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Maximum Power Point Tracking Performance Benchmarking of High Step-Up DC-DC Converters

Kenan AYTEN[1]*, Murat Mustafa SAVRUN[2]

[1] Osmaniye Korkut Ata University, Electrical & Electronics Engineering, 80010, Osmaniye, Turkey
[2] Adana Alparslan Türkeş Science and Technology University, Electrical & Electronics Engineering, 01250, Adana, Turkey

[1]https://orcid.org/0000-0003-2242-3269
[2]https://orcid.org/0000-0001-5847-5082
*Corresponding author: kenanayten@osmaniye.edu.tr

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ABSTRACT

Renewable energy sources (RESs) such as photovoltaic panels (PV) and fuel cells (FC) are frequently equipped with DC-DC converters to regulate output voltage and to extract maximum energy because of their intermittent nature. In addition to regulation capability, the DC-DC converters need to increase low output voltage levels of RESs with their high gain capability. Although conventional boost converters are a good candidate to reduce the number of series-connected PV panels, they have recently been replaced by high voltage gain step-up DC-DC converters due to the disadvantages of limited voltage gain and high switching stress. The main aims of the high gain converters are to provide high voltage gain and to extract maximum power from the PV systems. In this paper, the benchmarking of maximum power extraction capabilities of high step-up DC-DC converters for PV-powered systems, have been presented. Three different high gain step-up DC-DC converter topologies: (i) quadratic boost converter (QBC), (ii) three level boost converter (TLBC), (iii) stacked boost converter (SBC) have been analysed under maximum power point tracking (MPPT) mode that uses the Perturb and Observe (P&O) algorithm. 5.11 kW PV-powered system has been modelled in the MATLAB/Simulink environment for each converter using same design parameters. The aforementioned converters are simulated under different irradiances: 1000, 900, 850, 750 and 700. The performance comparison of the converters has been conducted for such metrics; the maximum PV power, converter efficiencies, output current and voltage ripples. Performance results show that; the TLBC topology excels with the advantages of higher energy extraction capability and efficiency values. The efficiency values of the converters are 98.9%, 98.1%, and 96.5% for TLBC, SBC, and QBC, respectively.

Yüksek Yükseltici DA-DA Dönüştürücülerin Maksimum Güç Noktası İzleme Performansı Karşılaştırması

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ÖZ

Fotovoltaik paneller (FV) ve yakıt hücreleri (YH) gibi yenilenebilir enerji kaynakları (YEK'ler), kesintili yapıları nedeniyle çıkış voltajını düzenlemek ve maksimum enerjiyi elde etmek için sıklıkla DA-DA dönüştürücülerle birlikte kullanılır. Düzenleme kabiliyetine ek olarak, DA-DA dönüştürücülerin yüksek kazanç kabiliyeti ile YEK'lerin düşük çıkış voltaj seviyelerini arttırması gerekir. Geleneksel yükseltici dönüştürücüler, seri bağlı FV panellerinin sayısını azaltmak için iyi bir aday olsa da, sınırlı voltaj kazancı ve yüksek anahtarlama stresi dezavantajları nedeniyle son zamanlarda bunların yerini yüksek voltaj kazançlı kademeli DA-DA dönüştürücüler almıştır. Yüksek kazançlı dönüştürücülerin temel amacı, yüksek voltaj kazancı sağlamak ve FV sistemlerden maksimum güç elde etmektir. Bu çalışmada, FV ile çalışan sistemler için yüksek kademeli DA-DA dönüştürücülerin maksimum güç elde etme yeteneklerinin kıyaslaması sunulmuştur. Üç farklı yüksek kazançlı yükseltici DA-DA dönüştürücü topolojisi: (i) ikinci dereceden yükseltici dönüştürücü (QBC: quadratic boost converter), (ii) üç seviyeli yükseltici dönüştürücü (TLBC: three level boost converter), (iii) yığınlı yükseltici dönüştürücü (SBC: stacked boost converter) maksimum güç noktası izleme (MGNİ) yöntemi altında analiz edilmiştir. Değiştir ve gözlemle (D&G) algoritmasını kullanan MGNİ yönetimi ile 5,11 kW FV destekli sistem, aynı tasarım parametreleri kullanılarak her bir dönüştürücü için MATLAB/Simulink ortamında modellenmiştir. Bahsi geçen dönüştürücülerin, 1000, 900, 850, 750 ve 700 gibi farklı ışınımlar altında benzetim çalışmaları gerçekleştirilmiştir. Dönüştürücülerin performans karşılaştırması, maksimum FV gücü, dönüştürücü verimlilikleri, çıkış akımı ve voltaj dalgalanmaları metrikleri ile yapılmıştır. Performans sonuçları, TLBC topolojisinin daha yüksek enerji elde etme kapasitesine sahip olduğunu ve daha yüksek verimlilik değerleri ile öne çıktığını göstermektedir. Dönüştürücülerin verimlilik değerleri TLBC, SBC ve QBC için sırasıyla %98,9, %98,1 ve %96,5'tir.

