PLECS

DEMO MODEL

Single-Phase PV Inverter with Partial Shading

Last updated in PLECS 4.3.1

1 Overview

This demonstration illustrates a grid-connected solar panel system with a boosted front end and a single-phase inverter back end. The boost converter is designed to operate the panel at its maximum power point (MPP). A maximum power point tracking (MPPT) algorithm is implemented to improve the performance of the solar panel under partial shading conditions. Further, the inverter is operated with an outer voltage loop to control the DC-link voltage and a synchronous regulator to maintain unity power factor.

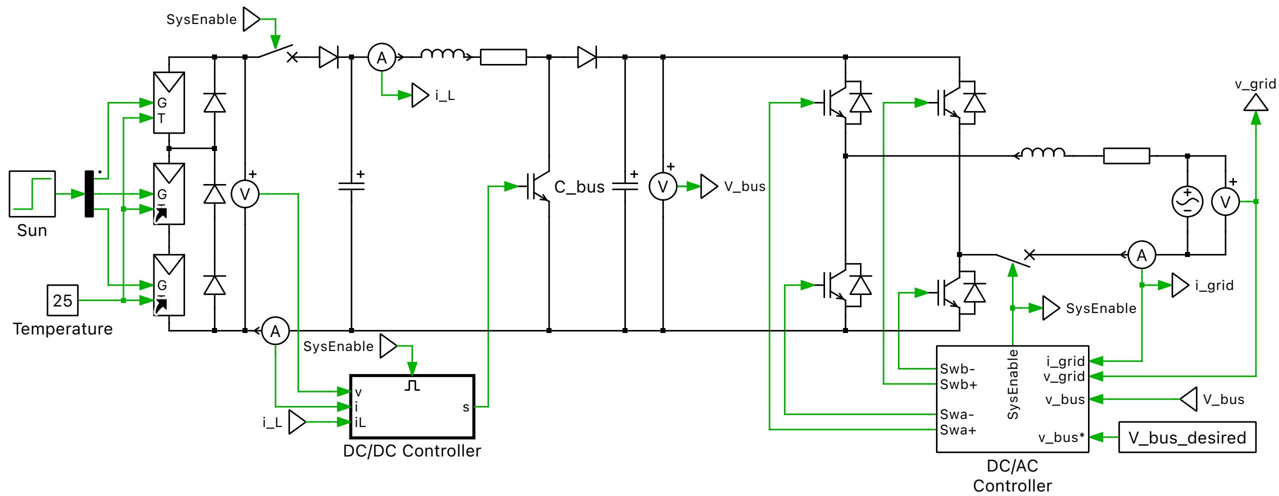

Fig. 1: Single-phase, two-stage, grid-connected PV inverter

Note

This model contains model initialization commands that are accessible from:
PLECS Standalone: the menu **Simulation > Simulation Parameters... > Initializations**
PLECS Blockset: right click in the **Simulink model window > Model Properties > Callbacks > InitFcn***

1.1 Photovoltaic System Model

An equivalent single-diode model proposed in [1] is used to implement the PV substring. The equation governing the current generated by the unit is given by:

$$I_{\mathrm{m}} = I_{\mathrm{PV}} - I_0 \cdot [e^{(V + \frac{R_{\mathrm{s}} I}{V_{\mathrm{t}} a})} - 1]$$

where I_{pv} is the current generated by the light incident on the unit, I_0 is the reverse saturation or leakage current of the diode, V is the terminal voltage, R_{s} is the equivalent series resistance, I is the terminal current, V_{t} is the thermal voltage, and a is the diode ideality factor. A detailed explanation of the model can be found in [1].

The PV model proposed in [1] has an inherent algebraic loop as the current generated by the PV panel (I_{m}) is a function of the terminal current (I). At the same time, I is a function of I_{m} and the series and parallel resistances (R_{s} and R_{p}). The PLECS model includes a low-pass filter to break the algebraic loop. The filter time constant is set to $1\mathrm{e}{-6}\,\mathrm{s}$.

The PV module consists of three of these substrings connected in series. Each substring has a bypass diode. The solar irradiance (input G) and temperature (input T) are assumed to be uniform across each substring. In the case of partial shading, the irradiance on each substring is unequal, decreasing the magnitude of the current generated by the shaded substring. In the absence of the bypass diode, this can cause reverse current and power dissipation in the shaded cells. The bypass diode allows the difference between the current generated by the shaded and unshaded substrings to flow through the bypass diode and avoids reverse current and power dissipation in the shaded cells [2].

