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Modeling and Control Of Stand-Alone Photovoltaic System Based On Split-Source Inverter

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Abstract—Stand-alone photovoltaic (PV) systems have been used in remote electrification for decades due to their low infrastructure cost and clean energy source. However, their dependency on environmental conditions is a concerning issue. Therefore, backup energy storage is required along with a Maximum Power Point Tracking technique (MPPT). A dc-dc converter is usually used to implement MPPT before the inversion stage resulting in two-stage architecture. Meanwhile, single-stage conversion systems offer superior privileges in reducing the overall system’s complexity, size, and cost. Among the single-stage boosting topologies, Split-Source Inverter (SSI) has been offered as an option with some advantages over the commonly used Z-source Inverter (ZSI). This paper presents step-by-step design procedures for a stand-alone PV system, including SSI and a Battery Storage System (BSS). Moreover, the small-signal model of the proposed system is analyzed to develop a robust control with superior dynamic characteristics. Finally, the control scheme is analyzed and simulated using MATLAB/Simulink.

Keywords—Stand-alone PV systems, Single-stage, Split-source inverter (SSI).

I. INTRODUCTION

With the surge in demand for electrical energy, Renewable Energy sources (RES) are extensively used to limit the dependency on fossil fuels. Among all the RES, PV systems have emerged as a significant candidate to satisfy the continuous increase in demand. Although grid-connected Photovoltaic (PV) systems are widely used, stand-alone PV systems remain predominantly the solution for rural irrigation and remote electrification [1]. However, it has the following drawbacks

- The PV output power depends on environmental conditions. Therefore, the utilization of energy storage devices such as the battery is mandatory in stand-alone systems. Moreover, MPPT algorithms are required to harvest the maximum available power from the PV panels.
- The partial shading effect becomes severe when long PV strings (many modules connected in series) are used. Therefore, a shorter string with a lower number of series modules should be used, and hence, the output PV voltage is low [2]–[3].

A bidirectional dc-converter is usually connected between the energy storage system and the dc-bus in the isolated two-stage PV systems as shown in Fig. 1(a). Moreover, another dc-dc converter boosts the dc-voltage of the PV panels into a higher value before the inversion stage, which is commonly a voltage source inverter (VSI). Therefore, this architecture is composed of two dc-dc converters and one inverter stage. This results in lowering the overall efficiency of the conversion and increasing the system cost. Another robust architecture is proposed in [4], where only one bidirectional dc-dc boost converter is supplied by the battery and connected in parallel with the system for MPPT control as shown in Fig. 1(b). Since the dc-dc converter is connected in parallel, only a fraction of the power (supplied by the battery) flows through it, resulting in high efficiency. However, this architecture can only be used when the PV voltage is high enough to supply the required ac-loads after the inversion stage by VSI. Hence, a long string of PV modules should be used, and hence the partial shading effect will be severe. To avoid this issue, the work in [5] proposes a complete control configuration shown in Fig. 1(c) where a dc-dc converter is connected in series between PV and VSI. The battery is interfaced with the dc-link via bidirectional dc-dc converter. The loads active power is sustained by maintaining constant dc-link voltage via the battery. However, the two-stage architecture includes a dc-dc converter and VSI, which increase the overall size and weight of the system.

However, single-stage topologies have been developed to replace the two-stage architecture due to their superior features in terms of the overall system complexity, size, and weight. One of these topologies is ZSI, which is proposed in [6] with PV stand-alone system. However, the SSI offers potential superior features compared with ZSI, which can be summarized as the following [7]–[10]:

- It has continuous input current and dc-link voltage.
- It has lower voltage stresses across the switches for high voltage gains (i.e., for low input voltage sources) so it’s more suitable for PV applications.
- It requires lower passive components count.
- It uses the same switching states as the standard VSI, which uses a different state for shoot-through.

Moreover, compared with the two-stage architecture, no additional active switch is required in the SSI. However, the SSI suffers from the following demerits:

- Rapid commutations for the input diodes.
- Higher current stresses for the lower switches.

