SEMIS Simulation Tool

Three 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 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 can select from a 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 3 LEVEL VSC CONVERTER

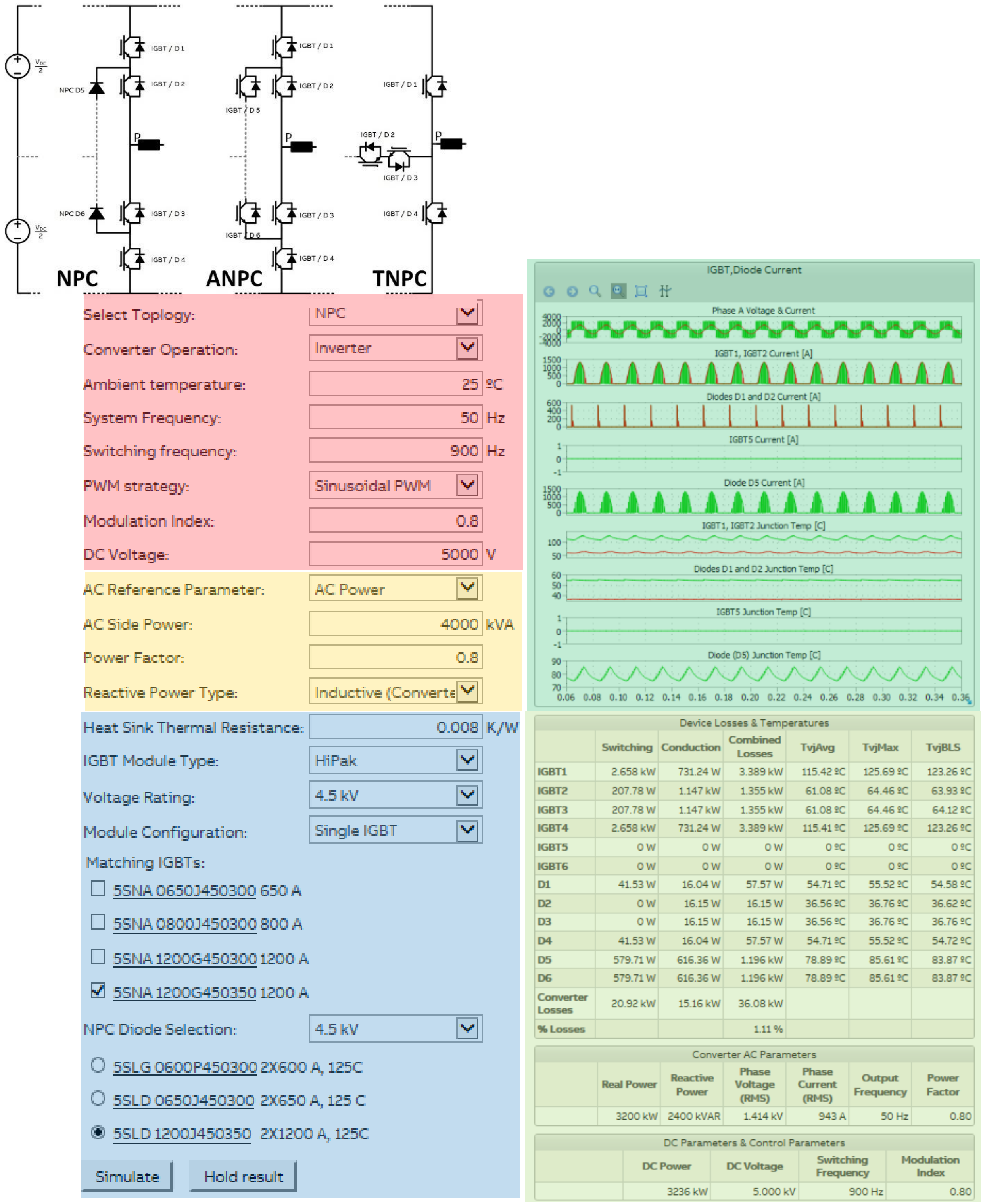
The use of powerful modular three-phase 3-level VSC converters are very popular and have been used in various grid-tied applications for DC-AC (Three-phase Inverter) and AC-DC (Three-phase Rectifier) operation. Both Three-phase Rectifier and Inverter operations are very common and this has resulted in the use of new Three-phase 3-level VSC widely in various products, due to the simplicity of its power and control architecture.

The three-phase 3-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



	Switching	Conduction	Combined Losses	TvjAvg	TvjMax	TvjBLS
IGBT1	2.658 kW	731.24 W	3.389 kW	115.42 ºC	125.69 ºC	123.26 ºC
IGBT2	207.78 W	1.147 kW	1.355 kW	61.08 ºC	64.46 ºC	63.93 ºC
IGBT3	207.78 W	1.147 kW	1.355 kW	61.08 ºC	64.46 ºC	64.12 ºC
IGBT4	2.658 kW	731.24 W	3.389 kW	115.41 ºC	125.69 ºC	123.26 ºC
IGBT5	0 W	0 W	0 W	0 ºC	0 ºC	0 ºC
IGBT6	0 W	0 W	0 W	0 ºC	0 ºC	0 ºC
D1	41.53 W	16.04 W	57.57 W	54.71 ºC	55.52 ºC	54.58 ºC
D2	0 W	16.15 W	16.15 W	36.56 ºC	36.76 ºC	36.62 ºC
D3	0 W	16.15 W	16.15 W	36.56 ºC	36.76 ºC	36.76 ºC
D4	41.53 W	16.04 W	57.57 W	54.71 ºC	55.52 ºC	54.72 ºC
D5	579.71 W	616.36 W	1.196 kW	78.89 ºC	85.61 ºC	83.87 ºC
D6	579.71 W	616.36 W	1.196 kW	78.89 ºC	85.61 ºC	83.87 ºC
Converter Losses	20.92 kW	15.16 kW	36.08 kW			
% Losses			1.11 %			

	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency	Power Factor
	3200 kW	2400 kVAR	1.414 kV	943 A	50 Hz	0.80

	DC Power	DC Voltage	Switching Frequency	Modulation Index
	3236 kW	5.000 kV	900 Hz	0.80

