Simple Solar Farm Model

Written for PSCAD X4 version 4.6.3

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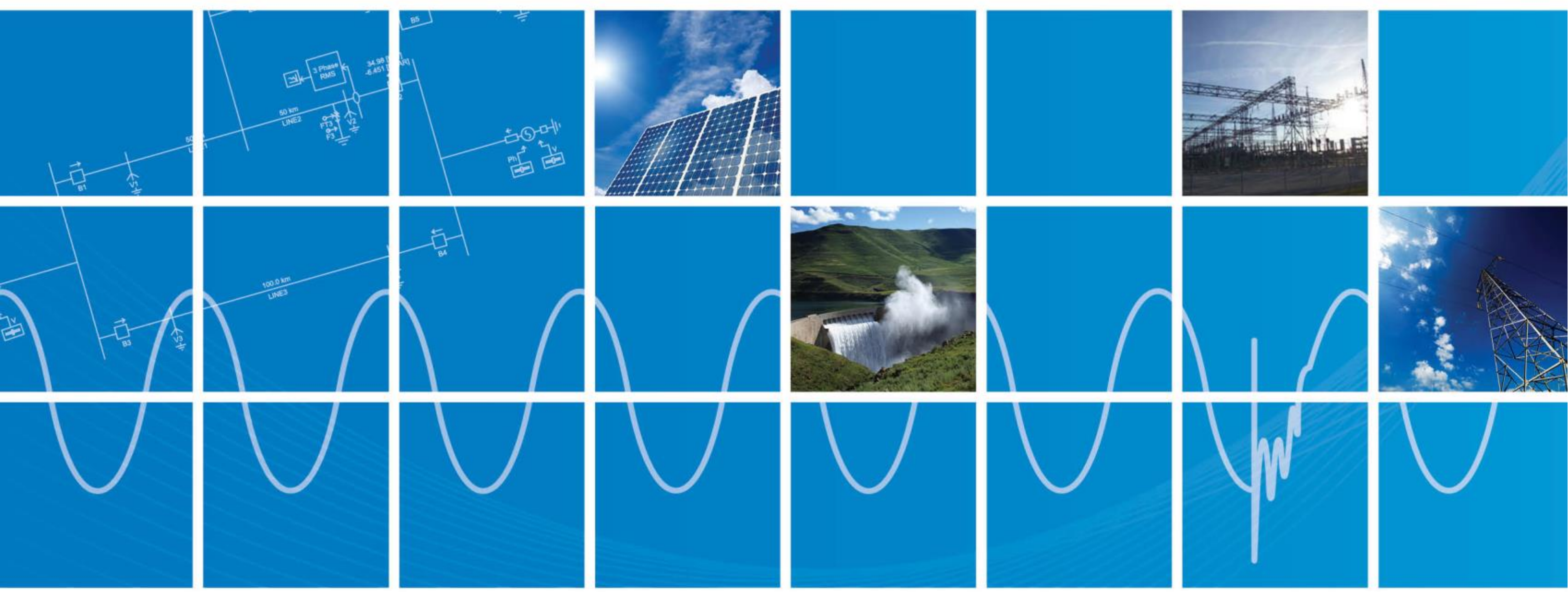
Revision 2



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Contents

1. Introduction

This document outlines the implementation of a simple solar farm in PSCAD. The solar farm consists of:

- Power plant controller (PPC): This controller is implemented in a basic form to monitor the overall operations of the solar farm at the point of connection (POC). Based on the measured values such as voltage and active and reactive powers and the mode of operation (i.e. voltage control, fixed reactive power control and power factor control), it adjusts the active and reactive power references for the inverters in the solar farm and also detects low and high voltage rid through conditions which promise improved power stability of the solar farm and consequently the interconnected network.
- PV Array: This component generates power as a function of irradiation and the temperature. It will show that how the parameters of the PV array can be modified to obtain a certain output power for the nominal of irradiation and the temperature. In this document the PV array generates a maximum power of 0.25MW at the nominal irradiation of 1000W/m^2 and nominal temperature of 28°C.
- Boost converter: This component controls the DC voltage or obtains the maximum power point tracking (MPPT).
- DC-AC inverter: This is the main power electronic component that is controlled such that the dynamics of the solar farm through various control scenarios can be achieved.
- Scaling Component: This component is used to model several units of inverters in a solar farm. In this example, the solar farm consists of 100 units.

Figure 1 shows the overall layout of the integration of the solar farm into an existing electrical network. The next sections will describe the components of the solar farm in more details.

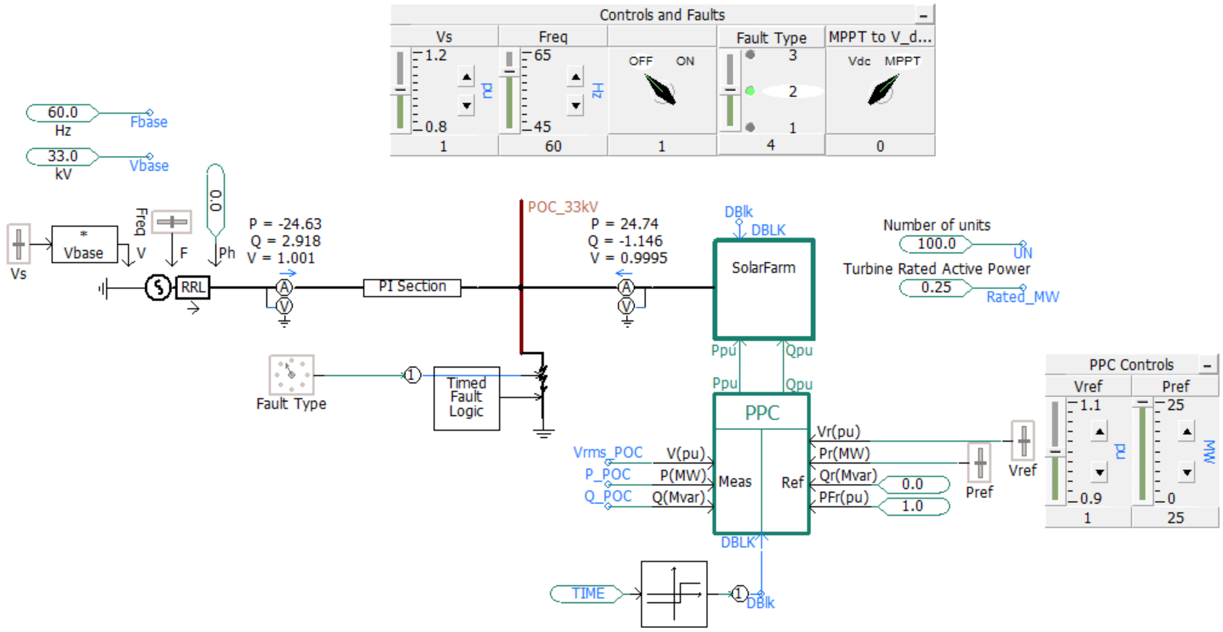


Figure 1: Overall solar farm model and equivalent voltage source (grid)

2. Simulation Setup

Load the workspace (i.e. SolarFarm.pswx) into PSCAD. The workspace is similar to what is shown in Figure 2with the name of the simulation cases and the hierarchy tree of the modules.

