Nonlinear Control for Positive Output Super Lift Luo Converter in Stand Alone Photovoltaic System

S. A. A Fallahzadeh, N. R Abjadi, A. Kargar, F. Blaabjerg

*Faculty of Engineering, Shahrekord University, Shahrekord, Iran

* Department of Energy Technology, Aalborg University, Aalborg, Denmark

ABSTRACT

This paper proposes a stand-alone photovoltaic (PV) system based on a DC-DC positive output super lift Luo (POSLL) converter. A conventional sliding mode control, a sliding mode controller using a simple sign function and a linear controller using proportional integrator (PI) are used for the control of the PV panel voltage and POSLL converter inductor current and these methods are compared together. The POSLL converter is a DC-DC converter with higher voltage gain compared to other conventional DC-DC converters, and has a good voltage regulation with a simple structure. The stability and accessibility of the proposed nonlinear controls are investigated widely. The internal dynamics of the proposed closed-loop control systems are also investigated. A practical implementation of the system on a hardware setup is performed using a low cost Discovery real time digital control platform. The experimental and simulation results demonstrate the validity of the proposed control schemes over a stand-alone real photovoltaic system.


1. INTRODUCTION

In recent years, with the increased use of renewable energy sources, photovoltaic (PV) generator systems have an inevitable effect on generation of electricity [1, 2]. In PV applications, several topologies are used to interface the PV generator with the grid or load. These are applied through power electronic devices such as DC-DC converters and DC-AC inverters. PV systems can work in isolated mode or grid-connected mode. The advantages of using the photovoltaic in generating electricity include the avoidance of pollutants emissions, silent operation, long lifetime and low maintenance requirement. Moreover, solar energy is abundant, free, clean and inexhaustible. When the connection of PV energy to the grid is infeasible or expensive, for example, in some remote areas, the stand-alone PV systems can be considered. Therefore, many PV systems operate in stand-alone mode, such a system consists of a PV generator, energy storage (for example a battery), DC to AC converters, AC and DC consumers and a power conditioning system [3].

DC-DC step-up converters are used in many electronic devices. The main requirements for these converters are to provide a large conversion ratio, high power density and high efficiency. Recently, more interests are devoted to DC-DC converters called Luo converters [4-5]. This is because of their universality and relative simplicity. One of the most interesting converters in the family of Luo converters is positive output super-lift Luo (POSLL) converter [6-9]. In fact, these converters consist of three types of converters: elementary circuit, re-lift circuit, and triple-lift circuit. Voltage gain and switching gain of POSLL DC-DC converter is more than other conventional converters like Boost, Cuk, Buck, Z-source converters. Also, the average of the inductor current in POSLL converter is less than those converters. So it can be used at higher powers. Moreover, the existence of an additional capacitor in its circuit causes the output voltage ripple be more reduced. Therefore,
a DC–DC POSLL converter is used to increase the voltage level of PV panel with a relatively higher voltage gain and a lower inductor current compared to a conventional Boost converter.

To control the desired objectives of PV systems, linear controllers are commonly used. The linear controllers are very useful to serve their purposes over a fixed set of operating points as these controllers are mainly designed based on linearized models of the PV systems. For this reason, linear controllers are unable to achieve desired control objectives under a wide variation of operating points, i.e., under fast changing of weather conditions and reference value. Nonlinear controllers are used to overcome the drawback of operating points for PV systems. In literature, there are different types of nonlinear controllers of PV systems such as Sliding Mode Controller (SMC), Feed-Back Linearizing (FBL) controller, and backstepping controller. In [9], a nonlinear controller based on passivity analysis is proposed for regulating the output voltage of a DC–DC boost power converter in a stand-alone PV system; however, the proposed control is not robust and one should control the input voltage to achieve the maximum power point tracking (MPPT) from PV panel. The sliding mode control technique offers several advantages compared to traditional control methods: stability, even for large line and load variations, robustness, good dynamic response and simple implementation. In [10], using a boost converter in a PV system again the output voltage is controlled which is not suitable for MPPT purposes, moreover, the stability of internal dynamic was not investigated. In [11], a robust backstepping controller is designed for a buck boost converter in a PV system which has a complicated structure. In [12], an adaptive fuzzy sliding mode control is designed for a boost converter in a PV system; using fuzzy control, there is no guaranty for overall system stability and the process of design is complicated. In [13], a backstepping sliding controller is designed for a boost converter which controls the input voltage; however, the proposed sliding variable depends to system parameters and the robustness of SMC is lost.

