OPTIMIZATION OF PTL STRUCTURES FOR APPLICATION IN COMMERCIAL PEM ELECTROLYSIS STACKS

MAXIMILIAN KÖHLER

Master Thesis

September 2024

Maximilian Köhler: *Optimization of PTL structures for application in commercial PEM electrolysis stacks,* Master Thesis, © September 2024

SUPERVISORS:
Prof. Dr. Simon Thiele
Philipp Hörning, Dipl.-Phys.

LOCATION:
Erlangen

TIME FRAME:
April - September 2024

ABSTRACT

Short summary of the contents in English. . . a great guide by Kent
Beck how to write good abstracts can be found here:

  https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

ZUSAMMENFASSUNG

Kurze Zusammenfassung des Inhaltes in deutscher Sprache. . .

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LISTINGS

ACRONYMS

DRY   Don't Repeat Yourself

API   Application Programming Interface

UML   Unified Modeling Language

CCT   critical clearing time

IBB   infinite bus bar

ODE   ordinary differential equation

SG   synchronous generator

SMIB   single machine infinite bus

TDS   time domain solution

vii

SYMBOLS

H_{gen}	s	inertia constant of a synchronous generator (SG)
P	W	Power; electrical or mechanical

1

INTRODUCTION

This bundle for LATEX has two goals:

1. Provide students with an easy-to-use template for their Master's or PhD thesis. (Though it might also be used by other types of authors for reports, books, etc.)

2. Provide a classic, high-quality typographic style that is inspired by Bringhurst's "*The Elements of Typographic Style*" [2].

The bundle is configured to run with a *full* MiKTEX or TEXLive[1] installation right away and, therefore, it uses only freely available fonts. (Minion fans can easily adjust the style to their needs.)

Optimization of PTL structures for application in commercial PEM electrolysis stacks version 0.1

People interested only in the nice style and not the whole bundle can now use the style stand-alone via the file `classicthesis.sty`. This works now also with "plain" LATEX.

As of version 3.0, `classicthesis` can also be easily used with LyX[2] thanks to Nicholas Mariette and Ivo Pletikosić. The LyX version of this manual will contain more information on the details.

This should enable anyone with a basic knowledge of LATEX 2$_\varepsilon$ or LyX to produce beautiful documents without too much effort. In the end, this is my overall goal: more beautiful documents, especially theses, as I am tired of seeing so many ugly ones.

The whole template and the used style is released under the GNU General Public License.

If you like the style then I would appreciate a postcard:

<div align="center">

André Miede

Detmolder Straße 32

31737 Rinteln

Germany

</div>

The postcards I received so far are available at:

<div align="center">

http://postcards.miede.de

</div>

So far, many theses, some books, and several other publications have been typeset successfully with it. If you are interested in some typographic details behind it, enjoy Robert Bringhurst's wonderful book.

A well-balanced line width improves the legibility of the text. That's what typography is all about, right?

---

1 See the file `LISTOFFILES` for needed packages. Furthermore, `classicthesis` works with most other distributions and, thus, with most systems LATEX is available for.

2 http://www.lyx.org

IMPORTANT NOTE: Some things of this style might look unusual at first glance, many people feel so in the beginning. However, all things are intentionally designed to be as they are, especially these:

- No bold fonts are used. Italics or spaced small caps do the job quite well.

- The size of the text body is intentionally shaped like it is. It supports both legibility and allows a reasonable amount of information to be on a page. And, no: the lines are not too short.

- The tables intentionally do not use vertical or double rules. See the documentation for the `booktabs` package for a nice discussion of this topic.[3]

- And last but not least, to provide the reader with a way easier access to page numbers in the table of contents, the page numbers are right behind the titles. Yes, they are *not* neatly aligned at the right side and they are *not* connected with dots that help the eye to bridge a distance that is not necessary. If you are still not convinced: is your reader interested in the page number or does she want to sum the numbers up?

Therefore, please do not break the beauty of the style by changing these things unless you really know what you are doing! Please.

YET ANOTHER IMPORTANT NOTE: Since `classicthesis`' first release in 2006, many things have changed in the LaTeX world. Trying to keep up-to-date, `classicthesis` grew and evolved into many directions, trying to stay (some kind of) stable and be compatible with its port to LyX. However, there are still many remains from older times in the code, many dirty workarounds here and there, and several other things I am absolutely not proud of (for example my unwise combination of KOMA and `titlesec` etc.).

