PyPowerSim: A Simple Python Toolkit for Wavefrom Analysis and Loss Simulation of Standard Converter Topologies (V.0.3)

1. Introduction

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. It is clear, that this toolkit cannot be anywhere near the capabilities of commercial software but will hopefully provide a better understanding due to the freely available source code. The toolkit is obviously not complete; thus, suggestions are always welcome.

1.1. Publication and Citation

The PyPowerSim toolkit is part of the following survey paper and tries to replicate the presented architectures and approaches. Please cite the following paper when using the PyPowerSim toolkit:

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When using the B6 architecture and the waveform analysis options please also refer to the following article:

Schirmer, Pascal A., Daniel Glose, and Ulrich Ammann. "Zero-voltage and frequency pattern selection for DC-link loss minimization in PWM-VSI drives." Electrical Engineering (2022): 1-10.

1.2. Dependencies

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 3.8
- Numpy
- Pandas
- Scipy

1.3. Folder Structure

The folder structure of the PyPowerSim system can be found below. Users should mainly work in \para for configuration of new devices and in \setup for saving parameter configurations as well as in \results for obtaining saved calculation results. The folder \src contains all source code and should only be modified if the user wishes to implement new functionalities.

Table 1: PyPowerSim folder structure.

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		
	|--	data	Contains functions for loading data
	|--	elec	Contains functions for electrical calculation
	|--	general	Contains general and helper functions
	|--	plot	Contains functions for plotting
	|--	therm	Contains functions for thermal calculations
	|--	topo	Contains implemented converter topologies

1.4. Limitations

Since the toolkit is still under development there are several things that need to be improved, are not yet implemented, or lack verification with numerical models or measurements. In the following a list of know issues and limitations is provided:

- 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 now.

2. Architecture

The architecture implemented in the PyPowerSim toolkit is exemplary illustrated for a B2 converter cell in Figure 1. The source code implementation of the PyPowerSim toolkit aims to follow the data follow of the implementation in Figure 1 for the interested reader to follow the data and signal flow path through the implementation.

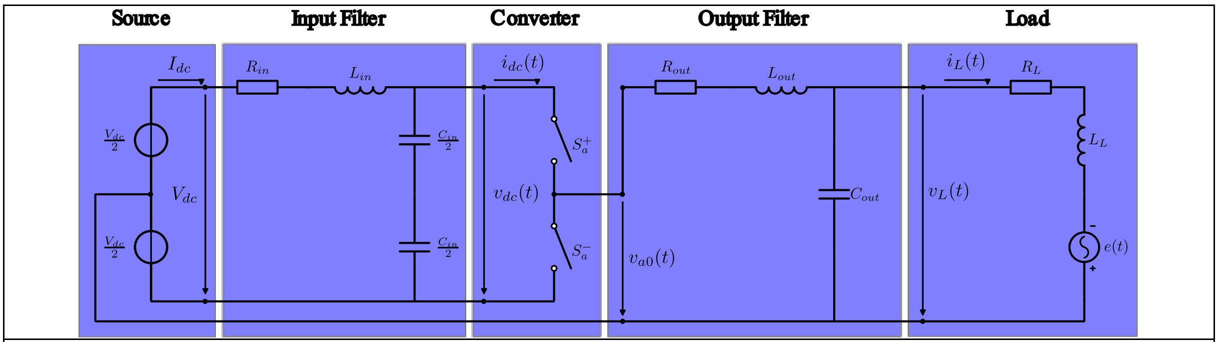

Figure 1: Proposed converter architecture as implemented in the PyPowerSim toolkit.

As illustrated in Figure 1 the architecture consists of five blocks namely the source, the input filter, the converter cell, the output filter and the load. Each of these blocks can be freely configured with the parameter setup described in Section 3. In the following a short description without consideration of the filter elements is provided. For the complete description please refer to the theory guide and the following theoretical works [REF].

The converter is power by a voltage source having a constant dc voltage of V_{dc}. The converter is controlled by a time domain switching function $s_a(t)$ translating the constant dc link voltage in a set of high-frequent voltage pulses as described in (1):

$$v_{a0}(t) = s_A(t)\frac{V_{dc}}{2} \tag{1}$$

The switching function can hereby be described as a set of on- and off-states of the high-side switch S_a^+ and the low-side switch S_a^- and can be expressed in the time-domain by the Fourier series in (2):

$$s_a(t) = \sum_{v=1}^{\infty}[a_v\cos(v\omega_{el}t) + b_v sin(v\omega_{el}t)] = \sum_{v=1}^{\infty} c_v e^{-jv\omega_{el}t} \tag{2}$$

where a_v, b_v, c_v are the Fourier series coefficients, v is the harmonic number and ω_{el} is the electrical circular frequency of the output current. The relation between the current and voltage on the load side can then be expressed by the following differential equation in (3):

$$v_L(t) = R_L i_L(t) + L_L\frac{di_L}{dt} + e(t) \tag{3}$$

where R_L, L_L are the resistance and the inductance of the load, $e(t)$ is the induced voltage, and $v_L(t), i_L(t)$ are the load voltage and current respectively.

