

# Smart Inverter Capabilities for Mitigating Over-Voltage on Distribution Systems with High Penetrations of PV

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**Abstract** — As the penetration level of PV on the distribution system grows, the current injection by PV can create over-voltage issues around the location of the interconnection of PV. Often, the voltage regulation in the feeder is not setup to handle these reverse current flows and inverse feeder voltage profile shape. The PV inverter can be used to absorb or inject reactive power to help negate the voltage change caused by the real power generation. Detailed analysis is performed to investigate the impact of PV output power factor and reactive power on the distribution system voltage. Several reactive control methods are demonstrated in simulation for a real distribution system with coincident high time-resolution measured load and irradiance data.

**Index Terms** — distributed power generation, photovoltaic systems, power distribution, power system interconnection, power system modeling, solar power generation

## I. INTRODUCTION

With deployment of distributed PV systems increasing rapidly, interconnection studies have shown that high voltage conditions can occur on the distribution system, especially under conditions of high penetrations of PV and when a large PV plant is connected to the end of a feeder [1-3].

### A. Example of High Voltages with PV

An example of this is shown for the distribution feeder in Fig. 1a with a 7.5 MW central PV plant (100% of feeder peak load). The feeder has an LTC at the substation with LDC and has two switched capacitors. The central PV system is connected at the end of the feeder on the furthest three-phase point that could thermally support a 7.5 MW PV plant. The simulation was run for the peak penetration week of April 20, 2011 to April 26, 2011 with coincident load and local irradiance data.

Fig. 1b shows the maximum and minimum voltage anywhere on the feeder for each second of 4/23/2011, demonstrating the

range of voltages. The red line in Fig. 1b is the maximum feeder voltage plotted through time with the 7.5 MW PV plant at unity power factor. The maximum voltage occurs at 11:48:19 on 4/23/2011, or hour 83.8 on the simulation hour timescale. The voltage profile plot along the entire feeder with the 7.5 MW PV plant is shown in Fig. 1c. Note that the voltage increases along the feeder to the PV plant at the end. In Fig. 1c, the dashed lines represent the voltage drop in the secondary transformers and secondary system.

### B. Solutions to High Voltages from PV

The goal is to enable deployment of high levels of PV on the distribution system without impact to customers. Voltage regulation equipment can be used to control the voltage, but solar variability can create frequent tap changes and wear the equipment [4].

A common solution to the high voltages issues from PV is to adjust the power factor to absorb reactive power. Due to the line impedance between generators and loads, voltage is commonly regulated using reactive power output control. In microgrids, generation is dispatched using droop control where reactive power output is varied by a voltage droop and real power output is varied by a frequency droop. On the distribution system, voltage can be controlled by switching capacitors that increase or decrease the reactive power in the system. STATCOMs are a power electronic solution to voltage regulation by controlling reactive power. Solar inverters can also be operated in the same manner as a STATCOM, where reactive power can be generated or absorbed to increase or decrease the voltage. The main purpose of the solar inverter remains as generating real power (kW) from the solar irradiance on the PV panels with the normal control logic, but additionally any remaining capacity of the solar inverter can be used to output kVAR regulate the voltage.

