Passivity Based Control for Interleaved Boost Single-Ended Primary-Inductance Converter for PV System

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Abstract. This paper addresses the challenges by enabling a novel Interleaved Boost-SEPIC converter (IBSC) for improving the Photovoltaic (PV) system's performance, controlled by a passivity-based proportional integral control strategy. The use of non-interleaved converters in PV systems leads to reduced efficiency due to challenges in controlling high-frequency switching, potentially resulting in decreased energy conversion efficiency and increased losses. Additionally, non-interleaved converters may exhibit weaker transient response characteristics, leading to slower voltage regulation and potential instability under varying load conditions. There is also a higher risk of electromagnetic interference (EMI) with non-interleaved converters, which can interfere with other electrical systems and equipment. The main objectives of the study are to improve PV system's performance by enhancing energy conversion efficacy and to provide stable outcomes with improved transient response. These objectives were achieved by the proposed IBSC, controlled by a passivity-based PI controller which aims for efficient regulation of converter voltage output, ensuring high efficiency and rapid transient response. The control scheme utilizes the converter's passive features to guarantee stable operation under various operating conditions. MATLAB simulations establish the robustness of recommended control system, the most important results are rapid transient response of 0.5s, high efficiency of 91% and robust performance for the Boost-SEPIC converter in PV systems. The significance of obtained results includes improved energy conversion, stable voltage regulation and enhanced reliability. On comparison, the proposed concept outperforms conventional ones in terms of efficiency, ripple reduction and stability making it a better solution for improving PV system performance.
Keywords: Interleaved Boost-SEPIC Converter (IBSC), Passivity-based control (PBC), Photovoltaic (PV) systems, Proportional-Integral (PI) Controller, Pulse width modulation.

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Control bazat pe pasivitate pentru convertorul primar cu inductanță unidirecțională boost intercalat pentru sistemul fotovoltaic

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Abstract. Această lucrare abordează provocările prin activarea unui nou convertor Interleaved Boost-SEPIC (IBSC) pentru îmbunătățirea performanței sistemelor fotovoltaice (PV), controlate printr-o strategie de control integral proporțional bazată pe pasivitate. Utilizarea convertoarelor neintercalate în sistemele fotovoltaice duce la o eficiență redusă din cauza provocărilor în controlul comutării de înaltă frecvență, ceea ce poate duce la scăderea eficienței conversiei energiei și la creșterea pierderilor. În plus, convertoarele neintercalate pot prezenta caracteristici de răspuns tranzitoriu mai slabe, ceea ce duce la o reglare mai lentă a tensiunii și la instabilitate potențială în condiții variate de sarcină. Există, de asemenea, un risc mai mare de interferență electromagnetică (EMI) cu convertoarele neintercalate, care pot interfera cu alte sisteme și echipamente electrice. Obiectivele principale ale studiului sunt de a îmbunătăți performanța sistemelor fotovoltaice prin îmbunătățirea eficienței conversiei energiei și de a oferi rezultate stabile cu un răspuns tranzitoriu îmbunătățit. Aceste obiective au fost atinse de IBSC-ul propus, controlat de un controler PI bazat pe pasivitate, care urmărește reglarea eficientă a tensiunii de ieșire a convertorului, asigurând o eficiență ridicată și un răspuns tranzitoriu rapid. Schema de control utilizează caracteristicile pasive ale convertorului pentru a garanta o funcționare stabilă în diferite condiții de funcționare. Simulările MATLAB stabilesc robustețea sistemului de control recomandat, cele mai importante rezultate sunt răspunsul tranzitoriu rapid de 0.5 s, eficiență ridicată de 91% și performanță robustă pentru convertorul Boost-SEPIC în sistemele fotovoltaice. Semnificația rezultatelor obținute include o conversie îmbunătățită a energiei, o reglare stabilă a tensiunii și o fiabilitate sporită.
Cuvinte cheie: convertor Interleaved Boost-SEPIC (IBSC), control bazat pe pasivitate (PBC), sisteme fotovoltaice (PV), controler proporțional-integral (PI), modulare pe lățime a impulsului.

Пассивное управление для чередующегося повышающего однотактного преобразователя первичной индуктивности для фотоэлектрической системы

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Аннотация. В данной статье рассматриваются проблемы, связанные с использованием нового преобразователя Interleaved Boost-SEPIC (IBSC) для повышения производительности фотоэлектрических (PV) систем, управляемого стратегией пропорционального интегрального управления на основе пассивности. Использование преобразователей без чередования в фотоэлектрических системах приводит к снижению эффективности из-за проблем с управлением высокочастотным переключением, что может привести к снижению эффективности преобразования энергии и увеличению потерь. Кроме того, преобразователи без чередования могут демонстрировать более слабые характеристики переходного отклика, что приводит к более медленному регулированию напряжения и потенциальной нестабильности в условиях изменяющейся нагрузки. Также существует более высокий риск электромагнитных помех (EMI) с преобразователями без чередования, которые могут мешать работе других электрических систем и оборудования. Основными целями исследования являются повышение производительности фотоэлектрических систем за счет повышения эффективности преобразования энергии и обеспечение стабильных результатов с улучшенным переходным откликом. Эти цели были достигнуты с помощью предлагаемого IBSC, управляемого ПИ-регулятором на основе пассивности, который направлен на эффективное регулирование выходного напряжения преобразователя, обеспечивая высокую эффективность и быстрый переходный отклик. Схема управления использует свойства пассивности преобразователя для обеспечения стабильной работы в различных условиях эксплуатации. Моделирование MATLAB устанавливает надежность рекомендуемой системы управления, наиболее важными результатами являются быстрый переходный отклик 0.5 с, высокая эффективность 91% и надежная работа преобразователя Boost-SEPIC в фотоэлектрических системах. Значимость полученных результатов включает улучшенное преобразование энергии, стабильное регулирование напряжения и повышенную надежность. При сравнении предлагаемая концепция превосходит существующие с точки зрения эффективности, снижения пульсаций и стабильности, что делает ее многообещающим решением для улучшения производительности фотоэлектрической системы.

Ключевые слова: чередующийся повышающий преобразователь SEPIC (IBSC), пассивное управление (PBC), фотоэлектрические (PV) системы, пропорционально-интегральный (PI) контроллер, широтно-импульсная модуляция.

