SEMIS Simulation Tool
Three Phase 2-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 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 substantial selection of topologies. With 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. 3 PHASE 2 LEVEL VSC CONVERTER

The use of powerful modular three-phase 2-level VSC converters are very popular and have been used in various grid-tied applications for DC-AC (Three-phase Inverter) and AC-DC (Three-phase Rectifier) operation. Both Three-phase Rectifier and Inverter operations are very common and this has resulted in the use of new Three-phase 2-level VSC widely in various products, due to the simplicity of its power and control architecture.

The three-phase 2-level VSC simplifies equipment design, improves response time and reduces losses.

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

- Three-Phase Two-level VSC with IGBT
- Three-Phase Three-level VSC with IGBT (NPC, TNPC, ANPC)
- Three-Phase Three-level VSC with IGCT (NPC, TNPC, ANPC)
- Three-Phase Three-level VSC with IGBT Half-Bridge MMC
- Three-Phase Three-level VSC with IGCT Half-Bridge MMC
- Three-Phase Three-level VSC with Full Bridge MMC
- Three-Phase Three-level VSC FACTS with IGBT Full Bridge
- Three-Phase Three-level VSC FACTS with IGCT Full Bridge

2. OVERVIEW

Figure 1 Three-Phase 2-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	Converter can be operated either as Inverter DC to AC or as Rectifier AC to DC	Selection

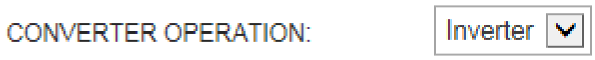

Figure 2 Converter mode selection

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 4 . The controller generates the switching pulses for the upper and lower IGBTs of the converter.

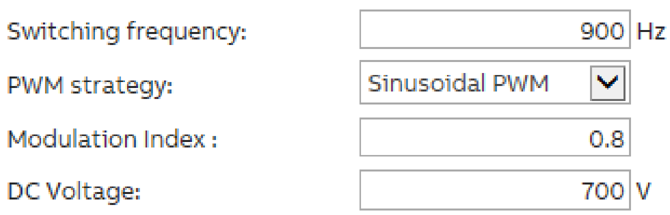

Figure 4 Controller input block

FREQUENCY	Converter AC output frequency	Range 12 to 100 Hz
SWITCHING FREQUENCY	Definition of switching frequency applied for PWM control (Phase-shifted PWM)	Range 200 to 5000 Hz
PWM Strategy	Definition of PWM strategy Three different Control methods are implemented, which are Sinusoidal PWM, Space Vector PWM and Third Harmonic Injection. Find technical background and explanations in Chapter 5	Selection
MODULATION INDEX	Definition of modulation index Sinusoidal PWM limit is 1.00 Space Vector PWM limit is 1.15 3rd Harmonic injection limit is 1.15	Range 0 .. 1 (1.15)
DC Voltage	Converter DC Pole-Pole Voltage	Range 100 to 4500 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).

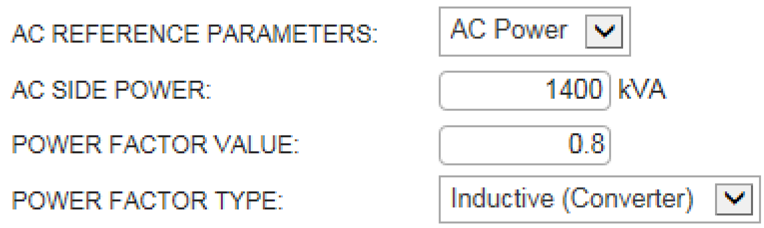

Figure 5 Grid/Load parameter input blocks

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 .. 4000 A
POWER FACTOR VALUE	Power Factor of the load/ connected grid	Range 0 .. 1
POWER FACTOR TYPE	The power factor type can be selected as Inductive or Capacitive based on lagging or leading power factor	Selection

