



Chair of High-Power Converter Systems  
TUM School of Engineering and Design  
Technical University of Munich  
Prof. Dr.sc. ETH Zürich Marcelo Lobo Heldwein

## Title of Master Thesis

Max Mustermann





# Title

## Master Thesis

to gain the academic title

Master of Science  
(M.Sc.)

in the degree program Electrical Engineering and Information Technology  
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## Declaration

The work in this thesis is based on research carried out at the Chair of High-Power Converter Systems, Technical University of Munich (TUM) supervised by M.Sc. Erika Mustermann. No part of this thesis has been submitted elsewhere for any other academic degree or qualification and it is all my own work unless referenced to the contrary in the text.

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Place, Date, Signature

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## Abstract

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Write a concise summary in 100 to 250 words maximum (half a page maximum for a thesis). You may write your abstract with the following guidelines: (i) State the general motivation of your research field in one or maximum two sentences, e.g. “Recently, kites are being investigated to generate sustainable power with a lower material demand compared to conventional wind turbines.” (ii) State the specific problem you are dealing with in one or maximum two sentences, e.g. “The automatic control of the kite is a major challenge.” (iii) Briefly state how you propose to solve the problem, e.g. “This paper proposes to use cascaded controllers consisting of …” (iv) Briefly state how you verified your idea and briefly state important results and possible/important limitations, e.g. “Simulations and experiments with a small-scale system demonstrated the validity and stability of the developed controllers. An efficiency of … was achieved.”—The abstract is only one paragraph. Avoid abbreviations if possible and do not use any references to other publications or to parts of this document. Write the abstract with the following in mind: The abstract serves anybody to decide if a work is relevant for his/her work. If the reader thinks that the abstract sounds relevant to him/her, he/she would then continue, and might read your conclusions right afterwards before reading all other sections. Consequently, abstract and conclusions are very important parts of your report/thesis.



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## Acknowledgments

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...if you would like to thank someone. In a thesis, acknowledgements are usually put on one of the first pages.

Munich, in September 2022  
Max Mustermann



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## Preface

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... if you would like to write a preface.

Munich, in September 2022  
Max Mustermann



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# CHAPTER 1

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## Introduction

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The first section is always titled “Introduction” or alternatively “Motivation”. In this first section, you briefly introduce your topic and motivate why it is interesting/important to actually think about it. E.g. in the first one or two paragraphs of a work related to kite power, you briefly introduce the idea/technology of kite power, also with a figure.

In the next one or two paragraphs, you describe the specific problem you are dealing with in your work, e.g. the control of the kite. You specifically state solutions other researchers published (with reference, about three to ten relevant/important references, depending on the problem/research field) and their shortcomings, you are trying to improve with your proposed solution, e.g.: “Musterfrau proposed in [42] to use model predictive control (MPC) to control all states of the kite. Musterdame improved the control scheme for real time execution in [43]. However, one shortcoming in these solutions is the complexity of the optimization algorithm of MPC. In this paper, a different approach is proposed, by using set of cascaded PID controllers and a switching logic. As a result, a relatively simple control structure which is executable in real time on low cost micro controllers is used to control the kite.” Give a few important/interesting details, what is different (or better) on your approach, but keep these statements short: Details follow in the main part. If a longer literature review is required, you can also have a section after the motivation titled “Related Works” or “Literature Review” or similar. You usually receive a few literature reference from your supervisor as a general starting point of your work. For more literature, have a look into the literature references of those literature references. Google Scholar or IEEEExplore with the extended search are further sources for your literature review. At the end, you should have at least ten papers, theses or dissertations in your literature list. This does not mean, that you have read and understood completely all these publications. However, you should have understood the key ideas, methods and results of a cited publication.

At the end of your literature review and introduction to your approach, state the specific new contributions of your work, e.g.: “The contributions of this study can be summarized as follows: (i) Proposal of cascaded PID controllers to control the kite. (ii) Derivation of the PID parameters and switching scheme for the different flight phases. (iii) Formal stability proof of

the controllers for all flight phases. (iv) Verification of the effectiveness of the control method through simulations and experiments with a small scale demonstrator.”

In the last paragraph, you briefly state how you organized your report by referring to specific sections, e.g.: “This paper is organized as follows: The next section gives a brief introduction to PID controllers. Sec. x derives the model equations with important assumptions and formulates the control problem. Sec. y proposes the solution and gives a formal stability proof. Secs. z–z2 show simulation and experimental results. Finally, conclusions and an outlook are given in Sec. z3.”