The simulation case SimpleSolarFarm.pscx contains of the Simple_PPC and VSC modules. The hierarchy tree is useful to understand what the active modules in the simulation are and navigate through them easily.

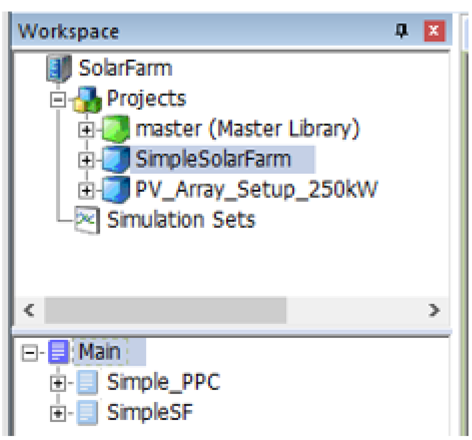


Figure 2: Workspace, simulation cases and hierarchy tree of modules

3. Power Plant Controller

The power plant controller is shown inFigure 3. This controller generates the reference active and reactive powers for the solar farm based on the measured and reference quantities.

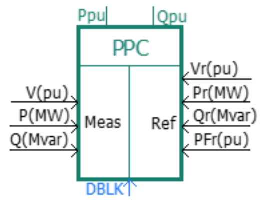


Figure 3: Power plant control

Table 1 shows the name, caption, type, unit and value for all the input parameters of the PPC. The properties can be seen by a right-click on the component and selecting View Properties which helps to realize the name of parameters and above mentioned information.

Note that the Con_mode parameter is used to choose one of the operation modesn namely; the POC voltage, power factor and fixed reactive power (Q) controller.

Table 1: Input parameters of PPC

Name	Caption	Type	Unit	Value
Scale	Number of Inverters	Integer		UN
Sbase	MVA Rating of Single Inverter	Real	MVA	Rated_MW
con_mode	Reactive Power Control Mode	Choice		1
HVRT	HVRT Detection Threshold	Real	pu	1.15
LVRT	LVRT Detection Threshold	Real	pu	0.85
Pmax	Pmax	Real	pu	1
Pmin	Pmin	Real	pu	0
Qmax	Qmax	Real	pu	0.6
Qmin	Qmin	Real	pu	-0.6

4. PV Array Setup

The purpose pf the example PV_Array_Setup_250kW.pscx is to obtain the important characteristic quantities such as short circuit current (ISC), open circuit voltage (VOC) and maximum power (PMAX) of the PV array. These quantities are important to design the Boost controller, which is described in Section 5.1. Figure 4 shows the circuit used to measure the mentioned quantities.

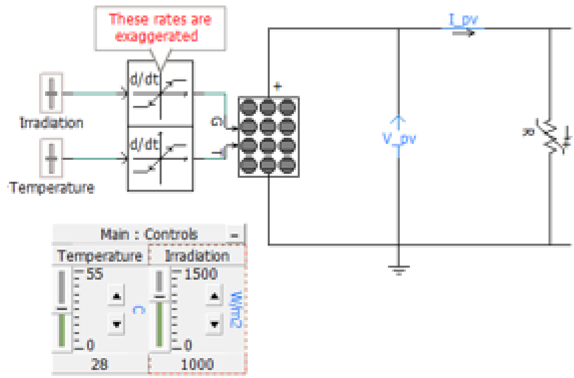


Figure 4: Simulation setup to measure short circuit current, open circuit voltage and maximum power of the PV array

To measure these quantities, the resistance (R) is varied from almost zero (0.001ohm short circuit condition) to a very high value (open circuit condition) as a function of simulation time (TIME) shown inFigure 5. Therefore the terminal voltage and current of the PV array (i.e. V_pv and I_pv) varies as a function of the resistance (R).

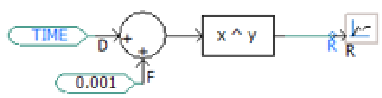


Figure 5: resistance variation as a function of time

Figure 6shows the variation of resistance (R) over the simulation time and the consequent variations of the terminal voltage V_pv and current I_pv. As can be seen the maximum power is about 0.25MW, the open circuit voltage is 1.015kV, and the short circuit current is 0.325kA.

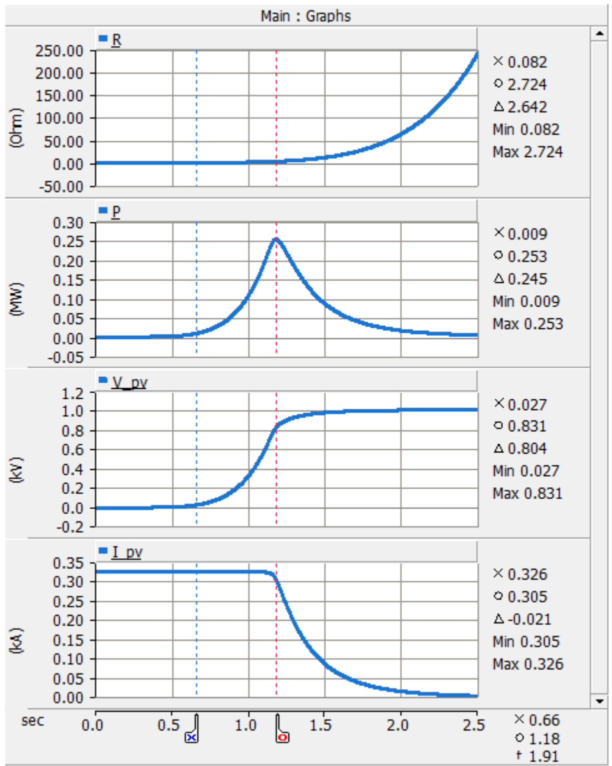
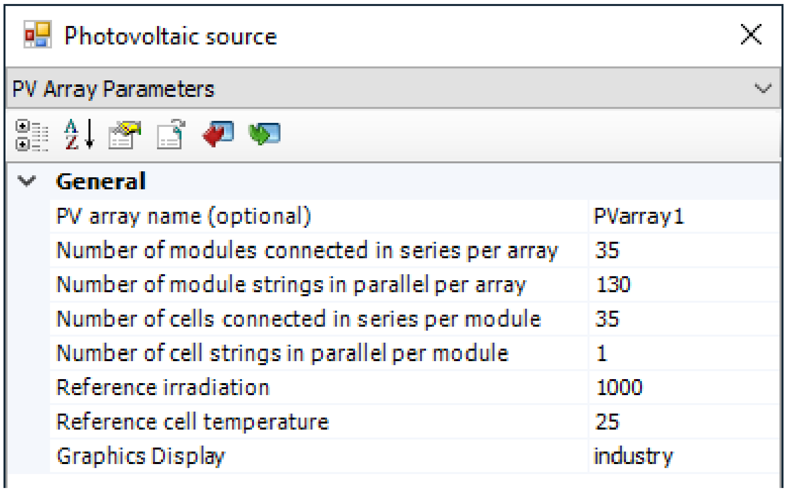