Fig. 1 and Table I summarizes the differences between all the discussed topologies. Based on the previous discussion, the SSI can be a significant potential candidate for PV applications.

SSI operation principles and modulation techniques are discussed in [7] Meanwhile, [8] discusses the application of SSI in grid-connected systems with constant voltage source. However, till now, the integration of SSI topology in PV systems has rarely been studied directly. Therefore, this paper focuses on this issue where it offers a detailed analysis, modeling, design procedure for a stand-alone PV system, and integrating the SSI topology with BES system. This paper is organized as follows: a quick review of principles and operation of the SSI in section II. The small-signal models for bidirectional dc-dc converter and dc-side of SSI are introduced in section III. Meanwhile, the detailed control strategy is indicated in section IV. Finally, step-by-step design procedures for a specific case study along with simulation results are explained in section V.
The power circuit of SSI, shown in Fig. 2, consists of the standard bridge of VSI incorporating an input inductor via three forward diodes $(D_1, D_2, D_3)$. The inductor is used to boost the dc-link voltage across the dc-link capacitor, $C$. The SSI uses the eight switching states $(S_0 - S_7)$ of the VSI. From which, the state $S_0 - S_6$ are used to charge the inductor. Meanwhile, only the zero state $S_7$ is used to discharge the inductor into the dc-link capacitor.

From the steady-state analysis and SSI equivalent circuits [7], the boosting factor $\beta$ which is the ratio between the dc-link voltage $(V_{inv})$ and the input supply voltage $(V_{pp})$ can be expressed as the following:

$$\beta = 1/(1 - (T_{ch}/T_s)) = 1/(1 - D)$$

where $T_{ch}$ is the inductive charging period within a complete switching period $T_s$ and $D$ the charging duty-cycle.

The inductor current ripples $\Delta I_L$ and the dc-link voltage ripples $\Delta V_{inv}$, that are essential for SSI design are given by [7]

$$\Delta I_L = DV_{pp}/(f_sL)$$

$$\Delta V_{inv} = (1 - D)I_L/(f_sC)$$

where $f_s$ is the switching frequency.

III. MODELING OF THE PROPOSED SYSTEM

The proposed system consists of SSI, which is supplied from a PV panel integrated with a battery. The battery is connected in across the dc-link capacitor $C_b$ via a bidirectional dc-dc converter. It should be noticed that the output voltage of the inverter is connected to loads through a filter. This section analyzes the SSI and the bidirectional dc-dc converter small-signal models required to design a robust control with an optimum dynamic behavior.

A. Small-Signal Model of the SSI

The SSI operation can be divided into two operating modes which are inductive charging and discharging modes. More details about each mode are as follows.

1) Inductive charging mode:

The equivalent circuit of this mode is shown in Fig. 3(a), in which the inverter bridge can be considered as a current source $i_{pn}$. Also, the battery with a bidirectional converter can be considered as a current source $i_y$. Therefore, the state-space equations can be obtained with the help of KVL and KCL as follows:

$$\begin{bmatrix} i_{ls} \\ v_{inp} \end{bmatrix} = \begin{bmatrix} \frac{R_s}{L_s} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_{ls} \\ v_{inp} \end{bmatrix} + \begin{bmatrix} 1/L_s & 0 \\ 0 & -1/C_s \end{bmatrix} \begin{bmatrix} v_{pp} \\ i_{pm} \end{bmatrix}$$

$$\dot{x} = A_1x + B_1u$$

where $v_{inp}$ is the dc-link voltage, $i_L$ the inductor current, and $v_{pp}$ the PV output voltage.

