Comparison Analysis between Various Boost Chopper Configurations

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Abstract: - This paper investigates the behaviors of various configuration of Boost DC chopper used in Photovoltaic energy systems or in various voltage regulators. The targeted boost converters are conventional Buck-Boost (BB), traditional single ended primary coil (TSEPIC) and modified single ended primary coil (MSEPIC). The comparison analysis in based on studying the chopper behaviors with respect to the modulation frequency, then studying the chopper behaviors with respect to duty operation cycle at optimized frequency. The subjected parameters are output voltage ripple, current ripples, overall efficiency, source current and voltage gain. A mathematical model for up mentioned performances is derived and a simulation model using Matlab/ Simulink platforms is conducted to follow these behaviors.
Simulation results indicate that each of those choppers has certain switching frequency at which they have optimized performances with respect to voltage gain and efficiency. Then there are optimized operation at certain frequency and duty cycle. MSEPIC converter indicates that with respect to efficiency, voltage gain and ripples that displayed better performances comparing with other converters, where the efficiency approaches 98% and the voltage gain exceeds 19 times the input voltage at duty cycle of 90% while the other converters have 3 times the source voltage. With respect to voltage and current ripples MSEPIC displayed minimum values where ΔVo is less than 0.7%. The conducted simulations confirm the better utilization and importance for using MSEPIC rather that either BB or TSEPIC with respect to voltage gain, efficiency, current stress on the power switches and related elements. The performances of proposed calculated algorithm for different converters are analyzed and verified by simulations with the help of MATLAB/Simulink.

Key-Words: -DC-DC Power Conversion, Buck-Boost Converter, Traditional SEPIC Converter, Modified SEPIC Converter, SMPS.

Received: May 4, 2021. Revised: December 20, 2021. Accepted: January 12, 2022. Published: February 8, 2022.

1 Introduction

In the last two decades, there has been a strong tendency towards using alternative energy sources in order to reduce the emissions of green gases harmful to the environment produced by the most used non-renewable energy resources such as coal, natural gas, fossil fuels etc. These sources facing serious problem related to their sustainability and create serious environmental challenges on short and long term.

In addition, the traditional sources suffer greatly from the expected depletion, the fluctuations of the global market, and the global political crises, or economic consequential crises.As well-known alternative sources of energy are inexhaustible, environmental friendly and fulfil the world demand toward minimizing the needs of reserve fossil fuels. Photovoltaic solar energy presents one of the most effectively used sources [1,2].

Usually integrating of the renewable energy generator with the local utility is realized throughout conditioning unit consist of DC chopper, inverter, filtering circuit and high voltage transformer. The DC chopper plays major role in regulating the PV voltage at values corresponding to maximum power at given irradiation [3].Meanwhile, DC converters are cheaper, with complex configuration, and requiring a certain elements of inductance and capacitance [4, 5]. Furthermore these converters are characterized with huge current and voltage ripples that can be limited by using LC- filter or large value capacitor [6]. DC-DC converters have various topologies such as Buck, Boost, Buck-Boost, and Cuk converters. Furthermore, boosting up the unregulated input DC voltage generated by the PV generator into a high output regulated non-inverting voltage can be realized throughout so called Single Ended Primary Inductor Converters (SEPIC). These converters are suffering from heavy electrical stresses yields from existing large values of inductance and capacitance that cause eventual failure and they are not the best choice and cost effective among these converters [8].

Recently, SEPIC and Buck-Boost converters found wide spread applications in PV solar systems and battery charging applications where the battery voltage can be regulated above and below the output voltage [7-12].

Furthermore, it is utilized in power factor correction applications and LED drivers [13-16]. In order to reduce the voltage stress across the switches, to increase the efficiency, and to increase the voltage gain a various combinations of boost with Cuk [17, 18], and Boost with SEPIC studied in [19,20]. The most important drawbacks of these configurations are high current ripples, low voltage gain, moderate efficiency and high voltage stress over the switching devices. To overcome these drawbacks a Modified SEPIC converter is developed by combining conventional SEPIC with Boost converter and diode-capacitor circuit as stated in [21]. This converter for PV system is capable of generating high voltage gain, low switching stress, and low conduction losses.

