Contribution of Three-Phase Photovoltaic Grid-Connected Power Systems to Grid Frequency Regulation

Hamed Taheri, Ouassima Akhrif, and Aime Francis Okou

Abstract— **This paper presents a modified control strategy of three-phase Photovoltaic grid-connected generation system. The PV system is connected to an electrical network where it contributes to frequency as well as terminal and DC-link voltage regulations. The innovation of the proposed control strategy is that it allows the Photovoltaic system to have a similar reaction to alterations in grid frequency as that of a traditional generator. The efficacy of the method is assessed by simulation in MATLAB/SIMULINK.**

Index Terms— **Photovoltaic; Frequency; Power System; Inverter; Control; MATLAB.**

I. Introduction

Recently the generation of electrical power from renewable energy resources is growing rapidly after the announcement of government targets for reduction of greenhouse gases. During this century, there remain huge concerns among scientific communities of rising the earth's temperature due to increase in greenhouse gases. Looking further ahead, if the U.S. is to achieve the ambitious target of an 83% reduction in carbon emissions by 2050 this will require that renewable sources contribute at least 50% of the energy used for electricity generation [1]. Photovoltaic (PV) power generation system, as one of the most significant renewable energy resources is increasingly being used over the past few years since it is clean, pollution free and inexhaustible. Generally, a PV system is categorized into stand-alone and grid-connected types. In the global market, a large proportion of PV power is supplied by the grid-connected type because of its investment saving, high efficiency, convenient topology and simple control strategy [2, 3].

The outputs of PV and wind generators are enormously affected by weather condition. In fact, they have some severe impacts on power system operations. Frequent voltage regulations in distribution lines may cause voltage fluctuations and flickers which accordingly damage the voltage-regulating devices. They also may cause frequency deviations of power systems which depreciate high PV-power penetration. The more distributed generation grows, the more storage capacity is required. It infers that the spinning reserve for frequency control also decreases. This becomes even more critical as sunlight or wind is not always present or predictable. If renewable energies are to provide a huge amount of grid power, they will need to maintain some power in reserve. Energy storage units seem to be viable options to provide frequency responsiveness and dispatch ability to PV or wind systems. Battery energy storage, superconducting magnetic energy storage, flywheel energy storage, electric double-layer capacitor may supplement spinning reserve. In fact, they will store power during normal operation and inject power during a fault, to maintain the proper grid frequency and voltage. These storage facilities will be newly deployed as distributed energy storage (DES). However, they require extra costs [4, 5, 6].

In conventional power system, each synchronous generator (SG) could response to the frequency deviation because of the kinetic energy stored in rotor. However, PV generators have no direct relation between power and frequency. Moreover, the typical concept of maximum power point tracking (MPPT) conflicts with frequency regulation. Therefore, one of the main challenges of current Photovoltaic grid-connected systems is that they are not well designed to participate in the frequency regulation of the electrical grid when it is affected by large disturbances. The more PV systems penetrate the electrical grid, the more their robustness and frequency regulation capabilities deteriorate. Therefore the frequency may change abruptly due to disturbances in generation or loads. Therefore, new trends of grid-connected PV systems require being equipped with a smart control unit which is able to contribute not only to voltage stability but to frequency regulation as well [7, 8].

In this paper a new two-level control strategy is presented. The first level controller is associated to the Photovoltaic source side which produces the duty cycle for a DC-DC boost converter. A frequency control loop (droop control) is added to this controller to contribute to power management of the Photovoltaic system. In fact, this frequency regulator plays a key role in determining the amount of power injected by PV arrays into the grid to constantly maintain its frequency stable. The second level controller is associated to the grid side and is applied to a three-phase DC-AC inverter connected to the grid to produce its switching signals. This controller is a multi-

Hamed Taheri is with the Electrical Engineering Department, École de technologie supérieure (ETS), Montréal (Québec), Canada (e-mail: hamed.taheri-ledari.1@ens.etsmtl.ca).

Ouassima Akhrif is with the Electrical Engineering Department, École de technologie supérieure (ETS), Montréal (Québec), Canada (e-mail: Ouassima.Akhrif@etsmtl.ca).

Aime Francis Okou is with the Department of Electrical and Computer Engineering, Royal Military College of Canada, Kingston (Ontario), Canada (e-mail: Aime.Okou@rmc.ca).

input multi-output controller (MIMO) which regulates on one hand the terminal voltage and on the other hand stabilizes the DC-link voltage. Our objective is mainly for the three-phase Photovoltaic grid-connected generation system to emulate exactly the reaction of a conventional generator to large disturbances in the grid. The proposed control strategy is tested on a model with one Photovoltaic grid connected system (representing a PV farm) and one conventional generator (a thermal unit in this case) using the SimPowerSystems blockset of Simulink in MATLAB. The results are compared to the traditional PV system control with no frequency regulation.

