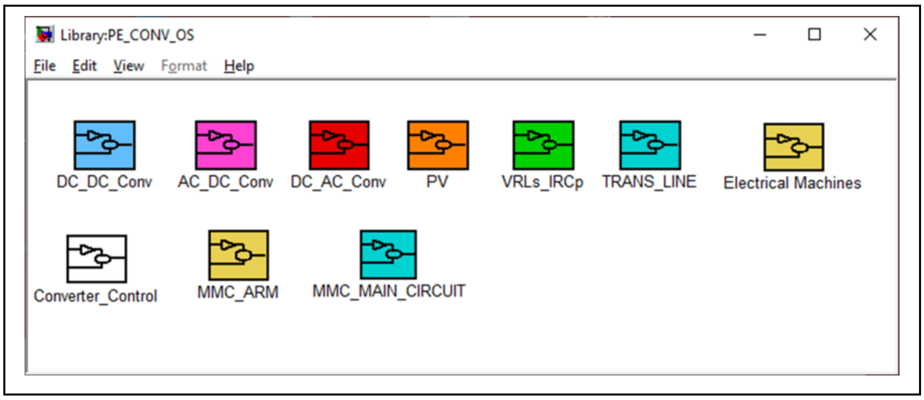
Open Source Simulink Power Electronics BLOCKSET

Prof. Dr. Samir Salama
Samir.salama@hs-duesseldorf.de
Samir.salama47@yahoo.de

Sim-PEX, Berlin, Germany
Samir.salama@sim-pex.com

The Open Source Simulink Power Electronics Blockset contains Simulink-blocks to model and simulate many of the well-known Power Electronics converters in Matlab/Simulink environment without a need for any power electronics toolbox. The Blockset is modelled using either the built-in Simulink-Blocks and/or the Simulink C-Language S-Functions.



Simulink Open Source Power Electronics Blockset

Some of the features of this new developed Simulink open source Power Electronics Blockset can be summarized as follows:

- All developed power electronics Simulink blocks use only Simulink, there are no need for any power electronics toolbox;
- The switching devices (Diode, Thyristor, IGBT, IGBT/Diode, etc.) are modelled as two values resistance (*Ron*=1e-3/ *Roff*=1e6), there are no need for switching functions, average or Aggregate models.
- Using only built-in Simulink-Blocks and/or the Simulink C-Language S-Functions. Using the C-S-Functions, the algebraic loops can be avoided as can be seen in the modelling of the photovoltaic array.
- They behave exactly like built-in Simulink blocks, they have their own parameters, and they can be copied and pasted. The model parameters can be changed either dynamically or interactively during the simulation;
- The blockset offers significant speed improvements due to the small system matrix dimensions. The simulation time cost using the blockset is some hundred times faster than the worldwide de facto standard EMT-based simulator.

- Power electronics Simulink Blocks containing non switching device can be simulated using multirate (multiples of the simulation step size)
- The current version of the open-source power electronics Simulink blockset can use Simulink *Normal* and *Accelerator* simulation modes. *Rapid Accelerator* simulation mode, *real time code generation* and the *Message Passing Interface* for multicore simulation are available only on the non-open-source power electronics Simulink blockset.

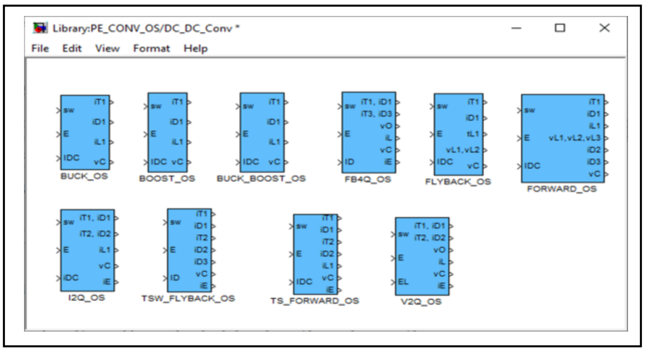
The Open Source Simulink Power Electronics BLOCKSET is available at no cost; it is user-friendly and is validated by comparing the results with the Simscape Electrical (Specialized Power Systems).

1. **DC-DC Converters**:

DC-DC converters can be mainly divided into two basic categories, based on the coupling of the load circuit.

- Directly coupled dc-dc converters
    - Buck-Converter
    - Boost-Converter
    - Buck-Boost-Converter
    - Full-Bridge DC-Converter
    - Current-two-Quadrant DC- Converter
    - Voltage-two-Quadrant DC- Converter
    - Full bridge four quadrant converter
- Magnetically coupled dc-dc converters
    - Flyback-Converter
    - Forward-Converter
    - Two-Switch Flyback-Converter
    - Two-Switch Forward-Converter

The Load circuit is a parallel combination of current source, capacitor and a load resistor. The capacitor and resistor values are defined as components of the Parameter-Vector of the Simulink-C-S-function block. They can be interactively changed during the simulation. The load current source and the input voltage source are defined as components of the Input-Vector of the Simulink-C-S-function block. They can be changed either dynamically or interactively during the simulation.



DC-DC Converters:

2. **AC-DC Converters**:

Line frequency non controlled and phase controlled converters find use mostly in high power applications such as electrochemical processes, high power dc and ac motor drives.

In these converters, current commutation from one device to the next occurs naturally under the influence of the ac voltages. Therefore the ac to controlled dc conversion is accomplished by means of thyristors.

The following converters are modelled as open source converters:

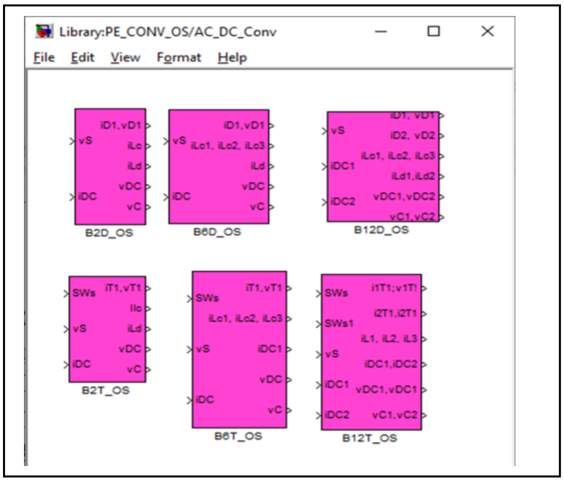
2.1 None controlled AC-DC Converters

- Single-Phase Full-Bridge Diode Converter B2D
- Three-Phase Full-Bridge Diode Converter B6D
- Three-Phase 2 Series Full-Bridge Diode Converter B12D

2.2 Controlled AC-DC Converters

- Single-Phase Full-Bridge Thystor Converter B2T
- Three-Phase Full-Bridge Thystor Converter B6T
- Three-Phase 2 Series Full-Bridge Thystor Converter B12T

The Load circuit is a parallel combination of current source, capacitor and a load resistor. The capacitor and resistor values are defined as components of the Parameter-Vector of the Simulink-C-S-function block. They can be interactively changed during the simulation. The load current source and the input voltage source are defined as components of the Input-Vector of the Simulink-C-S-function block. They can be changed either dynamically or interactively during the simulation.



AC-DC Converters

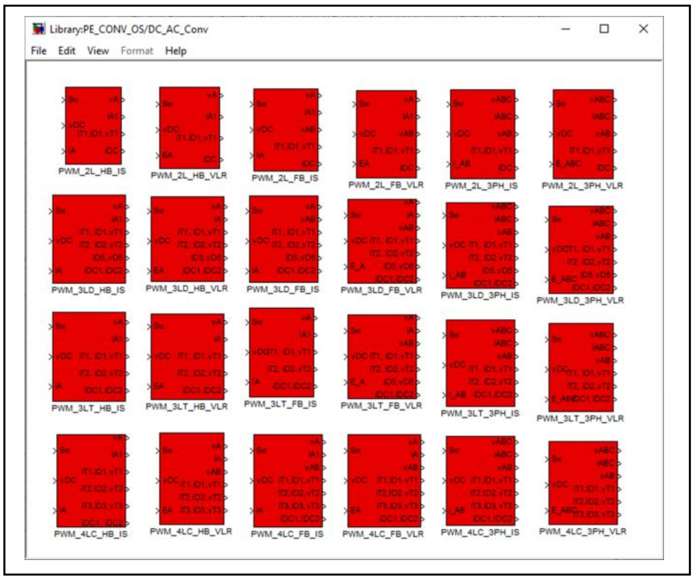
2. **DC-AC Converters**:

These converters are connected between a DC-source and an AC-source. The power flow can be from the DC- source to the AC-source or vice versa.

The Load circuit is either one current source IA, or a series connected voltage source, inductance and resistance VLR. The Load circuits for the 3-Phase inverters are either two current sources IAB, or three series connected voltage source, inductance and resistance 3VLR.

