AN ABSTRACT OF THE THESIS OF

Chee Sing Lee for the degree of Honors Baccalaureate of Science in Electrical and Electronics Engineering presented on May 27, 2008. Title: A Residential DC Distribution System with Photovoltaic Array Integration.

Abstract Approved:

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Ted K.A. Brekken

A DC distribution system targeted for residential settings has been designed and simulated. The system features the ability to draw power from both the utility and photovoltaic arrays. In times of surplus solar energy, the system is able to supply power back to the utility to facilitate net metering. The design of the DC distribution system centers on three power converters. First, an active rectifier is used to convert AC voltage from the utility to an intermediate DC-link voltage. It also ensures that current is drawn from the grid at near-unity power factor. A buck converter is used to step down the DC-link voltage to a 42 V bus which is used to power any DC loads in the household. The buck converter also has the task of regulating this bus. A boost converter is used to step up the output voltage of the PV array to the DC bus voltage. It also ensures that the array is operated at its maximum power point.

Key Words: photovoltaics, DC distribution, controller design, power converters

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A Residential DC Distribution System with Photovoltaic Array Integration

by

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Chee Sing Lee, Author

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Background

Usage of consumer electronics has increased steadily in recent decades; in 1999, 10% of U.S. residential electricity usage was attributed to consumer electronics [1]. The consequence of this is an increasing number of direct current (DC) loads present in the household. At present, these devices must each make use of an individual converter to draw power from the alternating current (AC) distribution system. Also, growing interest in conservation and renewable energy has fueled growth in the solar electricity market. In 2007 the world market grew by 62% to a record high of 2,826 MW. Growth in the United States alone was 57% [2]. Due to the nature of photovoltaic technology, these panels provide power with direct current, and require an inverter to be connected with the existing household. Along the same vein of energy conservation, light-emitting diodes have begun to emerge as a more efficient method of lighting. Again, these are DC devices, and the challenges of interfacing them with an AC distribution system are a significant roadblock in making them economical. To address these issues, this thesis presents a design for a residential DC distribution system. Such a system would remove the need for individual rectifiers for DC loads to draw power. Additionally, through the application of controlled switching converters, such a system could operate at near-unity power factor as seen by the utility. It could also facilitate energy outflow during periods of excess solar generation in net metering situations.

System Overview

The general block diagram for the system is shown in Figure 1. An active rectifier converts the single phase AC voltage from the local transformer to an intermediate DC link (250 VDC nominal), which interfaces with a DC-DC buck converter that steps it down to 42 VDC bus for use with home electronics and LED lighting. Electronic devices may connect to the DC bus via individual DC-DC converters. Another DC-DC converter is required to connect the system to photovoltaic arrays.

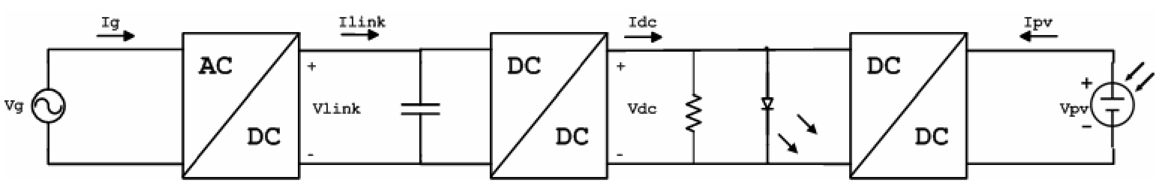

Figure 1 - Top level system overview

This project focuses on the design and control of each of the converter blocks in the described system. Control is required to regulate bus voltages, as well as provide bi-directional operation in order to allow current to flow back through the system to the utility in a net-metering scheme. The DC-DC converter interfaced with the PV array must be able to keep the array operating at the maximum power point.

Design and simulation of the system is conducted using the MathWorks MATLAB Simulink software, with the SimPowerSystems toolbox.

Conventions

The following naming conventions are used in the remainder of this work:

Table 1 - Naming Conventions

V_g, I_g	Utility voltage and current
I_{g_peak}	Utility current peak magnitude
V_{link}, I_{link}	Intermediate DC link voltage and current
V_{dc}, I_{dc}	Main DC bus voltage and current
V_{pv}, I_{pv}	PV Array voltage and current
R_{load}	DC Bus load

Active Rectifier

Overview and Requirements

The residential distribution system's point of interaction with the utility is the rectifier, which converts the incoming single phase AC voltage to an intermediate high voltage DC link, which is further stepped down by a buck converter to supply loads in the system. The rectifier must be able to satisfy the following requirements:

- Provide a low-ripple (< 2%) DC-link
- Bi-directional power flow for solar panel integration with net-metering schemes
- Provide near-unity power factor at utility

An H-bridge switching rectifier is chosen to meet the above criteria. This configuration uses two "legs", consisting of two transistor switches in series, across the DC bus. The utility voltage is applied across the middle of the two legs, creating an H shape in the schematic representation. The transistors are controlled to be either completely on or completely off. Thus, the switches dissipate power only during the very short rise and fall times, when significant voltages and currents are both present at the same time, minimizing power losses from switching. Figure 2 shows the schematic for the active rectifier.

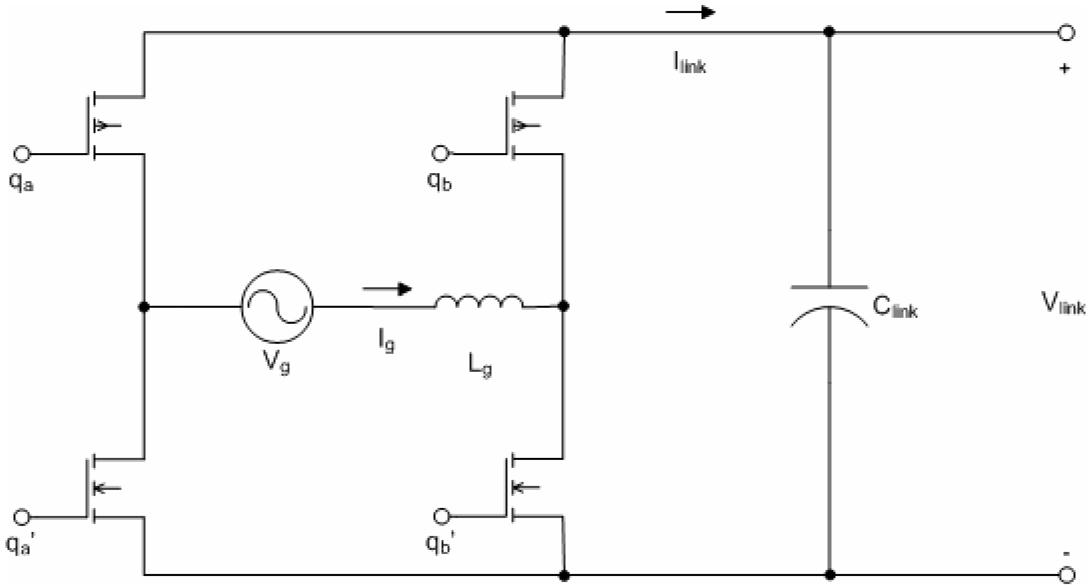

Figure 2 - Schematic diagram of active rectifier

Theoretical Basis

The transistor switches are controlled via pulse width modulation (PWM). In each leg, the two switches switch complementary to each other e.g. if Q_a is on, then Q_a' is off. In practice a short "dead time" of a few hundred nanoseconds, during which both switches are off, is inserted between transitions to ensure that there is never a short circuit across the DC link. The duty ratios for each leg, d_A and d_B, represent the amount of time each leg is connected to the positive side of the DC link, expressed as a fraction of the PWM period. Another quantity d_{AB}, is defined as

$$d_{AB} = d_A - d_B$$

This represents the fraction of the PWM period that the DC link is positively connected to the utility, and is the primary parameter for controlling the rectifier. Since d_A and d_B each vary from 0 to 1, d_{AB} has a range of -1 to +1. For an average model of the rectifier, the following relationships hold true:

$$V_{link} = \frac{V_1}{d_{AB}}$$

$$I_{link} = I_g \times d_{AB}$$

where V_1 represents the utility voltage seen by the switching legs, after the drop over inductance L_g.