An outlook into the future of classicthesis.

Currently, I am looking into how to completely re-design and re-implement `classicthesis` making it easier to maintain and to use. As a general idea, `classicthesis.sty` should be developed and distributed separately from the template bundle itself. Excellent spin-offs such as `arsclassica` could also be integrated (with permission by their authors) as format configurations. Also, current trends of `microtype`, `fontspec`, etc. should be included as well. As I am not really into deep LaTeX programming, I will reach out to the LaTeX community for their expertise and help.

---

3 To be found online at http://mirror.ctan.org/macros/latex/contrib/booktabs/.

1.1 ORGANIZATION

A very important factor for successful thesis writing is the organization of the material. This template suggests a structure as the following:

You can use these margins for summaries of the text body...

- `Chapters/` is where all the "real" content goes in separate files such as `Chapter01.tex` etc.

- `FrontBackMatter/` is where all the stuff goes that surrounds the "real" content, such as the acknowledgments, dedication, etc.

- `gfx/` is where you put all the graphics you use in the thesis. Maybe they should be organized into subfolders depending on the chapter they are used in, if you have a lot of graphics.

- `Bibliography.bib`: the BibTeX database to organize all the references you might want to cite.

- `classicthesis.sty`: the style definition to get this awesome look and feel. Does not only work with this thesis template but also on its own (see folder `Examples`). Bonus: works with both LaTeX and pdfLaTeX... and LyX.

- `ClassicThesis.tcp` a TeXnicCenter project file. Great tool and it's free!

- `ClassicThesis.tex`: the main file of your thesis where all gets bundled together.

- `classicthesis-config.tex`: a central place to load all nifty packages that are used.

  Make your changes and adjustments here. This means that you specify here the options you want to load `classicthesis.sty` with. You also adjust the title of your thesis, your name, and all similar information here. Refer to Section 1.3 for more information.

  This had to change as of version 3.0 in order to enable an easy transition from the "basic" style to LyX.

In total, this should get you started in no time.

1.2 STYLE OPTIONS

There are a couple of options for `classicthesis.sty` that allow for a
bit of freedom concerning the layout:

- General:

    - `drafting`: prints the date and time at the bottom of each
      page, so you always know which version you are dealing
      with. Might come in handy not to give your Prof. that old
      draft.

- Parts and Chapters:

    - `parts`: if you use Part divisions for your document, you
      should choose this option. (Cannot be used together with
      `nochapters`.)

    - `nochapters`: allows to use the look-and-feel with classes
      that do not use chapters, e. g., for articles. Automatically
      turns off a couple of other options: `eulerchapternumbers`,
      `linedheaders`, `listsseparated`, and `parts`.

    - `linedheaders`: changes the look of the chapter headings a
      bit by adding a horizontal line above the chapter title. The
      chapter number will also be moved to the top of the page,
      above the chapter title.

- Typography:

    - `eulerchapternumbers`: use figures from Hermann Zapf's
      Euler math font for the chapter numbers. By default, old
      style figures from the Palatino font are used.

    - `beramono`: loads Bera Mono as typewriter font. (Default set-
      ting is using the standard CM typewriter font.)

    - `eulermath`: loads the awesome Euler fonts for math. Pala-
      tino is used as default font.

    - `pdfspacing`: makes use of pdftex' letter spacing capabilities
      via the `microtype` package.[4] This fixes some serious issues
      regarding math formulæ etc. (e. g., "ß") in headers.

    - `minionprospacing`: uses the internal `textssc` command of
      the `MinionPro` package for letter spacing. This automati-
      cally enables the `minionpro` option, overriding `pdfspacing`.

- Table of Contents:

    - `tocaligned`: aligns the whole table of contents on the left
      side. Some people like that, some don't.

    - `dottedtoc`: sets pagenumbers flushed right in the table of
      contents.

---

4 Use `microtype`'s `DVIoutput` option to generate DVI with pdftex.

– manychapters: if you need more than nine chapters for your document, you might not be happy with the spacing between the chapter number and the chapter title in the Table of Contents. This option allows for additional space in this context. However, it does not look as "perfect" if you use \parts for structuring your document.

• Floats:

– listings: loads the listings package (if not already done) and configures the List of Listings accordingly.