In this study, the performances of modified SEPIC converter presented by [21] will be investigated and compared with other step-up converters.

2 Overview of Step-up Converters

Step-up converter has been popular in the last few years, especially for high voltage conversion in grid-connected PV systems. The obtained voltage from PV array has to be stepped-up before being transferred to the inverter, then to on the grid-connected system. Many step-up converters have been modified to improve its performance.

In [21], the illustrated in Fig.1 conventional SEPIC converterhas been modified by combining it with the Boost converter and diode-capacitor circuit as shown in Fig.2. This converter comprises the main switching device (S), three capacitors (C_1, C_2, and C_{out}), two diodes (D_1 and D_2) and two inductors (L_1 and L_2). The presence of the diode-capacitor circuit is able to reduce switching voltage stress on switching device.

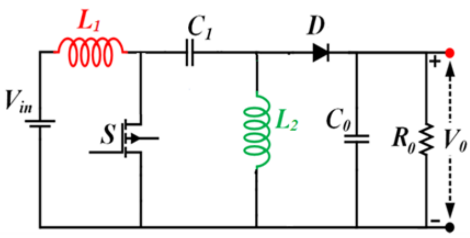


Fig.1: Traditional SEPIC converter.

The output voltage from Boost converter is used to chargesC₂. Furthermore, the voltage of second capacitorV_{C2} is applied to the L_2 during the conduction period of the switching device S. This condition increases the voltage gain that is obtained when compared to the conventional step-up converters.

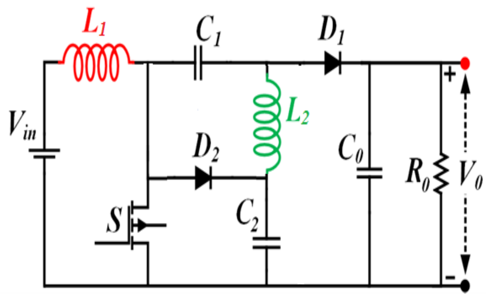


Fig. 2: Modified SEPIC converter.

In this study, the performance of modified SEPIC [21] will be investigated and compared to conventional step-up converters. Boost converter is often used for the basic of the conventional step-up converter [22].

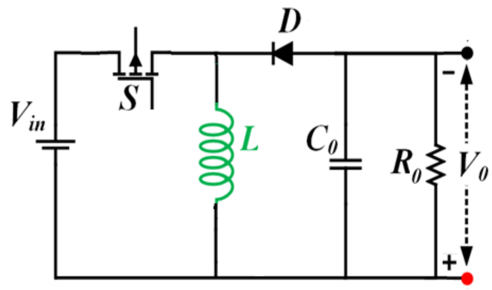


Fig.3 Inverting Buck-Boost converter.

Inverting Buck-Boost converter is the basic of the traditional SEPIC converter.

Its circuit comprises an inductor L,a diode D, an output capacitor C_{out} and the main switching device as shown in Fig.3 [23, 24]. Its output voltage however has negative polarity with respect to that of the supply voltage.The energy in SEPIC converter is transferred through capacitor C_1 and inductor L_1. Therefore, the switching voltage stress on SEPIC converter is higher than the Buck-Boost converter.

Table 1. Converter statistical data [21, 24, 25, 26].

Converter	D=0.9 (max ratio)	Power elements		Energy Storage Elements
		Controlled	Uncontrolled	

BB	9	1	1	2
TSEP	9	1	1	4
MSEP	19	1	2	5

Table1 compares the number of the main components of each converter. Where each component parameter in step-up converters is calculated by formulas respectively stated in table 2.