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1. Introduction

Recently, the integration of RESs has been an inevitable matter because of the limited fossil fuel reserves and carbon emissions resulting from thermal power generation. Therefore, RES-based applications are the focus of interest in recent years (İnci et al., 2021). One of the leading RES is PV panels having low cost and less complexity (Hernández-Callejo et al., 2019). The power production capacity of PV systems is affected by irradiance, temperature, and shadowing. In order to mitigate the adverse effect of the related parameters, PV-powered systems are integrated with regulator circuits that are endowed with MPPT algorithms. In recent, RESs are generally equipped with high step-up DC-DC converters in order to boost output voltage (Forouzesh et al., Lehman, 2017). In the literature, a lot of high step-up topologies have been proposed for the integration of RESs (Mohamed and Fardoun, 2016). The high step-up DC-DC converter topologies are classified in two as isolated and non-isolated (Schmitz et al., 2020). QBC, TLBC, and SBC, which are frequently used topologies in PV-powered applications, are some types of non-isolated topologies. QBC topology stands out with a low inductor current (Li et al., 2020). In the study of (Hu et al., 2020), an ultra-high step-up QBC based on coupled-inductor has been proposed and voltage gain has significantly enhanced. TLBC, which is the derivation of a traditional boost converter, has the advantages of reduced inductor size and low voltage stress on the switches (Raghavendran et al., 2021). High efficiency TLBC is available for high voltage application as a series resonant converter (Yang et al., 2021). In addition to benefiting from the advantages of the relevant topology, controller development studies have also been carried out to improve its performance. In the study (Guo et al., 2017), model predictive control is employed TLBC in PV systems. SBC is a converter that is capable of performing zero voltage switching and providing continuous input current (Park et al., 2011). Also, several studies have been presented regarding high step-up converter endowed with MPPT algorithms in PV system in recent years. TLBC have been integrated into PV systems with

MPPT capability in order to enhance the output voltage range (Raghavendran et al., 2021). In another study, performance of PV system equipped with quadratic boost converter have been analyzed under MPPT mode (Altin and Ozturk, 2016).

In addition to high voltage gain capability, the converters need to extract maximum power from PVs. In literature, various MPPT methods are proposed in terms of application purposes. One of the most famous MPPT methods is the P&O algorithm which is having easy implementation. On the other hand, new MPPT methods exist in the literature for special applications. In the study of (Kesilmiş, et al., 2020), the authors present a new MPPT method for partial shading conditions. In another study (Yazıcı, et al., 2021), the MPPT method based on the Fibonacci search algorithm has been proposed. In another study (Karabacak, 2019), the P&O-based MPPT method with higher-order sliding mode control for wind turbine systems has been presented.

As it is understood from the literature review, researchers focus on high gain converters and the integration of MPPT algorithms into converters in PV systems. In this paper, MPPT performance comparisons of high step-up converters: QBC, TLBC and SBC have been presented and analysed in detail. The pattern of the paper is organized as follows. The aforementioned converters topologies have been described in section 2, whilst PV characteristic and MPPT method is outlined in section 3. Section 4 presents the simulation results. Finally, conclusions and discussions are presented in Section 5.

