PyPowerSim: A Toolkit for Power Electronics Simulation

DR. PASCAL SCHIRMER

Version History

#	Version	Date	Comment	Editor	Lead
1	v.1.0	15.08.2024	Creating initial version.	Pascal Schirmer	Pascal Schirmer
2	v.1.1	25.08.2024	Revision and adding OM and filtering.	Pascal Schirmer	Pascal Schirmer

Content

A

SHORT INTRODUCTION

Aims and Goals

PyPowerSim is a simple python toolkit for evaluation of standard power converter topologies. The current version includes simulation architectures for a half-bridge (B2), a full-bridge (B4), and a three-phase full-bridge converter (B6) [1, 2]. The toolkit allows simple and fast calculation of power converter circuits including waveform, stead-state, and transient analysis using datasheet values of switching devices and DC-link capacitors. The aim is to illustrate the influence of PWM control methods to students and the interested reader without the use of commercial tools like SIMULINK, PLECs or LTSpice.

Dependencies

USED HARDWARE

- OS: WIN 10
- CPU: AMD 3700X
- RAM: 32 GB 3600 MHZ DDR4
- ROM: 1 TB SSD
- GPU: NVIDIA RTX 3700

SOFTWARE

The requirements of the PyPowerSim toolkit are summarized in the requirements.txt data file. In detail, the PyPowerSim Toolkit was implemented using the following dependencies:

- Python 3.11
- Numpy
- Pandas
- Scipy

Limitations and Known Issues

- The transfer functions for the input and output filter are not yet verified. Also, there is no protection against instability of the transfer functions.
- Soft switching architectures are not included yet.
- The interpolation methods for calculating the tabulated parameter options are only linear.
- Plotting error for average DC voltage in B6 configuration
- Currently back emf e(t) is model as a linear function of the modulation index. It would be better to model it using a dependency on the fundamental frequency
- Minor numerical issues

B

THEORETICAL BACKGROUND

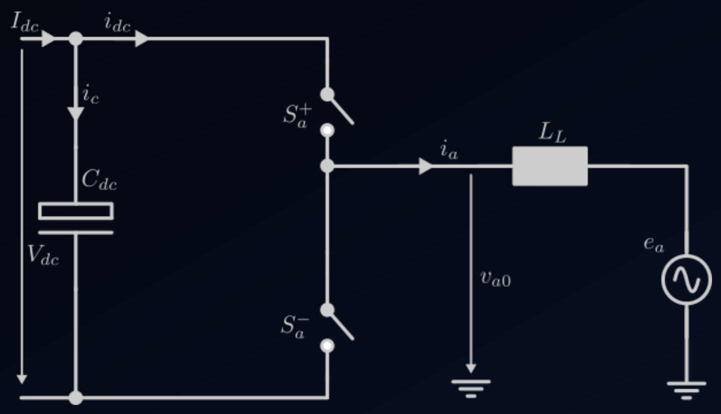
B1

INCLUDED TOPOLOGIES

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

Half-bridge (B2)

ARCHITECTURE



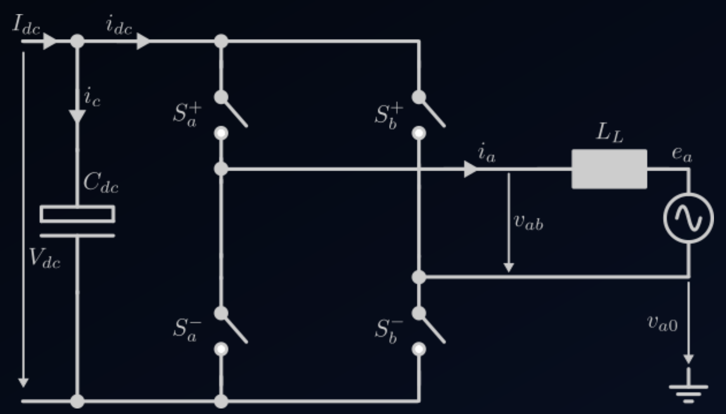
DESCRIPTION

- Voltage RMS: $V_{rms} = \frac{V_{dc}}{2}$
- Voltage Fund.: $V_1 = \frac{1}{\sqrt{2}} \frac{V_{dc}}{2} M_i$
- Voltage Distortion: $V_{thd} = \frac{V_{dc}}{2} \sqrt{1 - \frac{M_i^2}{2}}$
- Current Distortion: $I_{thd} \approx \frac{1}{\sqrt{48}} \frac{V_{dc}}{2} \frac{T_s}{L_L} \sqrt{\frac{3}{8} M_i^4 - M_i^2 + 1}$

Full-bridge (B4)

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

ARCHITECTURE



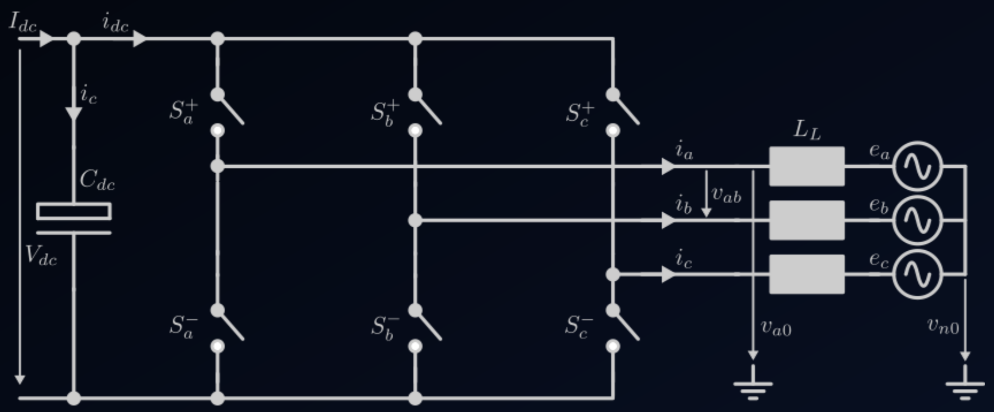
DESCRIPTION

- Voltage RMS: $V_{rms} = V_{dc}\sqrt{\frac{2}{\pi}M_i}$
- Voltage Fund.: $V_1 = \frac{1}{\sqrt{2}}\frac{V_{dc}}{2}M_i$
- Voltage Distortion: $V_{thd} = V_{dc}\sqrt{1 - \frac{\pi}{4}M_i}$
- Current Distortion: $I_{thd} \approx \frac{1}{\sqrt{48}}V_{dc}\frac{T_s}{L_L}\sqrt{\frac{3}{8}M_i^4 - \frac{8}{3\pi}M_i^3 + \frac{1}{2}M_i^2}$

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

Three Phase Full-bridge (B6)

ARCHITECTURE



DESCRIPTION

- Voltage RMS: $$V_{rms} \approx V_{dc}\sqrt{\frac{M_i}{\sqrt{3}\pi}}$$
- Voltage Fund.: $$V_1 \approx \frac{V_{dc}}{\sqrt{2}} M_i$$
- Voltage Distortion: $$V_{thd} \approx \frac{V_{dc}}{2}\sqrt{1-\frac{\sqrt{3}\pi}{8}M_i}$$
- Current Distortion: $$I_{thd} \approx \frac{V_{dc}M_i}{4L_L\sqrt{3}}\frac{T_s}{2}\sqrt{0{,}5 - 0.735M_i + 0.33M_i^2}$$

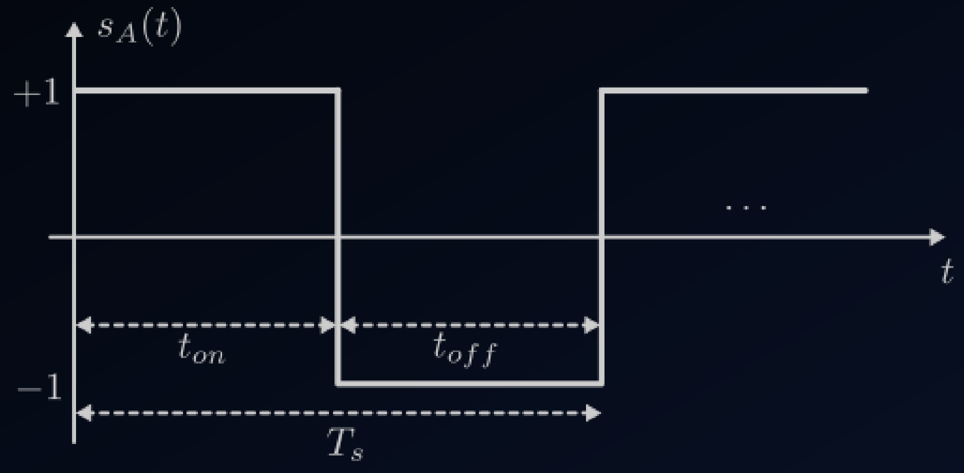
B2

PWM WAVEFORM GENERATION

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

Fundamental Frequency Control

WAVEFORM



DESCRIPTION

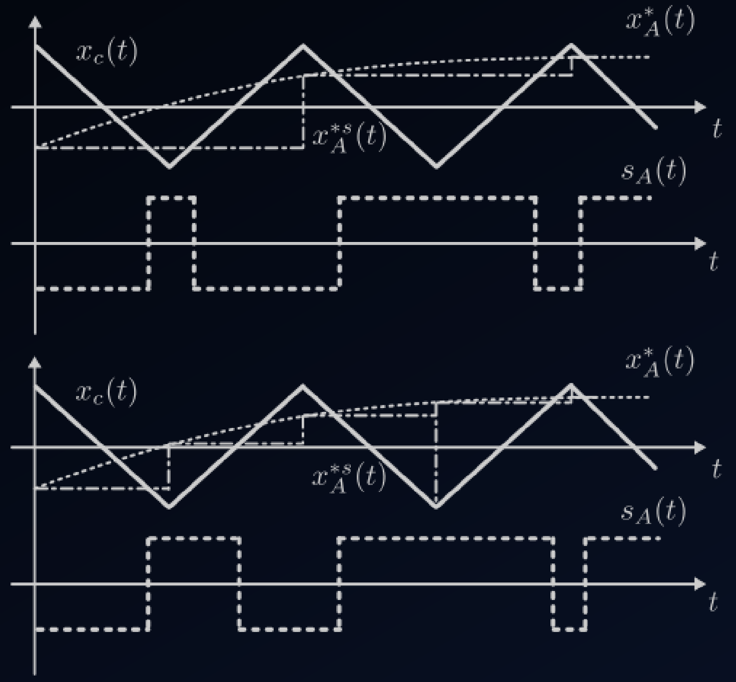
In fundamental frequency control, the phase legs are switched with the same frequency as the output frequency, i.e. the pulse number is equal to one.

$$s_a(t) = \frac{4}{\pi} \sum_{v=2n\pm1}^{\infty} \frac{1}{v} sin(v\omega_{el}t)$$

Carrier Based PWM

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

WAVEFORM



DESCRIPTION

Carrier based PWM techniques have been utilized often using a triangular carrier to compare the reference waveform and update the switching state.