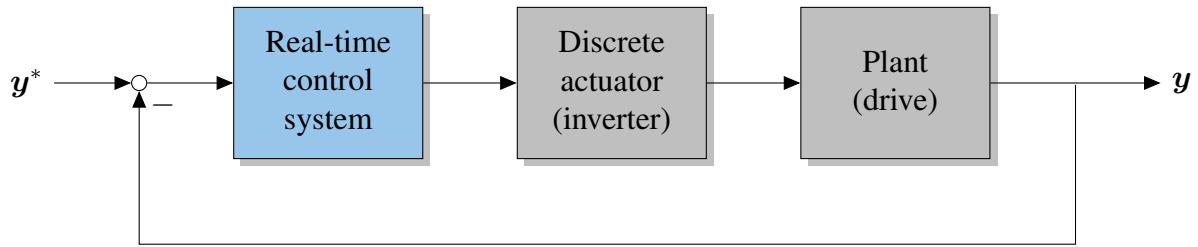


Figure 1.1: An example for TikZ picture

# CHAPTER 2

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## Background and motivation

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Example for the beginning of each chapter:

This chapter gives a brief overview of the used physical systems, their working principles and explains all necessary details which are needed to understand the systems which are used within this work. Furthermore, this chapter gives a short overview of the state of the art in control of electrical drive systems and highlights known problems in these methods. It is followed by a general introduction to Model Predictive Control (MPC) techniques with special focus on Finite-Set MPC (FS-MPC). Finally, the two major drawbacks of FS-MPC methods, the high calculation effort and the low time resolution compared to modulation-based methods, are explained in detail in order to clarify the motivation for this work.

### 2.1 Introduction to PID controllers

Depending on the topic, you might want to give a more detailed introduction of the problem (e.g. kite power) or the controller approach (e.g. the general control method). This section can be one to two pages long (for a thesis five to ten pages) and can be divided in subsections. If no further explanation is required, this section may be dropped: PID controllers probably do not need any further explanations.

### 2.2 Problem Description

Any new section should start with a brief introduction of the section, before a new subsection starts. Here, you could give a brief introduction (a few sentences) about your general modeling approach, e.g.: “In the following, a mathematical model of the kite is derived. Based on Newton’s mechanics, the dynamic equations and equations for each force component are given.” The title of this section can also be changed e.g. to “System Description” or “Model Equations” or similar.

### 2.2.1 Dynamic Equations

Newton's mechanics and the following assumptions are implied:

**Assumption 1:** *The kite is assumed as point mass with mass  $m_k$ .*

**Assumption 2:** *The flat earth is assumed as inertial (unaccelerated), cartesian reference frame, in which the kite's position is described by position vector  $r_k^i$ .*

**Assumption 3:** ...

For describing your model, highlight important assumptions with which the real world is abstracted in math. Thereby, it becomes clearer for which cases the model (and controller) is valid, or which limitations must be implied. You may use such assumption boxes in the text as you develop your model/controller step-by-step, or you list all implied assumptions at the beginning of the problem description.

... text ...

### 2.2.2 Gravitational Force

Text, math, assumptions, etc.

### 2.2.3 Further Subsections ...

Text, math, assumptions, etc.

### 2.2.4 Control Problem Formulation

Now you have transformed the real world into a simplified (based on assumptions) mathematical model. In the last subsection of the problem description, you could explicitly state the control problem you are trying to solve, e.g.: “The control problem can be formulated as follows: Find a controller, that stabilizes the system  $(x)-(y)$ , i.e. all eigenvalues of the closed loop system have negative real parts,

$$\forall i \in [1, n] : \Re\{\lambda_i\} < 0, \quad (2.1)$$

where  $\lambda_i$  is an eigenvalue.”

## 2.3 Proposed Solution

In this section, you describe your proposed solution. The title can also be changed to “Control Design” or “Design of a Control Method” or similar. Here you can also proof the stability, or formulate a theorem and push its proof to the appendix. Several subsections may be used.

## 2.4 Implementation and Results

Briefly describe how you verified your solution, e.g. describe the employed simulation software or the built demonstrator. State relevant parameters in a table, as in Tab. 2.1. Note also the correct use of indices of variables to be non-italic.

Table 2.1: Relevant Simulation Parameters.

| Parameter             | Symbol & Value   |
|-----------------------|--|
| tether voltage        | $U_{te} = 8 \text{ kV}$                                |
| tether current        | $I_{te} = 100 \text{ A}$                               |
| controller parameters | $(K_P, K_I) = (-0.5 \text{ A/V}, -3.5 \text{ A/(Vs)})$ |

Show and describe relevant simulated or measured data to give proof of the validity of the assumptions and proposed solution. Use matlab2tikz (<https://github.com/matlab2tikz/matlab2tikz>) for high quality plots as in Fig. 2.1. Note that the legend is placed in the caption as an elegant way to avoid a legend box on top of the plotted data or to avoid repetitions (e.g. blue is always phase  $\alpha$ ). Use appropriate axis scalings and dimensions, and keep them consistent if you compare different results. Note also that only the last plot has labels on the x-axis. Have a look into the Matlab script `Matlab2TikzExample.m` with which the figure was generated.

Figure 2.1: Measurement results: From top to bottom, voltage  $u_{\{\cdot\}}$  and current  $i_{\{\cdot\}}$  of the machine, with blue line for phase  $\alpha$  and red line for phase  $\beta$ .

## 2.5 Discussion

Results can be discussed and interpreted already in the results section. However, you can also just present the results there, and discuss and interpret them a special discussion section. Here you can also compare two possible variants of your controller or give a more thorough comparison of your approach to an earlier published approach.

