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Transition between Stand-Alone and Grid Connected Solar PV Microgrids

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Abstract. In this study, a solar photovoltaic microgrid, to sustainable energy and system efficiency, is being studied under different configurations. Solar modules, energy storage devices (battery), power electronics converters are used to validate the desired results. The study of stand-alone to grid-connected systems will be analyzed and tuned for a stable system performance. In the stand-alone tuning, the voltage and the frequency are the key driving parameters to be controlled and evaluated for proper operation of the microgrid. Also, the grid connected configuration will be studied and then both systems will be compiled together using a switching mechanism. The aim is developing a control system that enables the transition between the two configurations. The microgrid is simulated and tested using MATLAB/Simulink platform. The objective is to create a smooth transition of system with control mechanisms in different modes of the microgrid

Key words. Microgrid, solar energy, battery storage, stand-alone, grid-connected.

1. Introduction

Among other renewable sources in the field of power generation, solar photovoltaic (PV) power generation is becoming an important component in green energy production. Their scalability feature allows solar PV based microgrids to act as a convenient distributed form of energy to supply the power to small communities as well as larger areas of consumers these days. These systems can work autonomously alone as stand-alone mode or by combining with the main power grid, they can work into grid-connected operation for bi-directional power flow. Due to weather conditions, the PV generation is intermittent and considered as an irregular power source, which is one of the major drawbacks. In order to deal with this issue, maximum power point tracking (MPPT), when integrated with the PV system, allows to extract maximum power. Furthermore, using the storage can maintain stability of the overall system under dynamic behavior and varying conditions [1], [2].

Power electronics components, such as AC-DC, DC-AC and DC-DC converters, are required in solar PV microgrids with energy storage systems to interact with the electrical power system. DC-DC converters are mainly used for energy generation side such as for boosting up the solar PV power using MPPT or controlling bidirectional power flow in the battery control system. On the other hand, AC-DC controllers or inverters can be used in grid connected systems and feed the AC loads by controlling the frequency and the voltage [3]-[5].

Microgrids require crucial control methods to fulfil the stability and the dynamic behavior of the power flow throughout the system. A typical microgrid usually accomplishes many tasks such as maintaining power balancing while being connected to the main grid and switching autonomously to the stand-alone mode. While those modes are in effect, dynamic balance and steady state power flow throughout the system is very important to balance out the whole system with smooth outputs and parameters. While staying in the grid-connected mode, the operation is often easy as the main grid is present to identify any deficit or surplus in power. While the challenge mainly lies on the stand-alone mode as the entire system relies on the distributed energy sources. The solar PV energy depends vastly on environmental factors hence maintaining stable power flow is a major drawback. Autonomous switching from the grid-connected mode to the stand-alone mode can create several distortions in signals and hence in most cases manual switching is preferred with some minor control changes to operate in a smooth order. In this study, a microgrid system is proposed for a balanced load, and an autonomous switching, with minimal loss or distortions, is developed using a mechanism for better performance [6].

The objective of this paper is to run both systems in a simulated environment and discuss the drawbacks. Future work may include the study of both configuration in real-time environment and the assessment of the drawbacks in order to minimize them.

2. Controller for PV System

A typical PV system converts immense and clean solar energy into electricity. As the DC is the form of output from the PV, usually a DC-DC converter is affiliated at the output side of the PV module. A boost DC-DC circuit is implemented as this DC-DC converter is unidirectional [7]. By this, not only the voltage is stepped down or up, but also the maximum power point tracking (MPPT) procedure is permitted [8].

PV units consists of multiple PV arrays and the single PV array can be modelled by using the current-voltage equation as follows [9]

$$I_{PV} = N_p I_r - N_p I_0 \left[exp\left(\frac{q(V_{PV} + N_s R_s I_{PV})}{N_s nkT} \right) - 1 \right] - \frac{V_{PV} + \frac{N_s}{N_p} R_s I_{PV}}{\frac{N_s}{N_p} R_p} \quad (1)$$

where, q is the electronic charge, k is the Boltzmann constant, n is the ideality factor, T is the cell temperature, I_r is the irradiance current, I_0 is the diode saturation current, R_s is the series resistance, R_p is the shunt resistance, $N_s = N_m \times N_c$ (N_m is the number of panels connected in series in the array and N_c is the number of cells connected in series in the panel), N_p is the number of strings in parallel, I_{PV} and V_{PV} are the current and voltage outputs of the PV array, respectively.

