An Optimum Tuning Method for DC Bus Voltage Regulation in Double Stage Off-Grid PV Systems

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Abstract— **This paper presents an optimum control strategy to regulate DC bus voltage in Off-Grid PV systems. The topology of the Off-Grid PV systems chosen in this work is double- stage PV system. The DC bus voltage regulation is achieved by controlling a bidirectional DC-DC converter which is connected between PV and energy storage systems. Internally, the DC bus voltage regulation controller is composed from a current feedback controller which is cascaded with a voltage regulation system. Both controllers are conventional Proportional-Integral (PI) controllers. The PI control parameters for the inner current loop are determined by pole placement technique, whereas for the outer voltage regulation loop, the PI control parameters are determined by using symmetrical optimum (SO) method. From the simulation result it is showed that the stability of the DC bus voltage highly depends on the tuning parameter well known as symmetrical distance of the SO. The greater the symmetrical distance, the relative stability of the system will increase, but on the other hand the speed of response to disturbances will be slower.**

Keywords— Off-Grid PV system, Bidirectional DC-DC converter, symmetrical optimum, pole placement technique

I. INTRODUCTION

Nowadays, the harvesting of green energy is commonly found worldwide. The main reason behind this fact is the increasing of the global energy consumption and the depletion of fossil energy which happen in every year. One of the renewable energy sources that is widely used is solar - based energy sources [1-2]. By using PV panels, the solar energy is converted into electrical energy which then injected to the grid (on-grid PV system) or used directly (off -grid PV systems).

Although the on-grid PV system currently is the common topology used for the installation [3-4], but in certain cases, the off-grid PV system is the only option that can be used to extract solar energy [5-6]. Several reasons for using off-grid PV systems include: the unavailability of a power grid where the PV system is installed (for example inland locations, lake water areas or plantations) or it could also because the PV system is designed for an independent electrical system, for example to forming a DC microgrid systems [7-8].

Recently many commercial off-grid PV power extraction modules could be found easily at the market with power capacity ranges from hundreds of watts to tens of kilowatts. However, these PV power extraction modules are generally designed as battery chargers so that the output voltage of the system generally has a voltage level same with the specifications of the battery [9]. If the load that is installed requires a more higher voltage level, then the user needs an additional converter to be installed on the battery output.

The main objective of this work is to design a DC bus voltage regulation control system for an off-grid PV system. The PV system topology used in this study is a double stage topology which is commonly used for grid-connected renewable power generation systems [10]. By using this double stage PV system topology, the system output voltage used to drive the load is not limited by the battery system but can be adjusted according to the load voltage requirement. In addition, the other advantages of this double stage off- grid PV system is, the system can be easily improved to a DC Microgrid system.

In this study, the inner current feedback control system of the bidirectional converter is realized by using a unified control scheme proposed by Zhang et.al [11], so current feedback control only uses a single control loop that the realization of the software will be easy.

Although the bidirectional DC-DC converter voltage regulation system discussed in this paper is focused for the off-grid PV applications, the design methodology proposed in this paper generally could also be used for designing microgrid DC systems.

The remainder of the paper is organized as follows. Section 2 describes the general model of the off-grid photovoltaic model used in this study. In Section 3, the design of the bidirectional controller, both inner current control and DC bus voltage regulation control will be discussed, next, Section 4 present the simulation results. Finally, the conclusions are drawn at Section 5.

II. OFF GRID PHOTOVOLTAIC SYSTEM MODEL

Fig. 1 shows the general topology of double stages -based off-grid PV power generation system investigated in this study. The system technically composed from two main independent converter control system: (1) a PV controller system and (2) a DC bus voltage regulation control system.

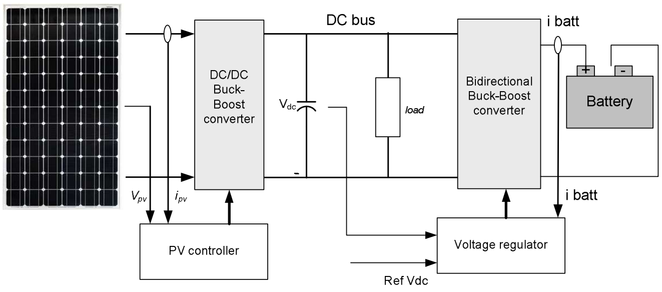


Fig.1. Double stages -based off-grid PV power generation system

A. PV Control Model

The PV controller generally designed to extract available maximum power from the PV module. The probably most popular PV power extraction algorithm is the perturb and observe (P&O) algorithm. The P&O algorithm is widely used for reasons of simplicity and speed of the maximum power tracking. Fig.2 below shows the standard P&O algorithm implemented in this research.