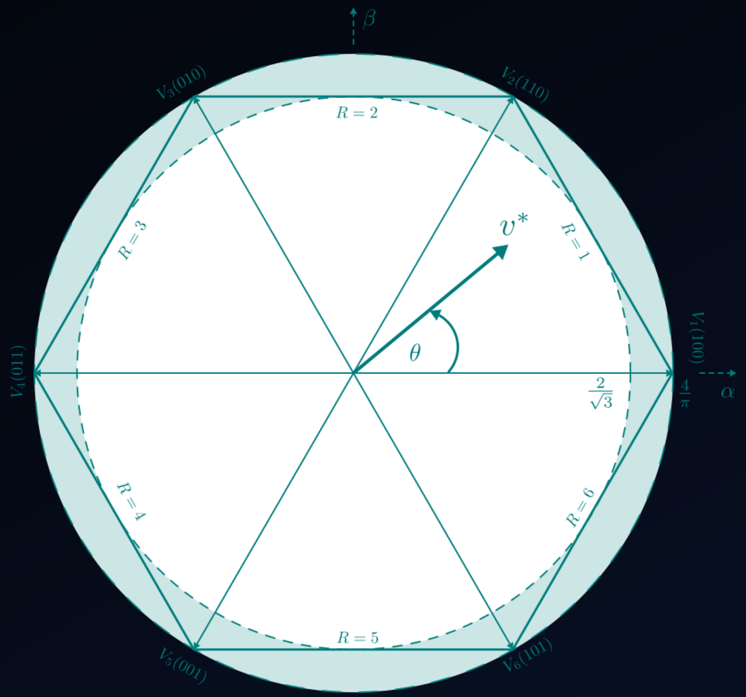
$$s_a(t) = \underbrace{\sum_{n=1}^{\infty} a_{0n} cos(n[\omega_{el}t + \varphi_{el}])}_{fundamental\ \&\ baseband\ harmonics}$$

$$+ \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \underbrace{a_{mn}\ cos(m[\omega_{sw}t + \varphi_{sw}] + n[\omega_{el}t + \varphi_{el}])}_{carrier\ \&\ sideband\ harmonics}$$

Literature:	[1, 2]
Images:	-
Software:	PyPowerSim
Example:	**defaultSweep**
Content:	Basics

Space Vector based PWM

SPACE VECTOR HEXAGON



DESCRIPTION

The space vector modulation approach reduces the three-phase voltages ($v_{a,b,c}$) on a two-dimensional orthogonal reference frame (α, β) representing the voltages as a rotating space vector $\vec{v}^* = V_1^* e^{-j\omega_{el}t}$ with amplitude V_1^*, angular speed ω_{el}, and displacement angle θ.

$$\sum_k \vec{v}_k d_k = \vec{v}^*$$

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \frac{\sqrt{3}}{2} M_i \begin{bmatrix} sin\left(\frac{\pi}{3} - \theta\right) \\ sin(\theta) \end{bmatrix}$$

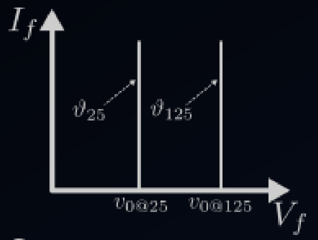
B3

DEVICE MODELING

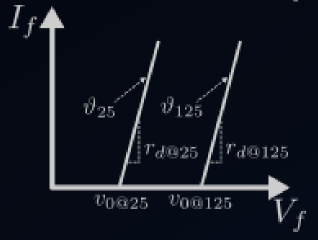
Literature:	[6,7]
Images:	-
Software:	PyPowerSim
Example:	**defaultSteady**
Content:	Basics

General Modeling Approaches

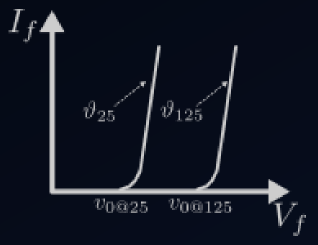
PARAMETER DEPENDENCIES



Constant Parameters



Linear Parameters



Non-Linear Parameters

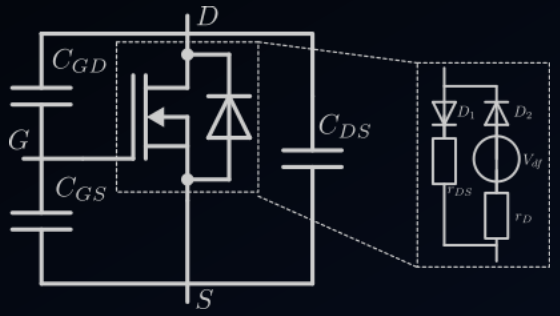
DESCRIPTION

For the modeling of the electrical characteristics, the toolkit offers three different possibilities, namely constant parameters (a), piece-wise linear approximations (b), or tabulated parameters (c), where each approach might include a temperature dependency.

Literature:	[6,7]
Images:	-
Software:	PyPowerSim
Example:	**defaultSteady**
Content:	Basics

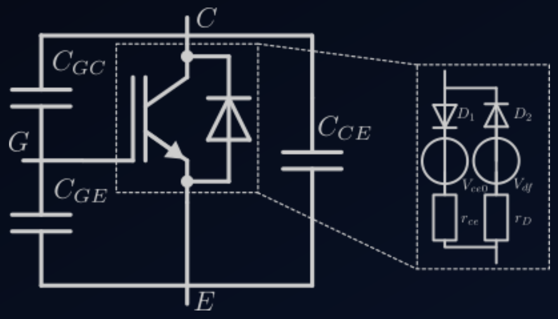
Switching Devices

CIRCUIT



MOSFET Device

IGBT Device



DESCRIPTION

Without loss of generality the total losses, conduction losses, and switching losses can be written as for both MOSFET and IGBT devices:

$$p_l(t) = p_c(t) + p_s(t) + p_b(t) \approx p_c(t) + p_s(t)$$

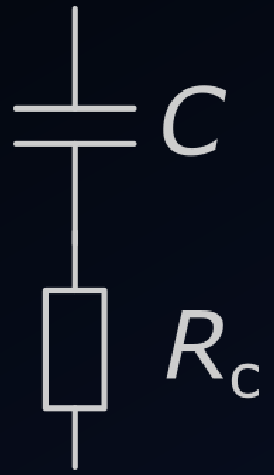
$$p_c^T(t) = v_T(t) \cdot i_T(t) = v_{T0} \cdot i_T(t) + r_T \cdot i_T^2(t)$$
$$p_c^D(t) = v_D(t) \cdot i_D(t) = v_{D0} \cdot i_D(t) + r_D \cdot i_D^2(t)$$

$$p_s^T = (E_{on,T} + E_{off,T}) \cdot f_{sw}$$
$$p_s^D = (E_{on,D} + E_{off,D}) \cdot f_{sw} \approx E_{on,D} \cdot f_{sw}$$

Literature:	[6,7]
Images:	-
Software:	PyPowerSim
Example:	**defaultSteady**
Content:	Basics

Capacitor Devices

CIRCUIT



DESCRIPTION

The DC-Link capacitor is modeled in the frequency domain using the harmonic capacitor current and the frequency dependent series capacitor resistance.

$$P_l^{CAP} = \sum_i R_c(f_i) \cdot I_{i,rms}^2 \approx R_c I_{c,rms}$$

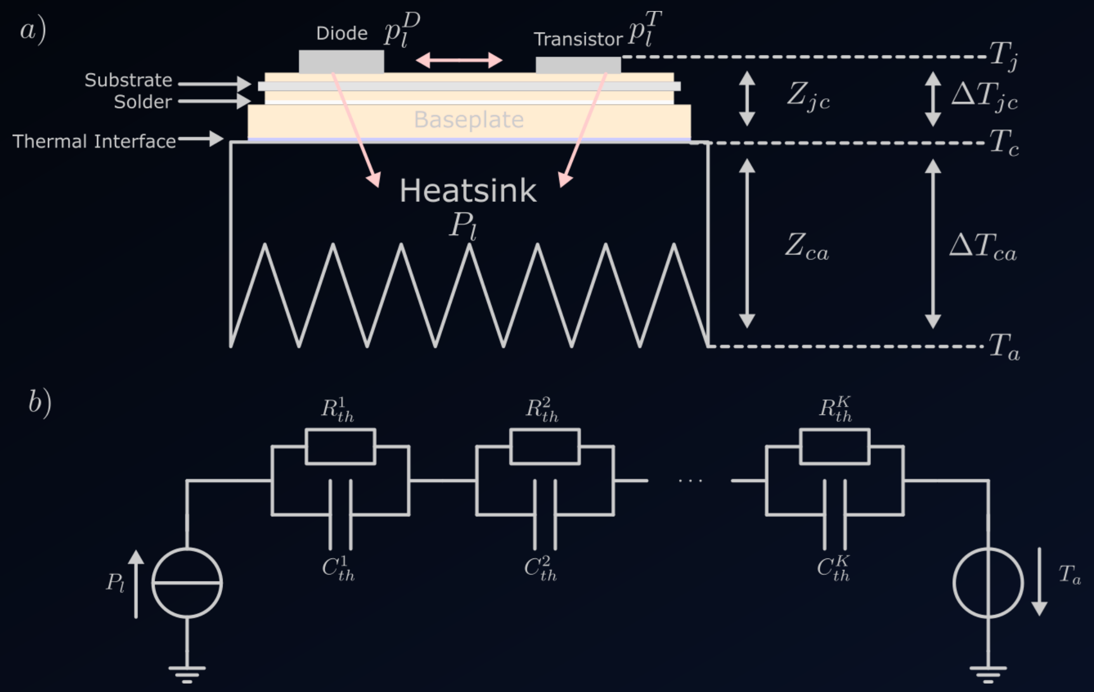
B4

THERMAL MODELING

Reduced Order Thermal Model

Literature:	[3]
Images:	-
Software:	PyPowerSim
Example:	**defaultTrans**
Content:	Basics

THERMAL STACKUP



DESCRIPTION

The transient thermal impedance can be expressed using a set of K exponential functions:

$$Z_{th}(t) = \sum_{i=1}^{K} R_{th}^{i} \left(1 - e^{-t/R_{th}^{i} C_{th}^{i}}\right)$$

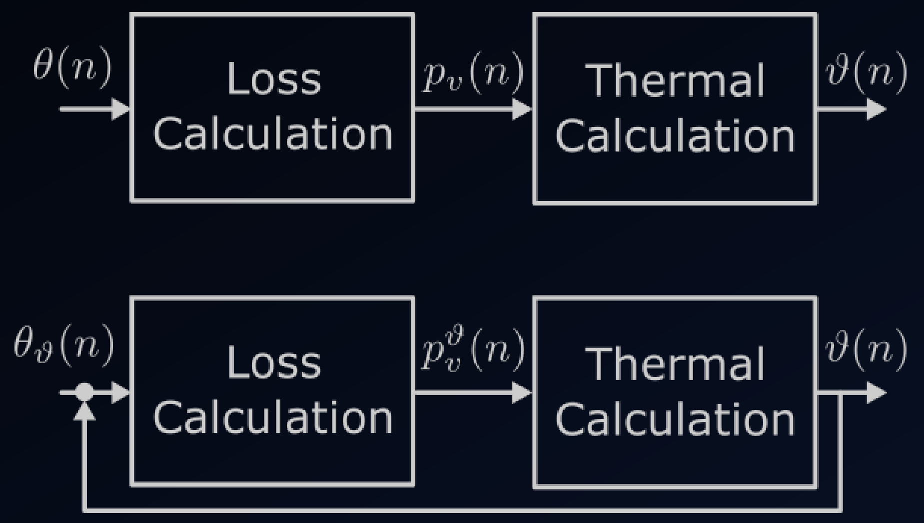
For a given impedance, the temperature can be calculated as follows [3]:

$$\vartheta(n) = \sum_{i=1}^{K} \left\{ \frac{2\tau_i - \Delta t}{2\tau_i + \Delta t} \vartheta_i(n-1) + \frac{R_{th}^{i} \Delta t}{2\tau_i + \Delta t} [p_v(n) + p_v(n-1)] \right\}$$

Literature:	[3]
Images:	-
Software:	PyPowerSim
Example:	**defaultTrans**
Content:	Basics

Electro-Thermal Modeling

ARCHITECTURE



DESCRIPTION

For calculating the results, the toolkit offers two different options, namely an approach with and without temperature feedback. Without feedback the temperature $\vartheta(n)$ for the n^{th} time-step is calculated neglecting temperature dependencies of the input parameters $\theta(n)$. Conversely, for the feedback operation the input parameters $\theta_\vartheta(n)$ are functions of the temperature leading to an iterative procedure for calculating $\vartheta(n)$.