The PV units modeled in this simulation correspond to an array of three parallel-connected KC200GT solar modules, with 54 series-connected solar cells in each KC200GT module. The parameters for each unit were chosen per Table 1 in [1].

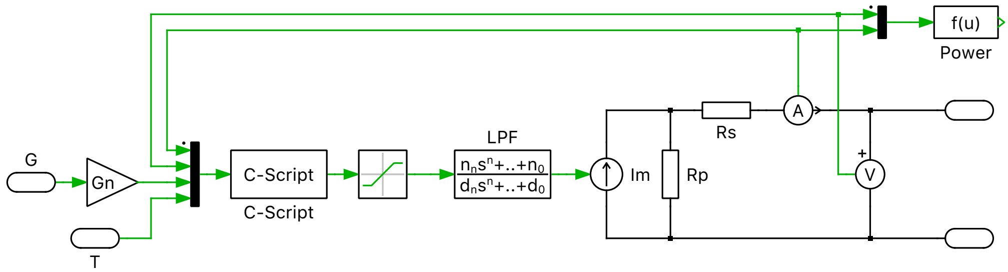

Fig. 2: Solar panel subsystem model

1.2 DC/DC Converter

A boost converter is controlled to operate the solar panel at the MPP. Two MPPT algorithms are implemented: Perturb and Observe (P&O), as proposed in [3], and Incremental Conductance (INC), as proposed in [4]. The P&O or INC algorithm can be selected from "MPP controller" in the "DC/DC Controller" subsystem.

These MPPT algorithms change the reference voltages to increase the output power of the solar panel. As the algorithm changes the reference voltage beyond the MPPT, power decreases. This decrease in power is detected and the reference voltage is changed in the opposite direction.

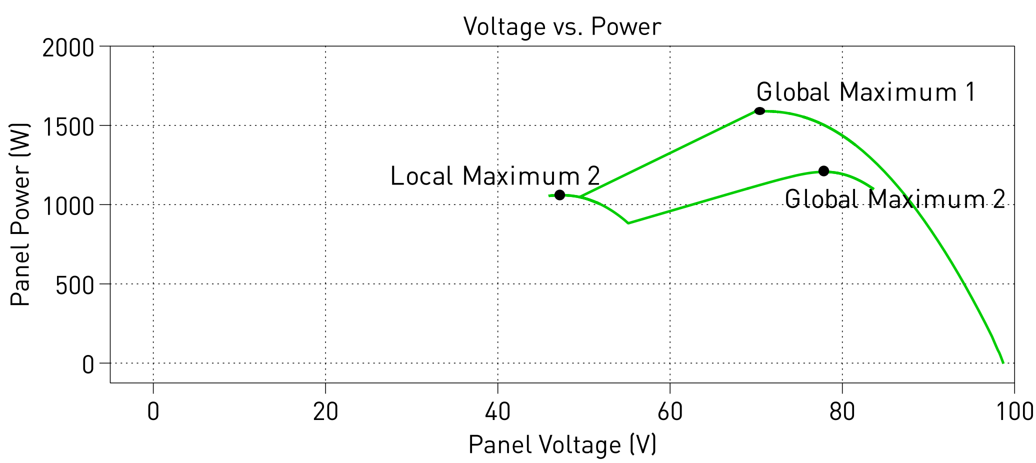

Fig. 3: Pover vs. voltage curve showing maximum power point tracking

In partial shading conditions, multiple local maximum power points (LMPP) occur, as can be seen in the plot above. These LMPPs are a result of the bypass diodes in the PV module [2]. If a single-stage MPPT algorithm is employed, depending on the starting voltage reference, the controller might get trapped in a LMPPs that is not the global maximum power point (GMPP). A second stage is required to operate the converter at the GMPPT. A voltage scan is performed across the entire voltage range for the PV system and the voltage at which maximum power is produced is recorded. This voltage range scan can be enabled as the second stage for the controller to operate the converter at the GMPPT.