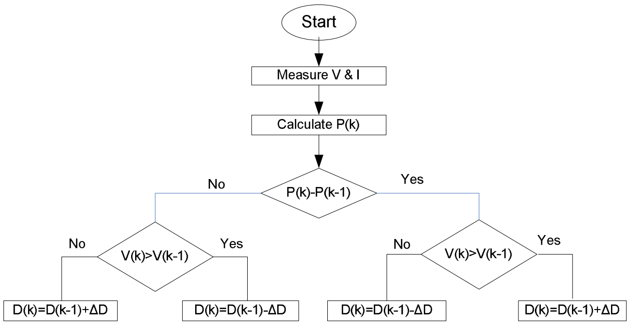


Fig.2. Standard P&O based-MPPT algorithm

As shown at Fig.2, the P&O algorithm is basically used to adjust the duty cycle of the PWM signal at the converter input so that the output impedance of the converter will be equal to the internal impedance of the PV system (impedance matching). The maximum PV power in this case will occur when the output impedance of the converter is equal to the impedance of the PV.

Conceptually, every PV power control system which is operated by using the MPPT method can be viewed as a constant power generation system, where the converter output voltage of the PV control system will depend on the characteristics of the load connected to the converter output. If the MPPT converter system is connected to the DC bus with a certain voltage level, then the output voltage from the MPPT converter will be the same with the DC bus voltage. This basic principle could be shown at Fig. 3.

B. Voltage Regulator

The main role of the voltage regulator system in the proposed system is to regulate the DC bus voltage at an expected voltage reference value. Fig. 4 shows the block diagram of the regulator control system used in this study. As shown at Fig. 4, this DC bus voltage regulator is built using a cascade control system: the inner loop current controller and the outer loop DC bus voltage controller. The current control used in this study is unified current control where the direction and magnitude of the current flow is dependent on battery and DC bus voltage ratio.

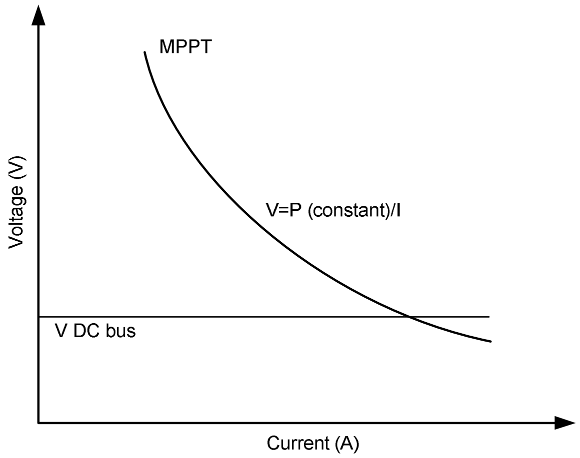


Fig.3. Characteristic of a constant power generation of the MPPT

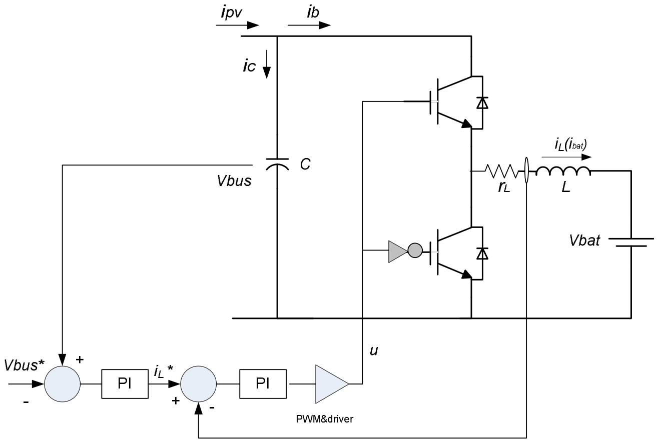


Fig.4. DC bus voltage regulator

From Fig. 4, then the dynamics of averaged inductor current and DC bus voltage respectively could be written as shown in Eq (1) and (2)