I. INTRODUCTION

In response to escalating energy demands and environmental concerns, renewable energy sources, particularly solar PV technologies, have garnered substantial attention [1-6]. PV systems enable efficient use of solar energy to generate electrical power, which, when coupled with appropriate converters, can be effectively utilized.

The deployment of non-isolated DC-DC converters in solar applications has been extensively explored, with boost converter. However, the high duty ratio operation of these converters leads to undesirable parasitic effects [7]. Although the 3-level boost converter offers a large voltage gain, it suffers from high switch voltage stress [8].

Despite advancements, coupled inductor-based converter topologies continue to face challenges like current and voltage stress, switching losses, and electromagnetic interference. These challenges are critical as they affect the reliability and efficiency of PV systems, which are essential for sustainable energy solutions. Interleaved converters have emerged as promising alternatives, minimizing ripple current and reducing the size of filters and current stress [9-13]. By combining the outputs of multiple converter channels, interleaved converters can handle higher power levels. Additionally, interleaved converters is easily scaled by adding more channels, making them versatile for an extensive range of power levels and applications. The High Gain DC-DC Converter [18] has high efficiency, optimal power extraction and flexible voltage conversion. However, it has high complexity, cost and maintenance. Then, the Interleaved Boost Converter (IBC) [19] has reduced ripple, improved performance, better MPPT performance. However, it has Intricacy, Expenses. The Interleaved high step up converter [20] has minimized voltage stress, high voltage gain, adjustable voltage gain and stress, reduced conduction losses, active clamp scheme. It has the drawbacks of complexity in terms of design, lead to higher costs, troubleshooting. Subsequently, the Three-Phase Interleaved Boost Converter [21] has reduced ripple, improved dynamic performance, direct battery connection, high efficiency and robust performance. However, it has advanced control algorithms, specialized components and higher maintenance requirements. The Interleaved hybrid Boost converter has reduced input ripple, cost reduction, extended service lifespan. Nevertheless, it requires a higher level of expertise, troubleshooting.

Conventional proportional-integral (PI) controllers have been extensively employed to control voltage output of boost converters. However, it has poor performance in quickly varying environmental conditions, like changing temperature or irradiance. It lacks adaptability, leading to slow dynamic response and steady state errors during transient conditions [14, 15]. Furthermore, it is sensitive to variations of system parameter and not inherently manage uncertainties in the PV system. Improper tuning of the PI gains also cause instability that diminishes system efficacy and stressing power electronic components [16, 17]. This work introduces several novel contributions aimed at overcoming the limitations of existing converter technologies and control strategies:

- A novel Interleaved Boost-SEPIC converter design that boosts the PV output source, offering reduced ripple, variable voltage conversion, and greater efficiency.
- A PBC is employed for output voltage management, ensuring stability and robust performance.

The subsequent parts of the manuscript is structured with description of suggested methodology in section 2, detailed system modelling in section 3, discussions on the simulation results and in-depth analysis of experimental findings in section 4 and the key outcomes of the research are summarized in the form of conclusion in section 5.

II. PROPOSED METHODOLOGY

The PV system is at the core, generating V_{PV} (PV voltage) and I_{PV} (PV current) from sunlight. These outputs are then fed into the interleaved Boost-SEPIC converter. This converter serves to raise the PV panel's low voltage output to a level where grid integration is possible. The interleaved configuration of the converter is crucial as it helps reduce ripple current, which improves the efficiency of the overall system.

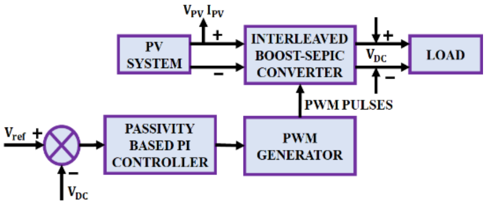


Fig. 1. Block diagram of the developed model

The passivity-based approach offers improved stability and robustness. It does so by leveraging the inherent passivity properties of the system, ensuring stable operation under a wide range of conditions. The regulated output voltage, denoted as V_{DC}, is crucial for ensuring stable power delivery to the DC load. This DC load could be any electrical device or system that requires power. PWM pulses are generated by the PWM generator, which determines duty cycle of the converter's switches, thereby regulating an output voltage. It showcases advancements in renewable energy integration and power electronics control, highlighting the potential for efficient and reliable solar energy utilization.

III. SYSTEM MODELLING

A. Interleaved Boost-SEPIC Converter

A power converter type for enhancing the voltage of PV system [18] that includes the characteristics of both boost and SEPIC converters is called an Interleaved Boost-SEPIC converter, which is showcased in Fig. 2.

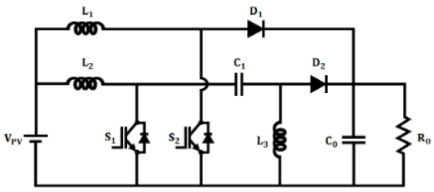


Fig. 2. Modelling of an Interleaved Boost-SEPIC converter.

Mode 1:

In stage 1 when S_1 is active and S_2 remains inactive and in Diode, D_1 is ON and D_2 is OFF as seen in Fig. 2 (a). Capacitor C_1 discharges to stabilize the output, while C_o charges to maintain a continuous and stable output voltage. This balanced operation ensures efficient energy transfer and minimal ripple in output current, enhancing the performance of the converter.

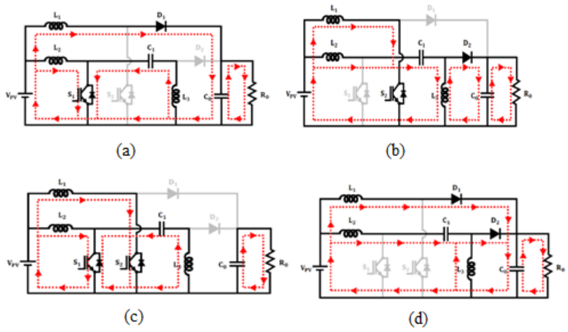


Fig. 2 Stages of Interleaved Boost-SEPIC converter (a) Stage 1 (b) Stage 2 (c) Stage 3 (d) Stage 4

On applying KVL,

$$V_{PV} - V_{L_2} = 0 \Rightarrow V_{PV} = V_{L_2} \quad (1)$$

$$V_{L_3} - V_{C1} = 0 \Rightarrow V_{L_3} = V_{C1} \quad (2)$$

$$V_{PV} - V_{L_1} - V_{C0} = 0 \quad (3)$$

$$V_{PV} = V_{L_1} + V_{C0} \quad (4)$$

$$V_{C0} = V_{R_O} = V_O \quad (5)$$

On substituting equation (5) in equation (4),

$$V_{L_1} = V_{PV} - V_O \quad (6)$$

Mode 2:

In stage 2, the S_1 is inactive and S_2 is active as seen in Fig. 2 (b). During this mode, the inductors L_2 and L_3 undergo a discharge process, releasing their stored energy, while the inductor L_1 is actively charged. Concurrently, diode D_1 is in the inactive state, preventing current flow through it, whereas diode D_2 is on, allowing current to pass through. This configuration ensures that the capacitors C_1 and C_o are charged.