- Pulse with modulated 2-Level HB Inverter-IS
- Pulse with modulated 2-Level HB Inverter-VLR
- Pulse with modulated 2-Level FB Inverter-IS
- Pulse with modulated 2-Level FB Inverter-VLR
- Pulse with modulated 2-Level 3-Phase Inverter-IS
- Pulse with modulated 2-Level 3-Phase Inverter-3VLR
- Pulse with modulated 3-Level HB NPC Inverter-IS
- Pulse with modulated 3-Level HB NPC Inverter-VLR
- Pulse with modulated 3-Level FB NPC Inverter-IS
- Pulse with modulated 3-Level FB NPC Inverter-VLR
- Pulse with modulated 3-Level 3-Phase-NPC Inverter-IS
- Pulse with modulated 3-Level 3-Phase-NPC Inverter-VLR
- Pulse with modulated 3-Level HB T Inverter-IS
- Pulse with modulated 3-Level HB T Inverter-VLR
- Pulse with modulated 3-Level FB T Inverter-IS
- Pulse with modulated 3-Level FB T Inverter-VLR
- Pulse with modulated 3-Level 3-Phase-T Inverter-IS
- Pulse with modulated 3-Level 3-Phase-T Inverter-VLR

- Pulse with modulated 4-Level HB FC Inverter-IS
- Pulse with modulated 4-Level HB FC Inverter-VLR
- Pulse with modulated 4-Level FB FC Inverter-IS
- Pulse with modulated 4-Level FB FC Inverter-VLR
- Pulse with modulated 4-Level 3-Phase FC Inverter-IS
- Pulse with modulated 4-Level 3-Phase FC Inverter-VL

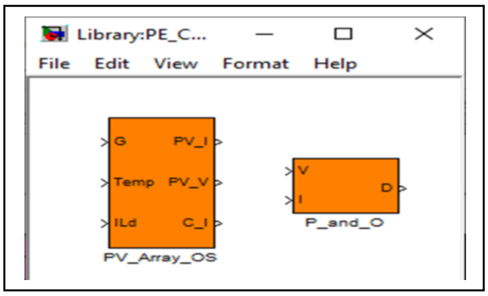


DC-AC Converters

3. Photovoltaic:

An ideal solar cell can be considered as a current source produced by the solar irradiation intensity falling on it. The recombination losses are represented by the diode connected parallel to the current source but in the reverse direction. The losses in the cell are modelled as a series and shunt resistances Rs and Rp respectively. The nonlinear Shockley diode equation is linearized about the operating point to get an appropriate companion model for the diode as a conductance in parallel with a current source.
This PV-Array can be used as a single PV-CELL, as a PV-MODULE composed of number N-Cells connected in series, as PV-STRING composed of number NMS- MODULEs connected in series and as PV-ARRAY composed of number NMP- STRINGs connected in parallel.

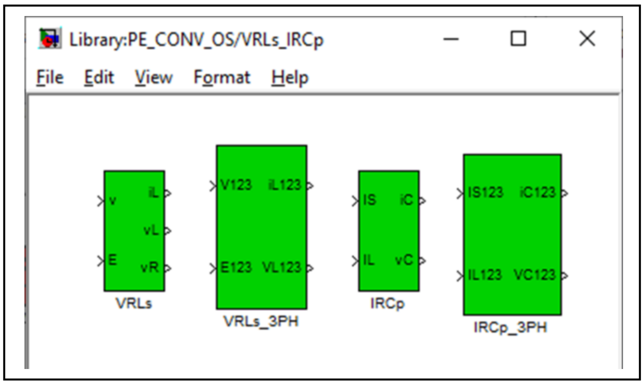
- PV-Array
- MPPT controller based on Perturb & Observe algorithm



Photovoltaic

4. **Passive circuit components**:

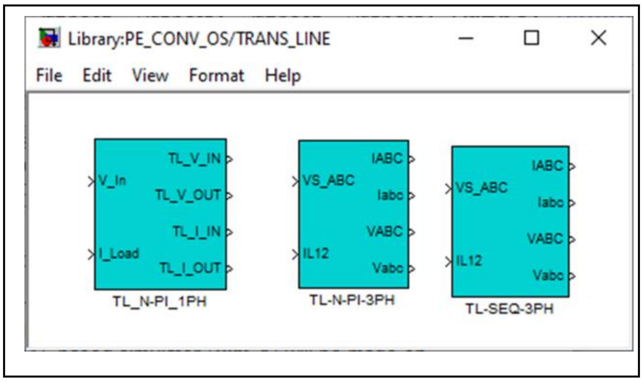
- Single Phase series Voltage source /Resistance/InductanceVRLs
- Three Phase series Voltage source /Resistance/InductanceVRLs_3PH
- Single Phase parallel Current source/Resistance/Capacitance IRCp
- Three Phase parallel Current source/Resistance/Capacitance IRCp_3PH



Passive circuit components

5. **Transmission Line**:

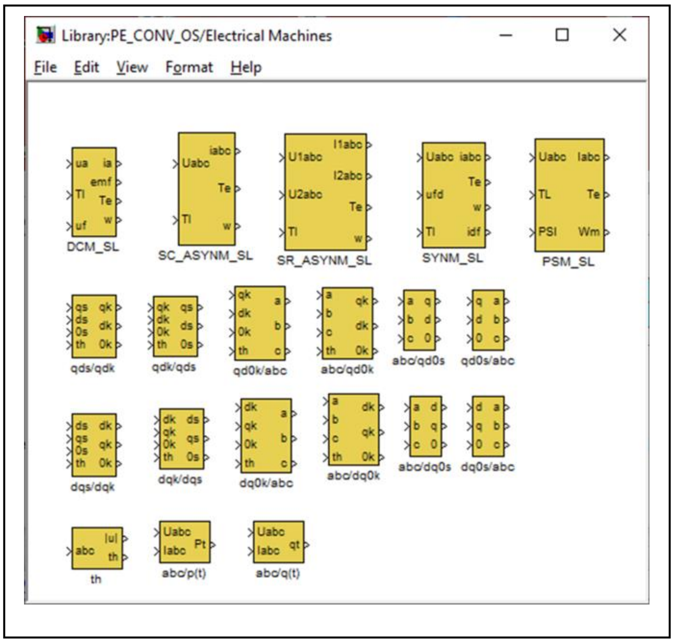
- Single Phase N-PI-Sections TL
- Three Phases N-PI-Sections TL
- Three Phases N-PI-Sections TL (Positive and Zero Sequence Parameters)



Transmission Line

6. **Electrical Machines**:

- Separately Excited DC-Motor (as Simulink Blocks)
- Squirrel-cage Induction Motor (as Simulink Blocks)
- Slip ring Induction Motor (as Simulink Blocks)
- Synchronous Motor (as Simulink Blocks)
- Permanent Magnet Synchronous Motor (as Simulink Blocks)
- Stationary qd0s to Rotating qd0k transformation
- Rotating qd0k to Stationary qd0s transformation
- Rotating qd0k to abc transformation
- abc to Rotating qd0k transformation
- abc to Stationary qd0s transformation
- Stationary qd0s to abc transformation
- Stationary dq0s to Rotating dq0k transformation
- Rotating dq0k to Stationary dq0s transformation
- Rotating dq0k to abc transformation
- abc to Rotating dq0k transformation
- abc to Stationary dq0s transformation
- Stationary dq0s to abc transformation
- abc to Amplitude and angle calculation
- Instantaneous active power using abc-components
- Instantaneous reactive power using abc-components



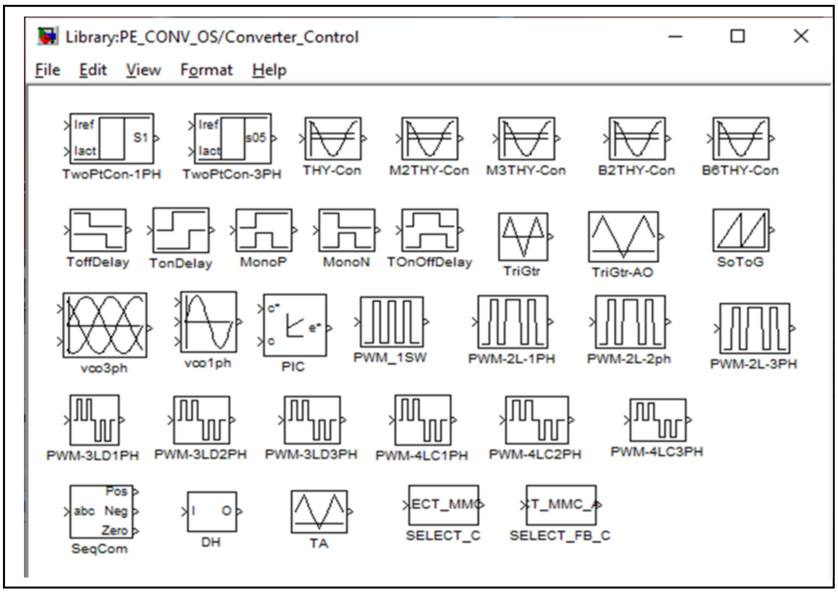
Electrical Machines

7. **Converter Control Blocks**

- Single phase hysteresis band controller with dead time protection
- Three phases hysteresis band controller with dead time protection
- One thyristor rectifier voltage controller based on cosine wave crossing method
- Two thyristor rectifier voltage controller based on cosine wave crossing method
- Three thyristor rectifier voltage controller based on cosine wave crossing method
- Single phase full bridge (B2) thyristor rectifier voltage controller based on cosine wave crossing method
- Three phases full bridge (B6) thyristor rectifier voltage controller based on cosine wave crossing method
- Turn-Off time delay
- Turn-On time delay
- Rising edge triggered Signal
- Falling edge triggered Signal
- Turn-on/Turn-off signal delay
- Triangular wave generator
- Triangular wave generator with offset and amplitude control
- Saw tooth wave generator
- Single phase voltage controlled oscillator
- Three phases voltage controlled oscillator
- PI-Controller with unti-windup
- Pulse Width-Modulator (PWM) based on Saw tooth wave generator
- One-Leg, 2-Level converter PWM based on triangular wave generator
- Two-Legs, 2-Level converter PWM based on triangular wave generator
- Three-Legs, 2-Level converter PWM based on triangular wave generator
- One-Leg, 3-Level converter (NPC) PWM based on triangular wave generator
- Two-Legs, 3-Level converter (NPC) PWM based on triangular wave generator
- Three-Legs, 3-Level converter (NPC) PWM based on triangular wave generator
- One-Leg, 4-Level converter (Floating Capacitors) PWM based on triangular wave generator
- Two-Legs, 4-Level converter (Floating Capacitors) PWM based on triangular wave generator
- Three-Legs, 4-Level converter (Floating Capacitors) PWM based on triangular wave generator

- Three phases abc-signals to positive/negative/Zero sequence transformation
- Third-harmonic signal generator.
- Triangular generator (TA).
- MMC sub-module selection for MMC-HB and MMC-CDSM Arms (SELECT_C).
- MMC sub-module selection for MMC-FB Arms (SELECT_FB_C).