Figure 6: Variation of the resistance (R) in the circuit (see Figure 4) and the consequence variations in current, voltage and power

The quantities such as maximum power, open circuit voltage and the short circuit current can be modified by changing the characteristic parameters of the PV array. Double-click on the PV array to edit the number of modules and cells of the PV array and irradiation (1000W/m^2) and temperature (28°C) references as shown inFigure 7.


Photovoltaic source

PV Array Parameters

General

PV array name (optional)	PVarray1
Number of modules connected in series per array	35
Number of module strings in parallel per array	130
Number of cells connected in series per module	35
Number of cell strings in parallel per module	1
Reference irradiation	1000
Reference cell temperature	25
Graphics Display	industry

Figure 7: Number of modules and cells of the PV array and its irradiation and temperature references

5. Solar Farm Power Circuit and Controls

The solar farm module is shown inFigure 8, in which the power electronic circuit and controllers are implemented. To edit the parameters, right-click on the module and select "Edit parameters". The parameters are shown inFigure 9.

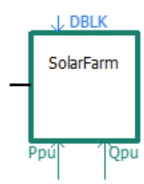


Figure 8: Solar farm module where the power electronic circuit and controllers are implemented

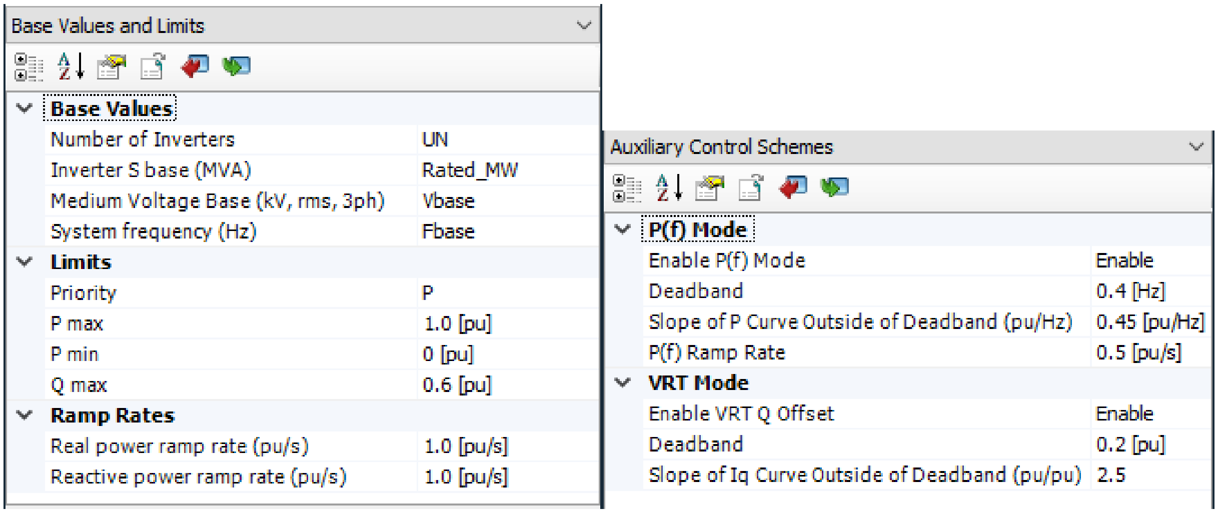


Figure 9: Solar Farm input parameters

Table 2 shows the name, caption, type, unit and value for all the input parameters. Note that the PR parameter is to choose the priority for the active power (P) controller and the reactive power (Q) controller. Also the P_f_ENAB is to enable or disable power-frequency droop and VRT_ENAB is to enable or disable the high and low voltage ride through capability.

Table 2: Input parameters of solar farm

NAME	CAPTION	TYPE	UNIT	VALUE
Scale	Number of Inverters	Integer		UN
System_Freq	System frequency (Hz)	Real	Hz	Fbase
Sbase	Base power of the inverter (MVA)	Real	MVA	Rated_MW
MV_Vbase	Base medium voltage (kV, L- to- L)	Real	kV	Vbase
INV_Vbase	Base inverter voltage (kV, L- to- L)	Real	kV	0.65
Vdc_Base	Base DC voltage [kV]	Real	kV	0.93
Lpu	Base leakage inductance of the inverter [pu]	Real	pu	0.2
Pramp	Real power ramp rate (pu/s)	Real	pu/s	1
Qramp	Reactive power ramp rate (pu/s)	Real	pu/s	1
PR	Priority	Choice		0
Pmax	P max	Real	pu	1
Pmin	P min	Real	pu	0
Qmax	Q max	Real	pu	0.6
VRT_ENAB	Enable VRT Q Offset	Choice		1
db_VRT	Deadband	Real	pu	0.2
m_VRT	Slope of Iq Curve Outside of Deadband (pu/pu)	Real	pu/pu	2.5
P_f_ENAB	Enable P(f) Mode	Choice		1
db_P_f	Deadband	Real	Hz	0.4
m_P_f	Slope of P Curve Outside of Deadband (pu/Hz)	Real	pu/Hz	0.45

rate_P_f	P(f) Ramp Rate	Real	pu/s	0.5

5.1 Boost Converter

The boost converter shown in Figure 10consists of the PV array at its input. The controller is shown inFigure 11. The two control modes discribed as follows can be chosen alternatively by a switch:

- DC voltage control mode. This mode maintains the DC voltage so that the voltage source converter (VSC) can control the active power on the DC link. This mode of operation is mostly used when the reactive power is set as priority for VSC (see Table 2 when PR = 1).
- Maximum power point tracing (MPPT) control mode. The maximum power yield is taken from the PV array using this mode of operation. This mode of operation is mostly used when the active power is set as priority for VSC (see Table 2 when PR = 0). The important characteristic quantities such as short-circuit current (ISC), open circuit voltage (VOC) and maximum power (PMAX) obtained in Section 4 are used to tune this controller mode.

