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Coordinated Harmonization of Stochastic Sources and Loads in Dual Independent PV Arrays

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***Abstract*— This paper introduces the modeling and controller design for two independent PV power plants feeding a common DC bus. We present the decentralized controller design for coordinated power flow control for each PV plant under stochastic loads and solar insolation conditions. The boost converters enable control of the bus voltage to desired levels under input and load disturbances. A simulation study is presented in the MATLAB/Simulink environment for the configuration described by combining the individual component models and controller designs. Numerical simulation results are presented that show the overall system stability and performance of the coupled PV system.**

I. Introduction

The United States and other countries are facing the integration of green renewable resources into existing aging Electric Power Grid (EPG) infrastructures. In particular the states within the US are faced with fast approaching deadlines due to Renewable Porfolio Standards (RPS). This is forcing the retrofit and patch in of renewables that can be done with existing options. Many of the proposed "Smart Grids" are simply overlaying information networks onto existing EPG infrastructures. At the heart of the EPG is the coordination and control of centralized dispatchable generation to meet customer loads. A new approach is required to formally address the green grid of the future with distributed variable generation, buying and selling of power (bi-directional flow), and decentralization of the EPG.

Many researchers are attempting to address this problem. For example, the Solar Energy and Grid Integration Systems (SEGIS) program is attempting to integrate large amounts of photovoltaic systems in the EPG.

> *Solar Energy Grid Integration Systems (SEGIS) concept will be key to achieving high penetration of photovoltaic (PV) systems into the utility grid. Advanced, integrated inverter/controllers will be the enabling technology to maximize the benefits of residential and commercial solar energy systems, both to the systems owners and to the utility distribution network as a whole. The value of the energy provided by these solar systems will increase through advanced communication interfaces and controls, while the reliability of electrical service, both for solar and non-solar customers, will also increase [1].*

The goal of this paper is to present a step toward addressing the integration of PV resources into the EPG [2], [3], [4], [5], [6], [7] by implementing multiple PV sources into a DC bus microgrid. Each PV source is modeled as a single boost converter with a cascaded PI controller that feeds a common DC bus. The load is treated as stochastic. The DC bus microgrid is modeled in MATLAB/Simulink. The effects of multiple stochastic supplies feeding a stochastic load is investigated.

This paper is divided into five sections. Section II develops the single boost converter for PV and the DC bus. Section III presents the DC bus with decentralized control. Section IV gives the results of the numerical simulations of constant and stochastic inputs for single PV boost converters and dual PV boost converters. Section V provides the summary and conclusions.

II. Singe Boost Converter for PV and DC Bus

The boost converter used for this study is a simple power conv erter with an output DC signal. This circuit is employed to *step-up* a source voltage to a higher, regulated voltage in a bus configuration. The ideal mathematical model for this circuit is given as [5]

$$\begin{aligned} L\frac{di_L}{dt} &= V_{PV} - v_0(1-u) \\ C\frac{dv_0}{dt} &= i_L(1-u) - \frac{v_0}{R} \end{aligned} \tag{1}$$

where i_L is the current across the inductor, v_0 is the voltage in the capacitor, u defines the switching position, V_{PV} is the photovoltaic array supplied voltage, and R, L, and C are given resistance, inductance and capacitance known parameters.

This boost converter system has been implemented in MATLAB/Simulink as shown in Fig. 1. Each boost converter is summed (capacitance, currents) into a DC bus configuration such that multiple converters can be easily added. The load is fed into the bus as a resistance converted into conductance as shown in Fig. 2.

III. DC Bus with Decentralized Control

Each boost converter contains a cascaded PI controller consisting of voltage and current feedback. For each feedack signal (voltage, current) a low pass filter is used to roll-off the high-frequency portion of the signal with all corner frequencies set at 600Hz. In addition, the switching position (in Eq. 1) is defined [5] to be $u \in \{0, 1\}$ and for signals outside of this range the control is considered saturated.

