SEMIS Simulation Tool
FACTS Full Bridge MMC 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. FACTS FULL BRIDGE MMC WITH IGBT

The use of powerful modular multilevel converters (MMC) for FACTS applications has resulted in the development of new STATCOM products, due to its superior characteristics and competitive costs. The converter module comprises of 3 phases with each phase having a several IGBT based full-bridge cells are connected in series to build up the requisite voltage. Each arm contains the phase reactor. The MMC 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
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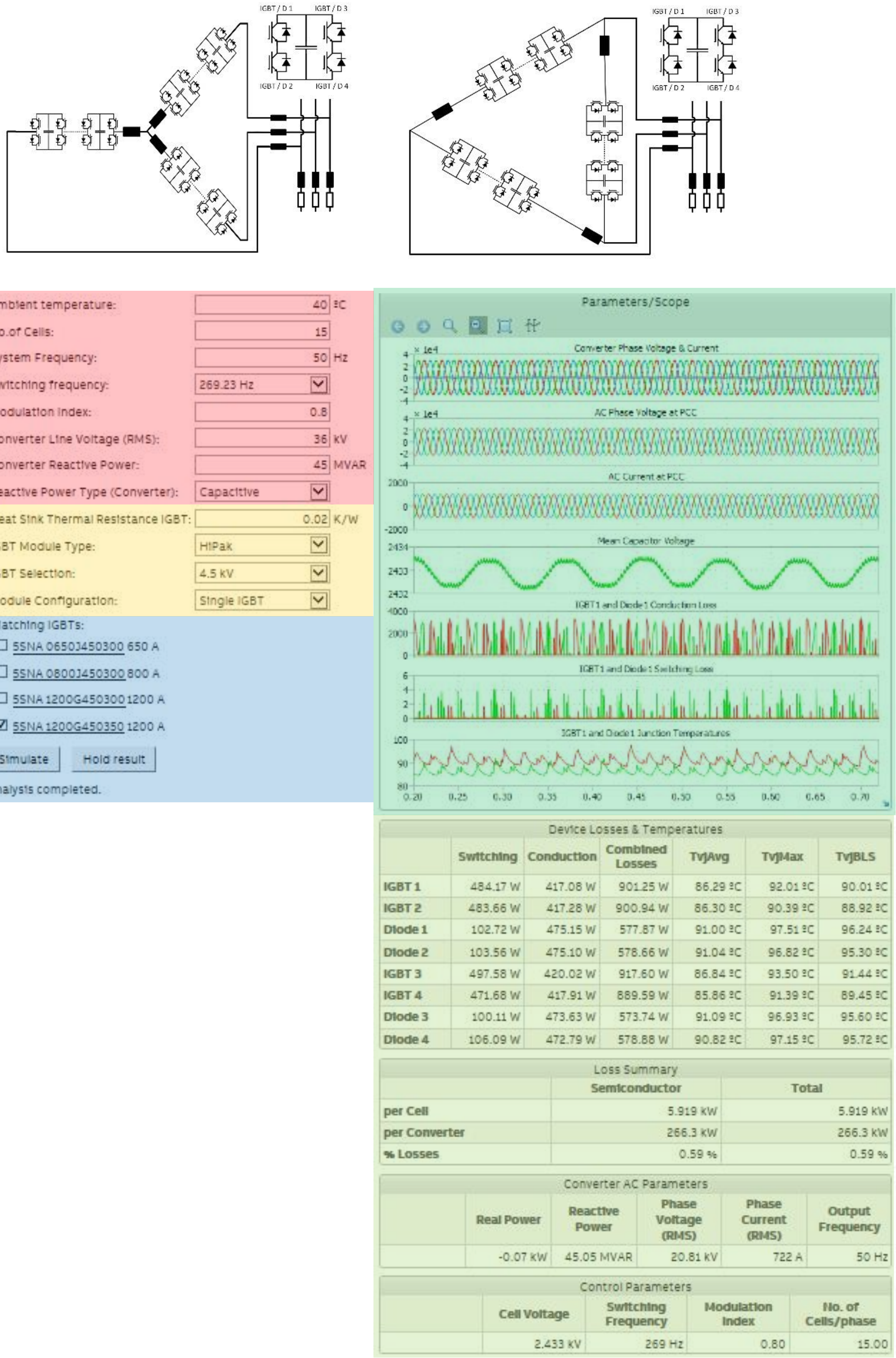
- Three-Phase Three-level VSC FACTS with IGCT Full Bridge Delta Connected