Controller Design

The controller for the active rectifier consists of an outer voltage loop which controls the parameter I_{g_peak}, the peak magnitude of the grid-side current I_g. A phase-locked loop (PLL) generates a sinusoidal waveform in phase with the grid voltage. The product of the PLL waveform and I_{g_peak} creates the desired grid current I_g, in phase with the grid voltage to achieve unity power factor. This parameter is fed into the inner control loop which generates the duty ratio d_{AB}. Figure 3 shows an overview of the control scheme.

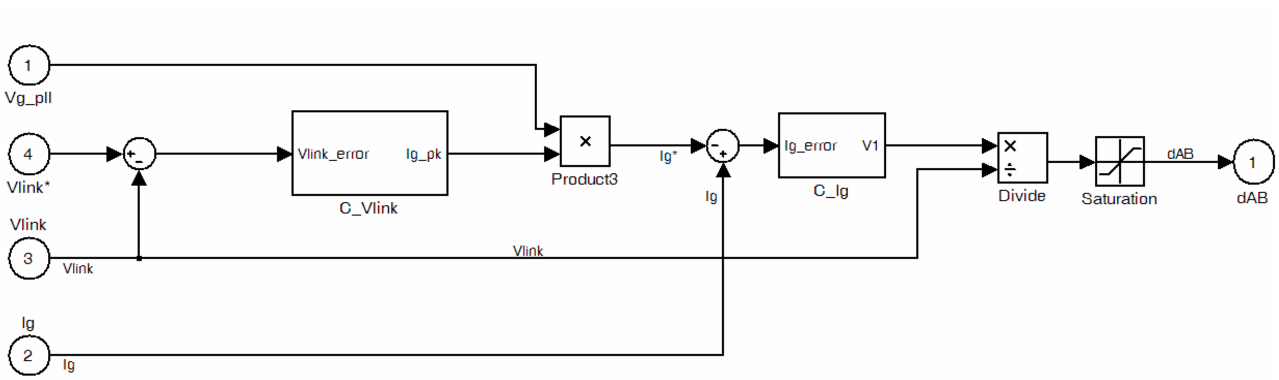

Figure 3 - Active rectifier control scheme

The inner loop controller uses a feed forward structure to derive d_{AB} from V_1. Hence, the controller is designed for the plant transfer function

$$\frac{I_g}{V_1} = -\frac{1}{sL_g}$$

The switching frequency of the converter is 200 kHz, so the bandwidth of the controller is limited at 20 kHz so that the plant can respond quickly to the controller output. A proportional controller is used with a gain of -254.

The outer loop controller acts on the plant transfer function

$$\frac{V_{link}}{I_g} = \frac{\frac{1}{C_{link}}}{s + \frac{1}{R_{load}C_{link}}}$$

Where R_{load} is a resistance modeling the load at the end of the DC link; it has an estimated value of 100 Ω. The controller is a proportional-integral design with a proportional gain of 1 and an integral gain of 6.

Photovoltaic Array Integration

Overview and Requirements

Solar energy is one of the most abundant forms of energy on earth, up to 1 kW/m^2 [3]. Photovoltaic cells harvest this energy and output it in the form of DC voltage. Integrating solar panels with the DC distribution system requires a DC-DC converter that fulfills two functions:

1. The operating voltage of the solar panels needs to be converted to the voltage of the DC bus. Most commercially available solar panels are configured to operate at either 12 V or 24 V [4]. In either case a boost converter would be necessary to step the voltage up to the 42 V DC bus.
2. The converter should draw current from the solar panels such that they operate at the maximum power point. This concept is explained in detail below.

Boost Converter

As previously mentioned, typical solar panel configurations operate at voltages of 12 V or 24 V. To properly interface with the 42 V DC bus in this design, a boost converter is used to step the voltage up. A typical boost converter topology is shown in Figure 4 [5].

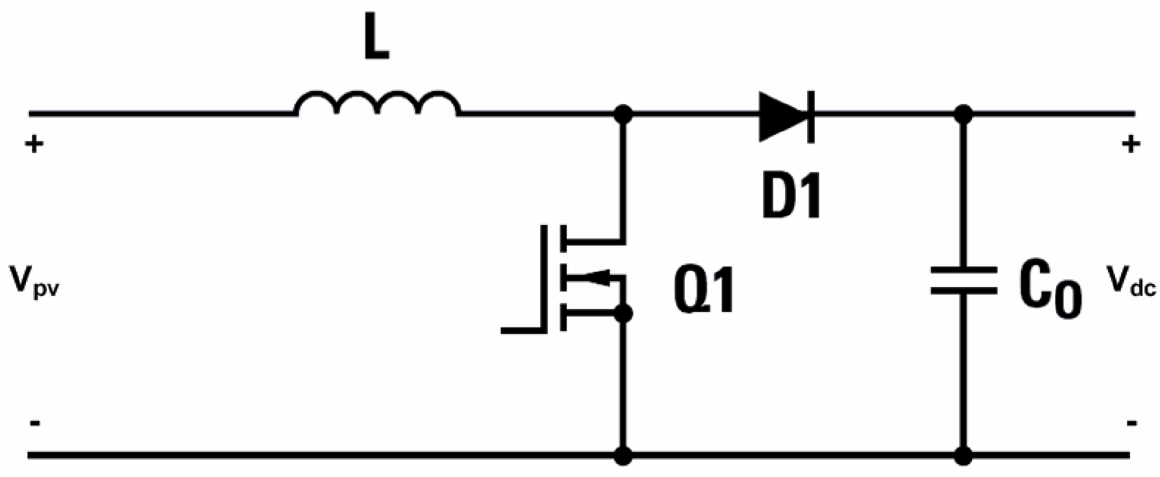

Figure 4 - Boost Converter Schematic [5]

When the switch Q_1 is in the on position, inductor L is connected to ground and the voltage drop across it is V_{in}. When the switch is off, current flows through the inductor and the diode to charge the capacitor. During steady state operation, the average voltage across the inductor is zero. Hence,

$$V_{pv}t_{on} + (V_{pv} - V_{dc})t_{off} = 0$$
$$V_{pv}(t_{on} + t_{off}) - V_{dc}t_{off} = 0$$
$$V_{dc} = V_{pv}\frac{t_{on} + t_{off}}{t_{off}} = \frac{V_{pv}}{1-D}$$

Where D is the duty ratio of the switch Q_1, and varies from 0 to 1. Thus, the output voltage V_{dc} is always greater than or equal to the input voltage V_{pv}.