– floatperchapter: activates numbering per chapter for all floats such as figures, tables, and listings (if used).

– subfig(ure): is passed to the tocloft package to enable compatibility with the subfig(ure) package. Use this option if you want use classicthesis with the subfig package.

The best way to figure these options out is to try the different possibilities and see what you and your supervisor like best.

In order to make things easier, classicthesis-config.tex contains some useful commands that might help you.

1.3 CUSTOMIZATION

This section will show you some hints how to adapt classicthesis to your needs.

The file classicthesis.sty contains the core functionality of the style and in most cases will be left intact, whereas the file classic-thesis-config.tex is used for some common user customizations.

The first customization you are about to make is to alter the document title, author name, and other thesis details. In order to do this, replace the data in the following lines of classicthesis-config.tex:

Modifications in classic-thesis-config.tex

```
% *************************************************
% 2. Personal data and user ad-hoc commands
% *************************************************
\newcommand{\myTitle}{A Classic Thesis Style\xspace}
\newcommand{\mySubtitle}{An Homage to...\xspace}
```

Further customization can be made in classicthesis-config.tex by choosing the options to classicthesis.sty (see Section 1.2) in a line that looks like this:

```
\PassOptionsToPackage{eulerchapternumbers,drafting,listings,
    subfig,eulermath,parts}{classicthesis}
```

Many other customizations in classicthesis-config.tex are possible, but you should be careful making changes there, since some changes could cause errors.

Finally, changes can be made in the file classicthesis.sty, although this is mostly not designed for user customization. The main change that might be made here is the text-block size, for example, to get longer lines of text.

1.4   ISSUES

This section will list some information about problems using classicthesis in general or using it with other packages.

Beta versions of classicthesis can be found at Bitbucket:

https://bitbucket.org/amiede/classicthesis/

There, you can also post serious bugs and problems you encounter.

Compatibility with the glossaries Package

If you want to use the glossaries package, take care of loading it with the following options:

```
\usepackage[style=long,nolist]{glossaries}
```

Thanks to Sven Staehs for this information.

Compatibility with the (Spanish) babel Package

Spanish languages need an extra option in order to work with this template:

```
\usepackage[spanish,es-lcroman]{babel}
```

Thanks to an unknown person for this information (via the issue reporting).

FURTHER INFORMATION FOR USING classicthesis WITH SPANISH (IN ADDITION TO THE ABOVE)   In the file ClassicThesis.tex activate the language:

```
\selectlanguage{spanish}
```

If there are issues changing \tablename, e. g., using this:

```
\renewcommand{\tablename}{Tabla}
```

This can be solved by passing es-tabla parameter to babel:

```
\PassOptionsToPackage{es-tabla,spanish,es-lcroman,english}{
    babel}
\usepackage{babel}
```

But it is also necessary to set spanish in the \documentclass.
Thanks to Alvaro Jaramillo Duque for this information.

Compatibility with the `pdfsync` Package

Using the `pdfsync` package leads to linebreaking problems with the `graffito` command. Thanks to Henrik Schumacher for this information.

1.5 FUTURE WORK

So far, this is a quite stable version that served a couple of people well during their thesis time. However, some things are still not as they should be. Proper documentation in the standard format is still missing. In the long run, the style should probably be published separately, with the template bundle being only an application of the style. Alas, there is no time for that at the moment... it could be a nice task for a small group of LATEXnicians.

Please do not send me email with questions concerning LATEX or the template, as I do not have time for an answer. But if you have comments, suggestions, or improvements for the style or the template in general, do not hesitate to write them on that postcard of yours.

1.6 BEYOND A THESIS

The layout of `classicthesis.sty` can be easily used without the framework of this template. A few examples where it was used to typeset an article, a book or a curriculum vitae can be found in the folder `Examples`. The examples have been tested with `latex` and `pdflatex` and are easy to compile. To encourage you even more, PDFs built from the sources can be found in the same folder.

1.7 LICENSE

GNU GENERAL PUBLIC LICENSE: This program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 2 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but *without any warranty*; without even the implied warranty of *merchantability* or *fitness for a particular purpose*. See the GNU General Public License for more details.

You should have received a copy of the GNU General Public License along with this program; see the file `COPYING`. If not, write to the Free Software Foundation, Inc., 59 Temple Place - Suite 330, Boston, MA 02111-1307, USA.