2. High Step-Up DC-DC Converter Topologies

In this section, topologies of DC-DC converters which are integrated with PV-powered system have been described. In order to evaluate the performance results of high gain topologies under MPPT operation, simulation models have been conducted in MATLAB/Simulink. Three different suitable high voltage gain DC-DC converter topologies are implemented and investigated: (i) QBC, (ii) TLBC, and (iii) SBC. The modeled PV-powered and high step-up DC-DC converter integrated system is presented in Figure 1. While the converters are operated with P&O algorithm, switches are triggered with 10 kHz switching signals. PV system includes 3 series modules, 8 parallel strings. The PV system is able to produce 5.11 kW, 4.61 kW, 4.37 kW, 3.87 kW and 3.61 kW powers under irradiances of 1000, 900, 850, 750 and 700, respectively.

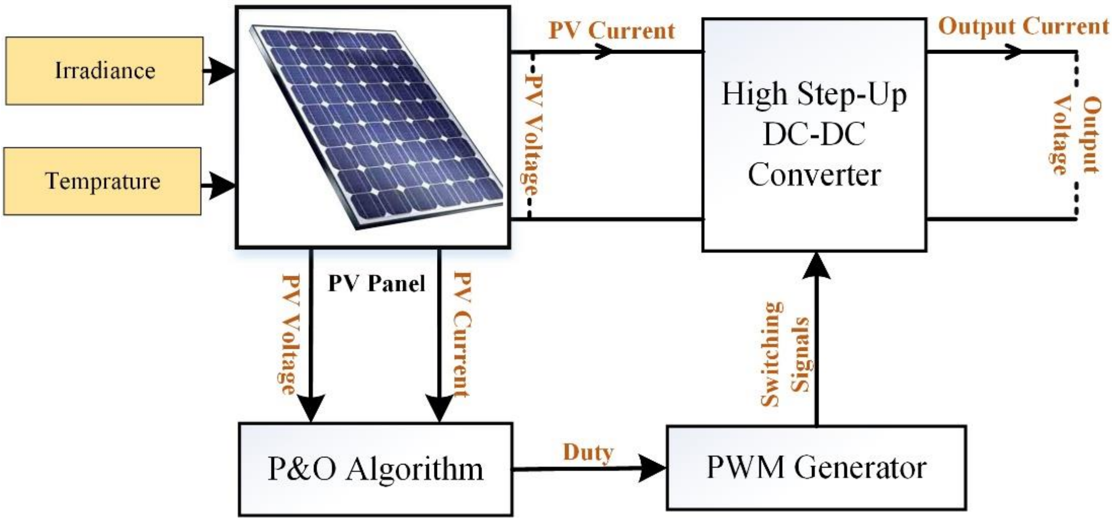

Figure 1. PV system scheme

The determined converters and their features are briefly summarized below and converter topologies have been presented in Figure 2. QBC has a wider voltage gain range with fewer elements and lower cost, against the complex high step-up boost converters. On the other hand, it can operate with higher efficiency than conventional single-switch converters thanks to low current ripple and voltage stress (Wijeratne and Moschopoulos, 2012). QBC is a topology with the specifications of low complexity and low cost, owing to having a single switch (Wang et al., 2019) and its topology has been shown in Figure 2a. TLBC which is derivative from conventional boost converter by integrating series capacitor and switch is another topology investigated in this study. TLBC which is illustrated in Figure 2b stands out with the low output voltage ripple and high voltage gain capabilities (Ganjavi et al., 2018). The last topology is SBC which has a higher step-up conversation ratio by means of a coupled inductor in comparison with the others. Also, SBC topology is able to provide zero voltage switching, continuous input current and reduced reverse recovery on diodes (Park et al., 2011). However, having a lot of component and series capacitor arrays, are disadvantages of SBC. SBC topology is presented in Figure 2c.