Figure 1 Page layout of 3-Phase NPC 3-Level converter

Grid definitions

Converter settings

IGBT selection

Results graphs

Results tables

Remark: For NPC topology the selection of diode is enabled

2.1 Three-phase 3-level VSC power circuit schematic

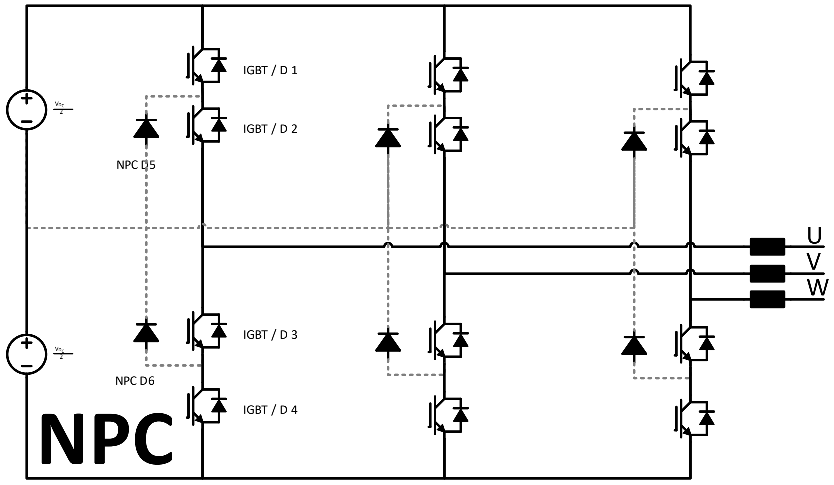


Figure 2 Three-phase 3-level NPC VSC power circuit schematic

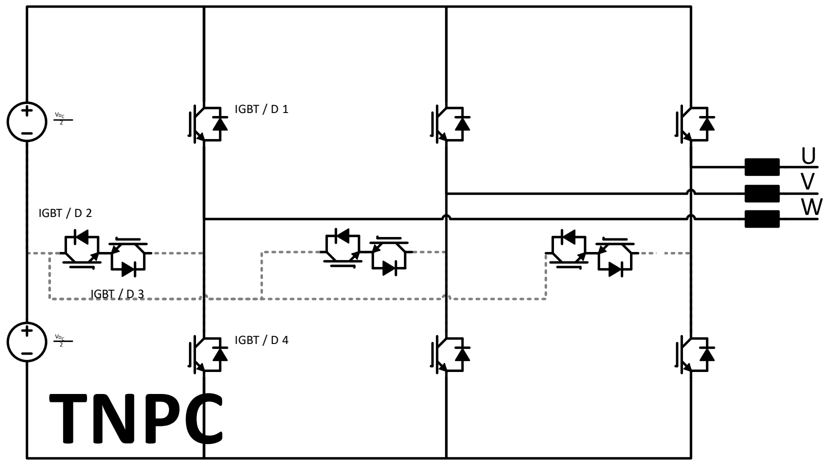


Figure 3 Three-phase 3-level TNPC VSC power circuit schematic

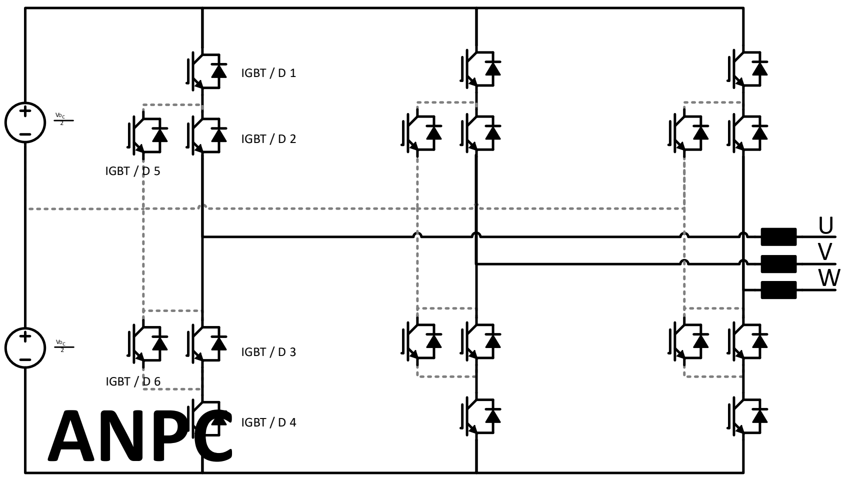


Figure 4 Three-phase 3-level ANPC VSC power circuit schematic

3. SIMULATION SETTINGS

3.1 Circuit parameters

3.1.1 Converter Operation

Select Topology	Topology can be selected either as NPC or as TNPC or as ANPC.	Selection
Converter Operation	Converter can be operated either as Inverter DC to AC or as Rectifier AC to DC	Selection

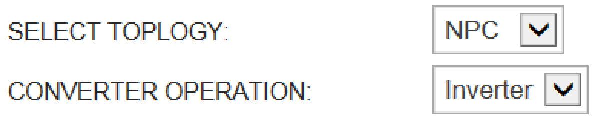


Figure 5 Converter topology and mode selection

3.1.2 Ambient temperature

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

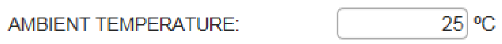


Figure 6 Ambient temperature input block

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.

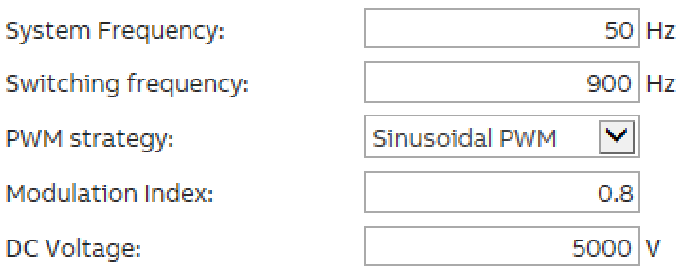


Figure 7 Controller input block

FREQUENCY	Converter AC output frequency	Range 1 to 500 Hz
SWITCHING FREQUENCY	Definition of switching frequency applied for PWM control (Phase-shifted PWM)	Range 200 to 10000 Hz
PWM Strategy	Definition of PWM strategy Different Control methods are implemented, which are SPWM, SVPWM, THIPWM and DPWMs	Selection

	ANPC topology has again 3 different controls. Find technical background and explanations in Chapter 5.	
MODULATION INDEX	Definition of modulation index Sinusoidal PWM limit is 1.00 Rest of PWMs limit is 1.15	Range 0 .. 1 (1.15)
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).