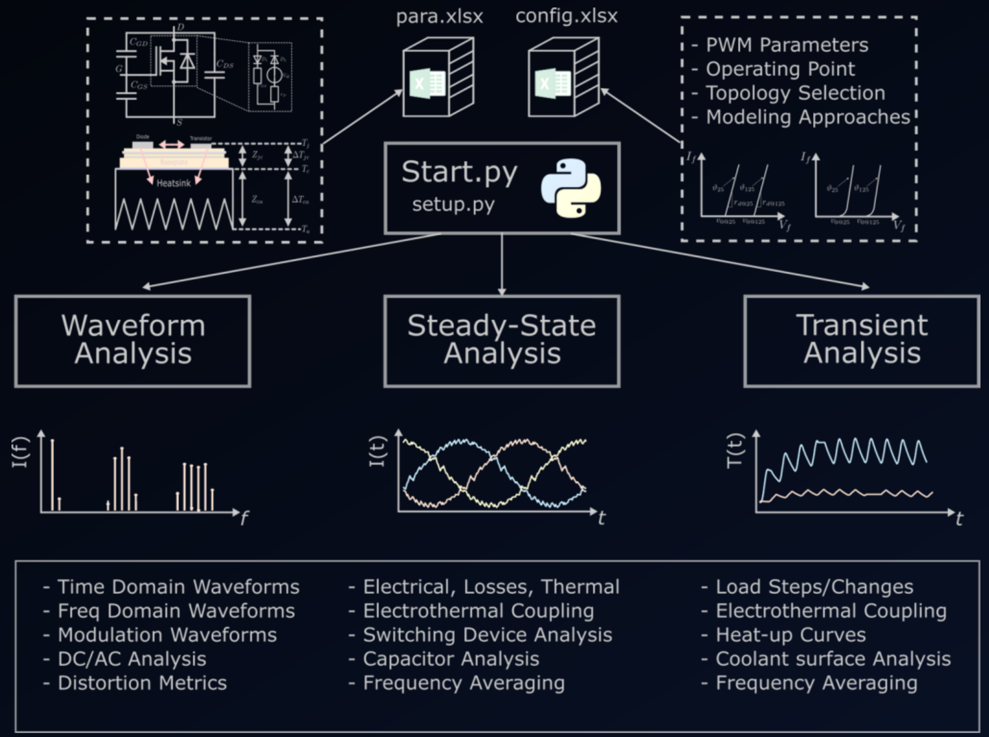
C

TOOLKIT OVERVIEW

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Description

Toolkit Overview

OVERVIEW



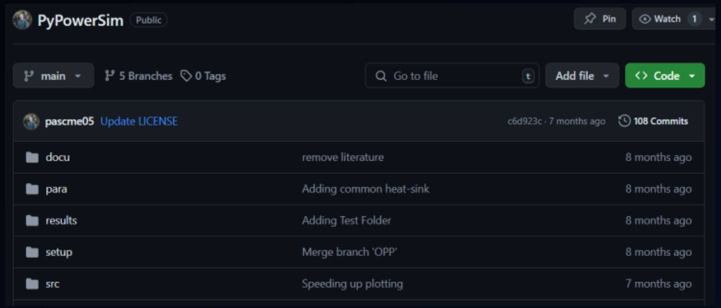
DESCRIPTION

- In waveform analysis, the modulation function is investigated in the time and frequency domains. Currents and voltages are analyzed for both the load side (AC) and the source side (DC), while harmonic distortions are evaluated as functions of the modulation index.
- In steady-state analysis, results are presented for one fundamental cycle, considering temperature feedback, i.e. till all temperatures have stabilized.
- In transient analysis, results are calculated for an arbitrary number of electrical periods using a constant step-width, while parameters are updated at specific intervals, e.g., after one fundamental period of the output.

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Description

Installation and Usage

STEP I: CHECK OUT GITHUB



Clone the latest version of the PyPowerSim Toolkit from Github: https://github.com/pascme05/PyPowerSim

STEP II: INSTALL PACKAGES

Install all necessary packages from the requirements.txt file to ensure the toolkit to run smoothly.

STEP III: RUN START.PY

To execute a new simulation three things are needed. First, a valid configuration file as discussed above. Second, valid parameter files for the switching devices and the capacitor. Third a start script as provided in start.py used for defining the configuration and the parameter .xlsx files as well as the simulation mode.

Project Structure

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Decription

PyPowerSim	Folder	Subfolder	Content
|--	docu		Contains the documentation
|--	para		
	|--	Cap	Contains the parameter files for the Cap
	|--	Swi	Contains the parameter files for the Switch
|--	results		Contains all results
|--	setup		Preconfigured setup sheets
|--	src		
	|--	cont	Contains functions for closed loop control
	|--	data	Contains functions for loading data
	|--	elec	Contains functions for electrical calculation
	|--	general	Contains general and helper functions
	|--	plot	Contains functions for plotting
	|--	pwm	Contains functions for PWM calculations
	|--	therm	Contains functions for thermal calculations
	|--	topo	Contains implemented converter topologies

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Description

Setup File

```python
# ==============================================================================
# Experiment
# ==============================================================================
# ------------------------------------------
# General
# ------------------------------------------
setup['Exp']['Name'] = "default"
setup['Exp']['Author'] = "Pascal Schirmer"
setup['Exp']['debug'] = 0

# ------------------------------------------
# Operating Mode
# ------------------------------------------
setup['Exp']['output'] = 'Mi'
setup['Exp']['type'] = 0

# ==============================================================================
# Input Files
# ==============================================================================
# ------------------------------------------
# Mission Profile and Config
# ------------------------------------------
setup['Exp']['conf'] = "default"

# ------------------------------------------
# Devices
# ------------------------------------------
setup['Exp']['Swi'] = "IKQ75N120CS6"
setup['Exp']['Cap'] = "Elco"

# ==============================================================================
# Plotting and Saving
# ==============================================================================
setup['Exp']['plot'] = 2
setup['Exp']['plotGen'] = 0
setup['Exp']['save'] = 0
```

Description

- Experiment
  - Define which output is controlled
  - Define operating mode
- Input Files
  - Define switching device and cap
  - Define config file
- Plotting and Saving
  - Activate or deactivate plotting
  - Activate or deactivate saving

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Description

Configuration File

Date	23.06.2024
Author	Dr. Pascal A. Schirmer
Version	v.1.0
File	default

#	Version	Date	Changes	Editor	Lead
1	v.0.0	17.08.2023	Initial implementation of the config template	Pascal Schirmer	Pascal Schirmer
2	v.0.1	17.02.2024	Review for python implementation	Pascal Schirmer	Pascal Schirmer
3	v.1.0	23.06.2024	First complete template	Pascal Schirmer	Pascal Schirmer
4					
5					

Legend

Color-Code	Meaning	Change
	Headings	No
	Information (can be changed for personal notes and markup)	Yes
	Input values	Yes
	Variable names read by toolkit	No

Name	Category	Description	Variable	Value	Unit
Fundamental Cycles	stat	number of fundamental cycles used for stationary analysis (at least 4)	cyc	4	-
Sweep Points	stat	number of datapoints for sweep analysis	W	20	-
Core Temp	stat	core temperature of all components	Tj	25.0	degC
Ref Temp	stat	reference temperature of all components	Tc	25.0	degC
Active Power	stat	output active power (Po) for power control	Po	1000	W
Reactive Power	stat	output reactive power (Qo) for power control	Qo	500	VAr
RMS Voltage	stat	output RMS phase voltage (V0) for voltage control	Vo	50	V
RMS Current	stat	output RMS phase current (Io) for current control	Io	25	A
Modulation Index	stat	modulation index (Mi) for distortion analysis	Mi	1.00	p.u.
DC Voltage	stat	DC-Link voltage	Vdc	600	V
Load Angle	stat	load angle output voltage	phi	0	deg
End Time	trans	maximum time for transient analysis	tmax	0.50	sec
Ref Temp	trans	reference temperature of all components	Tc	25.0	degC
Core Temp	trans	core temperature at t=0 of all components	Tj	25.0	degC

CHANGE LOG

- All changes to the templated are logged here
- New config files should be based on the default file

LEGEND

- Colour coding to indicate which cell should be changed an which not
- Colour code is valid throughout all worksheets

SETTINGS

- Four worksheets to adapt: experiment, data, topology, and parameters
- Each worksheet as drop downs a limits for the values

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	
Content:	Toolkit Description

Parameter File

Author	Pascal Schirmer	
Date	02/04/2023	
Datasheet	https://www.infineon.com/dgdl/Infineon-IKQ75N120CS6-DS-v02_02-EN.pdf	
Parameter	**Value**	**Unit**
Type	IGBT	
Qualification	JEDEC47/20/22	
PNR	IKQ75N120CS6	
Package	PG-TO247-3-46	
Vce	1200	V
Ic	75	A
Tj,max	175	°C

Parameter	Description	Model	Symbol	Typical
On-state resistance	Constant on-state resistance of the switch during conduction, e.g. Rdson	Linear	Ron	0.00E+00
Off-state conductance	Constant off-state conduction of the switch during blocking	Linear	Roff	0.00E+00
Switch-on loss	Typical switch-on energy from datasheet	Constant	Eon	5.15E-03
Switch-off loss	Typical switch-on energy from datasheet	Constant	Eoff	2.95E-03
Diode reverse recovery loss	Typical switch-on energy from datasheet	Constant	Erec	2.82E-03
Off-State blocking voltage	Rated blocking voltage, e.g. Vce or Vds, used for linearly scaling switching losses	Tabular	Vnom	6.00E+02
Forward voltage switch	Constant voltage drop across the switch during conduction, e.g. collector-emitter voltage (Vce) or drain-source voltage (Vds)	Tabular	Vf	1.85E+00
Forward voltage diode	Constant voltage drop across the diode during conduction	Tabular	Vfd	2.10E+00
Gate voltage	Gate supply voltage	Linear	Vg	1.50E+01
On-state resistance diode	Constant on-state resistance of the diode during conduction	Linear	RonD	0.00E+00
Off-state conductance diode	Constant off-state conduction of the diode during blocking	Linear	RoffD	0.00E+00
Gate resistance	Gate resistance of FET	Linear	Rg	4.00E+00
Temperature junction	Junction temperature at which the parameters are measured	Tabular	Tj	2.50E+01
On-State channel current	Rated channel current, e.g. Ice or Ids, used for linearly scaling switching losses	Linear	Inom	6.00E+02
Forward current switch	Forward current of the switch, e.g. collector-emitter current (Ice) or drain-source current (Ids)	Tabular	If	1.50E+02
Forward current diode	Forward current of the diode	Tabular	Ifd	7.50E+01
Rise-time	Current rise time between zero and I0	Constant	tr	4.40E-08
Fall-time	Current fall time between zero and I0	Constant	tf	3.10E-08
Reverse recovery time	Time of the reverse recovery effect	Constant	trr	4.40E-07
Reverse recovery charge	Amount of charge during reverse recovery	Constant	Qrr	4.70E-06
Gate plateau voltage	Gate plateau voltage during transient behavior	Constant	Vpl	5.00E+00
Input Capacitance	Equivalent Mosfet input capacitance Ciss = Cgd + Cgs	Tabular	Ciss	4.90E-09
Output Capacitance	Equivalent Mosfet output capacitance Coss = Cgd + Cds	Tabular	Coss	3.60E-10
Reverse Transfer Capacitance	Equivalent Mosfet reverse capacitance Ciss = Cgd	Tabular	Crss	2.25E-10

On-state voltage, Vce(Tj,Ice)/Vds(Tj,Ids)				
Ice/Ids (A)	**Tj (°C)**			
	25.00	**175.00**	**0.00**	**0.00**
0.00	0.00E+00	0.00E+00		
1.00	6.00E-01	5.50E-01		
5.00	9.00E-01	8.55E-01		
10.00	1.10E+00	1.05E+00		
20.00	1.20E+00	1.33E+00		
50.00	1.55E+00	1.91E+00		
100.00	2.00E+00	2.72E+00		
300.00	3.38E+00	5.57E+00		
0.00				
0.00				

Parameter	Description	Category	Symbol	Typical
Thermal resistance (JC)	Network of	1D-Foster	Rth_JC	1.80E-01
Thermal capacitance (JC)	Network of	1D-Foster	Cth_JC	3.14E+00
Thermal resistance (DC)	Network of	1D-Foster	Rth_DC	4.00E-01
Thermal capacitance (DC)	Network of	1D-Foster	Cth_DC	2.78E+00
Thermal resistance (CA)	Network of	1D-Foster	Rth_CA	1.00E+00
Thermal capacitance (CA)	Network of	1D-Foster	Cth_CA	1.00E-01

README

- General overview about the device parameters
- Link to the datasheet
- New devices should be based on the templates

ELECTRICAL PARAMETER

- Constant parameters are provided at the top
- Tabular parameters are provided separately in an own table

THERMAL PARAMETER

- Constant parameters thermal resistances and capacitances
- Transient thermal impedances

D

EXEMPLARY CALCULATIONS

Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	**journalXXX**
Content:	Example

Topology and Operating Conditions

SIMULATION SETTING

Parameter	Symbol	Value	Unit
Load frequency	f_{el}	50	Hz
Switching frequency	f_s	1050	Hz
PWM Method	-	SVM	-
DC Link Voltage	V_{dc}	600	V
Modulation Index	M_i	1.0	p.u.
Load Inductance	L	2.0	mH
Load Resistance	R	2.0	Ohm
Reference Temperature	ϑ_{ref}	25	degC
Thermal Resistance	R_{th}^{ca}	0.1	K/W