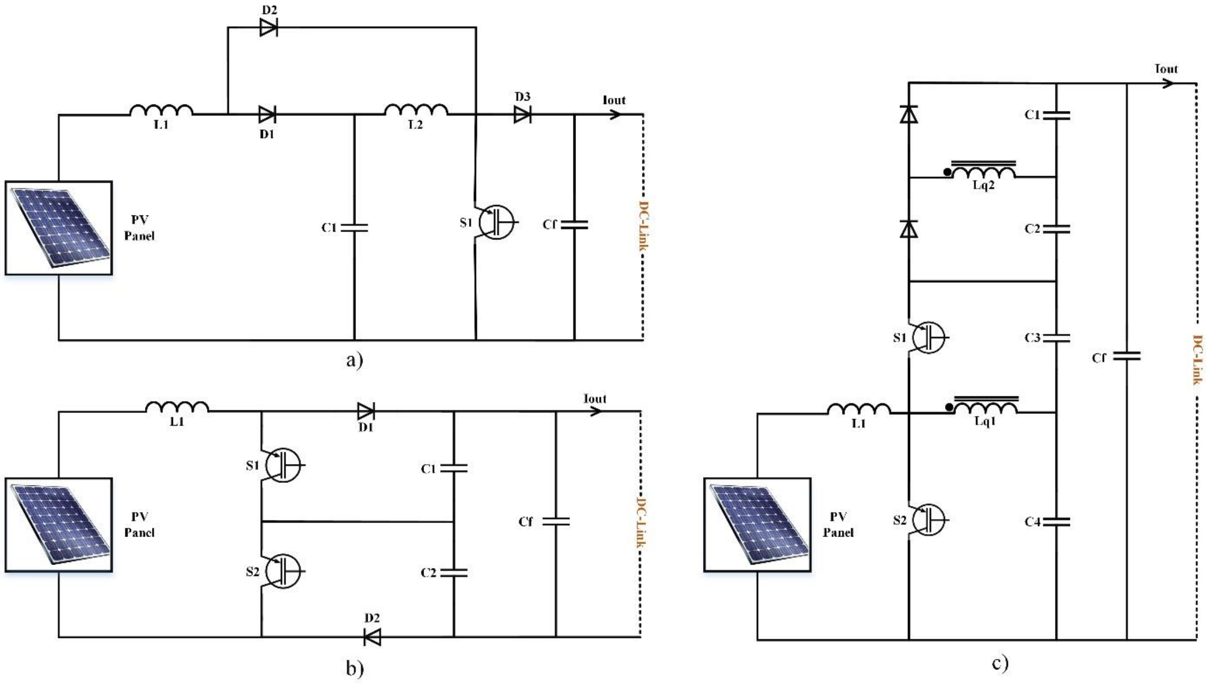

Figure 2. High step-Up DC-DC converters topologies a) QBC b) TLBC c) SBC

QBC topology contains an active switch and thus is relatively easy to control compared to latter topologies. Considering the duty cycle range, that can vary between 0-1, of the QBC, the relationship between the input (V_{in}) and output (V_{out}) voltages is computed using the S_1 duty cycle (D). It is expressed as;

$$V_{out} = \frac{V_{in}}{(1-D)^2} \tag{1}$$

Inductor currents of QBC can be expressed in equation 2 and 3. As seen from equations, augmentation of duty cycle is caused to increase input current (I_{L1}) higher from the output voltage (V_{out}) in QBC.

$$I_{L1} = \frac{V_{in}}{Z_L(1-D)^4} \tag{2}$$

$$I_{L2} = \frac{V_{in}}{Z_L(1-D)^3} \tag{3}$$

where, Z_L is output load and D is duty cycle of switch for QBC. In TLBC, S1 and S2 operate complementary and have same duty cycle value (D). If D is greater than 0.5, two switches are open in one period during (D-0.5) TS which is called shoot through period. This period is activated when high voltage gain is needed. Conversion ratio of TLBC can be calculated by equation 4.

$$V_{out} = \frac{2}{1-D} V_{in} \tag{4}$$

In SBC, duty cycle varies between 0 and 1. Due to the coupled inductor in the SBC topology, the voltage gain is connected to both the turn ratio of the coupled inductor and duty cycle of switches. Voltage gain of TLBC can be calculated by equation 5 (Park et al., 2011).

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \frac{V_{So}}{V_L} (1 + \frac{V_L}{V_{So}}) \approx \frac{1+n}{1-D} \tag{5}$$

where V_L is primary output voltage of coupled inductor and V_{So} is secondary output voltage of coupled inductor. A comparative analysis between existing high step-up converter topologies used in PV system is summarized in Table 1.

Table 1. Comparison of high step-up converters

Topologies	Number of switch	Number of capacitor	Number of inductor	Number of coupled inductor	Gain	Efficiency (~)
QBC	1	2	2	0	$\frac{1}{(1-D)^2}$	%98
TLBC	2	3	1	0	$\frac{2}{1-D}$	%98
SBC	2	5	1	1	$\frac{1+n}{1-D}$	%97

Table 1 presents the comparison of the aforementioned converters in terms of number of components and voltage gain values. While SBC have more component and lower efficiency than others, it has the high voltage gain capability thanks to the turns ratio of coupled inductors. QBC stands out with low complexity because of having single switch. On the other hand, it has exponential voltage gain capability according to the duty cycle. However, high duty cycle values can decrease efficiency and increase input current. Lastly, TLBC has the lower voltage gain capability with high efficiency value.