3. Parameters

The PyPowerSim toolkit offers a set of pre-implemented option to configure the architecture and the power electronics control. The complete list, including description and possible values, are tabulated in Table 2.

Table 2: Complete options for the configuration of the PyPowerSim tool.

General Settings				
Name	**Values**	**Default**	**Notes**	**Units**
Name	String	test	Name of the simulation setup	-
Author	String	Pascal	Author name of the toolkit	-
Debug	Integer	0	Freely configurable variable for debugging	-
Output	String	Mi	Output mode control	-
Type	0, 1, 2	0	(0) sweep analysis, (1) steady-state, (2) transient	-
Loop	CL, OL	CL	Closed loop (CL) or open loop (OL) simulation	-
freqPar	fs, fel	Fs	Update frequency of the parameters	-
freqAvg	None, fs, fel	None	Averaging cycle of the output variables	-
fsim	Integer	1e5	Simulation frequency	Hz
Tol	Double	1e-6	Numerical tolerant for iterations	-
Eps	Double	1e-12	Numerical small value	-
Int	Integer	20	Numerical value for number of integration steps	-
Plot	0, 1	1	(0) plotting inactive, (1) plotting active	-
save	0, 1	0	(0) results are not saved, (1) results are saved	-
Operating Point				
Tmax	Double	0.5	Maximum simulation time transient operation	Sec
Tc	Double	50	Initial junction temperature	C
Tj	Double	50	Case temperature (reference)	C
cyc	Integer	2	Number of cycles till stationary behaviour is assumed	-
W	Integer	25	Number of datapoints for sweeping	-
Po	Double	1000	Output power (active)	W
Qo	Double	500	Output power (reactive)	VAr
Vo	Double	50	Output voltage	V
Io	Double	25	Output current	A
Mi	[0, …,1]	1.0	Modulation index (for overmodulation till $4/\pi$	-
Vdc	Double	400	DC-link voltage of the converter	V
phi	[-180,180]	0	Load angle	Deg
Topology				
SwiName	String	IKQ75N120CS6	Name of the switch	-
CapName	String	Elco	Name of the capacitor	-
sourceType	B2, B4, B6	B6	Converter type	-
inpFilter	0, 1	0	(0) no input filter, (1) input filter	-
Rinp	Double	1e-3	Resistance input filter	Ohm
Linp	Double	2e-3	Inductance input filter	H
Cinp	Double	1e-3	Capacitance input filter	F
outFilter	0, 1	0	(0) no input filter, (1) input filter	-
Rout	Double	0	Resistance output filter	Ohm
Lout	Double	1e-3	Inductance output filter	H
Cout	Double	1e-3	Capacitance output filter	F
R	Double	5	Load resistance	Ohm
L	Double	5e-3	Load inductance	H
E	Double	0	Back electromotive force (EMF)	V
phiE	Double	0	Load angle EMF	Deg
wave	Con, sin, …	sin	Waveform load output	-
fel	Integer	50	Fundamental frequency output	Hz
Pulse Width Modulation (PWM)				
Type	FF, CB, SV	SV	(FF): fundamental frequency, (CB) carrier, (SV) space vector	-
Upd	SE, DE	DE	(SE): single edge update, (DE): double edge update	-
Samp	NS, RS	RS	(NS): natural sampling, (RS): regular sampling	-
Tri	RE, FE, SM, AM	SM	(RE): rising edge, (FE): falling edge, (SM): symmetrical, …	-
Int	0, 1	0	(0): non-Interleaved, (1) Interleaving	-
Td	Double	0	Dead time	Sec
Tmin	Double	0	Minimum on/off time	Sec
Loss	0, 1	1	(0) ideal loss-less, (1) losses modelled	-
swloss	0, 1		(0) based on energy, (1) based on integration of capacitances	-
sw	0, 1	0	(0) hard switching, (1) soft switching	-
fs	Double	1050	Switching frequency	Hz
seq	String	0127	Switching sequence	-
zero	String	SVPWM	Zero voltage vector splitting	-
Electrical and Thermal Parameters				
SwiMdl	Con, Pwl, Tab	Tab	(Con): constants, (Pwl): linear, (Tab): tabulated	-
SwiType	IGBT, MOSFET	IGBT	Switch type	-
SwiRecCon	D, DT	D	reverse conduction (D): diode channel, (DT): diode and transistor	-
SwiRecMdl	0, 1	0	reverse conduction model (0): Ideal, (1): including blanking time	-