3.2 Switch settings

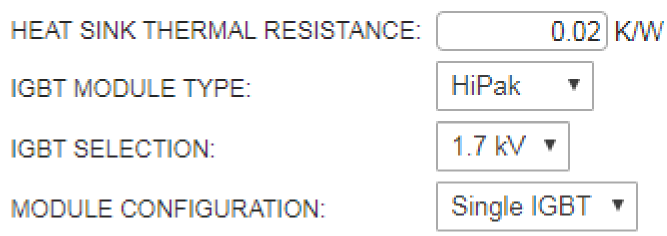

Figure 6 Thermal settings and IGBT selection

Heat Sink Thermal Resistance	Definition of thermal resistance of cooling system applied.	Range 0.0001 .. 0.5 K/W
Remark:	Include the thermal resistance of case to heatsink to ensure correct simulation results. The value entered is attributed to each individual switch shown in the electrical configuration schematic of the IGBT module data sheet. Therefore, if user selects a dual switch module, the Rth should be multiplied	

	with a factor of 2 to differentiate from the single switch case, if 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.	
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 data sheet from the ABB website.

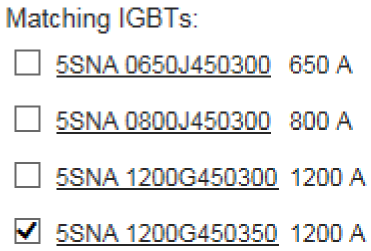

Figure 7 Matching IGBTs for selection

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.

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

Figure 8 Start of simulation

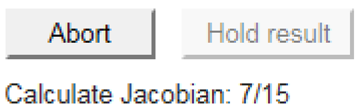

Figure 9 Simulation progress and termination

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:

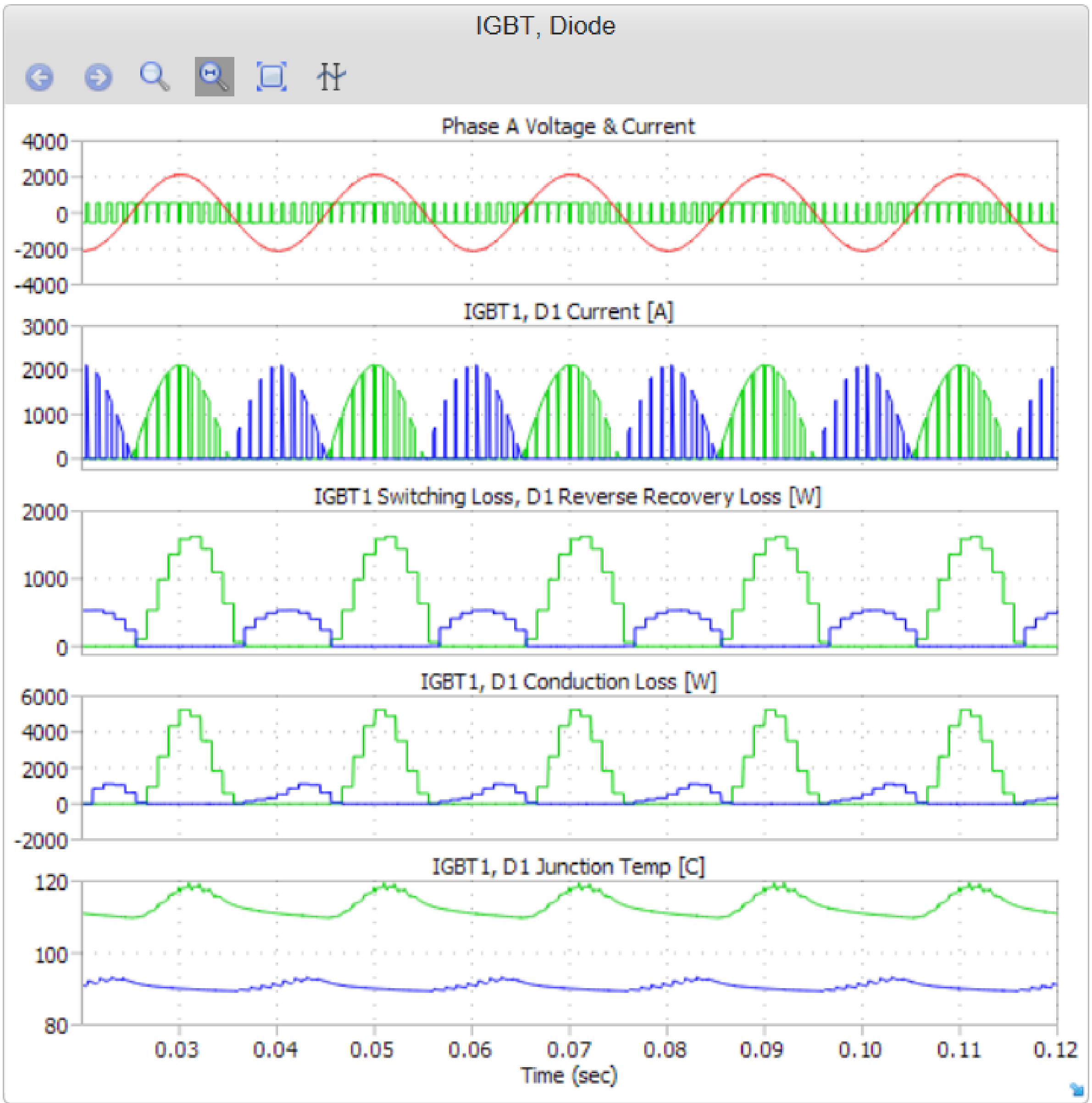

Figure 10 Graphical results of Three-phase 2-level VSC converter

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 wave forms values according cursor position selected.
Values are indicated for each parameter Color of wave form is indicated. Third column shows difference of two cursors per parameter.

Name	Cursor 1	Cursor 2	Delta
Time	0.050242	0.080315	0.030073
Phase A Voltage & Current			
Phase Voltage-A	708.4	-366.7	1075
Phase Current-A	2121	-2115	4236
IGBT1, D1 Current [A]			
IGBT current	2121	0.000	2121
Diode current	0.000	0.000	0.000
IGBT1 Switching Loss, D1 Reverse Recovery Loss [W]			
IGBT Switching Loss	1583	0.000	1583
Diode Reverse Recovery Loss	0.000	530.4	-530.4
IGBT1, D1 Conduction Loss [W]			
IGBT Conduction Loss	5230	0.000	5230
Diode Conduction Loss	0.000	529.5	-529.5
IGBT1, D1 Junction Temp [C]			
IGBT Junction Temperature	118.0	111.0	7.062
Diode Junction Temperature	90.11	90.87	-0.7623

Figure 11 Tabular indication of cursor position graph values

Remark:
The numerical values of each indicated parameter are shown according 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.

All calculations and simulation results are based on datasheet typical values.

All types of semiconductor losses are calculated according to PLEXIM PLECS software principle through reference of look up table and linear interpolation of the actual device current, voltage and junction temperature

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
per IGBT	523.52 W	1.333 kW	1.857 kW	113.14 °C	119.49 °C	118.36 °C
per Diode	188.57 W	272.65 W	461.23 W	90.75 °C	93.36 °C	92.64 °C
Converter Losses	4.27 kW	9.63 kW	13.91 kW			
% Losses			1.23 %			

Figure 12 Device Losses & Temperatures

Switching Loss	Single IGBT or Diode Losses during turn on and turn off events (dynamic)
Conduction loss	Single IGBT or Diode Losses during on state (static)
Combined losses	Sum of single IGBT or Diode switching and conduction loss.
Converter losses	Sum of all IGBT and 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 THREE-PHASE application, the kVA rating would correspond to total three-phase AC Power delivered by the converter.

