Power Management analysis and Coordination Control of Standalone Photovoltaic (PV) System

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Abstract: This paper mainly emphasizes and explains about the two possible topological configurations which plays a vital role in designing and ensuring the coordination control of a standalone PV system. The development of hybrid power generation systems is of major concern because of its controlling complexity. By comparing the topologies of series and parallel connected PV systems, one can assess the importance of parallel connected PV system over the series connected. The state diagram which is proposed in this paper helps in understanding the concept of coordination control between the generating source and load. Simulation results illustrates about the power flow aspect and operational characteristics of parallel connected PV system.

Keywords – Coordination control, Hybrid systems, Power Management, Standalone PV system, State diagram.

I. Introduction

Renewable energy sources have been attaining the maximum concern of interest today to compensate the conventional power generation through fossil fuels. Usually, the hybrid power generation systems will facilitate an environmental friendly alternative solution for standalone based applications [12]. The major confronting issue is to develop an eco-friendly, reliable, cost effective renewable energy based hybrid system to mitigate the problem of load management. Moreover, solar energy based energy harvesting can be served as a highest power density source, which makes it as a preferable option for power flow operations [6]. Section I gives a brief introduction about hybrid systems. Section II explains about the system architecture of hybrid system. Section III presents the component wise description. Section IV illustrates the power management state diagram. Section V shows the simulation results of topology considered and Section VI summarizes the conclusion part followed by references.

II. System Architecture

The system structure is designed such that, it inherently helps in combining the functions of both maximum power point tracking (MPPT) and battery charge regulation without compromising its overall efficiency. The most popular architectures of standalone PV systems proposed and implemented so far are mainly based on series connection of MPPT and battery between PV source and load as depicted in Fig: 1(a), as explained in [1],[2],[3],[4],[5],[15],[16],[17], series-parallel combination of MPPT and battery shown in Fig: 1 (b) as described in [6],[7],[8],[9]. But such systems have few demerits like high power loss, reduction in overall system efficiency, involves high cost in hardware realization with increased complexity. Also, there is necessity of adding battery charge regulation circuitry to the series connected MPPT circuits [15].Thus, in order to overcome such aforementioned drawbacks, it is highly necessary to choose a topology which specifically facilitates multiple functions.

![Fig: 1(a) Series connected MPPT structure; Fig: 1(b) Series-Parallel combination of MPPT structure](image-url)
The authors in [10] have already proposed and implemented a parallel connected MPPT system as shown in Fig: 2, which exactly resembles a hybrid system since it consists of an energy source namely PV and an energy storage unit called battery as mentioned in [11], [13]. It is basically a simple architecture that can be employed as a step-up/down converter, MPPT and battery bank charger respectively. The most important feature of this parallel structure is that, it needs only a single converter structure to realize the operation of both MPPT and battery charge/discharge regulation, thus reducing the energy processing stages.

![Parallel connected Bi-directional DC-DC converter Topology](image)

**III. Component Wise Description**

The following are the components simulated in MATLAB/SIMULINK environment.

1. **PV array**: The photovoltaic array has been modeled and simulated in MATLAB/SIMULINK. A single-Diode model of PV array [14] has been considered for the sake of simplicity reasons as shown in Fig: 3.

![PV Array Single-Diode model](image)

The basic equation of the PV array can be represented as:

\[
i_1 = I_{ph} - I_0 \left[ \exp \left( \frac{v_1 + R_i i_i}{v_i a} \right) - 1 \right] - \frac{v_1 + R_i i_i}{R_p}
\]

where \(i_1\) and \(v_1\) are the output current and voltage of the PV module.

2. **Bi-directional DC-DC converter topology**: Bi-directional converter shown in Fig: 2 can be considered as a multifunctional converter [10] which is having capability of working as MPPT controller, battery bank charger, step-up/down converter, battery regulator. The bi-directional converter operates as a buck converter in the battery charging mode and as a boost converter when the battery must supply the load or when the load requirement is higher than the energy generated. The power circuit operation are as given below in Fig: 4 (a), (b) and Fig: 5 (c), (d).
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Fig: 4 (a), (b) Buck mode of Operation (S₁=ON, S₂=OFF)

Fig: 5 (c), (d) Boost mode of Operation (S₁=OFF, S₂=ON)

State-Space representation of Bi-directional DC-DC converter topology:
There are two modes of operation namely: Buck mode and Boost mode. So, we obtain ‘4’ state equations as follows:

Buck operation mode:
ON state:
\[
\begin{bmatrix}
\frac{dl_c}{dt} \\
\frac{dv_c}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & 1/L \\
-1/C & -1/R_C C
\end{bmatrix} \begin{bmatrix}
i_L \\
i_f
\end{bmatrix} + \begin{bmatrix}
0 \\
-1/R_C C
\end{bmatrix} v_b
\]