The DC/DC controller comprises of a three-level, nested-loop structure. The MPP controller forms the outer loop and generates the voltage set point for the voltage controller. The voltage loop is used to control the input capacitor voltage of the boost converter. The voltage loop generates a current set point for the inner current loop. This current regulator is used to regulate the inductor current. The output of the current loop is used to derive the duty cycle for the boost converter.

1.3 DC/AC Converter

The output of the boost converter is connected to the DC-side of a single-phase voltage source inverter (VSI) via a DC-link capacitor. The VSI is regulated by a nested control scheme with an outer voltage loop and an inner current loop.

The outer voltage loop is used to control the DC-link voltage and maintain the voltage at the desired level. The voltage loop generates the grid current amplitude set point. Since the converter is operated with zero reactive power, the generated current set point from the voltage controller is equal to the set point of the q-axis current in the synchronous frame regulator.

The synchronous frame regulator reduces the complexity by transforming the AC system to an equivalent DC system and then implementing PI controllers for the d- and q-axis, respectively. In single-phase systems, unlike three-phase systems, not enough information is available to directly convert the AC current into the synchronous frame. In this simulation, the Fictive Axis Emulation (FAE) approach proposed in [5] is implemented. The grid current is assumed to be in line with the α-axis, and the β-axis currents are emulated using the FAE. The measured α and derived β currents are transformed into the dq-axis and fed into the synchronous-frame regulator. The angle used for the transformation is generated by a Phase-Locked Loop (PLL) that is modeled according to the second order generalized integrator model proposed in [6].

The synchronous frame regulator calculates a desired $\alpha\beta$ voltage vector set point. This vector is scaled by the peak grid voltage amplitude to generate the modulation index for the modulator. The modulation indices are used to generate the switching signals for the VSI using a unipolar modulator. The control structure for the DC/AC converter is shown below.

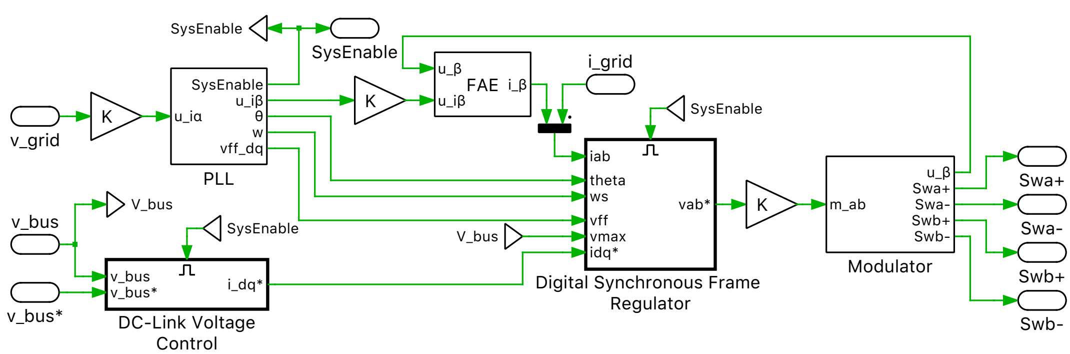

Fig. 4: Inverter controller

2 Simulation

The simulation demonstrates the operation of a grid-tied solar inverter operated at its MPP. Run the simulation with the model as provided and observe the trajectory of the power generated as a function of panel voltage in the scope labeled "P vs V".

The control system is initially disabled and the brakers remain open. Once the PLL has locked, all control systems are enabled and the brakers are closed. The reference voltage is changed resulting in a rise in the power generated by the solar panel until the MPP is reached. The panels are initially unshaded, but at $0.7\,\mathrm{s}$, Substring 3 experiences partial shading. The irradiance decreases from $100\,\%$ to $65\,\%$ of the nominal value ($1000\,\frac{W}{m^2}$). The GMPP search is enabled and the controller quickly reaches the global maximum. Re-run the simulation with the global search disabled and observe the difference in the solar panels' generated power under partial shading conditions.

The grid-side controller maintains the DC-link capacitor voltage at the desired $400\,\mathrm{VDC}$. It also maintaining unity power factor (as seen under the mask of the “Grid Analyzer” subsystem) and delivers power generated by the solar panels to the grid. Fig. 5 below shows the grid side voltage, current, and power when the system is operating with no partial shading.