The open source Simulink-Blocks "SELECT_C" and "SELECT_FB_C" are used to generate the switching signals for the switches in converter arm and to balance the capacitor voltages of the converter arm by selecting the suitable sub-circuits in the converter arm according to the switching command vector, the arm current vector and the previous state of charges of the capacitors in the arm.

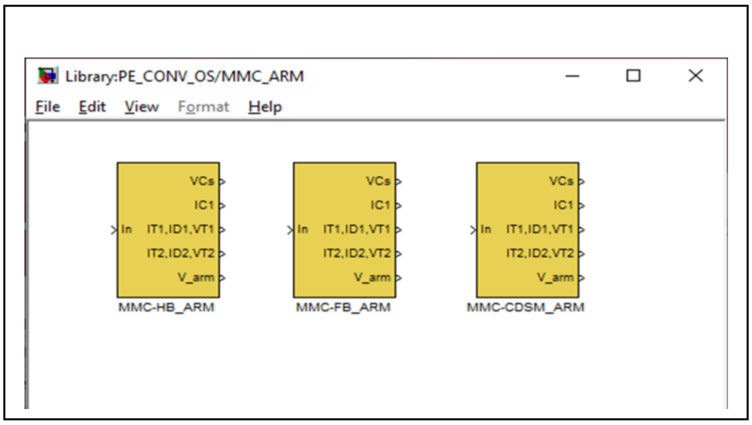


Converter Control Blocks

8.1 Modular Multi-Level Converter ARMs:

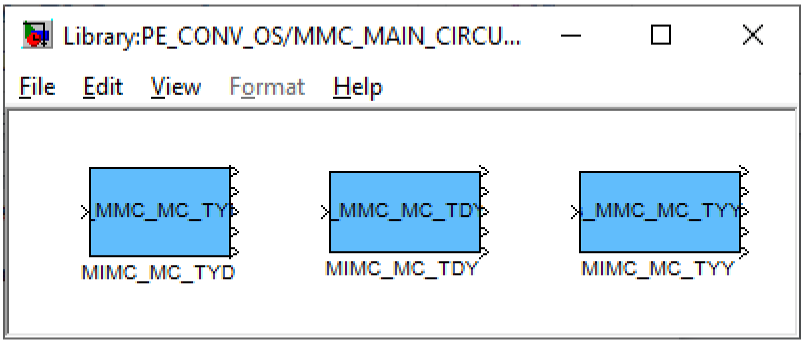
The developed open source Modular Multi-Level Converter Arms are modelled using series connection of MMC-Sub circuits. There are three of the well-known arm-sub circuits; the Half-Bridge (MMC-HB-ARM), the Full- Bridge (MMC-FB-ARM) and the coupled direct Sub-Module (MMC-CDSM-ARM). These Arms can be used for any number of MMC-Level by changing only the number of capacitors in the arm parameters.

- MMC_HB_ARM
- MMC_FB_ARM
- MMC_CDSM_ARM



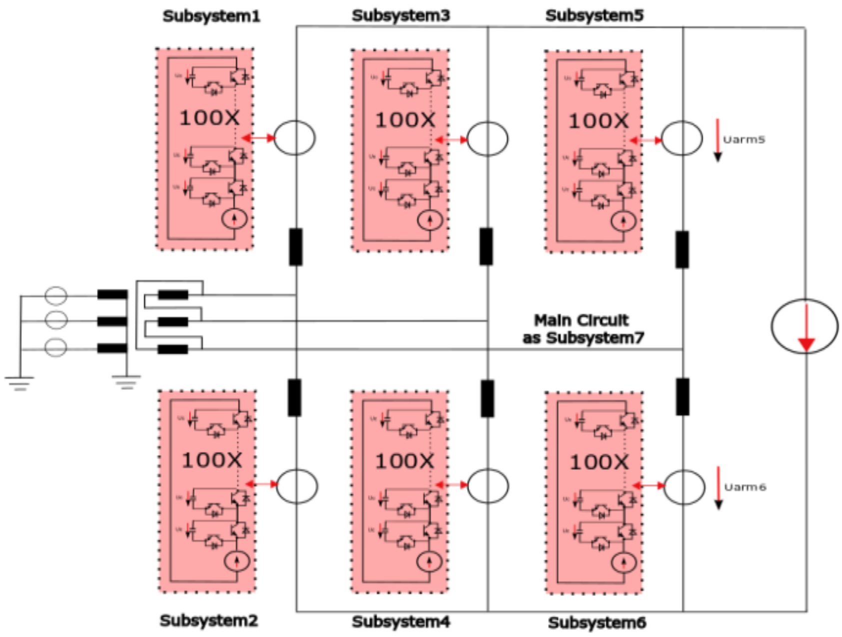
Modular Multi-Level Converter ARMs

8.2 Modular Multi-Level Converter Main Circuits:



Modular Multi-Level Converter Main Circuit

The three main converter circuits shown above are modelled as a Simulink C S-function block after replacing the converter arms with a voltage controlled voltage sources.



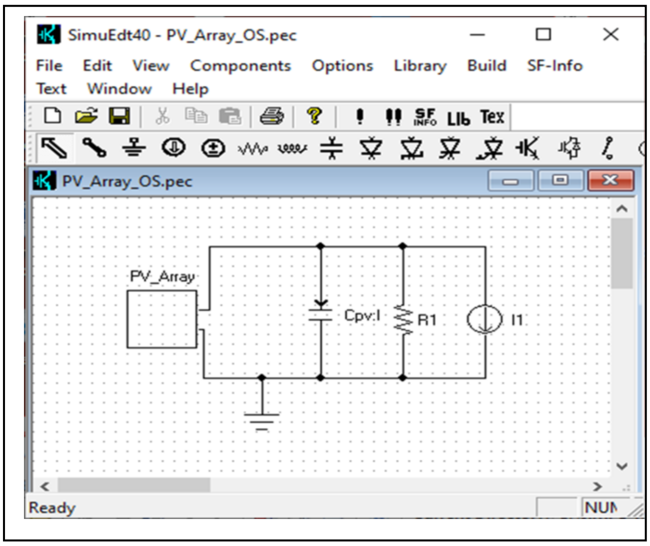
Grid connected 3-phase MMC- Converter main circuit.

The main circuit block sends the inductor current vector to the six converter arms blocks. Each of the six converter arms blocks sends the arm output voltage back to the main circuit block.

9. Examples of using the Simulink open source Power Electronics Blocks:

9.1 Simulation of Photovoltaic Array:

The electric circuit of the PV Array loaded with a current source in parallel with a load resistor and load capacitor shown in Fig. 9.1 is modelled as an open source Simulink block using the C-language S-Function Block "PV_Array_OS".



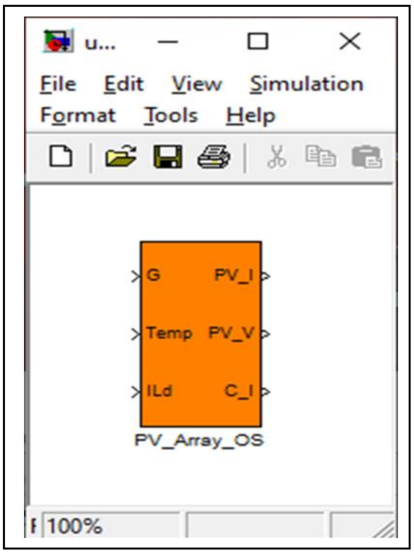
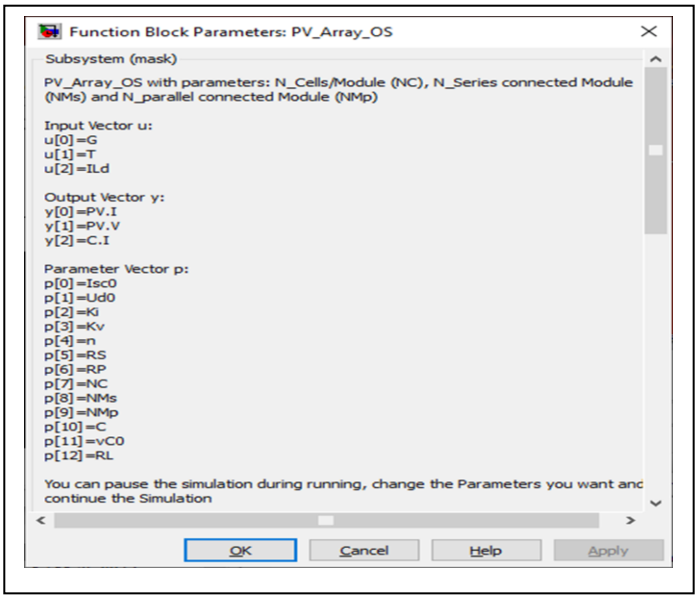


Fig. 9.1 Electric circuit of the PV Array and the open source Simulink block.

Double clicking the open source PV-Array Block shows the parameters used in the simulation. DATASheet:CRM175S125M-72.