In this paper, considering the merits of POSLL converter compared to conventional converters, the control of a stand-alone PV system consisting of a POSLL converter is investigated. Three different controllers: proportional–integral (PI) controller, sign function sliding mode controller (SF-SMC) and conventional sliding mode controller (CSMC) are used and compared. The detailed discussion on the existence and stability conditions of the CSMC and SF-SMC for POSLL converter are studied. The contributions of the paper are as follows: the state space equations of the proposed PV system are obtained using a model degree reduction to simplify the control design; two sliding mode controllers are designed for the PV+POSLL converter, and they are compared with conventional PI controllers. Considering sliding mode controllers, the attractiveness of the surfaces are presented and the stability of the internal dynamics are investigated and analyzed.

The behaviour of the POSLL converter in CCM has been analysed in Section 2. The voltage control based on PI, SF-SMC and CSMC is presented in Section 3. Both simulation and experimental results are presented in Section 4. Finally, the conclusion is given in Section 5.

2. PV SYSTEM MODEL

The stand-alone PV system connected to a load is shown in Figure 1. The system consists of PV panel and input capacitor, DC–DC POSLL converter and the load.

Voltage Lift (VL) technique has been widely used in power electronics systems. It has provided a good way to solve the problem of the output voltage and power transfer efficiency of DC–DC converters limitations. Figure 2-a shows an elementary circuit of the proposed system using POSLL converter, and Figures 2-b 3-c show the equivalent circuits when switch S is on (closed) and switch S is off (open), respectively.

From Figure 2-b, it can be seen that the capacitor \( C_i \) \((v_{ci})\) is charged to the input voltage of the converter \((v_{pu})\) when switch S is on. Since inductor \( L_i \) and capacitor \( C_i \) are connected in parallel, the current of inductor \( L_i \) \((i_{Li})\) will increase. As shown in Figure 2-c, during switch-off, the voltage across inductor \( L_i \) will become \(-\left(v_{ci} - ZV_{pu}\right)\), hence \( i_{Li} \) will decrease. The average of the inductor voltage is zero in steady state. It is assumed that \( UT \) is the period that switch S is on and \( (1-U)T \) is the period that switch S is off. As a result, the voltage gain (VG) of the POSLL converter is as follow:

\[
 VG = \frac{V}{V_o} = \frac{2-U}{1-U}
\]  

(Figure 1. The configuration of the proposed system controller)
where \( U \) and \( V_o \) are the duty cycle of the power switch and output voltage of converter, respectively.

The capacitor voltage \( v_{c_i} \) is fixed with the assumption that the capacitor value \( C_1 \) is large enough. Therefore, the following relation is obtained for all times \( v_{pv} = v_{c_i} \). As a result, the average model of the DC-DC POSLL converter is expressed as:

\[
\begin{align*}
\dot{L}_1 &= \frac{1}{L_1} (v_o - v_{pv}) U + (2v_{pv} - V_o) \\
v_o &= \frac{1}{C_2} (i_{L1} - \frac{v_o}{R} - i_{L1} U) \\
v_{pv} &= \frac{(i_{pv} - iL_1)U}{C_1+C_{pv}} + \frac{(i_{pv} - iL_1)(1-U)}{C_{pv}}
\end{align*}
\]

where \( U \in (0,1) \). The capacitor voltage \( V_{C_2} \) is fixed with the assumption that the capacitor value \( C_2 \) is large enough. Therefore, the state equations are obtained as:

\[
\dot{z} = \begin{bmatrix} 0 & 2 \frac{1}{L_1} & 0 \\ -1 & 0 & \frac{1}{C_v} \\ -\frac{i_{pv}}{C_{pv}} & \frac{i_{pv} - iL_1}{C_1+C_{pv}} & \frac{(i_{pv} - iL_1)}{C_{pv}} \end{bmatrix} u(t) + \begin{bmatrix} \frac{v_o - v_{pv}}{L_1} \\ \frac{v_{pv}}{C_v} \\ \frac{v_{pv}}{C_{pv}} \end{bmatrix}
\]

where

\[
z = [i_{L1} \ v_{pv} \ i] \rightarrow \dot{z} = [i_{L1} \ v'_{pv} \ i']
\]