On applying KVL,

$$V_{PV} = V_{L_1} \quad (7)$$

$$V_{PV} - V_{L_2} - V_{C1} + V_{L_3} = 0 \quad (8)$$

Using the average of these voltages,

$$V_{PV} - 0 - V_{C1} + 0 - 0 \Rightarrow V_{PV} = V_{C1} \quad (9)$$

$$V_{L_3} = V_{C0} = V_O \quad (10)$$

By equation (9) and equation (10) in equation (8),

$$V_{PV} - V_{L_2} - V_{PV} + V_O = 0 \Rightarrow V_{L_2} = V_O \quad (11)$$

Mode 3:

In mode 3, S_1 and S_2 remains active and the D_1 and D_2 is inactive as seen in Fig. 2 (c). During this phase, the inductors L_1, L_2 and L_3 begin to charge, storing energy from the input power source. Concurrently, the capacitors C_1 and C_o are in a state of discharge. An energy stowed in these capacitors is released, with C_o discharging directly to provide power to load.

$$V_{PV} = V_{L_1} = V_{L_2} \tag{12}$$

Mode 4:

During this stage, both S_1 and S_2 are inactive as seen in Fig. 2(d). Consequently, both diodes D_1 and D_2 are on. Moreover, in this phase, the inductors L_1, L_2 and L_3 are in discharging state, releasing their stored energy. Simultaneously, the capacitors C_1 and C_o are actively charging. Fig. 3 provides the operational waveforms of the converter.

On applying Volt second balance equation,

$$\left(V_{L_2}, \text{swclosed}\right)(DT) + \left(V_{L_2}, \text{swopen}\right)(1-D)_T = 0 \tag{13}$$

On substituting equation (1) equation (11) in equation (10),

$$V_{PV}(DT) + (V_O)(1-D)_T = 0 \tag{14}$$

On solving equation (14), in the proposed IBSC, the voltage gain is,

$$\frac{V_O}{V_{PV}} = \frac{D}{1-D} \tag{15}$$

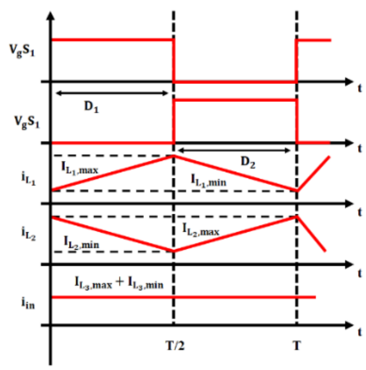


Fig. 3. Waveforms of the developed converter

Design Considerations

The inductor's values are provided as,

$$L_1 = L_2 = \frac{V_{PV}(min)}{\Delta L_{L_1} \times f} \tag{16}$$

Where, the term $V_{PV}(min)$ refers to the minimum input voltage

$$L_3 = \frac{V_O - 2V_{PV}}{\Delta L_{L_1}}\left(\frac{1-D}{f}\right) \tag{17}$$

The value of capacitors is given as,

$$C_1 = C_3 = \frac{I_0 \times D}{C_1 \times f} \tag{18}$$

$$C_2 = \frac{(1-D)V_O}{\Delta V_0 f R_0} \tag{19}$$

In comparison to employing a single converter, the utilization of an Interleaved Boost SEPIC converter with a PBC improves efficiency, lowers ripple, boosts reliability, increases power density, and improves dynamic responsiveness. The behaviour of the interleaved Boost-SEPIC converter with the passivity-PI controller darting repeated decreases or increases in solar flux over reduced time intervals, the controller sustain a stable power output although these oscillations.

B. Passivity Based PI Controller

In an Interleaved Boost-SEPIC converter, output voltage is largely managed by the PBC [25]. A PBC is based on the principles of energy based control and system reliability, assures the stable and robust performance of power electronic converters in dynamic conditions. This controller is formulated utilizing the Port Controlled Hamiltonian (PCH) model that models the energy dynamics of the system by considering both stored energy and dissipation. The PBC offers improved voltage regulation, fast transient response, diminished steady state error and enhanced system reliability under varying conditions.

The transfer function of PI controller is,

$$G_{PI}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \tag{20}$$

Where, an integral gain is denoted by K_i, proportional gain is K_p *and* Laplace variable is s.

The following is the dynamic system's PCH form expression:

$$\begin{cases} \dot{x} = \left[J(x) - R(x)\right]. \dfrac{\partial H(x)}{\partial x} + \zeta + g(x)u \\ y = g^T(x)\dfrac{\partial H(x)}{\partial x} \end{cases} \tag{21}$$

The state vector is denoted by $x \in R^n$; the interconnection and dissipation matrices are J, $R^n \to R^{n \times n}$ and $R(x) = R^T(x)$, respectively; H :

$R^n \to R$ is the function of total stored energy; g: $R^n \to R^{n\times m}$ matrix input; ζ external force; and, accordingly, the output function and control action are ,$u, y \in R^m, m < n$.