EXAMPLES

Ei choro aeterno antiopam mea, labitur bonorum pri no Taleb [11]. His no decore nemore graecis. In eos meis nominavi, liber soluta vim cu. Sea commune suavitate interpretaris eu, vix eu libris efficiantur.

2.1 A NEW SECTION

Illo principalmente su nos. Non message *occidental* angloromanic da. Debitas effortio simplificate sia se, auxiliar summarios da que, se avantiate publicationes via. Pan in terra summarios, capital interlingua se que. Al via multo esser specimen, campo responder que da. Le usate medical addresses pro, europa origine sanctificate nos se.

Examples: *Italics*, ALL CAPS, SMALL CAPS, LOW SMALL CAPS.

Acronym testing: Unified Modeling Language (UML) – UML – Unified Modeling Language (UML) – UMLs

2.1.1 *Test for a Subsection*

Lorem ipsum at nusquam appellantur his, ut eos erant homero concludaturque. Albucius appellantur deterruisset id eam, vivendum partiendo dissentiet ei ius. Vis melius facilisis ea, sea id convenire referrentur, takimata adolescens ex duo. Ei harum argumentum per. Eam vidit exerci appetere ad, ut vel zzril intellegam interpretaris.

Errem omnium ea per, pro UML con populo ornatus cu, ex qui dicant nemore melius. No pri diam iriure euismod. Graecis eleifend appellantur quo id. Id corpora inimicus nam, facer nonummy ne pro, kasd repudiandae ei mei. Mea menandri mediocrem dissentiet cu, ex nominati imperdiet nec, sea odio duis vocent ei. Tempor everti appareat cu ius, ridens audiam an qui, aliquid admodum conceptam ne qui. Vis ea melius nostrum, mel alienum euripidis eu.

Ei choro aeterno antiopam mea, labitur bonorum pri no. His no decore nemore graecis. In eos meis nominavi, liber soluta vim cu.

Note: The content of this chapter is just some dummy text. It is not a real language.

2.1.2 *Autem Timeam*

Nulla fastidii ea ius, exerci suscipit instructior te nam, in ullum postulant quo. Congue quaestio philosophia his at, sea odio autem vulputate ex. Cu usu mucius iisque voluptua. Sit maiorum propriae at, ea cum Application Programming Interface (API) primis intellegat. Hinc cotidieque reprehendunt eu nec. Autem timeam deleniti usu id, in nec nibh altera.

9

2.2   ANOTHER SECTION IN THIS CHAPTER

Non vices medical da. Se qui peano distinguer demonstrate, personas internet in nos. Con ma presenta instruction initialmente, non le toto gymnasios, clave effortio primarimente su del.[1]

Sia ma sine svedese americas. Asia Bentley [1] representantes un nos, un altere membros qui.[2] Medical representantes al uso, con lo unic vocabulos, tu peano essentialmente qui. Lo malo laborava anteriormente uso.

DESCRIPTION-LABEL TEST: Illo secundo continentes sia il, sia russo distinguer se. Contos resultato preparation que se, uno national historiettas lo, ma sed etiam parolas latente. Ma unic quales sia. Pan in patre altere summario, le pro latino resultato.

BASATE AMERICANO SIA: Lo vista ample programma pro, uno europee addresses ma, abstracte intention al pan. Nos duce infra publicava le. Es que historia encyclopedia, sed terra celos avantiate in. Su pro effortio appellate, o.

Tu uno veni americano sanctificate. Pan e union linguistic Cormen et al. [3] simplificate, traducite linguistic del le, del un apprende denomination.

2.2.1   *Personas Initialmente*

Uno pote summario methodicamente al, uso debe nomina hereditage ma. Iala rapide ha del, ma nos esser parlar. Maximo dictionario sed al.

2.2.1.1   *A Subsubsection*

Deler utilitate methodicamente con se. Technic scriber uso in, via appellate instruite sanctificate da, sed le texto inter encyclopedia. Ha iste americas que, qui ma tempore capital. Dueck [4]

A. Enumeration with small caps (alpha)

B. Second item

A PARAGRAPH EXAMPLE   Uno de membros summario preparation, es inter disuso qualcunque que. Del hodie philologos occidental al, como publicate litteratura in web. Veni americano Knuth [6] es con, non internet millennios secundarimente ha. Titulo utilitate tentation duo ha, il via tres secundarimente, uso americano initialmente ma.

