GE Energy

Modeling of GE Solar Photovoltaic Plants for Grid Studies

Prepared by:

Kara Clark

Nicholas W. Miller

Reigh Walling

Version 1.1

April 16, 2010

General Electric International, Inc.
One River Road
Schenectady, NY 12345
USA

Legal Notice

This report was prepared by General Electric International, Inc. (GEII) as an account of work sponsored by GE Energy business. Neither GE Energy nor GEII, nor any person acting on behalf of either:

1. Makes any warranty or representation, expressed or implied, with respect to the use of any information contained in this report, or that the use of any information, apparatus, method, or process disclosed in the report may not infringe privately owned rights.

2. Assumes any liabilities with respect to the use of or for damage resulting from the use of any information, apparatus, method, or process disclosed in this report.

Foreword

This document was prepared by GE Energy in Schenectady, NY. Technical and commercial questions and any correspondence concerning this document should be referred to:

Kara Clark
GE Energy
Building 53-302A, One River Road
Schenectady, New York 12345
Phone: (518) 385-5395
E-mail: kara.clark@ge.com

Revision History

Version 1.0 – September 9, 2009
Version 1.1 – April 16, 2010

Summary of Changes in Version 1.1

- Updated inverter size from 600 kW to 700 kW
- Updated current limits in LVPL and electrical control models
- Updated reactive power control figure, added new data to table
- Updated electrical control figure, added text describing input test signal

Table of Contents

Table of Figures

Table of Tables

1 Introduction

GE Energy is developing models of GE solar photovoltaic (PV) plants suitable for use in system impact studies. This report documents the current recommendations for dynamic modeling of solar plants that use photovoltaic cell arrays with a full converter interface to the power system. Throughout this document, such a PV system is simply referred to as a solar plant. Other types of solar generation, e.g. solar thermal facilities that use concentrators and steam generators without a full converter interface, should not be represented with this model. The model structure is based upon the GE full converter wind turbine generator models.

The model provided is as detailed as is appropriate for bulk power system studies. It is valuable to put the model limitations in the context of what analysis is required. Most important, this model is for positive sequence phasor time-domain simulations – e.g. PSLF or PSS/e. Second, this assumes that the analysis is mainly focused on how the WTGs react to grid disturbances, e.g. faults, on the transmission system. Details of the device dynamics have been substantially simplified. Specifically, the very fast dynamics associated with the control of the converter have been modeled as algebraic (i.e. instantaneous) approximations of their response. The model is not intended for use in short circuit studies or electromagnetic transient studies.

This model represents a solar plant with a dedicated feeder to the grid interconnection. It should not be used to represent distributed generation that is in compliance with IEEE 1547 and UL 1741.

2 Model Overview

A GE solar plant has many similarities to a wind plant that uses full converter wind turbine generators. Both consist of multiple small sources of electrical power, which are aggregated and injected into the transmission system at a single point. Both use a converter interface to the power grid. Both must meet system performance criteria, such as voltage regulation, reactive power control, and under-voltage tripping. Therefore, the solar plant model described in this document is based upon GE's wind plant models as described in "Modeling of GE Wind Turbine-Generators for Grid Studies". As solar plant technology, control philosophy, and/or interconnection requirements evolve, so will the model.

In practice, a solar plant has a local grid collecting the output from the converters into a single point of connection to the grid. Since the solar plant is made up of many identical converters, it is a reasonable approximation to parallel all the converters into a single equivalent large converter. This approach is used for the models presented in this report. However, there are limitations. Disturbances within the local collector grid cannot be analyzed. A single converter equivalent requires the approximation that the power output of all the converters will be the same at a given instant of time. For system impact studies, simulations are typically performed with the plant at maximum power output. Under this condition, the assumption that all converters are at the same, rated, output is not an approximation. For other conditions, this assumption presumes minimal geographic dispersion and uniform solar irradiation across the plant. It is also suitable when the aggregate dynamic behavior of converters with dissimilar array irradiations is about the same as that of an equivalent converter whose array receives the average level of irradiation. Simulations of bulk system dynamics using a single converter equivalent is adequate for most planning studies.

From a load flow perspective, standard generator and transformer models are required for initialization of the dynamic simulation program.

The fundamental frequency electrical dynamic performance of a solar plant is completely dominated by the converter. The control of active and reactive power is handled by fast, high bandwidth regulators within the converter controls, and can be greatly simplified for simulation of bulk power system dynamic performance. Two device models, a converter model and an electrical control model, are used to construct a solar plant model. An overview of this structure is shown in Figure 2-1.

The converter model injects real and reactive current into the network in response to control commands, and represents low and high voltage protective functions (e.g., low voltage ride through capability). The real power signals are initialized to the generator output in the power flow.

The control model includes closed loop reactive power controls, and voltage regulation with either a simplified emulator of GE's SolarCONTROL[1] solar plant

[1] Trademark of General Electric Company

supervisory control system or a separate, detailed control model. The control model sends a reactive command to the converter model.

In addition, user-written models can inject power profiles into the solar plant dynamic models, or to represent additional protective functions (e.g., over/under frequency).

The model allows reasonable customization of the control parameters to meet specific application requirements.

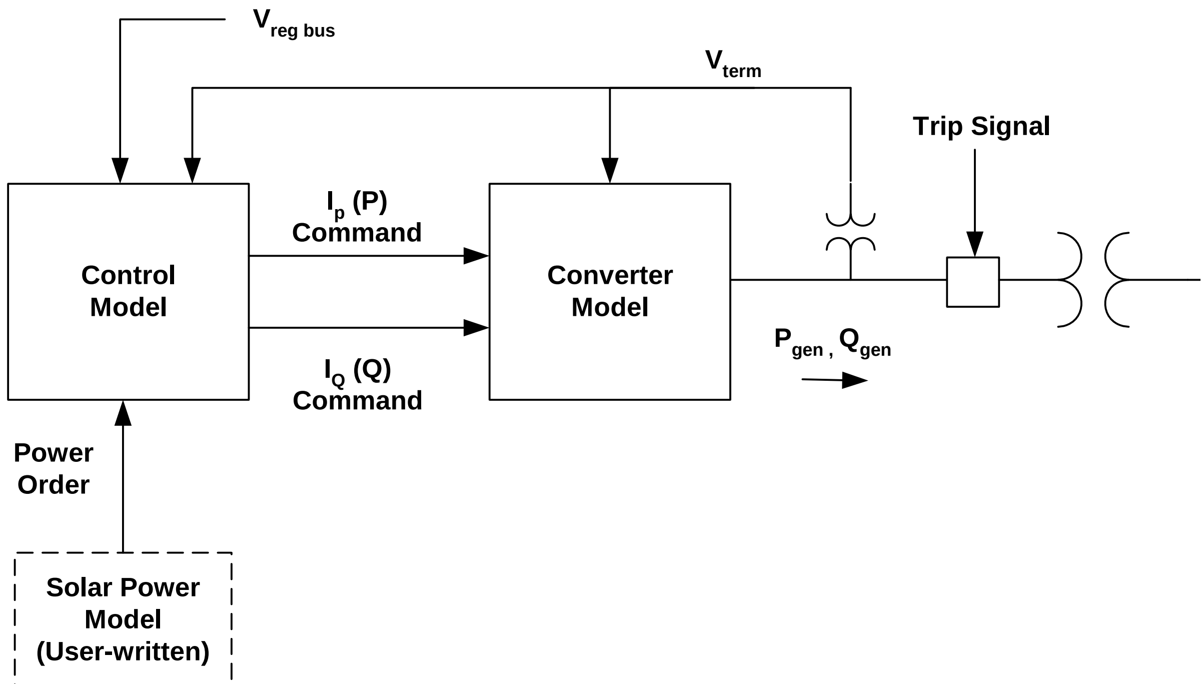

Figure 2-1. GE Solar Plant Dynamic Model Connectivity.

2.1 Load Flow Model

A simplified model of a GE solar plant is appropriate for load flow analysis. Such a model is shown in Figure 2-2. This model consists of a single generator and unit transformer with MVA ratings equal to N times the individual device ratings, where N is the number of converters in the plant. This is sufficient for smaller solar plants with a point of interconnection (POI) at 34.5 kV or below. Larger plants, connecting into higher voltage substations, typically require a second transformer to step from the collector voltage to the sub-transmission or transmission voltage level. Given the relatively small footprint of a solar plant, the collector system impedance and charging are neglected.

The aggregate solar plant is modeled as a conventional generator connected to a 480 V bus. The generator real power output (Pgen), maximum reactive power output (Qmax), and minimum reactive power output (Qmin) should match the solar plant capability. The reactive power capability will depend upon the number of converters provided, and how that capability is used to meet the interconnection requirements.

The capability of a single converter is shown in Table 2-1. The converter will prioritize reactive power production over real power production to ensure the overall converter current limits are respected.

To illustrate the trade-offs, consider a solar plant with a maximum real power output of 10.5 MW. It could be configured with 16 converters for a total MVA rating of 11.3 MVA, which would provide a +/-0.93 power factor range (+/-4.2 MVAr) at full power output. Alternatively, the same plant could be configured with 15 converters for a total rating of 10.6 MVA. This second plant would limit the maximum power output to 9.7 MW under conditions requiring reactive power output at +/-4.2 MVAr. Or it could deliver the full 10.5 MW, if the interconnection required no more than +/-0.99 power factor (+/-1.45MVAr). The load flow model should accurately reflect the capabilities of the plant under study.

