SEMIS Simulation Tool
Single Phase 3-level VSC with IGBT
User manual

INTRODUCTION

SEMIS is a web-based semiconductor simulation tool providing a thermal calculation of the semiconductor losses for common converter circuits. The simulation simplifies significantly the selection of the switching device and enables the optimal selection of semiconductors for further investigations.

The SEMIS Simulation Tool is a user-friendly online application found on ABB Semiconductors website www.abb.com/semiconductors/semis

SEMIS users select from a substantial selection of topologies. By assigning the circuit parameters and selecting the desired switching device, multiple ABB products can be simulated at the same time. Once a simulation is run, SEMIS returns comprehensive results on semiconductor losses as well as on the electrical parameters in the input and output of the circuit. The results are shown in both graphical (waveforms) and numerical (tables) way.

The SEMIS tool is based on the PLECS simulation software. PLECS users can download our product models in the XML file format from the ABB Semiconductors website and use them for their own simulations. For more specific topologies ABB offers customized converter simulations for non-standard topologies with PLECS simulation software on a project basis.

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1. 1 PHASE 3 LEVEL VSC CONVERTER

The use of powerful modular single-phase 3-level Neutral Point Clamped (NPC) converters are very popular and have been used in various grid-tied applications for DC-AC (Inverter) and
AC-DC (Rectifier) operation. Both Rectifier and Inverter operations are very common, which has resulted in the use of new Single-phase 3-level VSC widely in various products, due to the simplicity of its power and control architecture. The VSC rating can be significantly increased with Single-phase 3-level topology when compared to a Single-phase 2-level topology for the same device rating.

The Single-phase 3-level VSC simplifies equipment design, improves response time and reduces losses.

ABB offers the following Single-phase topologies for thermal analysis simulation with

- Single-Phase Two-level VSC with IGBT
- Single-Phase Three-level VSC with IGBT

2. OVERVIEW

Figure 1 Single-Phase 3-Level converter circuit in website

Grid definitions

Converter settings

IGBT selection

Results graphs

Results tables

3. SIMULATION SETTINGS

3.1 Circuit parameters

3.1.1 Converter Operation

Converter Operation	The converter can be operated either as Inverter DC to AC or as Rectifier AC to DC	Selection

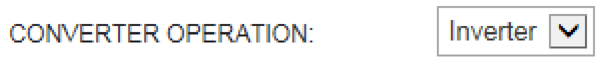

Figure 2 Converter mode selection

3.1.2 Ambient temperature

Ambient temperature	Definition of environmental temperature around the converter for temperature / cooling calculations	Range -25 .. 90 °C

Figure 3 Ambient temperature input block

3.1.3 Controller

The user can define the following parameters as seen in figure 5. The controller generates the switching pulses for the upper and lower IGBTs of the converter.

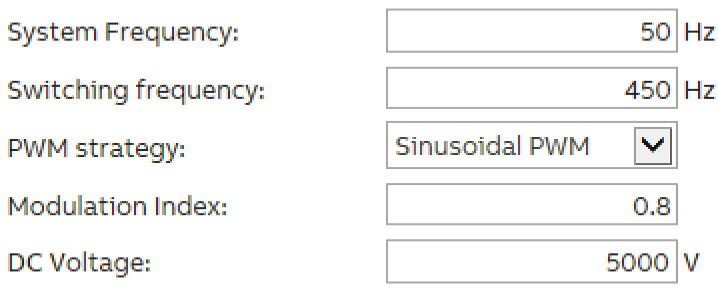

Figure 4 Controller input block

FREQUENCY	Converter AC output frequency	Range 1 to 300 Hz
SWITCHING FREQUENCY	Definition of switching frequency applied for PWM control (Phase-shifted PWM)	Range 200 to 10000 Hz
MODULATION INDEX	Definition of modulation index Over modulation is not possible	Range 0 ... 1
PWM Strategy	Definition of PWM strategy	Selection
DC Voltage	Converter DC Pole-Pole Voltage	Range 100 to 9000 V

3.1.4 Load parameters

The user can enter the desired reference converter AC side current (RMS) or AC power. Further, the user can provide the AC parameters such as power factor and the nature of reactive power to be supplied (Inductive or Capacitive).