Maximum Power Point

Figure 5 shows an approximate model of a photovoltaic cell [6]. The semiconductor properties are modeled by the diode, which provides a fixed bias voltage. As the amount of sunlight incident on the cell, known as insolation, increases, the current I_L also increases. The shunt and series resistances R_{sh} and R_s represent leakage currents and conductive losses respectively.

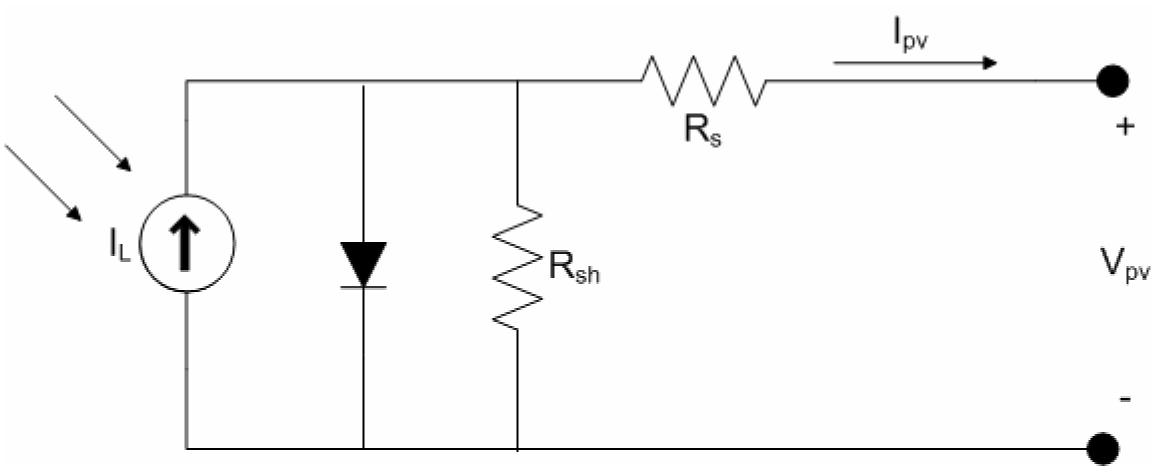

Figure 5 - Solar Cell Equivalent Circuit

Figure 6 shows a few I-V characteristics for an example solar cell, given varying amounts of sunlight. The output voltage remains relatively constant up to certain amount of current, after which the voltage rapidly drops. With more insolation, the amount of current that can be drawn before this occurs increases. The term maximum power point refers to the point on a particular I-V curve where the product of current and voltage is at its maximum, and is located approximately at the "knee" of the curve. The line tracing these points through varying insolation is also plotted in Figure 6.

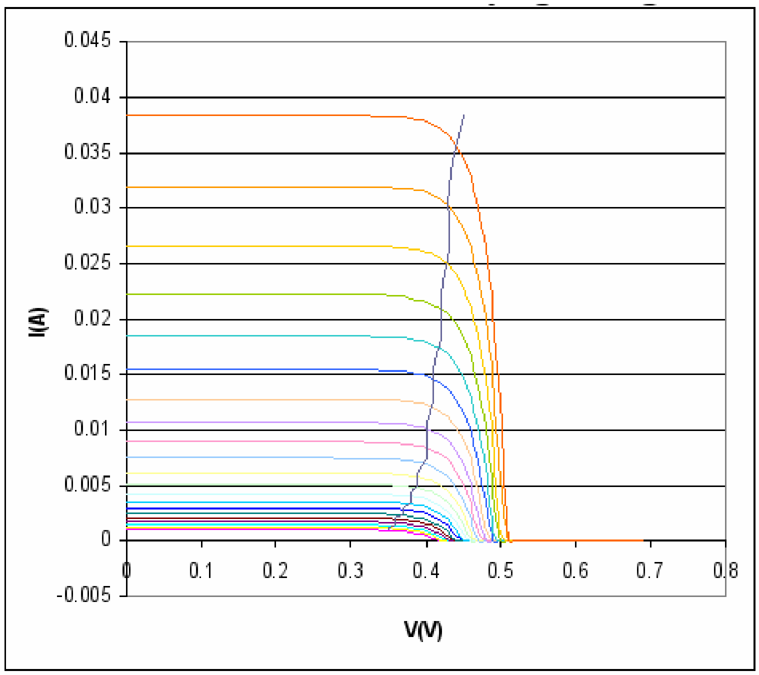

Figure 6 - Solar Cell I-V characteristics

Controller Design

A common algorithm used to track the maximum power point is known as the "Perturb and Observe" (P&O) method. At regular time intervals, the controller will change the duty cycle by a small amount. The resulting output power of the solar panel is observed, and compared to that from the previous time step. If an improvement is shown, then the controller will continue to change the duty cycle in the same direction at the next time step. Otherwise, the duty cycle will reverse the change at the next time step. This method of control has the advantage of being simple and easy to implement with microcontroller devices, needing only array power as input to output a converter duty cycle. However, when the array is operating in steady state, the controller will continue to perturb the duty cycle, resulting in oscillation about the maximum power point. The loss in efficiency will depend on the size of the duty cycle increment and the sampling time interval. Also, during periods of rapidly changing atmospheric conditions, the controller will deviate from the maximum power point, as it only considers duty cycle effects on the array power output [7].

To work around these drawbacks, a variation of the P&O algorithm, known as the Incremental Conductance method is used [8]. This algorithm exploits the fact that at the maximum power point, dP/dV = 0. Hence,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = 0$$
$$\frac{dI}{dV} = -\frac{I}{V}$$

Likewise, at voltages below the maximum power point,

$$\frac{dP}{dV} > 0$$
$$\frac{dI}{dV} > -\frac{I}{V}$$

and at voltages above it,

$$\frac{dP}{dV} < 0$$
$$\frac{dI}{dV} < -\frac{I}{V}$$

In order to implement this control method, instantaneous array voltage and current must be compared to those stored from the last time step to obtain dI and dV. In practice, dI/dV and –I/V will not be exactly equal, so a small error of E is allowed. If the quantity dI/dV + I/V is greater than +E, than the duty ratio is adjusted downwards to increase array voltage. If the quantity is less than –E, then the duty ratio will be adjusted upwards to decrease the array voltage. This comparison is made at fixed time intervals, which must be large enough for the boost converter to respond to the change in duty ratio. Figure 7 shows the flow of the incremental conductance algorithm.

