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Load Compensator with an Energy Storage for a Grid Connected PV Based Active Generator

K.M.S.Y. Konara^{1,2}, M. L. Kolhe¹ and Arvind Sharma¹

¹Faculty of Engineering and Science, University of Agder, PO Box 422, No 4604, Kristiansand, Norway

²Faculty of Engineering, University of Ruhuna, Galle, Sri Lanka

E.mails : konara@uia.no, mohan.kolhe@uia.no and arvind.sharma@uia.no

Abstract. At present, in order to build a sustainable economy with less greenhouse emission, the attention has been drawn towards the smart grid concept. In this context, grid connected photovoltaic (PV) systems play a major role. When it comes to grid connected PV systems, the intermittent nature of PV generation and the uncontrolled power injection may cause excess variations in the grid voltage, frequency and the power quality. Therefore, the concept of active generator with innovative energy management strategies is a good alternative with which the PV generated power can be injected to the grid in a controlled manner while achieving the output power quality, instantaneous power, balance, frequency control and voltage control. This work proposes an innovative architecture for a grid connected PV based active generator with multi sources; a PV array, battery and the grid supply which are connected to a common AC bus as well as it analyses the innovative load flow control strategy associated with the proposed architecture. To make sure an uninterruptable power supply to the load, PV arrays inject the generated power in maximum power point tracking mode and the battery compensates the power requirement in coordination with the grid while maintaining the frequency stability within the system. Therefore, this paper analyses the performance of the energy controller and the load management capability of the proposed system while achieving the frequency control.

1. INTRODUCTION

Though photovoltaic (PV) energy stands as one of the prominent sources of renewable energy in present, some problems can arise due to its stochastic nature when increasing the more penetration of PV generated power in uncontrolled manner. The intermittent nature of PV generation and the uncontrolled power injection with passive power conditioning devices can result power quality issues and may cause excess variations in the grid frequency and the grid voltage [1, 2]. Especially, on the day time of a clear sunny day, PV arrays may produce excess energy that can be stored in a local energy storage or injected to the utility grid in addition to supplying locally connected loads. In order to overcome from the aforementioned issues related with the uncontrolled PV integration, PV based active generator (AG) with embedded energy storage can be employed as a solution. But, this type of distribution systems with active generators necessitate innovative energy management and control strategies for increasing the more penetration of PV generated power without getting any power quality issues and frequency fluctuations [1, 3].



Ref [4] analyzes the power management capability of a grid integrated battery for a distributed energy system in order to provide the prescribed power to the grid. They have mainly focused on handling the power quality and correcting the power factor by using an active filter, when it is connected to a distributed energy system. The authors have discussed about eliminating the power fluctuations, but the frequency control and the voltage control are not addressed in this work. The demand management of a PV system with various storage technologies is presented in [5]. In the proposed architecture, multi sources are connected to a common DC bus and the voltage source inverter (VSI) connected to the DC bus has been controlled using current mode control. They have significantly focused on the demand management using different power shares of the multi sources but failed to address the frequency control of the utility grid. Ref [3] has focused on the control and power management of a grid-connected PV system with an energy storage but it has not given a significant attention to manage the frequency variations caused by the integration of intermittent PV generated power. Although considerable research efforts have been devoted to energy management of a grid connected PV based AG, less attention has been paid to control the frequency fluctuations result from the integration of the AG with the utility grid.

Most of the grid connected PV systems are based on the architecture shown in Figure 1. The VSI connected to the common DC bus is controlled using current mode control. The required current reference values of each power source in the AG are calculated using different mathematical models developed for each component of the AG. It can be observed that, the independent control of individual power sources has become inconvenient with this architecture.