Junction Temperature Avg

Junction temperature average during the simulation period

Junction Temperature Max

Maximum junction temperature during simulation period

Junction Temperature BLS

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

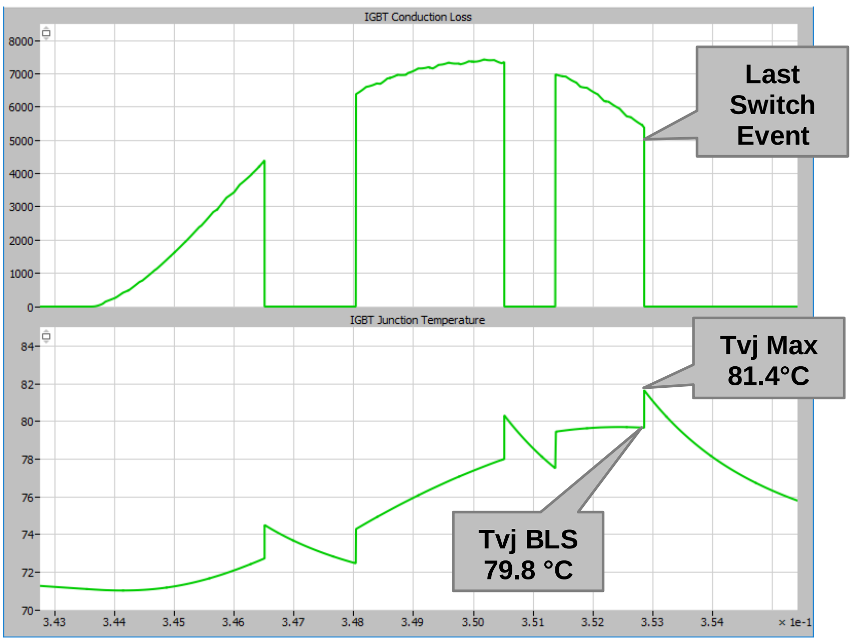

Figure 13 Definition of Tvj before last switch

Converter AC parameters

Simulation Results

AC Parameters						
	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency	Power Factor
	1.120 kkW	840.1 kVAR	311 V	1.500 kA	50 Hz	0.80

Figure 14 Converter AC Parameters

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

Reactive power Q — Q as supplied to grid as effective power (reactive) on converter AC side Calculation see in section 7.4.

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

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

Output frequency — According definition

DC Parameters & Control Parameters

DC Parameters & Control Parameters				
	DC Power	DC Voltage	Switching Frequency	Modulation Index
	1.134 kkW	1.100 kV	900 Hz	0.80

Figure 15 Control Parameters

DC Power — According AC Power/Current definition + Losses

DC Voltage — According definition

Switching Freq. — According definition

Modulation Ind. — According calculations defined in chapter 7.1

5. EFFICIENCY IMPROVEMENTS BY CONTROL STRATEGY

In some applications where higher output voltage and lower switching losses/harmonic distortion factor are required, standard Sinusoidal PWM(SPWM) technique is not capable of meeting these requirements and it is necessary to use other PWM techniques like Third Harmonic Injection PWM (THIPWM) and Space Vector PWM (SVPWM). Both THIPWM and SVPWM work on the principle of Zero Sequence Injection and both can operate at a maximum modulation index of 1.15, whereas the maximum modulation index of 1 applies for SPWM technique. Therefore, THIPWM and SVPWM techniques can produce 15% more maximum output AC voltage with lower switching losses for the same input DC voltage when compared to SPWM. But to realize this advantage, a floating neutral system (Delta load or Star Load with no neutral return) is necessary. Floating neutral prevents Zero Sequence currents (which includes DC and Integer multiples of 3rd harmonic Currents) from flowing as they see a high impedance path. Therefore, sinusoidal waveshape in the output voltage and current is retained even with the injection of Zero Sequence components on the input side. Since the maximum modulation is increased to 1.15, the output voltage and power for THIPWM and SVPWM techniques is increased by 15% for the same output AC side reference current.

Find in Figure 16 Results diagram comparison of control strategies below the direct comparison of the three control strategies and the influences on the various parameters with the 3 phase 2 level topology. Only adaption is the selection of the PWM and the setting to the maximum value of the modulation index. It is observed from the results, that THIPWM and SVPWM can transmit higher amounts of power and result in lower %losses compared to SPWM, while the junction temperature rise is similar for all three techniques.