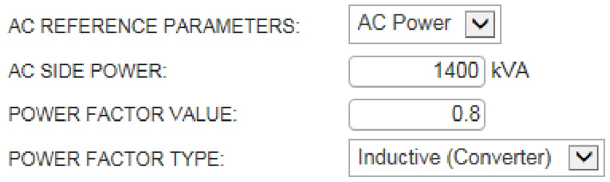


Figure 8 Grid/Load parameter input blocks

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
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

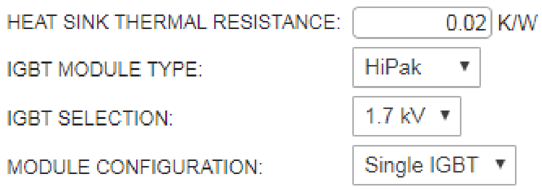


Figure 9 Thermal settings and IGBT selection

Heat Sink Thermal Resistance	Definition of thermal resistance of cooling system applied.	Range 0.0001 .. 0.5 K/W

Remark:	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.

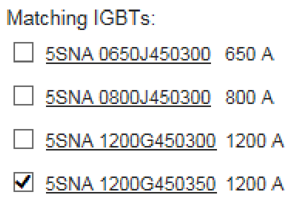


Figure 10 Matching IGBTs for selection

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 then 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 data sheet from the ABB website. This section/figure is not visible when the selected topology is TNPC.

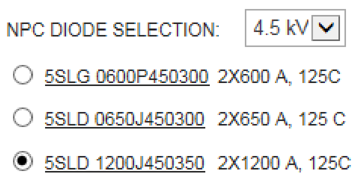


Figure 11 Matching NPC Diodes for selection

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

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 12 Start of simulation

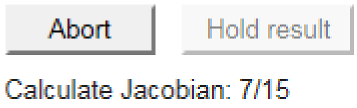


Figure 13 Simulation progress and termination

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:

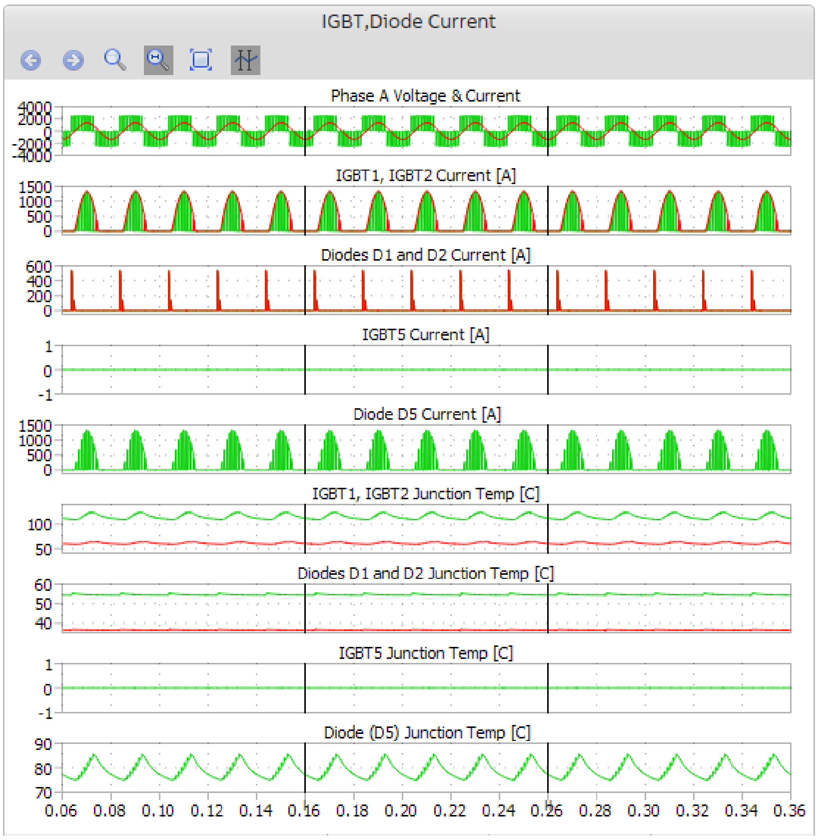


Figure 14 Graphical results of Three-phase 2-level VSC converter

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 Graph 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	0.16	0.26	0.1
Phase A Voltage & Current			
Phase Voltage-A	0.000	0.000	0.000
Phase Current-A	-1333	-1333	-0.0002553
IGBT1, IGBT2 Current [A]			
IGBT currents (a):1	0.000	0.000	0.000
IGBT currents (a):2	0.000	0.000	0.000
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
IGBT5 Current [A]			
Switch20	0.000	0.000	0.000
Diode D5 Current [A]			
Switch29	0.000	0.000	0.000
IGBT1, IGBT2 Junction Temp [C]			
IGBT junction temp (a):1	112.3	112.3	0.00005391
IGBT junction temp (a):2	60.19	60.19	-0.00002185
Diodes D1 and D2 Junction Temp [C]			
Diode junction temp (a):1	54.50	54.50	0.000002335
Diode junction temp (a):2	36.51	36.51	6.677e-7
IGBT5 Junction Temp [C]			
Switch31	0.000	0.000	0.000
Diode (D5) Junction Temp [C]			
Switch30	77.20	77.20	-0.00004155

Figure 15 Tabular indication of cursor position graph values

Remark:
The numerical values 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.

The indicated elements in the table upper IGBT etc. correspond to the different semiconductor positions in a full bridge cell as shown in Figure 2 Three-phase 3-level NPC VSC power circuit schematic.

