Sliding mode controlled PV-based bootstrap converter system with enhanced response and voltage stability

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ABSTRACT

In this paper, a straightforward method for locating the controller in a PV-based bootstrap converter system is presented. Recent developments in control strategies and power electronics have made it possible to create PV-based DC-to-AC converters for AC drives that are connected to 3-phase loads. High voltage gain is intended to be produced by the bootstrap converter (BSC). The BSC's purpose is to control load voltage. This study compares the time specification performance of the proportional resonant controller (PRC) and the sliding mode control (SMC) for photovoltaic systems with bootstrap three phase inverter (PV-BSTPI). For the delicate loads, steady voltage is typically more important. The BS-TPI system incorporates a closed loop control to fast achieve constant voltage. Choosing the best control approach is the aim. It is observed that the steady state error of SMC is 1.67 which is better when compared to PRC.

Keywords: 3-phase inverter, 3-phase LC filter, 3-phase load, Bootstrap-converter, PRC, SMC

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1. INTRODUCTION

Photovoltaic (PV) power is already nondeterministic due to its reliance on climatic and environmental variables. This creates significant challenges for diffusion and dispersion framework administrators as well as market administrators [1]. They are constantly required to regulate local creation that is unable to respond clearly to existing previous age repercussions. As a result, the impact of this vulnerability on organizational activities is severe. For example, huge edges of energy hold are important to have the choice to control the act of doing from earlier age plans, and the circulated energy assets of clever lattices should be managed under such vulnerability [2]. To attain such goals, projections of PV power for a specific time horizon should be available as early as a couple of days before the actual energy age. The essential writing on PV power gauging is extremely diverse. Most scientists and specialists use deterministic PV power estimation, which is the removal of a single value that predicts the true PV power at a specific time horizon [3]. Nonetheless, due to the inherent haphazardness of the real marvels, PV power gauging is best handled within probabilistic algorithms.

The technique of DC-DC conversion was first introduced in the 1920s. Initially, to obtain less voltage from the supply, a voltage divider or the use of variable resistance (rheostat) was attempted, which resulted in poor performance [4]. In addition, a multi-quadrant chopper for DC-DC conversion is being developed for industrial applications. As huge developments happened in the communication area, the requirement for low-voltage DC sources rose, resulting in extensive research in DC-DC converter topologies [5]. Initially, elementary circuit-based choppers were built for a few prototype models, and they met the
requirement. DC choppers are power electrical components that convert fixed DC voltage to variable DC voltage, hence the term DC-DC converters. According to their operation, converters are categorized as buck, boost, and buck-boost. Buck converters are used when the output voltage is less than the input voltage [6], whereas boost converters are used when the output voltage is greater than the input voltage. If the output voltage is larger than or less than the supply voltage, a Buck-boost converter is employed. The output voltage of Cuk converter is specified to be the inverse of the supplied voltage. It's also known as an inverting regulator [7]. The ON/OFF state of the switch controls the conversion ratio of these converters. DC-DC converters can now be operated at two different frequencies. One operates at high frequencies (10 kHz-1 MHz), while the other operates at lower frequencies. When the former is utilized at higher frequencies, the components L, C, and transformers become lighter and smaller in weight and size. The first is utilized for low and medium-power applications, while the second is used for high-power applications. The PWM technique [8] is used to turn on and off switches (IGBT or MOSFET). DC-DC converters are critical for maximizing the use of electricity from numerous sources. The output of the PV cell is quite low when dealing with grid-connected systems. To counteract this, boost converters are used to increase the output of PV cells. Traditional boost converters have disadvantages, such as slow switching and being unsuitable for high-power and high-temperature applications [9]. To improve the performance of DC-DC converters, enormous modifications have happened in the literature. Cascaded converters are made up of two converters connected back-to-back with additional switches. A quadratic boost converter (QBC) is an example of a cascaded converter with only one switch [10]. QBC is a new topology that outperforms conventional in terms of efficiency, voltage gain, and keeping the same number of switches. As this converter injects less current ripple into the source, the efficiency and lifespan of PV arrays rise [11]. Theoretical high voltage gain for classical boost and buck-boost converters can be produced by using extreme duty cycles. Maximum attainable voltage gain is limited to roughly five in practice due to switch speed limitations, parasitic components, and power losses [12]. Because of the advancement of high-voltage gain converters, many DC-DC converters have been presented. Many studies have been conducted, for example, on high-gain topologies using stages [13] and magnetic coupling. In addition to the foregoing, quadratic gain converters were developed as an option.