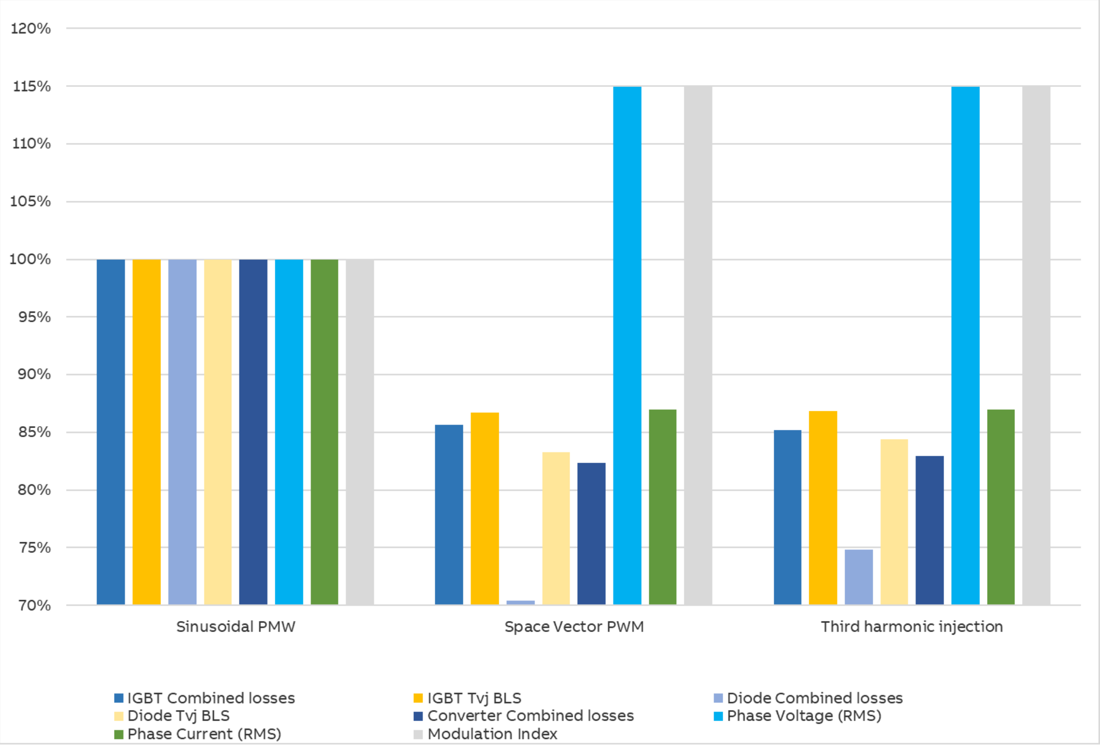

Figure 16 Results diagram comparison of control strategies

PWM	IGBT Loss [W]	IGBT Tvj [°C]	Diode Loss [W]	Diode Tvj [°C]	Losses [kW]	Losses [%]	Ph Volt [V]	Ph I [A]	Mod Index [1]
Sinusoidal	1960	110.74	539	92.3	14.99	1.84	354	943	1
Space vector	1679	95.99	379	76.88	12.35	1.52	407	820	1.15
3rd harmonic	1670	96.17	403	77.87	12.44	1.53	407	820	1.15

Figure 17 Results table comparison of control strategies

6. ALERTS & FEATURES

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

6.1 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

6.2 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 the voltage rating 1.7kV, Vdcmin = 200V & Vdcmax = 1100V

7. APPLIED CALCULATIONS

7.1 Input Parameter Definitions

PF	User defined load parameter / power factor corresponding to the desired angle between fundamental components of phase voltage and current (Cos ∂)
V_{DC}	Selected DC link voltage
$V_{Ph\_AC\_RMS}$	Phase voltage RMS
$I_{Ph\_AC\_RMS}$	Phase current RMS

7.2 Phase RMS Voltage of Grid/Load Definition

$$V_{PhRMS} = \frac{m * V_{DC\ Link}}{2\sqrt{2}}$$

7.3 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 line to neutral
$I_{TrueRMS}$	True phase current RMS AC
η	Power conversion efficiency

$$P_{DC} = V_{DC} * I_{DC}$$

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

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

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

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

According to:

$$P_{AC} = \frac{3}{n} \sum_{v=1}^{n} \widehat{u_v} \,.\, \widehat{\iota_v} . \cos \varphi_v = 3. V_{trueRMS} . I_{trueRMS} . PF$$

For Inverter or 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:

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

7.4 Reactive Power

Q	Effective reactive power on converter AC side [VAr] $Q = 3 * V_{Ph\_RMS} * I_{Ph\_RMS} * sin(\varphi_1)$
V_{PH_RMS}	Phase voltage (RMS)
I_{PH_RMS}	Phase current (RMS)
ρ_1	Fundamental power factor angle

8. 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, three-phase two-level VSC simulation model with loss and temperature estimation in PSCAD and to validate the steady-state results obtained through SEMIS-4 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 SEMIS web simulation tool are reliable.