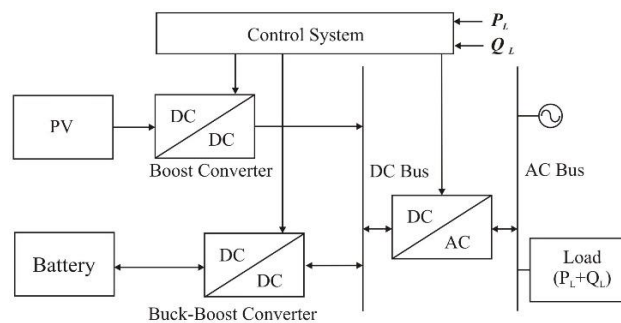


Figure 1. System architecture of the PV based AG

Therefore, this work proposes an architecture for a PV based AG with a common AC bus to which all the power sources are connected along with their own energy control system while maintaining the frequency control of the grid. To maintain reliable and healthy operation of the system, the availability and the accessibility of the battery should be taken into account when proposing a proper load management algorithm for a PV based AG system. Since the proposed system consists of two power sources, PV array and battery, a hierarchical approach with PID control and state-flow control are used for power dispatching from different sources. In this work, Matlab/Simulink[®] is used to model the power sources and the power conditioning devices and the logic controller for energy management is achieved with Stateflow[®] model.

2. The proposed architecture of the PV based AG and its components

Generally, a PV based AG consists of multi power sources which dispatch power to meet the load demand, power conditioning devices, locally connected loads and the energy control system. Basically, four different sub systems can be identified for designing a PV-AG; 1. Power generation subsystem 2. Power conditioning devices subsystem 3. Energy storage subsystem 4. Energy management subsystem. Depending on the power dispatching strategies and the constraints enforced by the utility grid, suitable components including power electronic converters and energy storage technologies are selected to the mentioned subsystems of the PV-AG.

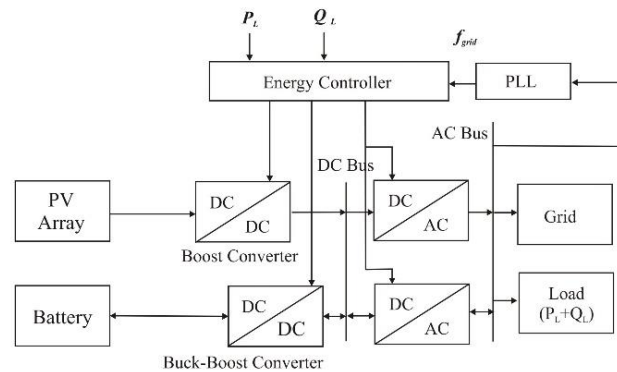


Figure 2. Proposed system architecture of the PV-AG for load management and frequency control

The proposed system architecture of the PV-AG for load management and frequency control is shown in Figure 2. The mentioned subsystems of the PV-AG are connected to a common AC bus to which the utility grid is connected. In order to achieve proper operation as an AG, power flow among the PV array, energy storage sub system, locally connected load and the grid should be properly coordinated.

2.1. Power generation subsystem

In this work, a 215 kW (peak) solar PV array is selected. The array consists of 54 strings in parallel and each string is having 20 panels in series. The specifications of Monocrystalline Solar Panel Merkasol 200W PV panels manufactured by Merkasol® [6] are employed to model the PV array output at the Maximum power point (MPP). The relevant technical data of the selected solar PV module is tabulated in Table 1.

Table 1. PV module data [6]

Electrical data	Parameters
Nominal output P_{mpp}	200 W
Nominal Voltage V_{mpp}	36.9 V
Nominal current I_{mpp}	4.55 A
Open circuit voltage V_{oc}	45.2 V
Short circuit current I_{sc}	5.72 A
Conversion efficiency	15.67%

To analyze the performance of the proposed demand management strategies, it is necessary to know the PV array output. The output of the PV array depends on the incident solar radiation, module temperature and the parameters of the cell. In this work, the variation of global tilted irradiation (GTI) data is considered as illustrated in Figure 3.