2) Inductive discharging mode:

The equivalent circuit can be sketched as shown in Fig. 3(b), and hence the state-space equations can be obtained as follows:

$$\begin{bmatrix} i_{ls} \\ v_{inp} \end{bmatrix} = \begin{bmatrix} \frac{R_s}{L_s} - \frac{1}{L_s} & 0 \\ 0 & \frac{1}{C_s} \end{bmatrix} \begin{bmatrix} i_{ls} \\ v_{inp} \end{bmatrix} + \begin{bmatrix} 1/L_s & 0 \\ 0 & -1/C_s \end{bmatrix} \begin{bmatrix} v_{pp} \\ i_{pm} \end{bmatrix}$$

$$\dot{x} = A_2x + B_2u$$
\[ i_x = [1 \ 0] \begin{bmatrix} i_{Ls} \\ v_{inv} \end{bmatrix} + [0 \ 0 \ 0] \begin{bmatrix} v_{pV} \\ i_{pn} \end{bmatrix} \ \text{y} = C_L x + D_2 u \]

The average state-space model can be obtained with the help of equations (4)-(7) as follows:

\[ \dot{x} = [A_1 d_s + A_2 (1 - d_s)]x + [B_1 d_s + B_2 (1 - d_s)]u \]

\[ y = [C_1 d_s + C_2 (1 - d_s)]x + [D_1 d_s + D_2 (1 - d_s)]u \]

\[ \begin{bmatrix} i_{Ls} \\ v_{inv} \end{bmatrix} = \begin{bmatrix} \frac{R_e}{L_s} & \frac{1 - d_s}{c} \\ \frac{1}{d_s} & \frac{1 - d_s}{c} \end{bmatrix} \begin{bmatrix} i_{Ls} \\ v_{inv} \end{bmatrix} + \begin{bmatrix} \frac{1}{d_s} & \frac{1}{c} \\ 0 & \frac{1}{c} \end{bmatrix} \begin{bmatrix} v_{pV} \\ i_{pn} \end{bmatrix} \]

\[ i_x = [1 - d_s \ 0] \begin{bmatrix} i_{Ls} \\ v_{inv} \end{bmatrix} + [0 \ 0 \ 0] \begin{bmatrix} v_{pV} \\ i_{pn} \end{bmatrix} \]

where \( d_s \) is the duty cycle of SSI.

Fig. 3. The equivalent circuit of the SSI dc side in the two modes (a) inductive charging mode. (b) inductive discharging mode.

Fig. 4. The equivalent circuit of dc-dc converter for both modes of operation. (a) mode (1). (b) mode (2).

The small-signal model can be obtained by using perturbation technique around the equilibrium point where each variable \( x(t) \) is replaced by its steady-state value \( X \) and a perturbed value \( \delta X \) and then neglecting the second-order terms. Based on that, the small-signal model can be written as:

\[ \dot{x} = A \dot{x} + B x \delta u + [(A_1 - A_2)X + (B_1 - B_2)U] \delta \]

\[ y = C x + D x \delta u + [(C_1 - C_2)X + (D_1 - D_2)U] \delta \]

\[ P_{ss} = P_1 d_s + P_2 (1 - d_s) \ \forall P \in \{A, B, C, D\} \]

\[ \frac{i_{Ls}}{v_{inv}} = \frac{-R_b}{L_s} \frac{1}{C_s} \frac{1 - D_s}{L_s} \frac{1}{C_s} \]

\[ i_x = [1 - D_s \ 0] \begin{bmatrix} i_{Ls} \\ v_{inv} \end{bmatrix} + [0 \ 0 \ 0] \begin{bmatrix} v_{pV} \\ i_{pn} \end{bmatrix} - I_s \frac{d_s}{L_s} \]

where \( D_s \) is the steady-state value of the duty-cycle at the equilibrium point. Taking Laplace Transform to equations (10)-(11) results in:

\[ i_{Ls}(s) = \frac{-(1 - D_s)}{R_b + L_s S} v_{inv}(s) + \frac{V_{inv}}{R_b + L_s S} \frac{d_s}{L_s} \frac{d_s}{L_s} \]

\[ v_{inv}(s) = \frac{R_b}{L_s S} i_{Ls}(s) - \frac{1}{L_s S} \frac{1}{C_s} \frac{1}{L_s S} \frac{1}{C_s} \]

\[ i_x(s) = (1 - D_s) i_{Ls}(s) - I_s \frac{d_s}{L_s} \]