SwiPara	Integer	1	Number of parallel switches	-
SwiSeries	Integer	1	Number of serial switches	-
CapMdl	Con, Pwl, Tab	Tab	(Con): constants, (Pwl): linear, (Tab): tabulated	-
CapType	Elco	Elco	Capacitor type	-
CapPara	Integer	1	Number of parallel capacitors	-
CapSeries	Integer	1	Number of serial capacitors	-
Heatsink	0, 1	1	(0): no heatsink, (1) heatsink modelled	-
Coupling	0, 1	0	0) no thermal coupling between, 1) thermal coupling (D and T)	-

4. Results

In the following chapter a set of reference results is provided using the B6 converter architecture and the “init.txt” setup file provide in \setup. The most relevant parameters are listed for convenience in Table 3.

Table 2: Parameters for calculating the reference results of the B6 converter.

Parameter	Symbol	Value	Unit
Load frequency	f_{el}	50	Hz
Switching frequency	f_s	1050	Hz
PWM Method		SVM	-
DC Link Voltage	V_{dc}	400	V
Modulation Index	M_i	1.0	-
Load Inductance	L	0.005	H
Load Resistance	R	5	Ohm
Reference Temperature	ϑ_{ref}	50	C

In detail, the results are calculated for the three different operating modes of the PyPowerSim toolkit, namely the waveform analysis (Section 4.1), the steady-state analysis (Section 4.2) and the transient analysis (Section 4.3). The three operating modes are displayed below.

4.1. Waveform Analysis

Below the simulation results of the waveform analysis are displayed. The modulation function is illustrated in Figure 2, the load currents and voltages in the time-, frequency- and modulation-domain are illustrated in Figure 3 and Figure 4.

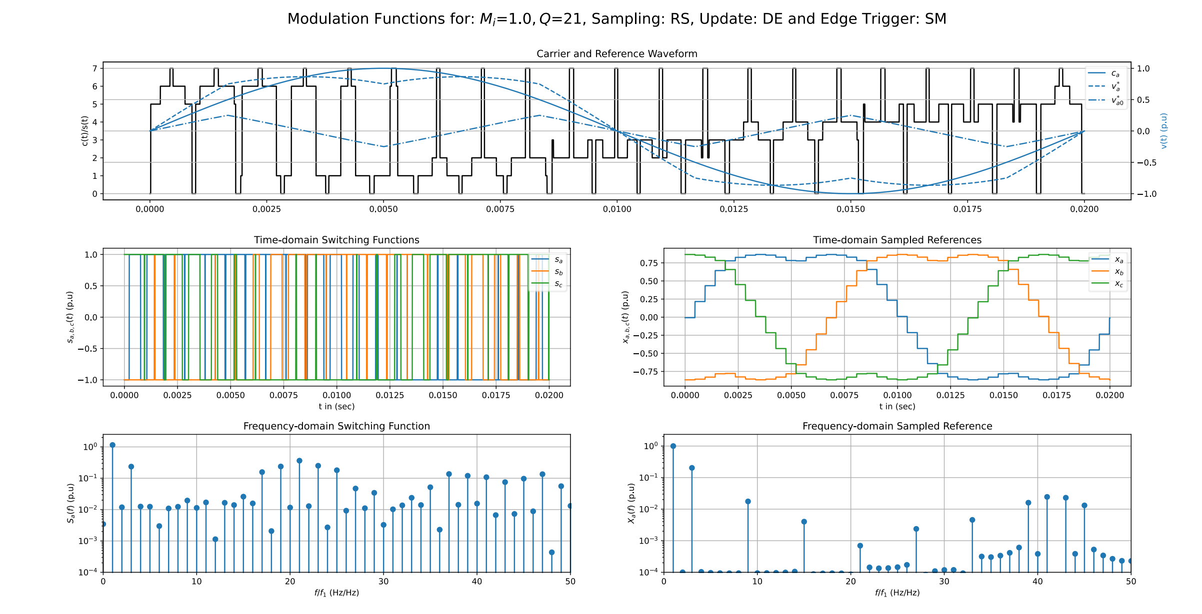

Figure 2: Modulation function of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$.