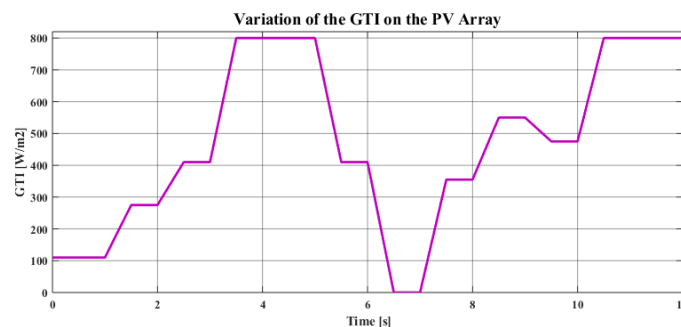


Figure 3. GTI variation on the PV array

2.2. Energy storage subsystem

In the proposed PV based AG system, lead-acid battery is used as the long-term energy storage. The battery capacity with reference to the load and the PV capacity has been selected based on the study presented in [3, 7, 8]. When the PV generated power is not sufficient to meet the load demand, the battery discharges its power at lower rate. The battery should maintain a high state of charge (SOC) by charging when excess energy is available within the system. In this work, the battery model available in MATLAB/Simulink® is used to implement the battery subsystem. The battery model is configured as a lead-acid battery with the parameters given in Table 2.

Table 2. Parameters of the battery

Parameters	Data
Nominal Voltage	400 V
Rated Capacity	200 Ah
Initial State Of Charge	80 %
Fully Charged Voltage	435.6 V
Nominal Discharge Current	13.9 A
Internal Resistance	0.02 Ω
Capacity(Ah)@Nominal Voltage	62.1Ah

2.3. Power conditioning devices subsystem

The system consists of one DC-DC boost converter, one bi-directional DC-DC buck-boost converter and two 3 ϕ VSIs as power conditioning devices. In the PV-AG system, the DC-DC boost converter connected with the PV array works in MPPT mode by controlling its output voltage [9]. The bi-directional DC-DC buck-boost converter connected with the lead-acid battery facilitates both charging and discharging modes as it is capable of handling bi-directional regulated power flow. In the VSIs, the DC sides are connected to the two DC-DC converters and the AC sides are connected to the common AC bus to consume and inject the frequency regulated AC power to the common AC bus.

2.4. Energy management subsystem

The energy management system is designed in hierarchical fashion as an event driven system with PID control and state-flow control. Hierarchical approach of controlling includes several hierarchical stages and each stage is responsible for doing a control task based on its hierarchical position [10]. In this design, this system includes four stages each having their own control task depend on the hierarchical position as illustrated in Figure 4.

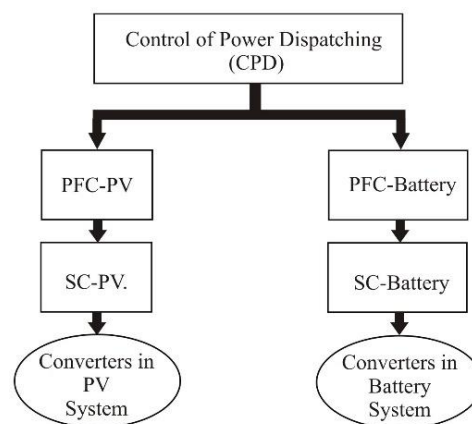


Figure 4. Energy management subsystem overview

3. Energy management and frequency control of the PV-AG

As described in 2.4, the whole control task is subdivided into three hierarchical stages as illustrated in Figure 4. Control of power dispatching (CPD) layer determines the availability and the accessibility of each source and the required power set points to achieve proper power dispatching among the available sources. Power shares are determined at the power flow control (PFC) level to control the system frequency. Based on the reference power signals calculated at the PFC, switching control (SC) level generates the required PWM signals to each converter to deliver the required power to the load.

3.1. Control of power dispatching (CPD)

At this stage, the availability and the accessibility of the considered power source for power dispatching are determined. The control layer is designed as an event driven system with state-flow control. In order to get the decision, SOC of the battery and the generation capacity of the PV array are considered. The state transition diagrams of CPD for PV array and battery are shown in Figure 5 (a) and (b) respectively [10].