2. OVERVIEW



	Switching	Conduction	Combined Losses	TvjAvg	TvjMax	TvjBLS
IGBT 1	484.17 W	417.08 W	901.25 W	86.29 °C	92.01 °C	90.01 °C
IGBT 2	483.66 W	417.28 W	900.94 W	86.30 °C	90.39 °C	88.92 °C
Diode 1	102.72 W	475.15 W	577.87 W	91.00 °C	97.51 °C	96.24 °C
Diode 2	103.56 W	475.10 W	578.66 W	91.04 °C	96.82 °C	95.30 °C
IGBT 3	497.58 W	420.02 W	917.60 W	86.84 °C	93.50 °C	91.44 °C
IGBT 4	471.68 W	417.91 W	889.59 W	85.86 °C	91.39 °C	89.45 °C
Diode 3	100.11 W	473.63 W	573.74 W	91.09 °C	96.93 °C	95.60 °C
Diode 4	106.09 W	472.79 W	578.88 W	90.82 °C	97.15 °C	95.72 °C

	Semiconductor	Total
per Cell	5.919 kW	5.919 kW
per Converter	266.3 kW	266.3 kW
% Losses	0.59 %	0.59 %

	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency
	-0.07 kW	45.05 MVAR	20.81 kV	722 A	50 Hz

	Cell Voltage	Switching Frequency	Modulation Index	No. of Cells/phase
	2.433 kV	269 Hz	0.80	15.00

Figure 1 FACTS Full Bridge MMC with IGBT circuit on website

Grid definitions

Converter settings

IGBT selection

Results graphs

Results tables

2.1 FACTS Full Bridge MMC with IGBT power circuit schematic

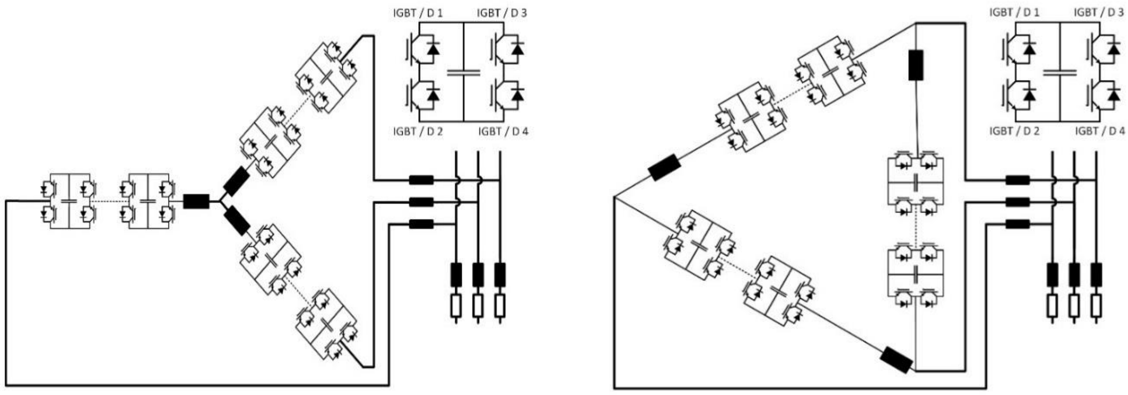


Figure 2 FACTS Full Bridge MMC Star & Delta Connected with IGBT schematic layout

3. SIMULATION SETTINGS

3.1 Circuit parameters

3.1.1 Ambient temperature

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

Figure 3 Ambient temperature input block

3.1.2 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 cell in the converter.

Figure 4 Controller input block

NO. OF CELLS	No. of cells in a phase leg	Range 2 to 20
SYSTEM FREQUENCY	Converter AC output frequency	Range 10 to 100 Hz
SWITCHING FREQUENCY	Definition of switching frequency applied for PWM control (Phase-shifted PWM)	Range 86 to 500 Hz
MODULATION INDEX	Definition of modulation index	Range 0 .. 1

3.1.3 Load parameters

The user can define the following parameters as seen in figure 5.