$$\frac{di_L}{dt} = -\frac{r_L}{L} i_L + \frac{V_{DC\,bus}}{L} u - \frac{1}{L} v_{batt} \tag{1}$$

$$\frac{dV_{DCbus}}{dt} = -\frac{1}{C} i_b + \frac{1}{C} i_{pv} \tag{2}$$

where i_L, v_{DCbus}, v_{batt}, i_b, i_{pv} and u respectively are the inductor current, DC bus voltage, battery voltage, boost converter current, PV current the average control signal, respectively. While C, L and r_L are the DC bus capacitance, inductance, and parasitic resistance of the inductor, respectively.

From eq. (1) It is clear that the equilibrium state of the inductor current can be represented as shown in eq. (3) below.

$$i_L = \frac{v_{DCbus}u - v_{batt}}{r_L} \tag{3}$$

As seen from eq. (2), if control output-u is greater than the ratio of the v_{batt}/v_{DCbus} then the inductor current will be positive (charging mode), and vice versa, if u is less than v_{batt}/v_{DCbus} then the inductor current will be positive (discharging mode). This relationship more clearly represented in Fig. 5

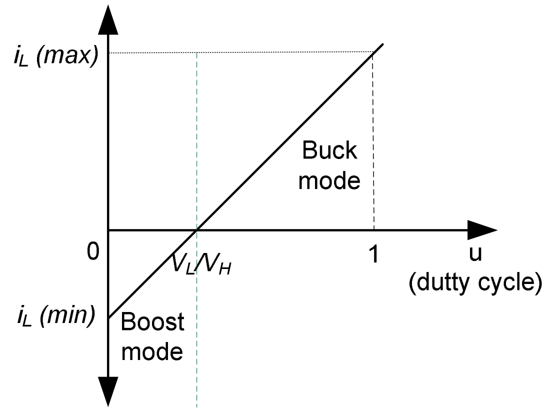


Fig. 5. Steady state relation between inductor current and control output

III. BIDIRECTIONAL DC-DC CONVERTER DESIGN

A. Current Controller

In the form of the Laplace variable model, eq. (1) basically could be represented as shown in eq. (4).

$$H(s) = \frac{I(s)}{u_c(s)} = \frac{K}{Ts+1} \tag{4}$$

Where in this case

$$K = \frac{v_{DC\,bus}}{r_L} \tag{5}$$

$$T = \frac{L}{r_L} \tag{6}$$

By using pole placement technique with the expected feedback time constant T_{cl} sec, the proportional and integral gains could be calculated respectively as shown at eq. (7) and (8).

$$K_p = \frac{T}{T_{cl}K} \tag{7}$$

$$K_i = \frac{K_p}{T_i} \tag{8}$$

Fig. 6 below shows the feedback feedforward-based current control which is implemented in this work. In this case u_{ff} is the ratio of v_{batt}/v_{Dcbus}.

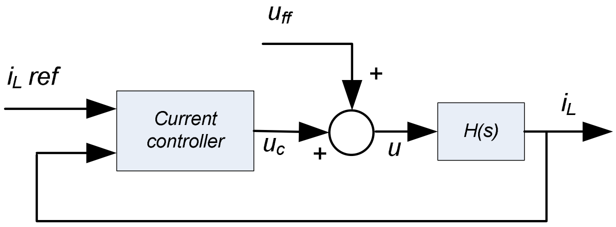


Fig.6. block diagram of the feedback-feedforward based current controller

By refer to Fig.7, the inductor current feedback transfer function could now simplify as shown at eq. (9) below.