B. Bidirectional Dc-Dc Converter Small-Signal Model

In a similar way to SSI, the operation of the bidirectional dc-dc converter can be divided into two modes which are

1) Mode (1):

The equivalent circuit in this mode can be described as shown in Fig. 4(a), where the inverter can be considered as a current source \( i_{pn} \). Also, the SSI can be considered as current source \( i_x \). Therefore, the resultant state-space equations are given as follows:

\[ \begin{bmatrix} i_{Lb} \\ v_{inv} \end{bmatrix} = \begin{bmatrix} -R_{lb} & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{Lb} \\ v_{inv} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} v_{cb} \\ i_{pn} \end{bmatrix} \]

(15)

2) Mode (2):

The equivalent circuit in this mode is shown in Fig. 4(b), and the state-space equations are given by

\[ \begin{bmatrix} i_{Lb} \\ v_{inv} \end{bmatrix} = \begin{bmatrix} -R_{lb} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_{Lb} \\ v_{inv} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} v_{cb} \\ i_{pn} \end{bmatrix} \]

(16)

where \( v_{cb} \) is the voltage across the capacitor \( C_b \). By using the same derivation shown in SSI, the small-signal model of the bidirectional dc-dc converter in s-domain can be obtained as the following:

\[ i_{Lb}(s) = \frac{-(1 - D_p)}{R_{lb} + L_b S} v_{inv}(s) + \frac{V_{inv}}{R_{lb} + L_b S} \frac{d_b}{L_b} \]

(17)

\[ v_{inv}(s) = \frac{(1 - D_p)}{C_b S} i_{Lb}(s) + \frac{L_b}{C_b S} d_b(s) - \frac{1}{C_b S} \frac{d_b}{L_b} \]

(18)

where \( d_b \) is the duty-cycle for the dc-dc converter.

IV. CONTROL SCHEME OF THE PROPOSED SYSTEM

The target of the control schemes, shown in Fig. 5, are to control the dc-link voltage, control the PV operating point to
harvest the maximum power available and keep the output dc voltage constant at the value required by the loads. The control scheme can be divided into three main controllers where each one has a certain purpose. In this section, each controller is discussed and analyzed.

A. Regulated modified SVM (RMSPWM)

Although modified space vector modulation (MSPWM) proposed in [7] ensures no input current and dc-link voltage ripples, it has only one manipulating parameter (which is the modulation index \( M \)) to control both the dc and ac side of the SSI. Therefore, the control of both dc and ac sides of the SSI are coupled. To decouple the ac and dc side control from each other, two independent manipulating variables must exist so that one of them is used to control the dc side and the other is used to control the ac side.

In regulated modified space vector modulation proposed by [8] and shown in Fig. 5, the minimum envelop of the per phase duty cycles \((d_a,d_b,d_c)\) are kept constant to \(1 - M_{dc}\) as shown in Fig. 6, instead of \((1 - M)\) used in (MSPWM). Therefore, the dc side can be controlled with \(M_{dc}\) while the ac side can be controlled with \(M\) and the boosting factor can be expressed by

\[
\beta = \frac{1}{(1 - D)} = \frac{1}{(1 - M_{dc})} \quad (19)
\]

Meanwhile, the peak output phase voltage \(V_{\phi_1}\) can obtained by

\[
\hat{V}_{\phi_1} = V_{inv} \frac{M_{ac}}{\sqrt{3}} \quad (20)
\]

It should be noticed that \(M_{dc}\) should be higher than \(M\) otherwise, high harmonic distortion will appear in the ac side due to overmodulation. To fulfill this condition, the dc-link voltage is expressed as follows:

\[
M_{ac(max)} = \frac{\sqrt{3}}{2} (\hat{V}_{\phi_1} + \Delta V) / V_{inv} \quad (21)
\]

\[
V_{INV} \geq E + \frac{\sqrt{3}}{2} (\hat{V}_{\phi_1} + \Delta V) \quad (22)
\]

where \(\Delta V\) is the maximum voltage drop across the LCL filter.