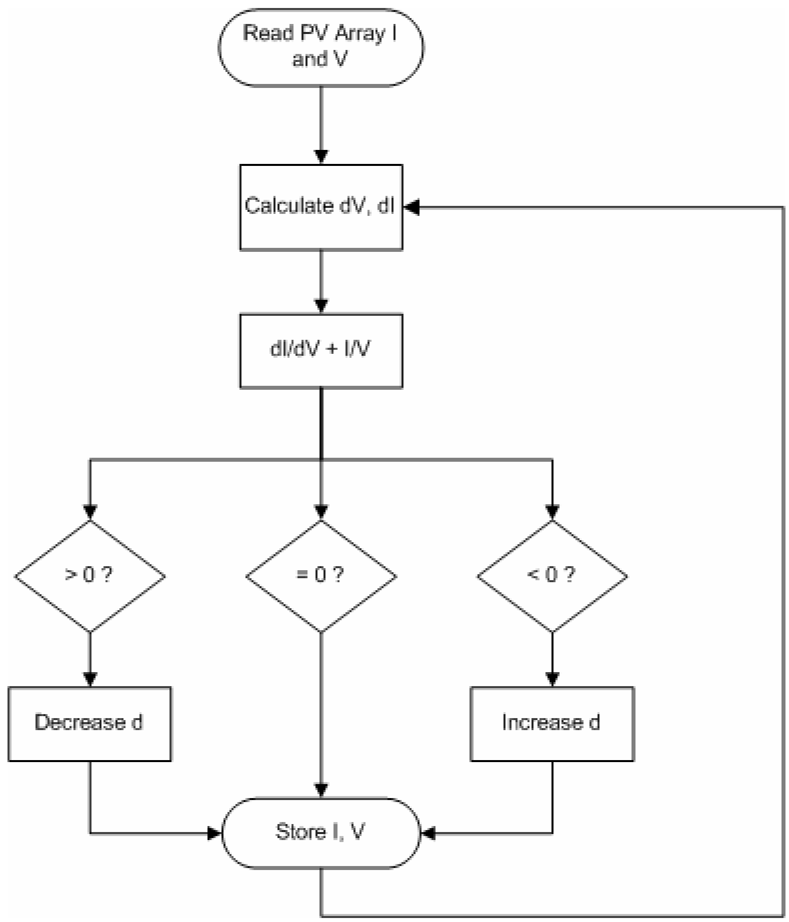

Figure 7 - Incremental Conductance Algorithm

In this design E = 0.7 Ω^{-1} and the duty ratio is adjusted in steps of 0.0001. The algorithm is iterated in time steps of 10 ms, or a frequency of 100 Hz.

Modeling of the Photovoltaic Array

The photovoltaic array is modeled as a single solar cell in SimPowerSystems following the equivalent circuit in Figure 5. The photocurrent and diode forward voltage drop are set at values typical for the output of an entire solar module: 7 A and 24 V respectively. To verify the PV Array model, the amount of insolation is held constant and the duty cycle of the boost converter is swept from 0 to 1, effectively sweeping the bias voltage of the PV array. The results are plotted in Figure 8.

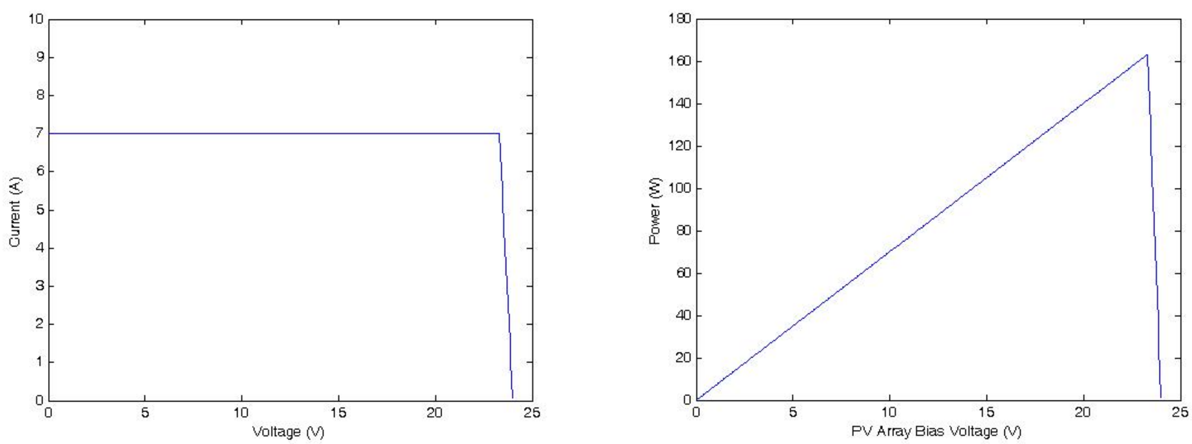

Figure 8 - IV and power characteristics for linear solar cell model

The plots show a cutoff voltages and corresponding maximum power point as expected. However, rather than a smooth “knee”, the curves show a sharp transition at those points. This is due to the fact that SimPowerSystems implements diodes using a piecewise linear model rather than a more accurate exponential model [8].

In an attempt to refine the simulation, the exponential PV model described in [9] was implemented. This model showed a more realistic IV and power characteristic, but introduced algebraic loops into the model that could not be resolved when simulating the entire system. Figure 9 shows a detail comparison of the IV characteristics of the two models.

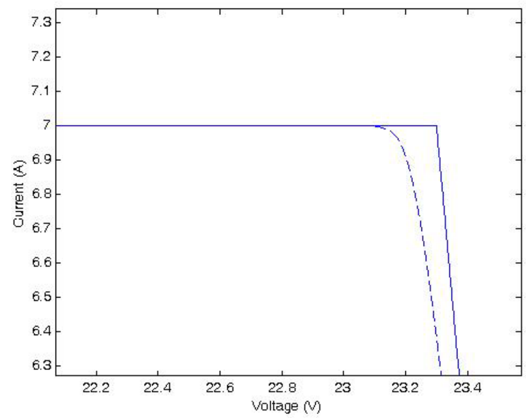

Figure 9 - Detail comparison of PV model IV characteristics

The linear model maintains constant current out to a slightly higher voltage than the exponential model. Hence, the linear model will provide a slightly overestimated power output over the exponential model.

A comparison of the power characteristics is shown in Figure 10. Because the power versus voltage characteristic of the linear model has such a sharp transition at the maximum power point, it is difficult for the incremental conductance algorithm to track to a point where dP/dV = 0. Hence, a larger error is necessary to avoid oscillations.

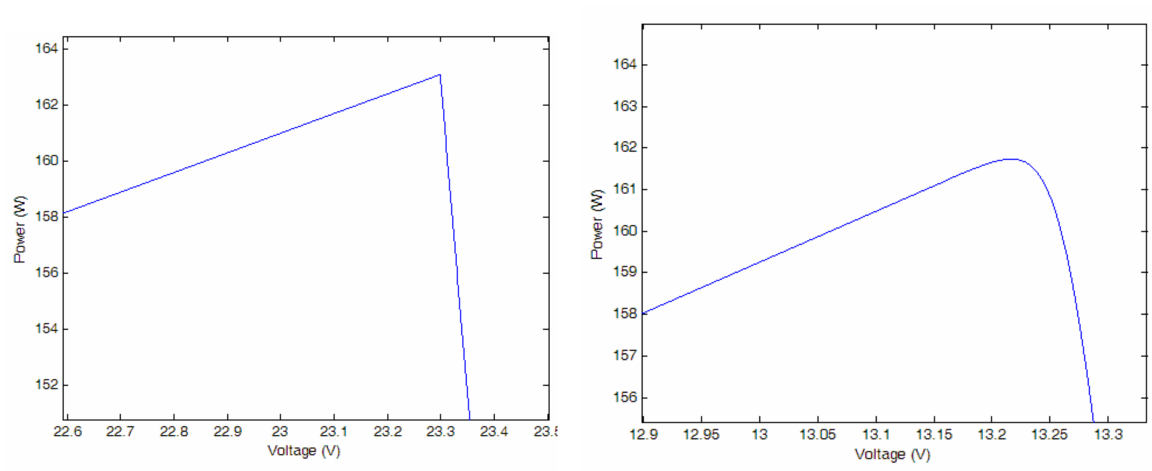

Figure 10 - Detail Comparison of PV power characteristics

Buck Converter

Overview and Requirements

The purpose of the buck converter is to step down the 250 V DC bus provided by the rectifier to a 42 V DC bus to be connected to home electronics and PV arrays. The converter should also regulate the 42 V bus and keep the voltage constant in response to perturbations.