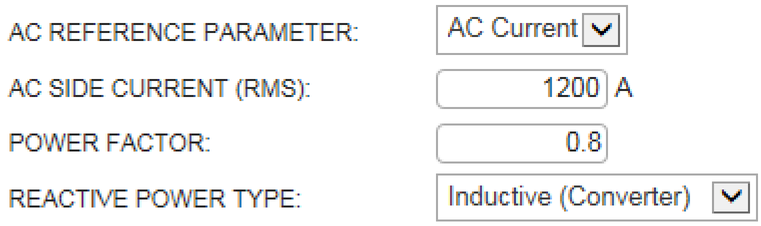

Figure 5 Grid/Load parameter input blocks

AC REFERENCE PARAMETERS	Load Reference can be selected as AC Power when AC Power is the reference AC Current when AC Current (RMS) is the reference	Selection
AC SIDE POWER	AC Side Power demand from the load / connected grid	Range 1 .. 5000 kVA
AC SIDE CURRENT(RMS)	AC Side Current demand from the load/ connected grid	Range 1 .. 5000 A
POWER FACTOR VALUE	Power Factor of the load/ connected grid	Range 0 .. 1
REACTIVE POWER TYPE	The power factor type can be selected as Inductive or Capacitive based on lagging or leading power factor	Selection

3.2 Switch settings

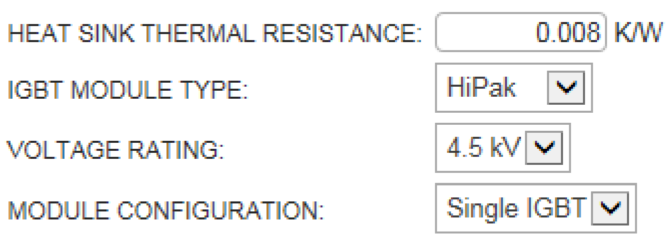

Figure 6 Thermal settings and IGBT selection

Heat Sink Thermal Resistance	Definition of thermal resistance of the cooling system applied.	Range 0.0001 .. 0.5 K/W
Remark:	The value entered is attributed to each individual switch is shown in the electrical configuration schematic of the IGBT module datasheet. Therefore, if a user selects a dual switch module, the Rth should be multiplied with a factor of 2 to differentiate from the single switch case, if the same heatsink would be used in both cases. Same applies for the case of full-bridge modules. The selected Rth is also accounted for the antiparallel diode position for which same consideration applies for its electrical configuration.	

Simulation Settings

IGBT module type	Select housing type of IGBT for filtering	Selection
IGBT selection	Select voltage class of IGBT for filtering	Selection
Module configuration	Select topology of IGBT module for filtering	Selection

3.2.1 Matching IGBTs

Once the previous IGBT properties are selected, the matching IGBT options appear. By clicking on the product code name the user may access the datasheet from the ABB website.

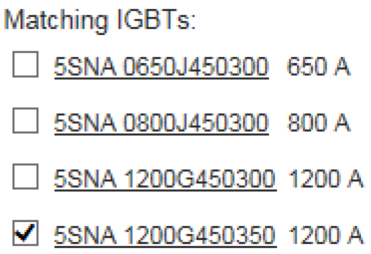

Figure 7 Matching IGBTs for selection

Up to 4 elements can be selected simultaneously and simulated. If one or more elements produce results exceeding the safe operating area (SOA), no results are returned. In this case, the user should run the simulation again with changed parameters and/or product selection to enable results within SOA operating conditions.

3.2.2 Matching NPC Diodes

Once the IGBT is selected, the user can select the matching NPC Clamp Diode based on the voltage and current ratings. By clicking on the product code name the user may access the datasheet from the ABB website.