Figure 2 illustrates the reference waveform (c_a), the average reference value of the phase voltage (v_a^*), and the star-point voltage for one fundamental cycle, as well as the switching states (black). The results are displayed in per unit format. In the middle the time-domain switching function of the three phases can be found ($S_{a,b,c}$) as well as the sampled time domain reference waveform ($x_{a,b,c}$), below the frequency domain representations can be found respectively. The frequency representations are also in per unit format, normalized to the fundamental frequency of the waveform. The baseband and the dominating sidebands of the switching sequence can clearly be seen.

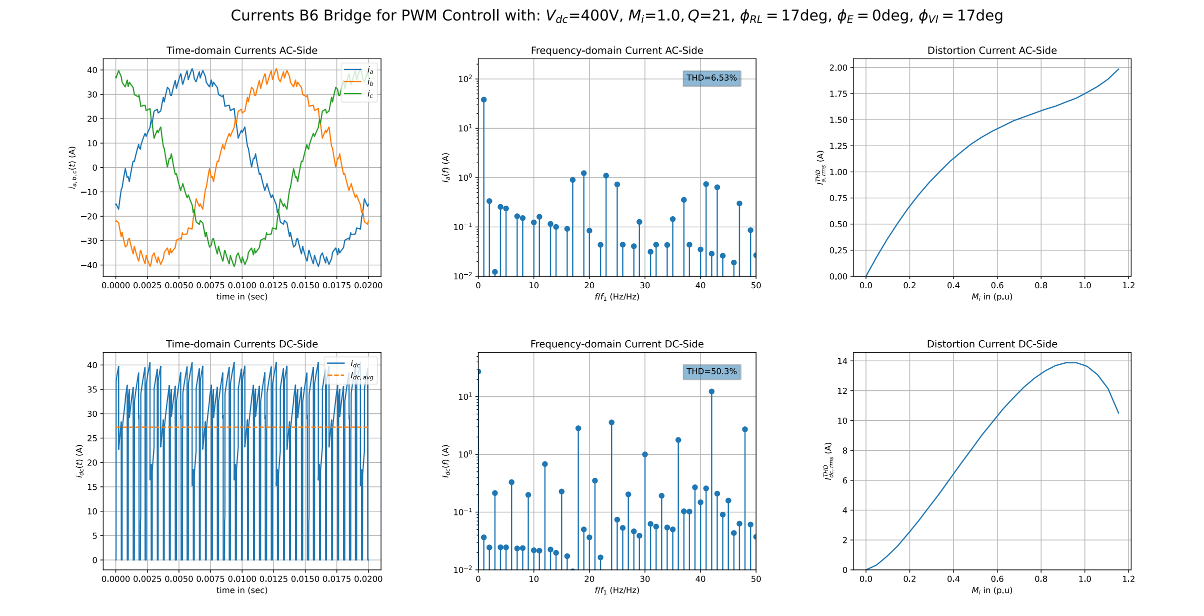

Figure 3: Currents of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The load angle is equal to $\varphi = 17\ deg$.

The time-, frequency-, and modulation-domain currents of the symmetrical three-phase RL load ($i_{a,b,c}$) are displayed on the top of Figure 3, while the DC-link current (i_{dc}) is displayed on the bottom. The total harmonic distortion current for both phase ($I_{a,rms}^{THD}$) and DC-link ($I_{dc,rms}^{THD}$) are shown as function of the modulation index. It should be noted that the any integer multiple of the third harmonic and the third harmonic itself do not appear in the frequency spectrum similar as the harmonic being equal to the pulse number. Again, the baseband and sideband harmonics can be clearly seen.