A typical distribution substation interconnection would be at a 15, 25 or 35 kV-class voltage level, requiring a suitably rated padmount transformer with an impedance of about 6% on the transformer MVA rating. For larger plants, a substation transformer would also be necessary. It should also be suitably rated for the size of the plant, with an impedance of about 10% on the transformer MVA rating.

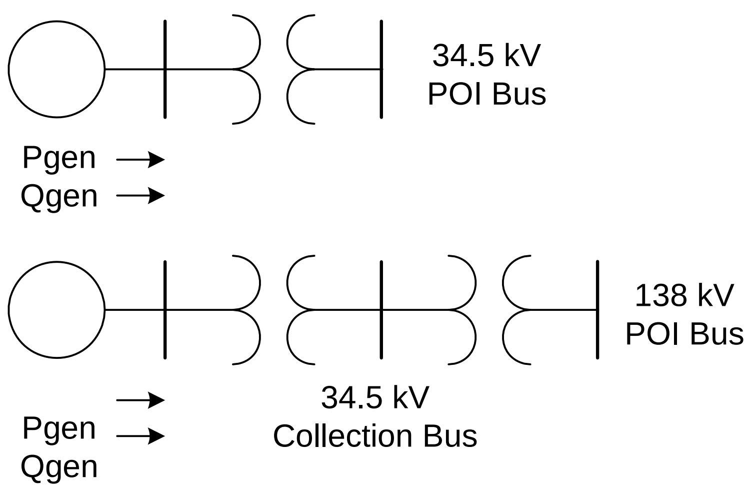

Figure 2-2. Simplified Solar Plant Power Flow Model Examples.

Table 2-1. Single Converter Rating.

Generator Rating	707 kVA
Pmax	700 kW
Pmin	0 kW
Qmax	99 kVAr*
Qmin	-99 kVAr*
Terminal Voltage	480 V

*These values are for +/- 0.99 power factor.

2.2 Initial Conditions for Dynamic Simulation

The load flow provides initial conditions for dynamic simulations. The conditions outlined above are generally applicable to the dynamic model presented below. The maximum and minimum active and reactive power limits must be respected in order to achieve a successful initialization.

If the solar plant's electrical control is customized to meet a particular set of desired performance objectives, then the load flow must be initialized in accordance with those customized rules. For example, it is possible to inject or absorb reactive power (e.g., regulate voltage) at zero real power with a converter system (SolarFREE Reactive Power[2]). Therefore, the real power at the generator in the power flow must be zero for this type of simulation.

The dynamic solar plant models have the option to use the SolarCONTROL supervisory control system to regulate a measured bus voltage, such as the POI. Line drop compensation may also be used to regulate the voltage some distance into the transmission system. If these features are selected in the dynamic models, then the generator in the load flow model needs to regulate the corresponding bus.

Inconsistencies between the power flow and the dynamic model will result in an unacceptable initialization.

[2] Trademark of General Electric Company

3 Dynamic Model Description

This section presents the engineering assumptions, detailed structure, and data for each of the component models necessary to represent a GE solar plant.

3.1 Converter Model

This model (**gewtg** in PSLF) is the equivalent of the converter, and provides the interface between the solar plant and the network. It is an algebraic, controlled-current source that computes the required injected current into the network in response to the real and reactive current commands from the electrical control model. This controlled-current source also incorporates the low voltage power logic and the fast-acting converter controls that mitigate over-voltages by reducing reactive current output.

The model is shown in Figure 3-1. The real and reactive current command signals are developed in the electrical control model described in Section 3.2. The real current command signal is initialized to match the generation power output from the power flow. It remains constant unless a user-written model is used to provide a power profile that varies with time. The low-pass filters on the incoming command signals are simple approximations to the complex, fast electronic control system. This small lag (0.02 seconds) provides a reasonable representation in the time frame of interest. As with all positive sequence fundamental frequency analysis, sub-cycle behavior is not meaningful.

The Low Voltage Power Logic (LVPL) reduces system stress during and immediately following sustained faults by limiting the real current command with both a cap and a ramp rate limit. Under normal operating conditions, the filtered terminal voltage is above a user-specified breakpoint (brkpt) and there is no upper limit. When the voltage falls below the breakpoint during a fault, a cap is calculated and applied. When the voltage is below a user-specified zero-crossing point (zerox), the cap becomes zero. The user-specified ramp rate limit (rrpwr) is key to the post-fault power recovery. During this recovery period, the voltage will exceed the breakpoint and the cap is removed. However, the real current command rate of increase will be restricted by the ramp rate limit.

The actual converter controls include a phase-locked loop (PLL) to synchronize with the system. However, the PLL dynamics are extremely fast relative to the PSLF time frame, and under normal grid operating conditions result in effectively perfect tracking. Under transient conditions of severe voltage depression and relatively high system impedance, delivery of active current becomes limited. The fast control actions effectively result in reduced active current delivery. This fast action is captured in the model by a low voltage active current management function. This is a linear reduction of active current injection for terminal voltages below 0.8 pu. This effect is modeled within the network solution (i.e. without state variables), which is consistent with the overall algebraic modeling of current injection by the converter model. The reactive current delivery remains high under these transient conditions, providing voltage support and short circuit strength.

The fast controls will also act to limit excess voltage on the terminals by suppressing reactive current injection when the terminal voltage rises excessively. This effect is modeled by a high voltage reactive current management function in the network solution, which drives reactive current injection down to limit terminal voltage to 120%. Reactive current injection is limited to the machine rating.

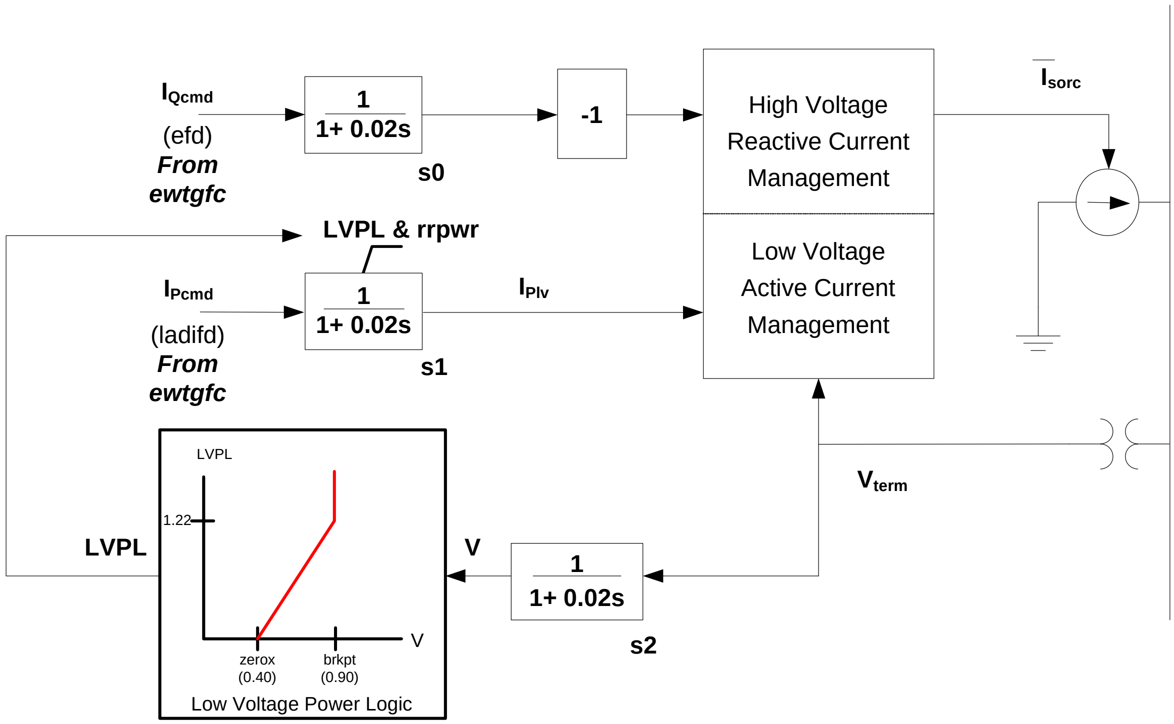

Figure 3-1. Converter Model.

3.1.1 Fault Ride Through

The converter model also includes over/under voltage protective functions. GE solar plants have "zero voltage ride through" (ZVRT) capability. Voltage ride through requirements are defined such that a plant must not trip for events that are less severe than the defined thresholds and time durations. Plants may tolerate more severe events without tripping. Use of the model therefore does not ensure that the plant will trip, only that it is allowed to do so. The thresholds and time durations for this protection will vary significantly from one project to another as equipment designs are modified to meet specific grid codes or interconnection agreements. Recommendations for modeling the protection functions are as follows:

- **For feasibility and reliability impact studies of future projects:** An objective of the study should be to establish the voltage and frequency excursions that may occur. Therefore, either do not include the protection model or else set the trip levels consistent with applicable grid codes for the project.
- **For facility studies for projects in the design phase**: Use trip settings consistent with performance commitments. The results of the study should

indicate acceptable settings for the actual protective devices to satisfy system requirements while providing adequate protection for the equipment.

- **For studies involving in-service projects:** Use the actual trip settings of the protective equipment.

Table 3-1 gives voltage trip levels and durations for the ZVRT option available with SolarRIDE-THRU[3]. It is important to note that the low voltage thresholds are a stepwise fit to a curve that defines the equipment minimum performance specifications. Figure 3-2 shows this graphically; with the step-wise curve representing the trip points in the table. The step-wise curve is conservative, in that it is always inside the specification. As noted above, low voltage ride through requirements vary from application to application. The tripping thresholds and durations should be chosen to appropriately represent the application under study.