$$H_{icl}(s) = \frac{I_L(s)}{I_L^*(s)} = \frac{1}{T_{cl}s+1} \tag{9}$$

B. Voltage regulator

By assuming the boost converter is lossless and the the parasitic inductance is relatively small then the boost converter input power will be the same with the output power, or can be written as shown at (10):

$$v_{DC\,bus} i_b = v_{batt} i_L \tag{10}$$

So that current i_b can be solved:

$$i_b(s) = \frac{v_{batt}}{v_{DC\,bus}} i_L \tag{11}$$

By substituting (11) into (2), we get

$$\frac{dV_{DCbus}}{dt} = -\frac{v_{batt}}{C}\frac{1}{v_{DC\,bus}} i_L + \frac{1}{C} i_{pv} \tag{12}$$

It can be seen from equation (12) that the DC bus voltage dynamics has a nonlinear equation. By linearizing in the region of the working point, eq. (12) can be simplified to (13) bellow.

$$\frac{dV_{DCbus}}{dt} = -\frac{v_{batt}}{Cv_{DC\,bus*}} i_L + \frac{1}{C} i_{pv} \tag{13}$$

Or it can be written in the form of the transfer function

$$\frac{V_{DCbus}(s)}{i_L(s)} = -\frac{v_{batt}}{sCv_{DC\,bus*}} \tag{14}$$

By considering (9), then equation (14) can be rewritten in standard form bellow.

$$\frac{V_{DCbus}(s)}{i_{L*}(s)} = -\frac{K}{Ts}\frac{1}{(T_{cl}s+1)} \tag{15}$$

Where in this case $K = v_{batt}$ and $T = Cv_{DC\,bus}\,*$

Based on the optimum symmetrical control system, the magnitude of K_p and T_i could be calculated by using (16) and (17). The reader is urged to refer [12] and [13] for the detailed explanation of the optimum symmetrical tuning method.

$$K_P = \frac{T}{aK.T_{cl}} \tag{16}$$

$$T_i = a^2 T_{cl} \tag{17}$$

IV. SIMULATION RESULTS

For speeding up the simulation execution time, in this study the MPPT power extraction system was emulated as a constant power generation system. Fig. 7 shows the simulation block diagram of the investigated Off-grid PV system. For this simulation purposes, the model parameters used in this work are shown in Table 1.

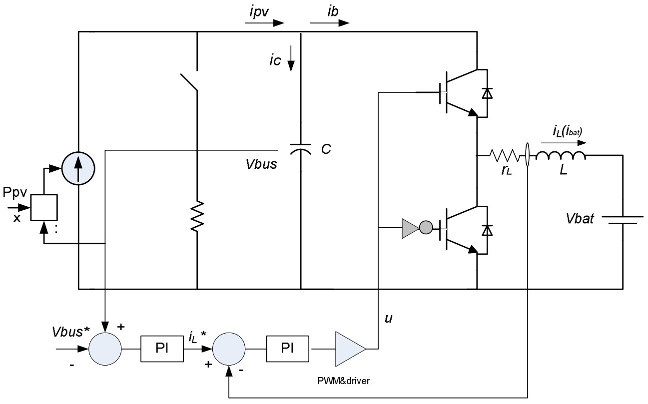


Fig.7. Simulation block diagram

Based on the parameters in Table 1, the current feedback control parameters can be represented as shown in Table 2. While Table 3 shows the DC bus regulation control parameter values for several symmetrical distance (a) investigated in this study.

Table 1. System Parameters

Parameter	Value
Vbatt (volt)	12
L (mH)	10
r (ohm)	0.05
C (uF)	1200
*VDc bus** (volt)	72

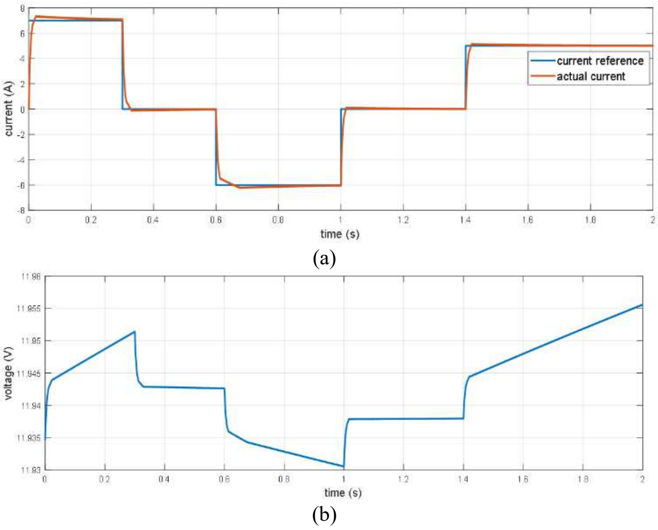
Table 2. Inner Control Parameters (T_{cl}=0.005)

