Grid-Connected PV Array

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Description

Two demos illustrate use of SimPowerSystems for modeling a PV array connected to a utility grid.

- **PVarray_Grid_IncCondReg_det.mdl** is a detailed model of a 100-kW array connected to a 25-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the "Incremental Conductance + Integral Regulator" technique.

- **PVarray_Grid_PandO_avg.mdl** is an average model of a 200-kW array connected to a 25-kV grid via two DC-DC boost converters and a single three-phase VSC. The MPPT controller based on the "Perturb and Observe" technique is implemented by means of a MATLAB Function block that generates embeddable C code.

The detailed model contains:

- PV array delivering a maximum of 100 kW at 1000 W/m^2 sun irradiance.
- 5-kHz boost converter (orange blocks) increasing voltage from PV natural voltage (272 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by the MPPT controller that uses the "Incremental Conductance + Integral Regulator" technique.
- 1980-Hz (33*60) 3-level 3-phase VSC (blue blocks).
  The VSC converts the 500 V DC to 260 V AC and keeps unity power factor.
- 10-kvar capacitor bank filtering harmonics produced by VSC.
- 100-kVA 260V/25kV three-phase coupling transformer.
- Utility grid model (25-kV distribution feeder + 120 kV equivalent transmission system).

For this detailed model, the electrical circuit is discretized at 1 μs sample time, whereas sample time used for the control systems is 100 μs.

The average model contains:

- Two PV arrays delivering each a maximum of 100 kW at 1000 W/m^2 sun irradiance.
- Two average models of boost converter (orange blocks) increasing voltage from PV1 and PV2 voltages to 500 V DC. The two MPPT controllers use the "Perturb and Observe" technique.
- Average model of VSC (blue blocks). The VSC converts the 500 V DC to 260 V AC and keeps unity power factor.
- 20-kvar capacitor bank filtering harmonics produced by VSC.
- 200-kVA 260V/25kV three-phase coupling transformer.
- Utility grid model (25-kV distribution feeder + 120 kV equivalent transmission system).

In the average model the boost and VSC converters are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. Such a model does not represent harmonics, but the dynamics resulting from control system and power system interaction is preserved. This model allows using much larger time steps (50 μs), resulting in a much faster simulation.

Note that in the average model the two PV-array models contain an algebraic loop. Algebraic loops are required to get an iterative and accurate solution of the PV models when large sample times are used. These algebraic loops are easily solved by Simulink.

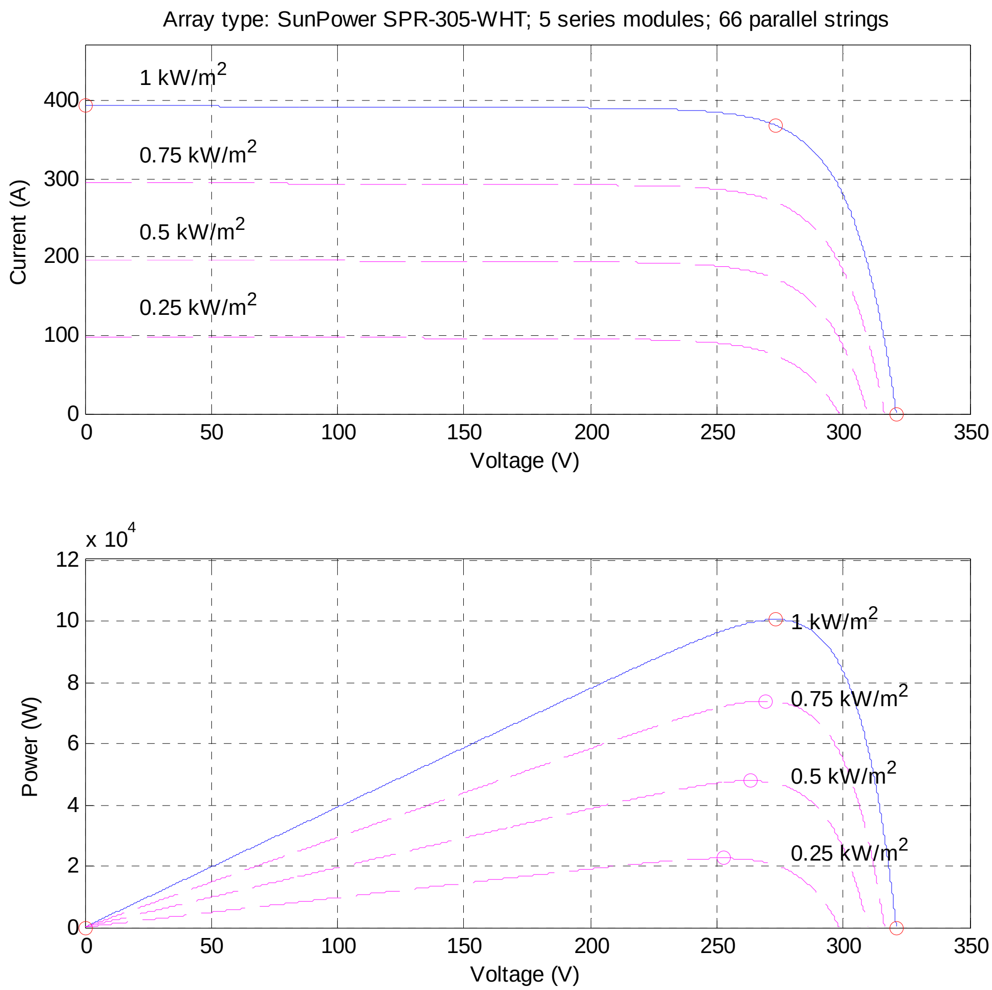
PV array

The 100-kW PV array of the detailed model uses 330 SunPower modules (SPR-305). The array consists of 66 strings of 5 series-connected modules connected in parallel (66*5*305.2 W= 100.7 kW).