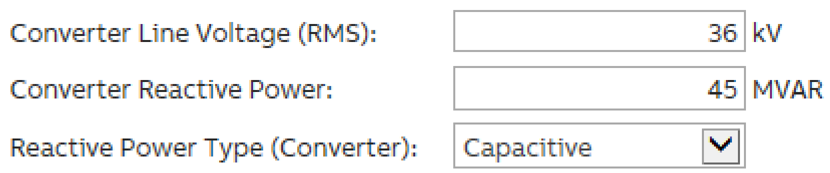


Figure 5 Grid/Load parameter input blocks

CONVERTER LINE VOLTAGE (RMS)

	AC Line voltage of converter	Range 1 .. 1000 kV

CONVERTER REACTIVE POWER

	Reactive Power supplied by converter	Range 1 .. 1000 MVAr

REACTIVE POWER TYPE	Reactive power type can be selected as Inductive or Capacitive based on load requirement	Selection

3.2 Switch settings

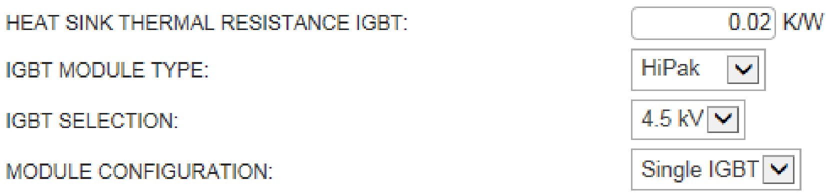


Figure 6 Thermal settings and IGBT selection

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

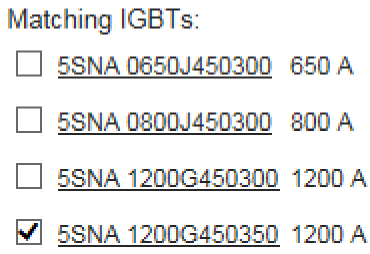


Figure 7 Matching IGBTs for selection

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.

3.3 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 a 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 8 Start of simulation

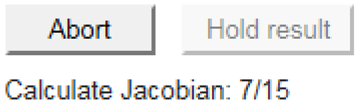


Figure 9 Simulation progress and termination

4. SIMULATION RESULTS

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

Graphical results	Visual analysis of waveforms for fast and efficient detection of most significant sources
Numerical 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:

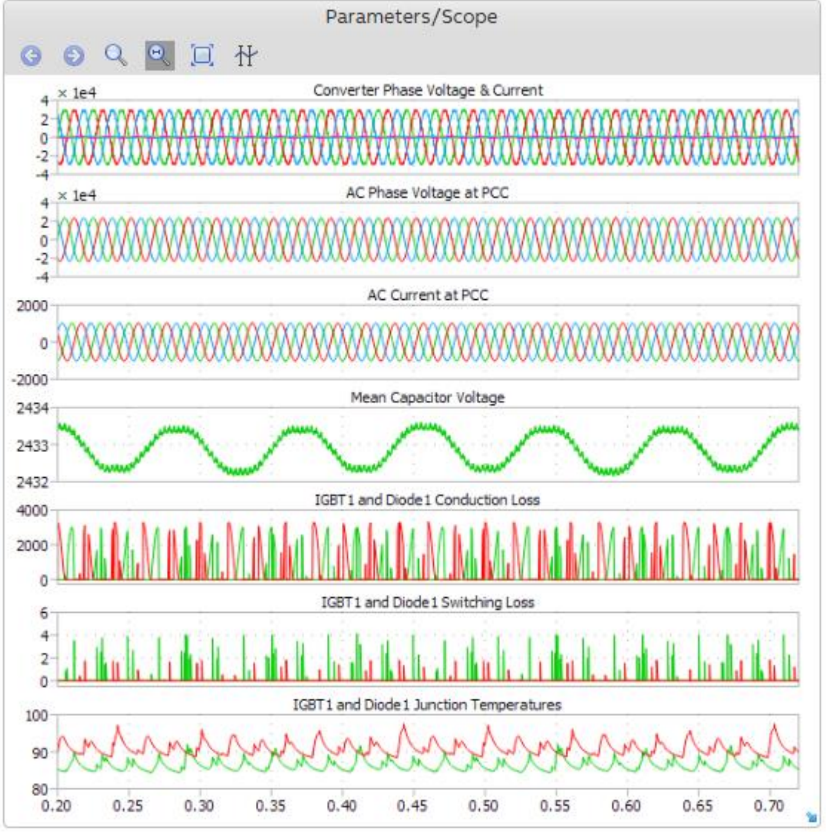


Figure 10 Graphical results of FACTS Full Bridge MMC with IGBT

4.1.2 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

4.1.3 Parameters values indication

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

Name	Cursor 1	Cursor 2	Delta
Time	0.37333	0.54667	0.17333
Converter Phase Voltage & Current			
Measured voltage:1	-2.685e+4	2.442e+4	-5.126e+4
Measured voltage:2	2.434e+4	0.000	2.434e+4
Measured voltage:3	0.000	-2.686e+4	2.686e+4
Measured current:1	513.0	509.8	3.175
Measured current:2	509.7	-1023	1532
Measured current:3	-1023	512.8	-1535
AC Phase Voltage at PCC			
Measured voltage:1	-2.036e+4	2.036e+4	-4.073e+4
Measured voltage:2	2.036e+4	0.00008379	2.036e+4
Measured voltage:3	0.00002118	-2.036e+4	2.036e+4
AC Current at PCC			
Measured current:1	513.0	509.8	3.175
Measured current:2	509.7	-1023	1532
Measured current:3	-1023	512.8	-1535
Mean Capacitor Voltage			
Gain2	2433	2433	-0.01447
IGBT1 and Diode1 Conduction Loss			
IGBT conduction loss	0.000	1065	-1065
Diode conduction loss	0.000	0.000	0.000
IGBT1 and Diode1 Switching Loss			
IGBT switching loss	0.000	0.000	0.000
Diode switching loss	0.000	0.000	0.000
IGBT1 and Diode1 Junction Temperatures			
IGBT junction temp	87.89	84.60	3.287
Diode junction temp	89.10	91.11	-2.020

Figure 11 Tabular indication of cursor position graph values

Remark:
The numerical values of 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 IGBT1 etc. correspond to the different semiconductor positions in a full-bridge cell as shown in Figure 2.

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
IGBT 1	484.17 W	417.08 W	901.25 W	86.29 ºC	92.01 ºC	90.01 ºC
IGBT 2	483.66 W	417.28 W	900.94 W	86.30 ºC	90.39 ºC	88.92 ºC
Diode 1	102.72 W	475.15 W	577.87 W	91.00 ºC	97.51 ºC	96.24 ºC
Diode 2	103.56 W	475.10 W	578.66 W	91.04 ºC	96.82 ºC	95.30 ºC
IGBT 3	497.58 W	420.02 W	917.60 W	86.84 ºC	93.50 ºC	91.44 ºC
IGBT 4	471.68 W	417.91 W	889.59 W	85.86 ºC	91.39 ºC	89.45 ºC
Diode 3	100.11 W	473.63 W	573.74 W	91.09 ºC	96.93 ºC	95.60 ºC
Diode 4	106.09 W	472.79 W	578.88 W	90.82 ºC	97.15 ºC	95.72 ºC

Loss Summary		
	Semiconductor	Total
per Cell	5.919 kW	5.919 kW
per Converter	266.3 kW	266.3 kW
% Losses	0.59 %	0.59 %

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.
Cell losses	Sum of IGBT and Diode losses in a full-bridge cell
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 the simulation period