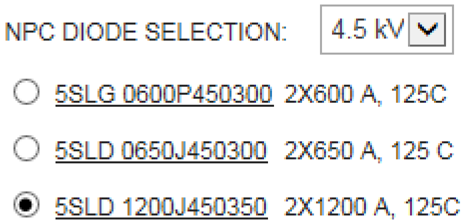

Figure 8 Matching NPC Diodes for selection

3.3 Selection of Articles / Start simulation

To simulate one or more articles, select from the list by activating the checkbox

Simulate	Starts the simulation The progress of the simulation is shown with the number of calculated Jacobian.
Abort	Stops the simulation; No results generated
Hold results	To compare multiple simulations, results can be held for later viewing By selecting the button, result are hold after the simulation has finalized for later comparison with succeeding simulations

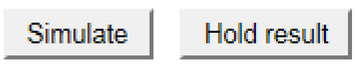

Figure 9 Start of simulation

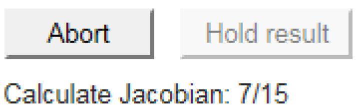

Figure 10 Simulation progress and termination

4. SIMULATION RESULTS

The simulation results are displayed in two different ways for all selected articles simulated.

Graphical results - Waveforms	Visual analysis of waveforms for fast and efficient detection of most significant sources
Numerical / Tabular results	Numeric indication of all simulations values for direct comparison

Remark: To hide curves of selected articles, unselect in the table “Results History”

4.1 Graphical Output – Waveforms

When the simulation finishes the semiconductor and AC side waveforms are shown as follows:

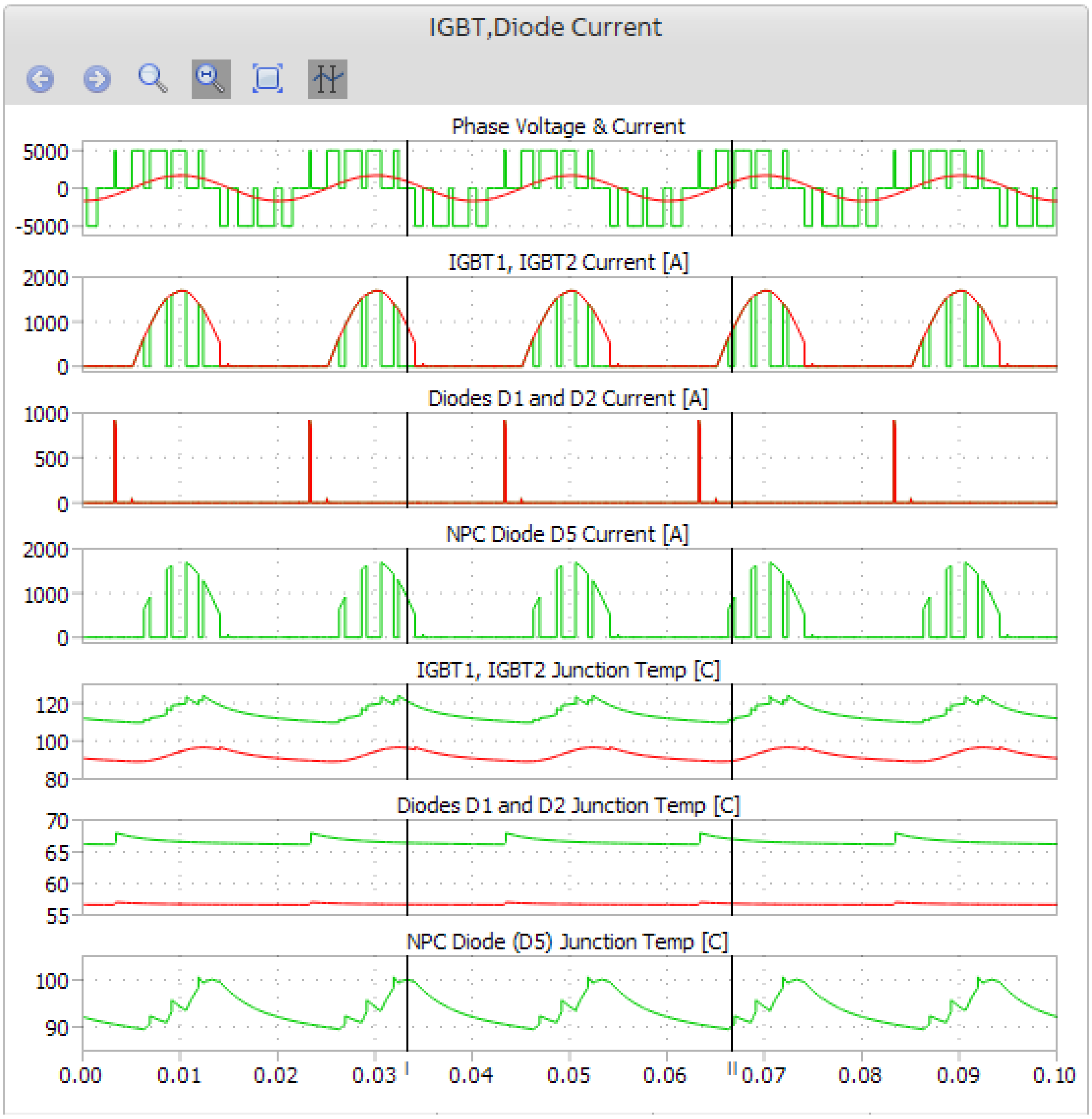

Figure 11 Graphical results of Single-phase 3-level VSC converter

4.1.1 Control

For an indication of values within the graph, a cursor can be activated to show curve values in a table.

Sections of graphs can be zoomed in by click, move and release mouse button for more details

Hold result — Hide selectively waveforms of products

Rest zoom to full view

Activate cursors and to show parameter values table according to the cursor position

Zoom selectable rectangle

Zoom horizontal or vertical band

4.1.2 Parameters values indication

Tabular indication of graphical waveforms values according to cursor position selected.
Values are indicated for each parameter. Color of the waveform is indicated. The third column shows the difference between the two cursors per parameter.

Time	0.033333	0.066667	0.033333
Phase Voltage & Current			
Phase Voltage-A	0.000	0.000	0.000
Phase Current-A	900.6	799.1	101.5
IGBT1, IGBT2 Current [A]			
IGBT currents (a):1	0.000	0.000	0.000
IGBT currents (a):2	900.6	799.1	101.5
Diodes D1 and D2 Current [A]			
Diode currents (a):1	0.000	0.000	0.000
Diode currents (a):2	0.000	0.000	0.000
NPC Diode D5 Current [A]			
Diode currents (a):5	900.6	799.1	101.5
IGBT1, IGBT2 Junction Temp [C]			
IGBT junction temp (a):1	120.9	111.2	9.740
IGBT junction temp (a):2	96.23	89.33	6.900
Diodes D1 and D2 Junction Temp [C]			
Diode junction temp (a):1	66.43	67.02	-0.5938
Diode junction temp (a):2	56.65	56.78	-0.1348
NPC Diode (D5) Junction Temp [C]			
Diode junction temp (a):5	100.1	90.09	10.01

Figure 12 Tabular indication of cursor position graph values

Remark:
The numerical values each indicated parameter are shown according to the position of the respective cursor in the graph. Drag cursor to investigate about full details

4.2 Numerical / Tabular results

The following parameters are given in a tabular format in multiple sections.

The indicated elements in the table upper IGBT etc. correspond to the different semiconductor positions in a full-bridge cell as shown in power circuit.

As converter losses, the aggregated losses in all 3 phase legs are accounted for.

In addition to the semiconductor losses, there are also losses occurring in the passive components (e.g. Resistances, grid-impedances, etc.). These Losses are not taken into consideration for this simulation. For the simplicity of the simulation, it is assumed that all semiconductors in one phase leg are loaded symmetrically and no voltage asymmetries do exist.