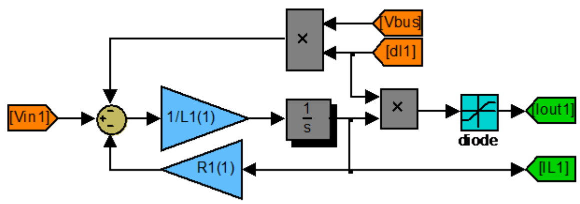

Fig. 1. Single boost converter system in MATLAB/Simulink

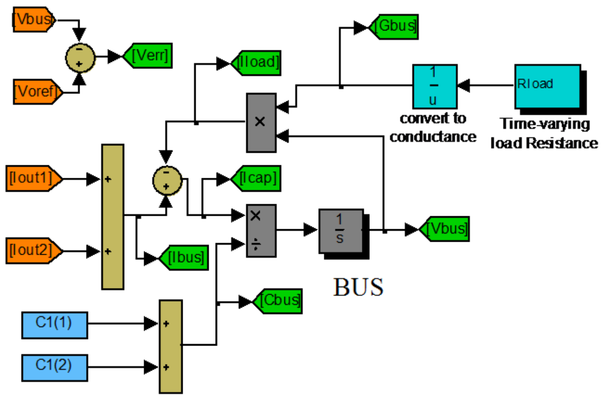

Fig. 2. DC Bus configuration in MATLAB/Simulink

This configuration is shown in Fig. 3 and follows reference [8]. Each controller is decentralized and are tuned for independent control. In the next section several case studies are investigated. This configuration was used to determine the effectiveness of decentralized control with respect to harmonization of multiple PV sources supplying a stochastic load.

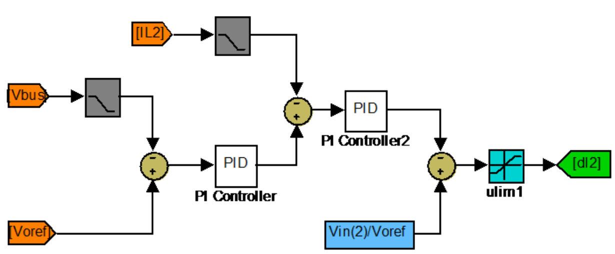

Fig. 3. Cascaded PI controller in MATLAB/Simulink

IV. Results of the Numerical Simulation

In the following subsections both single boost converter runs and dual boost converter runs will be discussed. The scenario is representative of a microgrid with a single PV input and a dual PV input to a DC bus supplying a varying load. The nominal peak voltage is 80 Volts from the PV inputs. Two sets of runs will be reviewed for each configuration with a constant voltage input and a stochastic voltage input servicing a stochastic load. The goal is to demonstrate the effect of multiple stochastic sources feeding a DC bus to meet the requirements of a stochastic load. Multiple sources are fed into the DC bus with independent control to assess the need for coordinated harminzation to meet overall bus voltage. The following simulation results demonstrate the effects of distributed decentralized control of dual independent PV arrays. Note a primary specification is to stay within $\pm 5\%$ tolerance of the nominal bus voltage ($v_{bus} = 120\sqrt{2}v = 169.70v$).

A. Single PV boost converter constant input

The reference case for the single boost converter is a constant 80 v input as shown in Fig. 4. The bus voltage response is shown in Fig. 5 after the intial transient the bus voltage remains within $\pm 5\%$ of the desired value. The stochastic bus load profile is given in Fig. 6. The response for the single PV controller is shown in Fig. 7.

