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

MASTER THESIS

by

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Maximilian Köhler: *Modeling of Fast-Switching Transformers for Voltage Stability Studies in Python,*
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Contents

> *Two things are infinite: the universe and human stupidity; and I'm not sure about the universe.*
>
> **— Albert Einstein**

1 Introduction

Some blibla as introduction. [1]

This is a figure in the margin to demonstrate something small or bring a hint as side-note.

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This is a second side note for testing out some options.

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[MK1]: Write a nice introduction.

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?

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.

> *So many books, so little time.*
>
> **— Frank Zappa**

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

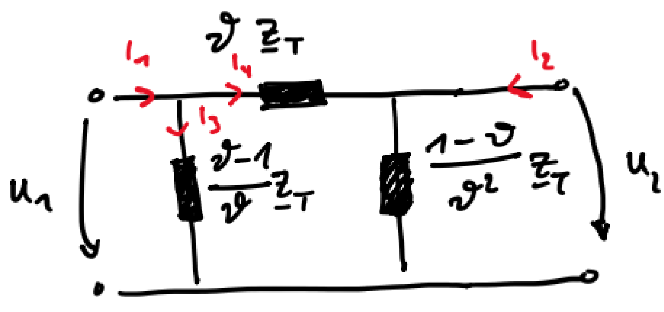

Figure 2.1: Π-representative circuit of a transformer with a longitudinal tap changer; own figure after [1], [2]

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

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

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.

Π-admittance matrix

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

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.

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

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

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

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.

2.2 Voltage stability basics

2.2.1 Voltage stability definitions, classifications, and conditions

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
- 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** [3], [4]

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

2.2.2 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:

Jacobian Matrix

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

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

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.

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 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.

Part I

Methodical

> *You only live once, but if you do it right, once is enough.*
>
> **— Mae West**

3 Transformer Equipment Modeling

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

Hier steht ein Beispielkommentar.

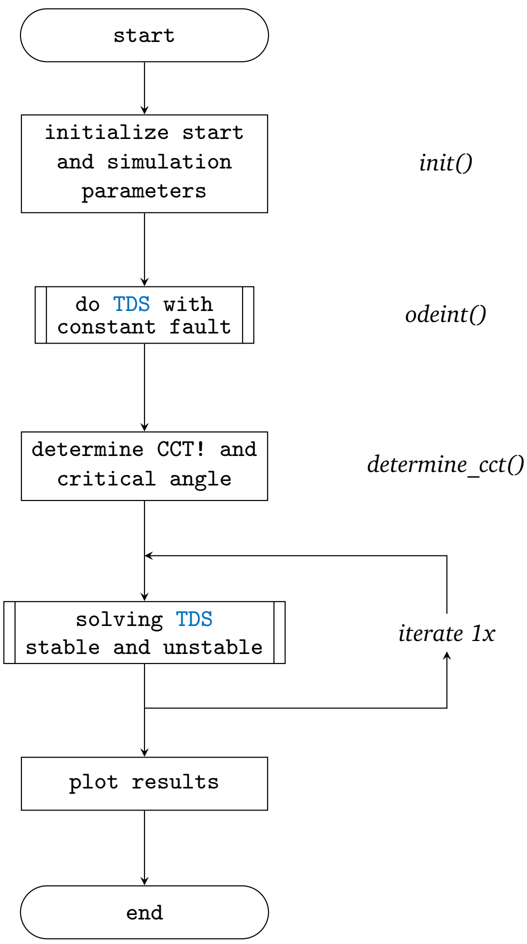

Figure 3.1: Program plan proposal for determining the **CCT!** (**CCT!**) t_{cc}, critical power angle δ_{cc} and the Time Domain Solution (TDS) of the Single Machine Infinite Bus (SMIB)-model; including the associated main function name

3.1 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.

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 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 [5]. A scheme of this control loop is shown in Figure 3.2.

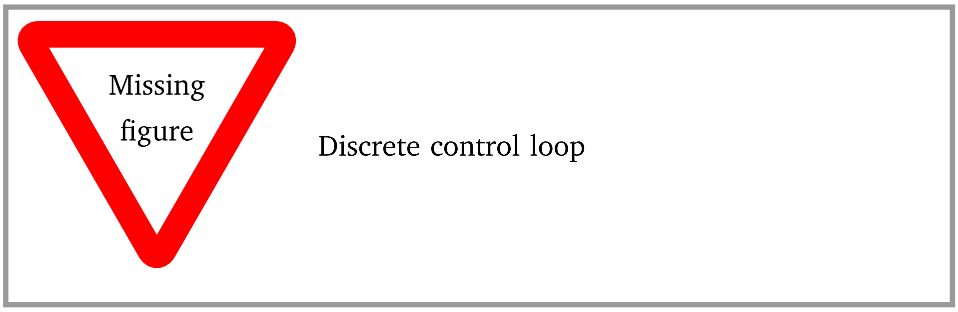

Figure 3.2: Discrete control loop of an OLTC; scheme based on Milano [5]

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.

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

3.3.2 Continous Control Loop

3.3.3 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], [6]. 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 3.3.