	K_p	K_i
	0.0278	0.1389

Table 3. Outer control Parameters for several a

a	K_p	K_i
2	0.72	36
3	0.48	10.66
4	0.24	3

By using the control parameters in Table 2, the response of the current feedback system along with the battery output voltage could shown at Fig. 8



(a)

(b)

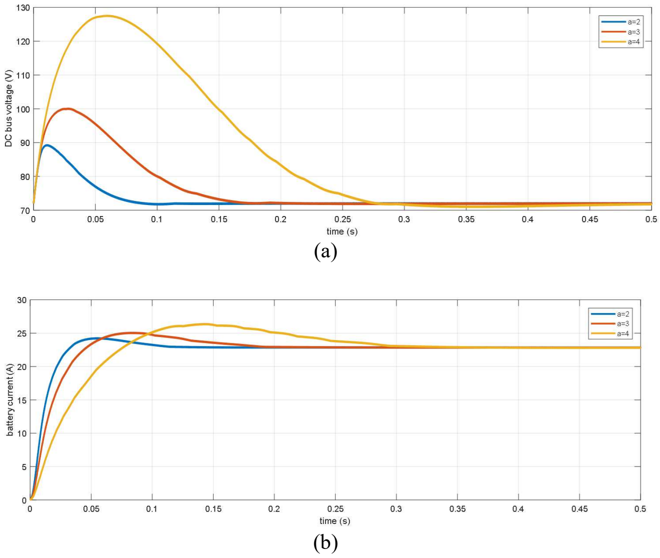
Fig.8. Simulation result of current controller: (a) response current to varying reference (b) battery voltage profile

Based on the simulation results in Fig. 8, it appears that the current control system designed is fit with the design specification. In this case, the current feedback response has a time constant of about 0.005 second.

To determine the effect of the symmetric distance (a) on the stability of the DC bus voltage regulator system, in this study, three different values of the symmetrical distance-a were tested. Fig. 9 (a) and 9 (b) respectively show the transient response of the DC voltage output and the inductor current (battery current) due to 300 watts power change in the PV system.

As shown in the two figures, the transient response of the DC bus voltage and battery current will be more sluggish for the bigger symmetrical distance-a. From the plots, it can be seen that for symmetrical distance-a =2, 3, 4 the settling time of response are 0.1 s, 0.17 s and 0.27 s, respectively. Based on the responses, it appears that, for the case of the power injection of the PV system, the symmetrical distance value of 2 will produce the fastest response without producing excessive overshoot.

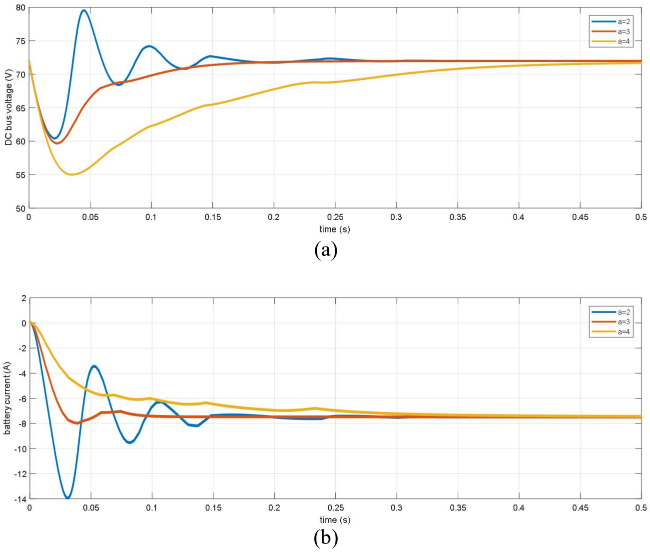
However, by using this small value of symmetrical distance, the system response will experience excessive oscillation when a disturbance is happened in the form of the change of resistive loads on the DC bus. Figure 10 (a) and (b) respectively show the output response of the DC bus voltage and the inductor current as the result of increasing the load by 60 ohms.