The paper is organized as follows: Section 2 describes briefly the dynamic model of the Photovoltaic system. Section 3 presents all the components of the proposed control strategy while section 4 presents simulation results on a test model and comparison to a more traditional scheme without frequency regulating consideration.

II. MODELING OF THE PV MODULE

The output power of a PV array depends on several environmental parameters, such as the solar irradiance and the temperature of the cell. The PV array is modeled by joining several cell models in a module and various module models in an array. Among the various modeling methods of PV modules, the two diode model is known to be as the most accurate [9, 10]. Since the main objective of this paper is to assess a novel control approach for participation of PV generators in frequency regulation of grid, the more traditional and simpler cell model extracted from the single diode model is used (see Eq. 1, [11]). The error obtained when comparing with real PV panel is neglected.

$$I = I_{pv} - I_D = I_{pv} - I_{sat}[e^{\frac{V+IR_s}{V_t}} - 1] \qquad (1)$$

where I_{pv} is the current generated by incidence of light; I_D is the diode current; I_{sat} is the reverse saturation current; V_t is The thermal voltage; Rs is the series resistance; V is the terminal voltage and I is the output current. The detailed traditional Matlab/Simulink model of PV is presented in Fig. 1. The inputs of the model are the irradiance and temperature. This model can accurately emulate the dynamical behavior of a PV in electrical circuits with additional benefits that irradiance and temperature can be time varying during simulation. This model will be connected to the power system network using power electronic converters for frequency regulation of grid as well as voltage regulation purposes as shown in Fig.2.

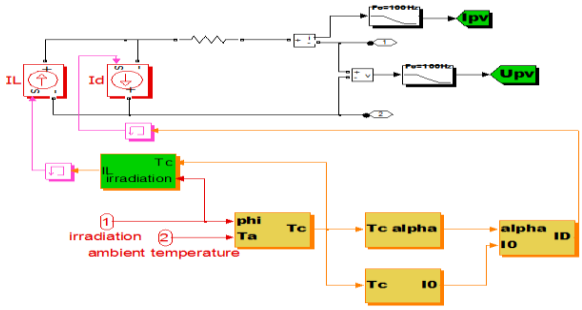

Fig. 1. Model of Photovoltaic module

III. PROPOSED CONTROLLER

In this section, a modified controller of Photovoltaic power generation system is presented. The designed controller should be able to support the grid frequency as well as the grid terminal voltage during common incidents occurring in the power system.

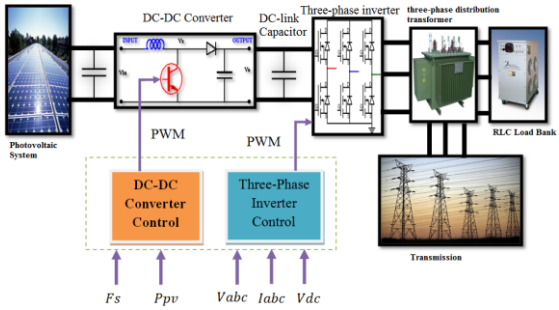

Fig. 2. Three-Phase PV grid-connected power network

The controller includes two levels; the first one as depicted in section A is related to the control of DC-DC converter and generates the appropriate duty cycle for frequency regulation as well as PV power control. . The second level of control is a multi-input multi-output controller (MIMO) based on the well-known PI technique. This control block generates the signals for switches of three-phase DC-AC inverter in order to support regulation of terminal voltage as well as DC-link voltage. Its detailed control algorithm is described in section B.

A. FREQUENCY REGULATION

In order to provide the appropriate frequency response, Photovoltaic generators must be able to increase or decrease their outputs with system frequency variations. Therefore for power increment capability, PV generators must be de-loaded to provide a margin. If PV generators do not operate at maximum power point (MPP), the de-loading can be provided using an appropriate control technique. The proposed control block of DC-DC boost converter is shown in figure 3 where P_{ref} is the de-loaded power of PV, F_s is the grid frequency and P_{pv} is the measured PV power. The output of the block is the duty cycle for the converter. Similar to droop control of conventional power plants [6], with the grid-tied PV

generators if the grid frequency is changed due to any common grid contingency, the frequency loop generates the required power increment and adds it to the de-loaded power to compensate for grid frequency deviation. Therefore by equipping the controller with an online frequency loop, PV generator is constantly capable of providing the necessary amount of active power in order to maintain its satisfactory response. As a result, PV source could react such as conventional power plants in frequency maintenance of grid.