Open the PV-array block menu and look at model parameters.
Manufacturer specifications for one module are:

- Number of series-connected cells : 96
- Open-circuit voltage: Voc= 64.2 V
- Short-circuit current: Isc = 5.96 A
- Voltage and current at maximum power : Vmp =54.7 V, Imp= 5.58 A

The PV array block menu allows you to plot the I-V and P-V characteristics for one module and for the whole array. The characteristics of the SunPower-SPR305 array are reproduced below.



I-V and P-V characteristics of PV array

Red dots on blue curves indicate module manufacturer specifications (Voc, Isc, Vmp, Imp) under standard test conditions (25 degrees Celsius, 1000 W/m^2).

Using the "Module type" pop-up menu, you can choose among various array types for your simulation. Ten different types are proposed. The module characteristics were extracted from NREL System Advisor Model (https://sam.nrel.gov/).

The average model uses two 100-kW PV arrays. PV1 uses SunPower-SPR305 modules and PV2 uses Kyocera-DD205GX-LP modules.

Boost converter

In the detailed model, the boost converter (orange blocks) boosts DC voltage from 273.5 V to 500V. This converter uses a MPPT system which automatically varies the duty cycle in order to generate the required voltage to extract maximum power.

Look under the mask of the "Boost Converter Control" block to see how the MPPT algorithm is implemented. For details on various MPPT techniques, refer to the following paper:
Moacyr A. G. de Brito, Leonardo P. Sampaio, Luigi G. Jr., Guilherme A. e Melo, Carlos A. Canesin "Comparative Analysis of MPPT Techniques for PV Applications", 2011 International Conference on Clean Electrical Power (ICCEP).

VSC converter

The three-level VSC (blue blocks) regulates DC bus voltage at 500 V and keeps unity power factor.
The control system uses two control loops: an external control loop which regulates DC link voltage to +/- 250 V and an internal control loop which regulates Id and Iq grid currents (active and reactive current components).
Id current reference is the output of the DC voltage external controller. Iq current reference is set to zero in order to maintain unity power factor. Vd and Vq voltage outputs of the current controller are converted to three modulating signals Uref_abc used by the PWM three-level pulse generator.
The control system uses a sample time of 100 μs for voltage and current controllers as well as for the PLL synchronization unit. In the detailed model, pulse generators of Boost and VSC converters use a fast sample time of 1μs in order to get an appropriate resolution of PWM waveforms.

Demonstration

1. Run the *PVarray_Grid_IncCondReg_det* model for 3 seconds and observe the following sequence of events on Scopes.

Note: In order to speed up simulation, select the "Accelerator" mode before starting simulation. Using the Accelerator with this demo provides a performance gain of approximately 7X.

- From t=0 sec to t= 0.05 sec, pulses to Boost and VSC converters are blocked. PV voltage corresponds to open-circuit voltage (Nser*Voc=5*64.2=321 V, see V trace on Scope Boost). The three-level bridge operates as a diode rectifier and DC link capacitors are charged above 500 V (see Vdc_meas trace on Scope VSC).

- At t=0.05 sec, Boost and VSC converters are de-blocked. DC link voltage is regulated at Vdc=500V. Duty cycle of boost converter is fixed (D= 0.5 as shown on Scope Boost) and sun irradiance is set to 1000 W/m^2. Steady state is reached at t=0.25 sec. Resulting PV voltage is therefore V_PV = (1-D)*Vdc= (1-0.5)*500=250 V (see V trace on Scope Boost). The PV array output power is 96 kW (see Pmean trace on Scope Boost) whereas maximum power with a 1000 W/m^2 irradiance is 100.7 kW. Observe on Scope Grid that phase A voltage and current at 25 kV bus are in phase (unity power factor).

- At t=0.4 sec MPPT is enabled. The MPPT regulator starts regulating PV voltage by varying duty cycle in order to extract maximum power. Maximum power (100.7 kW) is obtained when duty cycle is D=0.453. At t=0.6 sec, PV mean voltage =274 V as expected from PV module specifications (Nser*Vmp=5*54.7= 273.5 V).

- From t=0.7 sec to t=1.2 sec, sun irradiance is ramped down from 1000 W/m^2 to 250 W/m^2. MPPT continues tracking maximum power. At t=1.2 sec when irradiance has decreased to 250 W/m^2, duty cycle is D=0.485. Corresponding PV voltage and power are Vmean= 255 V and Pmean=22.6 kW. Note that the MMPT continues tracking maximum power during this fast irradiance change.

- From t=1.5 sec to 3 sec various irradiance changes are applied in order to illustrate the good performance of the MPPT controller.

2. Run the *PVarray_Grid_PandO_avg* model.

   - Compared to the detailed model, this average model runs a lot faster.

   - Observe the performance of the two Perturb and Observe MPPTs under various irradiance changes. It can be seen that this type of MPPT controller tracks maximum power only while irradiance stays constant.