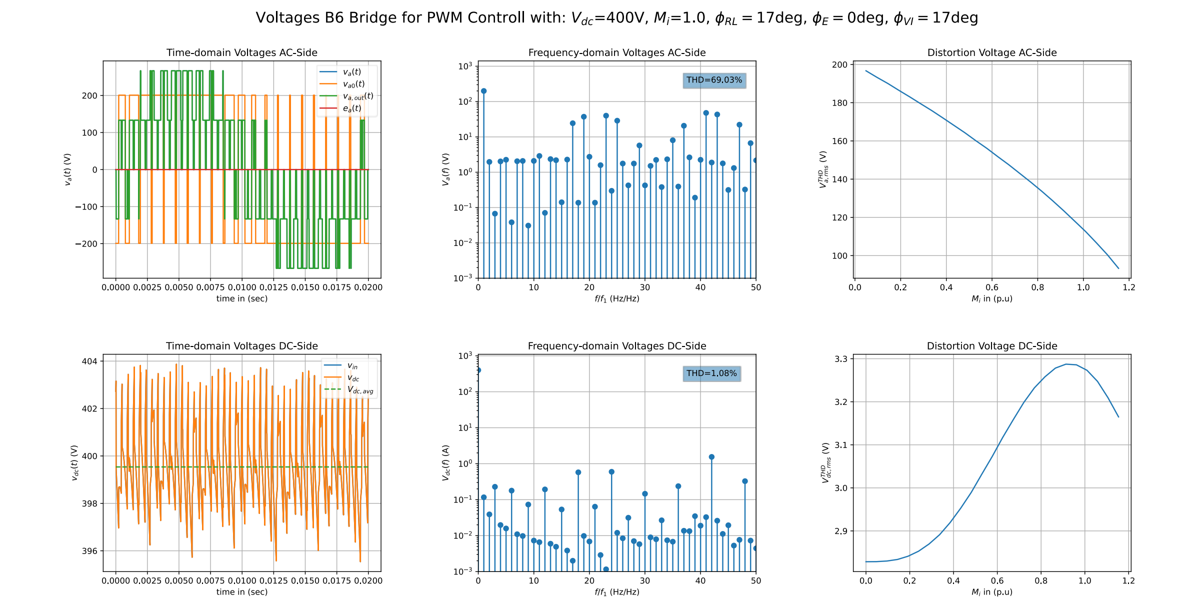

Figure 4: Voltages of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The load angle is equal to $\varphi = 17\ deg$.

The time-, frequency-, and modulation-domain voltages of the symmetrical three-phase RL load (v_a) are displayed on the top of Figure 3, while the DC-link voltage (v_{dc}) is displayed on the bottom. In detail, both the phase-to-neutral (v_{a0}) as well as the phase-to-phase voltage are shown (v_a). The total harmonic distortion voltage for both phase ($V_{a,rms}^{THD}$) and DC-link ($V_{dc,rms}^{THD}$) are shown as function of the modulation index.

4.2. Steady-State Analysis

In this Section the results for the steady-state analysis are presented, the results are calculated in closed-loop condition, such that the losses are extracted for the stabilized temperature of the junction. The time-domain results for the currents, the voltages, as well as the conduction and switching losses for the six switches are illustrated in Figure 5.

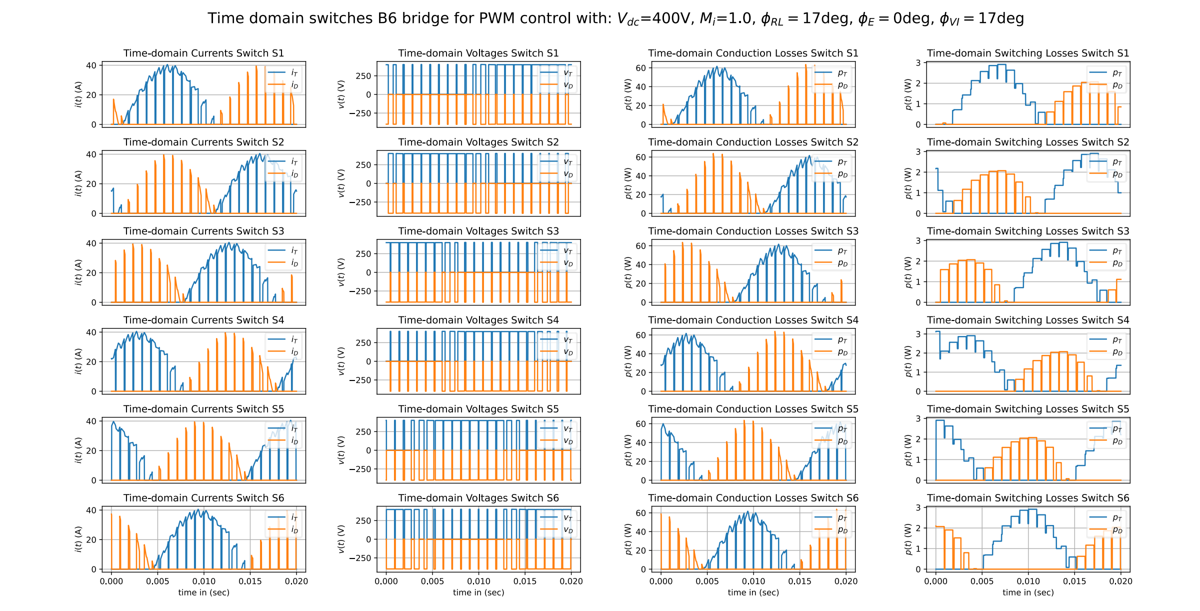

Figure 5: Time-domain currents, voltages, and losses of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The load angle is equal to $\varphi = 17\ deg$.