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

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	2.658 kW	731.24 W	3.389 kW	115.42 ºC	125.69 ºC	123.26 ºC
IGBT2	207.78 W	1.147 kW	1.355 kW	61.08 ºC	64.46 ºC	63.93 ºC
IGBT3	207.78 W	1.147 kW	1.355 kW	61.08 ºC	64.46 ºC	64.12 ºC
IGBT4	2.658 kW	731.24 W	3.389 kW	115.41 ºC	125.69 ºC	123.26 ºC
IGBT5	0 W	0 W	0 W	0 ºC	0 ºC	0 ºC
IGBT6	0 W	0 W	0 W	0 ºC	0 ºC	0 ºC
D1	41.53 W	16.04 W	57.57 W	54.71 ºC	55.52 ºC	54.58 ºC
D2	0 W	16.15 W	16.15 W	36.56 ºC	36.76 ºC	36.62 ºC
D3	0 W	16.15 W	16.15 W	36.56 ºC	36.76 ºC	36.76 ºC
D4	41.53 W	16.04 W	57.57 W	54.71 ºC	55.52 ºC	54.72 ºC
D5	579.71 W	616.36 W	1.196 kW	78.89 ºC	85.61 ºC	83.87 ºC
D6	579.71 W	616.36 W	1.196 kW	78.89 ºC	85.61 ºC	83.87 ºC
Converter Losses	20.92 kW	15.16 kW	36.08 kW			
% Losses			1.11 %			

Figure 16 Device Losses & Temperatures

Remarks: Cells with “0” numbers indicate not used semiconductor for selected topology

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

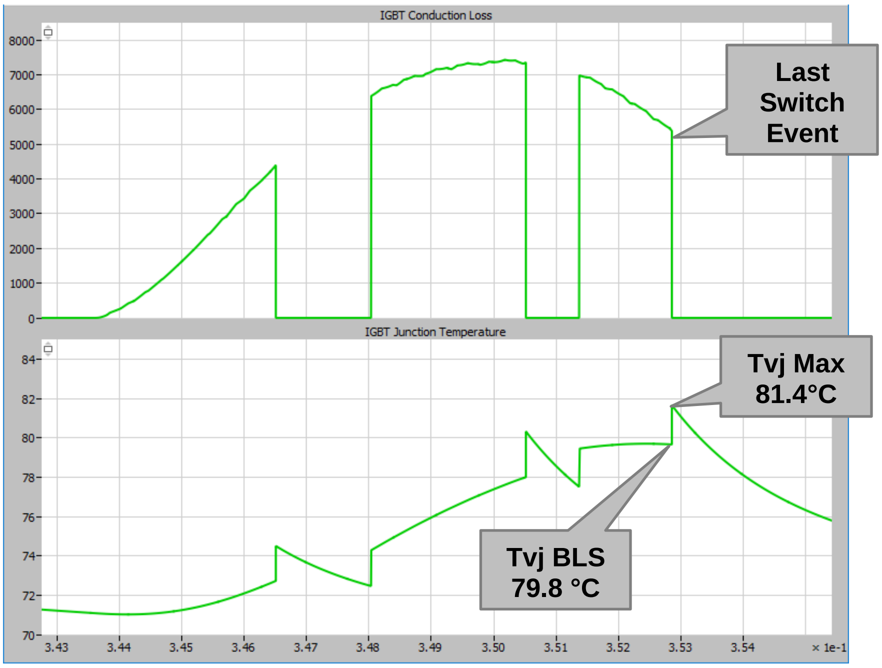


Figure 17 Definition of Tvj before last switch

Converter AC parameters

Converter AC Parameters						
	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency	Power Factor
	3200 kW	2400 kVAR	1.414 kV	943 A	50 Hz	0.80

Figure 18 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 8.4.

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
	3236 kW	5.000 kV	900 Hz	0.80

Figure 19 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 8.2

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), Space Vector PWM (SVPWM) and Discontinuous PWMs(DPWM). 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 20 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.

