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**

![Three-Phase 2-Level converter circuit in website](image)

**Converter settings**
- **Converter Operation**: Inverter
- **Ambient Temperature**: 25 °C
- **System Frequency**: 50 Hz
- **Switching Frequency**: 900 Hz
- **PWM Strategy**: Sinusoidal PWM
- **Modulation Index**: 0.8
- **DC Voltage**: 1100 V
- **AC Reference Parameters**: AC Power
- **AC Side Power**: 1400 kVA
- **Power Factor Value**: 0.9
- **Power Factor Type**: Inductive (Converter)
- **Heat Sink Thermal Resistance**: 0.02 K/W
- **IGBT Module Type**: HiPak
- **IGBT Selection**: 1.7 kV
- **Module Configuration**: Single IGBT

Matching IGBTs:
- [ ] SSNA 1800E170100 1800 A
- [ ] SSNA 1800E170100 1800 A
- [ ] SSNA 2400E170035 2400 A, 150°C
- [ ] SSNA 3600E170035 3600 A, 150°C

Results tables:
- **Device Losses & Temperatures**
  - per IGBT: 523.57 W, 1.333 kW, 1.857 kW
  - per Diode: 107.70 W, 272.78 W, 406.48 W
- **Converter Losses**: 4.27 %, 9.64 %, 13.90 %
- **% Losses**: 1.23 %

Results graphs:
- **IGBT1, Diode**
  - Phase Voltage & Current
  - IGBT1 Switching Loss, Diode Reverse Recovery Loss
  - IGBT1 D1 Conduction Loss
  - IGBT1, D1 Junction Temp

**Figure 1** Three-Phase 2-Level converter circuit in website
Simulation Settings

3. SIMULATION SETTINGS

3.1 Circuit parameters

3.1.1 Converter Operation

Converter can be operated either as Inverter DC to AC or as Rectifier AC to DC.

Converter Operation: Inverter

Figure 2 Converter mode selection

3.1.2 Ambient temperature

Ambient temperature defines the environmental temperature around the converter for temperature/cooling calculations.

Ambient Temperature: 25 °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.

Switching frequency: 900 Hz

PWM strategy: Sinusoidal PWM

Modulation Index: 0.8

DC Voltage: 700 V

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 Selection

Three different Control methods are implemented, which are Sinusoidal PWM, Space Vector PWM and Third Harmonic Injection. Find technical background and explanations in Chapter 15.

MODULATION INDEX: Definition of modulation index Range 0 .. 1 (1.15)

Sinusoidal PWM limit is 1.00
Space Vector PWM limit is 1.15
3rd Harmonic injection limit is 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).

![Grid/Load parameter input blocks](image)

**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

**AC SIDE POWER**

AC Side Power demand from the load / connected grid

**AC SIDE CURRENT (RMS)**

AC Side Current demand from the load / connected grid

**POWER FACTOR VALUE**

Power Factor of the load / connected grid

**POWER FACTOR TYPE**

The power factor type can be selected as Inductive or Capacitive based on lagging or leading power factor

3.2 Switch settings

![Thermal settings and IGBT selection](image)

**HEAT SINK THERMAL RESISTANCE:**

Definition of thermal resistance of cooling system applied.

**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.
Simulation Settings

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.

<table>
<thead>
<tr>
<th>IGBT module type</th>
<th>Select housing type of IGBT for filtering</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT selection</td>
<td>Select voltage class of IGBT for filtering</td>
<td>Selection</td>
</tr>
<tr>
<td>Module configuration</td>
<td>Select topology of IGBT module for filtering</td>
<td>Selection</td>
</tr>
</tbody>
</table>

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.

Matching IGBTs:

- [ ] FSNA 0550.I450300 650 A
- [ ] FSNA 0800.I450300 800 A
- [ ] FSNA 1200G450300 1200 A
- [x] FSNA 1200G450350 1200 A

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
- [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:

![Graphical results of Three-phase 2-level VSC converter](image)

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

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

- 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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Cursor 1</th>
<th>Cursor 2</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>0.050242</td>
<td>0.090315</td>
<td>0.039073</td>
</tr>
<tr>
<td>Phase Voltage &amp; Current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase Voltage-A</td>
<td>708.4</td>
<td>-366.7</td>
<td>1075</td>
</tr>
<tr>
<td>Phase Current-A</td>
<td>2121</td>
<td>-2115</td>
<td>4236</td>
</tr>
<tr>
<td>IGBT1, D1 Current [A]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGBT current</td>
<td>2121</td>
<td>0.000</td>
<td>2121</td>
</tr>
<tr>
<td>Diode current</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>IGBT1 Switching Loss, D1 Reverse Recovery Loss [W]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGBT Switching Loss</td>
<td>1583</td>
<td>0.000</td>
<td>1583</td>
</tr>
<tr>
<td>Diode Reverse Recovery Loss</td>
<td>0.000</td>
<td>530.4</td>
<td>-530.4</td>
</tr>
<tr>
<td>IGBT1, D1 Conduction Loss [W]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGBT Conduction Loss</td>
<td>5230</td>
<td>0.000</td>
<td>5230</td>
</tr>
<tr>
<td>Diode Conduction Loss</td>
<td>0.000</td>
<td>529.5</td>
<td>-529.5</td>
</tr>
<tr>
<td>IGBT1, D1 Junction Temp [C]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGBT Junction Temperature</td>
<td>118.0</td>
<td>111.0</td>
<td>7.062</td>
</tr>
<tr>
<td>Diode Junction Temperature</td>
<td>90.11</td>
<td>90.87</td>
<td>-0.7623</td>
</tr>
</tbody>
</table>

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.
The indicated elements in the table upper IGBT etc. correspond to the different semiconductor positions in a full bridge cell as shown in Error! Reference source not found..