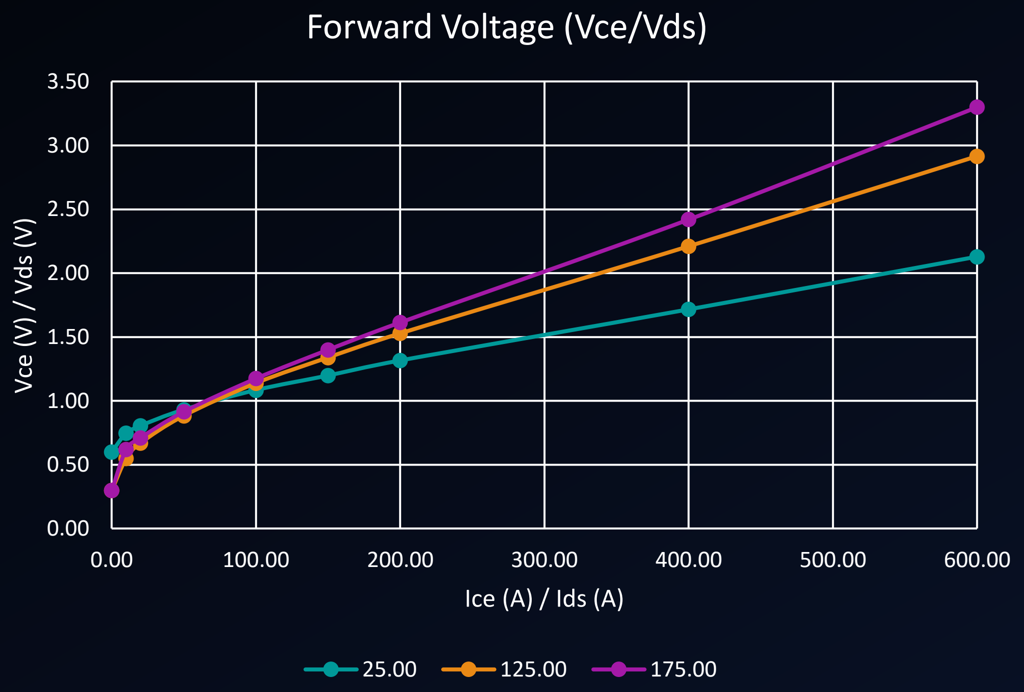
SEMICONDUCTOR PARAMETERS

Parameter	Symbol	Value	Unit
Collector-Emitter Saturation	v_{CE0}	1.50	V
Diode Forward Voltage	v_{D0}	1.60	V
On-Switching Energy	E_{on}	18.4	mJ
Off-Switching Energy	E_{off}	23.6	mJ
Reverse Recovery Charge	E_{rec}	13.4	mJ
Thermal Resistance Junction-Case	R_{th}^{jc}	0.08	K/W

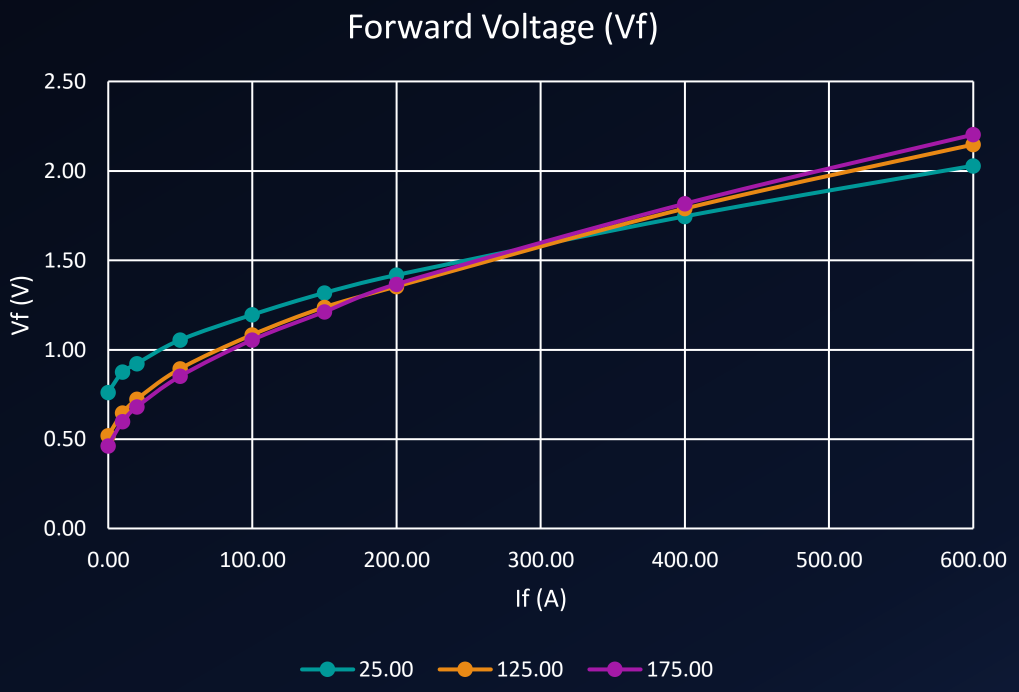
Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	**journalXXX**
Content:	Example

Switching Device Parameters (Static)

TRANSISTOR



DIODE

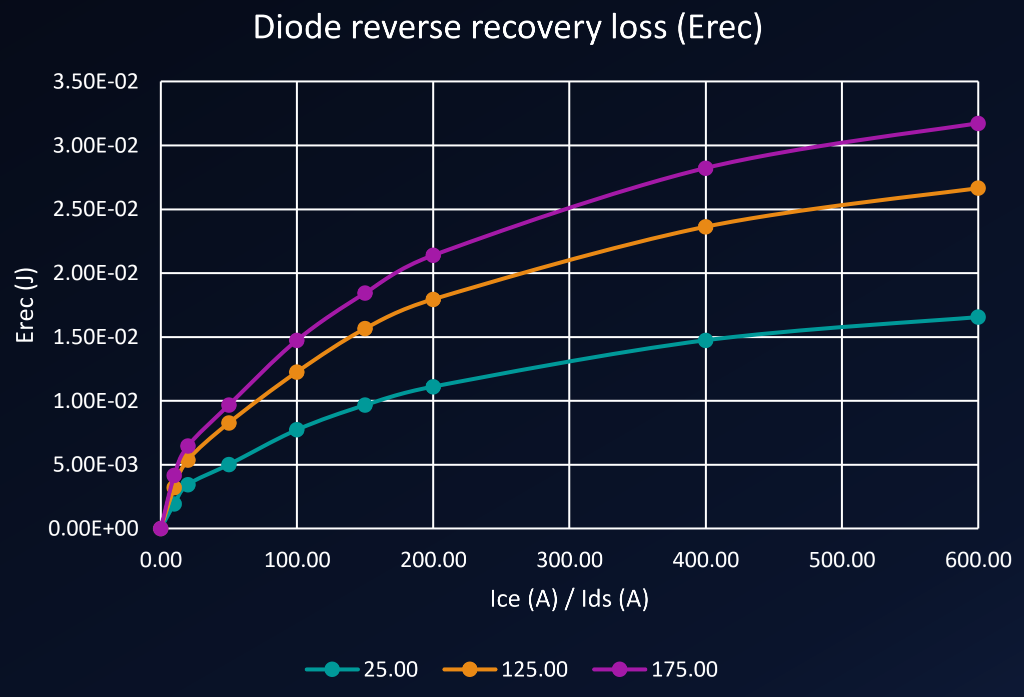


Literature:	[]
Images:	-
Software:	PyPowerSim
Example:	**journalXXX**
Content:	Example

Switching Device Parameters (Dynamic)

TRANSISTOR

DIODE



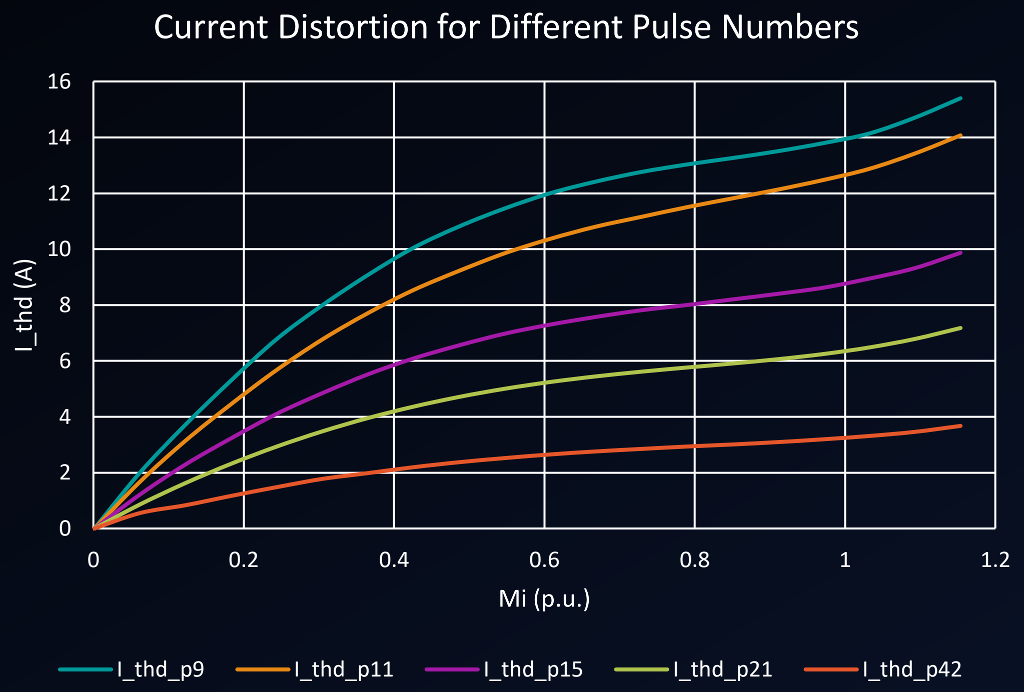
D1

WAVEFORM ANALYSIS

Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSweep**
Content:	Example

Current Distortion

SWEEP ANALYSIS



DESCRIPTION

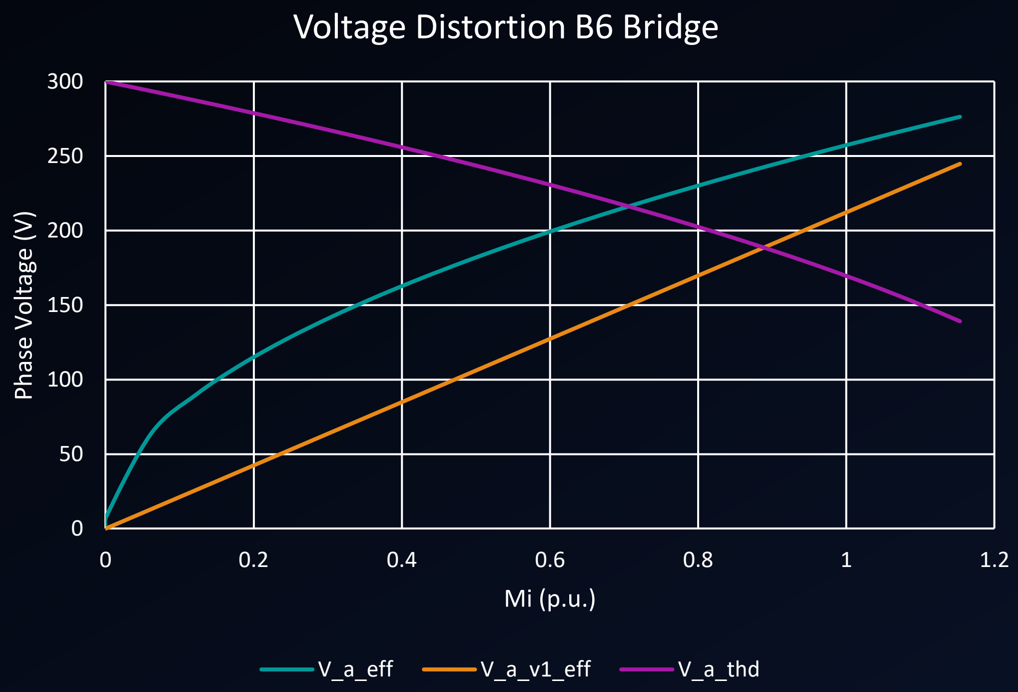
In the waveform analysis, the modulation index is varied, and the current distortions are observed. The results for the linear modulation region are illustrated for different pulse numbers (9 – 42):

- High pulse numbers lead to lower harmonic distortions $I_{thd} \sim f_{sw}$.
- The distortion over the modulation index has the same shape for different pulse numbers

Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSweep**
Content:	Example

Voltage Distortion

SWEEP ANALYSIS



DESCRIPTION

Voltage distortions as well as the effective voltage are indirectly and directly proportional to the modulation index, thus decreasing or increasing with more voltage applied to the load.