Device losses and temperatures

Device Losses & Temperatures						
	Switching	Conduction	Combined Losses	TvjAvg	TvjMax	TvjBLS
IGBT1	1.724 kW	1.064 kW	2.788 kW	114.75 °C	124.06 °C	121.39 °C
IGBT2	134.11 W	1.828 kW	1.962 kW	92.26 °C	96.71 °C	96.56 °C
D1	73.18 W	22.02 W	95.20 W	66.59 °C	67.98 °C	66.33 °C
D2	0 W	21.92 W	21.92 W	56.69 °C	57.00 °C	56.75 °C
NPC D5	333.60 W	858.28 W	1.192 kW	93.71 °C	100.67 °C	95.73 °C
Converter Losses	8.70 kW	15.21 kW	23.91 kW			
% Losses			0.87 %			

Figure 13 Device Losses & Temperatures

Switching Loss — Single IGBT, Diode or Clamp Diode Losses during turn on and turn off events (dynamic)

Conduction loss — Single IGBT, Diode or Clamp Diode Losses during on state (static)

Combined losses — Sum of single IGBT, Diode or Clamp Diode switching and conduction loss.

Converter losses — Sum of all IGBT, Diode and Clamp Diode losses

% Losses — Defined as the (%) ratio of calculated combined converter losses with respect to the converter MVA rating i.e., total apparent power flow. Since the converter is meant for a SINGEL-PHASE application, the kVA rating would correspond to total single-phase AC Power delivered by the converter.

Junction Temperature Avg — Junction temperature average during the simulation period

Junction Temperature Max — Maximum junction temperature during the simulation period

Junction Temperature BLS

Junction temperature at the time point just before the last switching, after which the maximum junction temperature is achieved

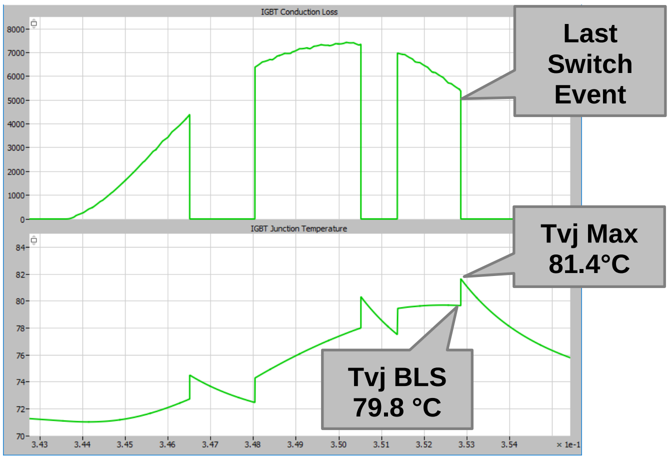

Figure 14 Definition of Tvj before the last switch

Converter AC parameters

Converter AC Parameters						
	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency	Power Factor
	2715 kW	2036 kVAR	2.828 kV	1.200 kA	50 Hz	0.80

Figure 15 Converter AC Parameters

Real power P Active power / real power output of the converter

Reactive power Q Q as supplied to the grid as effective power (reactive) on converter AC side Calculation see in section 6.4.

Phase voltage RMS According AC phase value according 1st order harmonics of AC frequency

Phase current RMS According AC phase value according 1st order harmonics of AC frequency

Output frequency According to the definition

DC Parameters & Control Parameters

DC Parameters & Control Parameters				
	DC Power	DC Voltage	Switching Frequency	Modulation Index
	2739 kW	5.000 kV	450 Hz	0.80

Figure 16 Control Parameters

DC Power According AC Power/Current definition + Losses

DC Voltage According definition

Switching Freq. According to the definition

Modulation Ind. According to calculations defined in chapter **Error! Reference source not found.**

5. ALERTS & FEATURES

The system verifies results and generated warning messages in case of limits are violated.