OFF state:
\[
\begin{bmatrix}
\frac{dl_c}{dt} \\
\frac{dv_c}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & 0 \\
0 & -1/R_C C
\end{bmatrix} \begin{bmatrix}
i_L \\
i_f
\end{bmatrix} + \begin{bmatrix}
0 \\
1/L
\end{bmatrix} v_b
\]

Boost operation mode:
ON state:
\[
\begin{bmatrix}
\frac{dl_c}{dt} \\
\frac{dv_c}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & 0 \\
-1/R_C C & -1/R_C C
\end{bmatrix} \begin{bmatrix}
i_L \\
i_f
\end{bmatrix} + \begin{bmatrix}
0 \\
-1/R_C C
\end{bmatrix} v_b
\]
OFF state:

\[
\begin{bmatrix}
\frac{di_c}{dt} \\
\frac{dv_c}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & \frac{-1}{L} \\
\frac{1}{C} & \frac{-1}{R_i C}
\end{bmatrix} \begin{bmatrix}
i_L \\
v_c
\end{bmatrix} + \begin{bmatrix}
0 \\
\frac{1}{C}
\end{bmatrix} i_f + \begin{bmatrix}
0 \\
\frac{-1}{R_i C}
\end{bmatrix} v_b
\]

IV. Power Management Strategies

The power flow model which is shown in Fig: 6 describes about the different modes of transition (or) power flow from PV source to the load and converter. The converter includes the MPPT algorithm and battery. Incremental Conductance (InC) MPPT algorithm which is described in [18] is used to operate the PV array at maximum power point (MPP) respectively.

Fig: 6 State diagram (or) power flow diagram.

Modes of transition: From Fig: 6, the power flow conditions are explained as described below:

- **Mode 1 (M1):** operation without load \((I_L=0; I_f=I_c)\)
  When load is not connected, the battery is charged with the PV module current \((I_f=I_c)\).

- **Mode 2 (M2):** operation with load current less than MPP current \((I_L<\text{Impp})\)
  If the load current value \((I_L)\) is lower than the PV module MPP current \((\text{Impp})\), part of the energy generated by the PV module is used to supply the load, and another part is used to charge the battery.

- **Mode 3 (M3):** operation with load current equal to MPP current \((I_L=\text{Impp})\)
  In this condition, the power processed by the dc-dc converter is zero. The efficiency of the power system can be considered close to 100% because the maximum power of the PV module is transferred to the load without any power processing by dc-dc converter.

- **Mode 4 (M4):** operation with load current higher than MPP current \((I_L>\text{Impp})\)
  All the energy generated by the PV module is supplied to the load. The additional power that is necessary to complement the load power must be supplied by dc-dc converter. The battery is discharged in this condition.

- **Mode 5 (M5):** operation without solar irradiation \((I_f=0)\)

The dc-dc converter supplies the load during operation when there is no solar irradiation or under shading condition. The battery will be in discharging condition and the dc-dc converter operates as boost converter.

where

- \(I_f\) = photovoltaic current;  \(I_L\) = load current;  \(I_c\) = converter current;  \(\text{Impp}\) = Current at maximum power point.

V. Simulation Results

Simulation results of PV array with Bi-directional converter is as shown below:

(a) Only Buck mode of operation with load variation:

In buck mode of operation, \(I_{\text{Impp}} = I_f + I_L\)

where \(I_{\text{Impp}}\) = Current at MPP, \(I_f\) = Converter current, \(I_L\) = Load current.
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**Impulse plot in buck mode including load variation**

**Variation in Load current in buck mode of operation**

**Variation in converter current when load changes**
(b) Only Boost mode of operation with load variation:
In boost mode, $I_{mpp} + I_c = I_L$. 

![Graph showing $V_{mpp}$ in boost mode of operation](image1)

![Graph showing $I_{mpp}$ current in boost mode of operation](image2)

![Graph showing variation of Load current in boost mode of operation](image3)
(c) Both Buck and Boost modes of operation with load variation:

- **Vmpp in both buck and boost mode of operation**
- **Impp in both buck and boost mode of operation**
- **Variation in Load current in both mode of operation**
VI. Conclusion

This paper mainly explained about the importance of coordination control and power flow diagram of parallel connected PV array system. The simulation results show the variation of $V_{mp}$ and $I_{mp}$ at different modes of operation of the bi-directional DC-DC converter topology. There is a considerable reduction in the cost of circuit and model is simple to analyze. The state equations are also presented in this paper to understand the system behavior.

References