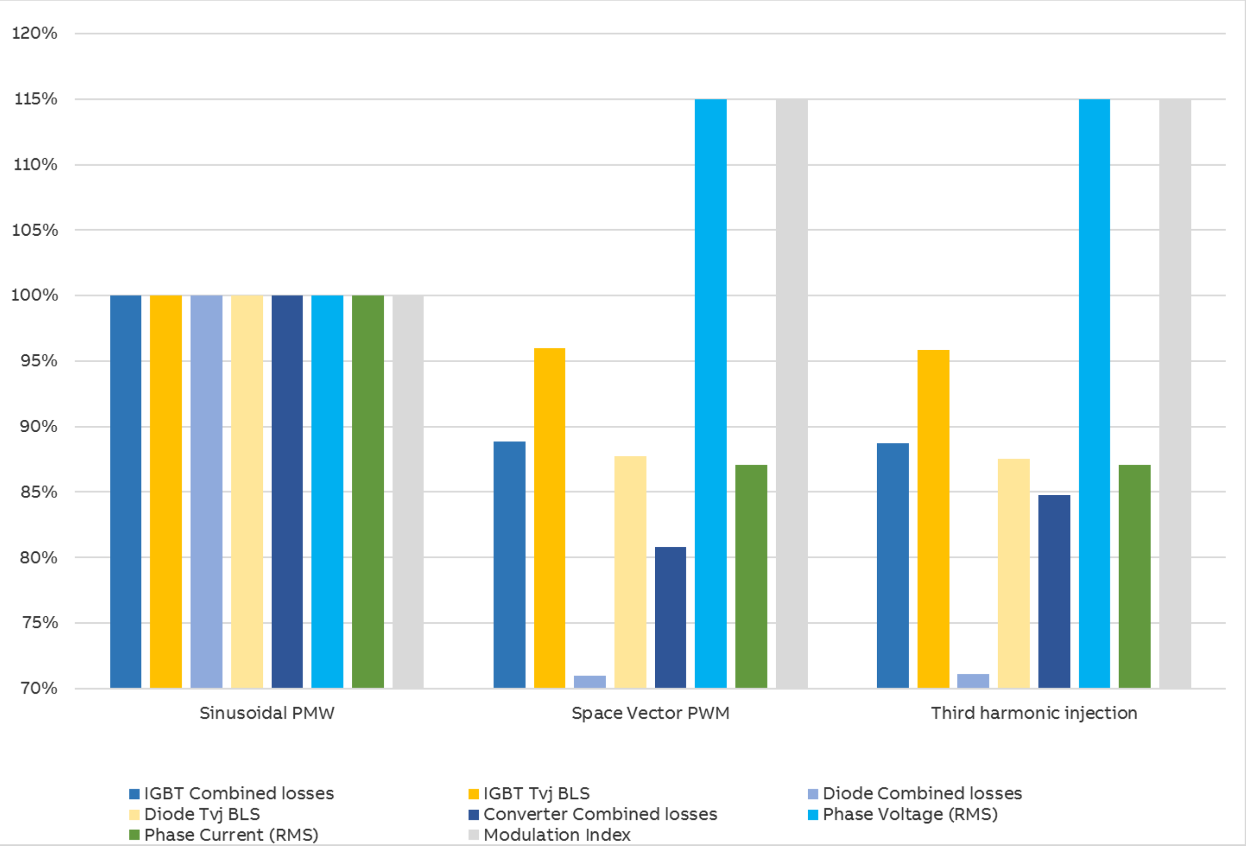


Figure 20 Results diagram comparison of control strategies for NPC

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	2287	49.4	663	39.25	8.85	1.09	707	471	1
Space vector	2031	47.42	471	34.43	7.15	0.93	813	410	1.15
3rd harmonic	2029	47.35	472	34.37	7.50	0.93	813	410	1.15

Figure 21 Results table comparison of control strategies for NPC

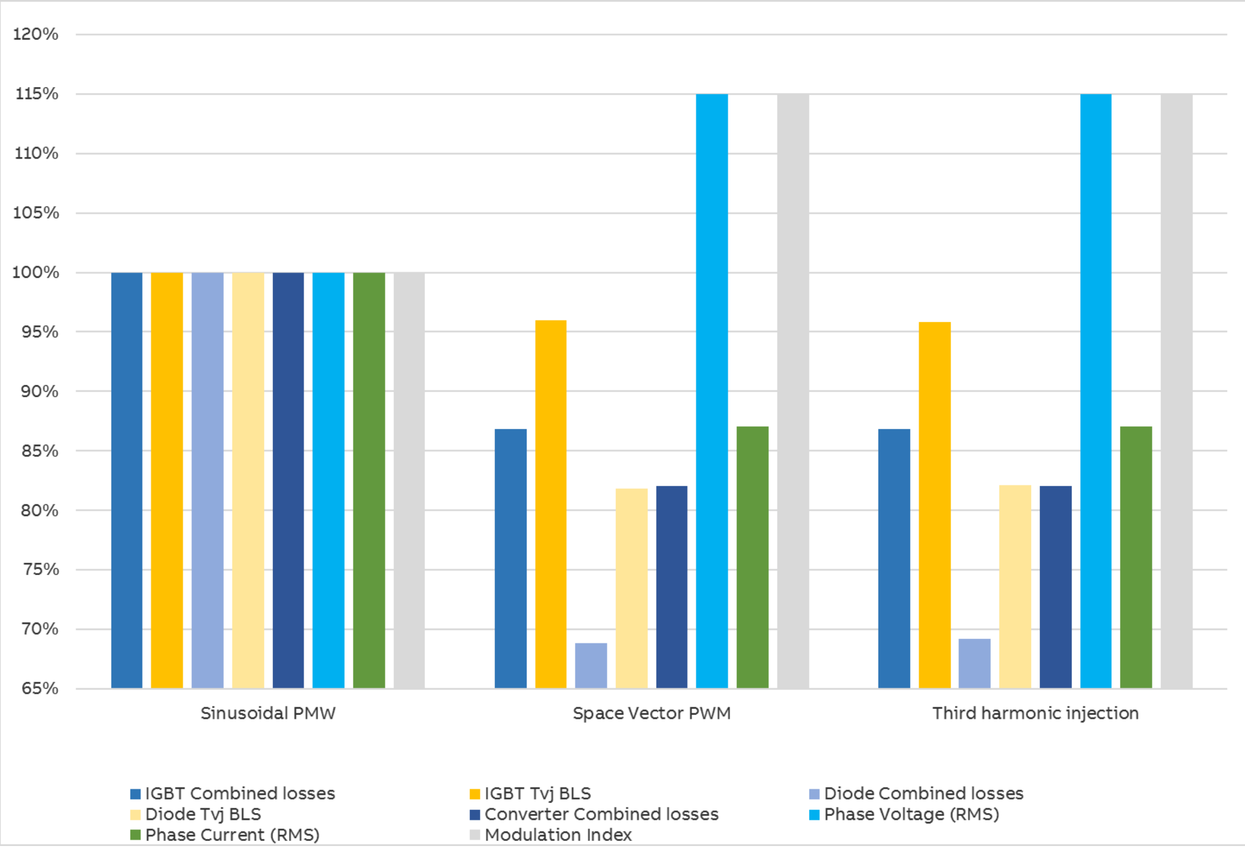


Figure 22 Results diagram comparison of control strategies for TNPC

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	1759	49.4	651	42.74	7.23	0.9	707	471	1
Space vector	1528	47.42	448	34.96	5.93	0.74	813	410	1.15
3rd harmonic	1527	47.35	450	35.1	5.93	0.74	813	410	1.15

Figure 23 Results table comparison of control strategies for TNPC

ANPC topology works on standard sinusoidal PWM and three different controls are implemented under sinusoidal PWM namely, DF-PWM, LF/HF PWM and HF/LF PWM. DF-PWM implements high frequency switching over all switches, LF/HF PWM implements low frequency switching over outer switches and high frequency switches over inner switches and HF/LF PWM implements high frequency switching over outer switches and low frequency switches over inner switches.

6. SIMULATION CONDITIONS

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 the reference to the lookup table and linear interpolation of the actual device current, voltage and junction temperature.

7. ALERTS & FEATURES

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

7.1 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

7.2 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

8. APPLIED CALCULATIONS

8.1 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

8.2 Fundamental Phase Voltage RMS of Converter Definition

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

8.3 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.