The above equations can be written in the following canonical form

\[
\dot{z} = f(z) + g(z) u(t)
\]

where

\[
f(z) = \begin{bmatrix} 0 & 2 \frac{1}{L_1} & 0 \\ -1 & 0 & \frac{1}{C_v} \\ -\frac{i_{pv}}{C_{pv}} & \frac{i_{pv} - iL_1}{C_1+C_{pv}} & \frac{(i_{pv} - iL_1)}{C_{pv}} \end{bmatrix} z
\]

\[
g(z) = \begin{bmatrix} \frac{1}{L_1} (v_o - v_{pv}) \\ \frac{i_{pv} - iL_1}{C_1+C_{pv}} \end{bmatrix}
\]

3. CONTROL OF SYSTEM

Figure 1 shows the overall schematic diagram of a stand-alone PV system with the proposed controls. In this section, three controllers including PI, CSMC and SF-SMC are presented.

3. 1. DC-DC POSLL Converter

In this section, the performance of linear control using two series PI controllers is presented. The reference value of the solar panel terminal voltage is determined by the MPPT algorithm and the control system is used to track the reference. Dual-loop control strategy is chosen for the POSLL converter, where the output of the outer voltage loop is set as the reference value for the inner current loop which is shown in Figure 3. \( K_1 \& K_2 \) are gains of the PI controllers and \( T_1 \& T_2 \) are time constants of the PI controllers, in second.

3. 2. SMC Controller Using Sign Function (SF-SMC)

The control objective is the convergence of the input voltage \( V_{pv} \) to a desired equilibrium value \( V_{pv}^{ref} \). A direct control is an approach in which the output variable \( V_{pv} \) is used to synthesize a suitable sliding surface representing the desired objective. The alternative is then to use, as a sliding surface coordinate function, a function
that, when set to zero, reproduces the desired equilibrium value of the input inductor current, in correspondence with the desired output equilibrium voltage, this method is known as indirect method.

3. 2. 1. Direct Controller Method a Direct control approach in which the output variable $v_{pv}$ is used to synthesize a suitable sliding surface representing the desired objective is presented. In this method, the sliding variable is considered as:

$$s_1 = e(z, t) \text{ where } e(z, t) = v_{pv} - v_{pv, ref}$$

(7)

Equating the derivative of the sliding variable to zero, the equivalent control is obtained as:

$$s_1 = \frac{\partial e(z, t)}{\partial z} = L_x e(z, t) + L_y e(z, t) u_{eq}(z, t)$$

(8a)

$$u_{eq}(z, t) = \frac{-L_y e(z, t)}{L_x} = \frac{c_{pv} + c_1}{c_1}$$

(8b)

where

$$L_x e(z, t) = \frac{\partial e(z, t)}{\partial z} f_1(z, t) + \frac{\partial e(z, t)}{\partial v_{pv}} f_1(z, t) = \frac{i_{r} - i_{L_i}}{c_{pv}}$$

$$L_y e(z, t) = \frac{\partial e(z, t)}{\partial z} f_2(z, t) + \frac{\partial e(z, t)}{\partial v_{pv}} f_2(z, t) = \frac{i_{L_i} - i_{r}}{c_{pv} + c_1}$$

(9)

Considering necessary condition in (13), this equivalent control is not possible because $u_{eq}(z, t) > 1$.