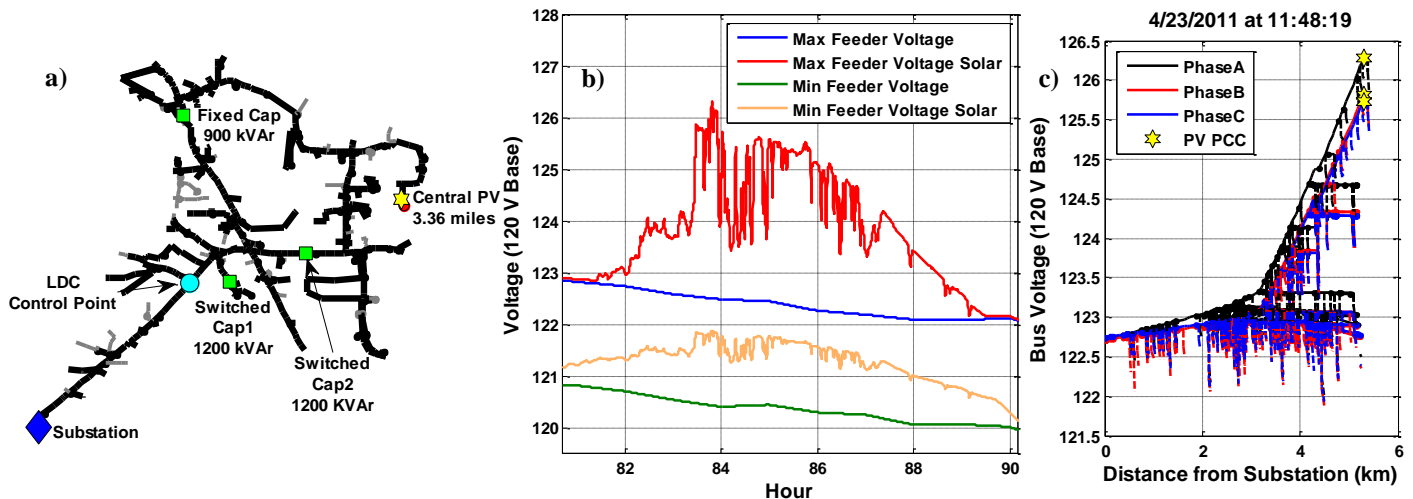


Fig. 1. a) Feeder circuit map used for simulating 7.5 MW central solar plant at unity power factor for b) the fourth day (4/23/2011) of the simulation with c) the over voltage condition occurring at 11:48:19

## II. ANALYSIS OF POWER FACTOR IMPACT ON VOLTAGE

Even a slight change in the PV output power factor to 0.95, decreases the voltage at 11:48:19 from 126.3V to 123.4V at the PV point of common coupling (PCC). Literature includes extensive discussions about the impact to the distribution system from absorbing volt-ampere reactive (Var) and changing the power factor on distributed resources with different possible power factor control strategies [5-7].

The var output of the inverter can be controlled many different ways. A fixed constant var output could be specified to always output the same reactive power. A schedule could be specified to vary the var output by time of day. Because the kW output of the solar inverter increases the voltage at the PCC, the kVAR output could also be specified as a function of the kW output. Finally, the var output of the inverter could be controlled based on the voltage at the PCC.

varying power factors, which demonstrates the exact impact that the power factor of the PV output has on the distribution system voltage. With a leading (absorbing) power factor, the voltage at the end of the feeder decreases, and with a lagging (producing) power factor, the voltage increases.

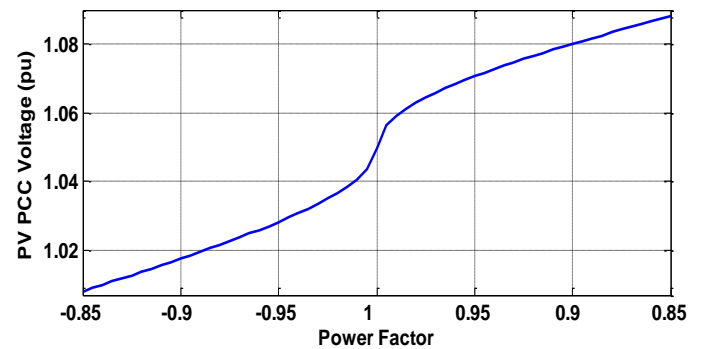


Fig. 3. Voltage (pu) at the PV PCC on 4/23/2011 at 11:48:19 for different PV output power factors for the 7.5 MW PV plant

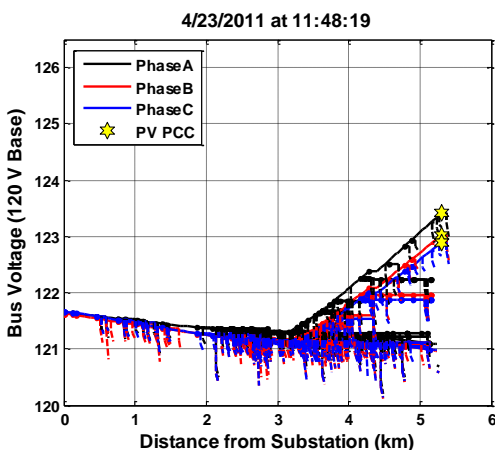


Fig. 2. Simulation with 7.5 MW central solar plant at 0.95 leading power factor for 4/23/2011 at 11:48:19.

Fig. 3 shows the PV PCC voltage for the fixed instant in time (4/23/2011 at 11:48:19) with the 7.5 MW PV output at

Generally, as the PV output power increases, the voltage rises at the PV PCC because of impedance between the PV and the closest voltage regulation equipment. As shown in Fig. 3, the PV PCC voltage is also a function of PV output power factor. An analysis of the PV PCC voltage as a function of both output power and power factor for 4/23/2011 at 11:48:19 is shown in Fig. 4.