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

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

According to:

$$P_{AC} = 3 * \sum_{v=1}^{n} \widehat{u_v} \, . \, \widehat{\iota_v} . \cos \varphi_v$$

If current/voltage is free from harmonics, then

$$P_{AC} = 3 * V_{Ph\_RMS} . I_{Ph\_RMS} . PF$$

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:

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

8.4 Reactive Power

Q Effective reactive power on converter AC side [VAr]

$$Q = 3 * \sum_{\nu=1}^{n} \widehat{u_\nu} . \hat{\iota_\nu} . \sin \varphi_\nu$$

If current/voltage is free from harmonics, then

$$Q = 3 * V_{Ph\_RMS} . I_{Ph\_RMS} . \sin \varphi_1$$

9. 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-5 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 $R_{th(h\text{-}a)}$ 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 5 NPC Three phase three-level VSC with IGBT**
Tester:	**Tirthasarathi Lodh, Harshavardhan Marabathina**
Date	**2019-11-02**
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 [%]			0.59%			0.26%			0.31%			0.52%			0.28%
Max difference [%]			1.96%			3.45%			1.56%			2.37%			1.18%
Device Losses & Temperatures															
Switching Losses IGBT 1 (W)	2994	2969	0.84%	2888	2876	0.42%	1636	1628	0.49%	914	910	0.44%	272	272	0.00%
Switching Losses IGBT 2 (W)	680	673	1.03%	304	303	0.33%	403	404	-0.25%	5120	5086	0.66%	8614	8536	0.91%
Switching Losses Diode 1 (W)	146	146	0.00%	74	74	0.00%	107	107	0.00%	994	974	2.01%	1841	1824	0.92%
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)	602	600	0.33%	618	617	0.16%	384	378	1.56%	253	247	2.37%	61	61	0.00%
Conduction Losses IGBT 1 (W)	1310	1293	1.30%	1183	1174	0.76%	904	893	1.22%	141	139	1.42%	6	6	0.00%
Conduction Losses IGBT 2 (W)	2288	2273	0.66%	2115	2110	0.24%	2562	2544	0.70%	1956	1915	2.10%	679	671	1.18%
Conduction Losses Diode 1 (W)	58	57	1.72%	29	28	3.45%	121	120	0.83%	1527	1515	0.79%	1212	1201	0.91%
Conduction Losses Diode 2 (W)	58	57	1.72%	28	28	0.00%	121	121	0.00%	1532	1525	0.46%	1210	1206	0.33%
Conduction Losses NPC Diode 5 (W)	940	931	0.96%	918	915	0.33%	1501	1491	0.67%	1465	1459	0.41%	604	604	0.00%
Combined Losses IGBT 1 (W)	4304	4262	0.98%	4071	4049	0.54%	2540	2520	0.79%	1055	1049	0.57%	279	278	0.36%
Combined Losses IGBT 2 (W)	2968	2946	0.74%	2419	2413	0.25%	2965	2947	0.61%	7076	7002	1.05%	9292	9206	0.93%
Combined Losses Diode 1 (W)	204	203	0.49%	102	102	0.00%	228	227	0.44%	2521	2489	1.27%	3053	3025	0.92%
Combined Losses Diode 2 (W)	58	57	1.72%	28	28	0.00%	121	121	0.00%	1532	1525	0.46%	1210	1206	0.33%
Combined Losses NPC Diode 5 (W)	1541	1531	0.65%	1537	1532	0.33%	1885	1869	0.85%	1718	1706	0.70%	665	665	0.00%
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	57	1.72%	54	54	0.00%	58	58	0.00%	70	70	0.00%	82	82	0.00%
Junction Temperature Avg Diode 1 (°C)	51	50	1.96%	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)	54452	53994	0.84%	48944	48749	0.40%	46434	46103	0.71%	83413	82620	0.95%	86994	86281	0.82%
Losses Efficiency	1.34	1.34	0.00%	0.77	0.76	1.30%	3.9	3.88	0.51%	1.38	1.37	0.72%	0.98	0.97	1.02%
AC Parameters															
Real Power (kW)	3994	3984	0.25%	6329	6329	0.00%	1143.6	1143	0.05%	-6024	-6018	0.10%	-8922	-8910	0.13%
Reactive Power (kVAR)	3995	3974	0.53%	4746	4747	-0.02%	-1929	-1929	0.00%	-8032	-8027	0.06%	4321	4321	0.00%
Phase Voltage RMS (V)	954	954.5	-0.05%	1414	1416	-0.14%	346	344.5	0.43%	1273	1274.5	-0.12%	1909	1909	0.00%
Phase Current RMS (V)	1973	1968	0.25%	1865	1866	-0.05%	2158	2153.5	0.21%	2630	2625	0.19%	1731	1729.5	0.09%
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	0.708	-0.14%	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)	4049	4038	0.27%	6378	6378	0.00%	1190	1189	0.08%	-5940	-5935	0.08%	-8835	-8835	0.00%
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 24 Validation SEMIS / PSCAD results comparison 3 level 3 phase NPC