3. 2. 2. Indirect Controller Method Consider the following sliding variable for inductor current

$$e(z, t) = i_{L_i} - i_{L_i, ref}$$

(10)

where $i_{L_i, ref}$ is the reference value of $i_{L_i}$ that is obtained from comparison of PV panel voltage $v_{pv}$ and its reference $v_{pv, ref}$ using a proportional integrator (PI) controller. One can drives the output function $e(z, t)$ to zero by a discontinuous control which means that the inductor current coincides with the desired average equilibrium inductor current. Applying the Lie derivative theory:

$$L_x e(z, t) = \frac{\partial e(z, t)}{\partial z} f_1(z, t) + \frac{\partial e(z, t)}{\partial v_{pv}} f_1(z, t) = \frac{2v_{pv} - v_e}{L}$$

$$L_y e(z, t) = \frac{\partial e(z, t)}{\partial z} g_1(z, t) + \frac{\partial e(z, t)}{\partial v_{pv}} g_1(z, t) = \frac{v_e + v_{pv}}{L}$$

(11)

where $f_1$ and $g_1$ are the first and second rows of $f(z, t)$ in Equation (8), respectively. Also $g_2$ and $g_3$ are the first and second rows of $g(z, t)$ in Equation (6), respectively. $L_x e(z, t)$ is the Lie derivative of $e(z, t)$ relative to $f(z, t)$. The equivalent control according to $e(z, t) = i_{L_i} = 0$ is obtained as:

$$u_{eq}(z, t) = \frac{-L_y e(z, t)}{L_x e(z, t)} = \frac{-2v_{pv} + v_e}{V_{pv} - v_{pv}}$$

(12)

The ideal sliding dynamics occurs when $u_{eq}(z, t)$ acts on the system as a feedback function while the system is ideally satisfying the condition $e(z, t) = 0$. Let assume that $L_x e(z, t) > 0$ in a neighborhood of manifold $S = \{e(z, t) = 0\}$ (i.e., $L_x e(z, t)$ is strictly positive, “above” and “below” $S$ in the vicinity of this surface), then $e(z, t)$ should be strictly negative at the point $z$. So, one must choose the control that beats the positive incremental effect that this term has over the derivative of $e$. We must then let $u(z, t) = 0$. $e(z, t)$ for this control input entirely coincides with $L_x e(z, t)$. It follows that being $L_x e(z, t) > 0$ in an open neighborhood of $S$, it is necessary that $L_x e(z, t)$ be strictly negative in a neighborhood of $S$.

Let now assume that the point $z$ is located “below” the surface, i.e., $e(z, t) < 0$ then, it can be seen that for the trajectories to reach and cross the sliding manifold $S$, $e(z, t)$ must be strictly positive. Since $L_x e(z, t) > 0$ and $L_y e(z, t) < 0$, one must choose $u(z, t) = 1$ so as to
magnify the positive incremental effect of \( L_e e(z,t) \) over the time derivative of \( e(z,t) \).

The necessary and sufficient condition for the local existence of a sliding state over the smooth manifold \( S = \{ e(z,t) = 0 \} \) is that the equivalent control satisfies:

\[
0 < u_{eq}(z,t) < 1, \ z \in S
\]  

(13)

Since \( L_e e(z,t) > 0 \), in a sufficiently large open neighborhood of the sliding surface \( S \), the control law, that locally forces the state trajectories to reach the sliding surface and thus acquires the possibility of “crossing” this surface, is given by

\[
u(z,t) = \begin{cases} 
1 & \text{if } e(z,t) < 0 \\
0 & \text{if } e(z,t) > 0 \end{cases} , u = 0.5(1-\text{sign}(e(z,t)))
\]  

(14)

Figure 4 shows the block diagram of this proposed controller.

3. 2. 2. 1. Accessibility of The Sliding Surface

The accessibility condition which can be obtained from direct Lyapunov theorem is used to show the surface is attractive. When \( u(z,t) = 1 \), according to Equation \(2) \) \( e(z,t) = V_m / I_s \) has positive value because input voltage of system is positive. When \( u(z,t) = 0 \), the time derivative of \( e(z,t) \)

\[
e(z,t) = \frac{\frac{V}{L_s} - V}{L_s} < 0 \Rightarrow V > \frac{V}{L_s}
\]

is a negative because the voltage gain \( G \) of the POSLL converter is \( \frac{V}{L_s} - \frac{2 \cdot D}{1 - D} \), (where \( D \) is the duty cycle of the power switch), this shows the voltage gain \( G \) can changes from 2 to infinite theoretically.