The irradiance current is related to the solar irradiance, G, and the cell temperature, T, and expressed by

$$I_r = I_{r,STC} \left(\frac{G}{G_{STC}} \right) [+\alpha_T(-T_{STC})] \quad (2)$$

where, $I_{r,\,STC}$ is the irradiance current under STC (Standard Test Conditions), GSTC is the irradiance under STC, α_T is the temperature coefficient of the short-circuit current.

The power of the PV array is expressed by

$$P_{PV} = I_{PV} \times V_{PV} \quad (3)$$

The DC-DC boost converter is assumed ideal and the voltages are related by the expression

$$V_{dc} = V_{PV} \left(\frac{1}{1-d_1} \right) \quad (4)$$

where, d_1 is the duty cycle to operate the IGBT s_1.

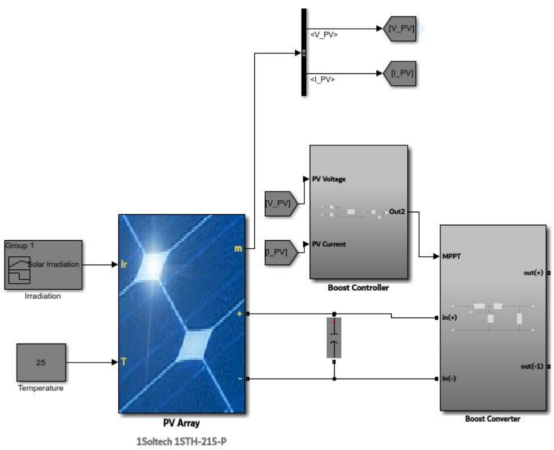
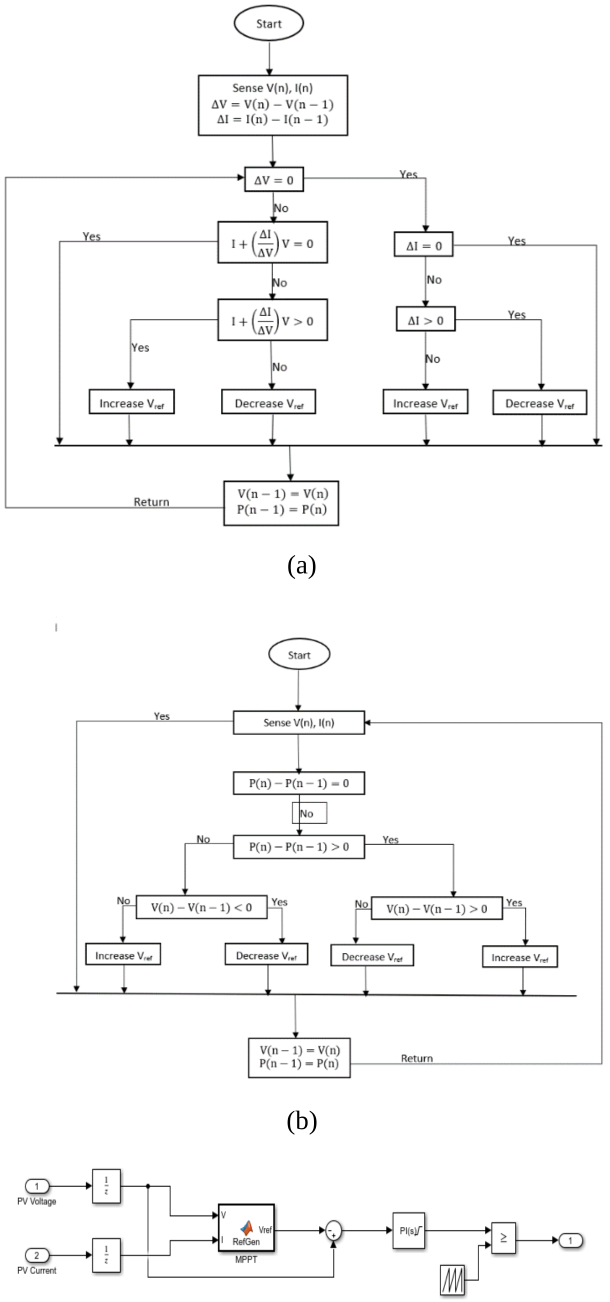