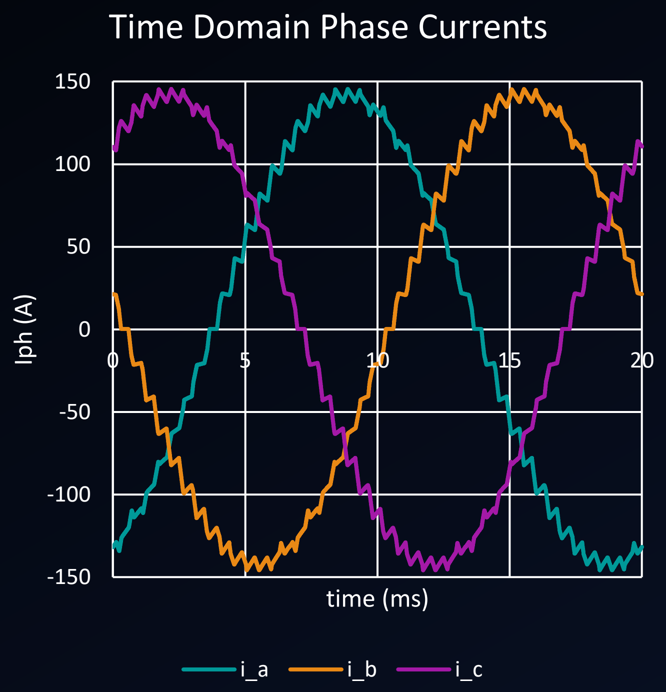
D2

STEADY STATE ANALYSIS

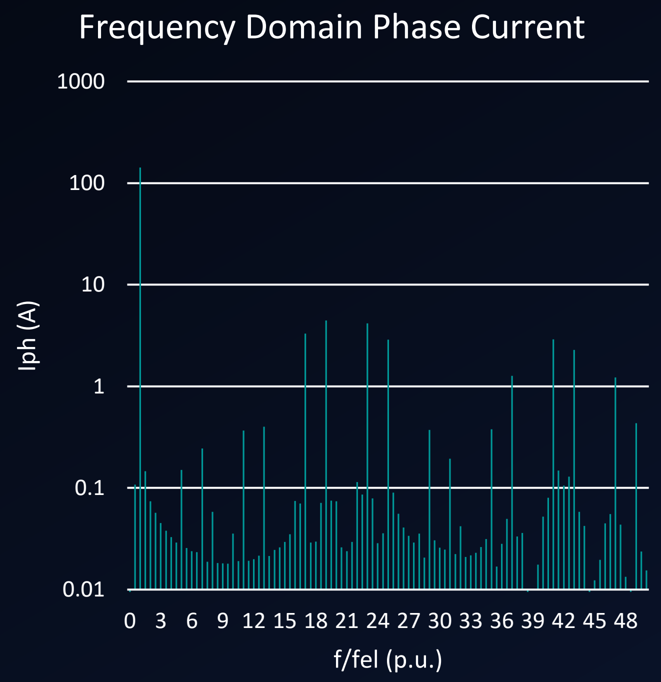
Current Waveforms Load Side (AC)

Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

TIME DOMAIN



FREQUENCY DOMAIN



DESCRIPTION

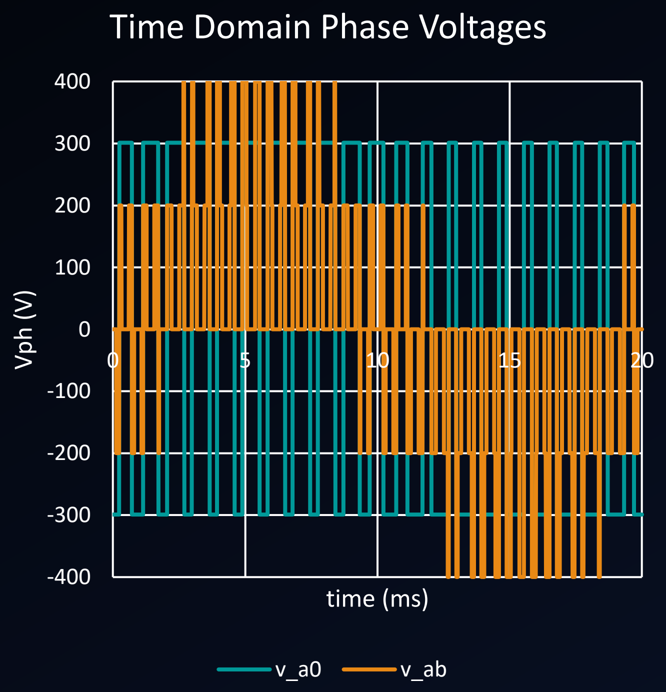
As can be seen the output current is sinusoidal and shows the expected spectrum with fundamental and base-band harmonics:

- Fundamental frequency with amplitude of 101 A
- Side-band harmonics around the pulse number of 21
- No third harmonics

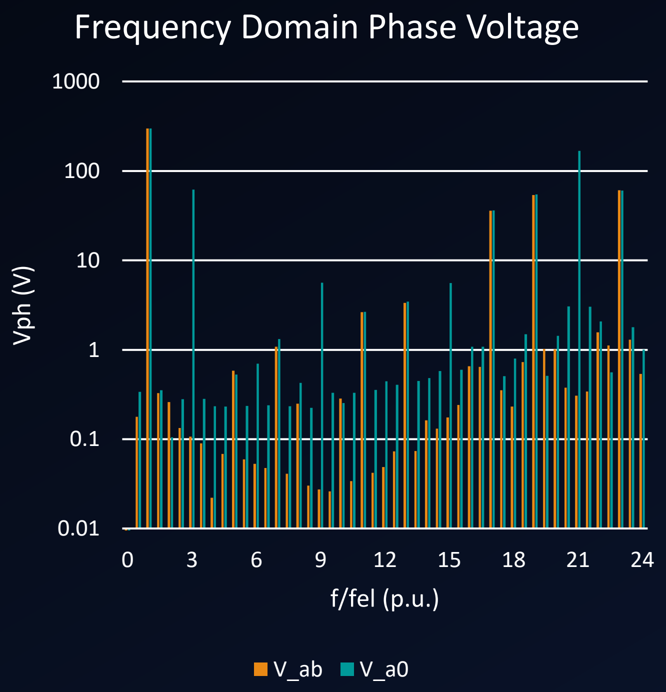
Voltage Waveforms Load Side (AC)

Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

TIME DOMAIN



FREQUENCY DOMAIN



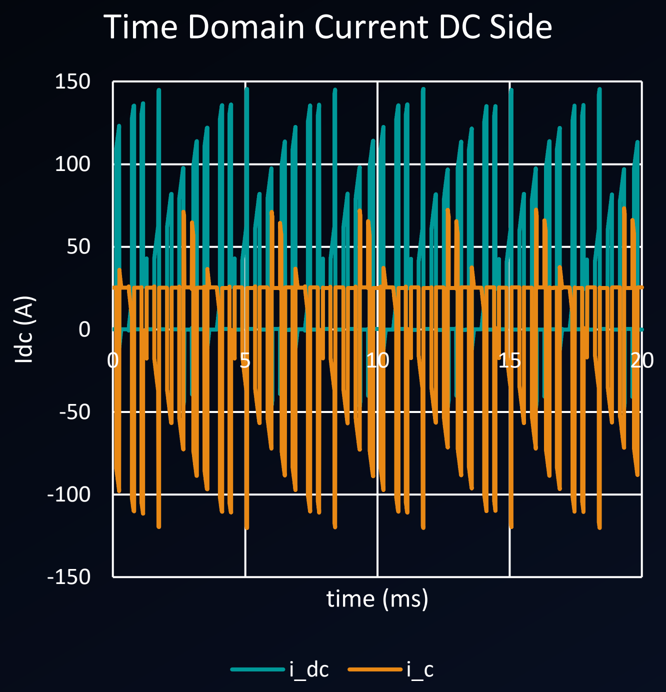
DESCRIPTION

Line-to-neutral and line-to-line voltage have different time and frequency domain representations. In detail, while for the line-to-neutral voltages third order harmonic are visible they are getting eliminated due to the symmetry of the three-phase system.

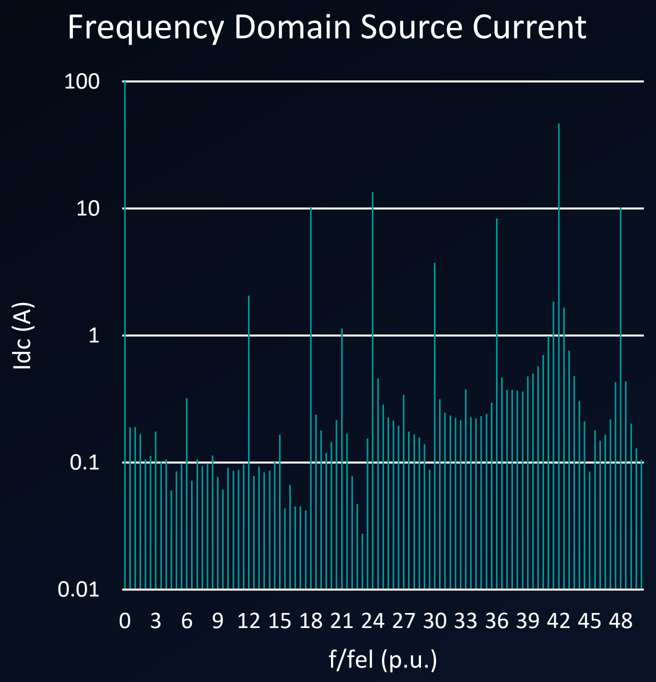
Literature: []
Images: -
Software: PyPowerSim
Example:
Content: Basics

Current Waveforms Source Side (DC)

TIME DOMAIN



FREQUENCY DOMAIN



DESCRIPTION

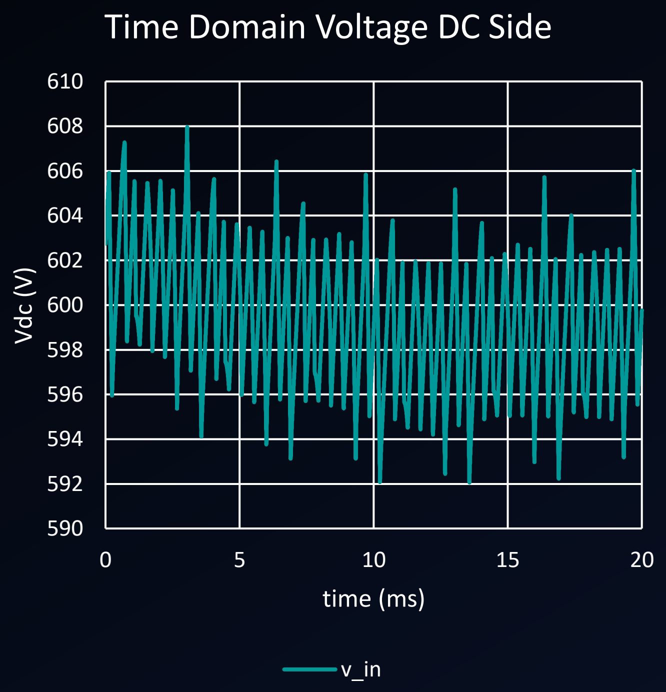
Inverter input current pulsates with twice the frequency of the load current:

- DC Component of 102 A indicating active power transfer
- DC Link capacitor current pulsating with q=42
- Side-band harmonics with ± 3 around switching frequency