Any other desired protective functions (e.g., over/under frequency) would need to be implemented with additional protective device or user written models.

Table 3-2 includes recommended settings for the converter model. The maximum allowed ramp rate limit, rrpwr, is 20, and the minimum allowed is 3. The LVPL breakpoint, brkpt, must be greater than or equal to 0.4, less than or equal to 1.0, and greater than the zero-crossing, zerox.

Table 3-1. Zero-Voltage Ride Through (ZVRT) Thresholds and Durations.

V (%)	ΔV (pu)	Time (sec)
75	-0.25	1.9
50	-0.50	1.2
30	-0.70	0.7
15	-0.85	0.2
110	0.10	1.0
115	0.15	0.1

[3] Trademark of General Electric Company

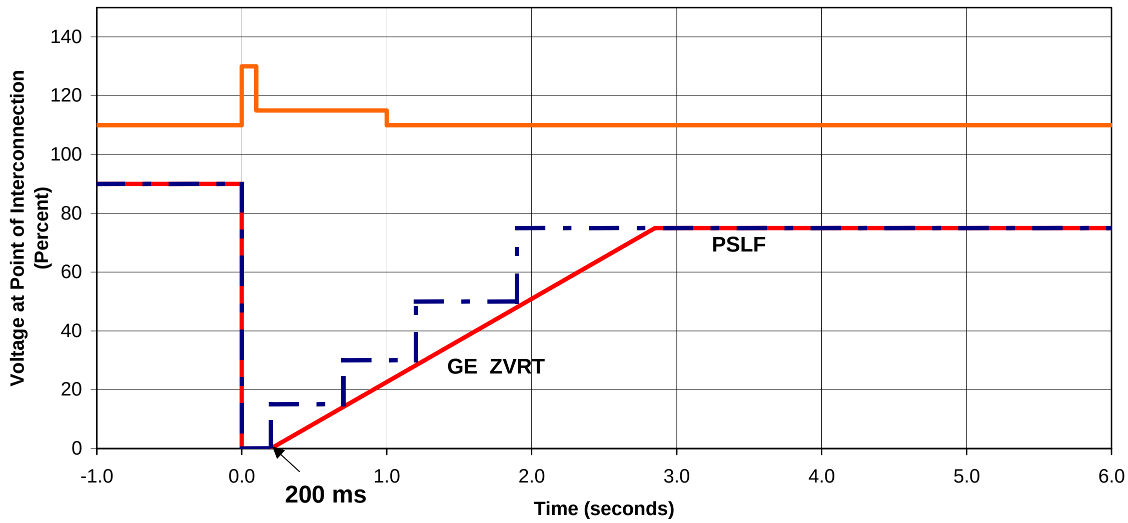

Figure 3-2. ZVRT Model Settings and Equipment Specification.

Table 3-2. Converter Model Parameters.

Parameter Name	Recommended Values
lpp	0.8
dvtrp1	-0.25
dvtrp2	-0.50
dvtrp3	-0.70
dvtrp4	-0.85
dvtrp5	0.10
dvtrp6	0.15
dttrp1	1.9
dttrp2	1.2
dttrp3	0.7
dttrp4	0.2
dttrp5	1.0
dttrp6	0.1
fcflg	1
rrpwr	10.
brkpt	0.9
zerox	0.4

3.2 Control Model

This control model (**ewtgfc** in PSLF) dictates the active power to be delivered to the system based on the power flow initial conditions or a user-written solar power profile (P_{ord}). It dictates the reactive power to be delivered based on the supervisory VAr controller output (Q_{ord}). Q_{ord} can either come from a separate model, or from the SolarCONTROL voltage and reactive control emulator function included in the control model. Qord can also be held constant or determined by a power factor regulator. The model consists of the following control functions:

SolarCONTROL Emulator
Power Factor Regulator
Electrical Control

The overall block diagram for the Reactive Power Control and the Electrical Control is shown in Figure 3-3. These controls are described in more detail in the following sections.

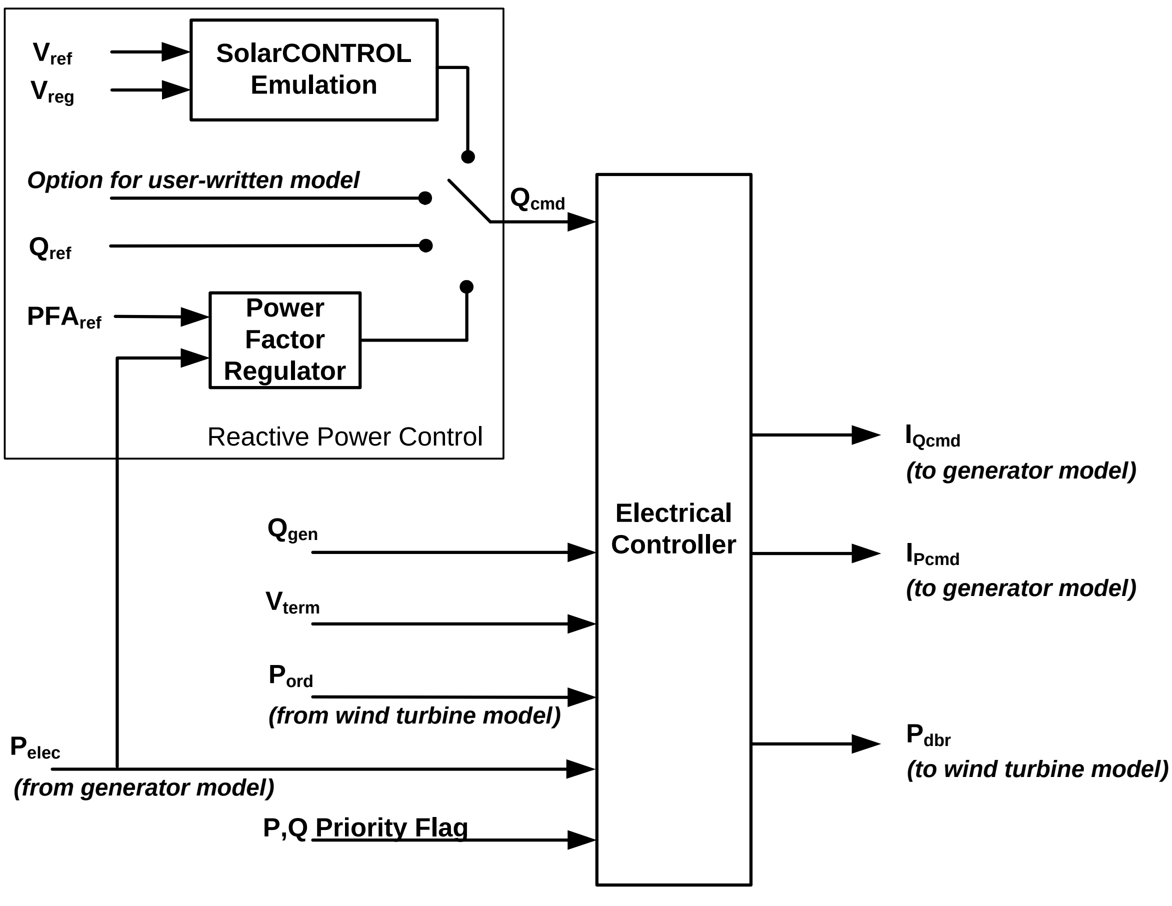

Figure 3-3. Overall Reactive Power and Electrical Control Model.

3.2.1 Reactive Power Control

A more detailed representation of the Reactive Power Control is shown in Figure 3-4.

The SolarCONTROL emulator function represents a simplified equivalent of the supervisory VAr controller portion of the entire solar plant management system (SolarCONTROL). The function monitors a specified bus voltage and compares it to a reference voltage. Three regulated bus options are available: the terminal bus, a user-specified remote bus (e.g., the POI), or a synthesized point in the power system. The latter bus is synthesized from local voltage and current measurements, and the compensating reactance, Xc. The regulator itself is a PI controller. The time constant, T_c, reflects the delays associated with cycle time, communication delays, and additional filtering in the controls. The voltage measurement lag is represented by the time constant T_r. Table 3-3 gives suggested settings for the SolarCONTROL emulator model.

The other reactive power control method available is power factor control. It is enabled by setting pfaflg to 1. The data associated with this mode are also shown in Table 3-3. The appropriate flag and gain settings to represent various control strategies are described in Section 0.