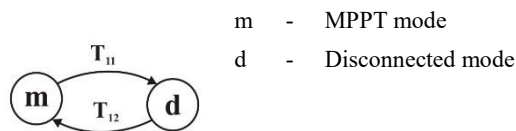


Figure 5(a). State transition diagram of CPD for the PV array

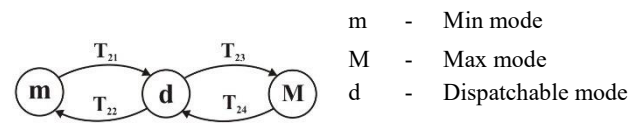


Figure 5(b). State transition diagram of CPD for the battery

State transition logics of CPD for PV array and battery are tabulated in Table 3. (a) and (b) respectively. The flow chart of the state transition logic of the battery is illustrated in Figure 5 [10].

Table 3(a). State transition logic of CPD for the PV array

State Transition	Logic
T11	$[P_{pv}(t) > P_{pv,min}]$
T12	$[P_{pv}(t) < P_{pv,min}]$

Table 3(b). State transition logic of CPD for the battery

State Transition	Logic
T21	$[SOC(t) > SOC_{min}]$
T22	$[SOC(t) < SOC_{min}]$
T23	$[SOC(t) > SOC_{max}]$
T24	$[SOC(t) < SOC_{max}]$

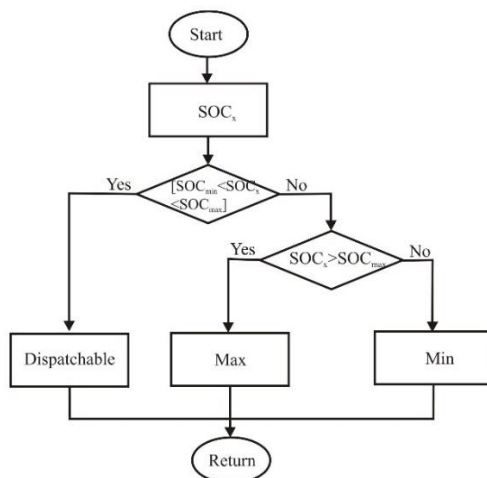


Figure 5. State transition logic of the battery

- $P_{pv}(t)$ - current PV generation of the array
- $P_{pv,min}$ - minimum PV generation
- $SOC(t)$ - current state of charge of the battery
- SOC_{max} - maximum allowable state of charge of the battery for dispatching
- SOC_{min} - minimum allowable state of charge of the battery for dispatching

3.2. Power flow control (PFC) and PWM switching control (SC)

In the dispatchable mode, the PV array inject the maximum available power in MPPT mode with the help of the closed loop control developed at the PFC layer for PV and then the load demand is compensated by the battery and the grid if these two power sources are determined as accessible or available at the CPD stage. To facilitate the battery in both charging and discharging modes, three P_{set} values are obtained from the CPD-battery stage depending on its current state; d , m and M . Based on this, the PFC of the battery controls the required power share of the battery while controlling the frequency. According to the required reference current components (i_{d_ref} and i_{q_ref}) of both the power sources calculated at the PFC layer, required PWM signals for VSIs are generated.