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

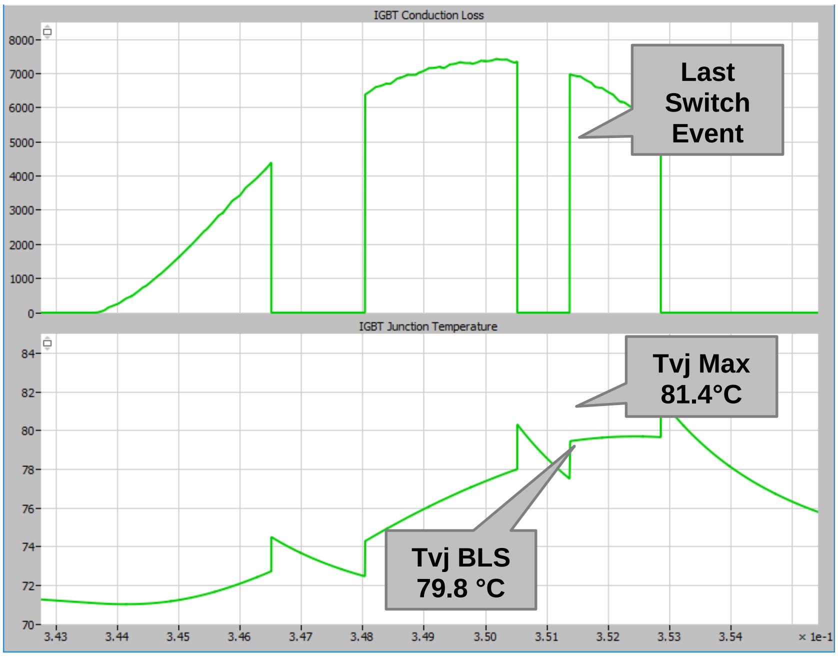


Figure 13 Definition of Tvj before the last switch

Converter AC parameters

Converter AC Parameters					
	Real Power	Reactive Power	Phase Voltage (RMS)	Phase Current (RMS)	Output Frequency
	-0.07 kW	45.05 MVAR	20.81 kV	722 A	50 Hz

Figure 14 Converter AC Parameters

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

Reactive power Q — Q as supplied to load 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

Control Parameters

Control Parameters				
	Cell Voltage	Switching Frequency	Modulation Index	No. of Cells/phase
	2.433 kV	269 Hz	0.80	15.00

Figure 15 Control Parameters

Cell Voltage — Average capacitor voltage of a cell in a phase leg

Switching Freq. — According to the definition

Modulation Ind. — According to calculations defined in chapter 6.2

No. of Cells — Number of cells per phase leg

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, the alert message is displayed
Warning message	IGBT temperature out of the safe operating area

5.2 Cell Voltage

Parameter	Cell Voltage
Verification	If the Cell voltage is greater than the safe operating voltage rating of IGBT and/or diode, the alert message is displayed
Warning message	For the voltage rating 1.7kV, Vcellmin = 200V & Vcellmax = 1100V

6. APPLIED CALCULATIONS

6.1 Input Parameter Definitions

V_{cell}	Cell Voltage
n_{cell}	No. of cells in a phase leg
$V_{LL\_AC\_RMS}$	Line voltage RMS

6.2 Line-Line RMS Voltage of Grid/Load Definition

$$V_{LL\_AC\_RMS} = \frac{\sqrt{3} * m * n_{cell} * V_{cell}}{\sqrt{2}}$$ for Star connected

$$V_{LL\_AC\_RMS} = \frac{m * n_{cell} * V_{cell}}{\sqrt{2}}$$ for Delta connected

6.3 Real Power

P_{DC}	DC power / real power absorbed from DC side of VSC calculated according
P_{AC}	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

$$V_{trueRMS} = \sqrt{\frac{1}{n} \sum_{\nu=1}^{n} \widehat{u_\nu^2}}$$

It includes all harmonic components NOT ONLY 1st order of output frequency.

$$I_{trueRMS} = \sqrt{\frac{1}{n} \sum_{\nu=1}^{n} \widehat{\iota_\nu^2}}$$

It includes all harmonic components NOT ONLY 1st order of output frequency.

According to:

$$P_{AC} = \frac{3}{n} \sum_{\nu=1}^{n} \widehat{u_\nu} \,.\, \widehat{\iota_\nu} . \cos \varphi_\nu = 3 . V_{trueRMS} . I_{trueRMS} . PF$$

In the FACTS application, real power is equal to zero ideally.