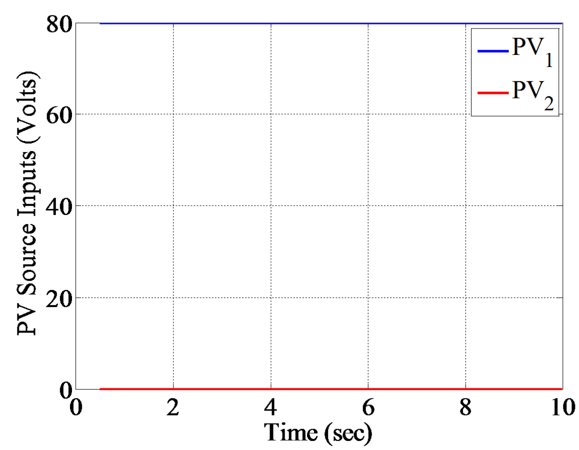

Fig. 4. Single constant PV reference input

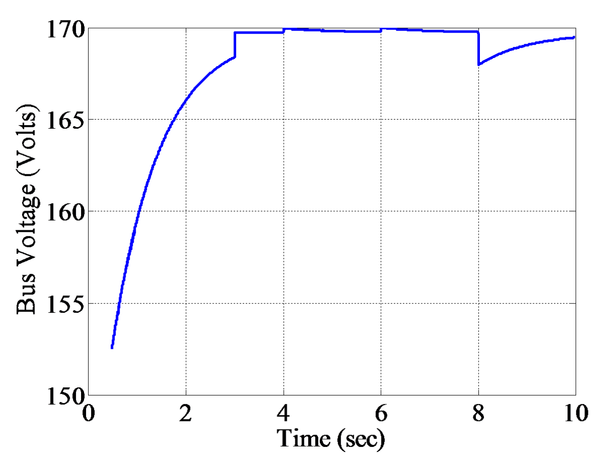

Fig. 5. Single constant input bus voltage

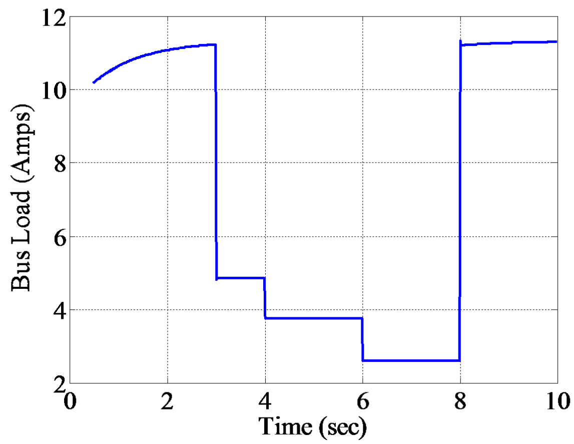

Fig. 6. Single constant input bus load

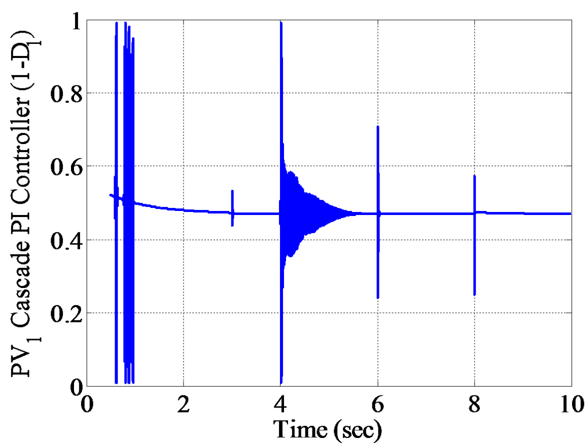

Fig. 7. Single constant input PV controller effort

B. Single PV boost converter variable input

The reference case for the single boost converter is a variable 52 v ±28v at 1 Hz input as shown in Fig. 8. The bus voltage response is shown in Fig. 9 after the intial transient the bus voltage remains within ±5% of the desired value. The stochastic bus load profile is given in Fig. 10. The response for the single PV controller is shown in Fig. 11. The stochastic behavior of both the supply and the load are evident in these responses.

C. Dual PV boost converters constant input

The reference case for the dual boost converters are a constant 50 v and 30 v inputs as shown in Fig. 12. The bus voltage response is shown in Fig. 13 after the intial transient the bus voltage remains within ±5% of the desired value. The stochastic bus load profile is given in Fig. 14. The response for the dual boost PV controllers are shown in Figs. 15 and 16, respectively. For constant dual boost converter inputs the DC bus is harmonized for the stochastic load.