3. 2. 2. 2. Proof of The Internal Stability

Considering the state space equations and the designed control law, the system relative degree is one. So the system has internal dynamic and its stability should be investigated. This analysis can be done by zero dynamic study. According to Equations \(2) \) and \( 10 \) the corresponding internal dynamic is given by:

\[
\begin{align*}
\dot{i}_p &= \left(\frac{p_v - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} + \frac{v_{pv}^2 - 2 v_{pv} + v_{pv}}{v_{pv} - p_v}\right) v_{pv} - v_p \\
\dot{i}_v &= \frac{1}{c_2} \left( i_v - \frac{v_p - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \right)
\end{align*}
\]  

(15)

To check the stability of the equilibrium point of \(15 \), it is linearized around the equilibrium point \( \overline{I}_{p_s} \). The corresponding Jacobian matrix \( J \) is given by:

\[
J = \begin{bmatrix} J_{11} & J_{12} \\
J_{21} & J_{22} \end{bmatrix}
\]  

(16)

where

\[
\begin{align*}
J_{11} &= \frac{\partial i_p}{\partial p_v} \left( \frac{v_p - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \right) + \frac{v_{pv}^2 - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \\
J_{12} &= \frac{\partial i_p}{\partial v} \left( \frac{v_p - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \right) + \frac{v_{pv}^2 - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \\
J_{21} &= \frac{\partial i_v}{\partial p_v} \left( \frac{v_p - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \right) + \frac{v_{pv}^2 - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \\
J_{22} &= \frac{\partial i_v}{\partial v} \left( \frac{v_p - \frac{v_p^2}{Q} - 2 v_{pv} + v_{pv}}{v_{pv} - p_v} \right) + \frac{v_{pv}^2 - 2 v_{pv} + v_{pv}}{v_{pv} - p_v}
\end{align*}
\]  

(17)

In \(17 \), based on the PV generation modeling, \( i_{pv} \) is substituted by:

\[
i_{pv} = I_{ph} - I_{s} (exp(AV_{pv}) - 1)
\]  

(18)

where

\[
A = \frac{q}{N \gamma KT}
\]

(19)

Thus, \( I_{s} = I_{s} \frac{T}{T_s} \exp \left[ \frac{qE_{GD}}{\gamma K} \left( \frac{1}{T_s} - \frac{1}{T} \right) \right] \)

\[
I_{ph} = [I_{sc} + K_r (T - T_r)] \lambda / 1000
\]

where \( i_{pv} \) is the photocurrent (current generated by radiation); \( I_s \) is the cell reverse saturation current; \( I_{sc} \) is the cell saturation current at \( T_r \); \( I_{s} \) is the short circuit current at 298.15K and 1Kw/m²; \( K_r \) is the short circuit current temperature coefficient of \( I_{sc} \); \( \lambda \) is the solar radiation; \( E_{GD} \) is the band gap for silicon; \( \gamma \) is the ideality factor; \( T_r \) is the reference temperature; \( T \) is the ambient temperature input; \( q \) is the electron charge \( (q = 1.6 \times 10^{-19}) \); \( K \) is the Boltzmann’s constant \( (K = 1.3806505 \times 10^{-23}) \).

With embedding steady state values in \( J_{11} \) of \( 14 \) one can obtain that the absolute value of the first term in \( J_{11} \) is larger than the absolute value of the second term in \( J_{11} \), so \( J_{11} \) has negative value. \( J_{11} \) has positive value because \( i_{pv} > \overline{I}_{p_s} \) and also \( J_{21}, J_{22} < 0 \). Since the following conditions are absolutely satisfied,

\[
\begin{align*}
\begin{cases} 
J_{11} J_{12} > 0 \\
J_{21} J_{22} < 0
\end{cases}
\end{align*}
\]  

(20)

So \( J \) is negative definite and the linearized system is strictly stable. Hence, based on the indirect Lyapunov stability theorem, the equilibrium point is asymptotically stable in the real non-linear system.
3.3 SMC Controller Using Sign Function (SF-SMC)