Changing the voltage by adjusting the Var output (Volt/Var control) is prohibited by IEEE Std 1547 [8] which stipulates that the inverter “shall not actively regulate the voltage at the PCC”. This means that the solar inverter is not allowed to directly measure voltage at the PCC and adjust its output accordingly. For this reason, Volt/Var control is not considered here. Other authors have studied how to implement Volt/Var control and the impact to the distribution system [5, 9]. Some authors [10, 11] have also investigated distributed optimal control strategies for the distribution system as a whole.

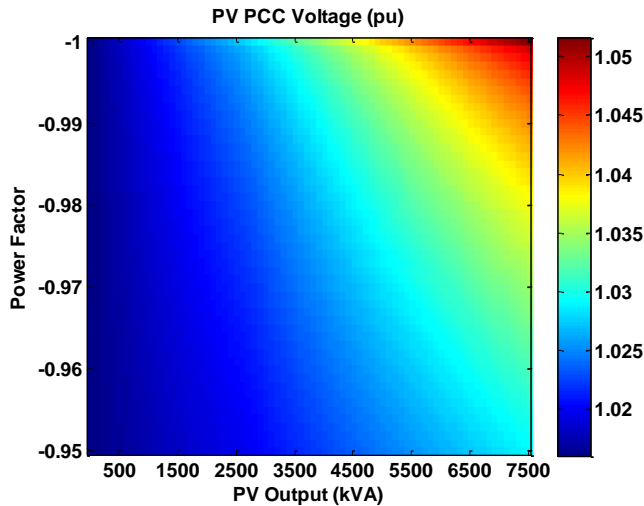


Fig. 4. Voltage (pu) at the PV PCC as a function of PV output power and power factor for 4/23/2011 at 11:48:19

As indicated in Fig. 5, the var generation from the PV inverter is envisioned as varying from capacitive to inductive as system voltage varies over a utility-defined range. When the voltage is around nominal voltage, the solar inverter does not output any reactive power. The y-axis is in terms of per unit available vars. The available vars is the headroom in the kVA rating of the inverter left after subtracting whatever amount of active power is being produced. Because of the variability in solar irradiance, even at a single system voltage on the x-axis, the reactive power generated may vary as the available vars (y-axis) varies with the solar power kW output.

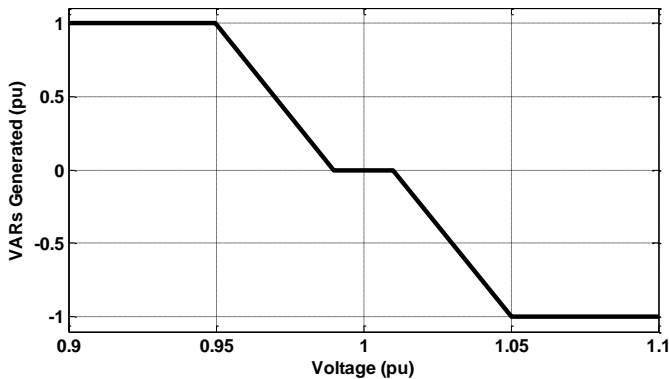


Fig. 5. PV volt/var control curve with deadband.

### III. POWER FACTOR CONTROL STRATEGIES

Other than the fixed lagging power factor previously mentioned, two other possible control strategies are proposed for adjusting the output power factor without directly measuring the bus voltage. The first power factor control strategy is to adjust the power factor by time of day. If the distribution engineers know from experience that high voltages occur at specific times of day on the feeder, either from the solar output or the load, the power factor of the PV can be

decreased during these times. An example is shown in Fig. 6. This example simply decreases the power factor when the solar production is expected to be the highest in the middle of the day. The solar inverter could also be set to output Vars at certain times of day to support the voltage.

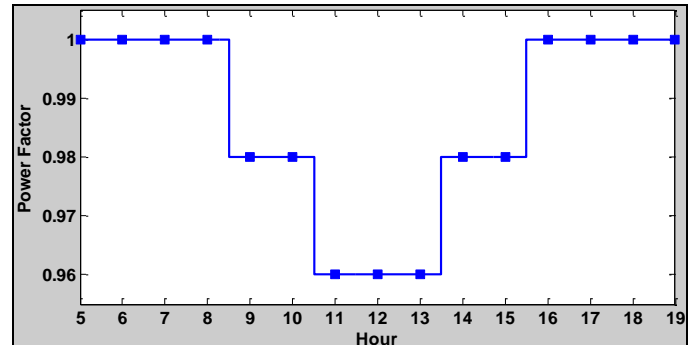


Fig. 6. Example power factor schedule

The power factor schedule shown in Fig. 6 was used to run the same peak penetration week simulation with the 7.5 MW PV plant at the end of the feeder. The simulation results are shown in Fig. 8 for this power factor schedule. This power factor schedule is advantageous because in the mornings and evenings when the solar output is low, the solar output is at unity power factor, which helps support the voltage.