Parameters of the open source PV-Array

Input Vector u[0,1,2]:

u[0]= actual solar radiation G (W/m^2)

u[1]= Cell's actual temperature in degree centigrade (ºC).

u[2]= Load current source ILd

Output Vector y[0,1,2]:

y[0]= PV-Array output current

y[1]= PV-Array output voltage.

y[2]= Load capacitor current IC1

Parameter Vector p{0:12}:

The parameters used in the simulation are:

p[0]= Short Circuit Current at STC Isc0/Module	= 5.28 A
p[1]= Open Circuit Voltage at STC Ud0/Module	= 44.5V
p[2]= Short Circuit Current Temp Coeff. Ki/Module	= 2e-3 A/^{o}C
p[3]= Open Circuit Voltage Temp. Coeff. Kv/Module	= -0.1558 V/^{o}C
p[4]= Diode Idealty Factor n	=1
p[5]= Series Resistance RS	= 0.05 Ohm
p[6]= Parallel Resistance RP	=400 Ohm
p[7]= Number Cells/Module	=72
p[8]= Number Series Modules	=1
p[9]= Number Parallel Modules	=1
p[10]= Load Capacitance	=1e-3 A
p[11]= Init Cap Voltage	=0
p[12]= Load Resistance	=10e3 Ohm

Fig. 9.2 shows the Simulink model for the simulation of the PV_Array_OS, and Fig. 9.3 shows the module I-V and the module P-V under various irradiances (1000 W/m^2, 500 W/m^2, and 100 W/m^2) and constant temperature of 25^{o}C. Fig. 9.4 shows the array I-V and the array P-V under various temperature (25, 50 and 100 ^{o}C) and constant irradiances of 1000 W/m^2.

At the end of simulation, the C-S-Function block of the Open Source PV_Array_OS delivers the following information:

S-Function NAME	=	PV_Array_OS
System Matrix Dimentions	=	3 * 3

As can be see, the System Matrix Dimensions of the 72-Cell-Module is very small (3*3)

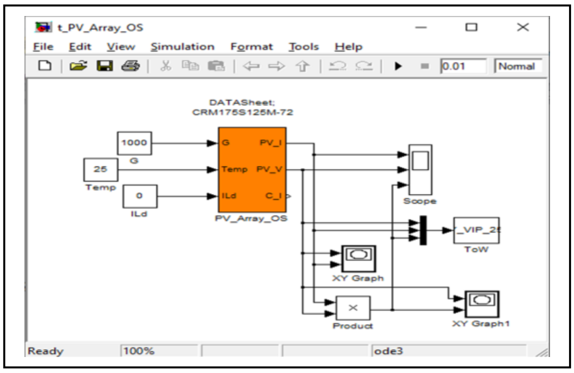


Fig. 9.2 Simulink model for the simulation of the PV_Array_OS

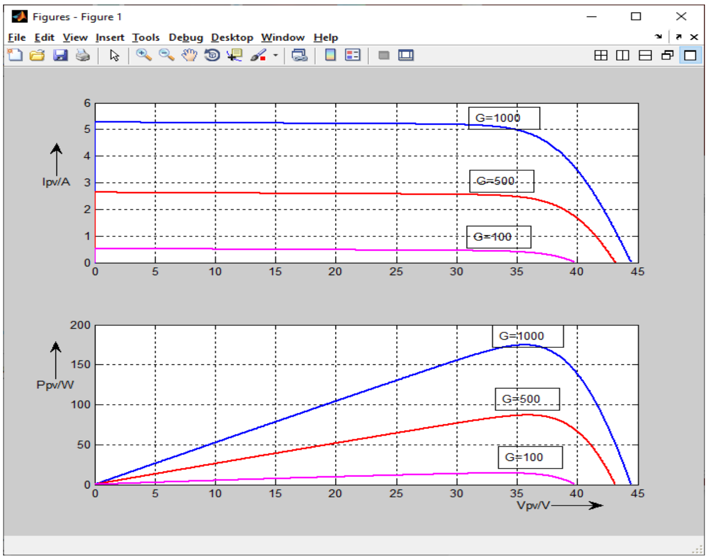


Fig. 9.3 Module I-V and the Module P-V under various irradiances and constant temperature of 25°C

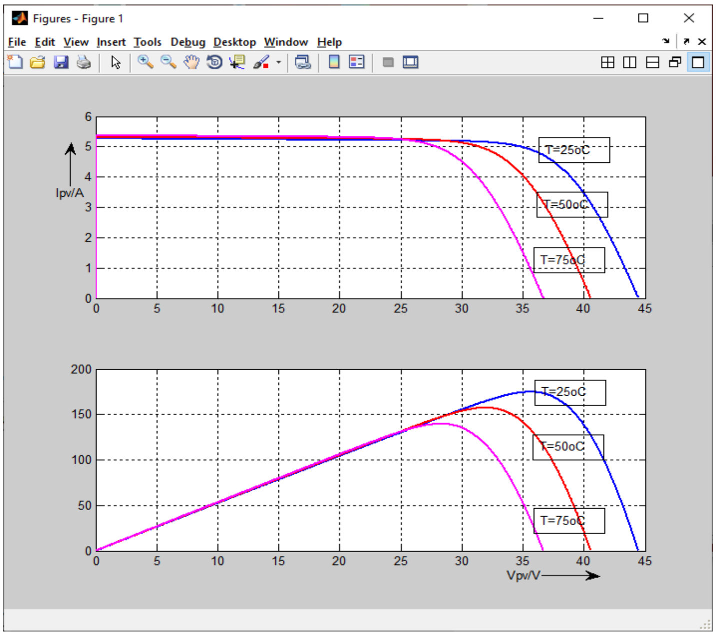
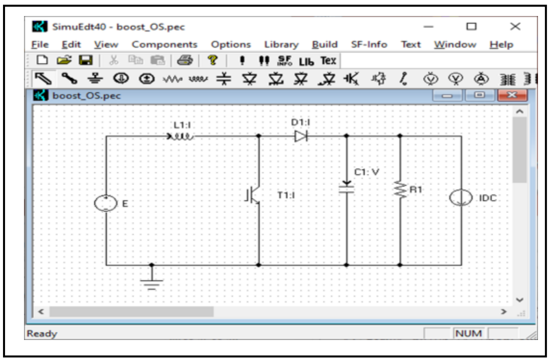


Fig. 9.4 Module I-V and the Module P-V under various temperatures and constant irradiances (1000 W/m^2)

9.2 Boost Converter Simulation:

The power electronic circuit of the Boost converter shown in Fig.9.5 is modelled as a Simulink Block using the C-language S-Function Block of Simulink shown in Fig. 9.6. The switching devices (Diode and IGBT) are modelled as two values resistance (*Ron*=1e-3/ *Roff*=1e6).



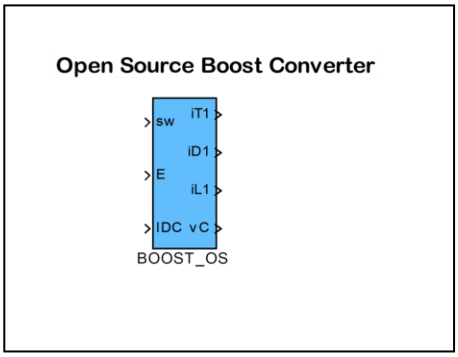


Fig. 9.5 Power electronic circuit of the Boost converter

Fig. 9.6 Open Source Boost con.

Double clicking the Open Source Boost converter Block shows the parameters used in the simulation.

As can be seen, the input vector ***u[0,1,2]*** of the Open Source Boost-converter is as follows:

- ***u[0]*** = the switching signal for the IGBT.
- ***u[1]*** = the value of the input DC-Voltage ***E***.
- ***u[2]*** = the value of the load current ***IDC***.

The output vector ***y[0,1,2,3]*** is as follows:

- y***[0]*** = IGBT current ***iT1***;
- ***y[1]*** = Diode current i***D1***;
- ***y[2]*** = Inductor current i***L1***;
- ***y[3]*** = Capacitor Voltage v***C1***.

The parameter vector ***p{0:4}*** is as follows:

- p***[0]*** = Inductance value ***L1***.
- ***p[1]*** = initial inductor current ***iL10***.
- ***p[2]*** = Inductance value ***C1***.
- ***p[3]*** = initial capacitor voltage ***VC10***.
- ***p[4]*** = Load Resistance value.

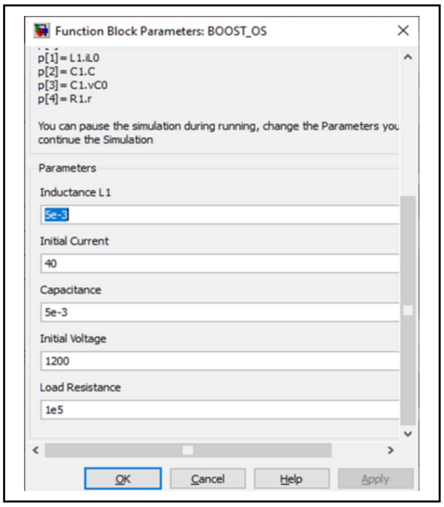


Fig. 9.7 Parameters of the Boost Conv.

Figure 9.8 shows the Simulink model of the Open Source Boost converter including Pulse width modulator (PWM).

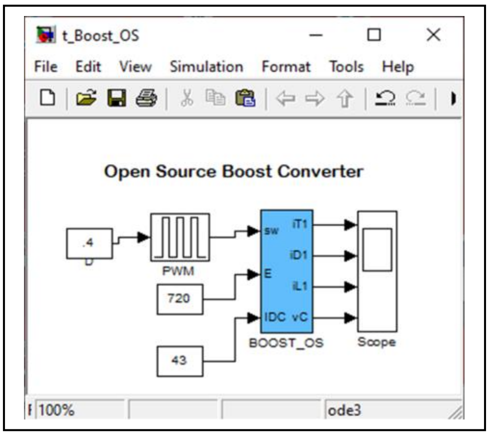


Fig. 9.8 Simulink model of the Boost Converter

The PWM control block is taken from the open source control-Library “Converter Control”. The modulation index D is set to =0.4, the switching frequency is set to 1000 Hz. The Input voltage is set to 720 V and the value of the load current source is set to 43 A.