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**

![Figure 12 Device Losses & Temperatures](image)

<table>
<thead>
<tr>
<th>Losses Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Loss</td>
<td>Single IGBT or Diode Losses during turn on and turn off events (dynamic)</td>
</tr>
<tr>
<td>Conduction loss</td>
<td>Single IGBT or Diode Losses during on state (static)</td>
</tr>
<tr>
<td>Combined losses</td>
<td>Sum of single IGBT or Diode switching and conduction loss.</td>
</tr>
<tr>
<td>Converter losses</td>
<td>Sum of all IGBT and Diode losses</td>
</tr>
<tr>
<td>% Losses</td>
<td>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.</td>
</tr>
</tbody>
</table>

**Converter AC parameters**

![Figure 13 Definition of Tvj before last switch](image)
Simulation Results

**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**

**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](image)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoidal</td>
<td>1960</td>
<td>110.74</td>
<td>539</td>
<td>92.3</td>
<td>14.99</td>
<td>1.84</td>
<td>354</td>
<td>943</td>
<td>1</td>
</tr>
<tr>
<td>Space vector</td>
<td>1679</td>
<td>95.99</td>
<td>379</td>
<td>76.88</td>
<td>12.35</td>
<td>1.52</td>
<td>407</td>
<td>820</td>
<td>1.15</td>
</tr>
<tr>
<td>3rd harmonic</td>
<td>1670</td>
<td>96.17</td>
<td>403</td>
<td>77.87</td>
<td>12.44</td>
<td>1.53</td>
<td>407</td>
<td>820</td>
<td>1.15</td>
</tr>
</tbody>
</table>

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 (\( \cos \phi \))
- **V\(_{DC}\)**: Selected DC link voltage
- **I\(_{DC}\)**: Mean value of DC current waveform
- **V\(_{Ph,AC,RMS}\)**: Phase voltage RMS
- **I\(_{Ph,AC,RMS}\)**: Phase current RMS

7.2 **Line-Line RMS Voltage of Grid/Load Definition**

\[
V_{LLRMS} = \frac{m \cdot V_{DC Link}}{2\sqrt{2}}
\]

7.3 **Real Power**

- **P\(_{DC}\)**: DC power / real power absorbed from DC side of VSC calculated according to the real / active power transferred to converter output calculated as:
- **P\(_{AC}\)**: 
- **V\(_{TrueRMS}\)**: True phase voltage RMS AC line to neutral
- **I\(_{TrueRMS}\)**: True phase current RMS AC
- **\( \eta \)**: Power conversion efficiency

\[
P_{DC} = V_{DC} \cdot I_{DC}
\]

\[
V_{trueRMS} = \sqrt{\frac{1}{n} \sum_{v=1}^{n} u_{v}^2}
\]

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

\[
I_{trueRMS} = \sqrt{\frac{1}{n} \sum_{v=1}^{n} i_{v}^2}
\]

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

According to:

\[
P_{AC} = \frac{3}{n} \sum_{v=1}^{n} u_{v} \cdot i_{v} \cdot \cos \phi_{v} = 3 \cdot V_{trueRMS} \cdot I_{trueRMS} \cdot PF
\]

For Inverter or Rectifier mode, the DC power definition \( P_{DC} \) can be computed as

\[
P_{DC} = P_{AC} + P_{Loss\text{Converter}}
\]
Applied Calculations

Defined as the Loss (%) \( \eta \) 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 (%) \( \eta \) is given by:

\[
\eta = \frac{P_{Loss\,Converter}}{P_{DC}} \times 100\%
\]

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

\[
\eta = \frac{P_{Loss\,Converter}}{P_{AC}} \times 100\%
\]

7.4 Reactive Power

\( Q \) \hspace{1cm} \text{Effective reactive power on converter AC side [VAr]}
\( Q = 3 \times V_{Ph\,RMS} \times I_{Ph\,RMS} \times \sin(\varphi_1) \)

\( V_{Ph\,RMS} \) \hspace{1cm} \text{Phase voltage (RMS)}

\( I_{Ph\,RMS} \) \hspace{1cm} \text{Phase current (RMS)}

\( \rho_1 \) \hspace{1cm} \text{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 ($V_d$), 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 $R_{th(c-a)}$ 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.

![Figure 18 Validation SEMIS / PSCAD results comparison 2 level 3 phase](image)
## 9. USER MANUAL REVISION HISTORY

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Page</th>
<th>Change Description</th>
<th>Date / Initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>all</td>
<td>DC voltage definition change</td>
<td>2020-03-04 PGGI/HM</td>
</tr>
<tr>
<td>1.2</td>
<td>all</td>
<td>Initial version in new design</td>
<td>2019-08-22 PGGI/DS</td>
</tr>
</tbody>
</table>

## 10. SIMULATION SOFTWARE RELEASE HISTORY

<table>
<thead>
<tr>
<th>Rev.</th>
<th>New topic</th>
<th>Fixed defects</th>
<th>Tvj influence</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>DC Voltage to 2 DC sources</td>
<td>-</td>
<td>No</td>
<td>2020-03-04 PGGI / HM</td>
</tr>
</tbody>
</table>
Contact

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