As can be seen in Figure 5 all switches are loaded symmetrically do the symmetrical reference waveform and the switching sequence and are shifted by 120 degrees do to the symmetrical three-phase RL load. In Figure 6 the resulting temperature are illustrated showing results when starting from initial condition, i.e. $\vartheta = 50\ C$.

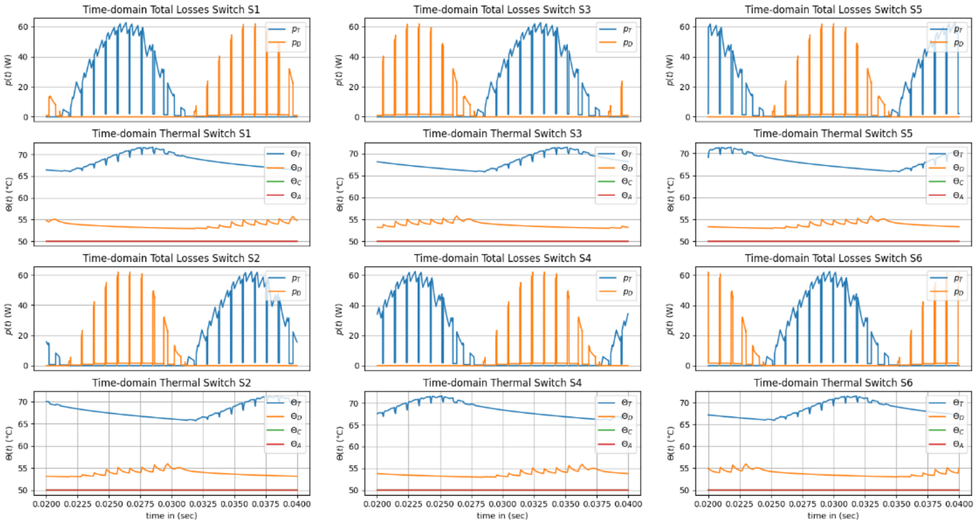

Figure 6: Time-domain losses and temperatures for the six switches and diodes of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The load angle is equal to $\varphi = 17\ deg$.

4.3. Transient Analysis

In this Section the results for the steady-state analysis are presented, the results are calculated in closed-loop condition such that the parameters are updated after every fundamental period, i.e. $T_s = 20\ ms$. The results are averaged once over the switching sequence, thus displaying junction temperature swing in Figure 7, and once are average over the fundamental cycle thus illustrating the self-heating due to the internal losses in Figure 8. It should also be noted, that in Figure 8 the parameter updates and the positive coupling of the channel resistances and voltages with the junction temperature are visible.

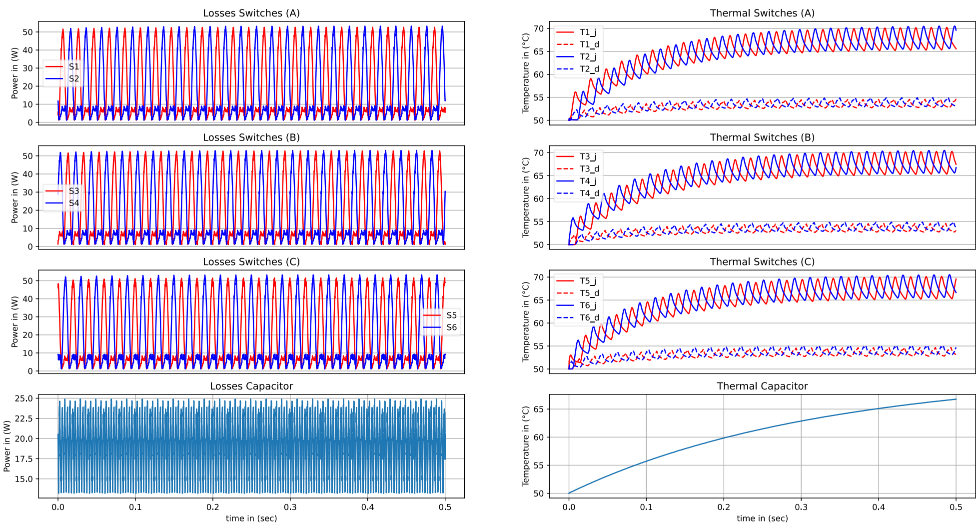

Figure 7: Transient time-domain losses and temperatures for the six switches and diodes of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The values are average over the switching cycle.