5.1 Junction Temperature

Parameter	Junction temperature
Verification	If the junction temperature BLS of IGBT and/or diode is above its maximum junction temperature limit, alert message is displayed
Warning message	IGBT temperature out of safe operating area

5.2 DC Voltage

Parameter	DC Voltage
Verification	If the DC voltage is greater than safe operating voltage rating of IGBT and/or diode, alert message is displayed
Warning message	For 3.3kV IGBT Vdcmin = 200V & Vdcmax = 2600V NPC Diode – For 3.3kV Diode Vdcmin = 200V & Vdcmax = 2600V

6. APPLIED CALCULATIONS

6.1 Input Parameter Definitions

PF	User defined load parameter / power factor corresponding to the desired angle between fundamental components of phase voltage and current (Cos φ_1)
V_{DC}	Selected DC link voltage
V_{Ph_RMS}	Fundamental Phase voltage RMS
I_{Ph_RMS}	Fundamental Phase current RMS

6.2 Fundamental Phase Voltage RMS of Converter Definition

$$V_{Ph\_RMS} = \frac{m * V_{DC\,Link}}{\sqrt{2}}$$

6.3 Real Power

P_{DC} P_{AC}	DC power / real power absorbed from DC side of VSC calculated according real / active power transferred to converter output calculated as:
$V_{TrueRMS}$	True phase voltage RMS AC
$I_{TrueRMS}$	True phase current RMS AC
η	Power conversion efficiency

$$V_{trueRMS} = \sqrt{\sum_{v=1}^{n} \widehat{u_v^2}}$$

It includes all harmonic components <u>NOT ONLY</u> 1st order of output frequency.

$$I_{trueRMS} = \sqrt{\sum_{v=1}^{n} \widehat{i_v^2}}$$

It includes all harmonic components <u>NOT ONLY</u> 1st order of output frequency.

According to:

$$P_{AC} = \sum_{v=1}^{n} \widehat{u_v} \, . \, \widehat{i_v} . \cos \varphi_v$$

If current/voltage is free from harmonics, then

$$P_{AC} = V_{Ph\_RMS} . I_{Ph\_RMS} . PF$$

For Inverter mode, the DC power definition P_{DC} can be computed as

$$P_{DC} = P_{AC} + P_{LossConverter}$$

For Rectifier mode, the DC power definition P_{DC} can be computed as

$$P_{DC} = P_{AC} - P_{LossConverter}$$

Defined as the Loss (%) η is the ratio of calculated combined converter losses with respect to the converter input power.
For Inverter mode, the P_{DC} is the main input power definition. Loss (%) η is given by:

$$\eta = \frac{P_{LossConverter}}{P_{DC}} * 100\%$$

For Rectifier mode, the P_{AC} is the main input power definition. Loss (%) η is given by:

$$\eta = \frac{P_{LossConverter}}{P_{AC}} * 100\%$$

6.4 Reactive Power

Q Effective reactive power on converter AC side [VAr]

$$Q = \sum_{\nu=1}^{n} \widehat{u_\nu} \, . \, \widehat{\iota_\nu} . \sin \varphi_\nu$$

If current/voltage is free from harmonics, then

$$Q = V_{Ph\_RMS} . I_{Ph\_RMS} . \sin \varphi_1$$

7. VALIDATION OF SEMIS RESULTS WITH PSCAD

To ensure supplied simulation results are reliable, each SEMIS topology is validated with another simulation system or compared to real measurement data.

The circuit topology is reconstructed in PSCAD to validate the results obtained from the SEMIS web simulation tool. The objective of the work is to develop an open-loop, grid-connected, single-phase three-level VSC simulation model with loss and temperature estimation in PSCAD and to validate the steady-state results obtained through SEMIS-9 web simulation model using sinusoidal pulse-width modulation.

The IGBT and Diode XML data which was created from the device datasheets for SEMIS simulations is modified to individual .txt files for switch turn-on energy (E_{on}), switch turn-off energy (E_{off}), diode reverse recovery energy (E_{rec}), on-state voltage drop of IGBT (V_t), and on state voltage drop of diode (V_d) at different temperatures, to make the data readable in PSCAD.

The PSCAD and SEMIS circuit models are made as identical as possible to prevent any errors in validation due to the dissimilarities. Junction to Case and Case to Heat sink thermal resistances for the IGBT and Diode have been captured from the device datasheet while the Heat sink to ambient thermal resistance $R_{th(h-a)}$ is assumed as 2K/kW with different ambient temperatures.