Results analysis according settings

Topology	**SEMIS 4 Three phase two-level VSC with IGBT**
Tester:	**Tirthasarathi Lodh, Harshavardhan Marabathina**
Date	**February 8, 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 [%]			0.05%			0.16%			0.37%			0.22%			0.31%
Max difference [%]			0.49%			0.87%			1.41%			1.76%			1.73%
Device Losses & Temperatures															
Switching Losses IGBT 1 (W)	3775	3761	0.37%	3269	3252	0.52%	2091	2077	0.67%	6431	6419	0.19%	9095	9049	0.51%
Switching Losses Diode 1 (W)	824	825	-0.12%	743	741	0.27%	489	484	1.02%	1492	1478.5	0.90%	2267	2249	0.79%
Conduction Losses IGBT 1 (W)	1858	1866	-0.43%	1717	1702	0.87%	1770	1745	1.41%	1110.5	1091	1.76%	347	341	1.73%
Conduction Losses Diode 1 (W)	531.5	529	0.47%	493	491	0.41%	876	871	0.57%	2411.5	2407	0.19%	1566	1559	0.45%
Combined Losses IGBT 1 (W)	5634	5628	0.11%	4986	4954	0.64%	3862	3822	1.04%	7541	7510	0.41%	9442	9390	0.55%
Combined Losses Diode 1 (W)	64	64	0.00%	1236	1232	0.32%	1365	1355	0.73%	3904	3886	0.46%	3833	3807	0.68%
Junction Temperature Avg IGBT 1 (°C)	76	76	0.00%	72	72	0.00%	65.5	65	0.76%	92	92	0.00%	88.5	88	0.56%
Junction Temperature Avg Diode 1 (°C)	64	64	0.00%	62	62	0.00%	61	61	0.00%	92	92	0.00%	80	80	0.00%
Converter Losses (W)	41935	41892	0.10%	37336	37117	0.59%	31361	31061	0.96%	68672	68375	0.43%	79650	79186	0.58%
Losses Efficiency	2.06%	0.0205	0.49%	1.16%	1.16%	0.00%	5.20%	5.15%	0.96%	2.28%	2.26%	0.88%	1.79%	1.78%	0.56%
AC Parameters															
Real Power (kW)	1997	2004	-0.35%	3171	3176	-0.16%	572	572	0.00%	-3012	-3027	-0.50%	-4462	-4456	0.13%
Reactive Power (kVAR)	1998	1998	0.00%	2379	2382	-0.13%	-964	-967	-0.31%	-4015	-4012	0.07%	2161	2169	-0.37%
Phase Voltage RMS (V)	477	476	0.21%	707	707	0.00%	173	174	-0.58%	636	633	0.47%	954	954	0.00%
Phase Current RMS (V)	1973	1978	-0.25%	1869	1869	0.00%	2157	2154	0.14%	2630	2637	-0.27%	1731	1734	-0.17%
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%	-0.51	-0.51	0.00%	-0.6	-0.6	0.00%	0.9	0.9	0.00%
DC Parameters & Control Parameters															
DC Power (kW)	2039	2031	0.39%	3209	3213	-0.12%	603	603	0.00%	-2943	-2958	-0.51%	-4382	-4376	0.14%
DC Voltage (V)	1500	1500	0.00%	2500	2500	0.00%	700	700	0.00%	2000	2000	0.00%	3000	3000	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 18 Validation SEMIS / PSCAD results comparison 2 level 3 phase

9. USER MANUAL REVISION HISTORY

Rev.	Page	Change Description	Date / Initial
1.3	all	DC voltage definition change	2020-03-04 PGGI/HM
1.2	all	Initial version in new design	2019-08-22 PGGI/DS

10. SIMULATION SOFTWARE RELEASE HISTORY

Rev.	New topic	Fixed defects	Tvj influence	Date
1.2	Averaging time period is equal to gcd of system and switching frequencies	-	No	2020-05-21 PGGI/HM
1.1	DC Voltage to 2 DC sources	-	No	2020-03-04 PGGI/HM

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