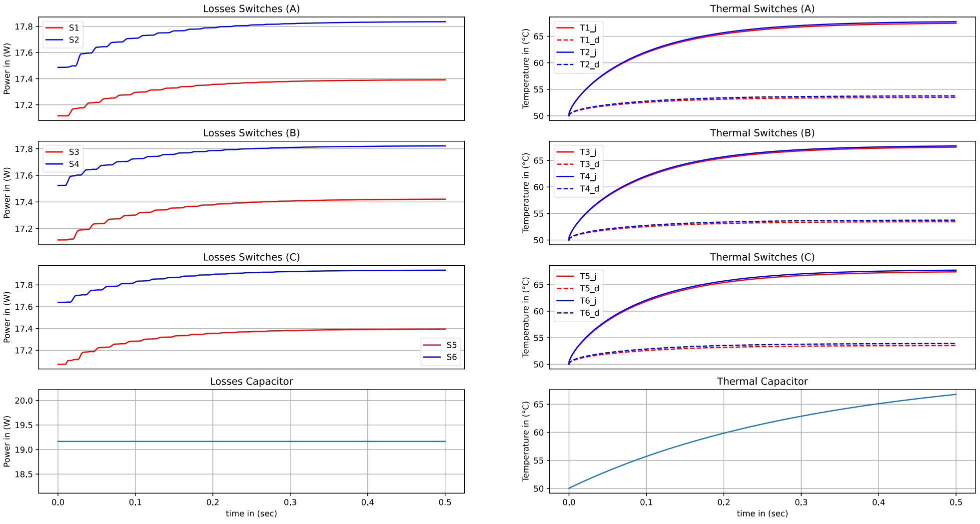

Figure 8: Transient time-domain losses and temperatures for the six switches and diodes of a B6 converter using space vector modulation and a standard switching sequence (0127) with a pulse number of $Q = 21$ and $M_i = 1.0$. The values are average over the fundamental cycle.

5. Quick Start

For a first test run use start.py to calculate the results presented in Section 4. The parameters are loaded from \para using the switch 'IKQ75N120CS6' and the capacitor 'Elco'. After observing and understanding the results from Section 4 the interested user can change the parameters in start.py according to Table 2 and investigate the effect of different parameter settings. The following configurations are in general interesting:

- Effects on the switching frequency and switching sequence.
- Effects on the PWM method and its parameters
- Effects on the load or induced voltage

Of course, the interested user can always parameterize their own components using the templates for both switching devices as well as capacitors.

6. Brief Comparison

To enable comparison with more advanced numerical power electronic simulation tools such as PLECs and SIMULINK two comparison have been made. The first comparison aims to do an exact comparison with the SIMULINK model from [3] enabling one to one comparison. The second comparison aims to compare to a practical application when parameterizing the toolkit based on datasheet parameters and comparing it to an official Infineon Websim PLECs application [4]. The results are presented in Section 6.1 and Section 6.2.

6.1. SIMULINK Comparison

The SIMULINK model from [3] enables two configurations, namely a piece-wise linear simulation and a simulation based on tabulated parameters. Both options are compared for the IGBT model using the parameter set tabulated in Table 3.

Table 3: Parameters for performing the SIMULINK comparison.

Parameter	Symbol	Value	Unit
Load frequency	f_{el}	60	Hz
Switching frequency	f_s	2000	Hz
PWM Method		Carrier based	-
DC Link Voltage	V_{dc}	200	V

Modulation Index	M_i	0.8	-
Load Inductance	L	0.005	H
Load Resistance	R	0 / 1	Ohm
Reference Temperature	ϑ_{ref}	25	C

The results for both evaluations are tabulated in Table 4 using an RL load and in Table 5 for using a pure inductive load respectively. As can be seen in both evaluation the total losses are being calculated with a maximum error of 6.6%, while switching losses show usually higher errors than conduction losses.

Table 4: Results for the SIMULINK comparison with RL load.

Comp	**Piece-Wise Linear**			**Tabulated**		
	Simulink	**PyPowerSim**	**Error**	**Simulink**	**PyPowerSim**	**Error**
IGTB-Swi	0.59 W	0.54 W	8.5%	0.37 W	0.42 W	13.6%
IGBT-Con	6.54 W	6.42 W	1.8%	11.4 W	11.1 W	2.7%
Diode-Swi	0.07 W	0.06 W	14.3%	0.21W	0.33 W	57.1%
Diode-Con	3.56 W	3.48 W	2.2%	16.2 W	17.8 W	9.9%
Total	10.8 W	10.5 W	2.8%	28.2W	29.7W	5.3%

Table 5: Results for the SIMULINK comparison with L load.