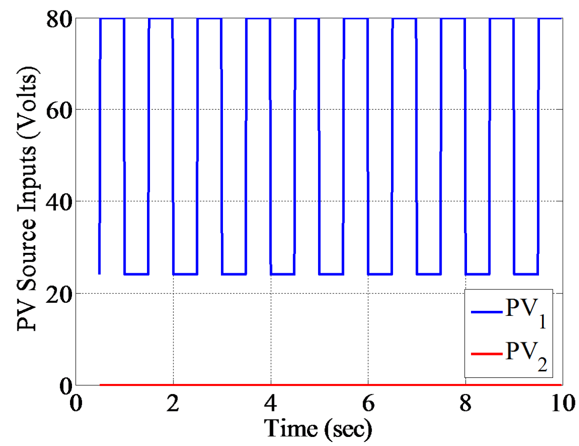

Fig. 8. Single variable PV reference input

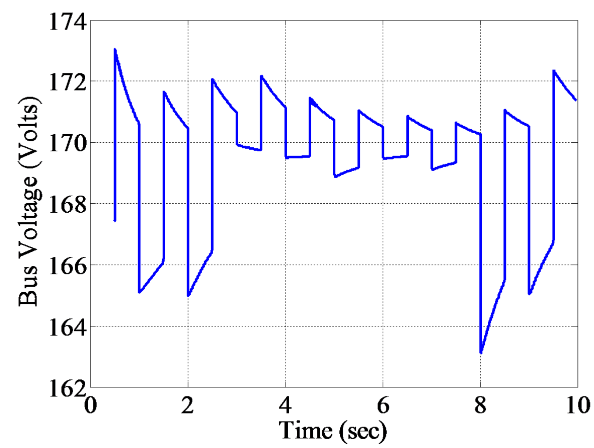

Fig. 9. Single variable input bus voltage

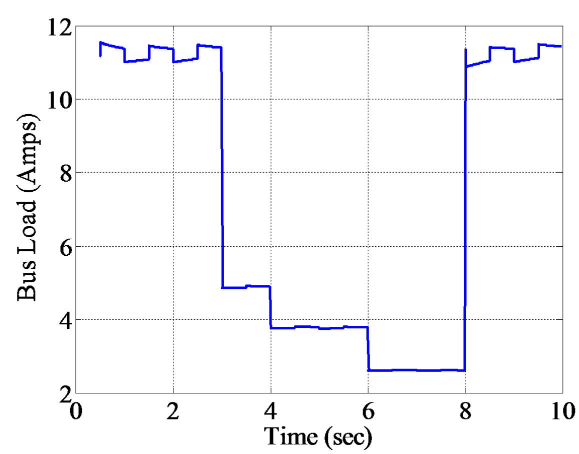

Fig. 10. Single variable input bus load

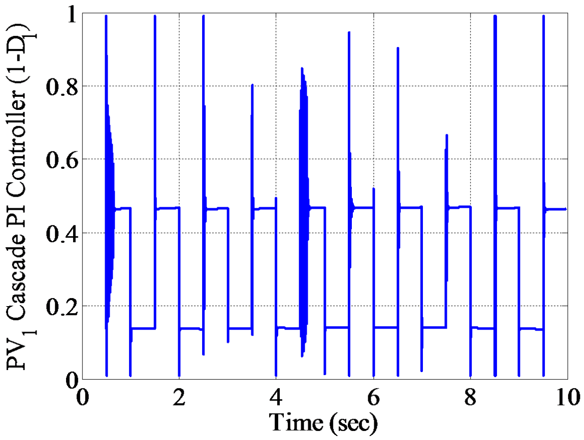

Fig. 11. Single variable input PV controller effort

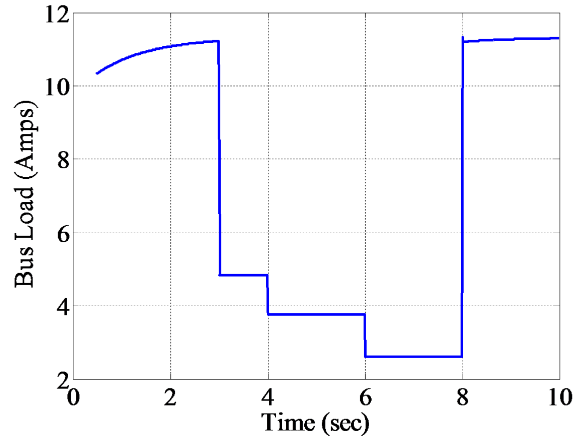

Fig. 14. Dual constant input bus load

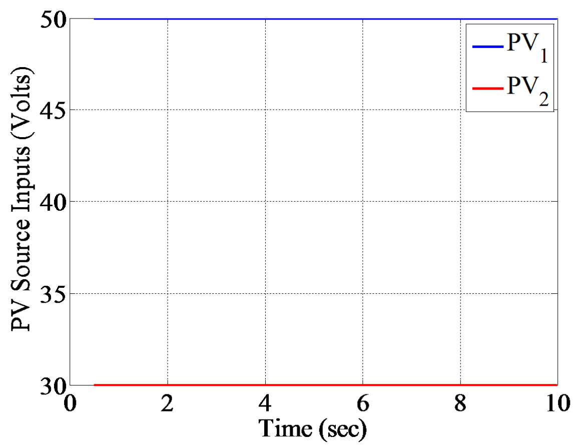

Fig. 12. Dual constant PV reference input

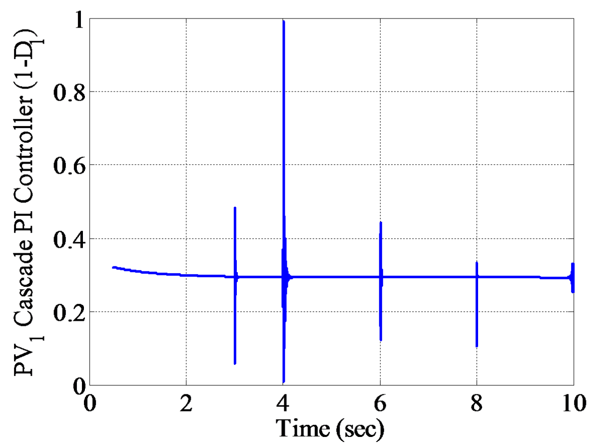

Fig. 15. Dual constant input PV_1 controller effort

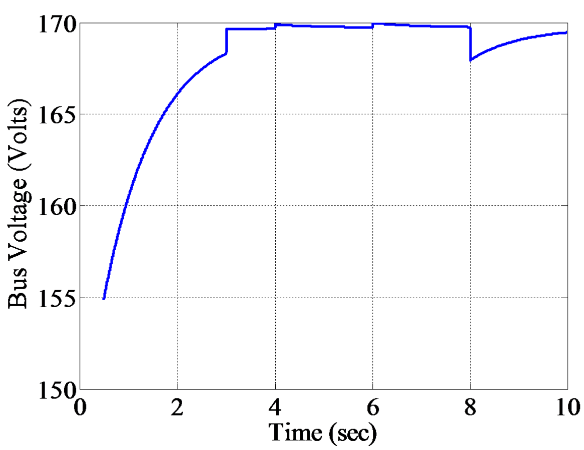

Fig. 13. Dual constant input bus voltage

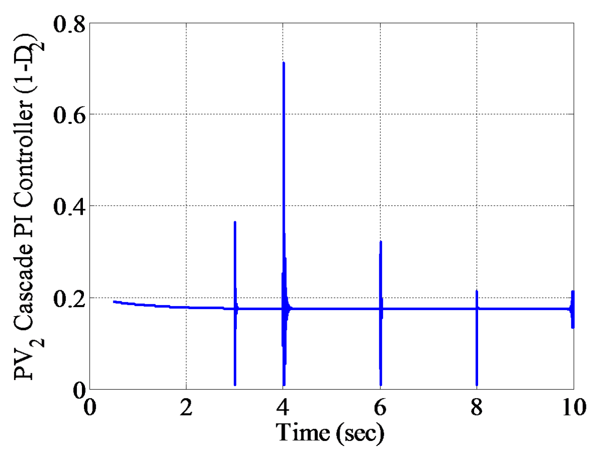

Fig. 16. Dual constant input PV_2 controller effort

D. Dual PV boost converters variable input

The reference case for the dual boost converters are a variable 32 v ±18v and 20 v ±10v at 1 Hz input as shown in Fig. 17. The bus voltage response is shown in Fig. 18 after the intial transient the bus voltage are no longer within ±5% of the desired value. The stochastic bus load profile is given in Fig. 19. The response for the dual boost PV controllers are shown in Figs. 20 and 21, respectively. The stochastic behavior of both the dual supplies and the load are evident in these responses. For variable dual boost converter inputs the DC bus is not harmonized for the stochastic load. This implies that the decentralized control strategy is not sufficient to meet the desired bus voltage tolerances. The next step is to investigate advanced coupled control architectures.