## 2.6 Conclusions and Outlook

Every paper ends with the section “Conclusion(s)” or “Conclusion(s) and Outlook”. Briefly summarized your work including motivation and general problem, your proposed approach and a summary of important/relevant results. The latter can have qualitative and quantitative statements, e.g. “The system showed stable behavior in experiments. An efficiency of up to  $x\%$  was achieved.” You may also give a short outlook on possible further steps or plans. However, the outlook should be relatively short—your work should be considered as finished.



# CHAPTER 3

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## Further Guides for Your Report or Thesis

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In the following, a few further guidelines (dos and don'ts) are given.

### 3.1 Guidelines for Your Presentation

#### 3.1.1 Template, Software and Language

For an Engineer's Internship Report, Seminar Paper, Researcher's Report, Bachelor Thesis and Master Thesis you are invited to use this  $\text{\LaTeX}$  template. You can also extract a few tips on writing in  $\text{\LaTeX}$  (e.g. the tilde in Fig. `\sim\ref{key}` to avoid a line break).

$\text{\LaTeX}$  is highly (!) recommended, but any other software (e.g. Word, OpenOffice) may be used. TUM provides some templates (also for presentations) which may be used: <https://portal.mytum.de/corporatedesign>

English is preferred, but depending on the topic, German is also fine.

In any case, consult your supervisor for his/her specifications for your work.

#### 3.1.2 Structure

A possible structure is given in the main part of this document. Generally, the motivation/introduction section usually has no subsections and may be up to two pages long (up to about three pages for a thesis). Limit the number of chapter levels/section levels (section, subsection, subsubsection) to three or four maximum.

If your topic is different from a controller design, the structure of your report/thesis can be different from the here proposed one. However, the abstract, the motivation/introduction and the conclusions and outlook sections remain as presented. For the structure of other topics of reports/theses, have a look into published papers with similar topics to yours. If your topic is a literature review, have a look e.g. in [1].

### 3.1.3 Page Count

For a bachelor or master thesis, the page count should be below 100 or maximum 150. In any case, be concise. Usually, it is not hard to write many pages, but to write few concise pages. It would be ideal if you can write as concise as 5 pages for a report or 50 pages for a thesis.

### 3.1.4 Style of Writing: Equations

It is a good style to handle any equation as part of a sentence. Instead of writing: “The gravitational force depends on the mass.

$$F = mg'' \quad (3.1)$$

You should write: “The gravitation force depends on the mass and is given by

$$F = mg.'' \quad (3.2)$$

As the equation is at the end of the sentence, it ends with a period. Here is another example with an accessory sentence (usage of a comma in the equation): “The gravitational force is

$$F = mg, \quad (3.3)$$

where  $m$  is the mass.”

Derive all your equations with symbols first. Afterwards and if appropriate, you can calculate numerical results or just list parameters and results in a table.

### 3.1.5 Style of Writing: Math Symbols

Use common math symbols and try to reduce the amount of used symbols if possible, but do not let room for ambiguity. A good practice is to write scalars normal  $s$ , vectors bold  $v$ , matrices bold and capitalized  $M$  and nature constants normal and non-italic  $c$ . Use consistent multiplication symbols. A good practice is to use no multiplication symbol for variables,  $F = mg$  and a centered dot for numbers,  $F = 1 \text{ kg} \cdot 9.81 \text{ m/s}^2$ . Do not use  $F = 1 \text{ kg} * 9.81 \text{ m/s}^2$  or  $F = 1 \text{ kg} \times 9.81 \text{ m/s}^2$  or  $F = 1 \text{ kg}.9.81 \text{ m/s}^2$ . These three symbols are reserved for convolution, cross product and point-separator. Function names are written normal, i.e. write  $\sin(x)$  (i.e.  $\$ \backslash \sin(x) \$$ ) instead of  $\sin(x)$ . You can also define your own function names with  $\$ \backslash operatorname{myFunc} (x) \$$  which becomes  $\text{myFunc}(x)$ .

Every symbol needs to be explained at its first use, even if it is somewhat obvious such as mass  $m$ : The symbol  $m$  could have also been used for an amount as in  $\sum_{i=1}^m x_i$ .

Use appropriate braces in equations and make use of  $\backslash left$  and  $\backslash right$ .

### 3.1.6 Style of Writing: Braces and Footnotes

Reduce the usage of (braces) in the text and footnotes to a minimum. Either a statement is relevant and it could be in the normal text, or it is not so important and might be not written at all.

### 3.1.7 Style of Writing: Sentence Length, Adjectives, Superlatives, Assessments

Write short and concise sentences, best just in the form noun, verb, object, e.g. “Fig. x shows a block diagram of the controller.” Avoid assessing adjectives/superlatives and the word “very”, e.g. do not write “Kite power has enormous advantages and the proposed controller achieves a very high efficiency.” Generally, only use statements that cannot be argued. The example sentence can be improved e.g. as follows: “Kite power has some advantages compared to conventional wind turbines, such as a lower material demand. The proposed controller achieved an efficiency of  $x\%$ .” In that example, there is little to no room for arguments against the statements. You may let the reader assess your results, as in the last sentence of that example. Note that this is the difference of a scientific style of writing compared to the style usually used in marketing or journalism.