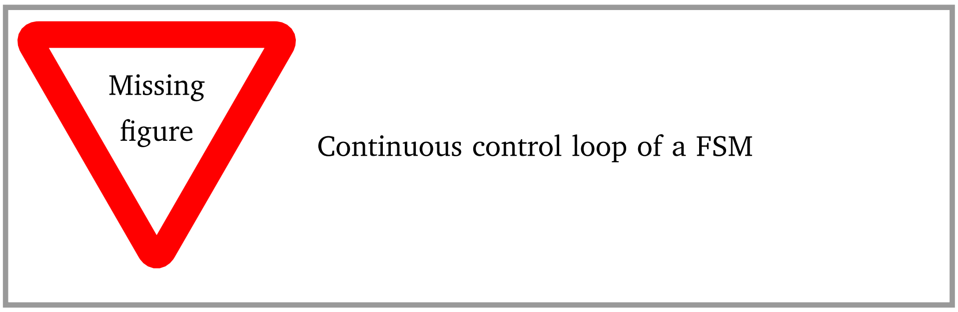

Figure 3.3: Continuous control loop of a FSM; scheme based on Burlakin, Scheiner, Mehlmann, *et al.* [2]

Continuous Control Loop for best Stability Assessment

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

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“?

Part II

Practical Application: Simulation

> *If you tell the truth, you don't have to remember anything.*
>
> **— Mark Twain**

5 Verification setup and results

5.1 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 6. 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 [7], *IEEE Guide for Load Modeling and Simulations for Power Systems* [8], and Van Cutsem, Glavic, Rosehart, *et al.* [3].

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 [7], and is shown in Figure 5.1. The generator and the IBB are represented by synchronous machines, developed and discussed by Kordowich and Jaeger [9]. The specific model details are included in **??**, additionally the simulation setup for verification is described in Table 5.1.

Figure 5.1: Single Machine Infinite Bus (SMIB) model for verification and validation of the Python framework; own figure after [1], [7]

Table 5.1: 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.

IEEE nine-bus system

Nordic test system

5.2 Results from the Python Framework

5.3 Comparison to Results from PowerFactory

Single Machine Infinite Bus (SMIB) Model

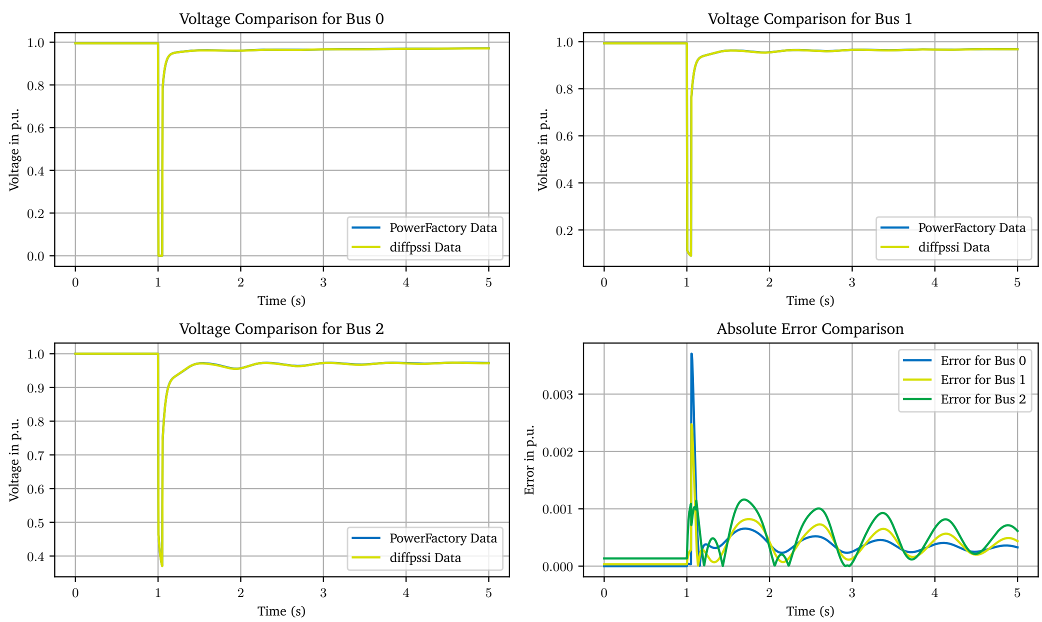

Figure 5.2: Comparison of the Π-modeled transformer in the SMIB model between PowerFactory and the Python framework

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

> *Insanity is doing the same thing, over and over again, but expecting different results.*
>
> — **Narcotics Anonymous**

6 Case study

6.1 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

6.2 Simulation

6.3 Results

> *The aim of argument, or discussion, should not be victory, but progress.*
>
> **— Joseph Joubert**

7 Discussion of the results

> *In three words I can sum up everything I've learned about life: it goes on.*
>
> **— Robert Frost**

8 Summary and outlook

Some conclusion.

Some outlook and nice blibla.

Acronyms

FSM	Fast Switching Module
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. $\vec{F}$)
- 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.

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