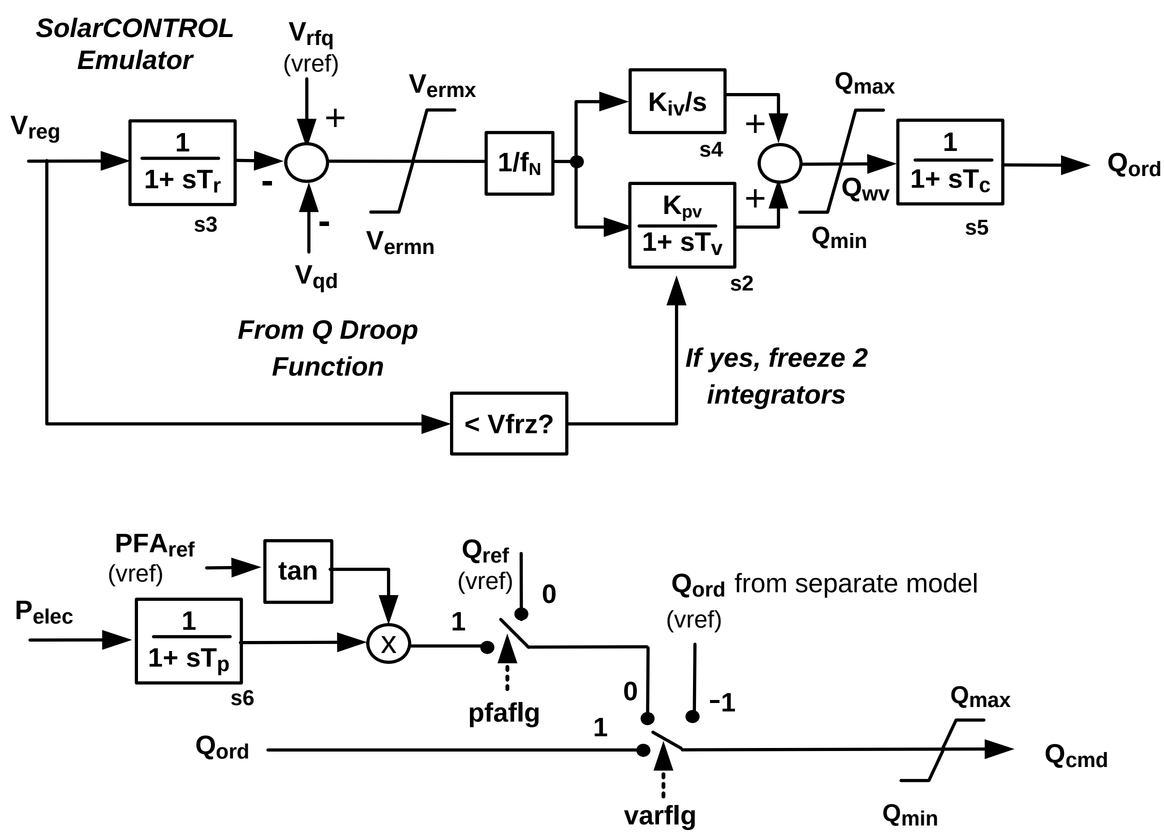

Figure 3-4. Reactive Power Control Model.

Table 3-3. Reactive Power Control Parameters (on Generator MVA Base).

Parameter Name	Recommended Value
T_r (sec)	0.02
T_v(sec)	0.05
f_N	1.0
T_c(sec)	0.15
K_{pv}	18.
K_{iv}	5.
Q_{max} (pu)	0.14*
Q_{min} (pu)	-0.14*
T_{pwr} (sec)	0.05
X_c (pu)	0.0
V_{ermn} (pu)	-0.1
V_{ermx} (pu)	0.1
V_{frz} (pu)	0.7

*Provides +/- 0.99 power factor at the terminals. Limits of +/- 0.436 pu reactive power would provide +/- 0.90 power factor at the terminals, but the converter system would need to be oversized relative to the real power rating.

The PI gains, K_{pv} and K_{iv}, are field adjustable to meet performance objectives and may be adjusted in the model, if necessary. The values given in the table are rough upper limits, based on GE simulation and experience. They should be suitable for systems with a short circuit capacity of 5 or more times the solar plant rating. These higher gains will give better voltage response to grid voltages disturbances. However, higher gains result in increased risk of instability – not unlike the way AVR gains can destabilize conventional synchronous machines. As a system weakens, the effective closed-loop response gets faster. Thus, selection of higher gains for system performance must be accompanied by analysis that assures stable operation under all credible operating conditions – especially the minimum short circuit strength condition.

The parameter, f_N, is used to represent wind plants with a reduced number of wind turbines on-line. For solar plants, this parameter should be set to 1.

The Q Droop function, shown in Figure 3-5, is a relatively slow-acting function that reduces the effective voltage reference (V_{rfq}-V_{qd}) as reactive power changes. This improves coordination between multiple integral controllers regulating the same point in the system. By default, the Q Droop function is disabled. It may be enabled by setting the gain parameter, K_{qd}, to a non-zero value. Typical data are shown in Table 3-4. There are three options for the reactive power input to this function: reactive power generated by the WTG, reactive power flow in a user-specified branch, or a synthesized reactive power. The latter is the reactive power flow in the user-specified branch plus a secondary term, $X_{qd}*I_m^2$, where I_m is the magnitude of the current flowing in that branch.

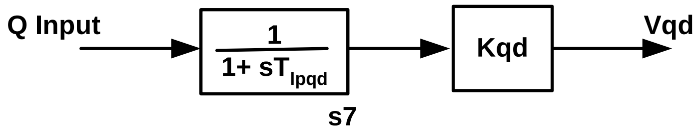

Figure 3-5. Q Droop Function Model.

Table 3-4. Q Droop Function Parameters.

Parameter Name	Recommended Value
T_{lpqd} (sec)	5.0
K_{qd}	0.04
X_{qd} (pu)	0.0

3.2.2 Electrical Control

A more detailed representation of the Electrical Control is shown in Figure 3-6. This model is a simplified representation of the converter control system.

The volt/var control monitors the generator reactive power, Q_{gen}, and terminal voltage, V_{term}, to compute the reactive current commands I_{Qcmd} required to meet the Q_{cmd} from the Reactive Power Control. The Q_{cmd} signal is compared to the reactive power generated by the converter, and the resulting error is integrated with a gain of Kqi, to generate a voltage reference, Vref. Thus, the reactive power command is implemented via a slowly changing voltage reference. The subsequent voltage control block is significantly faster. The voltage reference is compared to the actual terminal voltage, and the resulting voltage error is multiplied by a gain and integrated to compute the reactive current command I_{qcmd}. Thus, a drop in terminal voltage, e.g., in response to a system fault, results in an immediate large voltage error and an increased reactive current command.

As noted above, the power order (P_{ord}) is initialized to match the generation power output from the power flow. It remains constant unless a user-written model is used to provide a power profile that varies with time. The real current command signal, $I_{Pcmd,}$ is developed from this power order and the terminal voltage.

The dynamic braking resistor (DBR) function is provided for GE's full converter wind plants, and is therefore in this model. This function will not be included in a solar plant. The associated data are set to zero.

The details of the converter current limit are shown in Figure 3-7. The objective of this function is to prevent the combination of the real and reactive currents from exceeding converter capability. Depending upon the value of a user-specified flag, pqflag, either real or reactive power has priority. It is expected that GE solar plants will give reactive power priority over real power.

When reactive power has priority, the calculation of the limit on the reactive current begins by determining the minimum of a hard reactive current limit, I_{qhl}, and a voltage dependent limit, I_{qmxv}. The voltage dependent limit will be equal to the steadystate rating of the solar plant (as defined by the input parameter Q_{max}) at 1.0 pu voltage and will linearly increase as voltage drops. The maximum voltage dependent reactive current limit is 1.6 pu at zero voltage. The minimum of I_{qhl} and I_{qmxv} is compared to a maximum temperature dependent converter current, I_{maxTD}. That minimum is the maximum limit, I_{qmx}, applied to the reactive current order, I_{Qcmd}. The minimum reactive current, I_{qmn}, is the negative of this maximum limit. The remaining converter current capability, SQRT(I_{maxTD}^2 – I_{Qcmd}^2), becomes the maximum, I_{pmx}, applied to the real current order, I_{Pcmd}. No minimum is applied to the real current order. Reactive power priority is recommended, which is equivalent to the default value of 0 for pqflag.

When real power has priority, the real current order, I_{Pcmd}, is limited to the minimum of the maximum temperature dependent converter current, I_{maxTD}, and a hard active current limit, I_{phl}. The calculation of the limit on the reactive current begins by determining the minimum of a hard reactive current limit, I_{qhl}, and the voltage dependent limit, I_{qmxv}, as described above. The minimum of I_{qhl} and I_{qmxv} is compared to the remaining converter current capability, SQRT(I_{maxTD}^2 - I_{Pcmd}^2). That minimum is the maximum (capacitive) limit, I_{qmx}, applied to the reactive current order, I_{Qcmd}. The minimum (inductive) reactive current, I_{qmn}, is the negative of the maximum. No minimum is applied to the real current order.

An auxiliary test signal can be injected into the terminal bus voltage regulator via model[@index].sigval[0], as shown at the top of Figure 3-6. A user-written dynamic model (epcmod) is needed to generate the desired signal. The index of the solar converter model (@index) can be obtained using the model_index function.

Table 3-5 includes recommended settings for the electrical control model. The converter current limit, ImaxTD, is a function of time and operation. However, it is constant in this model (1.7 pu) and not user-specified.