3. MPPT Algorithm

The DC-DC converters have been controlled with P&O algorithm to extract maximum power from PV panel because of its simplicity and ease of implementation. While the controller monitors the PV voltage and current continuously, the algorithm perturbs the operating voltage of PV in order to regulate the instantaneous power flow. The PV panel voltage is increased or decreased to control whether the power is increased or decreased (Salman et al., 2018). The instantaneous PV power is compared with the power calculated in the previous sampling (Savrun & Atay, 2020). If the output power increases, the voltage perturbation continues in the same direction otherwise perturbation is reversed. Flow chart of P&O algorithm is shown in Figure 3. ΔD corresponds to perturbation size of the algorithm is determined as a low value in order to increase the sensitivity of MPPT (Suntio and Kuperman, 2019).

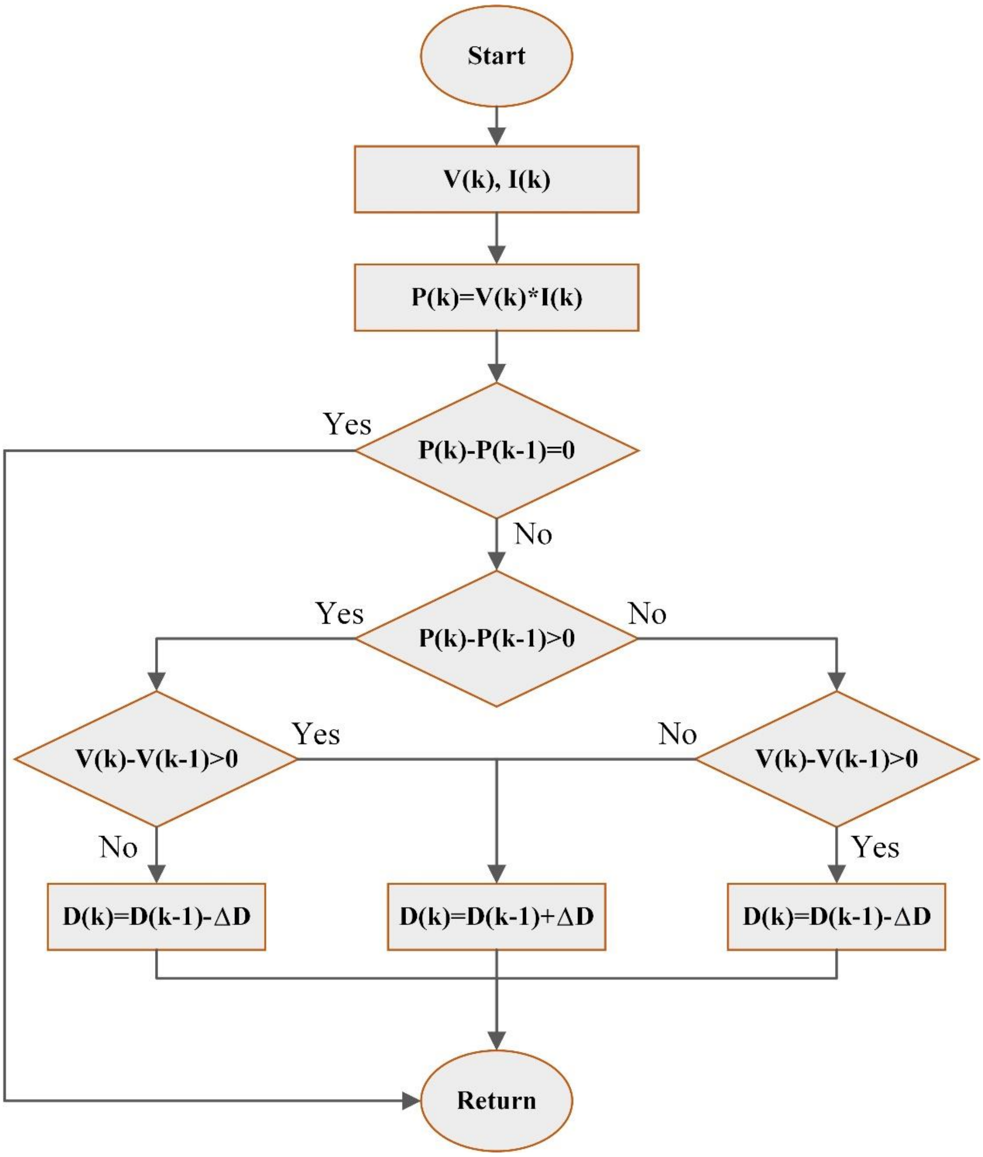

Figure 3. P&O algorithm flowchart

The performance evaluations of the DC-DC converters have been performed using a PV module in the rating of 5.11 kW, namely 1STH-215-P of the Soltech Company. The related PV cell have 213.5 W maximum power, 29 V maximum power voltage, 7.84 A maximum power current, 36.3 V open circuit voltage, 7.84 