B. MPPT Controller

The PV operating point is controlled via SSI duty-cycle \(M_{dc}\) in such a way that PV voltage is kept at the value corresponding to \(v_{mp}\) which is PV voltage at the maximum available power for specific temperature and radiation, while any MPPT algorithm can be used to obtain \(v_{mp}\).

Cascaded controllers can control PV voltage, as shown in Fig. 5, where the PV voltage \(v_{pp}\) is compared with \(v_{pm}\) and the error is passed through PI to generate the current reference, which is compared to the actual SSI input current, and the error is inputted to another PI to generate SSI control from each side.

As discussed in [11], a piecewise model can be used for the PV module where the nonlinear characteristics of the diode can be divided in many linear regions. Each can be approximated by a constant voltage source \(V_F\) and resistance \(R_F\), as shown in Fig. 7(a). Therefore, Norton equivalent circuit for PV module in a specific region can be described as shown in Fig. 7(b) where:

\[
R_N = R_F + \frac{R_{sh}R_D}{R_{sh} + R_D} \quad (23)
\]

\[
V_F + \frac{R_D (I_{sh}R_D - V_F)}{R_{sh} + R_D} \quad (24)
\]

\[
I_N = \frac{R_{sh}}{R_N} \quad (25)
\]

\[
R_{sh} = \frac{R_L}{1 - M}\]

\[
V_{sh} = \frac{V_L}{1 - M}\]

\[
I_{sh} = -\frac{V_L}{R_L}\]

\[
R_{D} = \frac{R_{L}}{1 - M}
\]

\[
V_{D} = \frac{V_L}{1 - M}
\]

\[
I_{D} = -\frac{V_L}{R_L}
\]

Fig. 5. The full control scheme of the proposed system.
where \( I_{ph} \) is photo-generated current and \( R_s \) and \( R_{sh} \) are the series and shunt resistances for the PV module.

For MPPT, the equilibrium points for relatively high radiations are in a region where \( R_p \) is a small value. However, in low values of radiation, \( R_p \) increases rapidly until reaching infinite value (open circuit) as the radiation tends to zero. For PV array with \( N_s \) and \( N_p \) series and parallel strings, respectively, the equivalent Norton resistance is:

\[
R_{N,eq} = \frac{N_s}{N_p} R_N
\]  

(25)

With the help of Norton equivalent circuit of PV array, the following equation can be obtained using KCL.

\[
i_c = C_{pv} \frac{dv_{pv}}{dt} = I_{ph} - \frac{v_{pv}}{R_{N,eq}} - i_{ls}
\]  

(26)

Applying the perturbation technique around the equilibrium point results in:

\[
\tilde{i}_c = C_{pv} \frac{d\tilde{v}_{pv}}{dt} = -\frac{\tilde{v}_{pv}}{R_{N,eq}} - \tilde{i}_{ls}
\]  

(27)

Notice that \( I_{ph} \) is constant for specific radiation. Transforming equation (27) into S-domain results in:

\[
v_{pv}(s) = -\left(\frac{R_{N,eq}}{R_{N,eq} C_{pv} s + 1}\right) \cdot \tilde{i}_{ls}(s)
\]  

(28)

Based on equations (12) and (28), the following equation can be obtained:

\[
g_{il} = \frac{\tilde{i}_{ls}(s)}{d(s)} = \frac{V_{inv} (R_{N,eq} C_{pv} s + 1)}{R_{N,eq} L_s C_{pv} s^2 + (L + R_{N,eq} R_L C_{pv}) s + R_L + R_{N,eq}}
\]  

(29)

Notice that the perturbation of the dc-link voltage in equation (12) is considered null since it is supposed to be kept constant by the bidirectional converter.