The simulation results using 10 µS fixed step solver are shown in Fig. 9.8.

At the end of simulation, the C-S-Function block of the Open Source Boost-converter delivers the following information:

System Matrix Dimentions = 4*4

Elapsed time is 0.054058 seconds.

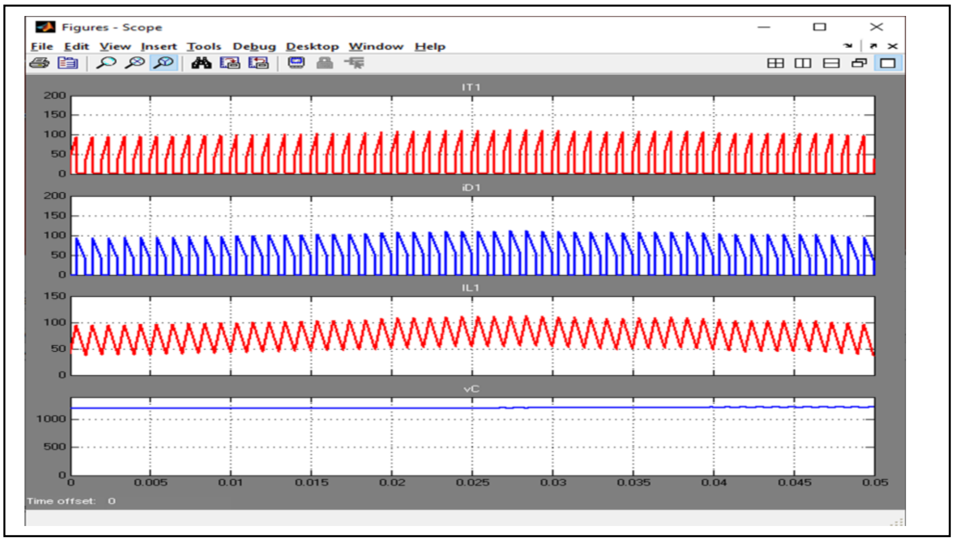


Fig. 9.9 Simulation results of the Boost Converter

9.3 Simulation of Grid Connected PWM 3-Level Neutral Point Clamped (NPC) DC/AC Converter:

The power electronic circuit of the Pulse Width modulated 3-Level NPC-converter loaded with 3-phase VLR-Circuits is shown in Fig. 9.10 and Fig. 9.11.

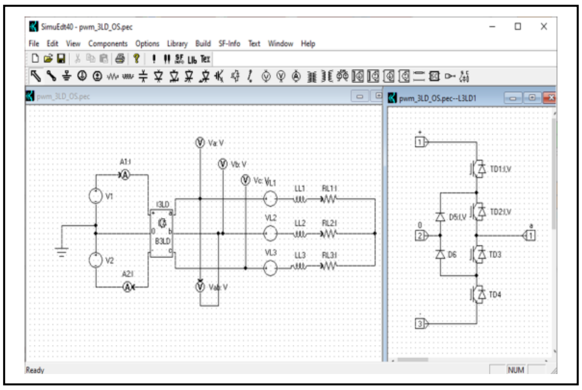


Fig. 9.10 3-Level NPC-converter

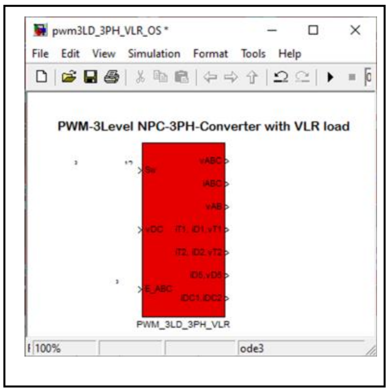


Fig. 9.11 Open Source 3-Level NPC 3-PH converter

Double clicking the converter Block PWM-3LD-3PH shows the parameters used in the simulation.

As can be seen, the input vector ***u{0:15}*** is as follows:

- ***u{0:11}*** = the switching signals for the IGBT1 to IGBT12.
- ***u[12]/2*** = the values of the input DC-Voltages ***VDC1 and VDC2***.
- ***u[13,14,15]*** = the values of the AC-load voltages ***EA,EB,EC***.
-

The output vector ***y{0:16}*** is as follows:

- y{0:2}		= Va,Vb,Vc
- y{3:5}		= Ia,Ib,Ic
- y[6]		= Vab.V
- y{7:9}		= T1.I,D1.I,T1.V
- y{10:12}	= T2.I,D2.I,T2.V
- y[13]		= D5.I
- y[14]		= D5.V
- y[15]		= IDC1
- y[16]		= IDC2

The parameter vector ***p[0,1]*** is:

- p[0]=RL
- p[1]=LL

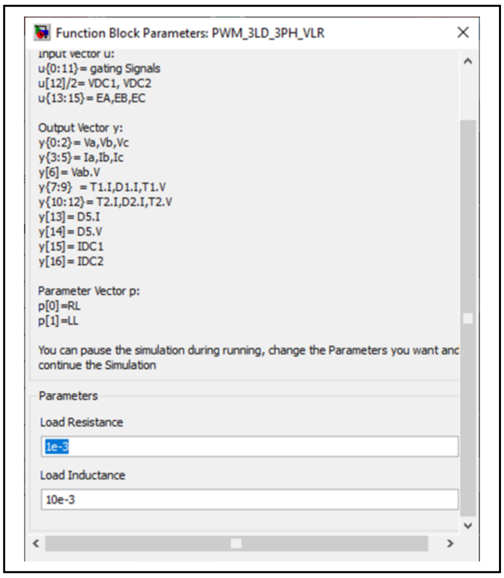


Fig. 9.12 Parameters of the Open Source 3-Level NPC 3-PH_VLR converter

Figure 13.13 shows the Simulink model of the Grid Connected 3-Level Neutral Point Clamped (NPC) DC/AC Converter including its (Id/Iq)-current control.

The PWM-3LD3PH control block is from the open source control-Library "Converter Control". It is based on level shifting of the triangular signals. The 1st triangular signal has the value from 0 to 1, is responsible for switching IGBT1 and IGBT3 and the 2nd triangular signal has the value from -1 to 0 is responsible for switching IGBT2 and IGBT4 of the same converter leg. The other converter legs are controlled by comparing the other modulation voltages and the triangular signals.

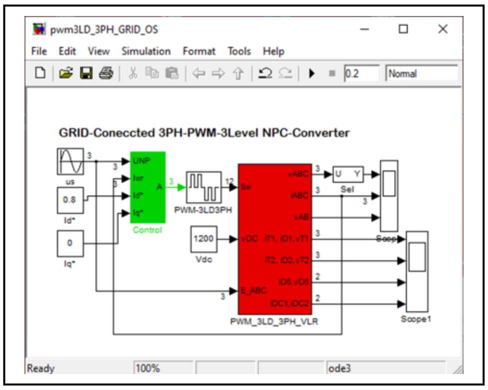


Fig. 9.13 Simulink model of the Grid-Connected 3PH-NPC Conv.

The modulation index vector A is a balanced thee phase system with amplitude of 0.8 per unit, the switching frequency is set to 1000 Hz. The Input DC-Voltage is set to 800 V and load voltage source vector E_ABC is a balanced three phase system with amplitude of 0 V, the load resistance RL=1 Ohm and the load inductance LL=1e-3 Henry .

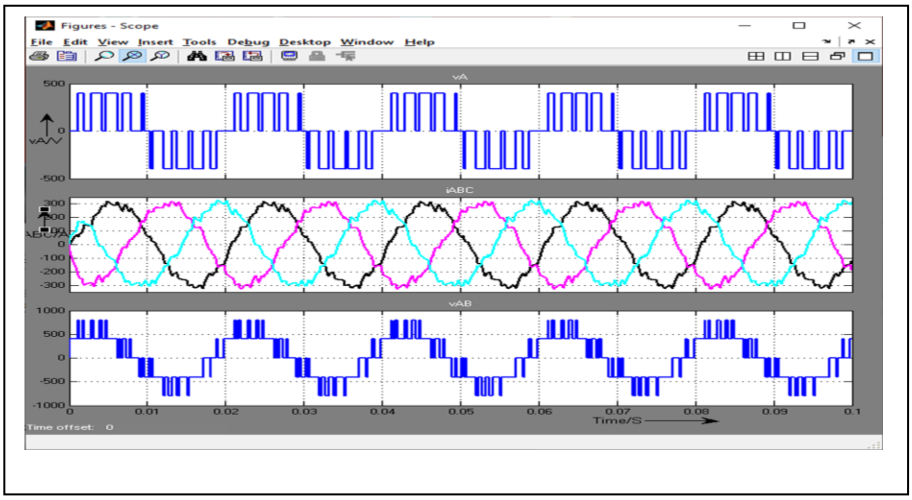


Fig. 9.14 Simulation results of the 3LD NPC-3PH-VLR Converter

9.4 Simulation of 3-Phase Grid Connected Photovoltaic Array

This simulation example is a combination of the 3 examples presented before. The system is partitioned into three open source Simulink C-S-function blocks as shown in Fig. 9.15:

- The photovoltaic Array CRM175S125M-72 containing 72 Cells/module, 20 series connected modules/string and 15 parallel connected strings/array (orange colour),
- The boost converter together with the perturb and observe method boost the output voltage to the point of maximum power of the photovoltaic Array (magenta colour),
- The Grid Connected PWM 3-Level Neutral Point Clamped (NPC) DC/AC Converter (red colour).