A short circuit current. The power-voltage characteristic of PV module has been captured for 5 different irradiances at 25° C in Figure 4. In the simulation model, 5.11 kW, 4.61 kW, 4.37 kW, 3.87 kW and 3.61 kW are maximum power of PV panel under the irradiance condition of: 1000, 900, 850, 750 and 700, respectively.

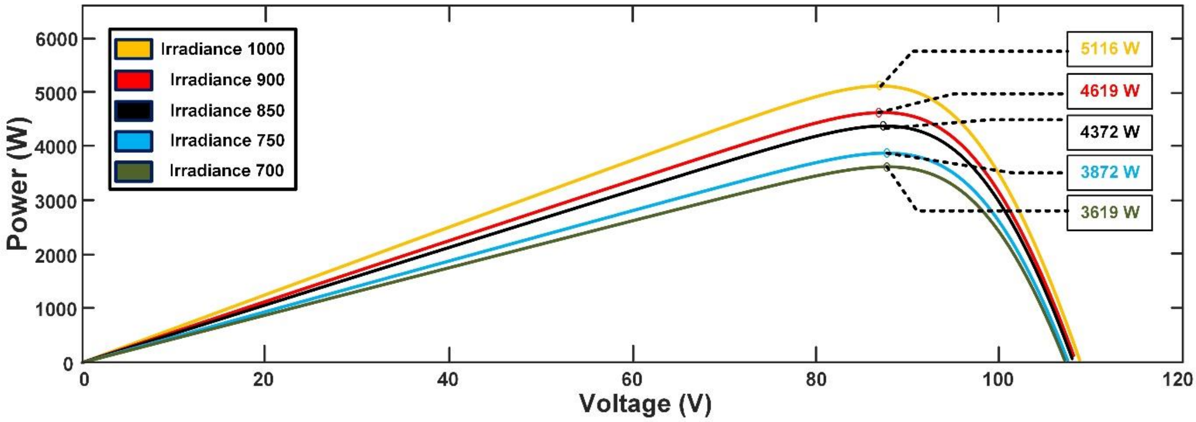

Figure 4. Power-voltage characteristic of PV

4. Simulation Results

The performance evaluations of the related topologies have been carried out with 5.11 kW PV-powered system on the MATLAB/Simulink environment. These converters have been simulated with the same design parameters and under the same irradiance conditions. The converters have been compared in the aspects of the maximum PV power, the energy efficiency of converters, output voltage and current ripple. Detailed performance results have been present in Table 2. TLBC has the best result in terms of getting maximum power from the PV panel as seen from Table 2. It is also above average in terms of voltage gain. However, the efficiency of TLBC decreases indirectly proportional with the irradiance. Also, the efficiency of SBC decreases indirectly proportional with the irradiance while the efficiency of QBC increases inversely proportional with the irradiance.