A dynamic system's stored energy function described as follows when looking at it from an energy perspective:

$$H(x) = \frac{1}{2}x^T Qx \qquad (22)$$

Where,

$x = (x1, x2)^T = (L \cdot i, C \cdot v)^T$ x1, and x2 Q $\in R^{n\times n}$

is a diagonally symmetric matrix that represents the capacitance's charge and the inductance flux, while the inductance the $Q = diag\{1/L, 1/C\}$ and the circuit characteristics.

$$J(x) = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, R(x) = \begin{pmatrix} 0 & 0 \\ 0 & 1/R \end{pmatrix} \zeta = (E, 0)^T, \ldots$$
$$g(x) = \begin{pmatrix} x_2 / C \\ -x_1 / L \end{pmatrix} \qquad (23)$$

where $\tilde{x} := x - x^*$ and acceptable equilibrium point of x is x^*.

$$H_d(x)\frac{1}{2}\tilde{x}^T Q_{\tilde{x}} \qquad (24)$$

Let us assume $J_d(x) = -J_d^T(x), R_d(x) = R_d^T(x) \geq 0$ are matrices. Given $H_d(x)$, such that

$$x^* = \operatorname{argmin} H_d(x) \qquad (25)$$

Assuming $u = \beta(x)$ exists, the following is an expression for the closed-loop dynamic system (27).

$$\dot{x} = [J_d(x) - R_d(x)]\frac{\partial H_d(x)}{\partial x} \qquad (26)$$

With x^* a steady state of balance. Based on principle of La Salle's invariant, if the major collection of invariants produced by the closed-loop dynamics (28) in

$$\left\{ x \in R^n \left| \frac{\partial H_d^T(x)}{\partial x} R_d \frac{\partial H_d(x)}{\partial x} = 0 \right. \right\} \qquad (27)$$

Comes to$\{x^*\}$. Asymptotically stable then is the closed-loop system.

Equation 26 is obtained by replacing (25) with $u = \beta(x)$. The storage function's time derivative is produced since negative symmetric matrix is $J_d(x)$ and a positive symmetric matrix is$R_d(x)$.

$$\dot{H}_d(x) = -\left(\frac{\partial H_d(x)}{\partial x}\right)^T R_d \frac{\partial H_d(x)}{\partial x} \leq 0 \qquad (28)$$

Consequently, $H_d(x)$ be thought of as a Lyapunov function and stable equilibrium point is x^* . In result (21) and principle of La Salle's invariant, the system's dynamic asymptotic stability is demonstrated.

$$[J_d(x) - R_d(x)]\frac{\partial H_d(x)}{\partial x} = \ldots$$
$$[J(x) - R(x)]\frac{\partial H(x)}{\partial x} + \varsigma + g(x)u \qquad (29)$$

Considering that $H_d(x) = H(x) + H_a(x), J_d(x) = J(x) + J_a(x)$, $R_d(x) = R(x) + R_a(x)$, u = d is duty ratio of an IGBT and $K(x) = \partial H_a(x)/\partial x = \partial H_d(x)/\partial x - \partial H(x)/\partial x$. Let $J_d(x) = 0, R_d(x) = diag(r1, 1/r2)$, where $r1$ and $r2$ are injected virtual impedances. Then, (29) is mentioned as follows

$$[J_d(x) - R_d(x)]\frac{\partial H_a(x)}{\partial x} = \ldots$$
$$-[J_a(x) - R_a(x)]\frac{\partial H(x)}{\partial x} + \varsigma + g(x)u \qquad (30)$$

Where

$$J_a(x) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, (x) = \begin{pmatrix} r_1 & 0 \\ 0 & 1/r_2 - 1/R \end{pmatrix},$$
$$K(x) = (-x_1^*/L - x_2^*/C) \qquad (31)$$

$$\begin{cases} \dfrac{x_1^*}{L} = \dfrac{r_1}{L}x_1 + \dfrac{d-1}{C}x_2 + E \\ \dfrac{x_2^*}{C}\dfrac{1}{r_2} = \dfrac{1-d}{L}x_1 + \dfrac{1}{r_2 C}x_2 - \dfrac{1}{RC}x_2 \end{cases} \qquad (32)$$

Here, by changing x_1, x_2 and (31), we obtain

$$I^* r_1 = i.r_1 + v(d-1) + E \qquad (33)$$

$$\frac{V^*}{r_2} = i(1-d) + \frac{v}{r_2} - \frac{v}{R} \qquad (34)$$

The duty ratio be derived here, where the predicted steady state values of v and i are V^* and I^*.

$$d = \frac{v - E + r_1\left(I^* - i\right)}{v} \tag{35}$$

The law of conservation of energy is able to be used to determine the connection between output voltage and inductance current at steady-state values, assuming that the DC/DC converter's loss is eliminated. As soon as the system achieves a condition of stability, that is

$$I^* = \frac{V^{*2}}{ER} \tag{36}$$

When (34) and (35) are combined, the duty ratio is

$$d = \frac{v - E + r_1\left(V^{*2} / ER - i\right)}{v} \tag{37}$$

Firstly, the PV system harnesses renewable solar energy, providing a sustainable power source. Secondly, the IBSC efficiently regulates the voltage output, ensuring optimal power transfer from the PV system. Additionally, the PBC enhances stability and responsiveness, effectively managing fluctuations in solar irradiance and load variations.

IV. RESULTS AND DISCUSSION

The significance of the developed Interleaved Boost-SEPIC converter and PBC approach in PV systems is demonstrated through MATLAB simulation. The performance of developed converter along with passivity based control is evaluated under four different test cases.

Table 1

Parameter Specification

Parameter	Rating
PV System	
Current (Short Circuit)	$8.95A$
Voltage (Open Circuit)	$37.25V$
Maximum Peak Voltage	$29.95V$
Total Power	$10KW$
Maximum Peak Current	$8.35A$
Peak Power	$150W$
Interleaved Boost-SEPIC Converter	
L_1, L_2	$5.5mH$
L_3	$7mH$
Input Capacitor, C_1	$870\mu F$
Output C_0 capacitor	$2200\mu F$
Load	100Ω

Case 1: Under Constant Condition

In Case 1, the functioning of the Interleaved Boost-SEPIC converter is seen in Fig. 4. Specifically, the solar intensity is kept constant at $1000\,W/m^2$ and the temperature is stabilized at 25℃.

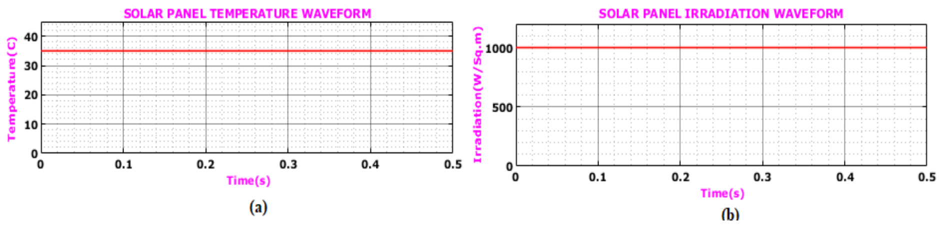


Fig. 4. Solar Panel Waveform.