(a)

(b)

Fig. 9. System response to a 300-watt PV power change: (a) DC bus voltage (b) inductor (battery) current



(a)

(b)

Fig. 10. System response to a 60-Ohm load change: (a) DC bus voltage (b) inductor (battery) current

Based on those plots, it appears that the selected the symmetrical distance-a will greatly affects the stability of the DC bus voltage system. The smaller the symmetrical distance-a, the less stability of the system.

For the certain symmetrical distance, the oscillations that occur due to changes in loading are strongly influenced by the magnitude of the load, the greater the load change, the more oscillating the transient response of the system will be, it is as shown in Fig. 11.

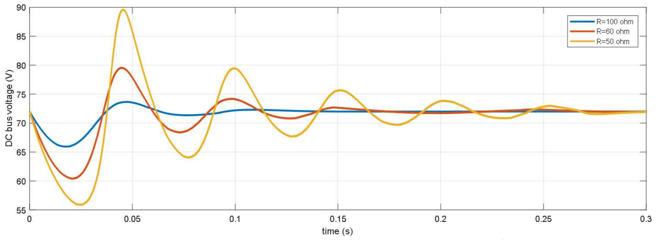


Fig. 11. DC bus voltage response to several load changes for a=2

Fig. 12 below shows the stability of the system power transfer between the PV power, load, and battery. In that simulation, the selected symmetrical distance-a is 3. For the power changes in Fig. 12, the DC bus voltage and inductor current responses are shown in Fig. 12 (a) and (b), respectively.

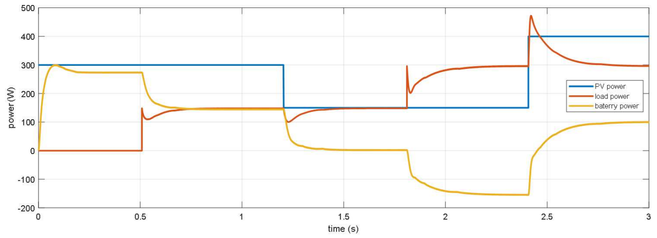
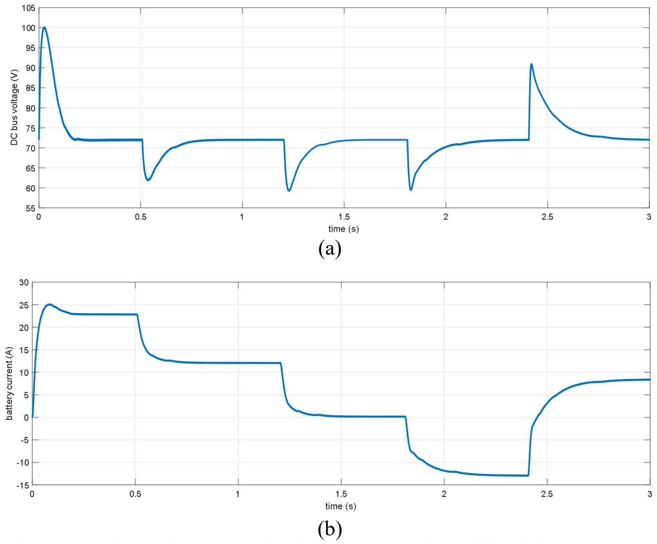


Fig. 12. Simulation result of power transfer between PV module, battery and load



(a)

(b)

Fig. 13. DC bus voltage (a) and inductor current (b) profile of Fig.12

V. CONCLUSION

The design and tuning rule of the bidirectional DC-DC converters for the double stage off-grid PV systems has been presented. In this work, the bidirectional converter is used as a bridge between PV system and the battery. Based on the simulation studies, the stability of the DC bus voltage highly dependent on the tuning parameter well known as symmetrical distance-a. The greater the symmetrical distance, the relative stability of the system will increase, but on the other hand the speed of response to disturbances will be slower.

ACKNOWLEDGMENT

The authors are grateful to Ministry of Research and Technology/National Research and Innovation Agency of Republic Indonesia for giving the full financial support for this works with PTUPT scheme (contract number 187-71/UN7.6.1/PP/2021)

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