A traditional boost converter is unsuitable for use in high-power industries where efficiency is critical because it has various switching characteristics that result in substantial I^2R losses [14]. As a result, a quadratic boost converter is constructed as a combination of two boost converters with only one active switch in the form of a MOSFET, resulting in lower losses and higher efficiency. QBC’s limitations include unstable voltage regulation and low saturation points [15].

Low-duty cycle QBC is achieved with a high step-up and conversion ratio [16]. The expression for the conversion ratio is created, and the converter's switching operating circumstances are taken into account and expressed as quadratic equations [17]. To enhance power quality and manage overvoltage and current, the QBC employs the average current mode control. Researchers currently have a challenging task dealing with the extremely complex design of DC-DC converters with high voltage gain and minute output ripple waves [18]. To avoid the difficulties of output ripple waves and voltage transfer gain. In comparison to all other conventional DC-DC converters, KY converters have developed a superior converter. In terms of the power loss in the filter inductor, the power loss in the output capacitor, and the transient current over parasitic resistors, KY converters outperform boost converters [19]. KY converter is a non-isolated DC-DC boost converter that runs in continuous conduction mode and has a low output voltage ripple [20]. A KY boost converter is a hybrid of a KY converter and a synchronous rectifier converter. While functioning, traditional boost converters generate a high amount of output voltage ripple, which causes noise. An LC inductance filter or comparable series resistance capacitor is added to the existing circuit to overcome this and reduce output voltage ripple. To reduce output voltage ripple, several regulating techniques such as SMC, coupling inductor, loop bandwidth control, and voltage control techniques [21] are applied. In real-time applications, achieving one right-half plane zero with the aforementioned approaches running in continuous conduction mode (CCM) is extremely challenging. To address this KY boost converter with two modes of operation: charging and discharging, gives a very low output ripple in continuous conduction mode.

Although the number of commitments committed to probabilistic PV power anticipating is much lower than that in the deterministic structure, writing audits, and rivalry overviews reveal a changed cutting edge. These approaches are typically classified as boosting, stacking, and packing. Boosting comprises building a "solid" model by consolidating a few more vulnerable ones, which are prepared repetitively. Stacking is the process of combining the findings of several models that are treated in the same or similar manner to create the final forecast [22]. Packing entails constructing the final expectation as a combination of the output of a similar model run on multiple occasions, with input data resample via substitution (i.e., bootstrap totaled).

The emerging planar exchanged hesitance engine SMC for precise situating is appropriate for obstruction hiding [23]. To begin, the mechanical structure, framework structure, and numerical model with
realized boundaries obtained using a failing-to-recall factor recursive least-squares computation are presented in sequence [24]. At that point, the SMC's exchanging capacity and arriving at the law were resolved. The control law is also deduced for the SMC. The SMC's security is also shown using the Lyapunov steadiness hypothesis.

Existing studies do not propose a single architecture capable of achieving requirements such as high gain, a wide range of operations, and low ripple when integrating PV and AC drives. There is no performance comparison of the quadratic-boost converter [25], KY step-up converter, and bootstrap converter (BSC). Constant voltage is generally in higher demand for loads. Closed loop control is used in the circuit to fast achieve constant voltage for closed loop (CL) BC-TPI. The primary goal of this study is to find the best controller for a CL-BC-TPI utilized in constant voltage situations.

Pulse width modulation (PWM) is the most used technique to control switching power supplies. The traditional PWM based power electronic circuits operates adaptively for a specific condition as they are modified based on averaging techniques. Nonlinear controller’s offer a good large signal transient over linear controllers like P, PI, and PID as latter do not react immediately to transient conditions. One of the best nonlinear controllers for variable structure systems is slide mode control as these systems are robust to parameter variations and external disturbances. Accordingly, the switched-mode converters used in PV system applications are the ideal target of this kind of controller [26], [27]. Either it being a DC-DC converter or being an inverter, the SMC has been used widely in the literature. Kim et al. applied the SM to control the inverter switches in order to force the followed current in the grid to pursue a generated reference current; the simulation and experimental results of this single-stage grid-connected PV system shown that the proposed controller can reduce current overshoot and contribute to the optimal design of power devices [28]–[35].