Fig. 1. DC-DC boost converter control with MPPT

As seen in Fig. 1, the duty cycle is carried out by the control structure for maximum power extraction. Both of the following MPPT algorithms, P&O and Incremental conductance methods have been tested and the results have been somewhere like each other hence P&O method was selected for final outputs due to ease of its understanding and as it is commonly used [10]. The MPPT provides the reference voltage for the PV voltage control loop. In this work, it is assumed that extracting the maximum power, available from the sunlight, by the PV array shall be always operating in all conditions.



(a)

(b)

(c)

Fig. 2. (a) Perturb and observe method (P&O) (b) Incremental conductance method (IC) (c) MPPT control system.

3. Energy Storage Control

In the microgrid, to stabilize and smoothen the fluctuations and disturbances created by the renewable energy sources and also while changing the mode of the load, using the energy storage system (ESS) is a feasible option [11]-[13]. To jointly provide a DC supply, the ESS is usually used to attach the RES on the DC side. The battery (e.g. Li-ion, supercapacitor, lead-acid, etc.) and DC-DC converter (e.g. buck, boost, buck-boost, etc.) are the two main components of the ESS. In Fig. 3, the aspects of the ESS with a bidirectional DC-DC buck-boost converter are given where the battery is modeled as a DC power source linked to the LV port.

The SOC of the battery is a key parameter reflecting the battery performance especially about the remaining capacity of the battery [6]. The SOC is calculated as

$$SOC(t) = 100\% \left(1 - \frac{\int_0^t I_{d(t)} dt}{Q_0}\right) \tag{5}$$

In practice, the battery works in constant current control while in islanded mode it works as constant voltage control driver. Also, it is ideal to set the range of SOC between 10% ~90% to avoid over battery discharge or charge.

4. Microgrid Configuration

A. Stand-alone Configuration

In this configuration, the MPPT controller is used at the primary level. The irradiance is tested up to 1000 unit and using the MPPT algorithm, a maximum output voltage of 376 V can be produced while being boosted by the boost converter. The temperature is being kept constant and the output of the boost converter is the DC input for our standalone inverter.

Firstly, from the load side, line to line voltages V_{abc} are sensed. Then, using the abc-dq transformation block the voltages are converted into the dq components. The amount of d-axis voltage is set according to the required reference to perform the desired control mechanism of voltages and the q-axis reference voltage is set to zero. Then, the dq components of the voltage are compared with reference voltages to detect the error. The error is then fed to a voltage controller based on proportional-integral (PI) control scheme through which, the parameters for the reference currents are detected. Then, the line-to-line currents are sensed and transformed similarly into dq components. These dq components of the current are compared with the reference currents which then again provides another error and similarly it is fed to a current controller [14]. Using the reverse transformation, references V_{abcref} which are used to generate the PWM signals for each IGBT in the inverter. This controller is designed to work in a balanced load configuration. The configuration is depicted in Fig. 4.