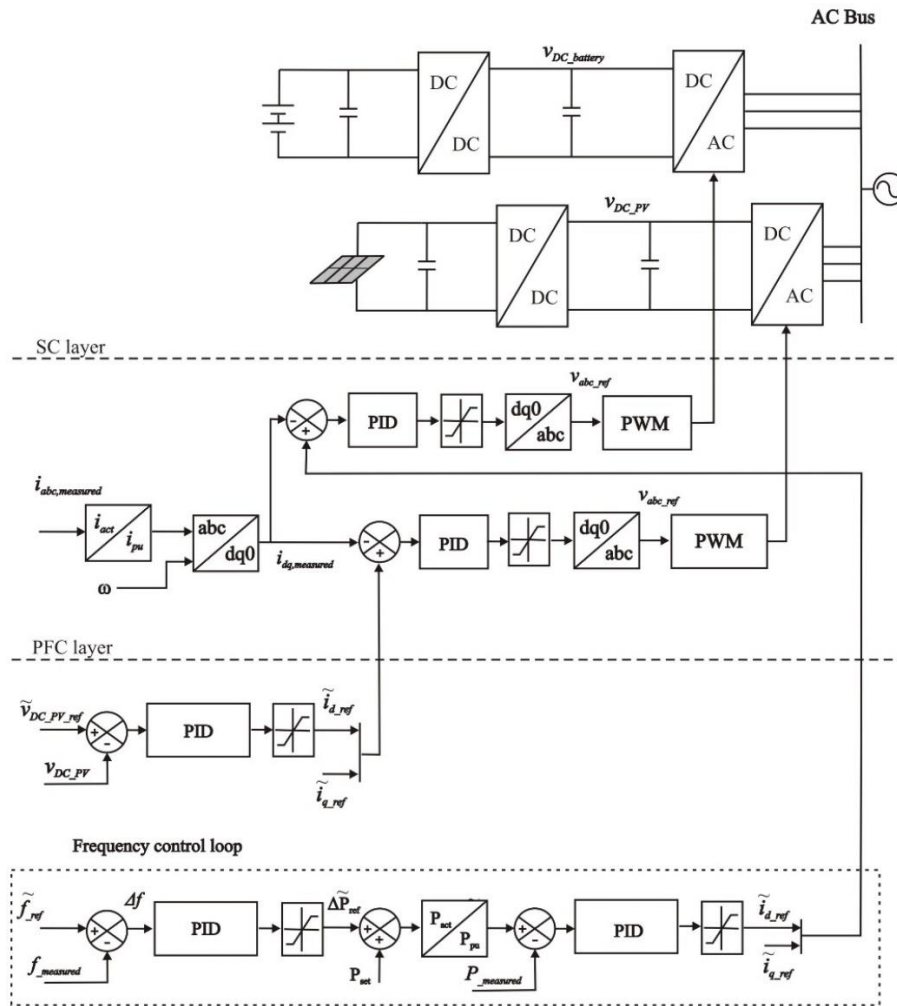


Figure 6. PFC and SC of the PV-AG

4. Results

This section provides the results which analyze the performance of the proposed control strategies of the PV-AG. Energy management capability of the proposed PV-AG architecture is evaluated for the load demand variation illustrated in Figure 7 and the GTI variation shown in Figure 3.

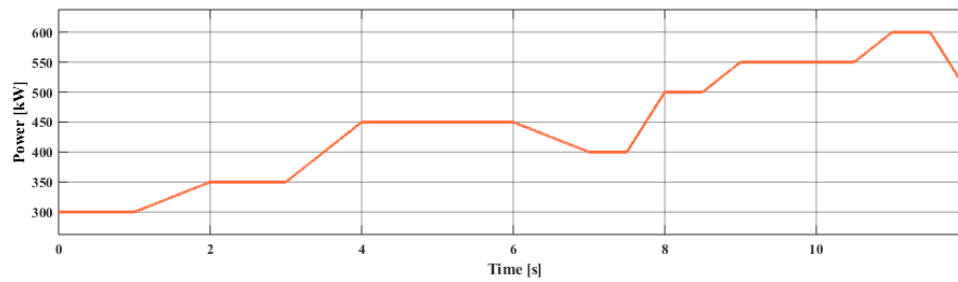


Figure 7. The variation of the load demand

4.1. Sharing the load demand among the multi-sources in the PV-AG

The share of the load demand among each power source is illustrated in Figure 8.