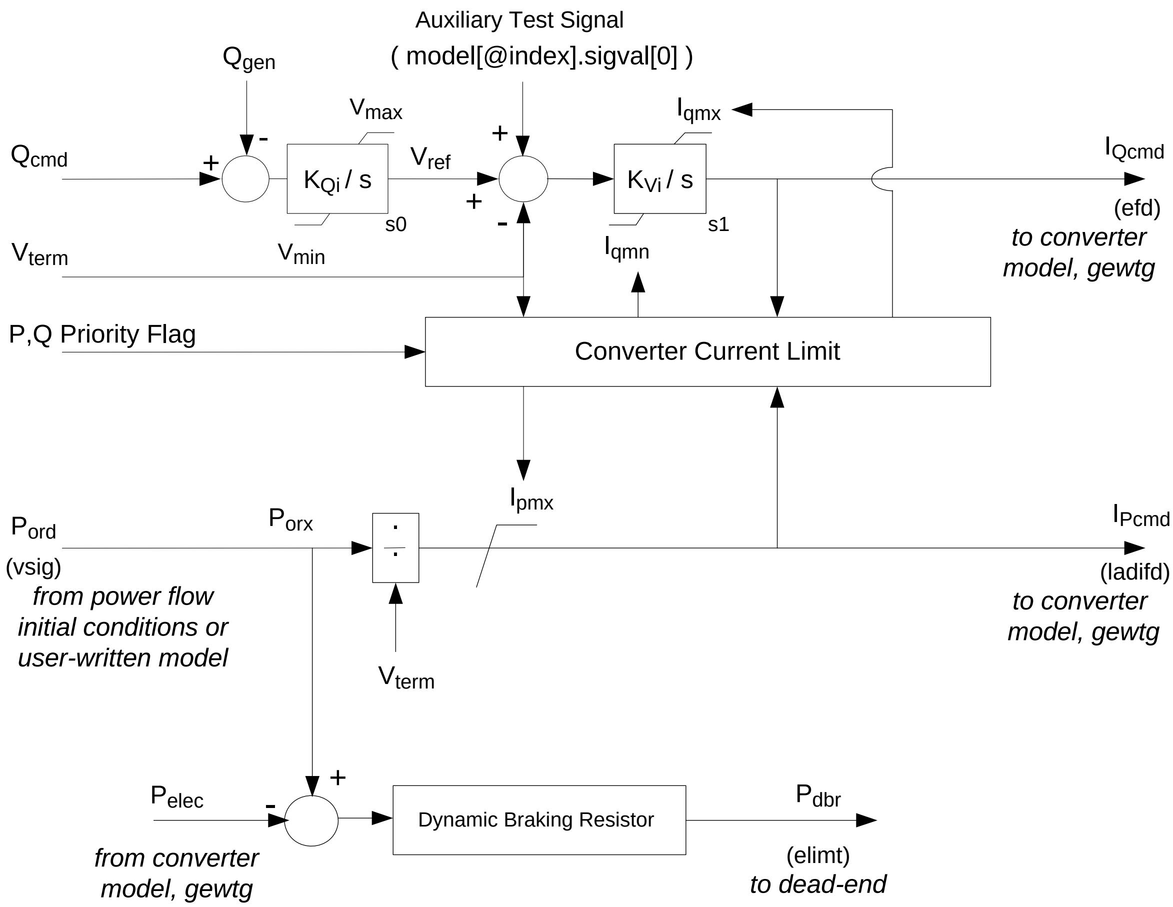

Figure 3-6. Electrical Control Model.

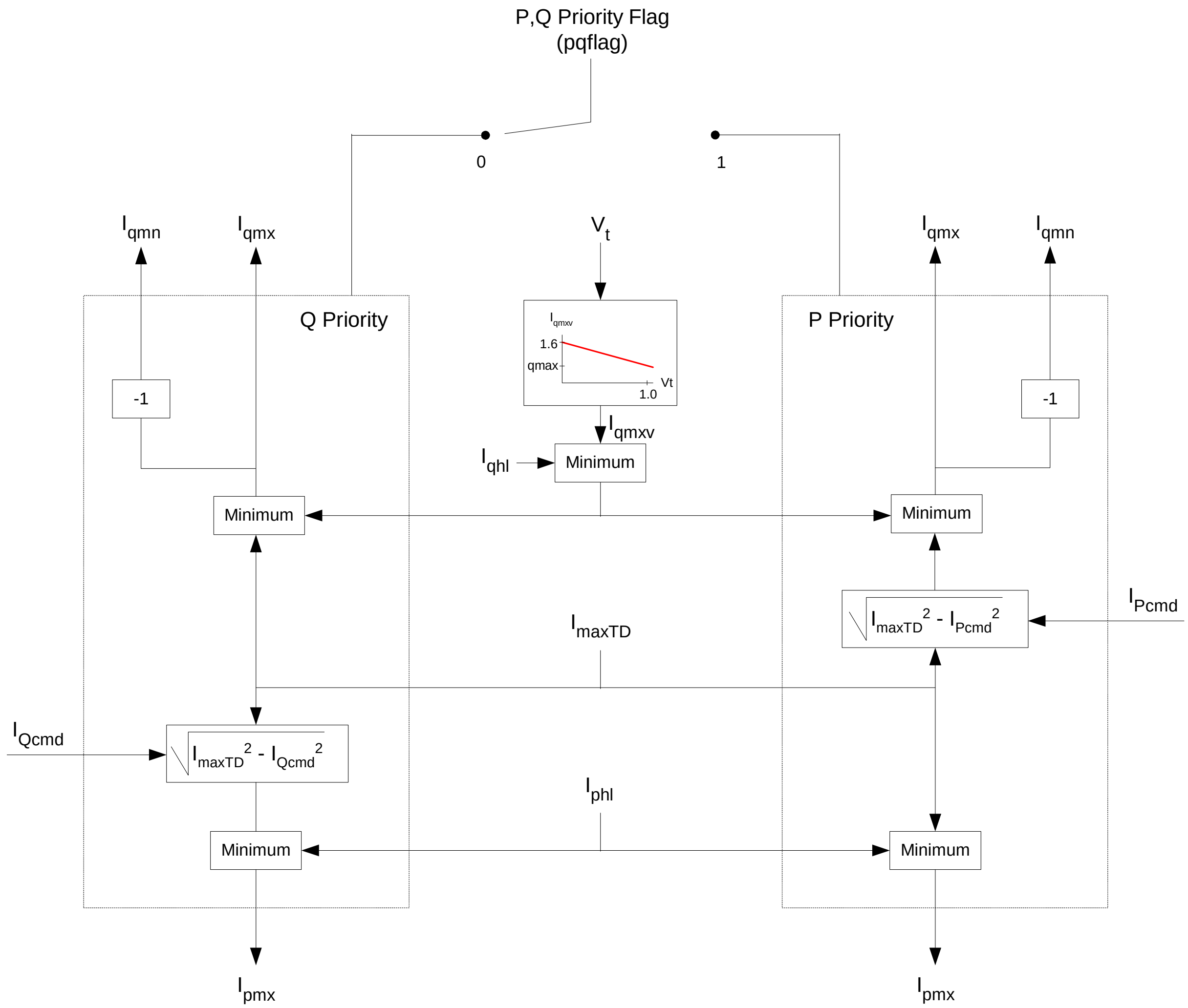

Figure 3-7. Converter Current Limit Model.

Table 3-5. Electrical Control Parameters.

Parameter Name	Recommended Value
Kqi	0.1
Kvi	120
Vmax	1.10
Vmin	0.90
Iphl	1.24
Iqhl	1.25
pqflag	0=Q priority
EBST	0.
Kdbr	0.

3.2.3 Control Strategies

A variety of control strategies can be represented, including voltage regulation of a remote bus or constant power factor control, both with and without the supervisory SolarCONTROL. The various strategies can be implemented by setting the **varflg**, **pfaflg,** and **Kqi** parameters as follows:

- **Operation with SolarCONTROL and with "volt/VAr" control** (**varflg = 1, pfaflg = 0, Kqi = 0.1)** This represents the normal configuration for a North American solar plant, using the SolarCONTROL emulator in the model to represent the plant level supervisory control.
- **Operation without SolarCONTROL and with "volt/VAr" control** (**varflg = 0, pfaflg = 0, Kqi = 0.001**) With the SolarCONTROL turned off, Kqi is reduced so there is a slow reset to desired reactive power and terminal voltage control is rapid. This combination of flags and Kqi = 0.1 can be used to emulate SolarCONTROL at a fixed plant reactive power control.
- **Operation without SolarCONTROL and with fast power factor control** (**varflg = 0, pfaflg = 1, Kqi = 0.5)** This represents a configuration where a set power factor angle is rapidly regulated by the converter control. Closed loop voltage control is not used on these systems, but is left in the model to approximately represent other means that are used to limit voltage excursions that would otherwise cause unit tripping.
- **Operation with SolarCONTROL and with fast power factor control (varflg = 1, pfaflg = 0, Kqi = 0.5)** This represents a reactive power control configuration that includes SolarCONTROL. It is similar to the first control option except the regulator gain is at a higher value. The power factor control flag, pfaflg, is set to zero because the signal from the SolarCONTROL is a reactive power order, rather than power factor angle.

4 Benchmark Simulations

The models described in this report have been implemented in GE's PSLF load flow and dynamic simulation software. Representative results using the PSLF models are presented in this section. Note that these simulations are not necessarily updated with each version of this document. Therefore, the simulations may not always use the latest model or data recommendations. They do, however, illustrate the general performance characteristics of the solar plant model. The data used for these simulations is shown in Section 4.3.

Upon request, GE will provide the PSLF benchmark simulation results to those who wish to implement the models in other simulation programs. The results can be supplied in ASCII format for cross-plotting in order to validate the model implementation.

4.1 Test System

One line diagrams of the test system are shown in Figure 4-1. The top diagram shows real and reactive power flow (MW, MVAr), and the bottom diagram shows impedances (pu on 100 MVA). The test system represents an aggregate model of a solar plant, with a single generator and substation transformer to the 34.5 kV point of interconnection (POI). The solar plant is rated 10 MW.