Five cases are simulated in PSCAD and SEMIS by varying different parameters like DC Voltage, Switching Frequency, System Frequency, Power Factor, Modulation Index, etc. with the electrical parameters presented in the tables below for comparison. The chosen operating modes cover all the possible combinations of rectifier, inverter, leading power factor, lagging power factor.

It was observed that the difference between the electrical parameters is minimal even after the variations in the operating conditions. It was also observed from the switching, conduction, total converter losses and the device junction temperatures that the results obtained from both SEMIS and PSCAD are very similar and the error percentage is within tolerance (<5%). Therefore, it can be concluded that the results obtained from the SEMIS web simulation tool are reliable.

Results analysis according settings

Topology	**SEMIS 9 Single phase three-level VSC with IGBT**
Tester:	**Tirthasarathi Lodh, Harshavardhan Marabathina**
Date	**February 11, 2019**
Instructions	1. Enter all values according the final results table in the column SEMIS 2. Enter all values according the final results from the PSCAD in the column PSCad 3. Verify the relative difference; Results must not vary more than 2 %

Parameter	**Set 1 SEMIS**	**Set 1 PSCad**	**Set 1 Difference**	**Set 2 SEMIS**	**Set 2 PSCad**	**Set 2 Difference**	**Set 3 SEMIS**	**Set 3 PSCad**	**Set 3 Difference**	**Set 4 SEMIS**	**Set 4 PSCad**	**Set 4 Difference**	**Set 5 SEMIS**	**Set 5 PSCad**	**Set 5 Difference**
Average difference [%]			0.32%			0.22%			0.34%			0.33%			0.16%
Max difference [%]			1.72%			1.30%			1.56%			2.37%			1.02%
Device Losses & Temperatures															
Switching Losses IGBT 1 (W)	2994	2980	0.47%	2889	2874	0.52%	1635	1629	0.37%	913	912	0.11%	273	273	0.00%
Switching Losses IGBT 2 (W)	680	676	0.59%	304	303	0.33%	404	404	0.00%	5119	5106	0.25%	8620	8569	0.59%
Switching Losses Diode 1 (W)	146	146	0.00%	73	73	0.00%	107	106	0.93%	993	979	1.41%	1842	1824	0.98%
Switching Losses Diode 2 (W)	0	0	0.00%	0	0	0.00%	0	0	0.00%	0	0	0.00%	0	0	0.00%
Switching Losses NPC Diode 5 (W)	601	601	0.00%	619	616	0.48%	384	378	1.56%	253	247	2.37%	61	61	0.00%
Conduction Losses IGBT 1 (W)	1310	1301	0.69%	1183	1172	0.93%	904	892	1.33%	141	140	0.71%	6	6	0.00%
Conduction Losses IGBT 2 (W)	2288	2285	0.13%	2115	2108	0.33%	2563	2547	0.62%	1956	1923	1.69%	679	673	0.88%
Conduction Losses Diode 1 (W)	58	57	1.72%	28	28	0.00%	121	120	0.83%	1527	1518	0.59%	1212	1204	0.66%
Conduction Losses Diode 2 (W)	58	57	1.72%	28	28	0.00%	121	121	0.00%	1532	1528	0.26%	1211	1209	0.17%
Conduction Losses NPC Diode 5 (W)	940	935	0.53%	918	915	0.33%	1501	1492	0.60%	1465	1463	0.14%	665	666	-0.15%
Combined Losses IGBT 1 (W)	4305	4281	0.56%	4071	4046	0.61%	2539	2522	0.67%	1055	1052	0.28%	280	280	0.00%