Table 2. Performance of high step-up converters

	Max. Power (Watt)		**Voltage Gain (V_{out}/V_{in})**		**Efficiency (P_{out}/P_{in})**	
Irradiance / Topologies	**1000**	**700**	**1000**	**700**	**1000**	**700**
QBC	5077	3594	2.27	1.90	%96.5	%97.2
TLBC	5110	3614	2.30	1.94	%98.9	%98.7
SBC	5077	3584	2.30	1.91	%98.1	%97.8

Generally, efficiency is expected to be maximum in operating power and operating power is 5.11 kW for this study. However, Table 2 illustrates that the QBC is different from TLBC and SBC in terms of the relationship between power and efficiency. The efficiency of QBC in 700 irradiances is higher than in 1000 irradiance. This difference depends on the duty cycle of the QBC. The duty cycle-efficiency curve of QBC is given in this study (Wijeratne and Moschopoulos, 2012).

Figure 5 shows PV powers in the MPPT operation mode of each topology for five irradiances as 1000, 900, 850, 750, and 700. Zoom in view figures illustrates the transient conditions which correspond to irradiance changes. As seen from the figure, the TLBC excels with energy extraction performance as well as the response time.

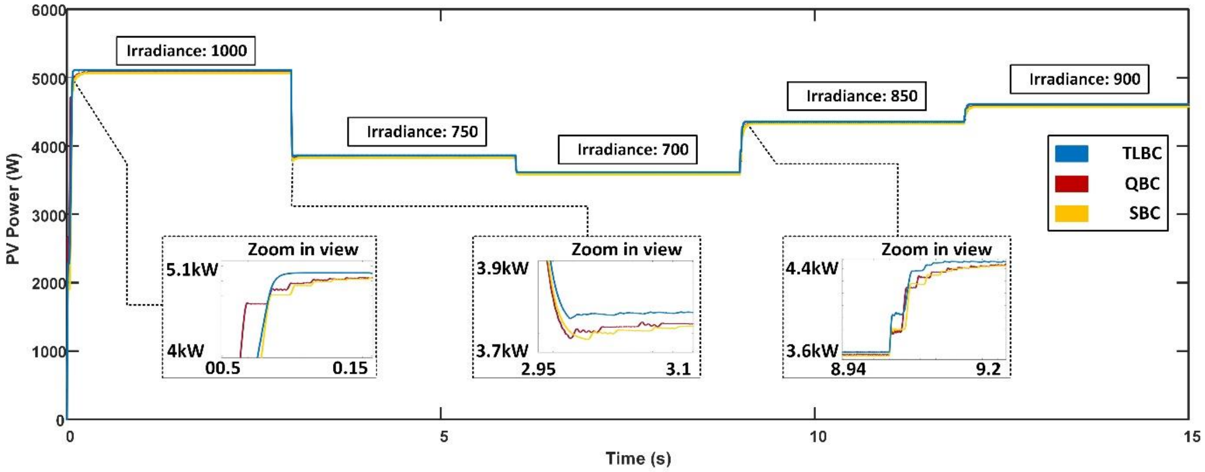

Figure 5. PV power analyzes

DC-link voltage and DC-link voltage ripple in MPPT operation mode of each topology for five irradiances have been shown in Figure 6. While TLBC is the best converter in terms of DC-link voltage ripple, QBC has the worst result.