The waveform in Fig. 5 shows a constant voltage level of 117V, indicating a reliable and stable electrical supply from the PV system. In addition to the steady voltage, the current waveform also stabilizes at 43A without distortion, demonstrating a smooth and uninterrupted flow of current.

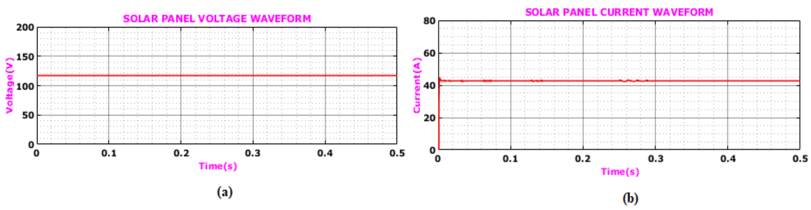
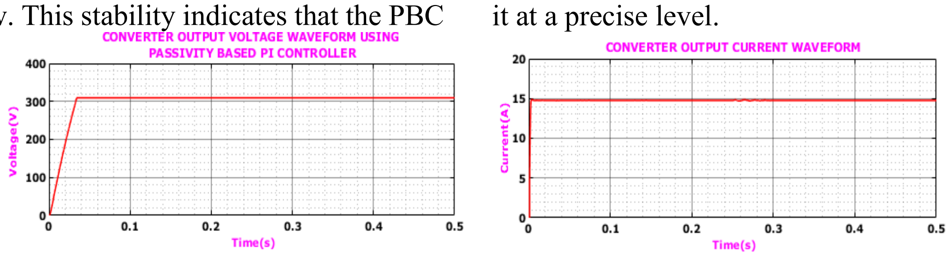


Fig. 5. Solar Panel Voltage and Current Waveform.

The voltage steadies at 305V in the provided Fig. 6, demonstrating a constant and steady voltage level at that particular moment. Furthermore, the current waveform stays constant at 15A, signifying a steady and uninterrupted current flow. This stability indicates that the PBC effectively manages output voltage, maintaining it at a precise level.



(a) (b)

Fig. 6(a). Waveform of converter output voltage utilizing PBC and (b) Converter output current.

The Fig. 7 illustrates a consistent power flow of 5000 watts without any distortion. This indicates a stable and uninterrupted transfer of electrical power.

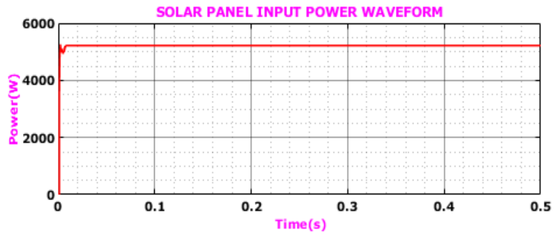


Fig. 7. Solar Panel input power waveform.

The diagram Fig. 8 displays a distortion-free steady power flow of 4575W, signifying a steady and uninterrupted flow of electrical power.

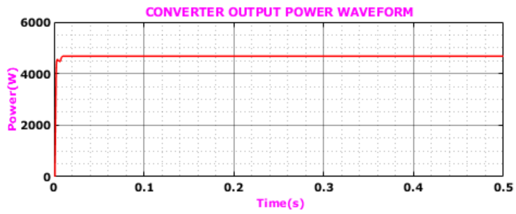
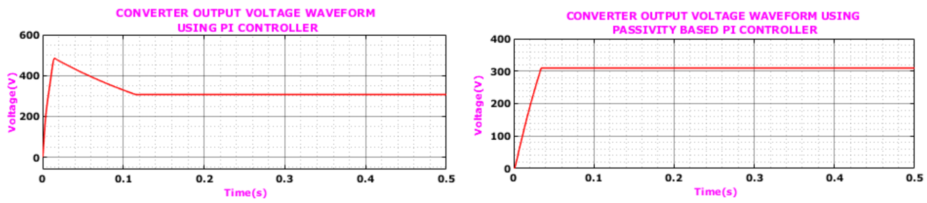


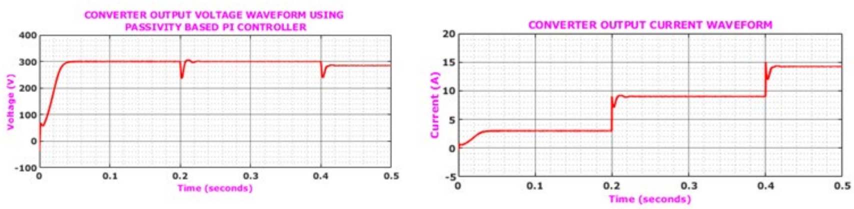
Fig. 8. Converter Output Power Waveform.

Fig. 9 illustrates the converter output voltage waveforms using two different control strategies: PI controller and PBC. The PBC demonstrates a more controlled and rapid rise in the output voltage, reaching approximately 300V without significant overshoot. The voltage stabilizes almost immediately, within 0.05 seconds, indicating a faster response time.



(a) (b)

Fig. 9 (a). Waveform of converter output voltage utilizing PI controller and (b) output voltage waveform utilizing PBC.



(a) (b)

Fig. 10. Output waveform under varying load condition (a) Voltage (b) Current.

Fig. 10 (a) represents the waveform of output voltage with PBC. The output voltage is gradually raised and by applying load the variations are occurred in voltage. With the aid of PBC, the voltage is settled at a steady value of 280 V with little fluctuations. The waveform of output current is illustrated in Fig. 10 (b). The output current is slowly improved and is varied due to the load. By exploiting the PBC, the current is maintained at 14 A with little oscillations.

Case 2: Under Constant Temperature and Varying Intensity

In this scenario, the temperature remains constant while the irradiation varies. The waveform Fig. 11 indicates a stable and constant temperature level, stabilizing at $35^{\circ}C$. Concurrently, the sun's irradiation also stabilizes at a consistent level of $1000(w/sq.m)$.