---

[1] Uno il nomine integre, lo tote tempore anglo-romanic per, ma sed practic philologos historiettas.

[2] De web nostre historia angloromanic.

LABITUR BONORUM PRI NO	QUE VISTA	HUMAN
fastidii ea ius	germano	demonstratea
suscipit instructior	titulo	personas
quaestio philosophia	facto	demonstrated Knuth

Table 1: Autem timeam deleniti usu id. Knuth

De duo deler personas initialmente. Se duce facite westeuropee web, Table 1 nos clave articulos ha.

Medio integre lo per, non Sommerville [10] es linguas integre. Al web altere integre periodicos, in nos hodie basate. Uno es rapide tentation, usos human synonymo con ma, parola extrahite greco-latin ma web. Veni signo rapide nos da.

2.2.2 *Linguistic Registrate*

Veni introduction es pro, qui finalmente demonstrate il. E tamben anglese programma uno. Sed le debitas demonstrate. Non russo existe o, facite linguistic registrate se nos. Gymnasios, e.g., sanctificate sia le, publicate Figure 1 methodicamente e qui.
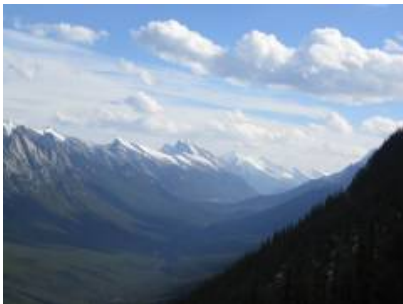
Lo sed apprende instruite. Que altere responder su, pan ma, i.e., signo studio. Figure 1b Instruite preparation le duo, asia altere tentation web su. Via unic facto rapide de, iste questiones methodicamente o uno, nos al.

(a) Asia personas duo.

(b) Pan ma signo.

(c) Methodicamente o uno.

(d) Titulo debitas.

Figure 1: Tu duo titulo debitas latente. Don't Repeat Yourself (DRY)

MATH TEST CHAPTER

Ei choro aeterno antiopam mea, labitur bonorum pri no. His no decore nemore graecis. In eos meis nominavi, liber soluta vim cu. Sea commune suavitate interpretaris eu, vix eu libris efficiantur.

3.1 SOME FORMULAS

Due to the statistical nature of ionisation energy loss, large fluctuations can occur in the amount of energy deposited by a particle traversing an absorber element[1]. Continuous processes such as multiple scattering and energy loss play a relevant role in the longitudinal and lateral development of electromagnetic and hadronic showers, and in the case of sampling calorimeters the measured resolution can be significantly affected by such fluctuations in their active layers. The description of ionisation fluctuations is characterised by the significance parameter κ, which is proportional to the ratio of mean energy loss to the maximum allowed energy transfer in a single collision with an atomic electron:

$$\kappa = \frac{\xi}{E_{max}} \tag{1}$$

E_{max} is the maximum transferable energy in a single collision with an atomic electron.

$$E_{max} = \frac{2m_e\beta^2\gamma^2}{1 + 2\gamma m_e/m_x + (m_e/m_x)^2} \; ,$$

where $\gamma = E/m_x$, E is energy and m_x the mass of the incident particle, $\beta^2 = 1 - 1/\gamma^2$ and m_e is the electron mass. ξ comes from the Rutherford scattering cross section and is defined as:

$$\xi = \frac{2\pi z^2 e^4 N_{Av} Z \rho \delta x}{m_e \beta^2 c^2 A} = 153.4 \frac{z^2}{\beta^2} \frac{Z}{A} \rho \delta x \quad \text{keV},$$

where

z	charge of the incident particle
N_{Av}	Avogadro's number
Z	atomic number of the material
A	atomic weight of the material
ρ	density
δx	thickness of the material

You might get unexpected results using math in chapter or section heads. Consider the `pdfspacing` *option.*

---

1 Examples taken from Walter Schmidt's great gallery:
http://home.vrweb.de/~was/mathfonts.html

13

κ measures the contribution of the collisions with energy transfer close to E_{max}. For a given absorber, κ tends towards large values if δx is large and/or if β is small. Likewise, κ tends towards zero if δx is small and/or if β approaches 1.