6.4 Reactive Power

Q — Effective reactive power on the converter AC side [VAr]

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

V_{PH_RMS} — Phase voltage (RMS)

I_{PH_RMS} — Phase current (RMS)

Defined as the Loss (%) η is the ratio of calculated combined converter losses with respect to the converter input power.
The Q is the main input power definition. Loss (%) η is given by:

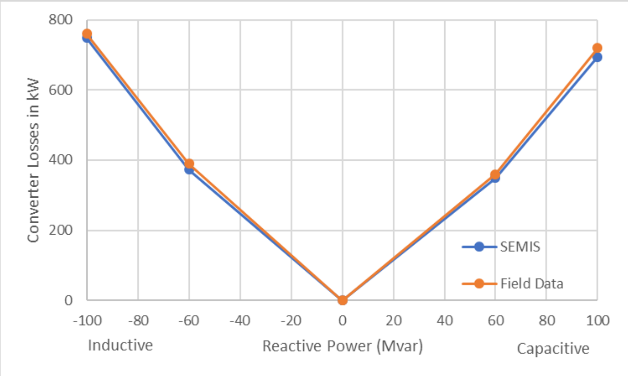
$$\eta = \frac{P_{LossConverter}}{Q} * 100\%$$

7. VALIDATION OF SEMIS RESULTS WITH ACTUAL FIELD DATA

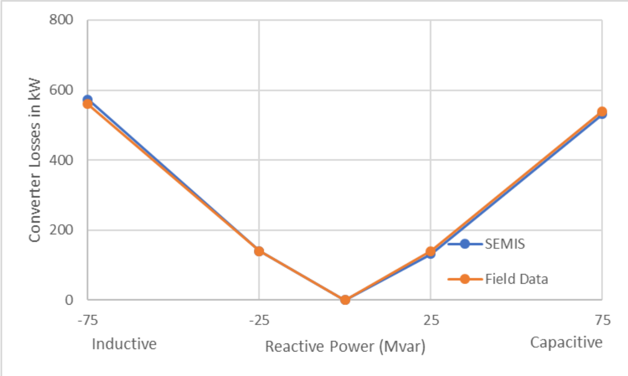
To ensure supplied simulation results are reliable, each SEMIS topology is validated with another simulation system or compared to real measurement data.

The total converter semiconductor losses of FACTS Full Bridge MMC with IGBT Star Connected for two cases with different reactive powers are validated with Actual Field Data.

The total converter losses in SEMIS and Actual Field Data are closely matching and the average deviation is well within tolerance (<5%) for both the cases as shown in Figure 16.



(a) Case 1



(b) Case 2

Figure 16 Validation of SEMIS results with Field Data for FACTS Full Bridge MMC with IGBT Star Connected

FACTS Full Bridge MMC with IGBT Delta Connected model is validated with FACTS Full Bridge MMC with IGBT Star Connected model by keeping equal cell voltages and phase currents. Five cases are simulated in both models by varying different parameters like converter line voltage, converter reactive power etc. with the electrical parameters presented in the tables below for comparison.

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 total converter losses and the device junction temperatures that the results obtained from both models are very similar and the error percentage is within tolerance (<5%).

Remark:

The deviation in the individual switch loss distribution between FACTS Full Bridge MMC with IGBT Star Connected and Delta Connected is because of phase angle difference between modulating signals in respective models due to topology differences. Also, the phase current contains 3rd harmonic in case of Delta connected STATCOM.