Results analysis according settings

Topology	**SEMIS 5 TNPC Three phase three-level VSC with IGBT**
Tester:	**Tirthasarathi Lodh, Harshavardhan Marabathina**
Date	**2019-11-02**
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 [%]			0.25%			0.35%			0.32%			0.50%			0.31%
Max difference [%]			1.72%			3.45%			1.33%			2.22%			1.29%
Device Losses & Temperatures															
Switching Losses IGBT 1 (W)	2994	2980	0.47%	2888	2876	0.42%	1636	1628	0.49%	914	909	0.55%	272	271	0.37%
Switching Losses IGBT 2 (W)	669	666	0.45%	300	299	0.33%	403	402	0.25%	5116	5077	0.76%	8592	8511	0.94%
Switching Losses Diode 1 (W)	146	146	0.00%	74	74	0.00%	107	107	0.00%	994	978	1.61%	1843	1826	0.92%
Switching Losses Diode 2 (W)	614	613	0.00%	629	627	0.00%	393	387	0.00%	277	271	0.00%	73	73	0.00%
Conduction Losses IGBT 1 (W)	1310	1299	0.84%	1183	1174	0.76%	904	892	1.33%	141	139	1.42%	6	6	0.00%
Conduction Losses IGBT 2 (W)	997	996	0.10%	954	954	0.00%	1646	1635	0.67%	1801	1761	2.22%	670	662	1.19%
Conduction Losses Diode 1 (W)	58	57	1.72%	29	28	3.45%	121	120	0.83%	1527	1513	0.92%	1211	1202	0.74%
Conduction Losses Diode 2 (W)	944	938	0.64%	921	918	0.33%	1510	1499	0.73%	1496	1488	0.53%	616	615	0.16%
Combined Losses IGBT 1 (W)	4304	4279	0.58%	4071	4050	0.52%	2540	2520	0.79%	1055	1048	0.66%	279	277	0.72%
Combined Losses IGBT 2 (W)	1666	1662	0.24%	1255	1253	0.16%	2049	2037	0.59%	6917	6838	1.14%	9292	9172	1.29%
Combined Losses Diode 1 (W)	204	203	0.49%	102	102	0.00%	228	227	0.44%	2521	2491	1.19%	3054	3028	0.85%
Combined Losses Diode 2 (W)	1557	1552	0.32%	1550	1545	0.32%	1902	1886	0.84%	1774	1759	0.85%	689	689	0.00%
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)	53	53	0.00%	51	50	1.96%	56	56	0.00%	69	69	0.00%	81	81	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)	58	58	0.00%	57	57	0.00%	62	62	0.00%	56	56	0.00%	50	50	0.00%
Converter Losses (W)	46388	46174	0.46%	41866	41700	0.40%	40312	40013	0.74%	73600	72817	1.06%	79706	78998	0.89%
Losses Efficiency	1.15	1.14	0.87%	0.66	0.65	1.52%	3.4	3.38	0.59%	1.22	1.21	0.82%	0.89	0.89	0.00%
AC Parameters															
Real Power (kW)	3994	3996	-0.05%	6329	6329	0.00%	1144	1143	0.09%	-6024	-6018	0.10%	-8927	-8910	0.19%
Reactive Power (kVAR)	3995	3988	0.18%	4746	4747	-0.02%	-1929	-1929	0.00%	-8032	-8027	0.06%	4323.5	4321	0.06%
Phase Voltage RMS (V)	954	956	-0.21%	1414	1416	-0.14%	346	344.5	0.43%	1273	1274.5	-0.12%	1909	1909	0.00%
Phase Current RMS (V)	1973	1973	0.00%	1865	1866	-0.05%	2158	2153.5	0.21%	2630	2625	0.19%	1732	1729.5	0.14%
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	0.708	-0.14%	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)	4040.5	4043	-0.06%	6371	6371	0.00%	1184	1183	0.08%	-5950	-5945	0.08%	-8847	-8831	0.18%
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 25 Validation SEMIS / PSCAD results comparison 3 level 3 phase TNPC

Results analysis according settings

Topology	**SEMIS 5 ANPC Three phase three-level VSC with IGBT**		
Tester:	**Harshavardhan Marabathina**		
Date	**June 8, 2021**		
Device used (.xml)	**5SNA 2000K452300, 5SNA 1200G330100**		
Limit acceptance level Green / Orange / Red	0%	2%	5%
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 %		