This slide mode controller has a high degree of design flexibility and its comparatively easy to design. It is used in various industrial applications like automotive control and furnace control. The overwork is related to the sliding mode-controlled PV-based bootstrap converter-inverter system. Sliding mode-controlled PV-based bootstrap converter-inverter system is recommended in this endeavor. Sliding mode control is a nonlinear control technique used to modify the dynamics of a nonlinear system by causing it to "slide" over a cross-section of its typical behavior.

The document is laid out as follows: i) The topology of the CL-BC-TPI is presented in section 2 of the manuscript, and performance analysis using the Simulink model is shown in part 3; ii) Section 3 discusses the control strategies; iii) Section 4 reports on result analysis; and iv) Section 5 reports on the CL-BC-TPI conclusions derived from this research.

2. PROPOSED TOPOLOGY

Figure 1 shows a block diagram of a PR controlled closed loop bootstrap with a 3-phase inverter (BC-TPI). PV yield is focused on BC matching load voltage with PV voltage. The yield of the bootstrap converter is converted to alternating current (AC) by using a [8] three-phase inverter, which creates a constant frequency at the load. The load voltage is measured and compared to the reference voltage. The voltage PRC is oblivious to voltage inaccuracy [9]. The reference voltage is compared to the actual voltage, and the error is used by the PRC [10] to update the pulse width of the bootstrap converter and TPI. As a result, this system functions as a voltage-mode-controlled BC-TPI.

Figure 2 shows a block diagram of an SM-controlled-closed loop bootstrap with a 3-phase inverter. In Figure 1, the PRC has been switched out for the suggested SMC. The voltage of the load is changed, and this new voltage is compared to the reference voltage to determine the voltage error. The voltage inaccuracy is inferred from the voltage standard deviation. The reference voltage is matched with the actual voltage and the error is utilized to update the PWM of the Bootstrap converter and TPI.

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The square of the error is integrated throughout the course of time by integral square error (ISE). Large errors will be punished more severely by ISE than smaller ones, due to the fact that the square of a large error will be a significantly larger value. Control systems that have been designed to minimize ISE will typically eliminate major errors rapidly, but they will allow little faults to continue for an extended length of time if they are allowed to do so. The controller input is given in (1). The controller input is given by (1).

\[ u(t) = V_{\text{ref}} - V \]  

(1)

Where \( u(t) \) is the input to the controller, \( V_{\text{ref}} \) is the reference voltage and \( V \) is the voltage at the load side.

3. SIMULATION RESULTS

The projected controller performance is analyzed in this section in three cases. In case 1, the performance of BC-TPI is presented in an open loop system. In case 2, the performance of the BC-TPI is presented using the PRC [11]. The performance of BC-TPI is presented using the SMC in case 3.

– Case 1: Open loop BC-TPI with source disturbance

The circuit diagram [12], [13] of open-loop-BC-TPI with source disturbance is delineated in Figure 3. Figure 4 illustrates the voltage that is measured across the PV of the BC-TPI, and its value is 48 V [10]. Table 1 contains the parameters that will be used for the simulation. Figure 5 illustrates the voltage that is present across BC, and its value is 336 V. The value of the output voltage of the inverter when it is connected to an R-load is shown in Figure 6, and it is 280 V. Figure 7 illustrates the inverter's output current when it is connected to an R-load, which has a value of 1.2 A. Figure 8 illustrates the output power of the inverter with an R-load, which has been calculated to be 460 W.