Based on equation (29), the closed-loop block diagram on the input current controller can be described as shown in Fig. 8(a).

\[
\text{Fig. 7. linearized and Norton equivalent circuits of PV module in a certain region.}
\]

\[
\text{Fig. 6. The per-phase duty cycles of RMSPWM.}
\]

\[
\text{Fig. 8. block diagram of all the controllers.}
\]

Based on equation (28), the following transfer function can be obtained:

\[
g_{v_{pv}}(s) = \frac{v_{pv}(s)}{\tilde{i}_{ls}(s)} = -\frac{R_{N,eq}}{R_{N,eq} C_{pv} s + 1}
\]  

(30)

Therefore, the block diagram of the PV voltage controller can be sketched as shown in Fig. 8(b) with the help of the closed loop transfer function of input current controller \( G_{cil} \) given by:

\[
g_{cil} = \frac{g_{il} P_{il}}{1 + g_{il} P_{il}}
\]  

(31)

C. De-link voltage controller

The de-link voltage is controlled by the duty-cycle of the bidirectional converter \( d_b \). Similar to the MPPT controller, the block diagram of the controller should be obtained. First, \( i_{pn} \) the current source that represents the inverter is obtained from the input-output active power balance assuming lossless inverter bridge and filter as follows:

\[
p_{in} = v_{inv} i_{pn} = p_o = 3 v_{ph}^2 R_{load}
\]  

(32)

\[\text{since } v_{ph} = \frac{V_{p}}{\sqrt{2}} \Rightarrow \frac{M}{\sqrt{6}} v_{inv}
\]  

(33)

Then

\[
i_{pn} = \frac{M^2 v_{inv}}{2 R_{load}}
\]  

(34)

so that

\[
i_{pn}(s) = \frac{M^2 v_{inv}(s)}{2 R_{load}}
\]  

(35)

where \( M \) is the modulation index, kept constant, as will be discussed in the following subsection.

By substituting the equations (14), (17), and (35) into equation (18), the following equation can be obtained:

\[
v_{\text{inv}}(s) = G_1 v_{eb}(s) + G_2 d_b(s)
\]  

(36)

where:

\[
G_1 = \frac{1 - D_b}{C s (R_{lb} + L_b s) + (1 - D_b)^2 + A (R_{lb} + L_b s)}
\]  

(37)

\[
G_2 = \frac{(1 - D_b) V_{ref} - I_{lb} (R_{lb} + L_b s)}{C s (R_{lb} + L_b s) + (1 - D_b)^2 + A (R_{lb} + L_b s)}
\]  

(38)

\[
A = \frac{M^2}{2 R_{load}} \frac{I_{lb} (1 - D_b)}{V_{ref}}
\]  

(39)
where: $D_b$ is the steady-state value of the bidirectional converter duty and $V_{ref}$ is the reference dc-link voltage.

By applying KCL on the node connecting the capacitor $C_b$ with the battery, the following equation can be obtained:

$$\frac{c_b V_{cb}}{dt} = \frac{(V_B - v_{cb})}{R_b} - i_{lb}$$

(40)

where $V_B$ and $R_b$ are the battery voltage and internal resistance. By applying any perturbation technique to equation (40) and transforming it to S-domain, the resultant equation is:

$$v_{cb}(s) = -\frac{l_{lb}(s)}{C_b s + \frac{1}{R_b}}$$

(41)

Substituting from equation (17) into (41) results in:

$$v_{cb}(s) = G_3 \tilde{d}_b(s) + G_4 v_{inv}(s)$$

(42)

where:

$$G_3 = -\frac{V_{ref}}{(R_b + L_b s)(C_b s + \frac{1}{R_b}) + 1}$$

(43)

$$G_4 = -\frac{1}{(R_b + L_b s)(C_b s + \frac{1}{R_b}) + 1}$$

(44)

Substituting from equation (42) into (36) results in:

$$G_{v_{inv}} \frac{v_{inv}(s)}{\tilde{d}_b(s)} = G_4 G_3 + G_2 \frac{1}{1 - G_1 G_4}$$

(45)

From (45), the block diagram of the dc-link voltage controller can be described as shown in Fig. 8(c).