The second power factor control strategy shown is controlling the power factor as a function of PV output power. In Fig. 4, the PV PCC voltage is shown to be a function of PV output, so the PF can be designed as a function of PV output to counteract the voltage increase. Because a detailed simulation cannot be completed for every PV plant being installed, a generic function for power factor like shown in Fig. 7 can be used. Similar to the concept for the power factor schedule, the power output is at unity power factor for lower solar outputs, which helps support the voltage and produces the most energy. Some authors such as [5] have proposed also making this a function of the X/R ratio at the point of interconnection.

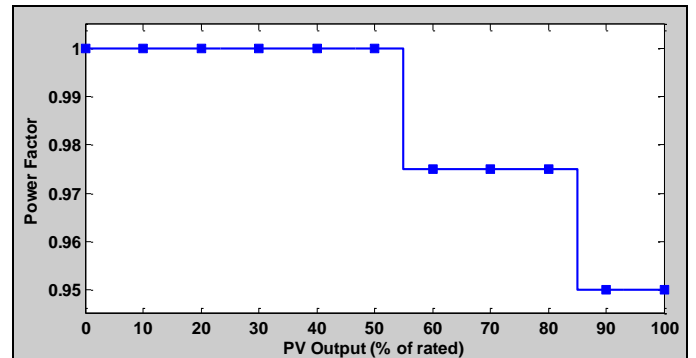


Fig. 7. Example of power factor as a function of PV output

The simulation was run with the 7.5 MW PV plant at the end of the feeder and the power factor function in Fig. 7. The results in Fig. 8 show lower voltages than when the PV plant is at unity power factor. The advantage of the power factor

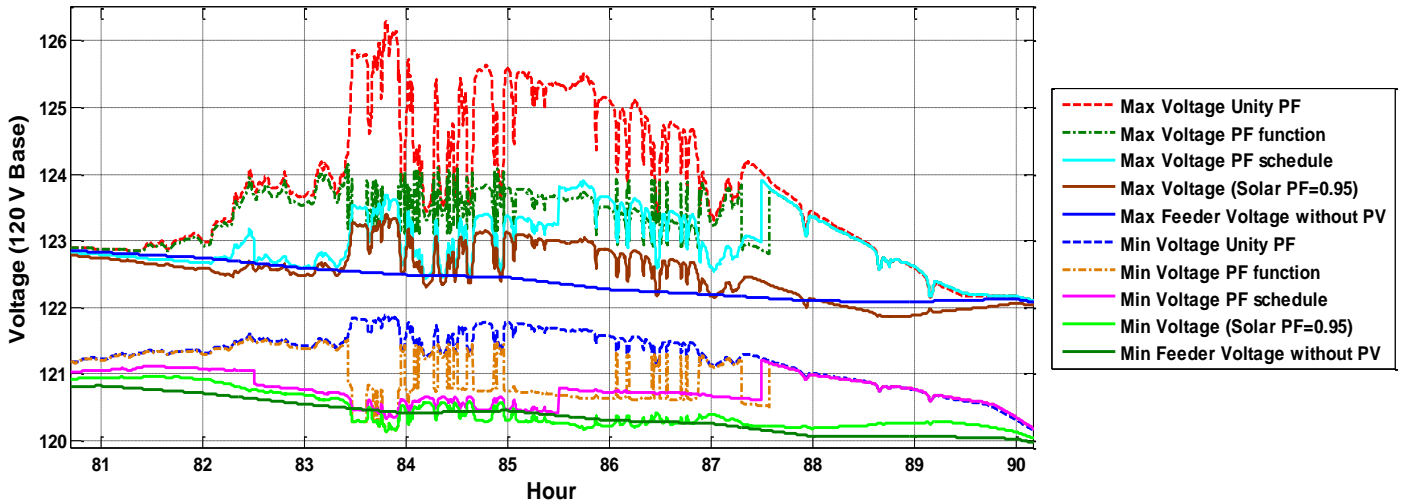


Fig. 8. Feeder voltages with varying ways of modifying solar output power factor (PF)

function is that it is directly proportion to the solar output, instead of assuming a certain amount of solar power at each time of day. The three methods (fixed power factor, power factor schedule, and power factor function) are graphed together in Fig. 8. These example control methods all bring the maximum feeder voltage within the appropriate limits.