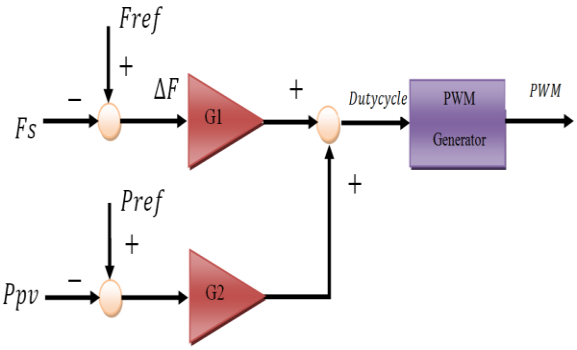

Fig. 3. The DC-DC converter control

B. VOLTAGE REGULATION

The voltage often alters with variations of reactive loads in distribution power systems. For the three-phase photovoltaic grid-connected generation system, it is very useful to have a control strategy for insuring voltage stability and saving investment by reducing reactive power losses. To date, several researches have been conducted to develop voltage control of DC-AC inverter. While our contribution concerns mainly frequency regulation, for voltage stability we are using a conventional dual-loop feedback control strategy which has been found encouraging [12, 13]. The typical topology used in this work is sketched schematically in figure 4. The external loop is a voltage loop that controls AC terminal voltage and DC-link voltages, while the internal loop is a grid-connected current loop. Once the error between the reference DC-link voltage (Vdc_{ref}) and the actual DC-link voltage (Vdc) is adjusted through PI control, it will be set as the current reference value (Id_{ref}) of the d-axis component of the grid-connected current. Once the error between the reference AC-terminal voltage (V_{ref}) and the actual AC voltage (V_i) is adjusted through PI control, it will be set as the current reference value (Iq_{ref}) of the q-axis component of the grid-connected current. With the abc/dqo conversion, the three-phase grid-connected currents i_a, i_b, i_c can be converted to I_d and I_q which will be compared to I_{dref} and Iq_{ref} and adjusted with PI control. With the dqo/abc conversion, the output will be regarded as modulation wave to be compared with triangular wave in PWM wave generator.

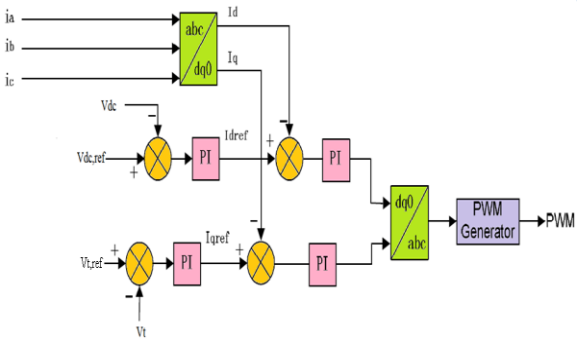

Fig. 4. The three-phase DC-AC inverter control

IV. SIMULATION AND RESULTS

To evaluate the performance of the proposed control strategy, a power system consisting of a 175W, grid-tied PV generator supplying an 1800V, 60Hz power grid with active and reactive power as depicted in figure 5 is deployed. The steam turbine is applied to the system at time equal 2 second. To examine the frequency regulating aptitude of the proposed control scheme, the requisite active power is altered by abrupt load increment of 66.5W at time t equal 6 second at bus B1. Before load disturbance, the PV generator was generating active power of 100W.

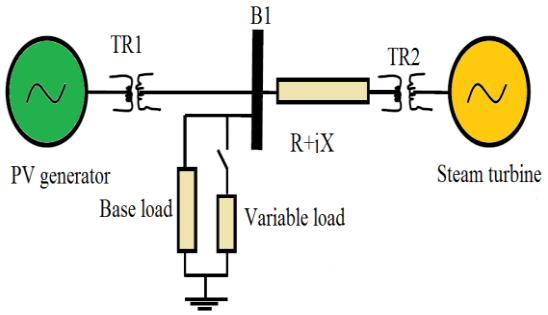

Fig. 5. Overall power system network model

Figure 6 illustrates the output active power during a sudden load increment for two cases: one with the proposed two-level control strategy and the other with the same controller but for which we removed the frequency regulation loop. Figures 6, 7 and 8 indicate that the controller without frequency regulation is insensitive to frequency variations due to load disturbance. In contrast, the controller equipped with frequency loop tries to contribute to the grid's frequency regulation by generating the required active power.