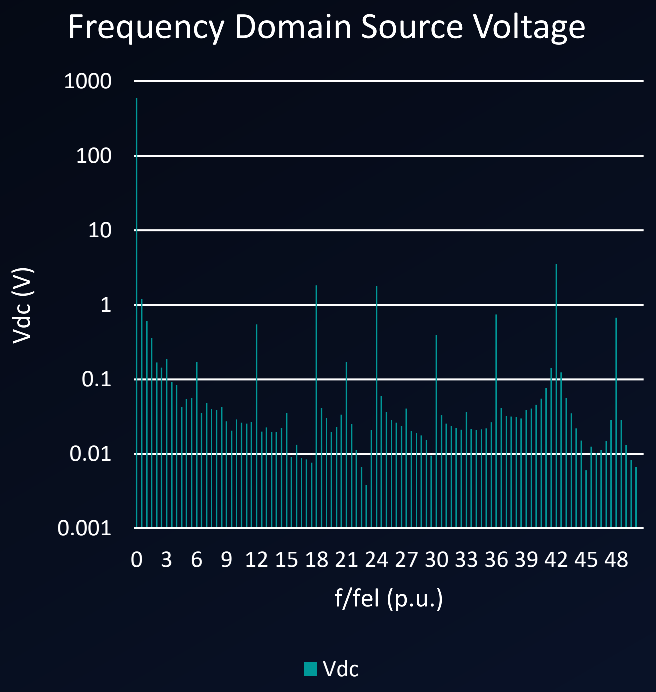
Voltage Waveforms Source Side (DC)

Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

TIME DOMAIN



FREQUENCY DOMAIN



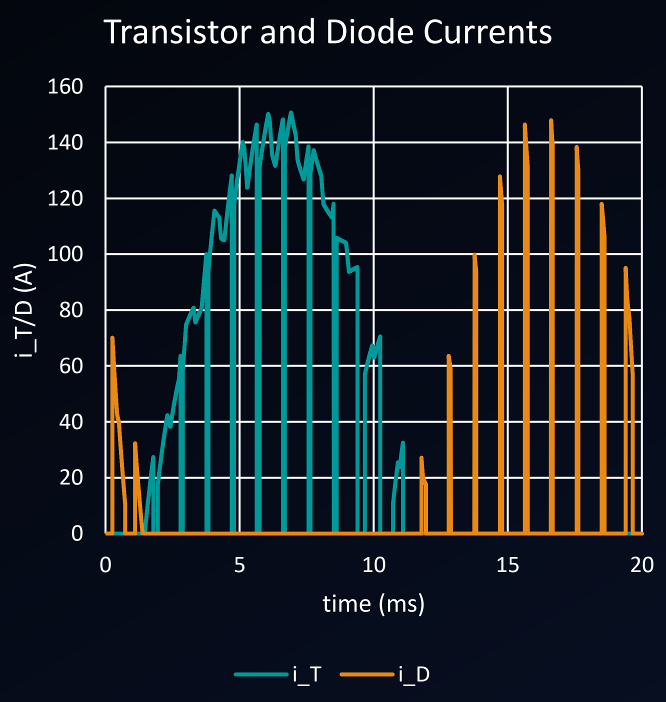
DESCRIPTION

The DC Link capacitor voltage can simply be determined by integrating the capacitor current and normalizing it to the value of the capacitance. Therefore, the voltage ripple reduces significantly compared to the current, while the distortion spectrum is just scaled by C_{dc}.

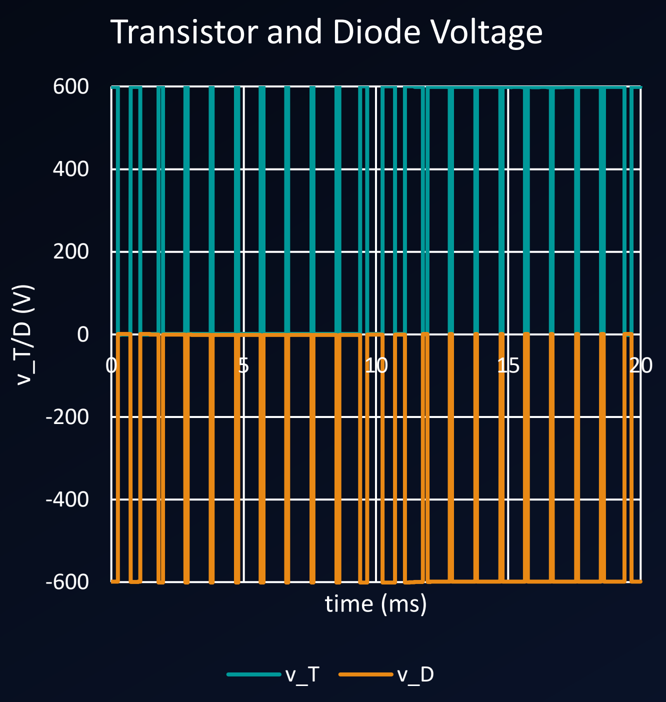
Literature:	[1,2]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

Steady State Switching Waveforms

CURRENT



VOLTAGE



DESCRIPTION

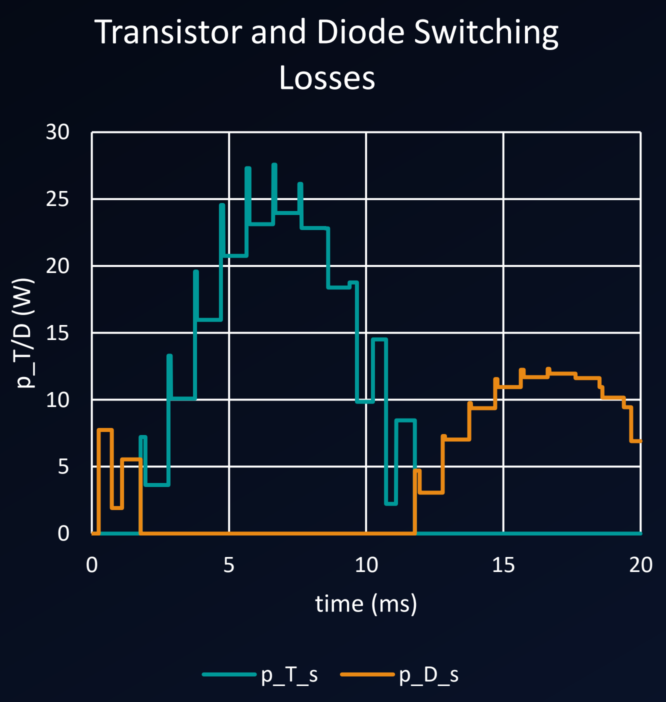
Transistor carries the current with respect to the active power transfer. The diode with respect to the reactive power transfer. Similar effects can be seen for the conduction and blocking voltages of transistor and diode.

Steady State Loss Waveforms

Literature:	[6,7]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

CONDUCTION LOSSES

SWITCHING LOSSES



DESCRIPTION

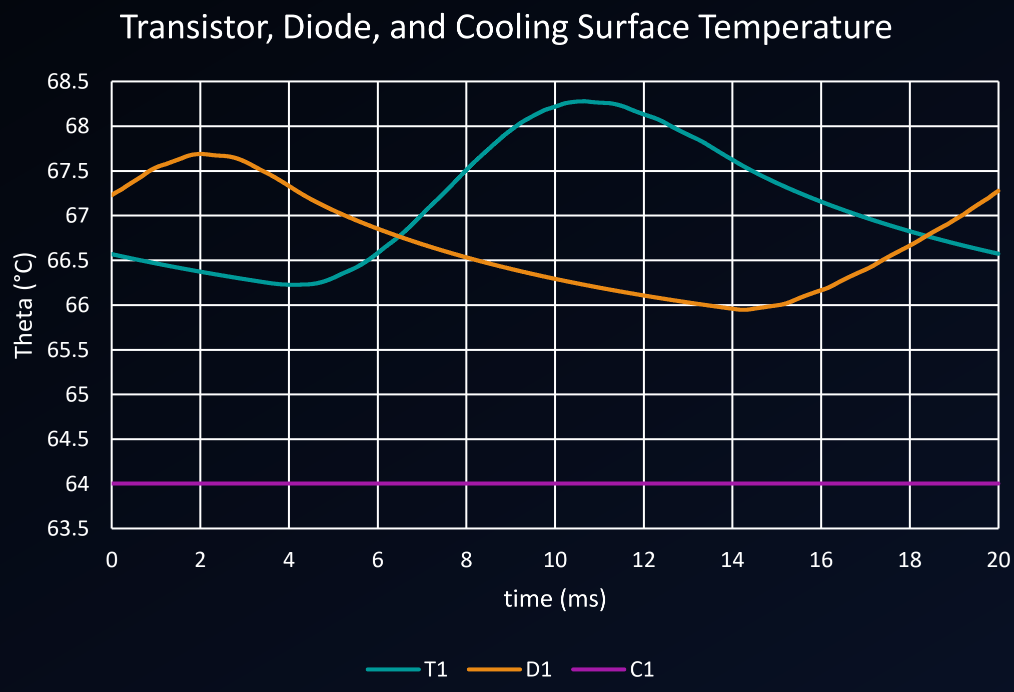
Conduction losses are roughly proportional to the square of the current. Switching losses depend on the instantaneous current, the voltage and the temperature of the switching device:

- Peak losses of transistor and diode are comparable
- Average loss are much higher for the transistor (active power transfer)

Literature:	[3]
Images:	-
Software:	PyPowerSim
Example:	**journalSteady**
Content:	Example

Steady State Thermal Waveforms

THERMAL WAVEFORM



DESCRIPTION

The cooling surface of the semiconductor device couples ideal transistor and diode an acts like an ideal low-pass filter providing a constant temperature reference for both devices.

- Diode and transistor are only coupled via the cooling surface without cross-coupling
- Diode and transistor do not mutually influence each other

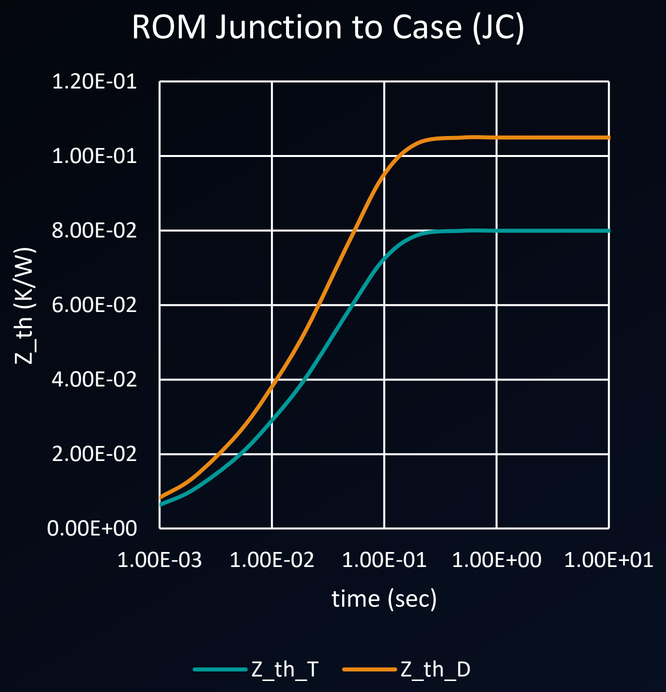
D3

TRANSIENT ANALYSIS

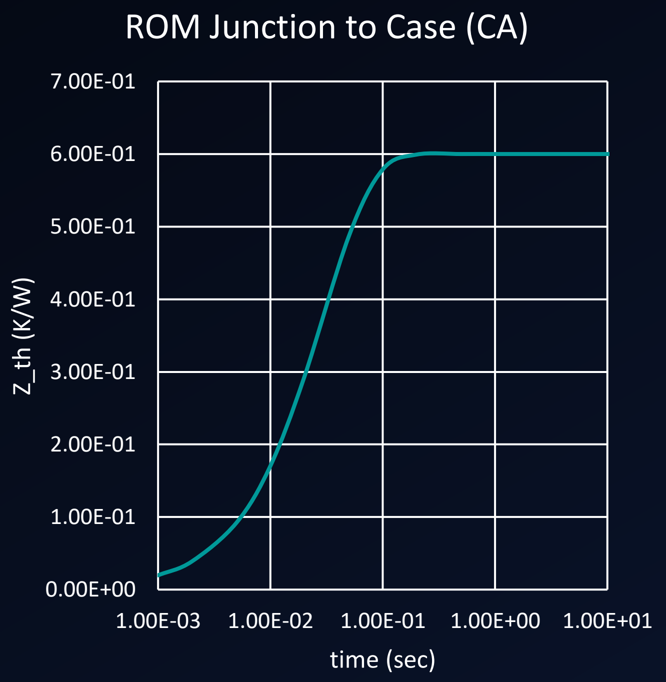
Literature:	[3]
Images:	-
Software:	PyPowerSim
Example:	**journalTrans**
Content:	Example