Description of Settings Set 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
Absolute average difference [%]			0.39%			0.44%			0.33%			0.19%			0.24%
Max difference [%]			2.32%			1.44%			3.78%			0.88%			0.77%
Device Losses & Temperatures															
Switching Losses IGBT 1 (W)	1013	1010.7	+ 0.23%	449.8	447.8	+ 0.44%	265.1	264.4	+ 0.26%	42.55	42.57	- 0.05%	1010	1007.8	+ 0.22%
Switching Losses IGBT 2 (W)	1339	1337.4	+ 0.12%	546	543.2	+ 0.51%	309.8	308.9	+ 0.29%	591.52	591.1	+ 0.07%	1355	1351	+ 0.30%
Switching Losses Diode 1 (W)	22.02	21.78	+ 1.09%	20.15	20.18	- 0.15%	8.14	8.16	- 0.25%	129.3	128.16	+ 0.88%	15.86	15.87	- 0.06%
Switching Losses Diode 2 (W)	297.73	296.06	+ 0.56%	215.54	214.5	+ 0.48%	136.07	135.8	+ 0.20%	169.35	167.9	+ 0.86%	296.4	295.12	+ 0.43%
Switching Losses IGBT 5 (W)	207.84	206.9	+ 0.45%	58.79	58.59	+ 0.34%	30.84	30.81	+ 0.10%	548.66	548.3	+ 0.07%	194.98	194.8	+ 0.09%
Switching Losses Diode 5 (W)	185.9	185.09	+ 0.44%	165.24	164.7	+ 0.33%	109.58	109.5	+ 0.07%	28.59	28.4	+ 0.66%	179.51	178.9	+ 0.34%
Conduction Losses IGBT 1 (W)	1007	1002	+ 0.50%	796.9	796.3	+ 0.08%	402.28	400.8	+ 0.37%	4.61	4.64	- 0.65%	1168	1161.7	+ 0.54%
Conduction Losses IGBT 2 (W)	1588	1580	+ 0.50%	1176	1171.4	+ 0.39%	520.48	518.7	+ 0.34%	194.14	193.14	+ 0.52%	1682	1673.2	+ 0.00%
Conduction Losses Diode 1 (W)	20.27	19.8	+ 2.32%	13.49	13.41	+ 0.59%	2.3	2.213	+ 3.78%	716.67	714.5	+ 0.30%	32.55	32.3	+ 0.77%
Conduction Losses Diode 2 (W)	333.63	332	+ 0.49%	240.36	236.9	+ 1.44%	74.07	73.6	+ 0.63%	900.68	898.28	+ 0.27%	256.54	254.6	+ 0.76%
Conduction Losses IGBT 5 (W)	328.62	328.7	- 0.02%	317.05	314.27	+ 0.88%	87.23	87.4	- 0.19%	175.21	174.06	+ 0.00%	234.38	233.5	+ 0.38%
Conduction Losses Diode 5 (W)	472.61	471	+ 0.34%	235.2	232.06	+ 1.34%	92.93	92.4	+ 0.57%	188.03	188.24	- 0.11%	412.18	410.8	+ 0.33%
Combined Losses IGBT 1 (W)	2021.00	2012.7	+ 0.41%	1247.00	1244.1	+ 0.23%	667.38	665.2	+ 0.33%	47.17	47.21	- 0.08%	2179.00	2169.5	+ 0.44%
Combined Losses IGBT 2 (W)	2928.00	2917.4	+ 0.36%	1722.00	1714.6	+ 0.43%	830.28	827.6	+ 0.32%	785.66	784.24	+ 0.18%	3037.00	3024.2	+ 0.42%
Combined Losses Diode 1 (W)	42.28	41.58	+ 1.66%	33.64	33.59	+ 0.15%	10.44	10.373	+ 0.64%	845.97	842.66	+ 0.39%	48.40	48.17	+ 0.48%
Combined Losses Diode 2 (W)	631.36	628.06	+ 0.52%	455.91	451.4	+ 0.99%	210.14	209.4	+ 0.35%	1070	1066.18	+ 0.36%	553.04	549.72	+ 0.60%
Combined Losses IGBT 5 (W)	543.07	535.6	+ 1.38%	375.84	372.86	+ 0.79%	118.07	118.21	- 0.12%	723.86	722.36	+ 0.21%	429.36	428.3	+ 0.25%
Combined Losses Diode 5 (W)	660.37	656.09	+ 0.65%	400.44	396.76	+ 0.92%	202.51	201.9	+ 0.30%	216.62	216.64	- 0.01%	591.69	589.7	+ 0.34%
Junction Temperature Avg IGBT 1 (°C)	53.37	53.31	+ 0.11%	72.06	71.99	+ 0.10%	42.10	42.04	+ 0.14%	47.42	47.39	+ 0.06%	55.61	55.54	+ 0.13%
Junction Temperature Avg IGBT 2 (°C)	70.67	70.57	+ 0.14%	87.57	87.33	+ 0.27%	47.86	47.78	+ 0.17%	59.46	59.43	+ 0.05%	71.55	71.44	+ 0.15%
Junction Temperature Avg Diode 1 (°C)	41.98	41.89	+ 0.21%	51.42	51.39	+ 0.06%	30.79	30.76	+ 0.10%	56.73	56.72	+ 0.02%	43.36	43.29	+ 0.16%
Junction Temperature Avg Diode 2 (°C)	60.63	60.52	+ 0.18%	73.35	73.13	+ 0.30%	40.60	40.63	- 0.07%	66.97	66.96	+ 0.01%	59.99	59.86	+ 0.22%
Junction Temperature Avg IGBT 5 (°C)	37.71	37.69	+ 0.05%	52.79	52.68	+ 0.21%	29.63	29.30	+ 1.11%	51.77	51.77	+ 0.00%	35.69	35.67	+ 0.06%
Junction Temperature Avg Diode 5 (°C)	42.02	42.01	+ 0.02%	60.19	60.04	+ 0.25%	34.64	34.62	+ 0.06%	49.98	49.98	+ 0.00%	39.87	39.86	+ 0.03%
Converter Losses (W)	40900.00	40748.58	+ 0.37%	25410.00	25279.86	+ 0.51%	12230.00	12196.10	+ 0.28%	22140	22075.74	+ 0.29%	41030.00	40857.54	+ 0.42%
Losses Efficiency	1.32	1.32	+ 0.34%	2.44	2.41	+ 1.26%	0.9	0.90	+ 0.52%	1.23	1.23	+ 0.12%	1.18	1.17	+ 0.43%
AC Parameters															
Real Power (kW)	3054	3056.9	- 0.09%	1018	1024	- 0.59%	1350	1350	+ 0.00%	-1800	-1797	+ 0.17%	3436	3436.5	- 0.01%
Reactive Power (kVAR)	2290	2292	- 0.09%	763.6	768.8	- 0.68%	653.8	655.3	- 0.23%	-871.8	-873.3	- 0.17%	2577	2580	- 0.12%
Phase Voltage RMS (V)	848	850	- 0.24%	424	426	- 0.47%	891	891.6	- 0.07%	636	635.4	+ 0.09%	954	954.7	- 0.07%
Phase Current RMS (V)	1500	1500	+ 0.00%	1000	1000	+ 0.00%	561	561.3	- 0.05%	1048	1047	+ 0.10%	1500	1500	+ 0.00%
Output Frequency (Hz)	50	50	+ 0.00%	50	50	+ 0.00%	50	50	+ 0.00%	40	40	+ 0.00%	50	50	+ 0.00%
Power Factor	0.8	0.8	+ 0.00%	0.8	0.8	+ 0.00%	0.9	0.899	+ 0.11%	0.9	0.9	+ 0.00%	0.8	0.8	+ 0.00%
DC Parameters & Control Parameters															
DC Power (kW)	3095	3097.65	- 0.09%	1043	1049.28	- 0.60%	1362	1362.20	- 0.01%	-1778	-1774.92	+ 0.17%	3477	3477.36	- 0.01%
DC Voltage (V)	3000	3000	+ 0.00%	1500	1500	+ 0.00%	2800	2800	+ 0.00%	2000	2000	+ 0.00%	3000	3000	+ 0.00%
Switching Frequency (Hz)	800	800	+ 0.00%	2000	2000	+ 0.00%	1200	1200	+ 0.00%	800	800	+ 0.00%	800	800	+ 0.00%
Modulation Index	0.8	0.8	+ 0.00%	0.8	0.8	+ 0.00%	0.9	0.9	+ 0.00%	0.9	0.9	+ 0.00%	0.9	0.9	+ 0.00%

Figure 26 Validation SEMIS / PSCAD results comparison 3 level 3 phase ANPC

10. USER MANUAL REVISION HISTORY

Rev.	Page	Change Description	Date / Initial
1.5	16, 17	Power Definitions	2021-11-26 PGGI/HM
1.4	6, 14 and 19	DPWM control enabled ANPC controls and validation results	2021-11-12 PGGI/HM
1.3	all	DC Voltage definition	2020-03-04 PGGI/HM
1.2	all	Initial version in new design	2019-08-22 PGGI/DS

11. SIMULATION SOFTWARE RELEASE HISTORY

Rev.	New topic	Fixed defects	Tvj influence	Date
1.4	THD of voltage & current measured	-	No	2021-11-30 PGGI/HM
1.3	Change of PWM to multiple carriers	Improvement of loss balance in phases	Minor	2021-11-12 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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