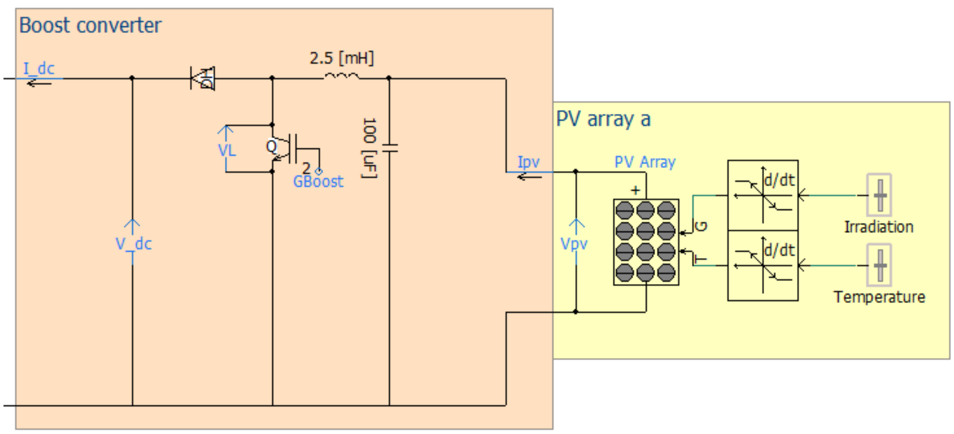


Figure 10: Electrical circuit of the Boost converter with connected PV array

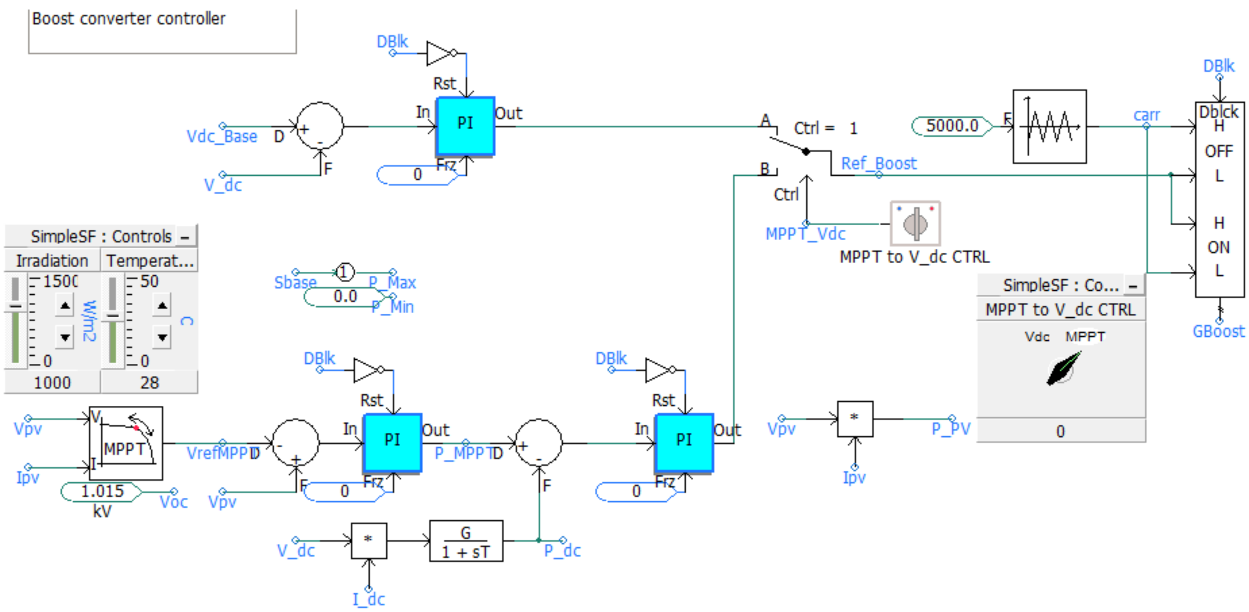


Figure 11: Boost controllers, DC voltage controller and MPPT control

5.2 Voltage Source Converter and Controls

Figure 12shows the power electronic circuit of the VSC converter, which consists of :

- Scaling component, described in Section 5.3
- The Damper and LCL filter, described in Section 5.3
- Phase lock loop (PLL) and ABC-to-dq transformation, described in Section 5.3
- Controller, described in Section 5.6

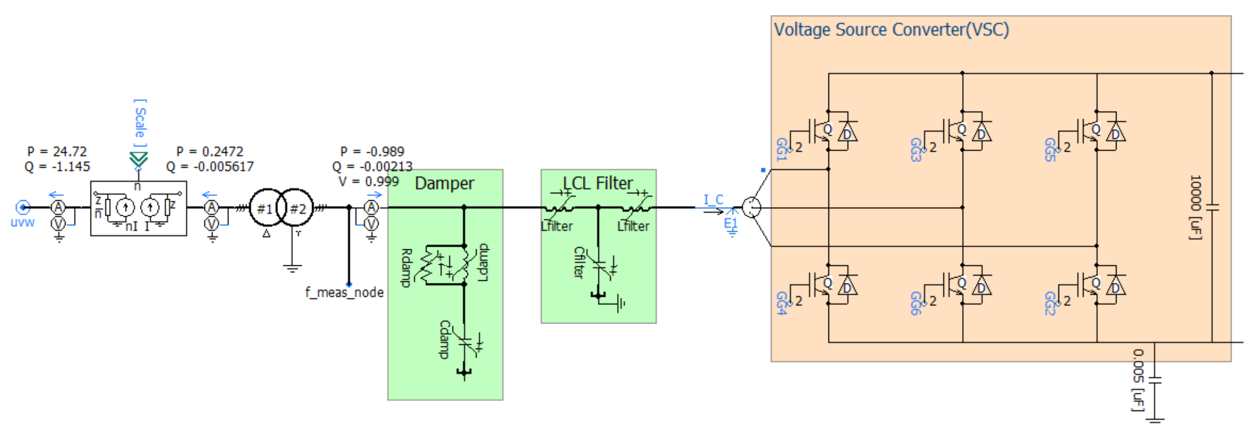


Figure 12: The electrical system consist of scaling component, delta-way transformer, damping circuit, filter, voltage source converter and the dc link capacitors

5.3 Scaling Component

The scaling component is modeled using the Method of Characteristics (otherwise known as Bergeron's Method) to represent the scaling component as an ideal loss-less distributed parameter branches, which account for travel time delays, in electric networks [1]. Figure 14 shows the scalinig component with the sending and receiving ends similar to an ideal (loss-less) transmission system.