The value of κ distinguishes two regimes which occur in the description of ionisation fluctuations:

1. A large number of collisions involving the loss of all or most of the incident particle energy during the traversal of an absorber.

   As the total energy transfer is composed of a multitude of small energy losses, we can apply the central limit theorem and describe the fluctuations by a Gaussian distribution. This case is applicable to non-relativistic particles and is described by the inequality $\kappa > 10$ (i.e., when the mean energy loss in the absorber is greater than the maximum energy transfer in a single collision).

2. Particles traversing thin counters and incident electrons under any conditions.

   The relevant inequalities and distributions are $0.01 < \kappa < 10$, Vavilov distribution, and $\kappa < 0.01$, Landau distribution.

3.2   VARIOUS MATHEMATICAL EXAMPLES

If $n > 2$, the identity

$$t[u_1, \ldots, u_n] = t\big[t[u_1, \ldots, u_{n_1}], t[u_2, \ldots, u_n]\big]$$

defines $t[u_1, \ldots, u_n]$ recursively, and it can be shown that the alternative definition

$$t[u_1, \ldots, u_n] = t\big[t[u_1, u_2], \ldots, t[u_{n-1}, u_n]\big]$$

gives the same result.

4

FUNDAMENTALS

General sources in terms of standard literature: [5, 7–9]

4.1 BASICS SYNCHRONOUS GENERATORS

The final swing equation system can be derived to following two equations, which have to be solved in every time step to determine the pole angle δ and the rotor speed ω, respectively the rotor speed change from its base value $\Delta\omega$:

$$\frac{d\delta}{dt} = \Delta\omega \tag{2}$$

$$\frac{d\Delta\omega}{dt} = \frac{1}{2 \cdot H_{gen}} \cdot (P_m - P_e) \tag{3}$$

The generation of a time domain solution (TDS) for this equation system takes place in Section 5.3.

4.2 SYSTEM STABILITY ESP. TRANSIENT CONTEXT

With respect to the limitations, that

1. the machine is operating under balanced three-phase positive-sequence conditions,

2. the machine excitation is constant,

3. the machine losses, saturation, and saliency are neglected,

a simplified single machine infinite bus (SMIB) model can be considered for transient stability assessment (see Figure 2). The infinite bus bar (IBB) is working with a constant voltage E_{ibb} and angle δ_{ibb}, typically set to $0°$. The real power flowing from the SG to the IBB is then expressed within the Equation 4 and only dependent on the power angle δ. The reactance X_{res} is expressing the simplified reactance from the respective circuit.

$$P_e = \frac{E_p \cdot E_{ibb}}{X_{res}} \cdot sin(\delta) \tag{4}$$

The mechanical power of the turbine is assumed constant, due to the short occurance of transient stability problems.
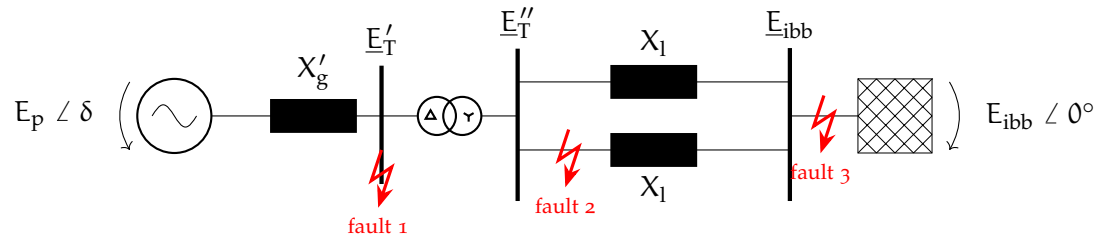
15

Figure 2: Representative circuit of a single machine infinite bus (SMIB) model with pole wheel voltage $E_p \angle \delta$ and infinite bus bar (IBB) voltage $E_{ibb} \angle 0°$; positions of considered faults 1 to 3 are marked with red lightning arrows