#### IV. VOLT/VAR CONTROL

The OpenDSS implementation details are described in [5]. One feature of OpenDSS exploited in VVControl is that control elements are modeled separately from the actual current-carrying elements. Control elements are treated differently than the standard power delivery or power conversion elements during the solution process. The solution algorithm is an iterative process of solving the power flow and allowing the control elements to take action. Thus, volt/var control decisions and actions are executed only on converged power flow solutions rather than during the power flow iterative process. The iterative process also has the advantage that the final solution for each time-step involves taking control actions immediately, instead of applying them after the power flow solution for the next time-step.

As an example of the volt/var control features, the control was simulated for the distribution feeder in Fig. 1a. The peak penetration week was simulated with results being shown for 4/20/11. The simulation uses hourly measured substation load data and irradiance data from the middle of the distribution feeder measured at 1-second resolution. The irradiance data was transformed to power output of a 7.5 MW central PV plant by using the wavelet variability model (WVM). A day was selected with variable irradiance to fully demonstrate volt/var control. The simulated real power plant output is the same in each simulation and can be seen in Fig. 12. The PV plant was connected at the end of the distribution feeder.

Three solar scenarios are simulated to compare the voltage at the PCC.

1. Unity power factor solar output
2. Volt/var control shown in Fig. 5 with a deadband around the voltage
3. Voltage regulation

Voltage regulation by the PV inverter can be implemented with the OpenDSS VVControl function by creating a VVC with a very steep slope around the desired voltage setpoint. With the steep slope, the solar inverter will deliver whatever reactive power is necessary to regulate the voltage until the inverter rating is reached. The results for the daily profile of voltage at the PCC for each of the three solar scenarios are compared to the basecase without PV in Fig. 10. The feeder voltage profile for the PV plant with and without volt/var regulation is shown in Fig. 11.

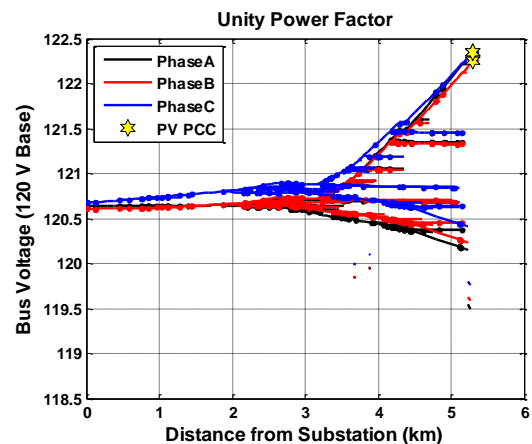


Fig. 9. Feeder voltage profile at 12:04 PM on 4/20/11 during the day's peak solar output with unity power factor.

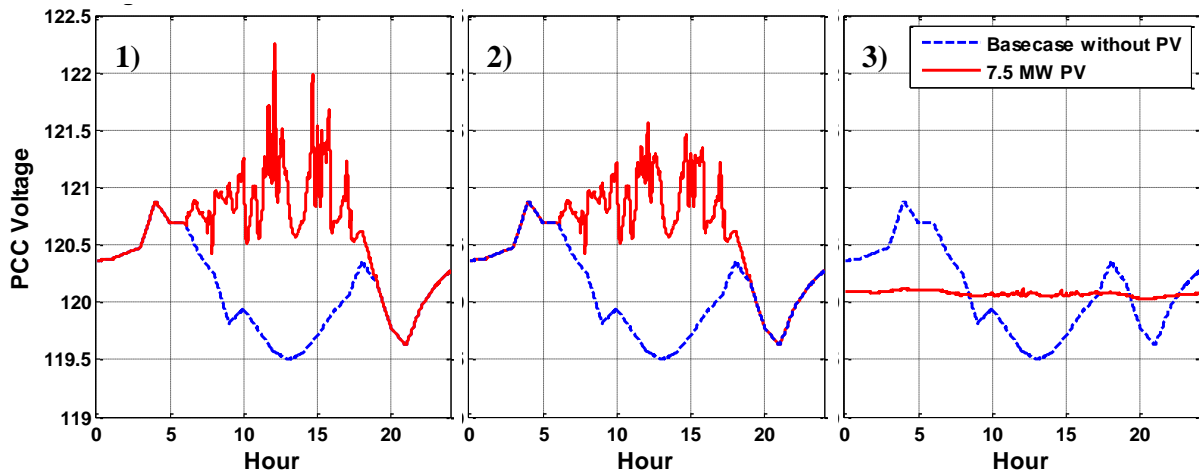


Fig. 10. PCC voltage for each of the three solar scenario: 1) unity power factor, 2) volt/var control with deadband, and 3) voltage regulation.