Thermal Impedance Switching Devices

IMPEDANCE JUNCTION - CASE



IMPEDANCE CASE - WATER



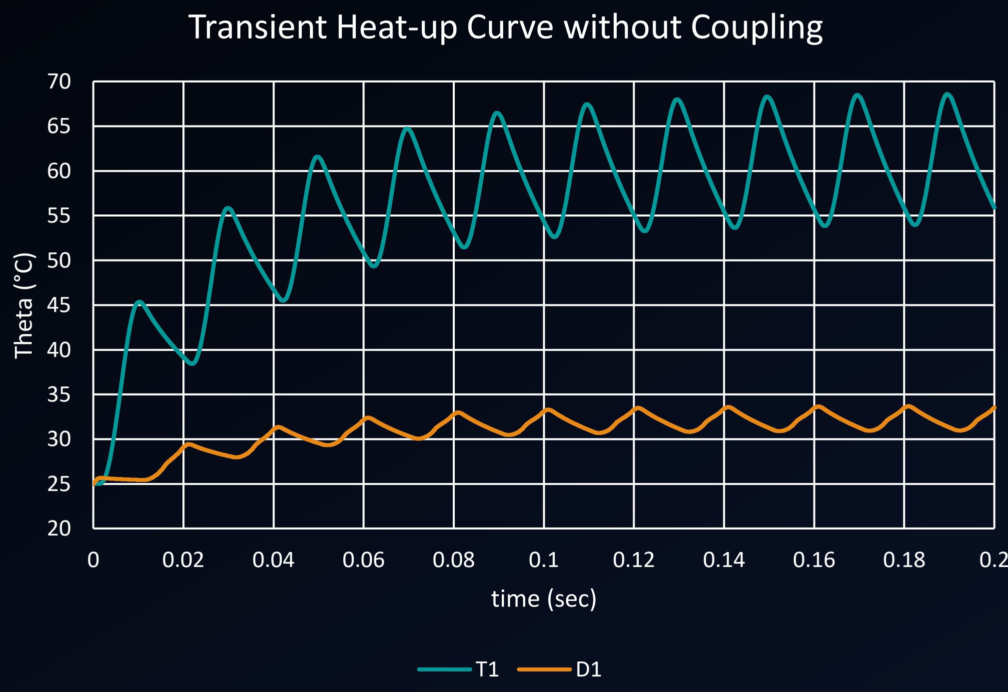
DESCRIPTION

To accurately evaluated the transient behavior of the switches the transient thermal impedance $Z_{th}(t)$ must be known to update the parameters depending on the temperature.

Transient Heat-Up Curve

Literature:	[3]
Images:	-
Software:	PyPowerSim
Example:	**journalTrans**
Content:	Example

WAVEFORM



DESCRIPTION

As can be seen, the thermal behavior of the temperature follows the shape of a 1D differential equation with the dominant time constants of the thermal impedance. The 50 Hz fundamental swing can be observed as well as the change of the losses with the temperature.

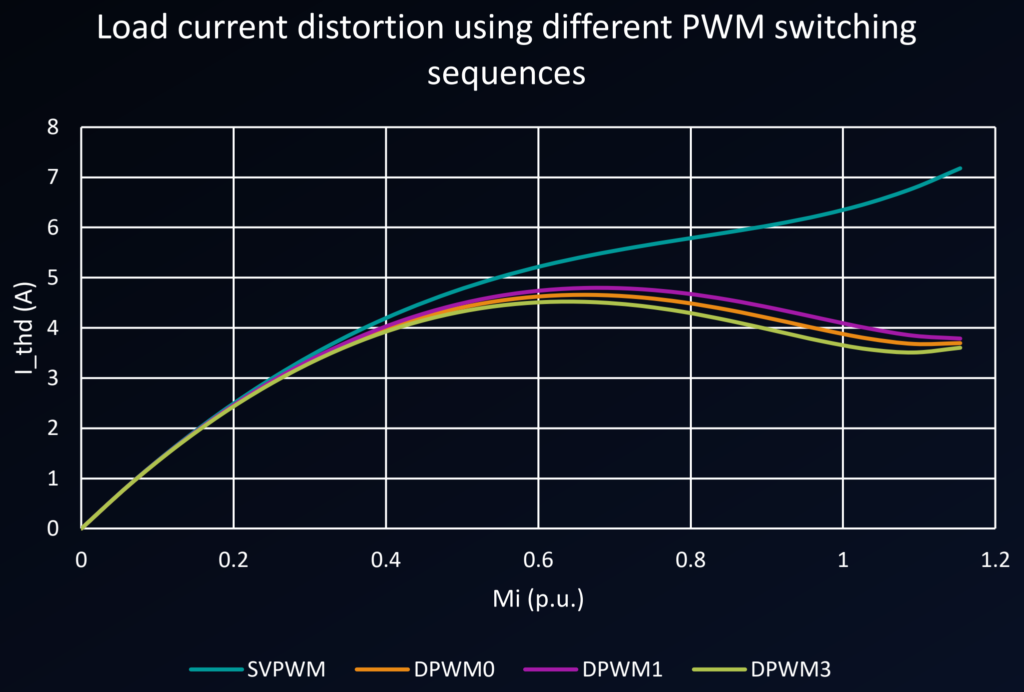
E

ADVANCED FUNCTIONALITIES

Literature:	[10]
Images:	-
Software:	PyPowerSim
Example:	**journalSweep**
Content:	Advanced

Comparing PWM Schemes

DISTORTION ANALYSIS



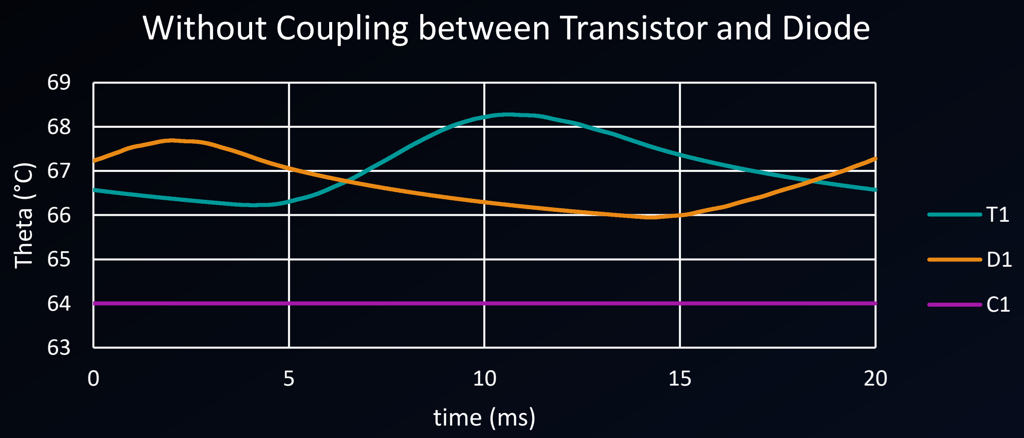
DESCRIPTION

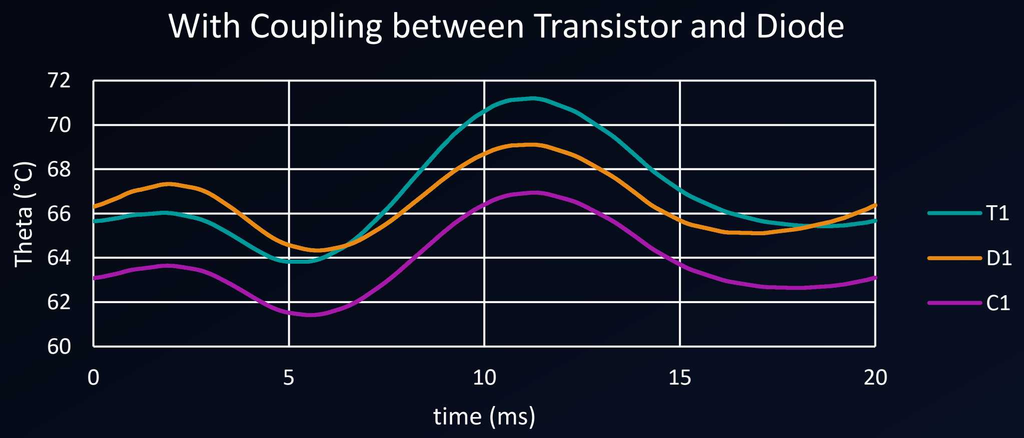
the harmonic current is determined by the switching sequence which is represented by the polynomial factor $K_{1,2,3}$. Therefore, different switching sequences have been investigated and are compared.

$$I_{thd} \approx \frac{V_{dc} M_i}{4L\sqrt{3}} \frac{T_{sw}}{2} \sqrt{K_1 + K_2 M_i + K_3 M_i^2}$$

Advanced Thermal Modeling

Literature:	[9]
Images:	-
Software:	PyPowerSim
Example:	**journalCoupling**
Content:	Advanced





Description

To improve the shortcomings of the utilized 1D Foster models the thermal coupling between transistor and diode through the heatsink of the power module is considered [4].

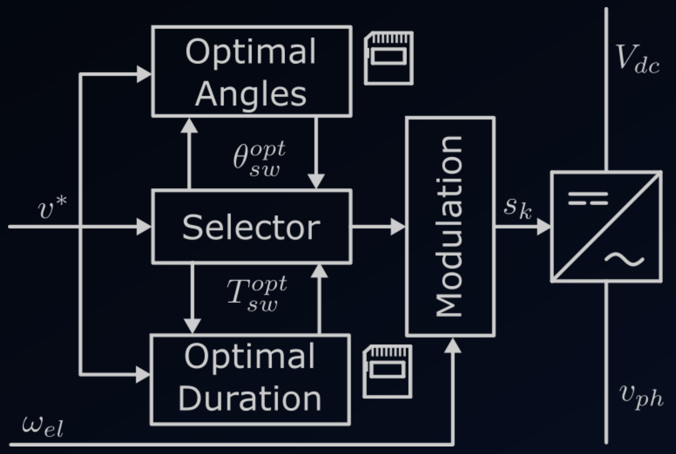
$$T_j = T_a + \Delta T_{ca} + \Delta T_{jc} = T_a + p_L * \dot{Z}_{ca} + p_L^T * \dot{Z}_{jc}$$

As can be seen be seen without considering coupling $\vartheta_{T/D}$ are only influenced by their own thermal impedance and losses, while the cooling surface acts like an ideal filter providing a constant reference temperature. When considering coupling via the cooling surface diode and transistor temperatures are mutually influenced by their respective losses, e.g. losses in the diode also lead to a temperature increase in the transistor and vice versa.