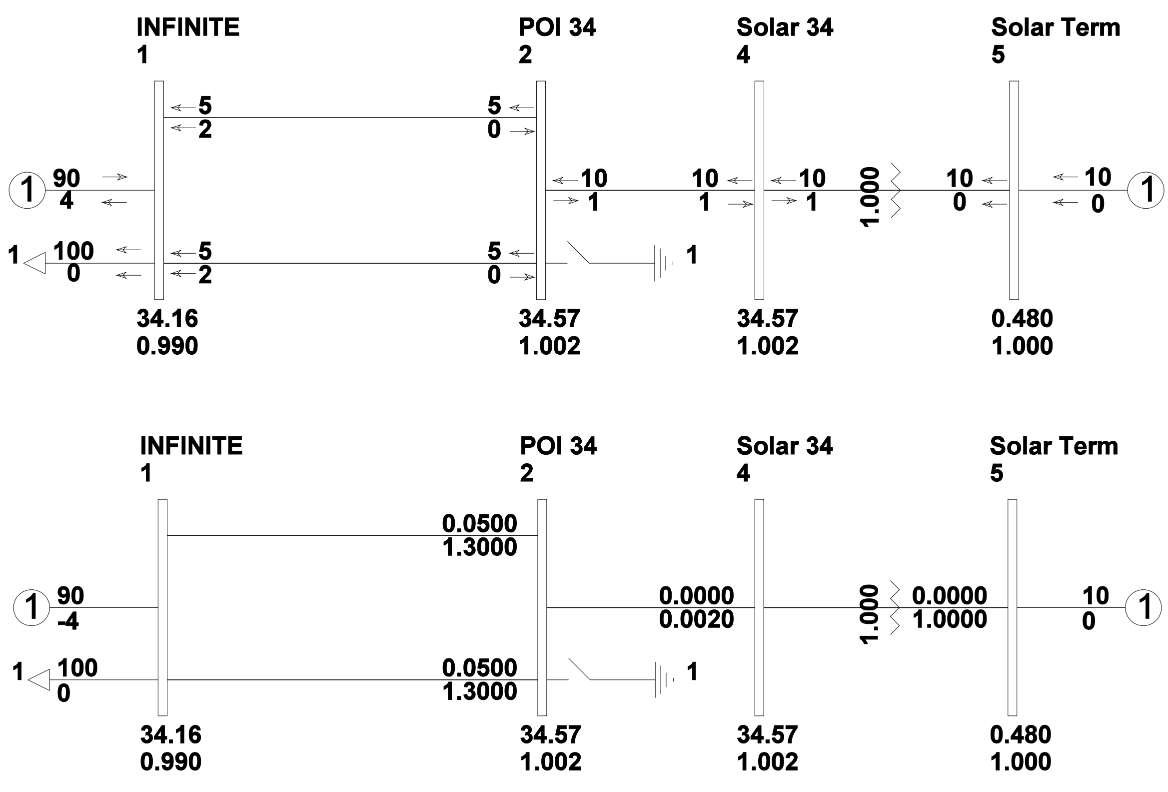

Figure 4-1. Test System.

4.2 Simulation Results

The following subsections describe simulation results illustrating the solar plant's overall performance, including voltage regulation, zero-power operation capability, converter current limit, and low voltage power logic. A variety of disturbances are represented – fault disturbances, capacitor switching events, and solar power profiles.

Plotted results are provided for each test simulation. Traces plotted together share the same scaling, as shown on the y-axis. Scaling for a particular trace can be confirmed by checking the legend below each plot. The same plot format was used for all simulations, and a brief description follows.

From top to bottom, the left column shows the solar plant terminal voltage (dark blue line, pu), point of interconnection voltage (red line, pu), and infinite bus voltage (green line, pu) in the first plot. The second plot shows the solar plant's real power output (dark blue line, MW). The third plot shows the final power order from either the power flow initialization or a user-written model to the electrical control model (dark blue line, pu). The fourth plot shows the real power current command from the control to the converter (ipcd, dark blue line, pu), the power command after the low voltage power logic (iplv, red line, pu), and the maximum real power current limit (ipmx, green line, pu).

From top to bottom, the right column shows the SolarCONTROL emulator voltage reference (vrfq, dark blue line, pu) and regulated voltage (vreg, red line, pu). The second plot shows the solar plant's reactive power output (dark blue line, MVAr). The third plot shows the reactive power order from the reactive power control (dark blue line, pu). The fourth plot shows the reactive power current command (iqcd, dark blue line, pu), the voltage dependent reactive current limit (iqxv, red line, pu), the maximum reactive current (iqmx, upper green line, pu) and the minimum reactive current (iqmn, lower green line, pu).

Note that per unit values of real and reactive power are on the MVA base of the converter model.

4.2.1 Fault Response

Three simulations illustrate the solar plant's response to grid disturbances. In all cases, the regulated bus was the 34.5 kV POI and the SolarCONTROL emulator was active. The converter current limits were implemented with Q priority.

In the first case, the 10 MW solar plant was configured with the minimum number of converters for a 0.99 power factor at the terminal bus. This is equivalent to a rating of 10.1 MVA, and a reactive capability of +/- 1.4 MVAr. The disturbance was a 3-phase fault to ground cleared by tripping one of the 34.5 kV lines from the POI bus to the Infinite bus. The solar plant's response is shown in Figure 4-2. The reactive power output of the solar plant was at its maximum during the fault in an effort to support voltage. After the fault was removed, the SolarCONTROL emulator quickly restores the voltage at the POI bus to its initial value. The effect of the low voltage power logic is seen in the post-fault real power recovery over 250 msec.

In the second case, the 10 MW solar plant was still configured for a 0.99 power factor. The disturbance was a prolonged, low voltage on the system. The solar plant's response is shown in Figure 4-3. In an effort to support the POI voltage, the solar plant was supplying maximum reactive power. Due to the Q priority in the converter current limiter, the real power output was reduced to below 9 MW for the duration of the low voltage event.

In the third case, the disturbance was again a prolonged, low voltage on the system. However, the 10 MW solar plant was configured with sufficient converters for a 0.90 power factor at the terminal bus. This is equivalent to a rating of 11.1 MVA, and a reactive capability of +/- 4.7 MVAr. Such a reactive capability could be required by the host utility or ISO for large or transmission connected solar plants. The solar plant's response is shown in Figure 4-4. With the additional reactive capability, the solar plant supplied both maximum reactive power and rated real power output during this low voltage event.

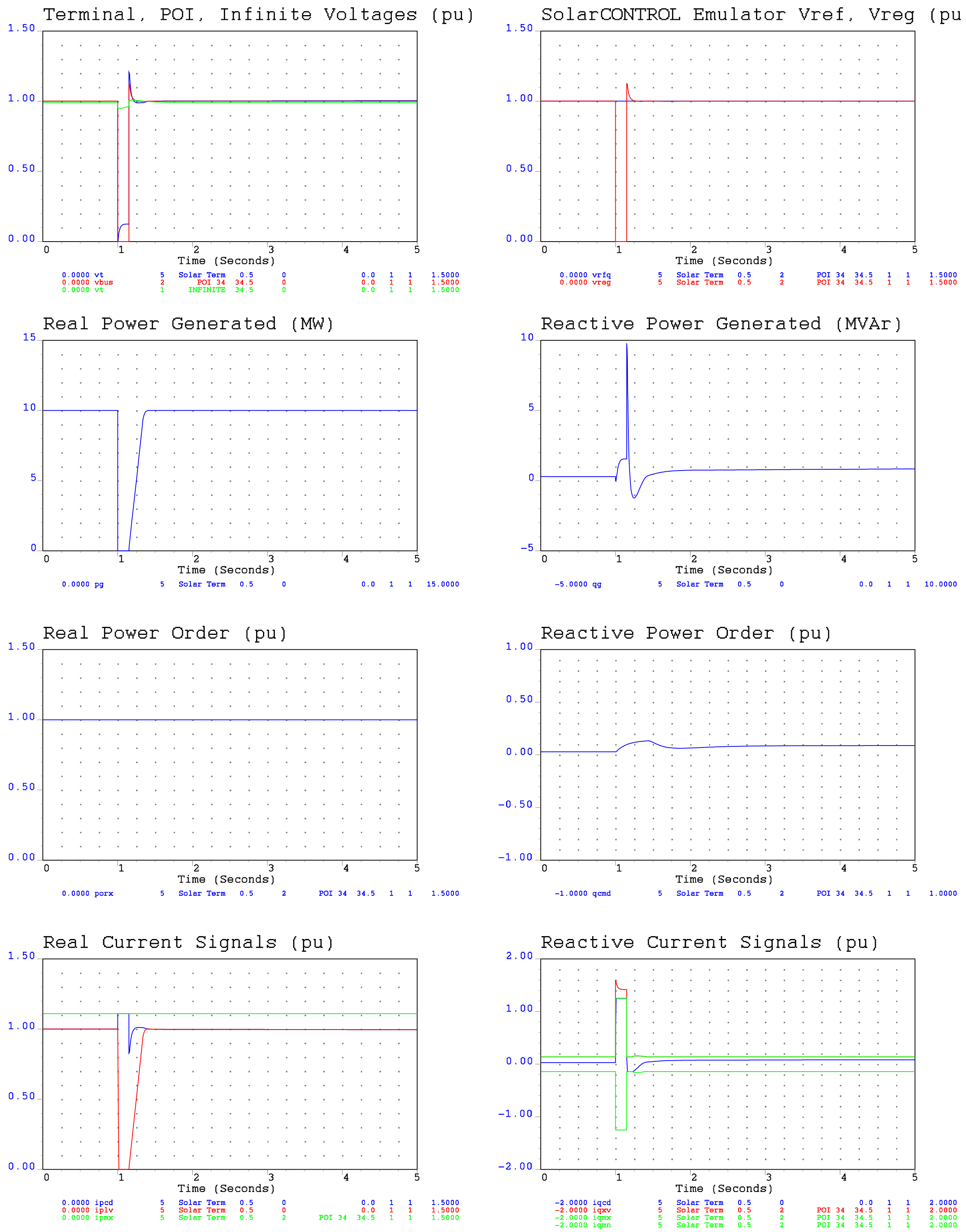

Figure 4-2. Solar Plant (Nominal Reactive Capability) Response to Line Fault.