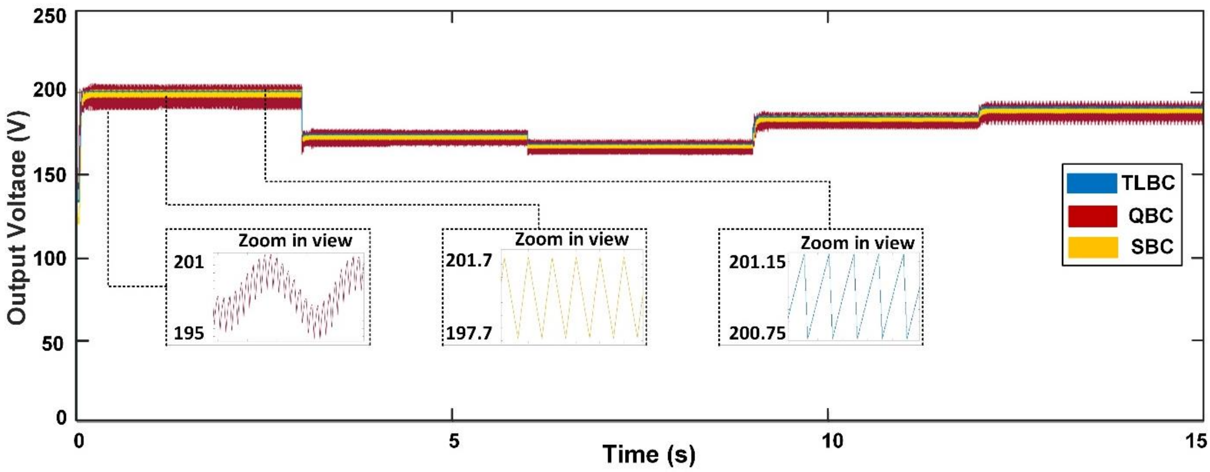

Figure 6. DC-link voltage analyzes

Output current and output current ripple in the MPPT operation mode of each topology for five irradiances are illustrated in Figure 7. While QBC has the worst result in terms of output current ripple, TLBC excels with the advantage of low output current ripple.

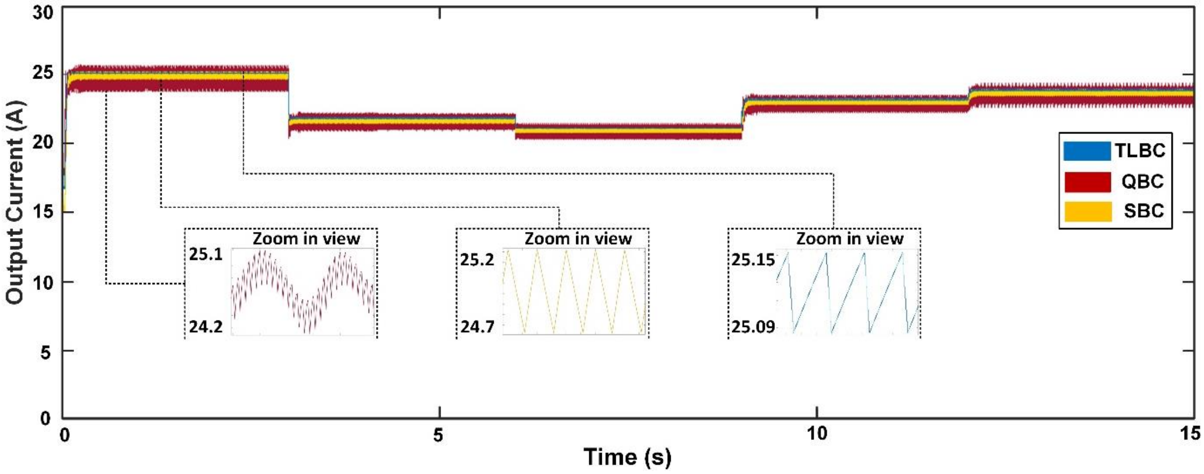

Figure 7. DC-link current analyzes

5. Conclusion

Renewable energy sources (RESs) have intermittent output power as well as low output voltage, therefore they are usually integrated with high voltage gain DC-DC converters to extract maximum energy and provide high gain at the output. The main goals of the emerging DC-DC converters are to extract maximum energy from PV panel and to provide high voltage gain. In this study, three different high voltage gain DC-DC converters have been designed and simulated for PV applications. Also, MPPT performance benchmarking of these converters has been presented. The power extraction capabilities by employing the P&O algorithm, efficiencies, and voltage gains of the related topologies have been investigated under different irradiance conditions. The performance results of each converter have been captured from the same proof-of-concept model of a 5.11 kW PV-powered system modelled in the MATLAB/Simulink. The performances of DC-DC converter topologies have been evaluated under different irradiances as 1000, 900, 850, 750, and 700. As a result, TLBC excels with the aspects of extracting maximum power from PV as well as performing the highest efficiency in comparison with other topologies. Although SBC and QBC lag behind TLBC in terms of maximum power output, they have high efficiency. As consequence, TLBC has been performed the best results for each aspect.

In PV applications, topology selection should be performed considering the design parameter and special purpose. For this reason, design parameters such as weight, size, frequency, and temperature and power play critical roles in the application. Since the SBC includes coupled inductor as a magnetic element, the size of converter can increase and efficiency can decrease in low switching frequency application. TLBC can select for the application which efficiency is important. However, it has a restriction in voltage gain capability in comparison with the other topologies. As for QBC, it can be used for in applications which is not sensitive for output ripple.

Statement of Conflict of Interest

The authors have declared no conflict of interest.

Author's Contributions

The contribution of the author's is equal.

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