The inputs to the boost converter are as follows:

- DC-voltage from the PV-Array,
- DC-load current from DC-link of the 3-Level NPC converter through a time delay block to break the algebraic loop,

The outputs from the boost converter are as follows:

- DC-inductor current to the PV-Array through a time delay block to break the algebraic loop,
- DC-Capacitor voltage to the DC-link of the 3-Level NPC converter,

The simulation results using 10 µS fixed step solver are shown in Fig. 9.16 and Fig. 9.17.

At the end of simulation, Simulink delivers the following information:

- The PV_Array_OS has a System Matrix Dimentions of 17*17;
- The boost_OS has a System Matrix Dimentions of 4*4;
- The pwm_3LD_3PH_VLR_OS has a System Matrix Dimentions of 27*27;
- The Elapsed time is 1.065783 seconds.

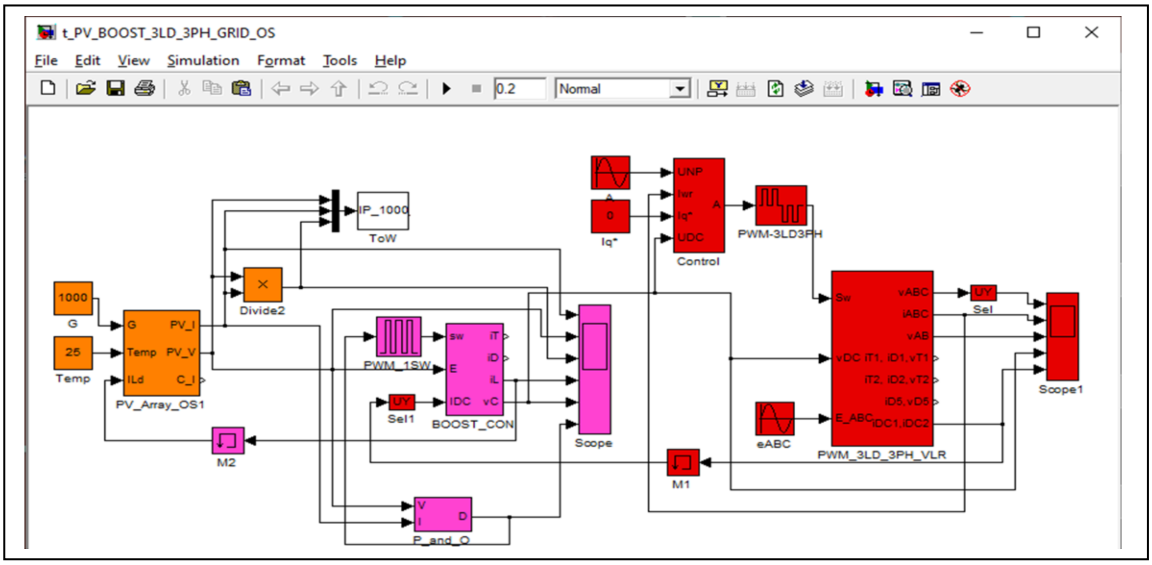


Fig. 9.15 Simulink model of the 3-Phase Grid Connected Photovoltaic Array

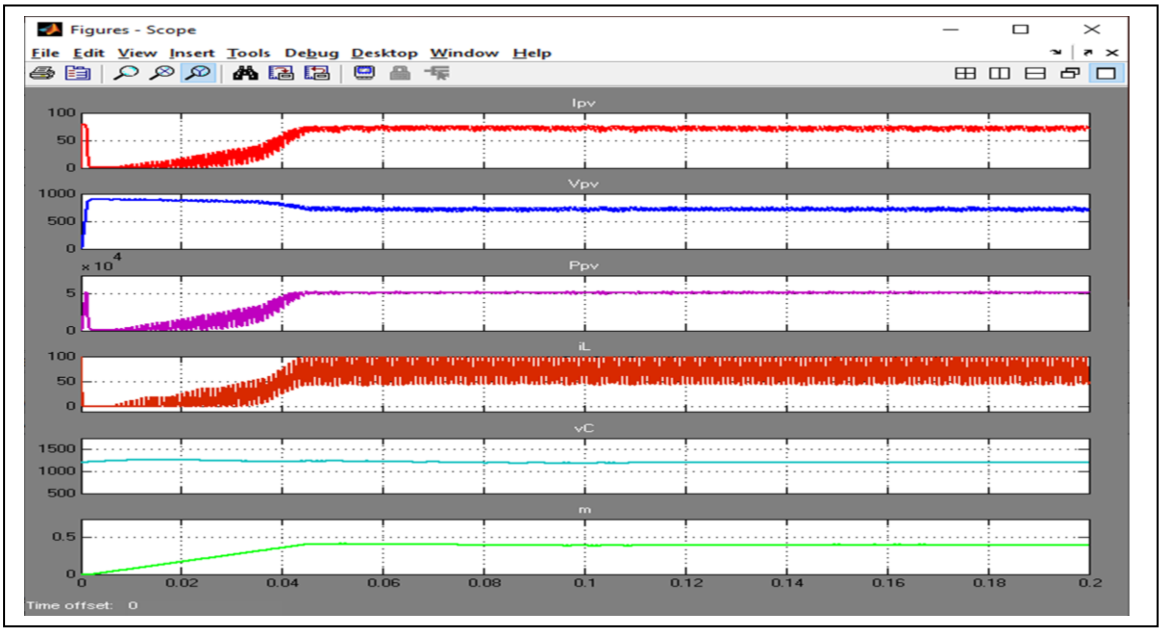


Fig. 9.16 Simulation results of the BOOST Converter

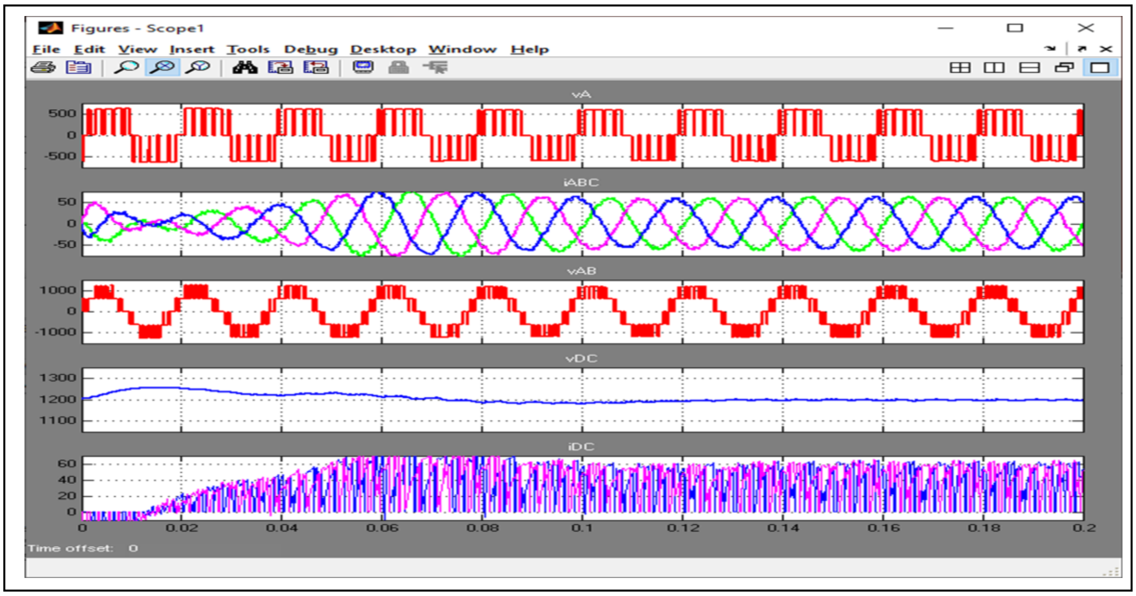


Fig. 9.17 Simulation results of the 3LD NPC-3PH-VLR Converter

9.5 Simulation of Grid connected 3-phase101-level MMC-Converter

The 3-phase 101-level MMC-converter shown in Fig. 9.18 is partitioned into seven sub-systems, each arm, containing 100 sub-modules is modelled as Simulink block (Arm1…Arm6) and the main converter circuit is also modelled as a Simulink block (Main Circuit) after replacing the converter arms with a voltage controlled voltage sources as shown in Fig. 9.19.

The circuit topologies of the 6-arms of the converter are the same, they use of the same parameter-vector, they need however different input-vector and deliver different output-vector. Therefore you need to model only one converter arm and use it (copy and paste) for the other converter arms.

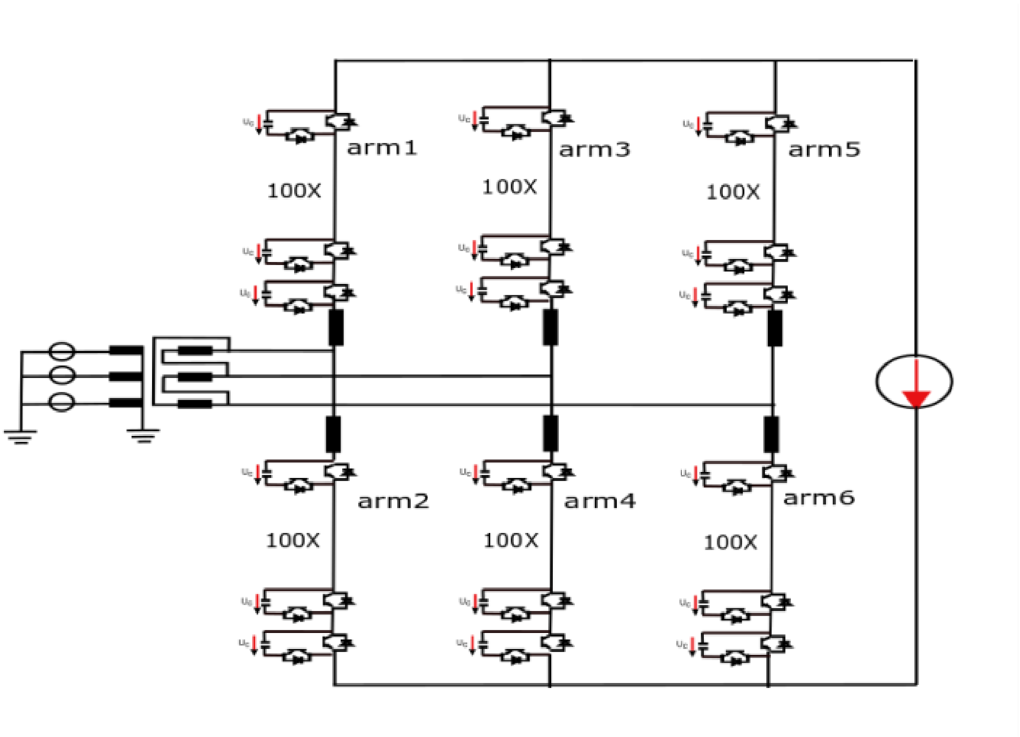


Fig. 9.18: Grid connected 3-phase101-level half-Bridge MMC Converter.