The conventional SMC (CSMC) approach is employed to regulate the output voltage as the outer loop based on proportional–integral (PI) controller and an inner loop. Furthermore, the stability of the proposed CSMC is confirmed. CMSM is used for control of inductor current \( i_{Lt} \) and capacitor voltage \( v_{pv} \) as shown in Figure 4. The following sliding variable is defined for this purpose:

\[
S_2(z,t) = K_1 \varepsilon_1 + K_2 \varepsilon_2
\]

where, \( K_1 \) and \( K_2 \) are positive constants; \( \varepsilon_1 \) is the error between \( i_{Lt} \) and its reference, and \( \varepsilon_2 \) is the error between \( v_{pv} \) and its reference which can be written as:

\[
\begin{align*}
\varepsilon_1 &= i_{Lt_{ref}} - i_{Lt} \\
\varepsilon_2 &= v_{pv_{ref}} - v_{pv}
\end{align*}
\]

where \( i_{Lt_{ref}} \) is the inductor current reference that is obtained from comparison of the PV panel voltage and its reference using the PI controller. \( v_{pv_{ref}} \) is the input capacitor voltage reference that can be obtained from an MPPT method.

Substituting (2) to the following equation the equivalent control law of POSLL converter can be obtained as Equation (25).

\[
S_2(z,t) = K_1 \varepsilon_1 + K_2 \varepsilon_2 = 0
\]

where

\[
\begin{align*}
e_1 &= i_{Lt_{ref}} - i_{Lt} \\
e_2 &= v_{pv_{ref}} - v_{pv}, \quad u(z,t) = 1 - \frac{M}{N}
\end{align*}
\]

where

\[
M = K_s (\frac{v}{L_i} - i_{Lt_{ref}}) + K_1 (i_{pv} - i_{Lt})
\]

\[
N = K_s (\frac{i_{pv}}{c_{pv} + c_i} - \frac{i_{pv}}{c_{pv}}) + K_1 (\frac{v}{c_{pv} + c_i} - \frac{v}{c_{pv}})
\]

The designed control input is as follow:

\[
u(z,t) = 1 - \frac{M}{N} - K_3 \text{sign}(S_2) - K_4 S_2
\]

where \( K_3 \) and \( K_4 \) are positive constants. \( K_3 \text{sign}(S_2) \) is a discontinuous term to overcome some uncertainties in the system and \( K_4 S_2 \) is the modified term which increases the speed of convergence to the sliding surface. To implement the control law (25), the obtained \( u(z,t) \) should be compared to a saw tooth waveform and the result is used to command the converter switch. A simple similar control law can be used as follow,

\[
u(z,t) = 0.5(1 - \text{sign}(e(z,t)))
\]

which gives the switch command directly.

3.3.1 Proof of The Stability

In this section the attractiveness of sliding surface \( s_2 = 0 \) using equivalent control law (25) is presented. The control law (27) can be rewritten as

\[
u(z,t) = \begin{cases} 
1 & \text{if } e(z,t) < 0 \\
0 & \text{if } e(z,t) > 0 
\end{cases}
\]

If \( u(z,t) = 1 \), \( \dot{s}_2(z,t) \) is obtained as

\[
\dot{s}_2(z,t) = K_1 (\frac{v}{L_i} - i_{Lt_{ref}}) + K_1 (i_{pv} - i_{Lt})
\]

With selecting \( K_1 \) and \( K_1 \) somehow that the absolute of the first term of Equation (29) becomes larger than the second term, \( \dot{s}_2(z,t) < 0 \).

If \( u(z,t) = 0 \), \( \dot{s}_2(z,t) \) is obtained as

\[
\dot{s}_2(z,t) = K_1 (\frac{v}{L_i} - i_{Lt_{ref}}) + K_1 (i_{pv} - i_{Lt})
\]

Since \( i_{pv} - i_{Lt} > 0 \), \( \dot{s}_2(z,t) > 0 \).

According to the above discussion, the accessibility condition is satisfied and the sliding surface is attractive.