**D. Ac voltage control**

Since the dc-link voltage is controlled to a specific value $V_{ref}$, the closed-loop control for ac voltage is not mandatory. Therefore, an open-loop scheme is used to control the ac voltage by keeping the modulation index at the value given by

$$M = \sqrt{3} V_{\phi 1}/V_{ref}$$

(46)

where $V_{\phi 1}$ is the required peak phase voltage of the load.

V. DESIGN PROCEDURES AND SIMULATION RESULTS

This section discusses step-by-step design procedures for a case study, along with the simulation results using MATLAB/Simulink toolbox. The case study is a system with a maximum load demand ($P_n$) of 8 kW and a load profile with an average power during the day (i.e., 24 hours) equals 1 kW. Based on this, the system can be designed as follows:

A. PV and battery sizing

PV and battery size are determined as discussed in [12]. Based on the case study load, the PV array consists of 9 parallel strings where four series-connected modules form each string. The specifications of each module are shown in Table II. Also, 36 kWh, 72 V battery is used as energy storage.

B. Determining the dc-link voltage

Based on equation (22), the dc-link voltage $V_{inv}$ can be selected to be 680 V for input voltage $V_{mp} = N_s v_{mp} \left|_{(at1000W/m^225^\circ C)} \right.$, peak phase voltage $V_{\phi 1} = 220\sqrt{2} V$ and maximum voltage drop $\Delta V = 10 V$.

C. SSI and bidirectional converter parameters

For SSI, the value of the inductance $L_s$ and capacitance $C_s$ can be determined based on the input current $I_{ls}$ and dc-link voltage $\Delta V_{inv}$ ripples, respectively. By using equations (2) and (3) for $f_s = 20\text{KHz}$, $\Delta I_{ls} = 2.5\text{A}$ and $\Delta V_{inv} = 0.2\%$ $v_{ref} = 1.25 V$ , $L_s = 1.9\text{mH}$ and $C_s = 450 \mu\text{F}$ . Notice that the rated current $I_{ls} = N_s i_{mp} \left|_{(at1000W/m^225^\circ C)} \right.$

For bidirectional converter, the inductance $L_b$ can be calculated as:

$$L = \frac{V_B D_B}{(\Delta I_l b f_s)}$$

(47)

For $f_s = 20\text{KHz}$ and $\Delta I_{lb} = 2\text{As}$ so $L_b = 1.6\text{mH}$

D. Controllers design

Based on the block diagram shown in Fig. 8, the gains of each PI controller can be obtained via linear time invariant (LTI) system analysis (using frequency loop-shaping). The gains of each controller are indicated in Table III. Fig. 9 shows the bode plots for the open loop transfer function of SSI input current and PV voltage control loops. Notice that the bode plots are sketched for the region where the maximum power points in relatively high radiation are located. In this region $R_T$ can be considered constant at $5.16\Omega$.

Notice that the transfer function of the dc-link voltage controller indicated in equation (45) depends on the steady-state value of the converter input current $I_{ls}$ and the value $A$ indicated in equation (39) which depends on the steady-state values of SSI input current and the load resistance before the disturbance occurs. Since all these values change during the operation, it is necessary to design the dc-link voltage controller to ensure stable operation for all operating conditions. Therefore, the limits of $i_{lb}$ and $A$ should be determined.

For $i_{lb}$, the maximum value can be expressed as:

$$i_{lb}\left|_{(max)}\right. = \frac{P_n}{V_{b}} = \frac{8\text{kW}}{72} = 111\text{A}$$

So $-i_{lb}\left|_{(max)}\right. \leq i_{lb} < i_{lb}\left|_{(max)}\right.$

(48)

For $A$, the minimum value that $A$ can’t reach occurs when there’s no load connected or in case of light loads (i.e., $R_{load}$ is close to infinite value) and very low radiation conditions (so $D_s$ is close to 1). Therefore, by equation (39) $A_{min} = 0$. The maximum value that $A$ can’t exceed occurs in case of the rated load conditions ($R_{load} = 18.15\Omega$, which corresponds to $P_n$) and standard radiation (i.e.,$1000\text{w/m}^2$), which results in $I_{ls} = N_s i_{mp}$. Therefore, $A_{max} \approx 0.04$.