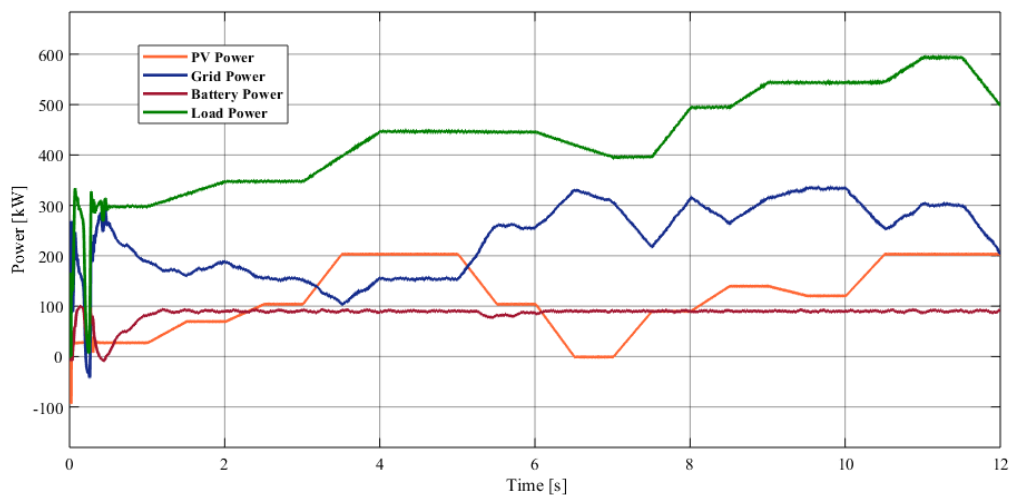


Figure 8. Load demand sharing among the multi-sources of the PV-AG

The PV based AG system starts supplying the load at 0 s. The system undergoes very short period of transients and becomes stable approximately within 0.35 s. It can be seen that the PV array injects the maximum available power to meet the load demand as it follows the GTI variation. The battery and the grid have shared the remaining power of the load demand. The battery has taken more or less constant power share through out the operation as it works as a long-term energy compensator while maintaining the frequency stability within the system. The grid has taken care of all fast dynamics of the load demand.

The variation of the frequency of the AC bus is shown in Figure 9. In this simulation, the grid frequency was configured as 50 Hz. As long as the PV-AG supplies the load demand, it keeps the system frequency within 49.8 Hz to 50.2 Hz with the proposed control strategies.

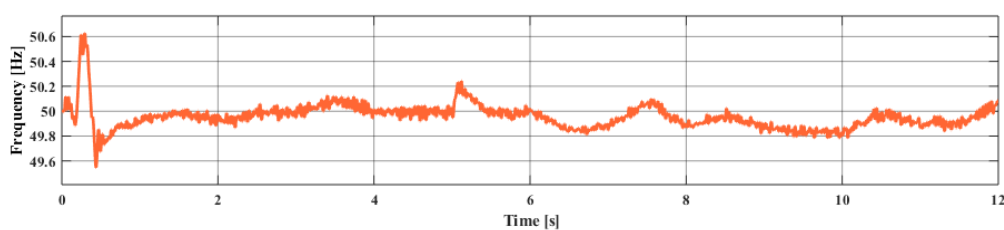


Figure 9. Frequency variation of the grid

5. Conclusion

When increasing the penetration of PV energy, power system stability issues will be arising due to the intermittent nature of PV generation. The PV based active generator (PV-AG) is an effective solution for increasing the penetration of PV produced energy without affecting the stability of the power grid. In this work, an AC coupled architecture for a PV-AG in which all the power sources (PV array, lead-acid battery) are connected to a common AC bus through the separate DC-DC and DC-AC conversion stages is developed and implemented as a simulation model. With the developed innovative control strategies for the proposed PV-AG architecture, the load demand of the AG system can be properly managed and controlled while maintaining the frequency stability within the system. With this proposed architecture, short-term load variations are handled by the utility grid. Therefore, as a future work, the system could be improved to handle the short-term fluctuations by the system itself with the lesser involvement from the grid.

6. Acknowledgement

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