3.3.2 Proof of The Internal Stability

The internal dynamic with conventional SMC method is expressed as:
\[ v_{eq} = \frac{1}{c_2} \left( i_{L_1} - \frac{v}{R} - i_{L_2} a_{eq} \right) \]  

(31)

where \( a_{eq} = \frac{M}{N} \) that M and N are described in Equation (25). To verify the internal stability, (31) is linearized around the equilibrium point \((i_{L_1}, v_{eq})\). Substituting (25) in Equations (31), (32) is obtained:

\[
\frac{\partial v_{eq}}{\partial v_{eq}} = \frac{1}{c_2} \left( 1 - \frac{1}{R} \left( \frac{K_1}{L} \right) \right) \frac{-K_1 K_2 (i_{p_1} - i_{l_1})}{(c_{p_1} + c_{l_1}) L} + \frac{K_2 (i_{p_1} - i_{l_1})}{(c_{p_1} + c_{l_1})} \]  

(32)

In Equation (32), if \( K_2 > K_1 \) is chosen large enough, then \( \frac{\partial v_{eq}}{\partial v_{eq}} < 0 \), thus the internal dynamic of conventional SMC method will be stable.

4. SIMULATION AND EXPERIMENTAL RESULTS

A DC–DC POSLL converter as depicted in Figure 2 with nominal parameters given in Table 1 is considered.

In order to show the effectiveness of the proposed controllers, simulation and practical results are obtained in three distinct tests. The PV module specifications are listed in Table 2. The step time of the simulation is 1 \( \mu s \). The switching frequency is 20 KHz. The experimental results have been obtained by a laboratory prototype depicted in Figure 5.

4.1. PI Controller Results According to Figure 3, two control loops are simulated and implemented in practical using the Discovery board. The outer loop PI controller coefficients set to \( K_1 = 1 \) and \( T_2 = 0.1 \). The inner loop PI controller coefficients are \( K_1 = 2 \) and \( T_1 = 0.1 \). In simulation results depicted in Figures 6(a) and 6(b), the converter input reference voltage is stepped down and up from \( V_{ref} = 8 \) to 4 V at \( t = 0.6 \) s and from 4 to 8 V at \( t = 2.6 \) s respectively. In practical test, the same input reference voltage is used. The practical obtained results are shown in Figure 6(c). It can be seen that the input voltage follows the reference value and the experimental results confirm the simulation results. It is worthwhile to note the converter capacitors are large (1mF) and they decrease the speed of the responses.

<p>| TABLE 1. Characteristic of system parameters for both the hardware and the simulation configurations. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{pv} )</td>
<td>Input Capacitor of system</td>
<td>100( \mu )F</td>
<td>( C_1 )</td>
<td>Boost Capacitor of converter</td>
<td>1mF</td>
<td>( C_2 )</td>
<td>Input Capacitor of converter</td>
<td>1mF</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>Inductor of converter</td>
<td>100( \mu )H</td>
<td>( R )</td>
<td>Load resistance</td>
<td>50( \Omega )</td>
<td>( V )</td>
<td>Voltage at maximum power</td>
<td>18.5 V</td>
</tr>
</tbody>
</table>

Figure 5. Experimental setup
Figure 6. Simulation and experimental results with step change of input voltage reference in PI controller. Simulation results: (a) input voltage and its reference, (b) output voltage, Experimental results: (c) input voltage (CH1), output voltage (CH2).

4.2 SF-SMC Controller Results In Figure 7 the DC-DC POSLL converter is controlled using SF-SMC method in order to achieve to reference value of PV panel regarding to (10). Like before, the converter input reference voltage is stepped down from $V_{pv_{ref}} = 8$ to $6$ V at $t = 0.6$ s and comes back to $8$ V at $t = 2.6$ s in obtaining simulation results. The same reference input voltage is used in experimental test. Figures 8 (a) and (b) show simulation results and Figure 8 (c) shows experimental results. Using one PI controller, tuning the controller is easier. Parameters of PI controller are set by try and error to $K = 0.1$ and $T = 1$.

4.3 Conventional SMC Results The conventional SMC block diagram is shown in Figure 7. The composition of linear controller (PI) and nonlinear controller is used for input voltage control of PV system. The parameters of control law (26) are selected by try and error to achieve the best response and stability. The values of $K_1$ to $K_4$ and $K$ of PI controller are listed in Table 3. Considering the same condition as the two previous controller tests, the simulation and practical results are shown in Figure 8.