Combined Losses IGBT 2 (W)	2968	2961	0.24%	2419	2411	0.33%	2967	2951	0.54%	7075	7028	0.66%	9299	9242	0.61%
Combined Losses Diode 1 (W)	204	203	0.49%	102	101	0.98%	228	226	0.88%	2521	2497	0.95%	3054	3028	0.85%
Combined Losses Diode 2 (W)	58	57	1.72%	28	28	0.00%	121	121	0.00%	1532	1528	0.26%	1211	1209	0.17%
Combined Losses NPC Diode 5 (W)	1541	1536	0.32%	1537	1531	0.39%	1885	1871	0.74%	1717	1710	0.41%	665	666	-0.15%
Junction Temperature Avg IGBT (°C)	66	66	0.00%	64	64	0.00%	55	55	0.00%	36	36	0.00%	33	33	0.00%
Junction Temperature Avg IGBT 2 (°C)	58	58	0.00%	54	54	0.00%	58	58	0.00%	70	70	0.00%	82	82	0.00%
Junction Temperature Avg Diode 1 (°C)	51	51	0.00%	49	49	0.00%	47	47	0.00%	51	51	0.00%	55	55	0.00%
Junction Temperature Avg Diode 2 (°C)	46	46	0.00%	45	45	0.00%	47	47	0.00%	54	54	0.00%	55	55	0.00%
Junction Temperature Avg NPC Diode 5 (°C)	55	55	0.00%	55	55	0.00%	58	58	0.00%	41	41	0.00%	31	31	0.00%
Converter Losses (W)	36300	36154	0.40%	32632	32467	0.51%	30961	30761	0.65%	55598	55260	0.61%	58038	57698	0.59%
Losses Efficiency	1.34	1.34	0.00%	0.77	0.76	1.30%	3.9	3.89	0.26%	1.38	1.37	0.72%	0.98	0.97	1.02%
AC Parameters															
Real Power (kW)	2663	2664	-0.04%	4219	4214	0.12%	762.5	760	0.33%	-4016	-4025	-0.22%	-5951	-5960	-0.15%
Reactive Power (kVAR)	2664	2647	0.64%	3164	3169	-0.16%	-1286	-1285	0.08%	-5354	-5363	-0.17%	2882	2897	-0.52%
Phase Voltage RMS (V)	1909	1907	0.10%	2828	2826	0.07%	693	693	0.00%	2545	2546	-0.04%	3818	3824	-0.16%
Phase Current RMS (V)	1973	1973	0.00%	1865	1865	0.00%	2158	2154	0.19%	2630	2632	-0.08%	1732	1732	0.00%
Output Frequency (Hz)	50	50	0.00%	25	25	0.00%	50	50	0.00%	40	40	0.00%	50	50	0.00%
Power Factor	0.707	0.707	0.00%	0.8	0.8	0.00%	-0.5	-0.5	0.00%	-0.6	-0.6	0.00%	0.9	0.9	0.00%
DC Parameters & Control Parameters															
DC Power (kW)	2699	2700	-0.04%	4252	4247	0.12%	793.5	791	0.32%	-3960	-3970	-0.25%	-5893	-5902	-0.15%
DC Voltage (V)	3000	3000	0.00%	5000	5000	0.00%	1400	1400	0.00%	4000	4000	0.00%	6000	6000	0.00%
Switching Frequency (Hz)	900	900	0.00%	500	500	0.00%	1000	1000	0.00%	800	800	0.00%	1200	1200	0.00%
Modulation Index	0.9	0.9	0.00%	0.8	0.8	0.00%	0.7	0.7	0.00%	0.9	0.9	0.00%	0.9	0.9	0.00%

Figure 17 Validation SEMIS / PSCAD results comparison 3 levels 1 phase

8. USER MANUAL REVISION HISTORY

Rev.	Page	Change Description	Date / Initial
1.4	12, 13	Power Definitions	2021-12-07 PGGI/HM
1.3	all	DC Voltage Definition change	2020-03-04 PGGI/HM
1.2	all	Initial version in new design	2019-09-03 PGGI/DS

9. SIMULATION SOFTWARE RELEASE HISTORY

Rev.	New topic	Fixed defects	Tvj influence	Date
1.3	THD of voltage & current measurement	-	No	2021-12-07 PGGI/HM
1.2	Averaging time period is equal to gcd of system and switching frequencies	-	No	2020-06-29 PGGI/HM
1.1	DC Voltage to 2 DC sources	-	No	2020-03-04 PGGI/HM

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