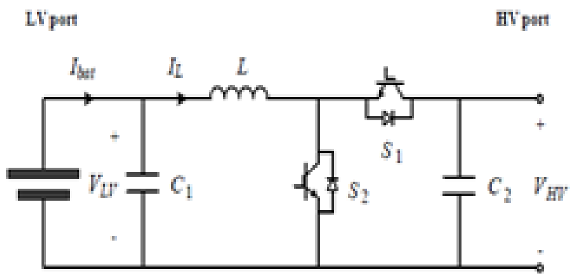


Fig. 3. Modeling of the ESS

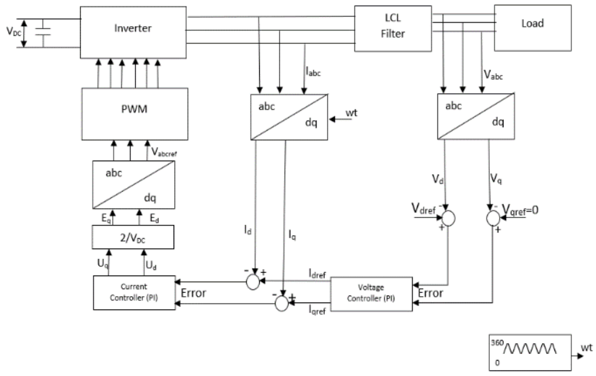


Fig. 4. Inverter control for stand-alone microgrid.

B. Grid-connected Configuration

The structure of the controller is almost similar to the stand-alone mode but there are few modifications in this section for better performance in the presence of the grid. It has been observed that in the stand-alone system the MPPT generates PWM signal for the boost controller but here the MPPT is used to generate the reference voltage for the DC bus voltage controller. Another difference is that a feed forward term is provided to the output of the DC bus voltage controller. The control of this configuration is depicted in Fig. 5.

While testing both modes of microgrids, the inverter side parameters and filter designs are set by

$$f_{res} = \frac{F_{sw}}{10} \tag{6}$$

where f_{res} is the resonant frequency and f_{sw} is the switching frequency of our system.

Using the typical power relation, the base parameters of the inverter are determined as follows

$$C = \frac{0.05*s}{(v^2*2*pi*f)} \tag{7}$$

$$L = \frac{1}{w_{sw}*\frac{I_g(sw)}{V_i(sw)}(1-\frac{w_{sw}^2}{w_{res}^2})} \tag{8}$$

$$L_{max} = \frac{0.2\times V_{grid}}{2\times\pi\times 50\times I} \tag{9}$$

where, C is the filter capacitance is the filter inductance and L_{max} is the maximum amount of inductance with respect to the grid voltage and all these parameters are used on the load end for islanded mode or when the grid is present, the use for a filter capacitance is not very essential.

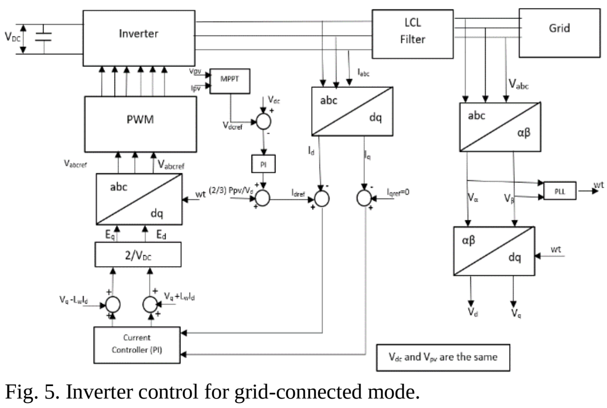


Fig. 5. Inverter control for grid-connected mode.

C. *Switching Transitions Mechanism*

The switching mechanism is based on a conditional algorithm that seamless makes the transition from the grid-connected to the stand-alone mode of the microgrid as shown in Fig. 6.
The conditional algorithm is developed mostly on the grid side portion. A switching mechanism is used to disconnect or connect the grid from the microgrid which can allow to operate in stand-alone mode when necessary. In this study, a switch has been used at the grid side with a state mode, called as the grid status. When the switch is ON, the inverting signals are computed by the grid mode inverter control, which generated four sets of PWM signals. On the other side, when the grid status if zero, the switching block executed four sets of different PWM signals from stand-alone or islanded mode of inverter control. It is depicted in Fig. 7.