Before submitting a revision to your supervisor, it is a good idea to read your report/thesis aloud. Try to identify sentences, that can be shorter or divided into two (or more). Try to identify arguable statements, and remove them if they are not required. Find any other possibilities for improvements. Your goal is to submit a perfect report without any mistakes (in your eyes).

### 3.1.8 Style of Writing: Explanations

Write your findings/proposals as easy to read as possible. Write for someone who has not dealt in detail with your topic for months, but has a basic knowledge of your topic. For a controller implementation or a simulation model, it might be a good idea to ask yourself the following question: Is it possible to replicate your controller/model just with the information given in the text? For a thesis, you might give all the source codes and screenshots of simulation models, but already the mathematical equations and explanations should be enough for the reader to replicate your results. Generally it is a good idea to start your explanation/modeling with an axiom or with key assumption(s), e.g. “according to Newton’s axioms, the dynamics of the kite is given by  $\dot{\mathbf{p}} = \mathbf{F}_\Sigma, \dot{\mathbf{r}} = m^{-1}\mathbf{p}$ , where …”, or for an electrical problem, “according to Kirchhoff’s current law, the capacitor current is given by …” Another start could be an equation based on conservation of power, energy or momentum. This is a point, where you can “pick up” an engineer/researcher of your field. From that point on, develop your model step-by-step. Use a similar step-by-step-approach for any other derivation such as your control method. You may also cite specific references to keep your derivation and page count short or to start your derivation from a more advanced “pick-up”-point. Your goal is to help the reader to understand your ideas and steps as easy as possible, without reading many other publications.

Write either in passive, e.g. “a current of 10 A was measured”, or in the first person, e.g. “we/I measured a current of 10 A”. Use the present tense for explanations which have no time dependence, e.g. “the induced voltage is a function of the speed”, and use the simple past tense for past actions, e.g. “the stability of the controller was proven” or “an efficiency of  $x\%$  was measured”. Other tenses are rare in a scientific report, see e.g. <https://www.ef.com/wwen/english-resources/english-grammar/verbs/> for the correct usage.

Use figures for your explanations. “An image can tell more than thousand words.” Ideally, important parts of your mathematical derivation can be “seen” already in the figures, e.g. a vector diagram supports a trigonometric equation of your derivation. Create high quality vector

images e.g. with Inkscape and its L<sup>A</sup>T<sub>E</sub>X export and create plots e.g. with matlab2tikz or Pgfpplots [https://de.overleaf.com/learn/latex/Pgfpplots\\_package](https://de.overleaf.com/learn/latex/Pgfpplots_package). Tip: use your favorite search engine and look for “latex drawing software”. Generally, labels should have the same (or similar) font and font size as the text of the template. It can take a lot of time to create a good/professional image or a good/professional plot, but it is worth it. A reader would usually first scan images, as they can summarize the most important parts of your work.

Push the figures/tables to appropriate locations in the text. A (sub)section title cannot be followed by a figure/table. Do not start a sentence with “But”. Do not use short forms such as “can’t” or “don’t”. Write it out, “cannot” and “do not”.

### **3.1.9 Style of Writing: Paragraphs**

Not every sentence is a paragraph, and a long section should have several paragraphs. Usually, the first sentence in a paragraph states a main point. Remaining sentences of the paragraph present information related to that main point.

### **3.1.10 Style of Writing: Abbreviations**

Only use very common abbreviations, do not invent your own. Keep the usage of abbreviations at a minimum. A common abbreviation is PID controller which does not need further explanations. Another one would be PMSM for permanent magnet synchronous machine, which is often used by electrical engineers, but might be unknown by others. The first usage of such an abbreviation should be in the form “the abbreviation (TA)”. Avoid abbreviations in the title of the report and in the abstract if possible.

### **3.1.11 Style of Writing: References, Citations**

Reference to all figures and all tables at least once with “see Fig. x” and “see Tab. y” or “as shown in Figs. x–y” or similar (in L<sup>A</sup>T<sub>E</sub>X with `as shown in Figs.\ref{tag1}–\ref{tag2}`). Reference equations with “solve (x) for m” (in L<sup>A</sup>T<sub>E</sub>X with `solve~\eqref{tag3}` for \$m\$).

Keep references to later sections of your report at a minimum, the only exception is the last part of the introduction to draw an outline. Do not write in future tense like “xy will be shown later”. Also avoid to write “xy was shown in the equations earlier” or “above”. Instead, always refer to specific sections, equations or figures.

Every statement or information from another source requires a reference to that source. This particularly also includes images. For images, the citation mark can be placed in the caption.

Do not start a sentence with a pure reference such as “(x) computes the force ...” or “[y] discussed MPC ...”. Instead write “Eq. (x) computes the force ...” or “In [y] MPC was discussed ...”. At the beginning of a sentence, you may also write out Equation, Figure or Table. In all other cases, use the short form Eq. (or just the equation number in braces, be consistent), Fig. or Tab. Do not alter the word for “Figure”, i.e. do not write “see Image x” or “see Picture y”. Always use “Fig. z”. An equation number is always in braces, a reference is always in square braces and all other numbers are in no braces.