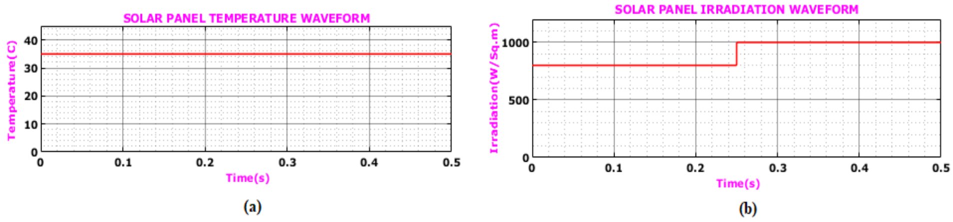


Fig. 11. Waveform of solar panel temperature and irradiation.

In the diagram Fig. 12, the voltage waveform first stabilizes before increasing to 117V and staying there. The current waveform, at 43A, is stable and distortion-free at the same time.

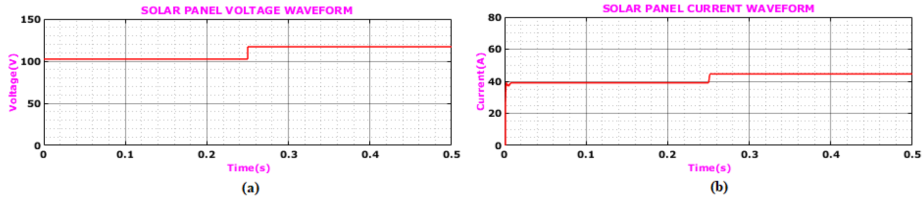


Fig. 12. Waveform of solar panel voltage and current.

Figure 13 (a) shows the waveform rising to 305V at first, then stabilizing and remaining there. At first, Fig. 13 (b) displays a rising waveform, followed by distortion-free stabilization at 15A.

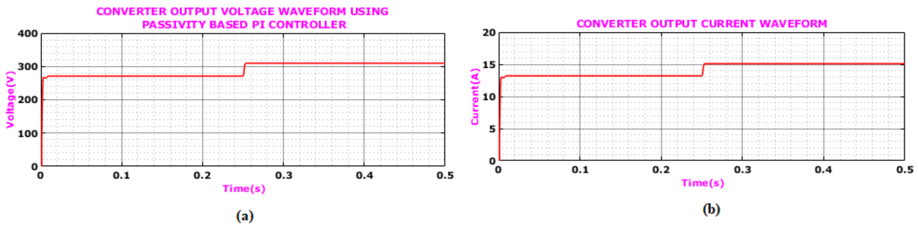


Fig. 13. (a) PBC. Waveform using converter output and (b) Current waveform of converter output.

A steady, distortion-free power flow of 5022 W at 0.25 S is depicted in the Fig. 14.

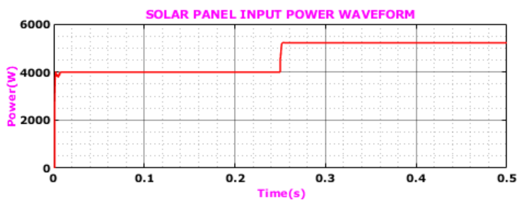


Fig. 14. Waveform of solar panel input power

The Fig. 15 shows a steady power flow of 4575W without distortion at 0.25 seconds, implying a constant and reliable supply of electricity.

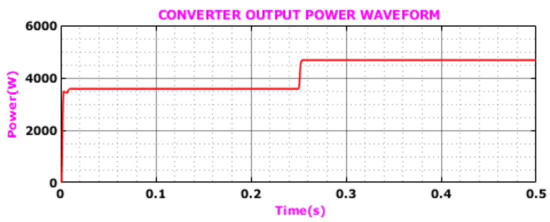


Fig. 15. Waveform of converter output power

Case 3: Under Shaded Conditions

In this scenario, the proposed converter and its controller are subjected to a test environment where the PV array experiences partial shading conditions.

The waveform in the illustration Fig. 16 shows how it gradually decreases from 50 cells to 45 cells before continuing to flow smoothly and distortion-free. This steady flow after a slow decline points to a regulated and reliable operation.

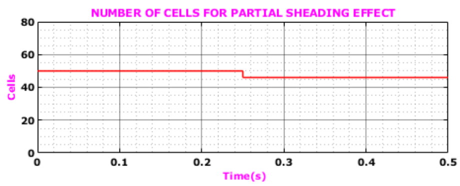


Fig. 16. Number of cells for partial sheading effect

At 0.25 seconds, the waveform in Fig. 17 (a) shows a constant, undistorted 110 volt flow. This indicates a constant voltage level, which is necessary to ensure that electrical systems and other equipment that rely on this voltage operate as intended. Fig. 17 (b)'s waveform displays an uninterrupted, steady flow of 40 amps at 0.25 seconds.

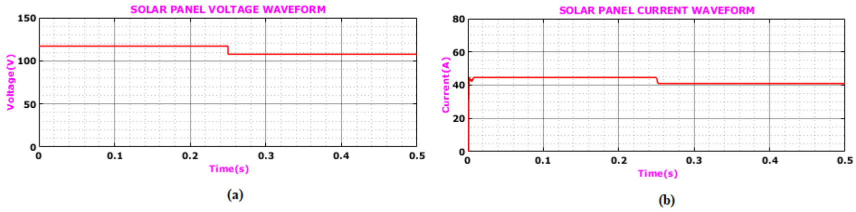


Fig. 17. Waveform of voltage and current in PV system

The Fig. 18 shows a constant, distortion-free power flow of 4525 W at 0.25 S. It shows that electrical power is being transferred steadily and continuously.

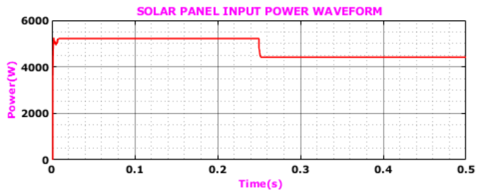


Fig. 18. Input power waveform of solar panel

The Fig. 19 implies a consistent and dependable supply of electricity by displaying a continuous power flow of 4000W without distortion at 0.25 seconds.

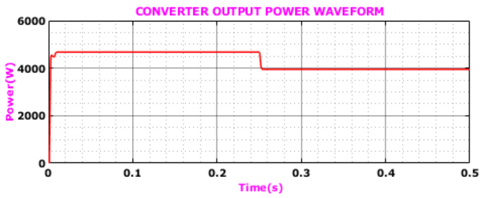


Fig. 19. Power waveform of converter output

The plot Fig. 20 illustrates the ripple in the input current (measured in amperes) for three distinct converters: SEPIC, Boost, and the converter under proposal. The suggested converter has the lowest ripple over the whole voltage range.