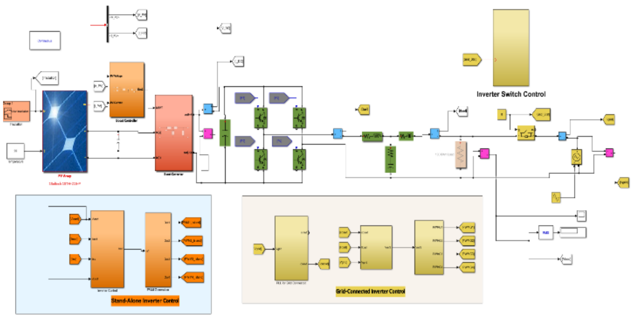


Fig. 6. Grid connected and stand-alone micrgrid

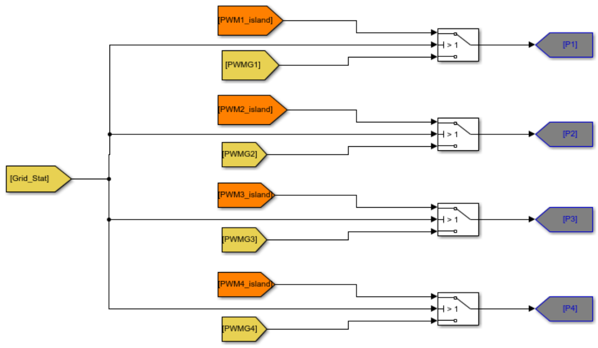


Fig. 7. Switching control for grid-connected to stand-alone mode.

5. Simulation Results

In the stand-alone mode configuration, a purely resistive load of 100 Ω has been tested at the load end with the grid status of the switching module being kept at zero (to keep the grid disconnected). It is observed at Fig. 8 that the solar PV irradiation profile and the output voltages behave accordingly but while observing the Fig. 11, at 0.4s when the grid is being activated, there is a disruption in the PV voltage, but the current seems to be performing in an adequate manner. Also, during the stand-alone configuration, the voltage and current profiles, shown in Fig. 9, where the load is seemed to work under decent parameters but while the grid gets activated, the load is still maintaining its course after a little disruption during switching period. The variation of the solar PV does not impact much on the current and voltage profiles while the gird gets introduced as we can see at figure Fig. 12.

While observing the power profiles at Fig. 10 and 13, the switching does create a little anomalous behavior but stabilizes as the execution period passes throughout the whole simulation time and does get better when the grid is being introduced.

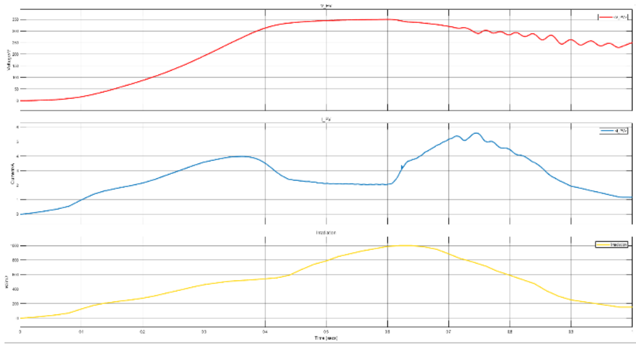


Fig. 8. PV voltage, PV current and solar irradiation for Stand-alone configuration.

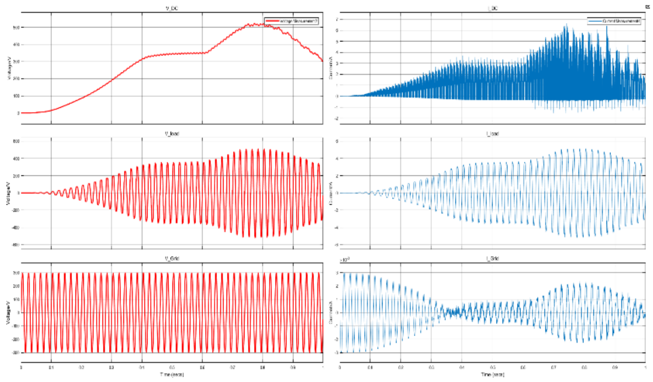


Fig. 9. Voltages (DC, load, grid) and currents (DC, load, grid) for stand-alone configuration.