Validation of SEMIS Results with Actual Field Data

Topology	SEMIS 4S FACTS Full Bridge MMC with IGBT Del		
Tester:	[illegible]		
Date	April 27, 2020		
Device used [.xml]	5SNA 2000K452300		
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 Delta	Set 1 Star	Set 1 Difference	Set 2 Delta	Set 2 Star	Set 2 Difference	Set 3 Delta	Set 3 Star	Set 3 Difference	Set 4 Delta	Set 4 Star	Set 4 Difference	Set 5 Delta	Set 5 Star	Set 5 Difference
Absolute average difference [%]			1.17%			1.14%			1.10%			1.61%			1.09%
Max difference [%]			8.15%			6.52%			8.16%			9.62%			7.94%
Device Losses & Temperatures															
Switching Losses IGBT1 [W]	356.29	345.32	4.22%	529.04	522.29	0.44%	910.26	880.19	4.45%	140.70	137.70	2.45%	856.06	799.47	6.64%
Switching Losses IGBT2 [W]	910.5	925.45	1.65%	559.52	517.45	6.52%	874.72	883.49	1.60%	149.47	129.67	9.62%	849.02	790.29	5.90%
Switching Losses Diode1 [W]	175.30	176.71	0.41%	197.19	187.60	4.79%	160.35	163.60	0.49%	57.07	51.60	9.44%	193.77	179.64	7.29%
Switching Losses Diode2 [W]	184.67	174.71	5.33%	190.37	189.59	0.75%	177.25	167.3	5.67%	56.09	54.92	4.52%	196.00	180.57	7.94%
Switching Losses IGBT3 [W]	874.74	946.01	8.15%	512.54	507.5	1.02%	840.51	909.09	8.16%	196.99	190.47	1.59%	779.99	822.09	5.64%
Switching Losses IGBT4 [W]	807.65	896.54	1.00%	502.09	592.59	6.00%	852.79	861.55	1.09%	149.50	142.09	4.47%	785.21	776.00	1.06%
Switching Losses Diode3 [W]	171.49	171.52	0.02%	189.45	190.09	4.06%	164.60	164.67	0.04%	57.44	55.20	3.76%	175.01	174.59	0.79%
Switching Losses Diode4 [W]	167.1	179.60	7.52%	186.49	185.49	0.54%	160.40	172.51	7.50%	59.02	56.52	5.02%	179.69	184.70	6.41%
Conduction Losses IGBT1 [W]	1110	1101	0.01%	470.02	476.59	0.52%	1107	1090	0.04%	292.77	299.37	0.20%	429.45	421.99	0.50%
Conduction Losses IGBT2 [W]	1109	1105	0.54%	479.04	476.29	0.74%	1106	1100	0.54%	299.49	292.19	2.44%	429.99	421.90	0.62%
Conduction Losses Diode1 [W]	352.27	349.05	0.37%	469.67	460.59	0.60%	951.56	941.7	1.02%	251.5	256.24	1.07%	414.60	419.00	0.99%
Conduction Losses Diode2 [W]	350.22	349.64	0.69%	469.45	460.64	0.64%	949.97	942.29	0.75%	252.05	255.79	1.45%	419.07	419.01	0.24%
Conduction Losses IGBT3 [W]	1111	1105	0.40%	477.35	474.41	0.62%	1109	1100	0.27%	292.09	290.60	2.26%	424.02	429.99	0.04%
Conduction Losses IGBT4 [W]	1107	1104	0.27%	475.51	474.79	0.16%	1104	1101	0.27%	295.9	290.29	0.04%	422.24	422.21	0.04%
Conduction Losses Diode3 [W]	346.02	341.1	0.60%	465.30	462.20	0.67%	946.04	939.74	0.67%	250.54	251.99	0.56%	412.45	411.04	0.45%
Conduction Losses Diode4 [W]	345.09	390.55	0.77%	464.5	462.00	0.52%	945.09	937.27	0.02%	257.92	251.02	2.45%	412.24	410.37	0.34%
Combined Losses IGBT1 [W]	2066	2017	2.37%	1002	990.69	0.94%	2025	1970	2.92%	499.55	491.19	0.56%	1200	1221	4.64%
Conduction Losses IGBT2 [W]	2020	2020	0.40%	1033	999.71	3.00%	1981	1989	0.40%	442.9	421.0	4.76%	1279	1220	4.16%
Combined Losses Diode1 [W]	1120	1120	0.74%	660.0	640.21	1.34%	1120	1111	0.00%	300.57	307.09	0.22%	600.45	592.72	2.59%
Combined Losses Diode2 [W]	1135	1110	1.50%	654.42	650.14	0.65%	1127	1109	1.60%	309.75	310.00	0.11%	609.35	599.50	2.60%