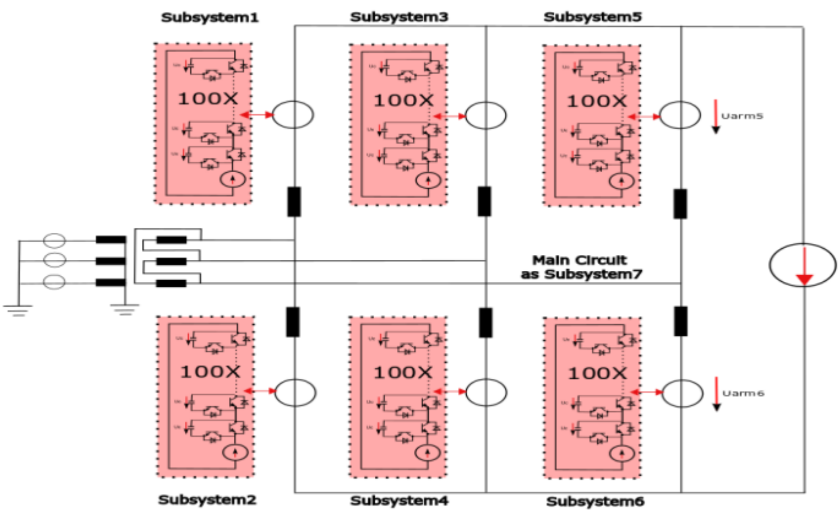


Fig. 9.19: Grid connected 3-phase101-level MMC after circuit partitioning into six separate arms and the main circuit.

As can be seen in Fig. 9.20, the main circuit block sends the inductor current vector to the six converter arms blocks. Each of the six converter arms blocks sends the arm output voltage back to the main circuit block.

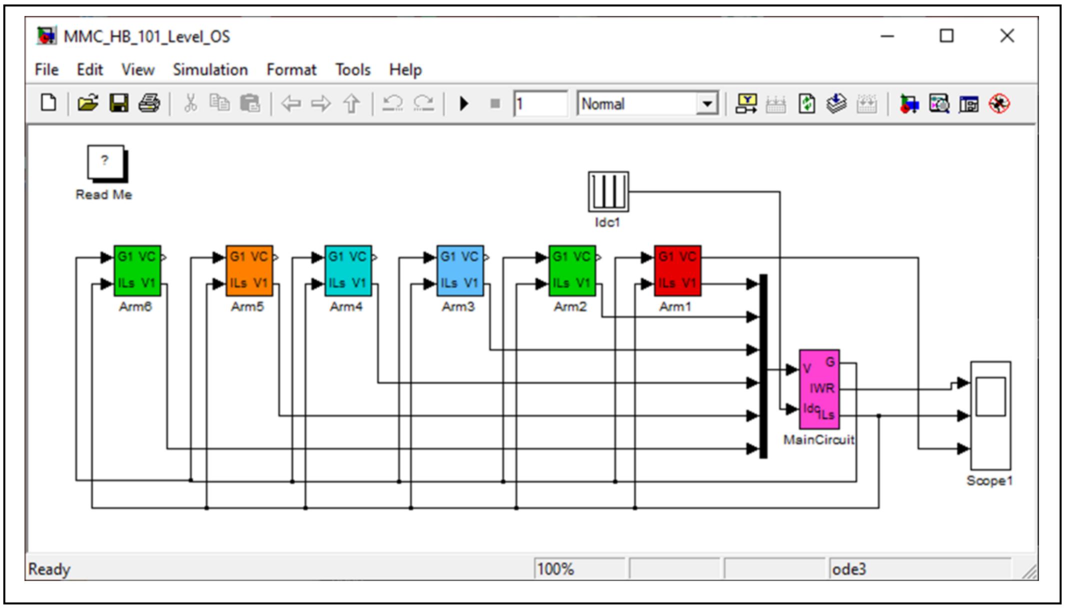


Fig. 9.20: Modelling the 101-Level MMC-Converter as 7 Simulink-Blocks

Double clicking Arm1 and Arm2 in Fig. 9.20 opens the content of the both arms as shown in Fig. 9.21a and Fig. 9.21b. As can be seen, the content of both arms are the same, the only difference are the utilization of the switching command victors and the arm current vectors. Arm1 gets the switching command vector u{0:99} and the arm current ILs(0). Arm2 gets the switching command vector u{100:199} and the arm current ILs(1) and so on for the other arms of the converter.

The open source Simulink-Block “ARM_CONTOL” is used to generate the switching signals for the 200 switches in converter arm and to balance the capacitor voltages of the 100 capacitors of the converter arm by selecting the suitable sub-circuits in the converter arm according to the switching command vector, the arm current vector and the previous state of charges of the capacitors in the arm.

Fig. 22: shows simulation results of the Grid connected 3-phase101-level MMC-converter. It is operating in three operation modes:

- from 0.0 to 0.1 in motoring mode;
- from o.1 to 0.15 in no load;
- from 0.15 to 0.25 in generating mode.

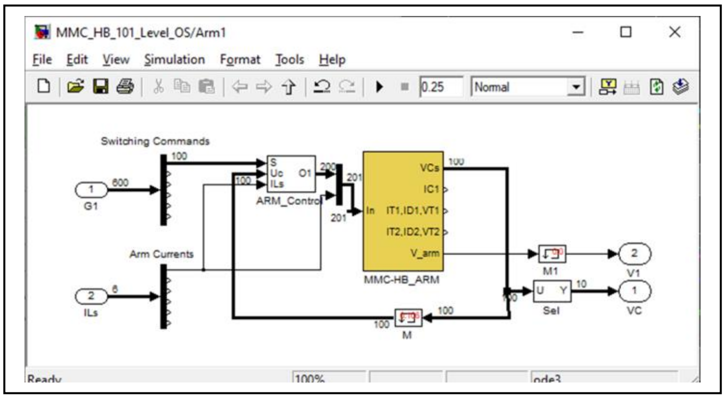


Fig. 9.21a: Simulink Model of arm1 of the 101-Level MMC-Converter

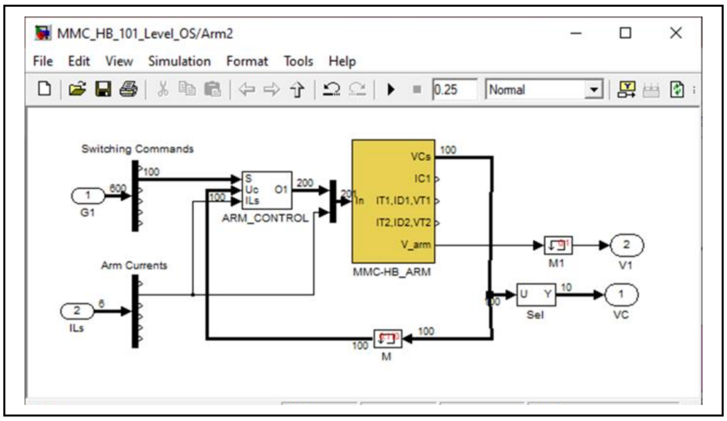


Fig. 9.21b: Simulink Model of arm2 of the 101-Level MMC-Converter

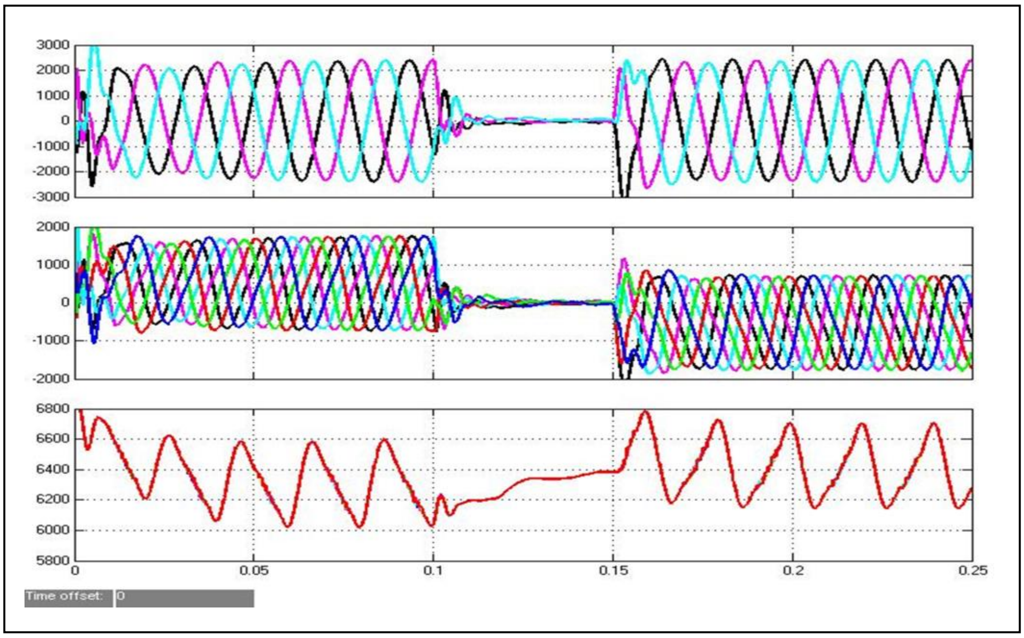


Fig. 9.22: Simulation results of the 101-Level MMC-Converter

It shows the following simulation results:

- The 3 phase load currents;
- The 6 converter arm currents;
- 10 capacitor voltages of arm1.