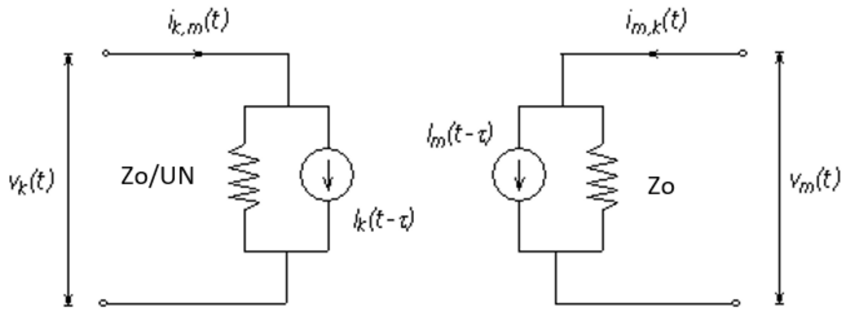


Figure 13: scaling component modelled as distributed branch interface (Single-Phase)

Therefore the sending and receiving end voltages and currents of the scaling component can be related as shown in (1):

$$V_m(t) = V_m(t-\tau) + Zo * I_m(t)$$

$$V_k(t) = V_k(t-\tau) + Zo/UN * I_k(t) \qquad (1)$$

$$I_k(t) = UN * I_m(t)$$

Where UN is the number of units and in this example, the solar farm has 100 units. In other words, the scaling component amplifies the output current of the inverter by UN (= 100). The scaling component is modelled similar to a transmission line with one simulation time step delay (Δt = τ) and one meter length as shown in (2):

$$travel\ time\ delay = simulation\ time\ step = \Delta t = \sqrt{L * C} \qquad (2)$$
$$C = \Delta t^2/L$$

where Δt, and *Zo* are simulation time step and the equivalent surge impedance, respectively.

The equivalent surge impedance can be calculated as (3):

$$Zo = \frac{L}{\Delta t} = X_{pu} * \frac{Z_b}{2\pi * freq} * \frac{1}{\Delta t} \quad (3)$$

Where

$$Z_b = \frac{Vbase^2}{Sbase} \quad (4)$$

The Vbase, Sbase and Xpu are the input parameters of the scaling compnent as sown in Figure 14.

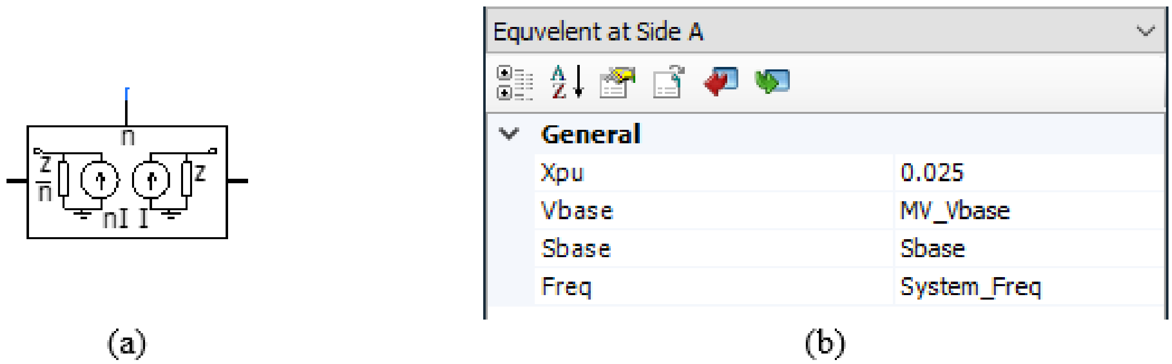


Figure 14: Scaling component to aggregate solar farm (a) the component (b) the input parameters where MV_Vbase is in kV, Sbase is in MW and System_Freq is in Hz

To minimize the effect of the scaling component, we can use part of leakage reactance of the connecting transformer or interconnected cables and transmission lines if there is any. A damping resistance may be used in parallel to this component to avoid numerical instability.

5.4 Damper and Low Pass Filter Design

The power electronic converters generate a considerable amount of harmonics. A damper along with a filter are used to damp low frequency oscillations to minimize the impact of harmonics on the grid. The structure of the damper and filter are represented inFigure 12. The methodology, used in this example to calculate the filter parameters, is demonstrated inFigure 15. The base quantities are equal to the rated power (INV_Sbase) and rated voltage (INV_Vbase, line to line, rms).

Note: As long as the default unit for inductor and capacitor are H and *u*F respectively, therefore the factors $1.e^{+6}$ and $1.e^{-6}$ are used to calculate the correct values.