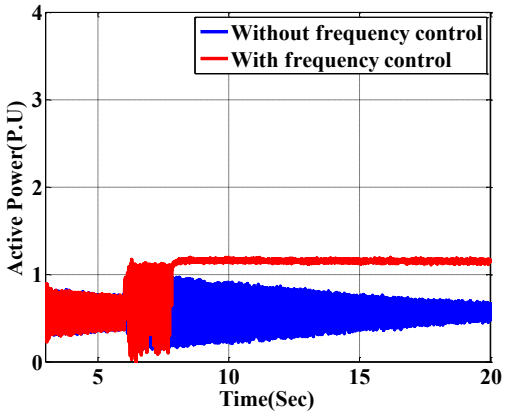

Fig. 6. The output active power during a sudden load increment

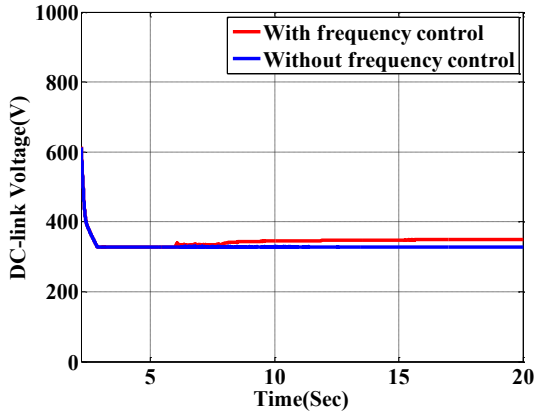

Fig. 9. The DC-link voltage during load increment

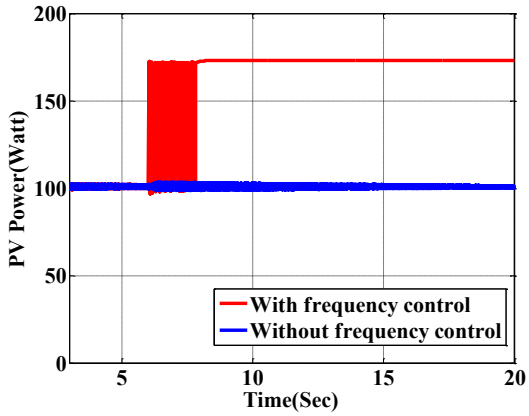

Fig. 7. PV power during sudden load increment

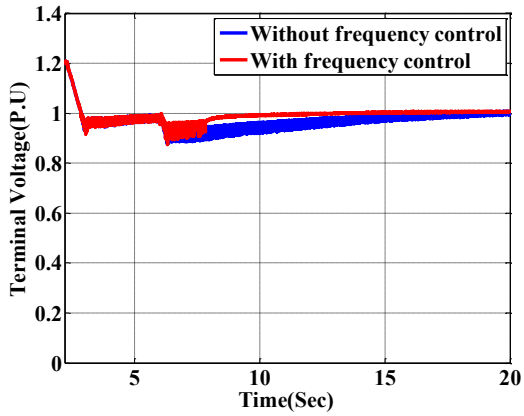

Fig. 10. The terminal voltage during sudden load increment

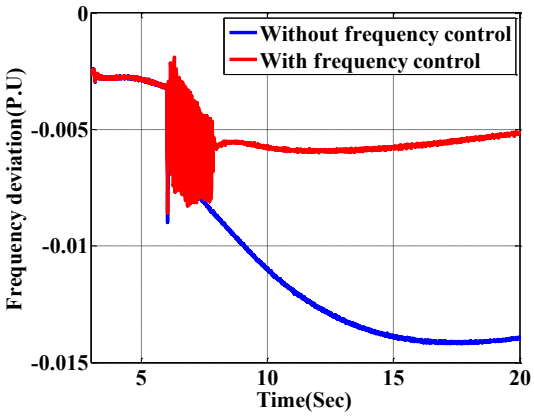

Fig. 8. Frequency deviation during sudden load increment

In addition to frequency control which is performed by DC-DC converter, voltage regulations namely DC-link and terminal voltage control are well insured by DC-AC inverter as illustrated in figures 9 and 10 respectively.

V. Conclusion

This paper proposes a modified controller in that a grid-tied PV system contributes not only to voltage but also to frequency regulation of the system. The paper verifies that with the presented control mechanism, PV generators are capable of reacting in the same manner as traditional generators under large disturbances in the electrical network. The control unit of the system essentially consists of two sections of DC-DC converter and three-phase DC-AC inverter controls. The PV side converter is responsible of supporting frequency and power management, while the grid side inverter maintains both DC-link and terminal voltage regulations. Future work will mainly concentrate using advanced nonlinear, multi-input multi-output (MIMO) control techniques to develop a smart controller insuring simultaneously voltage and frequency regulation for hybrid systems with PV generation connected to electrical grid in parallel with other types of renewable energy sources and energy storage units.

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