### 3.1.12 Style of Writing: Report Title

Keep the title short and concise. A good title is only one line, or maximum two lines. Do not use a title with more than three lines.

### 3.1.13 Style of Writing: Captions

Keep captions (e.g. of figures and tables) concise. They only describe what is shown. Discussions and interpretations are in the main text. The first letter of the first word of the caption is capitalized. The caption ends with a period.

### 3.1.14 Style of Writing: Lists

Lists should be used if appropriate. In a paper, you should use inline lists, e.g.: “The advantages of a PID controller are (i) the simplicity, (ii) the low computational demands and (iii) the stability.” In a thesis, you might use bullet points instead. Each item should sound similar, i.e. if the first item starts with a noun, all other items should also start with a noun. If the first item is a sentence, all other items should be a sentence, etc.

### 3.1.15 Spelling

Before you submit a revision to your supervisor, always use a spell checker for the complete document. Check for the correct use of “a”, “an”, “the” and plural.

### 3.1.16 Quotation Marks in L<sup>A</sup>T<sub>E</sub>X

The quotation mark symbol in L<sup>A</sup>T<sub>E</sub>X is not ". It is “quoted” or the respective UTF-8 symbols “quoted” (you might have shortcuts on your operating system).

Use bibtex (or alternatively biber) for the bibliography in L<sup>A</sup>T<sub>E</sub>X. For many publication databases you find the bibtex entry of a paper online (e.g. google books or IEEEExplore) which just needs to be copied and pasted into your bib file: Fig. 3.1 shows a screenshot from IEEEExplore. After clicking on “Download Citation”, copy the text and paste it into your “.bib” file.

### 3.1.17 Further Reading

Please also read “How to write for Technical Periodicals & conferences” by IEEE, <https://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/How-to-Write-for-Technical-Periodicals-and-Conferences.pdf>, at least Secs. 6–7. Another guide is <http://journals.aps.org/files/rmpguide.pdf>.

## 3.2 Guidelines for Your Presentation

In the following, a few guidelines (dos and don’ts) for your presentations are given:

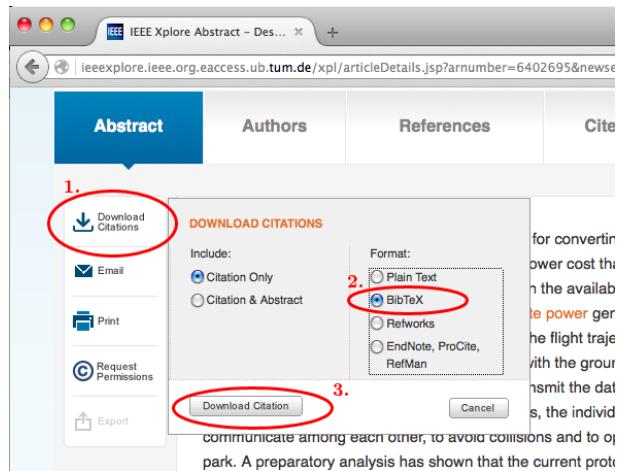


Figure 3.1: Downloading a bibtex entry from IEEEExplore.

- Do not create a bullet point-“standard” Power Point presentation.
- Place almost no math on the slides, except one can understand quickly, and if it helps to illustrate your idea.
- Instead, use images and graphs, with which you tell a story and sketch your idea. A story teller does not need to draw an outline at the beginning of the story.
- Place affiliation, dates, logos etc. only on the first slide (title slide). On all other slides, place only a slide number and do note place other boarders. Use a single color background, e.g. just black or white.
- Do not overload your slides.
- Use a similar structure as in your report/thesis: title, motivation incl. previous/related works, your approach/idea, your results, conclusions, outlook.
- Rehearse your presentation several times. Make sure, you are  $\pm 3$  min maximum within the set time limit. You usually need about 1 min per slide.
- Create your presentation with only one target: The audience shall understand your key idea. Mathematical details etc. can be found in your report/thesis.

# CHAPTER 4

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## Conclusion

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An example for conclusion chapter.

### 4.1 Summary

The goals of this work were

1. to find solutions to reduce the calculation effort for FS-MPC methods,
2. to increase the time resolution of FS-MPC methods in order to reduce ripples on the controlled variables and
3. a combination of the two last points, i.e. to find methods to reduce ripples on the controlled variables with less calculation effort.

Within this work solutions for all three items have been proposed and were proven experimentally.

It was also verified that FS-MPC methods offer several advantages over conventional PID controllers:

1. Multivariable control is easily possible (control of two currents, both flux and torque, and also the voltage balancing can be performed by one single FS-MPC controller).
2. Constraints can be considered without problems and nonlinearities can also be included.
3. FS-MPC controllers can easily operate the system at its physical limits. Conventional controllers mostly need additional (adaptive) schemes and feed forward controllers to achieve the same or similar dynamics.
4. FS-MPC controllers do normally not produce an overshoot which is usual for conventional controllers.