Note that the “Grid Analyzer” subsystem can be used to calculate the total active power, apparent power, and power factor. By default, these calculations are disabled to minimize computation time, but can be enabled by selection of the subsystem configuration.

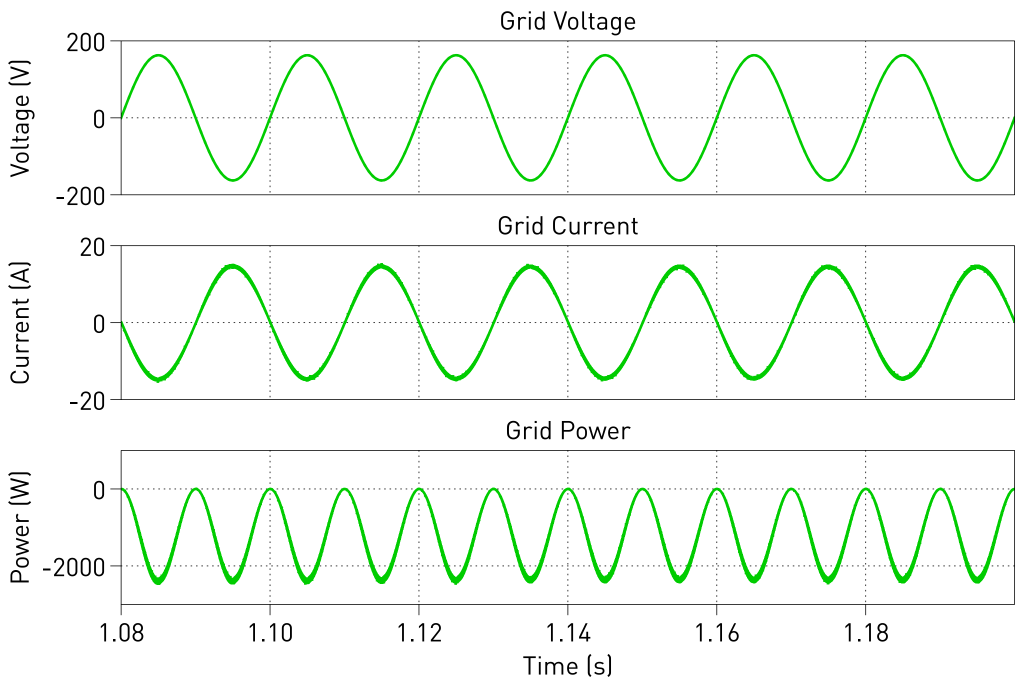

Fig. 5: Simulation results of grid signals

3 Bibliography

[1] M. Villalva; J. Gazoli; E. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays,” IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198-1208, May 2009.

[2] Y. Tong; R. Ayyanar, “Maximum-voltage-unit-guided MPPT algorithm for improved performance under partial shading,” 2013 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 2428-2434, 15-19 Sept. 2013.

[3] H. Abu-Rub; M. Malinowski; K. Al-Haddad, “Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications”, Wiley, 2014.

[4] B. Liu; S. Duan; F. Liu; P. Xu, “Analysis and Improvement of Maximum Power Point Tracking Algorithm Based on Incremental Conductance Method for Photovoltaic Array,” 7th International Conference on Power Electronics and Drive Systems (PEDS), 2007. pp. 637-641, 27-30 Nov. 2007.

[5] B. Bahrani; A. Rufer; S. Kenzelmann; L. Lopes, “Vector Control of Single-Phase Voltage-Source Converters Based on Fictive-Axis Emulation,” IEEE Transactions on Industry Applications, vol. 47, no. 2, pp. 831-840, March-April 2011.

[6] M. Ciobotaru; R. Teodorescu; F. Blaabjerg, "A New Single-Phase PLL Structure Based on Second Order Generalized Integrator," 37th IEEE Power Electronics Specialists Conference (PESC), 2006. pp. 1-6, 18-22 June 2006.

Revision History:

PLECS 4.3.1 First release

How to Contact Plexim:

☎ +41 44 533 51 00 Phone

+41 44 533 51 01 Fax

✉ Plexim GmbH Mail
Technoparkstrasse 1
8005 Zurich
Switzerland

@ info@plexim.com Email

https://www.plexim.com Web

PLECS Demo Model