Comp	**Piece-Wise Linear**			**Tabulated**		
	Simulink	**PyPowerSim**	**Error**	**Simulink**	**PyPowerSim**	**Error**
IGTB-Swi	0.68 W	0.60 W	11.8%	0.35 W	0.43 W	22.9%
IGBT-Con	6.24 W	5.63 W	9.8%	11.4 W	10.0 W	12.3%
Diode-Swi	0.07 W	0.10 W	42.9%	0.18 W	0.29 W	61.1%
Diode-Con	5.18 W	5.11 W	1.4%	27.6 W	31.3 W	13.4%
Total	12.2 W	11.4 W	6.6%	39.5 W	42.0 W	6.3%

6.2. PLECs Comparison

Second, the results of a B6 converter using an IGBT switch (IKQ75N120CS6) have been compared with the online available Websim toolkit from Infineon [4]. The simulation was performed using the parameters tabulated in Table 6.

Table 6: Parameters for performing the PLECs comparison.

Parameter	**Symbol**	**Value**	**Unit**
Load frequency	f_{el}	50	Hz
Switching frequency	f_s	1050 / 5000	Hz
PWM Method		SVM	-
DC Link Voltage	V_{dc}	400	V
Modulation Index	M_i	0.8	-
Load Inductance	L	0.005	H
Load Resistance	R	0 / 1	Ohm
Power Factor	PF	0.0 / 0.8	-
Reference Temperature	ϑ_{ref}	50	C

Four Evaluation have been conducted. One with high switching frequency and one with low switching frequency, while each simulation has been conducted using two different power factors. It must be noted, that do to the fact PyPowerSim being an open-loop toolkit that is not able to control the phase current the phase current are different for the two different power factor configurations. The results are presented in Table 7 and Table 8.

Table 7: Results for the PLECs comparison with low switching frequency.

Losses	**phi = 0.0 (Iph=71.8A)**						**phi = 0.8 (Iph=44.4A)**					
	PLECS		**PyPowerSim**		**Error (%)**		**PLECS**		**PyPowerSim**		**Error (%)**	
	HS	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**
IGTB-Swi	3.46	3.46	2.53	2.57	26.9	25.7	1.80	1.79	1.61	1.63	10.6	8.9
IGBT-Con	37.5	37.3	34.2	34.5	8.8	7.5	22.8	22.8	25.8	26.1	13.2	14.5

Diode-Swi	1.23	1.23	0.85	0.88	30.9	28.5	0.82	0.83	0.87	0.88	6.1	6.0
Diode-Con	35.2	35.0	34.3	34.4	2.6	1.7	8.95	8.89	8.25	8.40	7.8	5.5
Total	77.4	77.0	71.9	72.4	7.1	6.0	34.4	34.3	36.5	37.0	6.3	7.9

Table 8: Results for the PLECs comparison with high switching frequency.

Losses	**phi = 0.0 (Iph=71.8A)**						**phi = 0.8 (Iph=44.4A)**					
	PLECS		**PyPowerSim**		**Error (%)**		**PLECS**		**PyPowerSim**		**Error (%)**	
	HS	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**	**HS**	**LS**
IGTB-Swi	17.3	17.3	12.3	12.4	28.9	28.3	9.38	9.38	7.90	7.93	15.8	15.5
IGBT-Con	37.7	37.6	33.7	33.3	10.6	11.4	24.8	24.8	25.5	25.7	2.8	3.6
Diode-Swi	6.19	6.19	4.65	4.61	24.9	25.5	4.26	4.26	4.51	4.48	5.9	5.2
Diode-Con	37.4	37.3	33.7	34.3	9.9	8.0	10.3	10.3	8.20	8.46	20.4	17.9
Total	98.6	98.4	84.4	84.6	14.4	14.0	48.7	48.7	46.1	46.6	5.4	4.5

The result show that error of the total losses is in the range of 4.5% – 14.4%. Similarly like in the SIMULINK evaluation switching losses show higher errors compared to conduction losses. The errors are generally higher when being compared to the results presented in Section 6.1. This is probably due to the fact, that the parameters of the switch datasheet had to be estimated to be included in the parameter sheet.

7. Conclusion

A python implementation for simulation of standard power electronic converter topologies has been presented. While, several features have been included already, the toolkit is far away from being complete thus also some methods are still marked with to-be-implemented (tbi). New topologies, datasets, features, and functionalities will be successively added in the future. We hope the toolkit is useful to new researcher and students entering the area of power electronics simulation.

8. References

[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] https://de.mathworks.com/help/sps/ug/example-model-single-phase-half-bridge-inverter-ideal-switches-thermal.html

[4] https://plex.infineon.com/plexim/igbtmotor.html?_ga=2.179186855.2048512851.1683139451-1755933514.1675371105