Theory of Operation

A typical buck converter circuit is shown in Figure 11 [5].

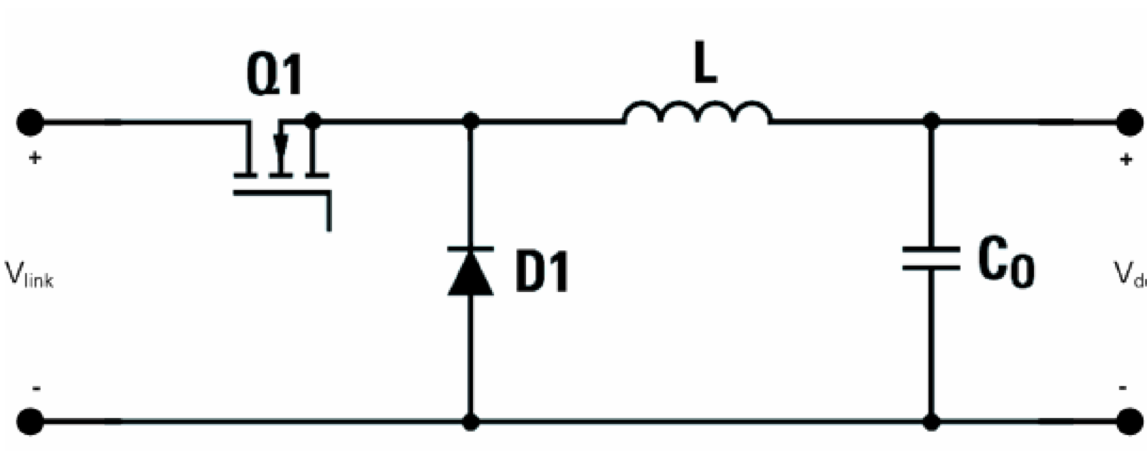

Figure 11 - Buck converter schematic [5]

When switch Q_1 is closed, diode D_1 is reverse biased and current through the inductor increases. When it is open, the diode is forward biased and the inductor has a negative voltage drop across it, causing the current flowing through it to decrease. If the converter is operating in steady state, i.e. the average current through the inductor is constant, then the relationship between the input and output voltage is given by

$$V_{dc} = V_{link} D$$

where D is the duty cycle of Q_1 and ranges in value between 0 and 1.

Controller Design

To regulate the DC bus voltage, a PI controller is used to control the duty ratio of the buck converter. Assuming a worst case bus voltage error of 5 V, controller gains are determined to correct for that error in one second. Because the controller outputs the buck converter duty ratio, controller effort is limited to range of 0 to 1. If the current controller output is at one extreme, then the worst case error should cause its output to change to the other extreme within the specified recovery time. Hence, the integral gain is chosen to be 0.2 for an output that goes from 0 to 1 in one second for an error of 5 V. The worst case error should also cause the proportional component to go to its maximum, so 0.2 is also used for the proportional gain.

Simulation Results

The Simulink simulation was run for 100 seconds with the following setpoints:

V_{link} = 250 V

V_{DC} = 42 V

V_{pv} = 24 V (open circuit)

The high voltage DC link capacitor begins with an initial charge of 220 V. During the simulation, the system experiences two disturbances:

- At t = 40 seconds, the resistive load in the DC bus is stepped up by a factor of 10. This would represent a load in the household being switched on.
- At t = 70 seconds, PV array insolation is stepped down by a factor of 3, conceivably due to cloud cover.

The maximum power point tracker takes about 30 seconds to find the maximum power point of the PV array. This is evidenced by the linear increase in PV array power output shown in Figure 12. The duty ratio then settles at a constant value as expected. The drop in insolation also produces the expected drop in PV array power.

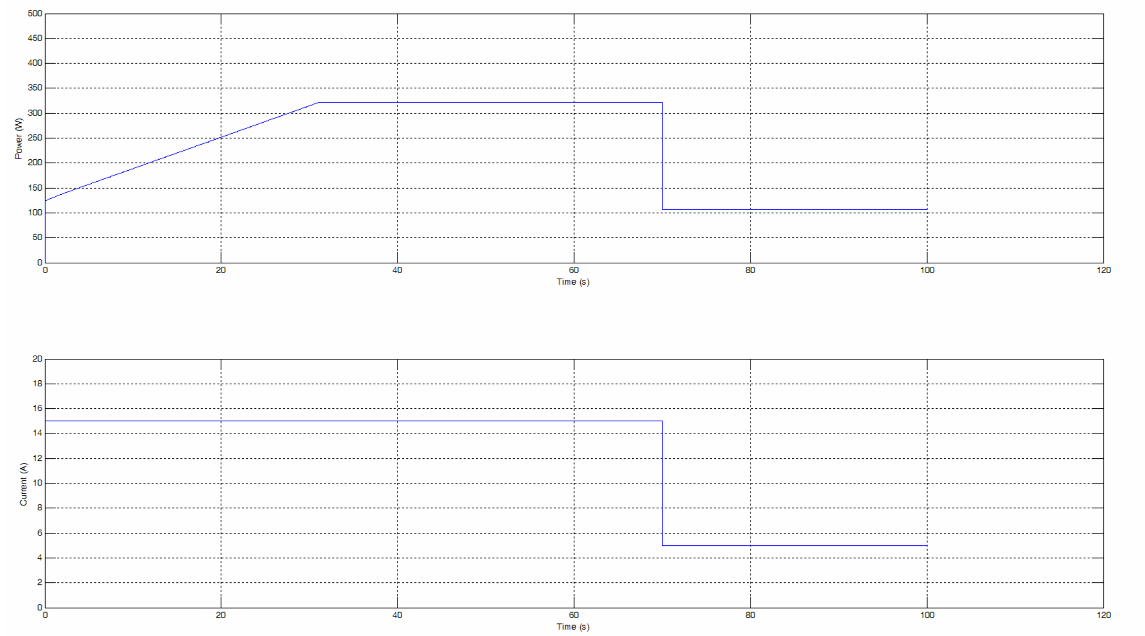

Figure 12 - PV array power output and insolation level

The buck converter controller provided effective regulation of the DC bus voltage. The largest disturbance only deviated from the setpoint by less than 7 mV and was restored within 0.4 seconds (Figure 13).