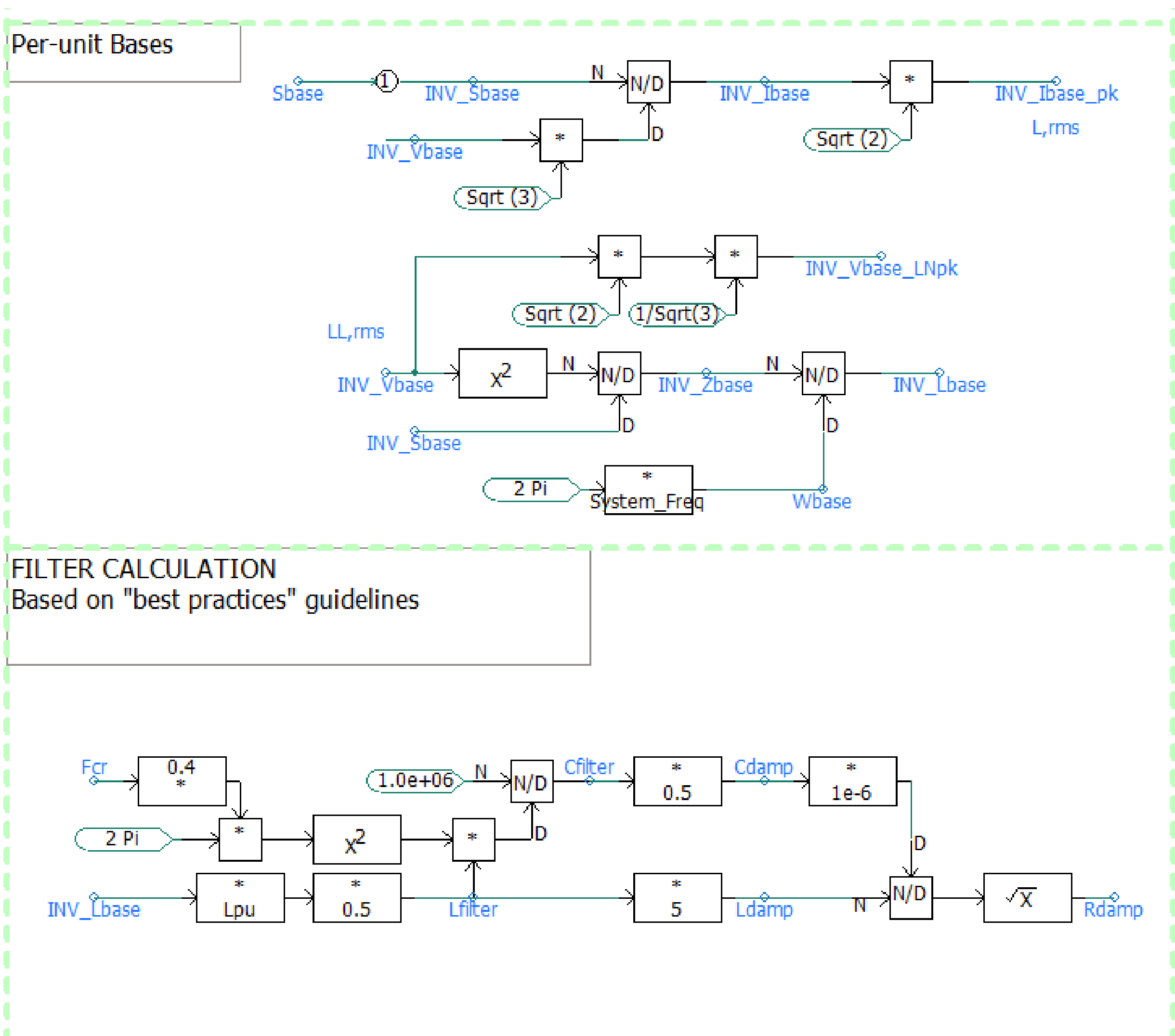


Figure 15: The procedure for calculating the filter and damper parameters

5.5 Phase Lock Loop (PLL) and ABC-to-DQ0 Transformation

The solar farm is based on a grid-tied scheme. Therefore it requires a PLL to obtain the correct phase angle (theta) of the voltage at POC. Based on the calculated phase angle (theta) the d-q components of the voltage and current are calculated using ABC-to-dq transformation as shown inFigure 16.

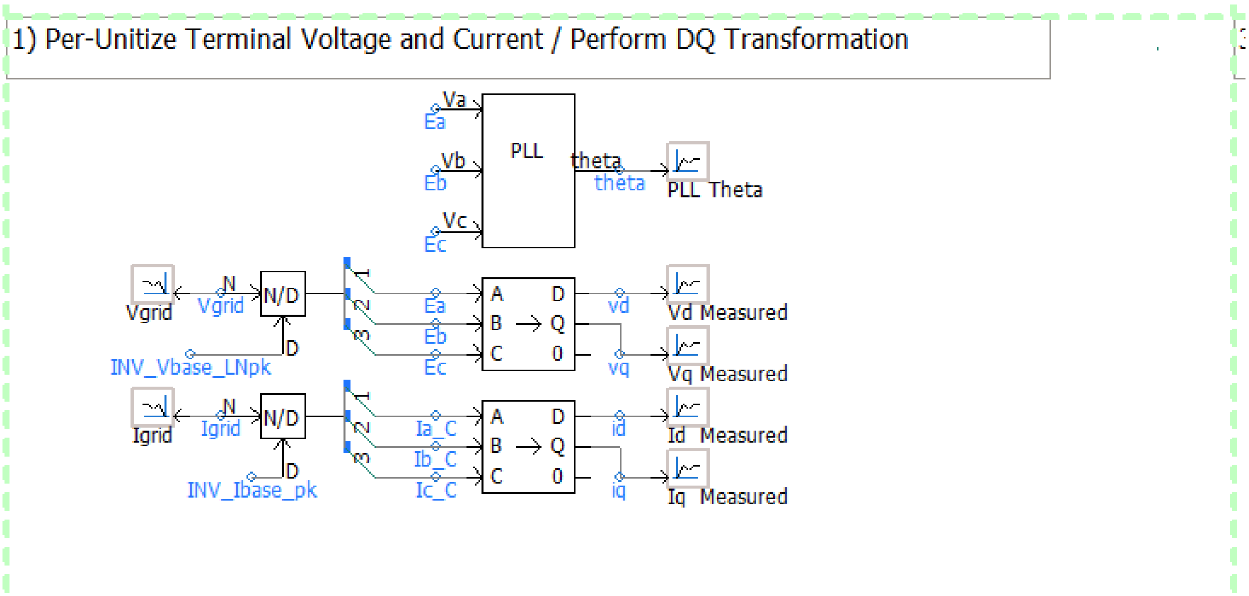


Figure 16: The PLL and the ABC-to-dq parameters

5.6 Controllers

The inverter is design to control the DC voltage (V_dc) or active power (P) and reactive power (Q). The DC voltage (V_dc) or active power (P) can be chosen alternatively by a switch as shown in Figure 17. The reference for the active power (Ppu1) is defined by frequency droop characteristic as shown in Figure 18. When the measured frequency (PLL_f) is higher than the base frequency (system_Freq), the reference active power (Ppu1) varies to some extent as a function of the slope of the deadband controller shown in Figure 19.