## 4.2 Final evaluation

As already mentioned, the applicability of direct switching strategies is highly dependent on the power range of the system: For medium- and high-voltage systems the system losses are dominated by the inverter switching losses. In this case switching frequencies of only a few hundred Hz per device are desired. For that reason industrial applications of FS-MPC methods have been reported mainly for high-power systems (MPDTC which was developed by ABB). Compared to classical DTC, MPDTC can lead to a further reduction of the switching frequency while maintaining at the same time the same quality of the control result. Sophisticated FS-MPC methods can partly even outperform Optimized Pulse Patterns for these types of drive systems [2].

In contrast to this, the presented work deals with low-voltage and smaller systems which are in the range of a few kW. For these applications a good quality of the controlled variables is usually much more important than a low switching frequency as in this case the inverter losses are less dominant. For these applications switching frequencies of 10–20 kHz per device can be easily handled. The conventional FS-MPC approach only allows to change an inverter switching state at the *beginning* of a sample which is the reason for undesired high ripples. Another very important drawback of FS-MPC is the high calculation effort which rises exponentially with the prediction horizon. Thus, in this work several extensions to FS-MPC in order to reduce the calculation effort and to reduce ripples on the controlled variables were presented. As the shown experimental results clearly verify, the proposed extensions can effectively reduce these two drawbacks of FS-MPC methods. These extensions could even be successfully implemented for more sophisticated inverter topologies (three-level NPC and FC) where several tasks have to be performed by one single FS-MPC (e.g. control of two currents and three FC voltages). Even despite the high number of possible switching states (27 for an NPC and 64 for an FC inverter), up to three prediction steps could be realized in real-time with sampling rates up to 16 kHz. For the proposed methods only one or two weighting factors have to be tuned (if any at all). Compared to linear controllers where parameter tuning is a work-intensive and crucial task, the proposed algorithms just need to be implemented and the weighting factors can be tuned quickly.

Although the methods presented within this work can enable FS-MPC strategies to become more attractive also for smaller and low-power (drive) systems, it is still questionable whether FS-MPC can outperform PWM-based MPC methods: For continuous-valued optimization tasks and linear systems the optimization problem can be solved analytically (e.g. with the MPT toolbox) which drastically reduces the calculation effort. PWM distributes the switching time points over the whole sample which leads to excellent control results in terms of ripples. Compared to the calculation of a VSP or to the implementation of an oversampled FS-MPC in hardware, the basic idea of PWM is ingeniously simple and has been proven to work well within the last decades. For multilevel inverters it is also possible to include a voltage balancing algorithm into the PWM which means that the overlaying controller only needs to calculate the voltages which should be applied—then it is not necessary to handle the voltage balancing within the control algorithm itself. Another drawback of FS-MPC is the varying switching frequency: Compared to PWM, FS-MPC methods produce an undesired audible noise which is much more annoying than the sound of PWM. Of course, it is also possible to modify the cost function such that a more or less constant switching frequency per device can be obtained. However, this can only be achieved at the expense of a deteriorated result regarding the main control objective (to mini-

mize the control deviation). Thus, in order to achieve the same control result in terms of ripples as without forcing a constant switching frequency, the sampling frequency and with it the time resolution of FS-MPC has to be drastically increased.

### 4.3 Outlook

There are several possibilities to extend and to modify the strategies which were presented in this work: One promising extension could be a method to calculate not only one but two or even more VSPs. If e.g. only one IGBT is allowed to switch at a time and if two VSPs are calculated within one sample, “online optimized” pulse patterns and a constant switching frequency could be obtained. Such an FS-MPC method would then be fully comparable to PWM in terms of ripples on the controlled variables. Another possibility would also be to increase the prediction horizon for VSP methods.

Another very promising application for (FS-)MPC is to perform direct speed or even position control for electrical drives. In this way all disadvantages which result from cascaded control loops could be overcome. Furthermore, it would then also be possible to operate the drive at its physical limits while still keeping all controlled variables within their allowed range.



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# APPENDIX A

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## List of symbols and abbreviations

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### A.1 List of symbols

**General remark:**

The following convention was used for variables:

|  |                  |
|--|------------------|
| Scalars are italic letters:                    | $x$              |
| Vectors are bold lower case letters:           | $\boldsymbol{x}$ |
| Matrices are bold upper case letters:          | $\mathbf{X}$     |
| References are marked with a star superscript: | $x^*$            |

**Used symbols:**

In the following the most important symbols are listed which are used within this work.

General symbols:

|                  |                                     |
|------------------|-------------------------------------|
| $\boldsymbol{x}$ | State vector                        |
| $\boldsymbol{u}$ | Input vector                        |
| $\boldsymbol{y}$ | Output vector                       |
| $\mathbf{A}$     | State matrix                        |
| $\mathbf{B}$     | Input matrix                        |
| $\mathbf{C}$     | Output matrix                       |
| $\mathbf{D}$     | Feedthrough matrix                  |
| $t$              | Time (continuous)                   |
| $k$              | Time (discrete, current sample)     |
| $\frac{d}{dt}$   | Time derivation                     |
| $T_s$            | Sampling time                       |
| $t_{sw}$         | Variable switching time point (VSP) |
| $\Delta$         | Difference                          |
| $J$              | Inertia                             |