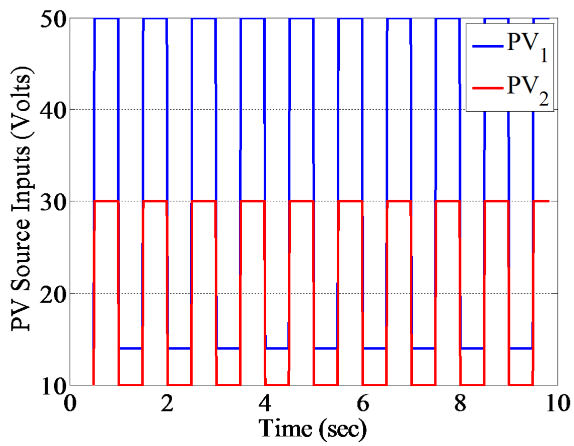

Fig. 17. Dual variable PV reference input

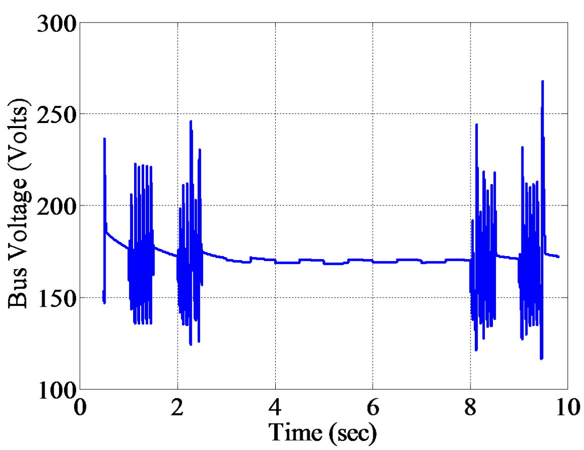

Fig. 18. Dual variable input bus voltage

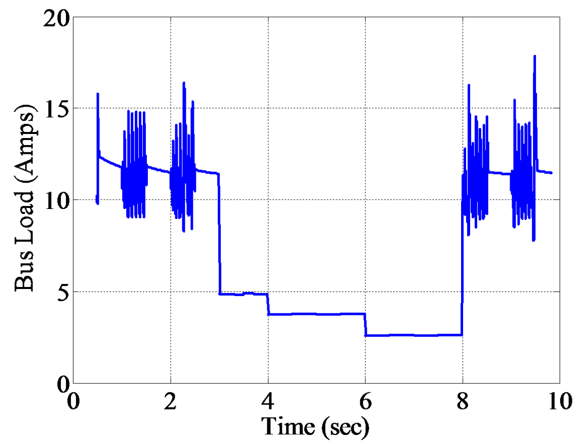

Fig. 19. Dual variable input bus load

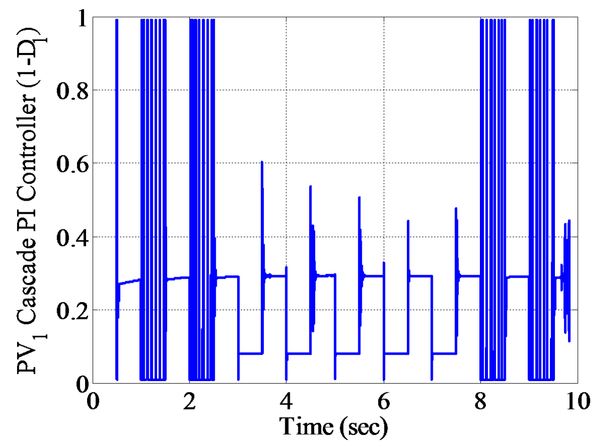

Fig. 20. Dual variable input PV_1 controller effort

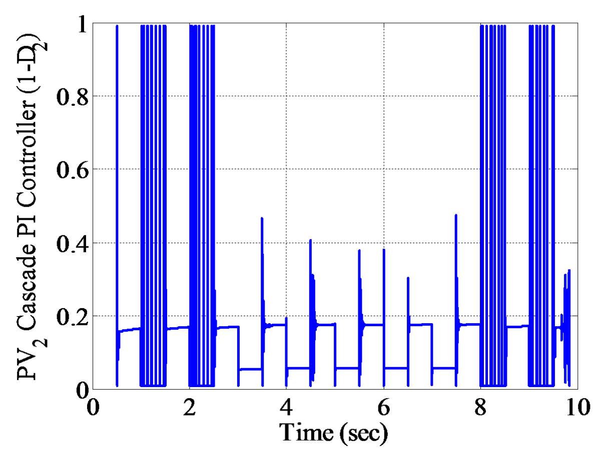

Fig. 21. Dual variable input PV_2 controller effort

V. Summary and Conclusions

This paper developed the modeling and controller design for two independent PV power plants feeding a common DC bus. A decentralized controller design for coordinated power flow control for each PV plant under stochastic loads and solar insolation conditions was presented. The boost converters enabled control of the bus voltage to desired levels under constant and some of the varable inputs and load disturbances. A simulation study was presented in the MATLAB/Simulink environment for the configuration described by combining the individual component models and controller designs. Numerical simulation results were presented that showed the overall system stability and performance of the coupled PV systems. Three out of the four cases for both single and dual boost converter cases showed coordinated harmonization and met the bus voltage tolerances. However, the last case did not harmonize the DC bus under stochastic supplies and loads. Consequently, the decentralized control strategy was not sufficient to meet the desired bus voltage tolerances. Future work will begin to investigate advanced coupled control architectures to address these shortcomings.

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