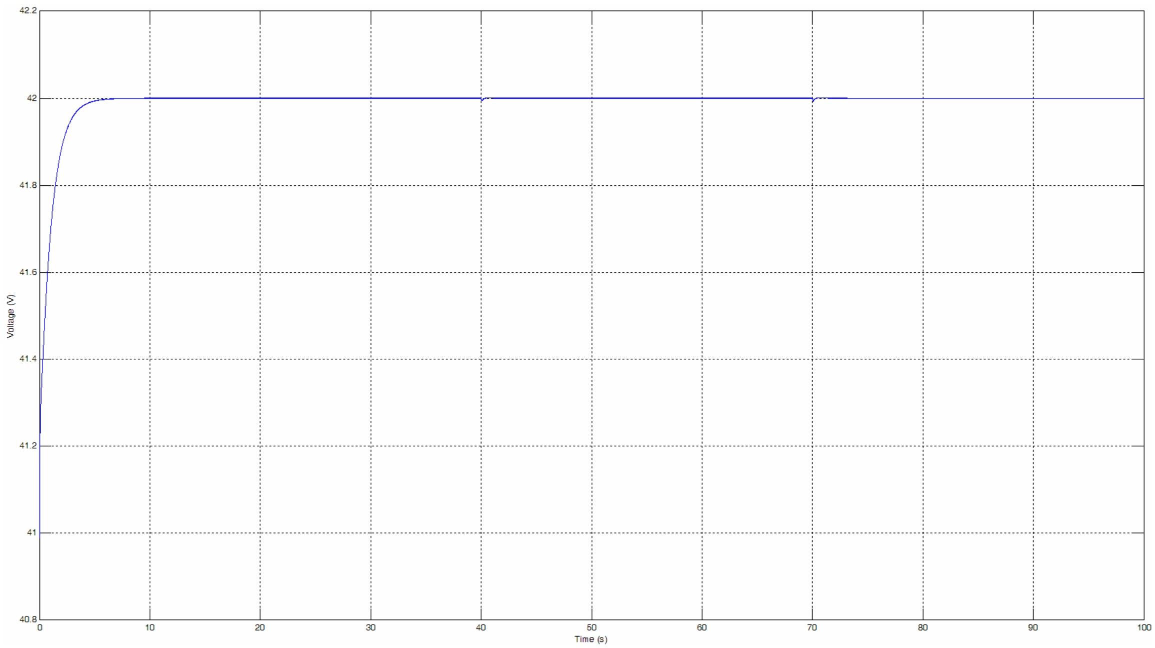

Figure 13 - DC bus voltage

These disturbances are reflected in the intermediate DC link voltage and similarly, the active rectifier controller rejects them effectively (Figure 14). The DC link current shows the bi-directional power flow capabilities of the system. Initially, the PV array supplies more than enough power for the load, and the surplus flows to the grid via the active rectifier. This can be seen through the negative value of I_{link}. As the two disturbances increase the load requirement and decrease the PV array power, I_{link} becomes increasingly positive, and power is drawn from the grid to make up for the deficit (Figure 15).

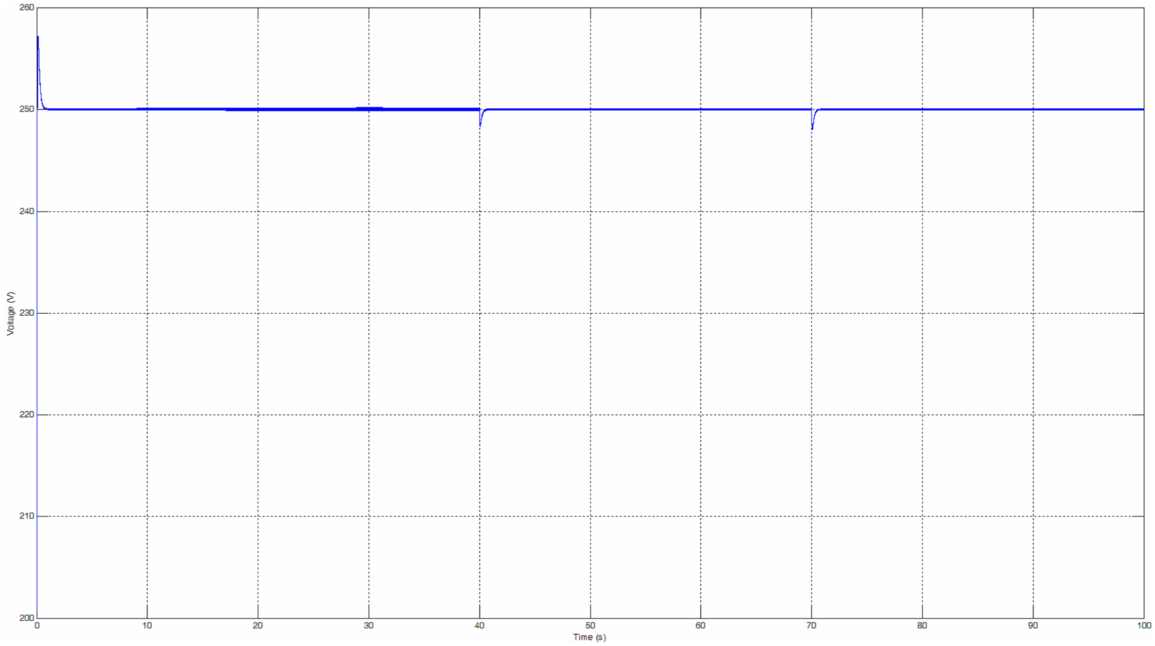

Figure 14 - DC link voltage

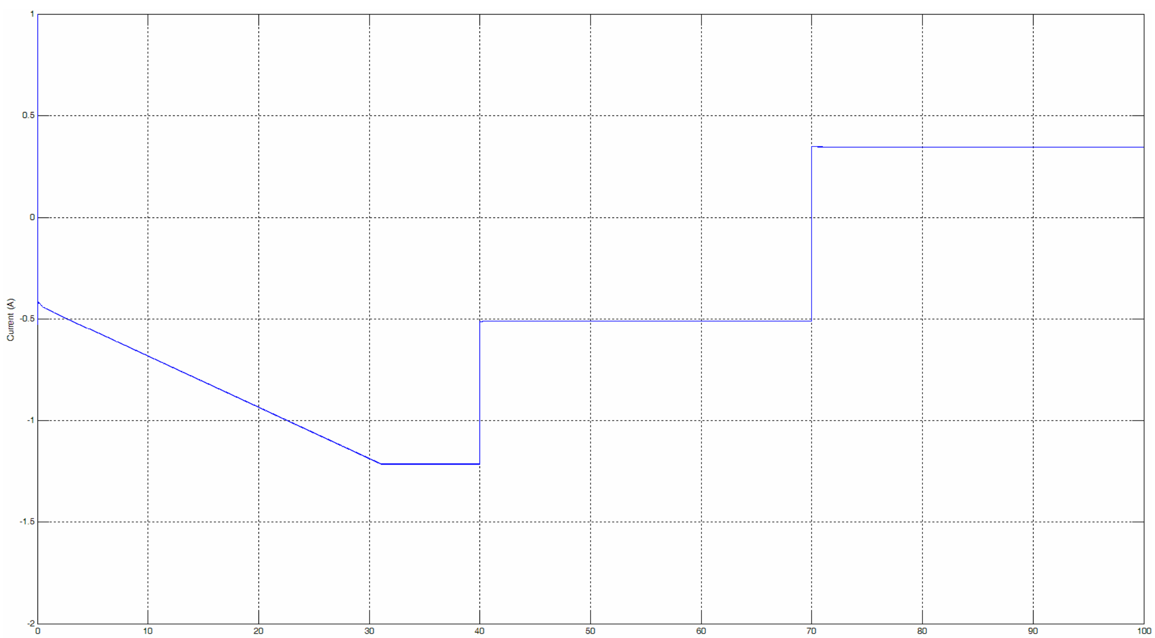

Figure 15 - DC link current

The active rectifier controller regulates the phase grid-side current I_g in relation to the voltage V_g to maintain near unity power factor. While the system is supplying power back to the grid, the magnitude of I_g is negative and the two waveforms are 180 degrees out of phase. When the utility is supplying power to the grid, the two waveforms are in phase. After the first disturbance, the direction of power flow remains the same, but less of the PV array power is supplied to the grid, this is reflected in the decreased amplitude of I_g, which remains 180 degrees out of phase (Figure 16). The second disturbance switches the direction of power flow, evidenced both by the sign of I_{link}, and the phase of I_g (Figure 17).