General electrical variables:

|                 |                                  |
|-----------------|----------------------------------|
| $a, b, c$       | Phases                           |
| $\alpha, \beta$ | Equivalent two-phase coordinates |
| $j$             | $\sqrt{-1}$                      |
| $v$             | Voltage                          |
| $i$             | Current                          |
| $R$             | Resistor                         |
| $C$             | Capacitor                        |
| $L$             | Inductor                         |

Induction machine parameters:

|                  |                             |
|------------------|-----------------------------|
| $v_s, v_r$       | Stator and rotor voltage    |
| $i_s, i_r$       | Stator and rotor current    |
| $\psi_s, \psi_r$ | Stator and rotor flux       |
| $\omega_m$       | Mechanical machine speed    |
| $\omega_{el}$    | Electrical machine speed    |
| $T_m$            | Mechanical machine torque   |
| $T_l$            | Mechanical load torque      |
| $P$              | Machine power               |
| $p$              | Number of pole pairs        |
| $R_s, R_r$       | Stator and rotor resistance |
| $L_s, L_r$       | Stator and rotor inductance |
| $L_m$            | Mutual inductance           |

Further variables and parameters:

|            |  |
|------------|--|
| $S_{xi}$   | Switch $i$ in phase $x$                            |
| $s_{xi}$   | Gating signal for switch $i$ in phase $x$          |
| $j$        | Cost function value                                |
| $w$        | Weighting factor                                   |
| $v_o, i_o$ | Inverter output voltage and current (UPS)          |
| $v_l, i_l$ | LC lowpass-filter output voltage and current (UPS) |

## A.2 List of abbreviations

|        |  |
|--------|--|
| AC     | Alternating Current                    |
| AD     | Analog to Digital (converter)          |
| CPLD   | Complex Programmable Logic Device      |
| CPU    | Central Processing Unit                |
| DA     | Digital to Analog (converter)          |
| DC     | Direct Current                         |
| DMTC   | Direct Mean Torque Control             |
| DSC    | Direct Self Control                    |
| DSP    | Digital Signal Processor               |
| DTC    | Direct Torque Control                  |
| EMI    | Electromagnetic Interference           |
| FC     | Flying Capacitor                       |
| FIFO   | First In First Out (buffer)            |
| FOC    | Field Oriented Control                 |
| FPGA   | Field Programmable Gate Array          |
| FS     | Finite-Set                             |
| FS-MPC | Finite-Set Model Predictive Control    |
| GPC    | Generalized Predictive Control         |
| HDL    | Hardware Description Language          |
| IGBT   | Insulated Gate Bipolar Transistor      |
| IM     | Induction Machine, Induction Motor     |
| ISA    | Industry Standard Architecture (bus)   |
| LCD    | Liquid Crystal Display                 |
| LP     | Linear Program                         |
| LTI    | Linear Time-Invariant                  |
| MILP   | Mixed Integer Linear Program           |
| MIQP   | Mixed Integer Quadratic Program        |
| MPC    | Model Predictive Control               |
| MPDTC  | Model Predictive Direct Torque Control |
| mpLP   | Multiparametric Linear Program         |
| mpQP   | Multiparametric Quadratic Program      |
| MPT    | Multiparametric Toolbox                |
| NP     | Neutral Point                          |
| NPC    | Neutral Point Clamped                  |
| PCC    | Predictive Current Control             |
| PTC    | Predictive Torque Control              |
| PWM    | Pulse Width Modulation                 |
| QP     | Quadratic Program                      |
| RAM    | Random Access Memory                   |
| RMS    | Root Mean Square                       |
| RPM    | Revolutions Per Minute                 |
| RTAI   | Real-Time Application Interface        |

|        |  |
|--------|--|
| SI     | International System of Units                                    |
| SVM    | Space Vector Modulation  |
| THD    | Total Harmonic Distortion  |
| UPS    | Uninterruptible Power Supply                                     |
| VHDL   | Very High Speed Integrated Circuit Hardware Description Language |
| VSP    | Variable Switching Point   |
| VSP2CC | Variable Switching Point Predictive Current Control              |
| VSP2TC | Variable Switching Point Predictive Torque Control               |

# APPENDIX B

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## Test bench data

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### B.1 Two-level inverter test bench

A quick overview of the two-level inverter test bench has already been given in chapter X. The complete test bench consists of a real-time computer system, two squirrel-cage induction motors, two two-level inverters and measurement devices. It is to be noted that for this test bench no DC link voltage measurement is possible.

#### B.1.1 Real-time computer system

The real-time computer system consists of a PC104 module with a 1.4 GHz Pentium M CPU, 1 GB RAM and a 60 GB hard disk. All components are mounted into a 19 inch rack. The system is running an Arch Linux distribution with an RTAI (real-time application interface) kernel patch. This RTAI kernel patch allows to program kernel modules which can be executed in real-time. The real-time control algorithm can be conveniently programmed in *C*.