It shows also the following information:

- S-Function NAME = MMC_HB_ARM;
- System Matrix Dimension = 200 * 200;
- Elapsed time is 4.181648 seconds.

The load currents are balanced and have very small current ripples despite the low switching frequency of only 50 Hz. It has a peak value of 2400 A for a 1000 MW load active power and DC-Voltage of 640 kV.

The capacitor voltages of the arm are balanced and have small ripples of only 800 volt. It is ca. 11.76% of the rated capacitor voltage of 6800 Volt.

The elapsed time for the simulation run of 0.25 second is 4.181648 seconds; this is very fast compared with the simulation speed any power commercial power electronics simulator.

To demonstrate the power of the developed open source MMC-HB-ARM, we will initialize the same Simulink model discussed above for the 101-Level-HB MMC-Converter with the initialization Matlab m-file for the 400-Level-HB MMC Converter. The number of capacitor/arm is now 400 and the rated capacitor voltage is 1700 Volt.

Fig. 23: shows simulation results of the Grid connected 3-phase 401-level MMC-converter under the same loading conditions as for the 101-level MMC-converter. The load active power is 1000 MW and the DC-Voltage is 640 kV

It shows also the following information:

- S-Function NAME = MMC_HB_ARM;
- System Matrix Dimension = 800 * 800;
- Elapsed time is 30.993404 seconds.

The simulation results are nearly the same as for the 101-level MMC-converter.

The elapsed time of 30.993404 seconds is less than 8 time of that for the101-level MMC-converter

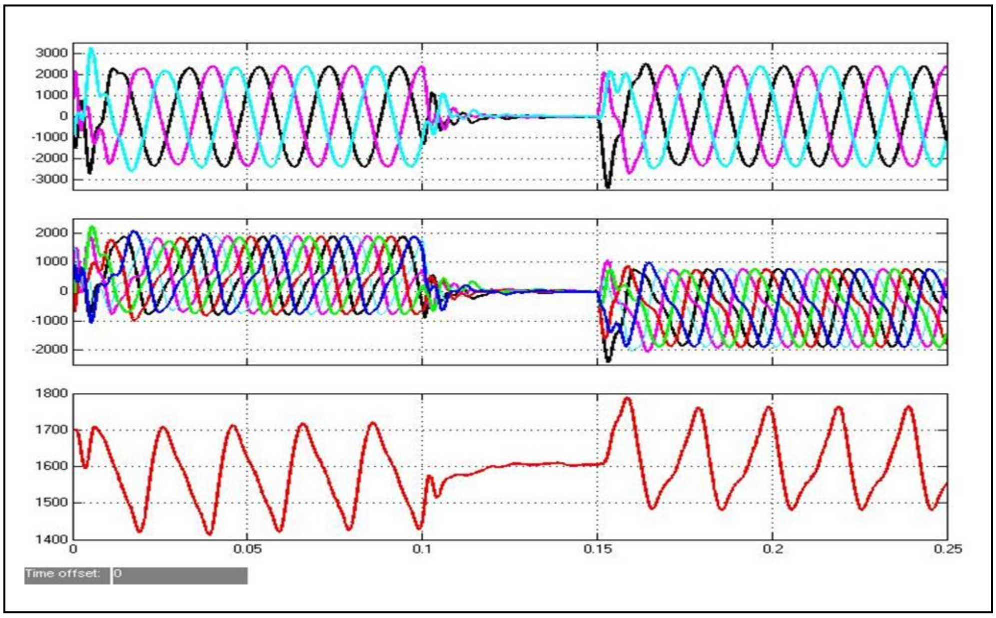


Fig. 9.23: Simulation results of the 401-Level MMC-Converter

10. Conclusion and future work

This report present an Open Source Power Electronics Blockset contains Simulink-blocks to model and simulate many of the well-known Power Electronics converters in Matlab/Simulink environment without a need for any power electronics toolbox. The Blockset is modelled using only the built-in Simulink-Blocks and/or the Simulink C-Language S-Functions.

Some of the features of this new developed Simulink open source Power Electronics Blockset can be summarized as follows:

- All developed power electronics Simulink blocks use only Simulink, there are no need for any power electronics toolbox. Only Matlab/Simulink should be installed on the PC.
- The switching devices (Diode, Thyristor, IGBT, IGBT/Diode, etc.) are modelled as two values resistance (*Ron*=1e-3/ *Roff*=1e6), there are no need for switching functions, average or Aggregate models.
- Using only built-in Simulink-Blocks and/or the Simulink C-Language S-Functions. Using the C-S-Functions, the algebraic loops can be avoided as can be seen in the modelling of the photovoltaic array.
- They behave exactly like built-in Simulink blocks, they have their own parameters, and they can be copied and pasted. The model parameters can be changed either dynamically or interactively during the simulation;

- The simulation is very fast, because each Simulink-block has a small system matrix.
- Power electronics Simulink Blocks containing non switching device can be simulated using multirate (multiples of the simulation step size)
- The current version of the open-source power electronics Simulink blockset can use Simulink *Normal* and *Accelerator* simulation modes. *Rapid Accelerator* simulation mode, *real time code generation* and the *Message Passing Interface* for multicore simulation are available only on the non-open-source power electronics Simulink blockset.

The users are encouraged and invited to extend and update this open source power electronics Simulink blocks.

11. References

[1]. Florin Iov, Anca Daniela Hansen, Poul Sørensen, Frede Blaabjerg "Wind Turbine Blockset in Matlab/Simulink", Aalborg University, March 2004

[2]. Christophe Batard, Frédéric Poitiers, Christophe Millet and Nicolas Ginot "Simulation of Power Converters using Matlab-Simulink", http://dx.doi.org/10.5772/46419.

[3]. J. Peralta, H. Saad, S. Dennetiere, J. Mahseredjian and S. Nguefeu, "Detailed and Averaged Models for a 401-Level MMC–HVDC System", *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1501-1508, 2012

[4]. H. Saad, J. Peralta, S. Dennetiere, J. Mahseredjian, J. Jatskevich, J. Martinez, A. Davoudi, M. Saeedifard, V. Sood, X. Wang, J. Cano, and A. Mehrizi-Sani, ― Dynamic averaged and simplified models for MMC based HVDC transmission systems, *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1723–1730, Jul. 2013

[5]. C. Ludois and G. Venkataramanan, "Simplified terminal behavioral model for a modular multilevel converter", *IEEE Trans. Power Electron.*, vol. 29, no. 4, pp. 1622–1631, Apr. 2014

[6]. J. Xu, A. M. Gole, and C. Zhao. The Use of Averaged-Value Model of Modular Multilevel Converter in DC Grid. *IEEE Transactions on Power Delivery*, 30(2):519–528, April 2015.

[7]. U. N. Gnanarathna, A. M. Gole, and R. P. Jayasinghe, "Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs," *Power Delivery, IEEE Transactions on*, vol. 26, pp. 316-324, 2011.

[8]. A. Beddard, M. Barnes, and R. Preece, "Comparison of Detailed Modeling Techniques for MMC Employed on VSC HVDC Schemes," *Power Delivery, IEEE Transactions on*, vol. 30, pp. 579-589, 2015.

[9]. J. Xu, C. Zhao, W. Liu, and C. Guo, ―Accelerated model of modular multilevel converters in PSCAD/EMTDC, *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 129–136, Jan. 2013.

[10]. S. Salama, “Fixed Admittance Matrix Technique for Real Time Power Electronics Simulation on Matlab/Simulink”, PCIM Europe digital days 2021; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 53-60.
[11]. P. Pejovic and D. Maksimovic, “A method for fast time-domain simulation of networks with switches,” *IEEE Trans. Power Electron*., vol. 9, no. 4, pp. 449–456, Jul. 1994.
[12]. S. Y. R. Hui and S. Morrall, “Generalised associated discrete circuit model for switching devices,” *IEE Proc. Sci., Meas. Technol*., vol. 141, no. 1, pp. 57–64, Jan. 1994.
[13]. Mu, Q., Liang, J., Zhou, X., Li, Y. and Zhang, X., “Improved ADC Model of Voltage Source Converters in DC Grids,” *Power Electronics, IEEE Transactions on*, vol. 29, no. 11, pp. 5738-5748, Nov., 2014.
[14]. S. Salama, "Simulation of power electronics systems using “Simupec”: the new power electronics toolbox for “Simulink/Matlab”, *Power electronics specialists Conference, 2004. PESC 04. IEEE 35th Annual,* vol. 5, pp 3409-3413.
[15]. MPI standard: http://www.mpi-forum.org/

[16]. William Gropp, Ewing Lusk, and Anthony Skjellum. Using MPI: Portable Parallel Programming with the Message-Passing Interface. MIT Press, 1994.

[17]. Massachusetts Institute of Technology (MIT): http://www.ll.mit.edu

[18]. https://www.hipc.org/hipc2004/posters/ sharma.pdf