Table 1. Simulation parameters of BC-TPI

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>( V_{\text{in}} )</td>
<td>48 V</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>10 mF</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>0.5 mH</td>
</tr>
<tr>
<td>( C_2, C_3 )</td>
<td>50 ( \mu )F, 10 mF</td>
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<tr>
<td>( L_2 )</td>
<td>3 ( \mu )H</td>
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</table>
Case 2: PR controlled closed loop BC-TPI

Figure 9 shows the circuit diagram for a PR controlled closed-loop BC-TPI with a 3-phase inverter [14]. To calculate the voltage error, the AC output of the TPI is first rectified and then compared to the reference voltage. The PRC receives the voltage error that was measured. To determine the voltage inaccuracy, the yield of PRC is compared with the actual voltage. To obtain an updated PWM for BSC, the voltage error is applied to the PRC. Figure 10 illustrates the voltage that is present across the PV of the BC-TPI, and its value is 58 V.

Figure 11 illustrates the voltage that is present across the load of the TPI, and its value is 336 V. Figure 12 and is 280 V [15]. Figure 13 illustrates the output current of the inverter when it is connected to an R-load, and its value is 2.78 A. Figure 14 [16] illustrates the output power of the inverter when it is connected to an R-load, and its value is 460 W.

Case 3: SM controlled closed loop bootstrap converter with 3-phase inverter

The schematic representation of the SM-controlled closed-loop BC-TPI may be seen in Figure 15. The voltage fault is sent to the SMC so that an updated PWM can be generated for the BSC. Figure 16 illustrates the voltage that is measured across the PV [17] of the BC-TPI, and its value is 58 V. Figure 17 illustrates the voltage that is present across the load of the TPI, and its value is 336 V.

Figure 18 illustrates the inverter’s output voltage when it is connected to a load, and the value of this voltage is 280 V. Figure 19 illustrates the output current of the inverter when it is connected to a load, and its value is 2.78 A [18]–[22]. Figure 20 illustrates the output power of the inverter with a load, which has been calculated to be 445 W.
Figure 9. Circuit diagram of PR controlled closed-loop BC-TPI

Figure 10. Voltage across PV of BC-TPI

Figure 11. Voltage across bootstrap converter

Figure 12. Output voltage of inverter with R–load

Figure 13. Current through R–load with PRC

Figure 14. Output power with PRC
Figure 15. Circuit diagram of closed-loop SM controlled BC-TPI

Figure 16. Voltage across PV of BC-TPI

Figure 17. Voltage across BC-TPI

Figure 18. Output voltage of inverter with R–load

Figure 19. Current through R–load

Figure 20. Output power of BC-TPI
4. RESULT ANALYSIS

The simulation results of SMC and PRC performed on the BS-TPIS are presented in this section. This section also includes a detailed comparison of both control strategies to system performance. Table 2 provides a quantitative summary of the performance characteristics of the BS-TPI between SMC and PRC. According to the data in Table 2, SMC has the quickest settling time ($T_s$) of 2.65 sec and PR controller requires an additional 0.55 sec. In comparison, the PRC has the highest maximum peak time ($T_p$) of 1.84 sec and the SMC has the lowest value of the two controllers. SMC has the fastest rise time ($T_r$) of 1.27 sec, while PRC requires an extra time. Also in comparison, the SMC is having the less steady state error (ESS) of 1.67 than the PRC.

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>$T_s$ (sec)</th>
<th>$T_r$ (sec)</th>
<th>$T_p$ (sec)</th>
<th>ESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRC</td>
<td>1.48</td>
<td>3.20</td>
<td>1.84</td>
<td>2.12</td>
</tr>
<tr>
<td>SMC</td>
<td>1.27</td>
<td>2.65</td>
<td>1.78</td>
<td>1.67</td>
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5. CONCLUSION

To simulate the performance comparison of PRC and SMC, Simulink is employed. We compare the output voltage and ripple voltage of the simulation results. The outcomes demonstrate that the SMC works better than the PRC. According to the simulation results, the SMC-based bootstrap BC-TPI results in a shorter settling time and a smaller amount of steady-state inaccuracy. A transformer less connection is possible with the help of a bootstrap converter. By creating a simple method for locating closed-loop controllers for BC-TPI, the current study makes a contribution. It has been determined that the SMC is the best controller for the BC-TPI System. The main advantage of using SMC is the simplicity with which the load voltage can be changed.

REFERENCES


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