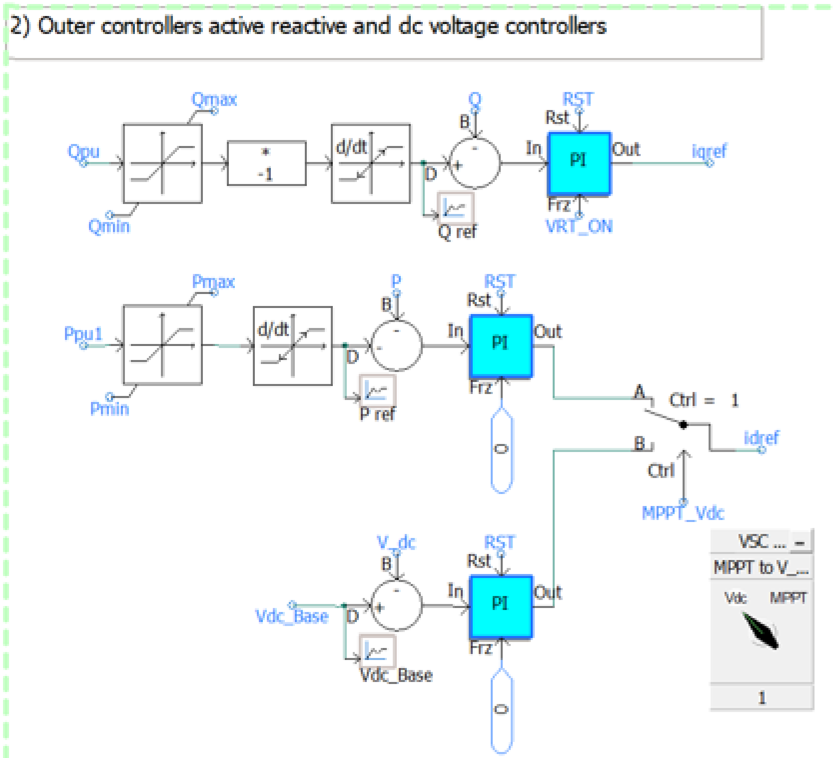


Figure 17: Outer controllers: DC voltage/active power control and reactive power control

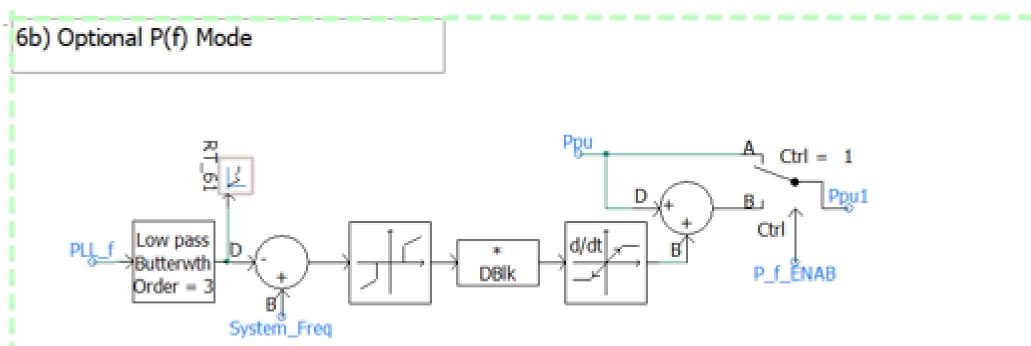


Figure 18: The frequency droop characteristic and the deadband controller

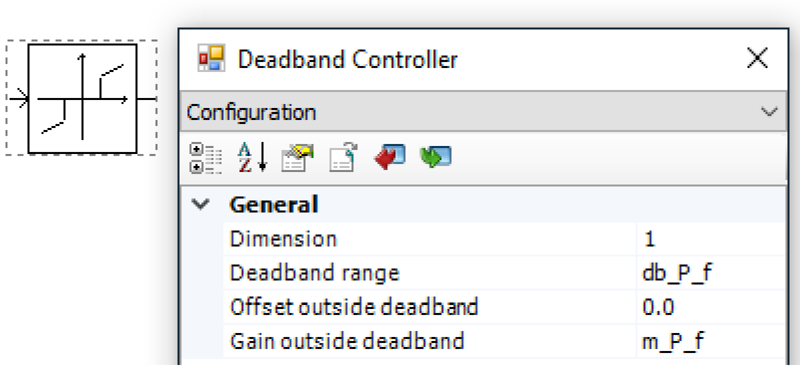


Figure 19: The deadband controller

The current of the inverter is limited by the limits of PI controllers. The limiting function can be chosen as active power (d-axis and priority signal is set to 1) or reactive power (q-axis and priority signal is set to 0) priority as shown inFigure 20. The maximum inverter current rating has been set to 1.2pu to make the invetere able to operat under low voltage ride trough.

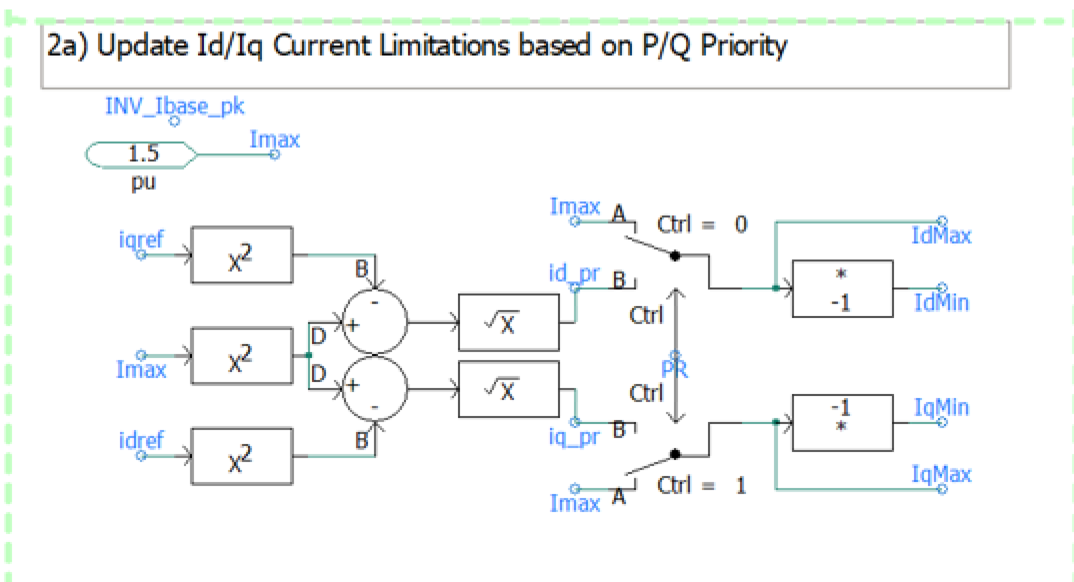


Figure 20: d- and q-frames current limit calculation

The inner current controls shown in Figure 21 are used to generate the converter reference voltages i.e. vd1 and vq1. In order to decouple the d- and q-frames (i.e. minimize their effect on each other) the terms Iq* Lpu and Id * Lpu are subtracted and added to d-frame and q-frame respectively.

The Lpu should be selected by the user as an input parameter for the inverter as shown in Figure 15.