4.4 Comparison and Discussion The three controllers proposed to control the input voltage of the PV system are compared and discussed in this section. Using each of these controllers, the reference input voltage is followed; however, the conventional SMC controller has a better performance. As shown in Figure 8(a), there is less error between PV voltage and its reference than SF-SMC controller and PI controller. Also, reference tracking in SF-SMC controller (Figure 9(a)) is better than PI controller (Figure 7(a)). The simulation results show that the delivered input voltage in PI controller comes with distortion, while the quality of input voltage in SF-SMC controller is acceptable, the practical results also confirm it.

Output voltages of the stand-alone PV system are brought in Figures 7(b), 8(b) and 9(b) for PI, SMC and SF-SMC controller, respectively. The output voltage of system changes with the change in the input voltage. Comparing output voltages of the proposed system with the presented controllers, shows that the output voltage of the system with SFC controller has more chattering.

Figure 7. Schematic diagram of the proposed controller using SF-SMC
TABLE 3. Constance of controller for CSMC

<table>
<thead>
<tr>
<th>Constance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>1000</td>
</tr>
<tr>
<td>$K_2$</td>
<td>1000</td>
</tr>
<tr>
<td>$K_3$</td>
<td>500</td>
</tr>
<tr>
<td>$K_4$</td>
<td>500</td>
</tr>
<tr>
<td>$K$</td>
<td>1</td>
</tr>
<tr>
<td>$T$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 8. Simulation and experimental results with step change of input voltage reference in SMC. Simulation results: (a) input voltage and its reference. (b) output voltage. Experimental results: (c). input voltage (CH1), output voltage (CH2).

Figure 9. Simulation and experimental results with step change of input voltage reference in SF-SMC. Simulation results: (a) input voltage and its reference. (b) output voltage. Experimental results: (c). input voltage (CH1), output voltage (CH2).

than others. In experimental results (Figures 9(c) and 8(c)) the output voltage of system with SF-SMC controller and the conventional SMC are almost the same and has a better quality than the results obtained with PI control. The maximum overshoot percent in input voltage using PI control, SF-SMC and conventional SMC are about %33, %50, 0 respectively, and the correspondent rise times are about 72, 64 and 72 ms respectively. Table 4 presents a summary of comparison of the performance and implementation of the proposed controllers.
### TABLE 4. Performance comparison of the proposed controllers.

<table>
<thead>
<tr>
<th>Description</th>
<th>Using PI controller</th>
<th>Using SF-SMC</th>
<th>Using CSMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference tracking</td>
<td>Not bad</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td>Quality of input voltage</td>
<td>Poor</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Practical implementation</td>
<td>Simple</td>
<td>Relatively simple</td>
<td>Difficult</td>
</tr>
<tr>
<td>operating point area</td>
<td>Wide</td>
<td>Very Wide</td>
<td>Very Wide</td>
</tr>
<tr>
<td>Stability</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Quality of output voltage</td>
<td>Good</td>
<td>Very good</td>
<td>Very good</td>
</tr>
</tbody>
</table>

### 5. CONCLUSION

Two sliding mode controllers suitable for regulating the DC bus voltage of a stand-alone PV system including a POSLL converter is presented and compared. The stability and accessibility of the proposed nonlinear controls are investigated with the theoretical analysis, the extended simulation, and experimental results. The proposed system takes advantages of a DC-DC POSLL converter such as; high voltage gain, smoother output voltage and lower inductance current. It has been shown that the use of a nonlinear controller in indirect control of the panel voltage results in more efficiency and better performance.

### 6. REFERENCES


Nonlinear Control for Positive Output Super Lift Luo Converter in Stand Alone Photovoltaic System

S. A. A Fallahzadeh\textsuperscript{a}, N. R Abjadi\textsuperscript{a}, A. Kargar\textsuperscript{a}, F. Blaabjerg\textsuperscript{b}

\textsuperscript{a}Faculty of Engineering, Shahrekord University, Shahrekord, Iran
\textsuperscript{b}Department of Energy Technology, Aalborg University, Aalborg, Denmark

\textbf{Paper Info}

\textit{Paper history:}
Received 27 September 2019
Received in revised form 27 October 2019
Accepted 16 January 2020

\textbf{Keywords:}
Photovoltaic
Sliding Mode Controller
Stand Alone
Super Lift Luo converter