$)
- 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. $\underline{I}$)
- 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.

List of Figures

List of Tables

List of Listings

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Author's declaration

I confirm that I have written this Master Thesis unaided and without using sources other than those listed and that this thesis has never been submitted to another examination authority and accepted as part of an examination achievement, neither in this form nor in a similar form. All content that was taken from a third party either verbatim or in substance has been acknowledged as such.

Erlangen, February 17, 2025

Maximilian Markus Veit Köhler, B. Eng.

Note:

For reasons of readability, the generic masculine is primarily used in this Master Thesis. Female and other gender identities are explicitly included where this is necessary for the statement.

Appendix

A Fundamentals

A.1 Description of the Power System Simulation process

In this appendix section, the general process of power system simulation is described. As this thesis is aiming to understand voltage stability and processes in longer periods of time, these explanations apply to pointer-based simulations, called RMS simulations. Meaning that the considered effects are slower electromechanical nature instead of faster electromagnetic ones. The in this thesis used Python framework „*diffpssi*“ is based on this type of simulation, and due to its open-source based nature traceable.

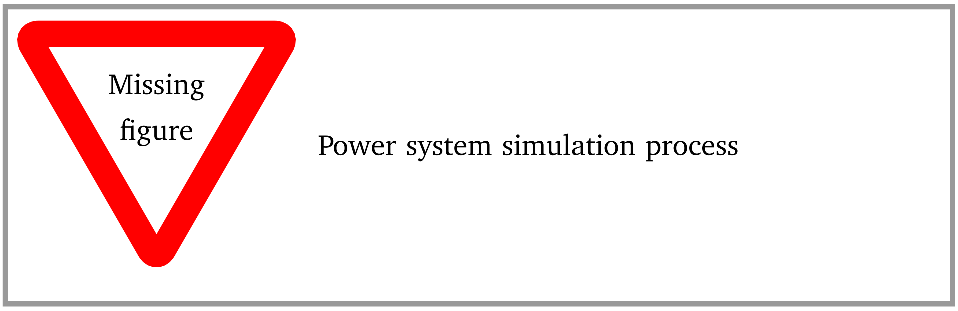

Figure A.1: Power system simulation process; own illustration

Really basic: (?)

- Phasor description
- Symmetricak Components
- RMS vs EMT simulation (-> meaning one cannot simulate other faults than 3ph w/o ground)

Less basic and more advanced:

- rountines in the framework
- two types: Algebraic and Differential equations have to be solved at each time step -> What is which? Which operational equipment is typically described with which type of equation?

A.2 Jacobian based voltage stability criterions

Danish [4] is showing, describing, and referencing some voltage stability indices based on the Jacobian matrix. The following table is a collection of these indices.

A.3 Comparison of System based and Jacobian based indices

Table A.1: Jacobian based voltage stability criterions; after Danish [4]

Index	Abbreviation	Calculation	Stability Threshold	Reference
Tangent Vector Index	**TVI!**	$\mathrm{TVI}_i = \left\lvert \frac{\mathrm{d}V_i}{\mathrm{d}\lambda} \right\rvert^{-1}$	depending on load increase	
Test Function		$t_{cc} = \left\lvert e_c^T \cdot \mathbf{J} \times \mathbf{J}_{cc}^{-1} \cdot e_c \right\rvert$	details are given in reference	
	i	$i = \frac{1}{i_0} \cdot \sigma_{\max} \cdot \left(\frac{\mathrm{d}\sigma_{\max}}{\mathrm{d}\lambda_{\mathrm{total}}} \right)^{-1}$	$i > 0$	
Minimum Eigenvalue		$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q$	all eigenvalues should be positive	
Minimum Singular Value		$\begin{bmatrix} \Delta\vartheta \\ \Delta V \end{bmatrix} = \mathbf{V} \sum^{-} 1 \mathbf{U}^T \begin{bmatrix} \Delta F \\ \Delta G \end{bmatrix}$	details are given in reference	
Predicting Voltage Collapse		$\frac{V}{V_0}$	the smallest index value	
Impedance Ratio		$\frac{Z_i i}{Z_i}$	$\frac{Z_i i}{Z_i} \leq 1$	