Combined Losses IGBT3 [W]	1906	2055	3.47%	909.05	904.71	0.02%	1949	2019	3.39%	420.40	437.19	2.02%	1282	1240	3.66%
Combined Losses IGBT4 [W]	1994	2000	0.30%	977.54	1007	3.04%	1957	1962	0.26%	445.40	441.10	0.97%	1207	1199	0.66%
Combined Losses Diode3 [W]	1110	1115	0.45%	640.02	659.10	0.67%	1111	1104	0.69%	307.90	307.29	0.24%	500.27	506.37	0.92%
Combined Losses Diode4 [W]	1119	1110	0.45%	651	647.57	0.53%	1106	1110	0.36%	311.14	307.55	1.16%	505.07	595.79	1.60%
Junction Temperature Avg IGBT1 [°C]	116.02	114.55	1.29%	79.14	70.0	0.49%	114.01	119.41	1.22%	62.49	62.39	0.16%	85.27	83.44	2.15%
Junction Temperature Avg IGBT2 [°C]	114.35	114.05	0.40%	79.02	70.71	1.39%	119.79	119.65	0.12%	62.01	62.02	1.26%	85.19	83.49	2.00%
Junction Temperature Avg Diode1 [°C]	116.07	115.45	1.29%	80.74	80.20	0.57%	115.61	114.39	1.06%	65.69	65.54	0.14%	84.65	82.99	1.96%
Junction Temperature Avg Diode2 [°C]	115.35	115.55	0.34%	81.17	80.24	1.45%	114.92	114.54	0.33%	65.00	65.47	0.62%	84.57	82.99	1.87%
Junction Temperature Avg IGBT3 [°C]	119.75	115.45	1.40%	70.59	70.46	0.17%	112.65	114.22	1.39%	62.29	62.54	0.50%	82.07	83.90	1.32%
Junction Temperature Avg IGBT4 [°C]	119.06	114.12	0.29%	70.91	79.01	0.05%	112.74	112.90	0.20%	62.99	62.7	0.37%	82.96	82.94	0.02%
Junction Temperature Avg Diode3 [°C]	114.76	115.30	1.05%	80.12	80.1	0.02%	119.79	114.9	0.90%	65.49	65.69	0.24%	82.40	89.29	0.90%
Junction Temperature Avg Diode4 [°C]	114.76	115.04	0.24%	79.95	80.49	0.60%	119.70	114.04	0.20%	66.04	65.72	0.44%	82.5	82.69	0.10%
Converter Losses [kW]	670.9	670.0	0.07%	957.4	955.9	0.59%	549.0	520	0.04%	479.9	477.0	0.04%	441.9	495.2	1.90%
Losses Efficiency	0.60	0.60	0.00%	0.6	0.59	1.67%	0.69	0.69	0.00%	0.957	0.954	0.04%	0.407	0.409	0.02%
Control Parameters															
Cell Voltage [V]	1070	1000	0.11%	1945	1944	0.05%	1009	1012	0.17%	2226	2227	0.04%	3462	3465	0.09%
Switching Frequency [Hz]	269.29	269.29	0.00%	269.29	269.29	0.00%	269.29	269.29	0.00%	159.046	159.046	0.00%	269.29	269.29	0.00%
No.of Cells per phase	10	10	0.00%	10	10	0.00%	14	14	0.00%	20	20	0.00%	20	20	0.00%
Modulation Index	0.9	0.9	0.00%	0.9	0.9	0.00%	0.9	0.9	0.00%	0.8	0.8	0.00%	0.8	0.8	0.00%
Converter AC Parameters															
Reactive Power [MVAR]	99.90	100.1	0.12%	-60.00	-60.065	0.02%	74.90	75.00	0.13%	-50.47	-50.457	0.03%	90.06	90.1	0.04%
Phase Voltage RMS [kV]	22.02	22.02	0.00%	22.02	22.02	0.00%	16.54	16.52	0.06%	25.02	25.02	0.00%	56.04	56.04	0.00%
Phase Current RMS [A]	1514	1515	0.07%	909	909	0.00%	1519	1519	0.13%	660	660	0.00%	899	899	0.00%
Output Frequency [Hz]	50	50	0.00%	50	50	0.00%	50	50	0.00%	50	50	0.00%	50	50	0.00%

Figure 17 Validation of FACTS Full Bridge MMC Delta Connected with Star Connected

8. USER MANUAL REVISION HISTORY

Rev.	Page	Change Description	Date / Initial
1.3	all	Included Validation results & Reactive Power Definition	2020-28-04 PGGI/HM
1.2	all	Inclusion of delta connected model	2019-23-12 PGGI/HM
1.1	all	Initial version in new design	2019-23-09 PGGI/HM

9. SIMULATION SOFTWARE RELEASE HISTORY

Rev.	New topic	Fixed defects	Tvj influence	Date
1.1	Reactive Power Definition	-	-	2020-28-04 PGGI/HM
1.0	Initial version	-	-	2019-23-09 PGGI/HM

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