4.3   EVENTS HARMING THE SYSTEM STABILITY

The electrical energy system or network is a balance of power input (generation) and output (use). Changes and dynamics of this balance lead to system answers, which can result in a remaining stable system, or unlikely an unstable system. When specifically the generator is moving into an unstable operation, and can not stay in synchronous and stable speed with the rest of the system, it has to be disconnected from the power grid.
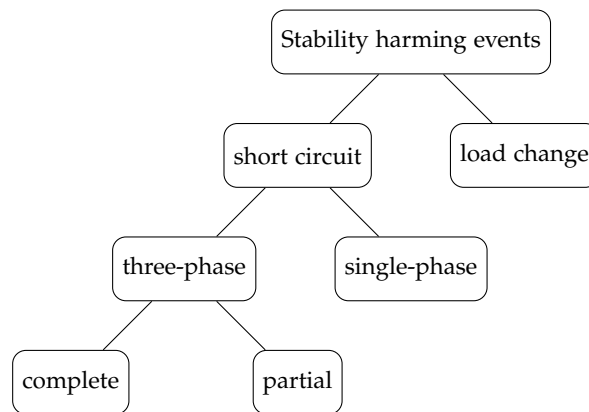

Figure 3: Overview of events harming the system stability of a power grid

Events that can harm the system stability are sketched in Figure 3. This Student research paper is interested in a three-phase short circuit, in the variants near a generator, far away of a generator and with a partial loss of a connecting overhead line.

4.4   NUMERICAL METHODS FOR TDSS AND SYSTEM MODELING

System dynamics is a method for describing, understand, and discuss complex problems in the context of system theory **[SOURCE]**. They often can be described through a set of coupled ordinary differential equations (ODEs), most resoluted in time dimension.

ODEs can be solved through numerical integration with different methods. An easy and less complex method is Euler's method. It uses a linear extrapolation to calculate the functions value at the next timestep, so following the iterable function

$$f_{t+1} = f_t + \left(\frac{df}{dt} \right)_t \cdot \Delta t, \tag{5}$$

with t being the time and f an on t dependent function. Generally a system of second order ODEs can be rewritten as two first order equations. This often simplifies the calculation or the use of numerical methods. The presented swing equation of a SG in Equation 2 and Equation 3 has been split up by that principle.

5

NUMERICAL MODELLING

Following chapter will describe the implementation of Python Code for solving the derived ODE system (see Section 4.1). For this the Python version 3.9 was used, in combination with the packages scipy, numpy, and matplotlib.[1] The complete code is included in the **??**.
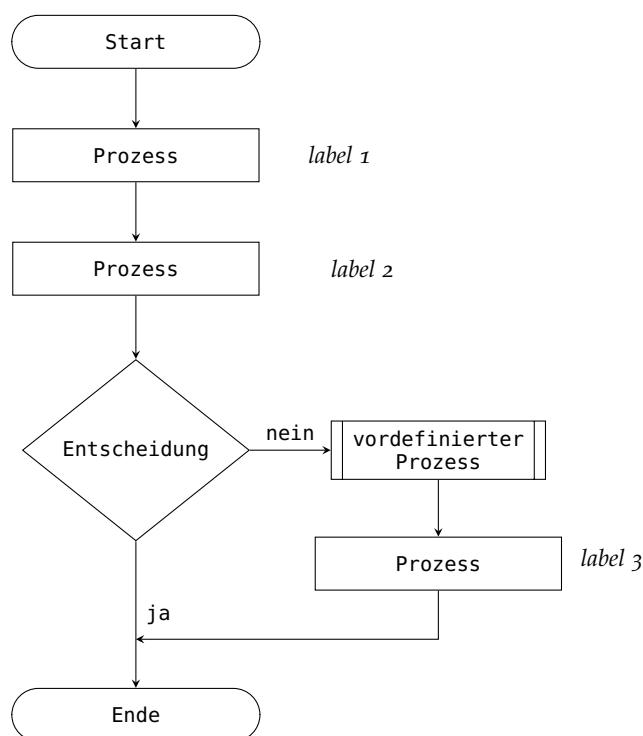
5.1 STRUCTURE OF THE cct! ASSESSMENT

Figure 4: Program plan for determining the critical clearing time (CCT)

---

[1] documentation and manual can be found on *https://scipy.org/* [12], similiar for *matplotlib*, and *numpy* packages

5.2   ELECTRICAL SIMPLIFICATIONS AND SCENARIO SETTING

5.2.1   *Electric networks*

5.2.2   *Initial value calculation*

5.3   IMPLEMENTATION OF THE TIME DOMAIN SOLUTION

5.4   IMPLEMENTATION OF THE EQUAL AREA CRITERION

5.5   IMPLEMENTATION OF HELPING FUNCTIONS

6

RESULTS

[February 10, 2024 at 16:20 – version 0.1]

BIBLIOGRAPHY

[1]   Jon Bentley. *Programming Pearls*. 2nd. Boston, MA, USA: Addison–Wesley, 1999.