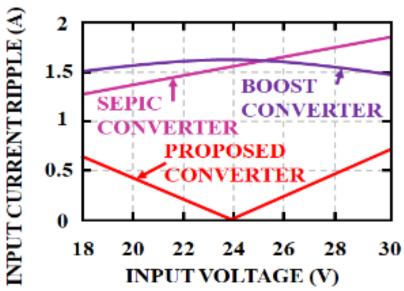


Fig. 20. Input Current Ripple

The table 2 lists various bidirectional and unidirectional converter topologies for power applications. The efficacy of PV system is nearly 85% and after developing the Interleaved Boost-SEPIC converter the efficacy is enhanced to 91%.

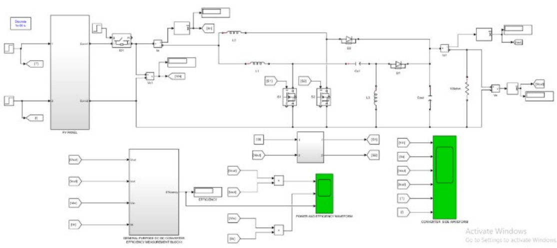


Fig. 21. Functional diagram

Fig. 21 represents the functional diagram of developed system in MATLAB. The PV array is linked to an IBSC converter reduces the current ripple. Then, the PBC manages the developed converter to assure the steady voltage in changing conditions.

Table 2

Comparison of developed with some approaches

Ref	Efficacy
[27]	85.35
[28]	90.6
[29]	Not Indicated
[30]	88
[31]	90
Developed	91

Table 3 compares the performance of different controllers including PI controller, Fuzzy controller, Sliding mode controller, Neural network controller, Genetic Algorithm (GA)-PI controller, Particle Swarm Optimization (PSO)-PI controller, Crow Search Optimization (CSO)-PI controller and proposed PBC. The PBC exhibits the best overall performance among the controllers evaluated. It achieves the shortest settling time of 0.05 seconds, The PBC also demonstrates the lowest overshoot of 0.5%. In terms of rise time, the PBC again outperforms others with a rapid rise time of 0.1 seconds. Additionally, the PBC achieves the lowest steady-state error of 0.05%, showcasing its precision in maintaining the desired output without significant deviation. When considering efficiency, the PBC leads with an impressive efficiency of 91%, highlighting its superior capability in converting input power to output power effectively.

Table 3

Performance Comparison of Various Controllers with PBC

Controller	Settling Time (s)	Overshoot (%)	Rise Time (s)	Steady-State Error (%)	Efficiency (%)
PI Controller	0.12	5	0.18	0.5	85
Fuzzy Controller	0.12	2	0.15	0.3	85.3
Sliding Mode Controller	0.13	3	0.16	0.4	85.2
Neural Network Controller	0.11	2	0.14	0.2	86
GA-PI Controller	0.14	4	0.17	0.45	88.5
PSO-PI Controller	0.12	2	0.15	0.3	88
CSO-PI Controller	0.1	2	0.13	0.1	89
Passivity-Based PI Controller	0.05	0.5	0.1	0.05	91

V. DISCUSSIONS

The findings from the MATLAB simulations demonstrate that the proposed Interleaved Boost-SEPIC converter, controlled by a PBC, significantly enhances the performance of PV systems. With an efficiency of 91%, indicating its potential for high-efficiency energy conversion in renewable energy applications. The minimal overshoot (0.5%) and rapid rise time (0.1 seconds) underscore the controller's capability to provide stable and precise voltage regulation.

Future research can explore the scalability of this converter for larger PV systems and its integration with other renewable energy sources. Limitations:

One key limitation is the complexity involved in the design and implementation of the passivity-based control strategy, which may pose challenges in practical applications. Additionally, the converter's performance under extremely high or low input conditions and its scalability to larger systems have not been thoroughly investigated.

VI. CONCLUSION

This research presents a unique Interleaved Boost-SEPIC converter with a PBC designed to enhance the performance of PV systems. The Interleaved Boost-SEPIC converter enhances the voltage of PV system with reduced switching losses. Then, the PBC assures stable and accurate voltage regulation that enhances the reliability in PV systems. The overall system demonstrates robustness in managing fluctuating the irradiance and load changes. It aids the sustainability goal by indorsing effective and consistent renewable energy utilization. The developed research is implemented in MATLAB/Simulink tool, proving its efficacy and applicability in real world renewable energy applications. Future research will focus on scaling the converter for larger PV systems, incorporating it with HRES and performing experimental validations to validate simulation outcomes. The outcomes contribute a substantial step toward advancing effective, stable and sustainable energy conversion in PV systems.

REFERENCES

[1] Ali M.N., Mahmoud K., Lehtonen M., Darwish M.M. An efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems. *IEEE Access*, 2021, vol. 9, pp. 26420-26430.

[2] Das D., Kalita P., Roy O. Flat plate hybrid photovoltaic thermal (PV/T) system: a review on design and development. *Renew Sustain Energy Rev*, 2018, vol. 84, pp. 111e30.

[3] Chiteka K., Arora R., Sridhara S.N., Enweremadu C.C. Influence of irradiance incidence angle and installation configuration on the deposition of dust and dust-shading of a photovoltaic array. *Energy*, 2021, vol. 216, pp. 119289.

[4] Perkins G. Techno-economic comparison of the levelised cost of electricity generation from solar PV and battery storage with solar PV and combustion of bio crude using fast pyrolysis of biomass. *Energy Conv Manage*, 2018, vol. 171, pp. 1573-88.

[5] Abdelkareem M.A., Sayed E.T., Mohamed H.O., Obaid M., Rezk H., Chae K.J. Nonprecious anodic catalysts for low-molecular-hydrocarbon fuel

cells: Theoretical consideration and current progress. *Prog Energy Combust Sci.*, 2020, vol. 77, pp. 100805.

[6] Said S.M., Aly M., Hartmann B., Alharbi A.G., Ahmed E.M. SMES-based fuzzy logic approach for enhancing the reliability of microgrids equipped with PV generators. *IEEE Access*, 2019, vol. 7, pp. 92059-69.