Fig. 10 shows bode plots for the open loop transfer function of the dc-link voltage control loop for different values of $A$ and $I_{lb}$. From these bode plots, it’s clear that the control loop is stable with satisfactory bandwidth. Finally, a MATLAB/Simulink model for the proposed system has been executed to validate the control scheme using the parameters indicated in Table IV. Fig. 11 shows the dynamic response of the system for variable loads where $R_{load}$ is the load equivalent resistance, $V_{inv}$ is the dc-link voltage, $v_{abc}$ are the line currents and $i_{lb}$ is the current discharging from the battery. Meanwhile Fig. 12 shows the steady-state behavior for constant load and radiation. Moreover, the PV controller is checked against the variation of radiation level following Ropp profile, discussed in [13], and shown in Fig. 13 (a) while Fig. 13(b) shows the
tracking performance due to the ramp variation of the radiation. Notice that \( P_{\text{max}} \) is the PV maximum power available in a certain radiation and \( P_{PV} \) is the PV output power.

\[
\begin{array}{|c|c|}
\hline
\text{Parameter} & \text{Value} \\
\hline
V_{mp} & 29\,\text{V} \\
I_{mp} & 7.35\,\text{A} \\
V_{oc} & 36.3\,\text{V} \\
I_{oc} & 7.84\,\text{A} \\
R_s & 0.39383\,\Omega \\
R_{sh} & 313.991\,\Omega \\
P_m & 213.15\,\text{W} \\
P_{PV} & 100\,\mu\text{F} \\
\hline
\end{array}
\]

**Table III PV Module Parameters**

\[
\begin{array}{|c|c|c|}
\hline
\text{Controller} & K_P & K_I \\
\hline
\text{DC-link voltage controller} & 7.974 \times 10^{-5} & 0.012941 \\
\text{SSI Input current controller} & 2.583 \times 10^{-3} & 8.1747 \\
\text{PV voltage controller} & -0.0683 & -247.09 \\
\hline
\end{array}
\]

**Table III PI Controller Gains**

\[
\begin{array}{|c|c|c|}
\hline
\text{Parameter} & \text{Value} & \text{Parameter} & \text{Value} \\
\hline
L_{f1} = L_{f2} & 0.64\,\text{mH} & C_s & 20\,\mu\text{F} \\
L & 1.6\,\text{mH} & R_L & 0.13\,\Omega \\
C_p & 450\,\mu\text{F} & f_s & 20\,\text{kHz} \\
f_1 & 50\,\text{Hz} & M & 0.7924\,\text{pu} \\
L_s & 1.9\,\text{mH} & R_{Ls} & 0.16\,\Omega \\
C_{sh} & 50\,\mu\text{F} & V_{in} & 680\,\text{V} \\
\hline
\end{array}
\]

**Table IVV Parameters of the Proposed System**

![Bode Diagram](image)

**Fig. 9.** Bode plots for the open loop transfer functions of SSI input current and PV voltage control loops.

![Bode Diagram](image)

**Fig. 10.** Bode plots for the open loop transfer function of the dc-link voltage control loop for different values of \( A \). (a) when the battery discharges the current rating, (b) the case when the battery charges the rating current, (c) variable input converter current at \( A = 0 \).

![Bode Diagram](image)

**Fig. 11.** Dynamic response due to load variations where PV operates at standard conditions of temperature and radiation.
VI. CONCLUSION

In this paper, the utilization of SSI in a stand-alone PV system is proposed. This system has lower size compared with the two-stage converter-based systems. It also doesn’t require several passive components such as ZSI-based systems. Moreover, it has less voltage stress across the inverter switches for high gains compared with ZSI which qualifies it to be a major candidate for PV systems. A control scheme for the proposed system is presented. Moreover, small-signal models for the converters are analyzed to achieve stable operation with optimum dynamic behavior. Then, step-by-step design procedures for the overall system are discussed. Finally, the system is simulated in MATLAB/Simulink to validate the control scheme.

REFERENCES