Both the DC bus voltage and intermediate DC link voltage contain ripple at a frequency of 120 Hz. The source of this ripple is the active rectifier. When the grid-side current and voltage are in phase, the DC-link current contains both a DC component and a second harmonic component [11]. The DC-link capacitor is sufficiently large that the voltage ripple seen on the DC bus is less than 1 mV peak-to-peak.

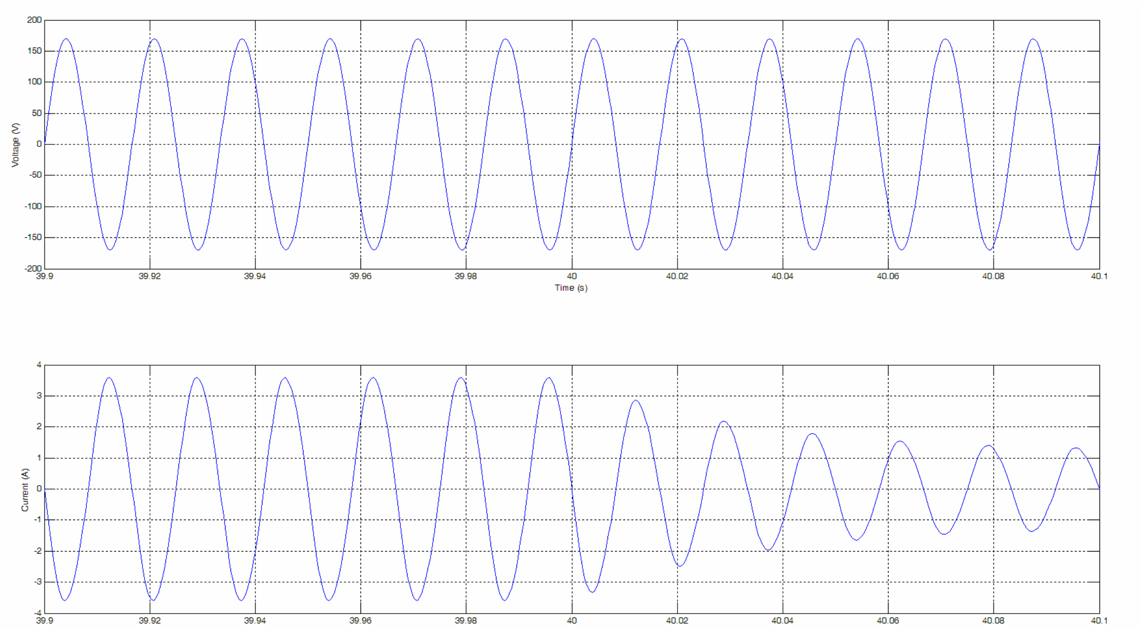

Figure 16 - Grid voltage and current at first disturbance

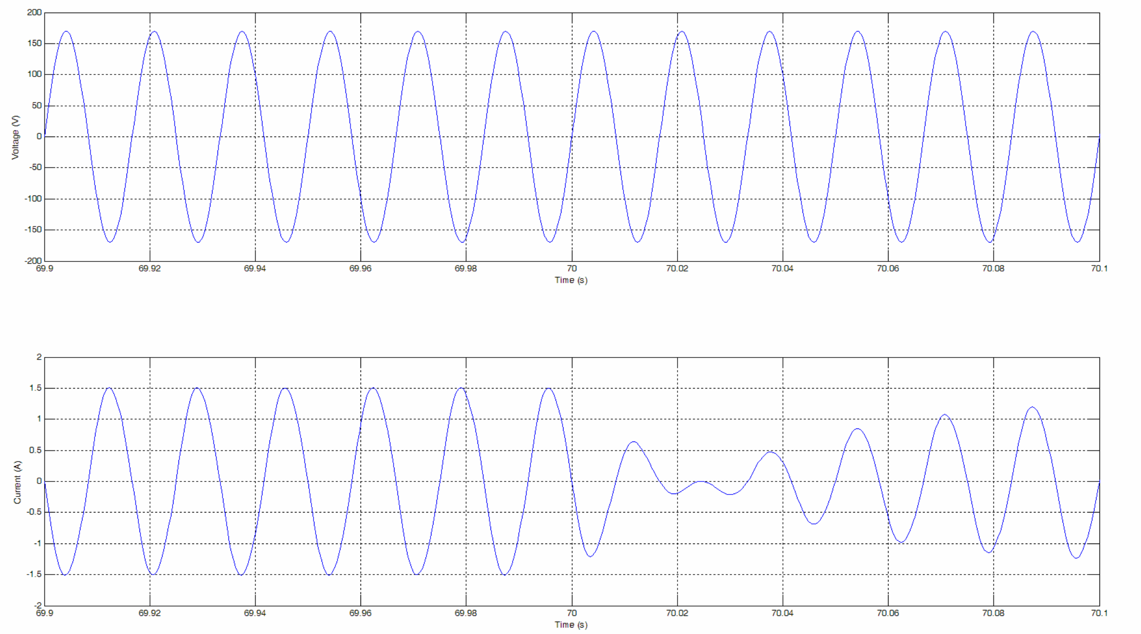

Figure 17 - Grid voltage and current at second disturbance

Conclusion

This work has demonstrated feasible design and control for a DC distribution system for residential settings. Current applications of photovoltaics in the home environment restrict the power output of the PV arrays to use within the household. The system presented here would allow surplus power to be sold back to the utility. This prospect is especially attractive because the afternoon hours coincide with both peak levels of insolation and peak power demand from the grid. A system based on these principles would doubtless find applications in the growing market for consumer solar power which could open a new avenue for powering household electronics. The focus of this work has been top level strategy and controller design. Further work could be directed toward implementations for the individual power converters or detailed characterization of household DC loads.