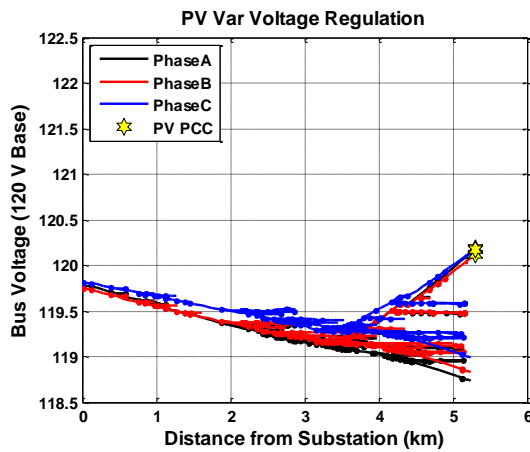


Fig. 11. Feeder voltage profile at 12:04 PM on 4/20/11 during the day's peak solar output with voltage regulation using var control.

For the voltage regulation case, a significant amount of reactive power is required. The reactive power output is shown in Fig. 12. In this simulation the inverter rating was never reached (lower solar on this cloudy day), so the exact number of required vars was always able to be generated or absorbed to regulate the voltage. Under extreme conditions of high solar power output (kW) or large voltage deviations, the PV inverter can hit the rating limit and would not be able to fully regulate the voltage.

## V. DISCUSSION

The benefit of decreased high voltages or supporting low voltages is not without consequence. The solar inverter must stay within its kVA rating. For demonstration purposes in the simulations shown, the inverter rating was assumed to be high enough to maintain the full solar output and the requested Vars. In reality, an inverter rated for the PV system would have very little capacity left for producing or absorbing Vars under high solar output weather conditions. This headroom for reactive power output between the inverter rating and the real power solar output varies throughout the day as the solar

irradiance varies. If the inverter control (fixed power factor, schedule, or function) requests a higher reactive power output than the available headroom of the inverter kVA rating, either the reactive power or the real power must be reduced from the specified conditions.

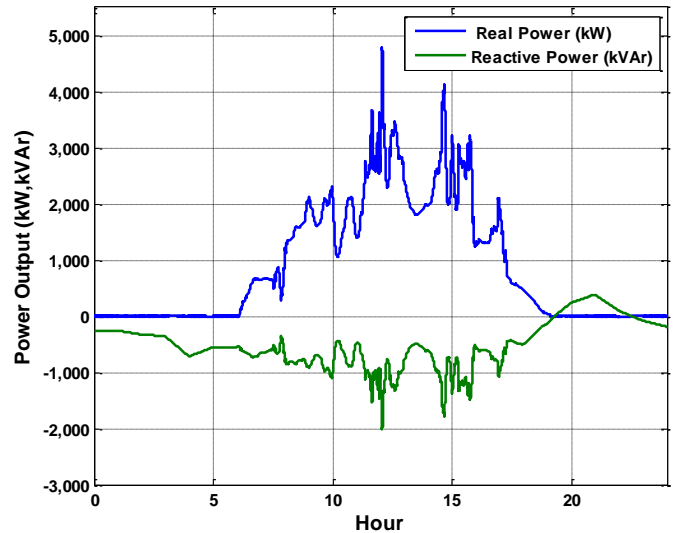


Fig. 12. PV plant power output using voltage regulation control on 4/20/11.

## VI. CONCLUSIONS

With increasing penetrations of solar on the distribution system, reactive power capabilities of inverters can be used to support voltage and mitigate any over voltage conditions caused by real power output. Detailed analysis was shown to demonstrate the exact impact of PV output power factor and reactive power on the distribution system voltage. Additionally, two methods are shown for controlling over-voltage conditions using a power factor schedule and a power factor function. Several other reactive power control algorithms will be included with the additional space of the final paper, such as the simulation results for Volt/Var control

that regulates voltage. Reactive power limiting based on inverter ratings will also be implemented.

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