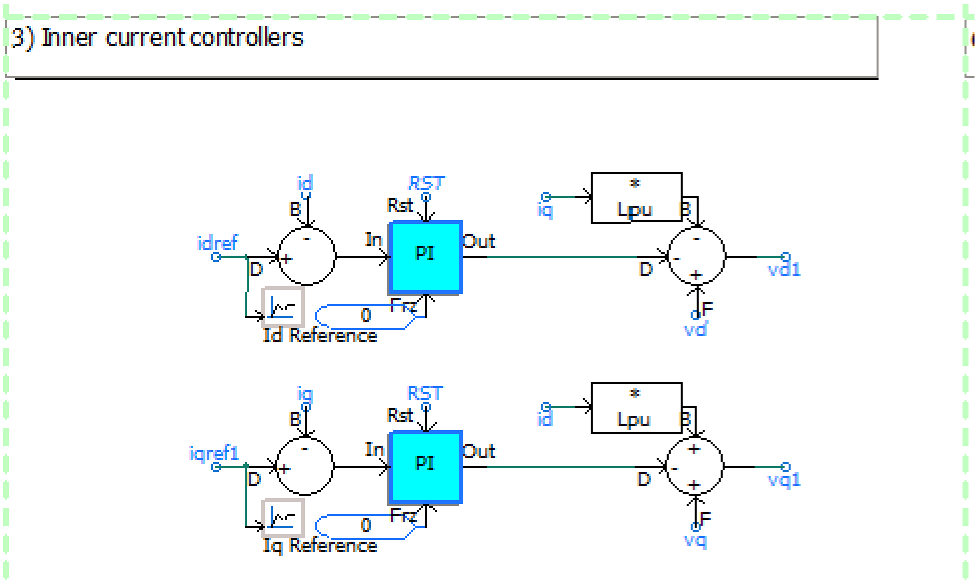


Figure 21: Inner current controllers and decoupled components

Figure 22shows the time domain voltage references (Ref_a, Ref_b and Ref_c) that are obtained from the phase domain reference voltages i.e. vd1 and vq1. The process starts with converting the rectangular vd1 and vq1 to polar domain. Then the magnitude (M) is divided by 0.5×Vdc_base to obtain the modulation index (m*) which is limited to 1.15 pu. Then polar domain is converted to the rectangular and applied to the dq-to-ABC transform component. The three-phase reference voltage waveforms are obtained using theta generated by PLL shown in Figure 16.

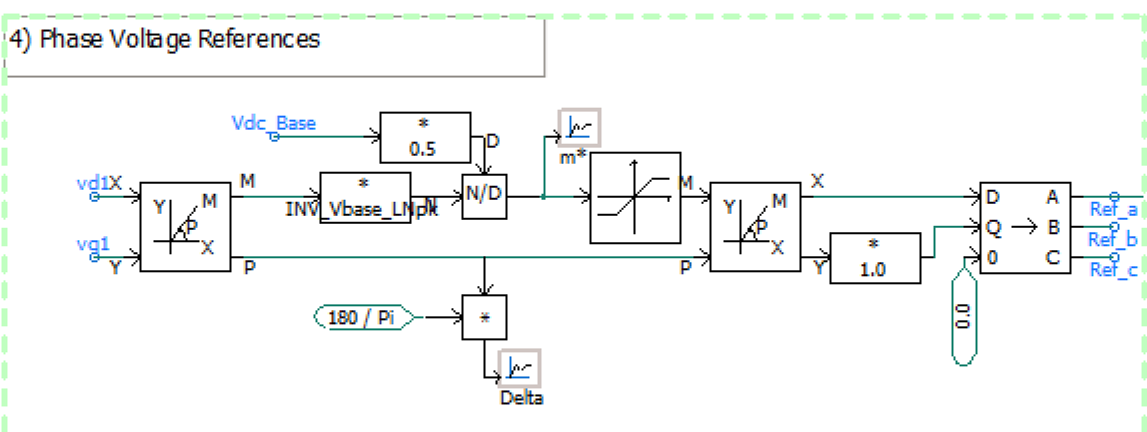


Figure 22: Reference voltages provided by grid-side controller

6. Simulation Results

The dynamic of the system is shown in Figure 23 when:

- PPC operates at POC voltage control mode,
- The inverter operates at P control mode, and
- Boost converter operates at MPPT mode.

A fault AB to ground fault occurs at 5s on the POC and the solar farm injects reactive power to maintain the stability of the voltage.

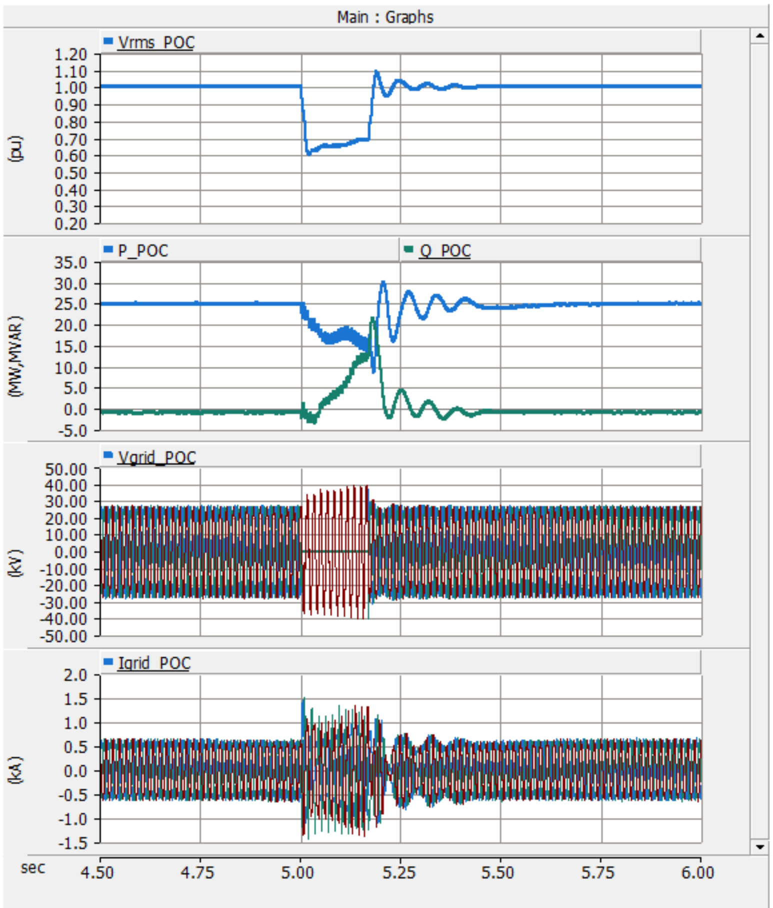


Figure 23: The dynamic of the system when the load is connected at 3.5 sec

7. Reference

1. H. W. Dommel, Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks, IEEE Transactions on Power Apparatus and Systems, PAS-88, #4, pp. 388-399, April 1969.

DOCUMENT TRACKING

Rev.	Description	Date
0	Initial	08/May/2019
1	General Improvements	19/June/2019
2	Update to Equation 3; Minor Fixes	21/June/2019