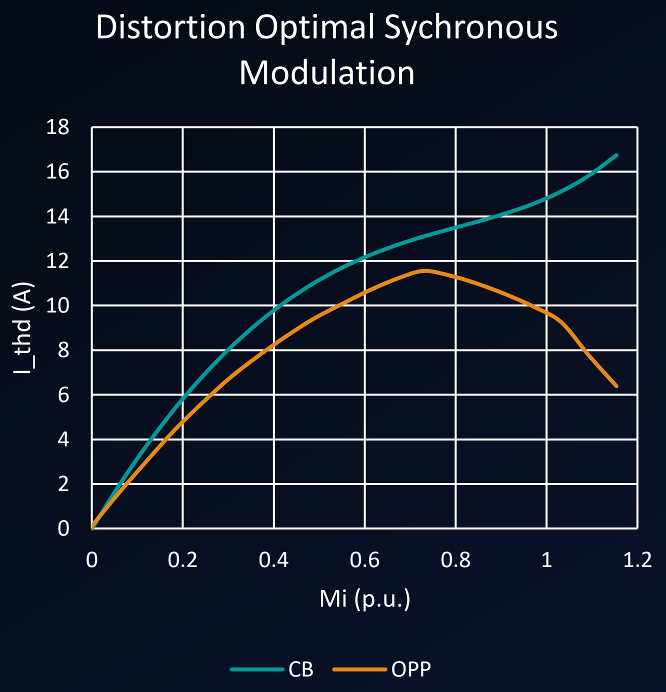
Literature:	[8]
Images:	-
Software:	PyPowerSim
Example:	**journalOPP**
Content:	Advanced

Optimal Synchronous Modulation

CONCEPT



DISTORTION



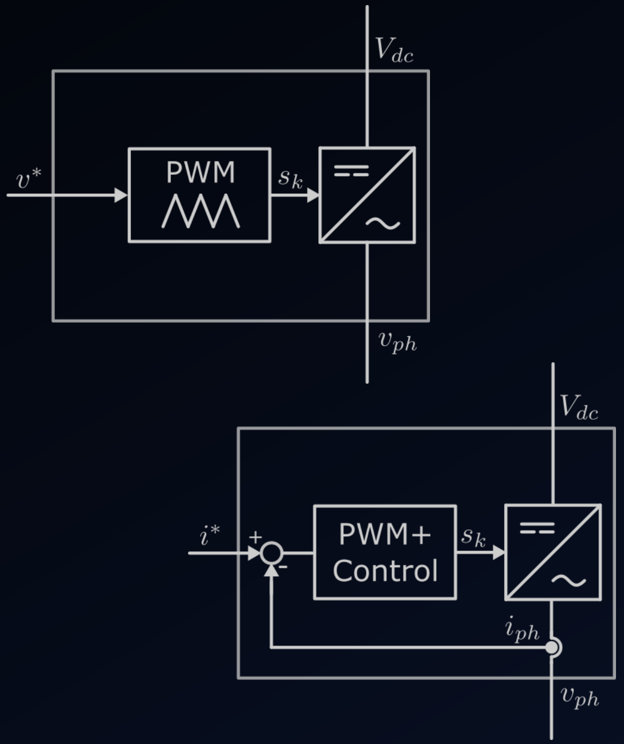
DESCRIPTION

As can be seen the optimized pulse patterns lead to a reduced total harmonic distortion over the completed modulation region. Unlike other techniques, e.g. selective harmonic elimination, not specific harmonics are suppressed but the rms value is minimized.

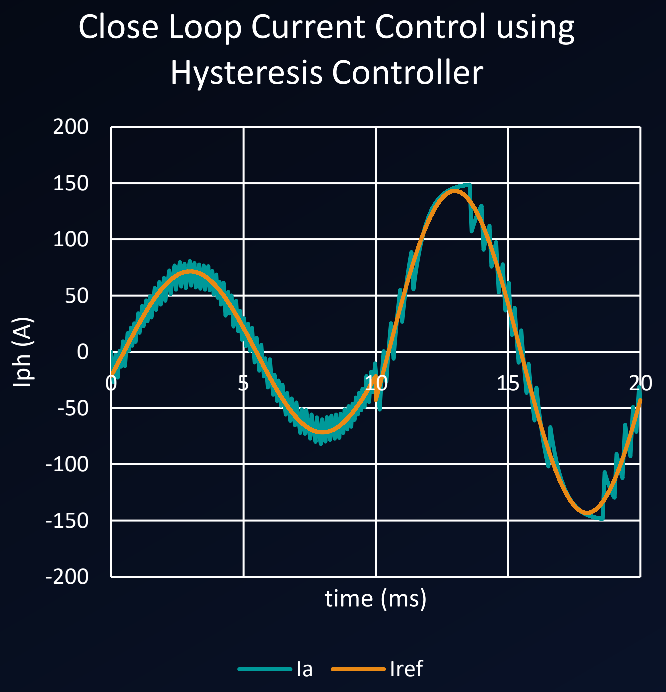
Closed Loop Control

Literature:	[2]
Images:	-
Software:	PyPowerSim
Example:	**journalClose**
Content:	Advanced

CONCEPT



DISTORTION



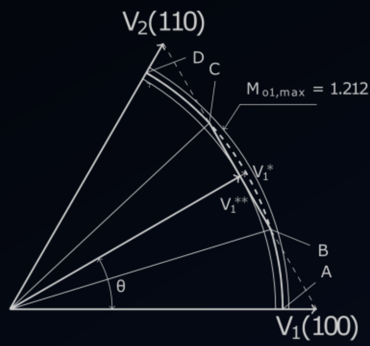
DESCRIPTION

As can be seen, the fundamental difference between the closed loop and open loop lies in the control of the output, i.e., the phase current of the converter cell and the feedback to the input. To illustrate the principle, a current load step from 50 - 100 A RMS is illustrated using hysteresis control with a controller frequency of 20 kHz and a hysteresis limit of $\pm 10\%$ with respect to the peak current.

Overmodulation

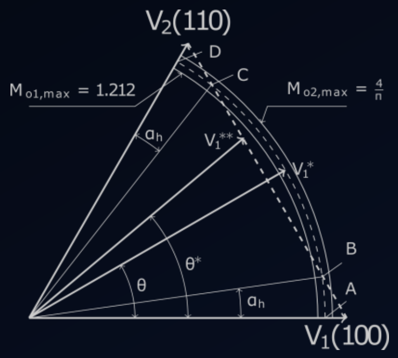
Literature:	[5]
Images:	-
Software:	PyPowerSim
Example:	**journalOvermod**
Content:	Advanced

CONCEPT

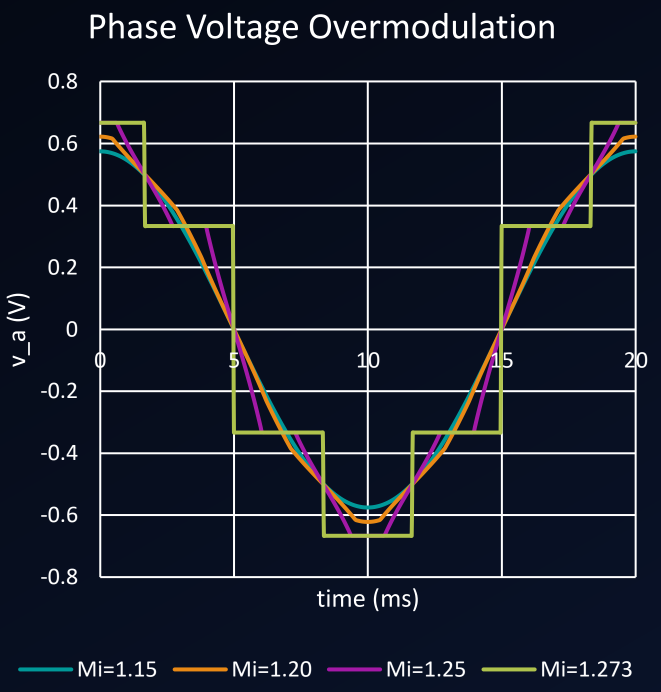


OM Region I

OM Region II



PHASE VOLTAGE



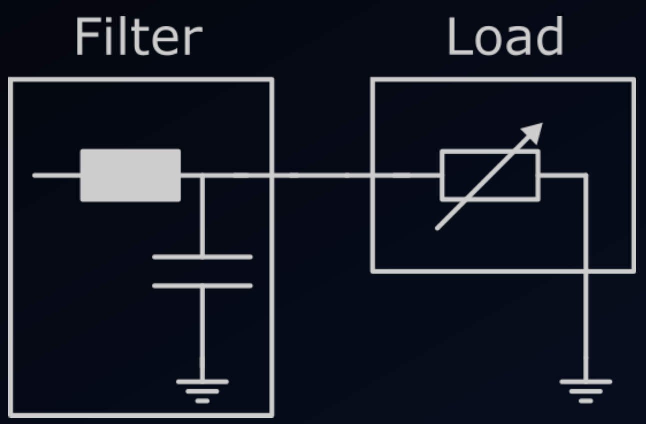
DESCRIPTION

To further increase the fundamental voltage the voltage space vector is increased following the boundaries of the hexagon while compensating for the loss in fundamental voltage at the vertex of the space vector diagram. The maximum voltage is generated in six-step mode when spending all available time at the vertex. The resulting phase voltage is shown in the figure on the left.

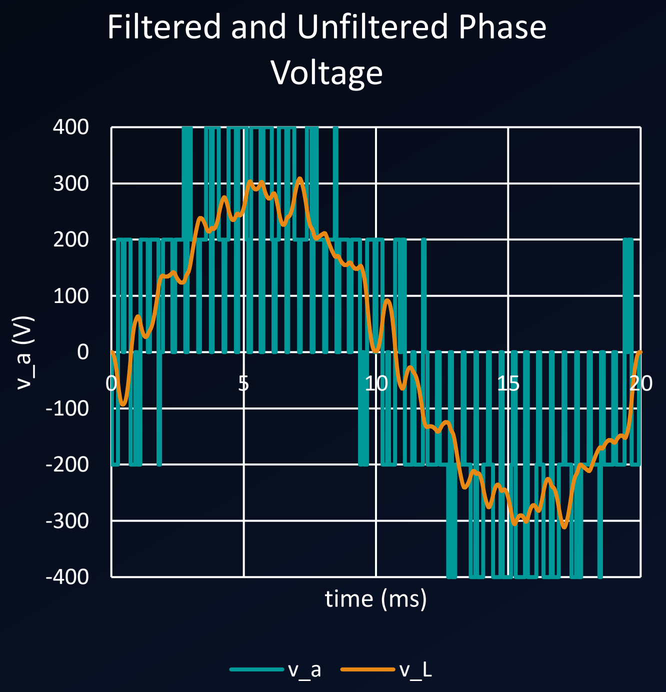
Literature:	[2]
Images:	-
Software:	PyPowerSim
Example:	**journalFilter**
Content:	Advanced

Output Filtering

CONCEPT



PHASE VOLTAGE



DESCRIPTION

In some applications, e.g. grid-connected converters, the output voltage and current must have very low harmonic distortion. In this case, an output filter can be used as shown in figure on the left. The filter uses an additional inductance and capacitance at the output generating a filter of third order together with the load inductance.

F

OUTLOOK AND CONCLUSION

Development and Future Goals

As failure and mistakes are inextricably linked to human nature, the toolkit is obviously not perfect, thus suggestions and constructive feedback are always welcome. If you want to contribute to the PyPowerSim toolkit or spotted any mistake, please contact me via: p.schirmer@herts.ac.uk. The following aspects will be improved in future version:

- Temperature, current, and frequency dependencies for the load parameters
- Calculation of long-term mission profiles
- Generation of efficiency maps for the converter operation range

G

REFERENCES

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[1] Holmes, D. Grahame, and Thomas A. Lipo. Pulse width modulation for power converters: principles and practice. Vol. 18. John Wiley & Sons, 2003.

[2] Jenni, Felix, and Dieter Wüest. Steuerverfahren für selbstgeführte Stromrichter. vdf Hochschulverlag AG, 1995.

[3] Touzelbaev, Maxat N., et al. "High-efficiency transient temperature calculations for applications in dynamic thermal management of electronic devices." Journal of Electronic Packaging 135.3 (2013): 031001.

[4] C. Sintamarean, F. Blaabjerg and H. Wang, "A novel electro-thermal model for wide bandgap semiconductor based devices," 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2013, pp. 1-10, doi: 10.1109/EPE.2013.6631982

[5] Holtz, Joachim, Wolfgang Lotzkat, and Ashwin M. Khambadkone. "On continuous control of PWM inverters in the overmodulation range including the six-step mode." IEEE transactions on power electronics 8.4 (1993): 546-553.

[6] D. Graovac and M. P¨urschel, “Igbt power losses calculation using thedata sheet parameters,” Infineon Application Note, 2009

[7] D. Graovac, M. Purschel, and A. Kiep, “Mosfet power losses calculationusing the data-sheet parameters,” Infineon Application Note, vol. 1, pp.1–23, 2006.

[8] J. Holtz, “Advanced pwm and predictive control—an overview,” IEEETransactions on Industrial Electronics, vol. 63, no. 6, pp. 3837–3844,2015.

[9] C. Sintamarean, F. Blaabjerg, and H. Wang, “A novel electro-thermalmodel for wide bandgap semiconductor based devices,” in 2013 15thEuropean Conference on Power Electronics and Applications (EPE).IEEE, 2013, pp. 1–10

[10] A. M. Hava, R. J. Kerkman, and T. A. Lipo, “Simple analytical andgraphical methods for carrier-based pwm-vsi drives,” IEEE transactionson power electronics, vol. 14, no. 1, pp. 49–61, 1999.