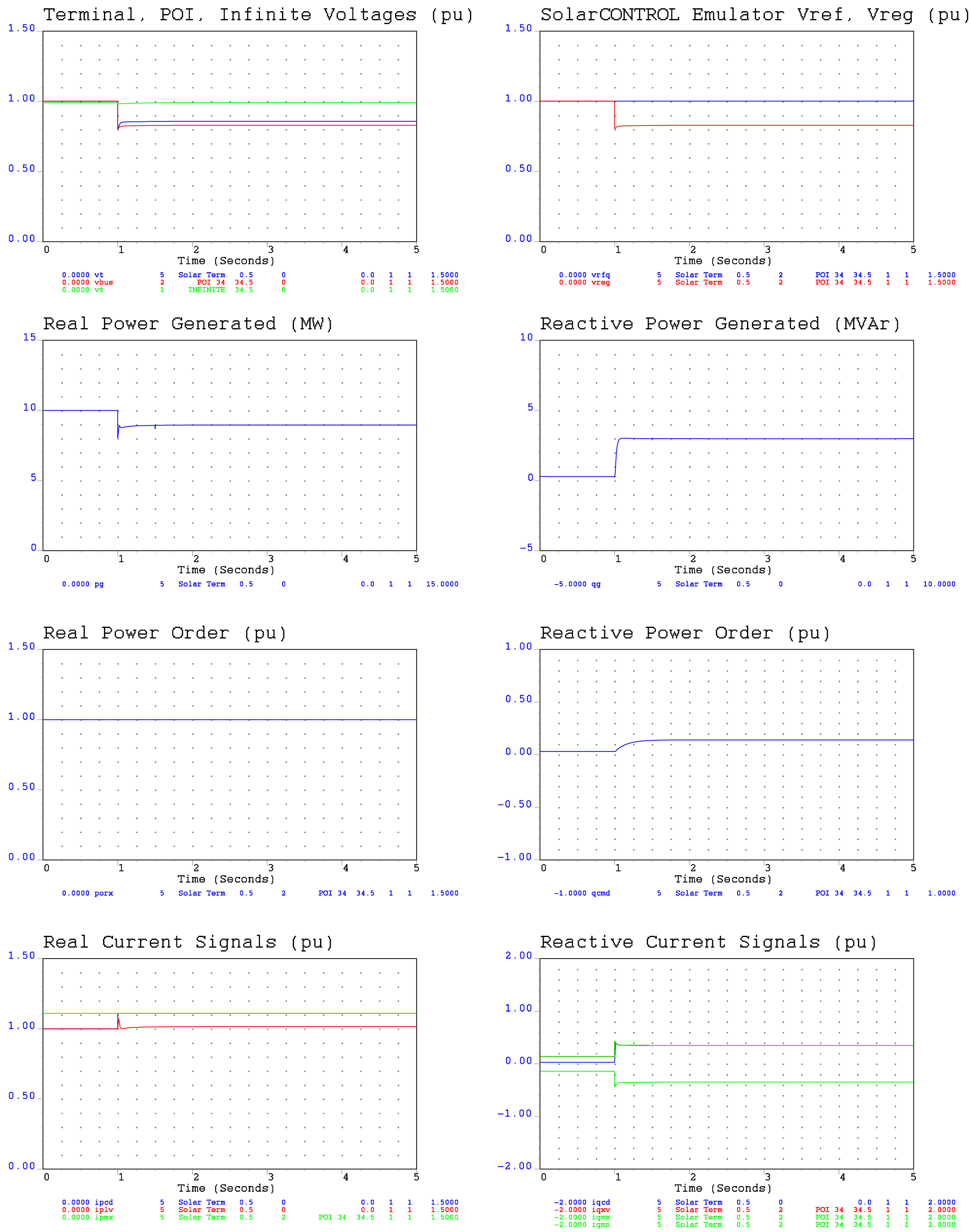

Figure 4-3. Solar Plant (Nominal Reactive Capability) Response to Prolonged Low Voltage Event.

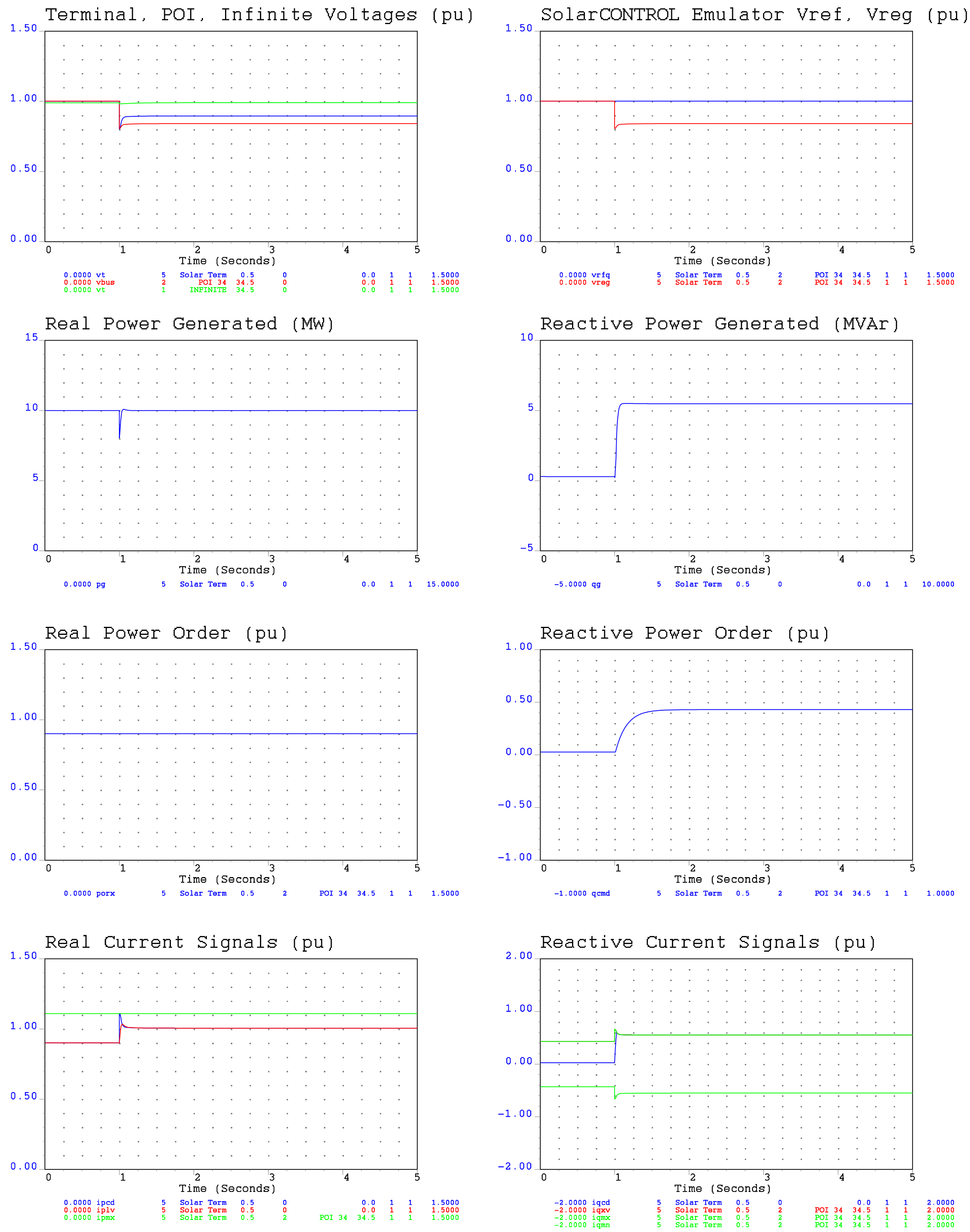

Figure 4-4. Solar Plant (Extended Reactive Capability) Response to Prolonged Low Voltage Event.

4.2.2 Capacitor Switching Response

The solar plant's response to a capacitor switching event was also tested. The 10 MW solar plant was configured with sufficient converters for a 0.90 power factor at the terminal bus. As noted above, this is equivalent to a rating of 11.1 MVA, and a reactive capability of +/- 4.7 MVAr. The regulated bus was the 34.5 kV POI and the SolarCONTROL emulator was active. The converter current limits were implemented with Q priority.

The solar plant's response is shown in Figure 4-5. At 1 seconds, a 4.5 MVAr shunt capacitor bank was switched in, and the POI and terminal bus voltages jumped by about 3%. The volt/var function reacted to the increase in terminal bus voltage with an immediate reduction of about 2 MVAr in reactive power output. Then the supervisory SolarCONTROL emulator acted to further reduce the reactive power output to its minimum. After about 10 seconds (more than is shown in the plot), the POI voltage settles out to just slightly (~0.3%) above its starting value. The solar plant has used all of its available reactive capability to return the POI bus voltage to its reference level.