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APPENDIX

Simulink Models

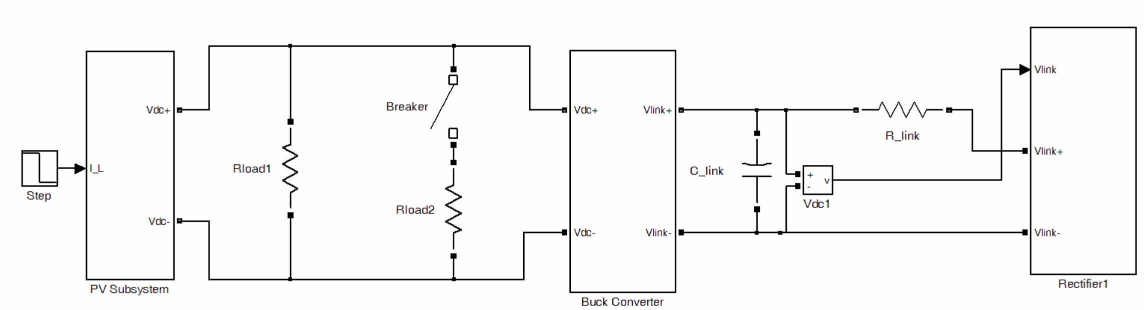

Figure 18 – Top-level model

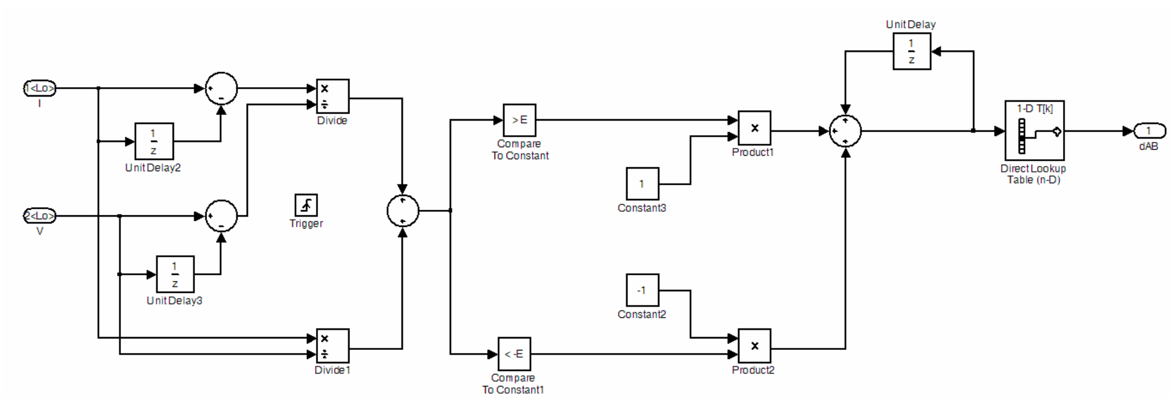

Figure 19 - Incremental conductance MPPT algorithm

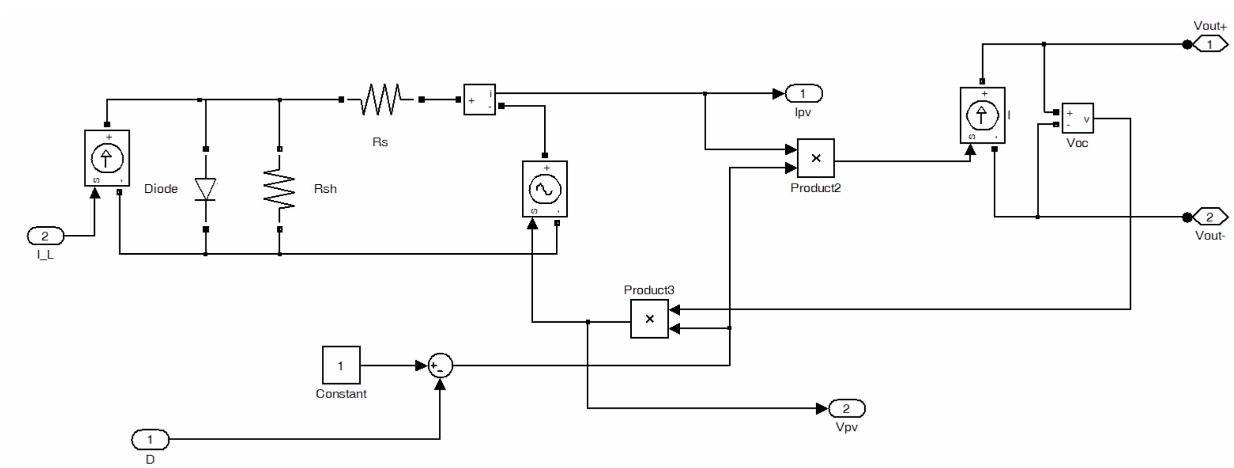

Figure 20 - PV array and boost converter model

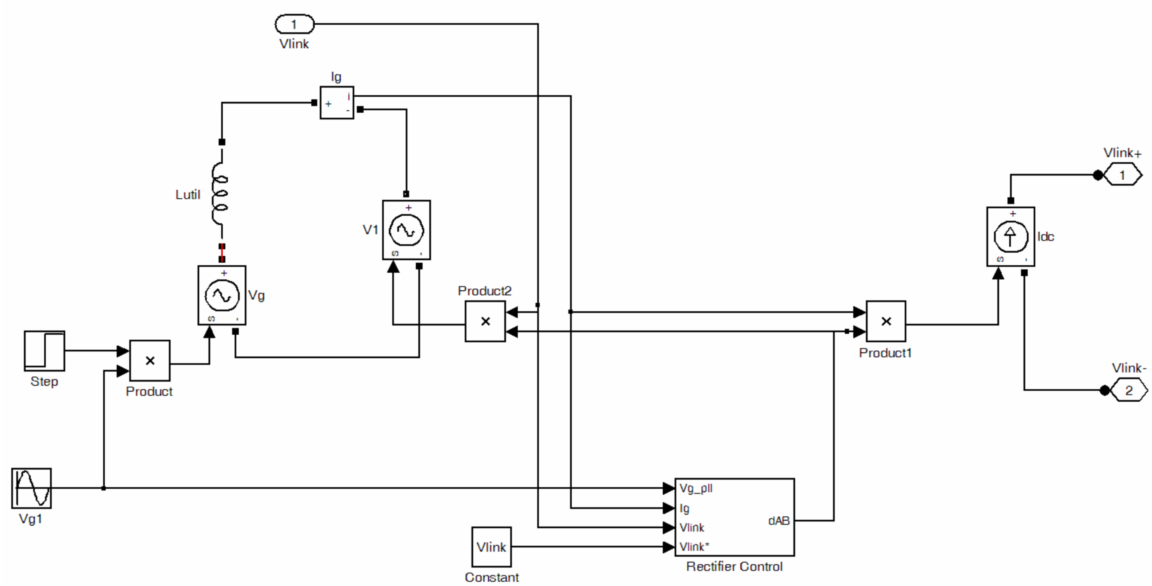

Figure 21 - Active rectifier model

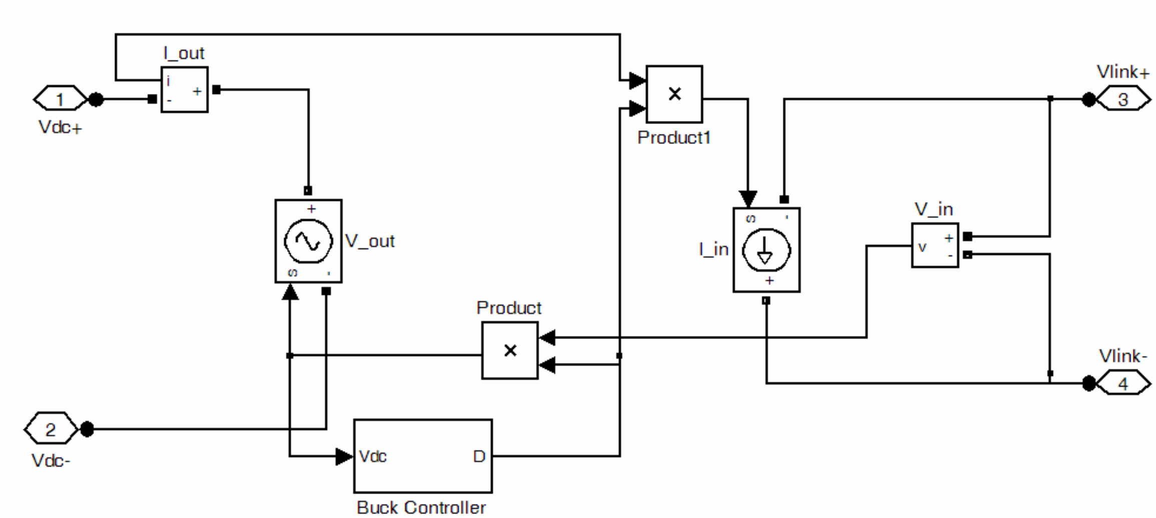

Figure 22 - Buck converter model