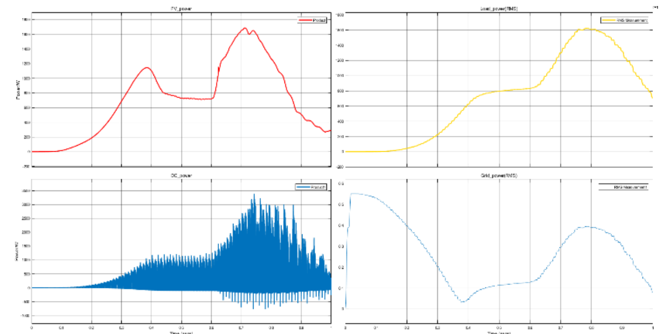


Fig. 10. Power (PV, DC, load, grid) for Stand-alone configuration.

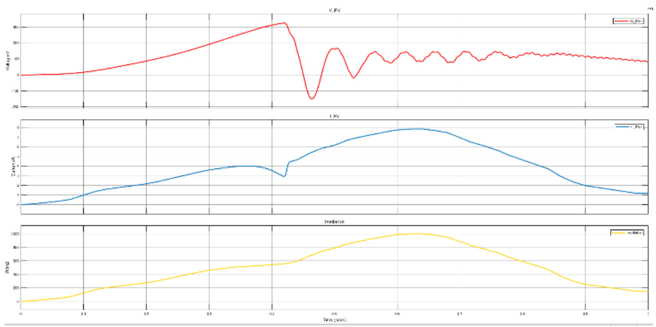


Fig. 11. Voltages (DC, Load, Grid) and currents (DC, load, grid) (Transition to grid-connected configuration at 0.4s).

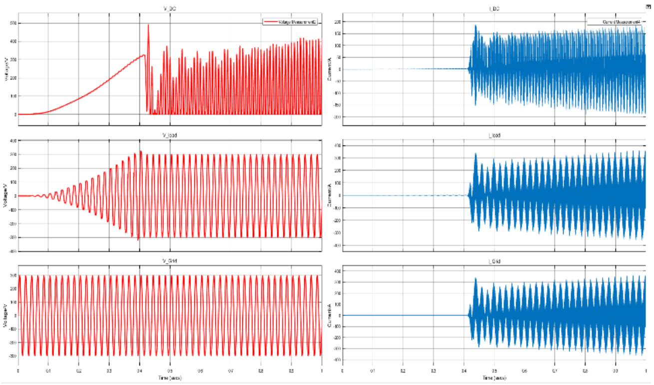


Fig. 12. Voltages (DC, Load, Grid) and Currents (DC, Load, Grid) (Transition to grid-connected configuration at 0.4s)

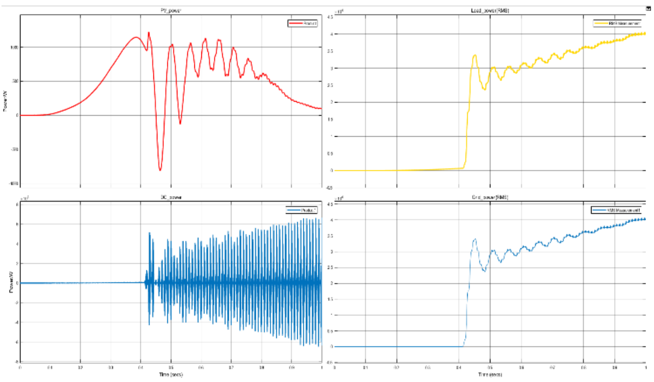


Fig. 13. Power (PV, DC, load, grid) (Transition to grid-connected configuration at 0.4s)

4. Conclusion

A solar PV microgrid has been implemented in MATLAB/Simulink environment. It can be operating in stand-alone and grid-connected modes. Control systems and a switching mechanism have been developed to operate the PV microgrid in both modes. The tests have been done for balanced load, but the controllers can be improvised to operate under unbalanced loads. Future works may include the control system of the battery storage to evaluate the storage capability in both configurations. Furthermore, real-time and physical implementation will be investigated in future work.

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