The necessary peripheral hardware for analog and digital in- and outputs is connected via the 16 bit ISA bus. The used 19 inch rack has space for up to twelve extension boards. In order to measure the signal from the current transducers, an AD card with two channels is used. The encoder signal can be read via a special encoder board. The most important extension card is responsible for the inverter gating (PWM) signals: In order to synchronize the generation of these gating signals with the control algorithm which is running on the real-time computer, this card also generates an interrupt for the real-time computer. Every time when such an interrupt occurs, the control algorithm is executed. Thus, the whole control algorithm is triggered by this extension card. As this board contains an FPGA, it is possible to modify the existing implementations for the generation of the gating signals according to the user's needs. The current implementation allows of course the generation of PWM signals but direct switching and switching at a VSP is also possible. Furthermore, the interrupt for the control algorithm also triggers the measurements of the AD converters such that it is possible to trigger the measure-

ments at the beginning of a sample. In order to conveniently output measured values, DA cards can be inserted into the system as well: Then, variables can be easily visualized and recorded with an oscilloscope. Another extension board with a four digit hexadecimal (16 bit) display and four hexadecimal switches can be used for status notifications and user interaction (start and stop of the control algorithm, reference value changes etc.). Further information about this system can be found in [3].

### B.1.2 Inverters

As already mentioned, the test bench consists of two inverters. Both inverters are supplied from a three-phase voltage source with an RMS phase to phase voltage of 400 V. Since the inverters cannot feed back energy to the three-phase grid, the DC link voltage will rise if a connected machine is operated in generator mode. In order to avoid damages of the system, a break chopper resistor can be connected to discharge the DC link such that the voltage level does not become critical. Since both machines are connected to each other, one drive is normally operated as motor while the other one works as generator. Thus, in order to avoid a frequent use of the break chopper resistor, the DC links of both drives are coupled together.

The controlled inverter is a modified Seidel/Kollmorgen Servostar 600 14 kVA inverter. It allows the user to directly command the IGBT gating signals from the real-time computer system. This inverter is connected to the working machine which is also controlled by the user. Consequently, the load inverter (Danfoss VLT FC-302 3.0 kW) is connected to the load machine. This inverter allows to perform speed and torque control of different machines. Furthermore, it can also be used to measure machine parameters.

### B.1.3 Induction machines

Table B.1: Parameters for the working machine of the two-level inverter test bench

| Parameter                              | Value                   |
|--|-------------------------|
| Nominal power $P_{\text{nom}}$         | 2.2 kW                  |
| Synchronous frequency $f_{\text{syn}}$ | 50 Hz                   |
| Nominal current $ i_{s, \text{nom}} $  | 8.02 A                  |
| Power factor $\cos(\varphi)$           | 0.85                    |
| Nominal speed $\omega_{\text{nom}}$    | 2772 rpm                |
| Number of pole pairs $p$               | 1                       |
| Stator resistance $R_s$                | 2.6827 Ω                |
| Rotor resistance $R_r$                 | 2.1290 Ω                |
| Stator inductance $L_s$                | 283.4 mH                |
| Rotor inductance $L_r$                 | 283.4 mH                |
| Mutual inductance $L_m$                | 275.1 mH                |
| Inertia $J$                            | 0.005 kg m <sup>2</sup> |

The two-level inverter test bench consists of two 2.2 kW squirrel-cage induction machines which are coupled to each other. The parameters of the working machine (driven by the controlled inverter) are given in Table B.1. The load machine is completely operated by the load inverter and hence, its parameters are not shown. The parameters were measured with the Danfoss load inverter. On both machines incremental encoders with 1024 points are mounted.

## B.2 FPGA-based test bench

In chapter X a quick overview of the FPGA-based test bench has already been given. It consists of the FPGA board which is shown in Figure X. The FPGA board is connected to an optics board which allows to transmit the IGBT gating signals optically to the inverter. Furthermore, one current measurement board and one board for voltage measurements are connected to the FPGA board. The two-phase three-level inverter just consists of two phase legs.

### B.2.1 FPGA board

The FPGA board which is shown in Figure X is used for the real-time computer system for the three-level inverter test bench. As the board uses an Altera Cyclone III FPGA with 40,000 logic elements, it is also possible to directly implement control algorithms on the FPGA which is clocked with 20 MHz. The board also has a very fast 12 bit AD converter. It allows to measure all eight different channels simultaneously with up to 65 megasamples per second. Because of this it is also possible to implement highly oversampled control algorithms and safety routines. The measurement boards can be connected to the FPGA board with RJ45 plugs. In order to deliver good measurement results and in order to have less EMI sensitivity, analog differential signalling is used for the measurements.

### B.2.2 Two-leg three-level inverter

As already mentioned, the two-leg three-level inverter uses the same design as the version with three phase legs. Another difference is that in this case the complete DC link capacitance is  $500 \mu\text{F}$  and the two flying capacitors both have a size of  $500 \mu\text{F}$ , too. For this inverter also a 12 V power supply is used for the optical interface for the gating signals and to provide auxiliary voltages for the gate drivers.

### B.2.3 Loads

As mentioned in chapter X, experimental results were conducted with a resistive-inductive load and for a UPS application. The loads were simply made of discrete components (resistors, inductors, capacitors and diodes for the nonlinear load in UPS configuration).



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