[7] Wuhua L., He X. Review of nonisolated high-step-up DC/DC converters in photovoltaic grid-connected applications. *IEEE Transactions on Industrial Electronics*, 2011, vol. 58, no.4, pp. 1239-1250.

[8] Lin B.R., Lu H.H., Hou Y.L. Single-phase power factor correction circuit with three-level boost converter. *Proceedings IEEE ISIE*, 1999, pp. 445-450.

[9] Parsa L., Dwari S. An efficient high-step-up Interleaved DC–DC Converter with a Common Active Clamp. *IEEE transactions on Power Electronics*, 2011, vol. 26, no. 1, pp. 66-78.

[10] Miwa B.A., Otten D.M., Schlecht M.F. High efficiency power factor correction using interleaving techniques. *Proceedings IEEE APEC*, 1992, pp. 557 -568.

[11] Garcia O., Zumel P., de Castro A., Cobo J.A. Automotive DC-DC bidirectional converter made with many interleaved buck stages. *IEEE Transactions on Power Electronics*, 2006, vol. 21, pp. 578 -586.

[12] Gules R., Pfitscher L.L., Franco L.C. An interleaved boost dc-dc converter with large conversion ratio", *Proceedings IEEE Int Symp. Ind Electronics*, 2003, pp. 411-416.

[13] Erickson R.W., Maksimovic D. Fundamentals of Power Electronics. *Kluwer*, 2001.

[14] Jeltsema D., Scherpen J.M. Tuning of passivity - preserving controllers for switched-mode power converters. *IEEE Transactions on Automatic Control,* 2004, vol. 49, no. 8, pp. 1333-1344.

[15] Ortega R., Garcia–Canseco E. Interconnection and damping assignment passivity-based control: A survey. *European Journal of control*, 2004, vol. 10, no. 5, pp. 432-450.

[16] Son Y.I., Kim I.H. Complementary PID controller to passivity-based nonlinear control of boost converters with inductor resistance. *IEEE Transactions on Control Systems Technology*, 2011, vol. 20, no. 3, pp. 826-834.

[17] Zeng J.W., Zhang Z., Qiao W. An interconnection and damping assignment passivity-based controller for a DC/DC boost converter with a constant power load. *IEEE Transactions on Industrial Electronics*, 2014, vol. 50, no. 4, pp. 2314–2322.

[18] Sreedevi, S. L., Geetha B. T. Optimal EV charging using ANT lion optimized ANN based MPPT with high gain modified zeta converter. *International Journal of Electrical and Electronics Engineering*, 2024 by SSRG-IJEEE Journal, 2024, vol. 11, no. 2.

[19] Zeng J.W., Zhang Z., Qiao W. An interconnection and damping assignment passivity-based controller for a DC/DC boost converter with a constant power load. *IEEE Transactions on Industrial Electronics*, 2014, vol. 50, no. 4, pp. 2314–2322.

[20] Kulasekaran P.S., Dasarathan S. Design and Analysis of Interleaved High-Gain Bi-Directional DC–DC Converter for Microgrid Application Integrated with Photovoltaic Systems. *Energies*, 2023, vol. 16, no. 13, pp. 5135.

[21] Kumar M., Panda G. Analysis of Conventional and Interleaved Boost Converter with Solar Photovoltaic System. *In 2022 International Conference on Intelligent Controller and Computing for Smart Power (ICICCSP)*, 2022, pp. 1-6, IEEE.

[22] Nouri T., Shaneh M., Benbouzid M., Kurdkandi N.V. An interleaved ZVS high step-up converter for renewable energy systems applications. *IEEE Transactions on Industrial Electronics*, 2021, vol. 69, no. 5, pp. 4786-4800.

[23] Pirashanthiyah L., Edirisinghe H.N., De Silva W.M., Bolonne S.R., Logeeshan V., Wanigasekara C. Design and Analysis of a Three-Phase Interleaved DC-DC Boost Converter with an Energy Storage System for a PV System. *Energies*, 2024, vol. 17, no. 1, pp. 250.

[24] Uzmus H., Genc N., Celık M.A. The Modified MPPT for PV System with Interleaved Hybrid DC-to-DC Boost Converter. *Electric Power Components and Systems*, 2023, vol. 51, no. 1, pp. 46-58.

[25] Charin C., Ishak D., Mohd Zainuri M.A., Ismail B. Modified levy flight optimization for a maximum power point tracking algorithm under partial shading. *Applied Sciences*, 2021, vol. 11, no. 3, pp. 992.

[26] Prabhakaran P., Agarwal V. Novel boost-SEPIC type interleaved DC–DC converter for mitigation of voltage imbalance in a low-voltage bipolar DC microgrid. *IEEE Transactions on Industrial Electronics*, 2019, vol. 67, no. 8, pp. 6494-6504.

[27] Dasari R.K., Dharmaraj G. I. Photovoltaic hybrid boost converter fed switched reluctance motor drive. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 2022, vol. 13, no. 1, pp. 275.

[28] Pan C.T., Chuang C.F., Chu C.C. A Novel Transformer-less Adaptable Voltage Quadrupler DC Converter with Low Switch Voltage Stress. *IEEE Trans. Power Electron*, 2014, vol. 29, no. 9, pp. 4787-4796.

[29] Garcia F.S., Pomilio J.A., Spiazzi G. Modeling and Control Design of the Interleaved Double Dual Boost Converter. *IEEE Trans. Ind. Electron,* 2013 vol. 60, no. 8, pp. 3283-3290.

[30] Lu S., Mu M., Jiao Y., Lee F.C., Zhao Z. Coupled Inductors in Interleaved Multiphase Three-Level DC–DC Converter for High-Power Applications. *IEEE Trans. Power Electron*, 2016, vol. 31, no. 1, pp. 120-134.
[31] Wang F., Lei Z., Xu X., Shu X. Topology Deduction and Analysis of Voltage Balancers for DC Microgrid. *IEEE J. Emerg. Sel. Topics Power Electron*, 2017, vol. 5, no. 2, pp. 672-680.
[32] Ahamadi T., Rokrok E., Hamzeh M. Mitigation of Voltage Unbalances in Bipolar DC Microgrids Using Three-Port Multidirectional DC-DC Converters. *Journal of Power Electronics*, 2018, vol. 18, no. 4, pp. 1223-1234.

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