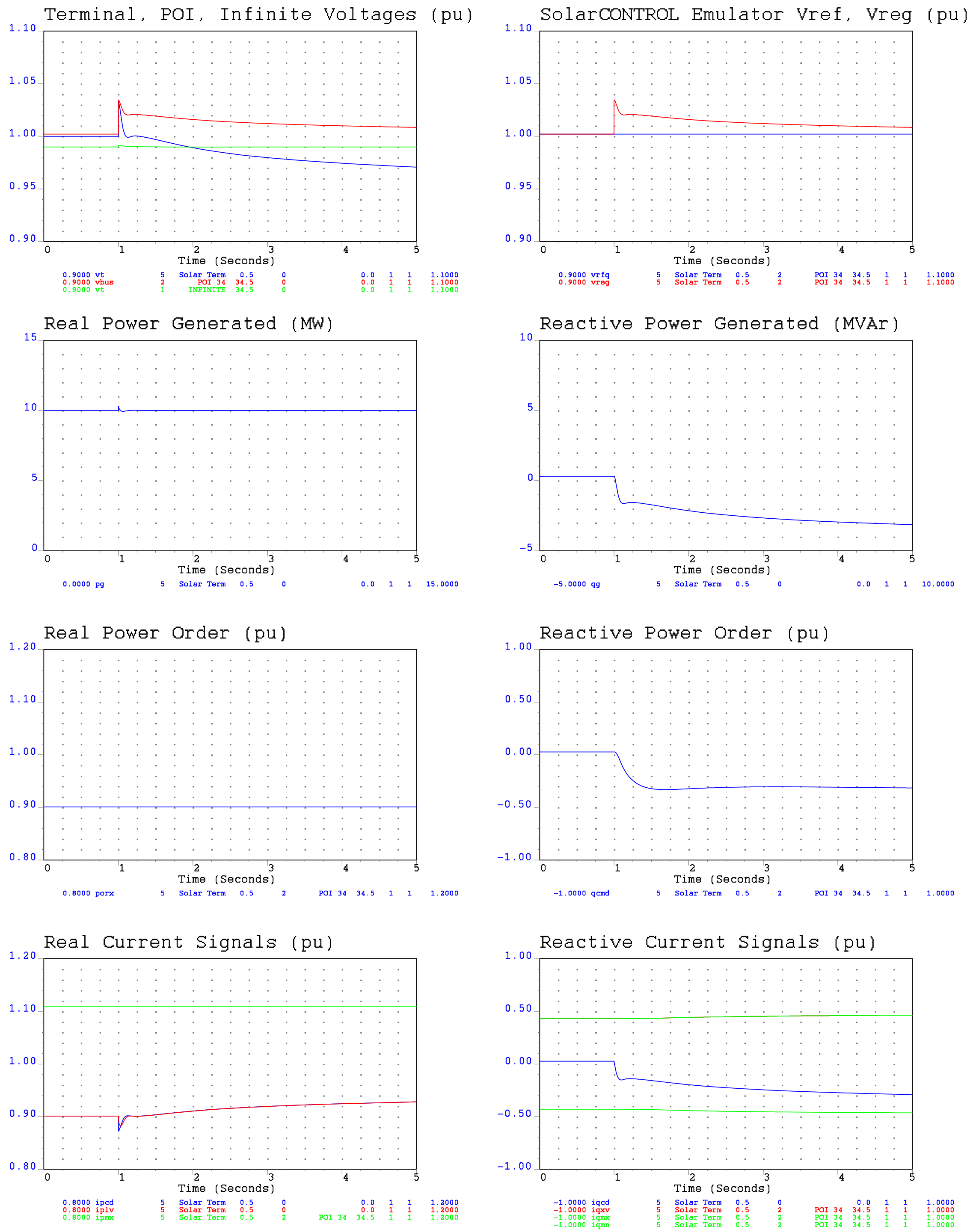

Figure 4-5. Solar Plant (Extended Reactive Capability) Response to Shunt Capacitor Switching.

4.2.3 Zero-Power Operation

An example of zero-power operation is shown in Figure 4-6. A user-written solar power profile was used to emulate a decline in solar plant output as the sun sets. The speed of this decline was set arbitrarily, with the objective of illustrating the zero-power function. During the decline in power output, minor changes in reactive power output were observed as the solar plant acted to regulate POI voltage. At about 105 seconds, the solar plant output reached zero. The solar plant, however, continued to generate reactive power in order to regulate voltage at the POI bus. This is further illustrated when a 4.5 MVAr shunt capacitor bank is switched in at about 110 seconds. The solar plant reduced its reactive power output to its minimum, to return the POI bus voltage at its initial value.

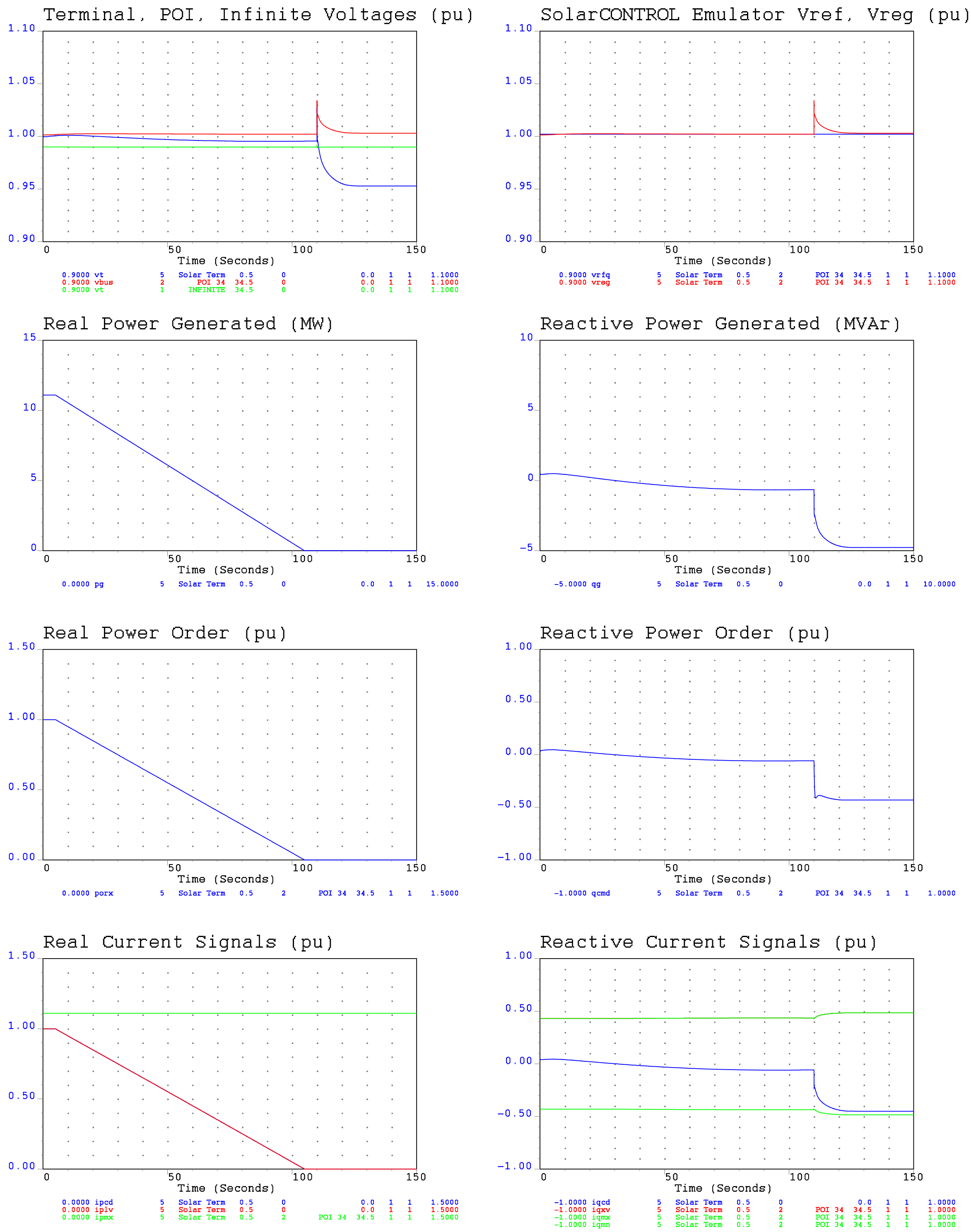

Figure 4-6. Solar Plant (Extended Reactive Capability) Operation at Zero Power Output.

4.3 Simulation Data

The converter and electrical control dynamic data used in the benchmark simulations are shown in Table 4-1 and Table 4-2, respectively.

Table 4-1. Solar Plant Converter Model Data for Simulations.

Model Parameter	Value
MVA	10.1 or 11.1
lpp	0.80
dvtrp1	-0.25
dvtrp2	-0.50
dvtrp3	-0.70
dvtrp4	-0.85
dvtrp5	0.10
dvtrp6	0.15
dttrp1	1.90
dttrp2	1.20
dttrp3	0.70
dttrp4	0.20
dttrp5	1.00
dttrp6	0.10
fcflg	1
rrpwr	5.0
brkpt	0.90
zerox	0.50

Table 4-2. Solar Plant Reactive Power and Electrical Control Model Data.

Model Parameter	Value
varflg	1
kqi	0.10
kvi	120.
vmax	1.10
vmin	0.90
qmax	0.14 or 0.43
qmin	-0.14 or -0.43
tr	0.02
tc	0.15
kpv	18.
kiv	5.
pfaflg	0
fn	1.0
tv	0.05
tpwr	0.05
iphl	1.11
iqhl	1.25
pqflag	0
kdbr	0.
ebst	0.

5 Conclusions

The solar plant model presented in this report is based on presently available design information and engineering judgment. It is expected to give realistic and correct results when used for bulk system performance studies. The modeling of solar plants for bulk power system performance studies, however, will continue to evolve as equipment improves, interconnection requirements change, and factory or field test data becomes available.

This document is continuously being updated to reflect these changes. Those using this document for modeling purposes are encouraged to verify that they are using the most up-to-date version. This document is available through the PSLF software website.