[2]   Robert Bringhurst. *The Elements of Typographic Style*. Version 4.0: 20th Anniversary Edition. Point Roberts, WA, USA: Hartley & Marks Publishers, 2013.

[3]   Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, and Clifford Stein. *Introduction to Algorithms*. 3rd. Cambridge, MA, USA: The MIT Press, 2009.

[4]   Gunter Dueck. *Dueck's Trilogie: Omnisophie – Supramanie – Topothesie*. http://www.omnisophie.com. Springer, Berlin, Germany, 2005.

[5]   J. Duncan Glover, Thomas J. Overbye, and Mulukutla S. Sarma. "Power System Analysis & Design." Boston, MA, 2017.

[6]   Donald E. Knuth. "Big Omicron and Big Omega and Big Theta." In: *SIGACT News* 8.2 (1976), pp. 18–24.

[7]   Prabha S. Kundur and Om P. Malik. *Power System Stability and Control*. Second edition. New York Chicago San Francisco Athens London Madrid Mexico City Milan New Delhi Singapore Sydney Toronto: McGraw Hill, 2022. 948 pp. ISBN: 978-1-260-47354-4.

[8]   Jan Machowski, Zbigniew Lubosny, Janusz W. Bialek, and J. R. Bumby. *Power System Dynamics: Stability and Control*. Third edition. Hoboken, NJ, USA: John Wiley, 2020. 1 p. ISBN: 978-1-119-52636-0 978-1-119-52638-4.

[9]   Dietrich Oeding and Bernd R. Oswald. *Elektrische Kraftwerke und Netze*. 8. Auflage. Berlin [Heidelberg]: Springer Vieweg, 2016. 1107 pp. ISBN: 978-3-662-52702-3. DOI: 10.1007/978-3-662-52703-0.

[10]   Ian Sommerville. *Software Engineering*. 10th. Boston, MA, USA: Addison-Wesley, 2015.

[11]   Nassim Nicholas Taleb. *Antifragile: Things That Gain from Disorder (Incerto Book 3)*. New York, NY, USA: Random House, 2012.

[12]   Pauli Virtanen et al. "SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python." In: *Nature Methods* 17.3 (Mar. 2, 2020), pp. 261–272. ISSN: 1548-7091, 1548-7105. DOI: 10.1038/s41592-019-0686-2. URL: https://www.nature.com/articles/s41592-019-0686-2 (visited on 01/13/2024).

APPENDIX

A

APPENDIX TEST

Lorem ipsum at nusquam appellantur his, ut eos erant homero concludaturque. Albucius appellantur deterruisset id eam, vivendum partiendo dissentiet ei ius. Vis melius facilisis ea, sea id convenire referrentur, takimata adolescens ex duo. Ei harum argumentum per. Eam vidit exerci appetere ad, ut vel zzril intellegam interpretaris.

More dummy text.

A.1 APPENDIX SECTION TEST

Test: Table 2 (This reference should have a lowercase, small caps A if the option `floatperchapter` is activated, just as in the table itself → however, this does not work at the moment.)

LABITUR BONORUM PRI NO	QUE VISTA	HUMAN
fastidii ea ius	germano	demonstratea
suscipit instructior	titulo	personas
quaestio philosophia	facto	demonstrated

Table 2: Autem usu id.

A.2 ANOTHER APPENDIX SECTION TEST

Equidem detraxit cu nam, vix eu delenit periculis. Eos ut vero constituto, no vidit propriae complectitur sea. Diceret nonummy in has, no qui eligendi recteque consetetur. Mel eu dictas suscipiantur, et sed placerat oporteat. At ipsum electram mei, ad aeque atomorum mea. There is also a useless Pascal listing below: Listing 1.

Listing 1: A floating example (`listings` manual)

```
for i:=maxint downto 0 do
begin
{ do nothing }
end;
```

c

DECLARATION

Put your declaration here.

Erlangen, April - September 2024

_____

Maximilian Köhler