Table 2. Step-up Converters Formulas

Parameters	Buck-Boost Converter	SEPIC Converter	Modified SEPIC Converter
Duty Cycle	$D = \frac{V_o}{V_o+V_{in}}$	$D = \frac{V_o}{V_o+V_{in}}$	$D = \frac{V_o - V_{in}}{V_o+V_{in}}$
Inductances	$L = \frac{V_{in}\, D}{\Delta i_L\, fs}$	$L_1 = \frac{V_{in}\, D}{\Delta i_{L1}\, fs}$ $L_2 = \frac{L_1}{2}$	$L_1 = \frac{V_{in}\, D}{\Delta i_{L1} fs}$ $L_2 = \frac{L_1}{2}$
Capacitors	$C_o = \frac{I_o\, D}{\Delta V_o\, fs}$	$C_1 = \frac{I_o\, D}{\Delta V_{C1}\, fs}$ $C_o = \frac{I_o\, D}{\Delta V_o fs}$	$C_1 = C_2 = \frac{i_{L2}\, D}{\Delta V_C\, fs}$ $C_o = \frac{I_o\, D}{\Delta V_o\, fs}$
Static Gain	$G = \frac{V_o}{V_{in}} = \frac{-D}{1-D}$	$G = \frac{V_o}{V_{in}} = \frac{D}{1-D}$	$G = \frac{V_o}{V_{in}} = \frac{1+D}{1-D}$
Capacitor Voltages	$V_{Co} = V_o$	$V_{C1} = V_{in}$ $V_{Co} = V_o$	$V_{C1} = \frac{D\, V_{in}}{1-D}$ $V_{C2} = \frac{V_{in}}{1-D}$ $V_{Co} = V_o$

3 Overview of Step-up Converters

Each parameter of buck-boost BB, traditional TSEPIC and modified MSEPIC converters is selected by default based on of formulas stated in table2, and its obtained results are presented in table 3.

Table 3. Converters Parameters

Converter Type	Vin, V	Vo, V	D	L1,mH	L2,mH	C1,µF	C2,µF	Co, µF	Ro, Ω
BB	56	Variable	0.1– .9	1.98	--	--	--	10	140
TSEPIC	56	Variable	0.1– .9	1.98	0.99	660	--	10	140
MSEPIC	56	Variable	0.1– .9	1.98	0.99	660	660	10	140

4 Optimized Switching Frequency

By using the component parameters stated in table 3, the different converters are simulated using MATLAB/SIMULINK [27], while the input voltage is kept constant at 56 V at given duty ratio of D=0.5 the overall efficiency for various types of converter topologies is calculated according to equation (1) .

$$\eta = \frac{V_o I_o}{V_{in} I_{in}} \quad (1)$$

The obtained simulation results of efficiency are stated in tables 4-6 for various converters respectively.

Table 4 shows Buck-Boost converter Performance at constant duty ratio of D=0.5 for different switching frequencies.

Table 4. Buck-Boost converter Performance at constant duty ratio of D=0.5 for different switching frequencies.

Parameters \ fs / kHz		10	20	30	40	50	60	70
Δi_L / A	Calculation.	1.414	0.707	0.4714	0.3535	0.2828	0.1903	0.1631
	Simulation	1.413	0.7062	0.4712	0.3532	0.2825	0.2354	0.2018
	$\Delta i_L/I_{Lmax}$	94%	61.5%	47%	36%	30%	26%	22%
ΔV_o/ V	Calculation.	2	1	0.6667	0.5	0.4	0.3333	0.2857
	Simulation	2.231	1.08	0.7822	0.6223	0.5291	0.4672	0.4229
	$\Delta V_o/V_o$	4%	1.9%	1.4%	1.1%	0.95	0.84%	0.76%
Gain (G)	Calculation.	1	1	1	1	1	1	1
	Simulation	0.989	0.994	0.995	0.996	0.996	0.996	0.996
Efficiency (η) / %		55.1	60.6	62.1	64.6	65.9	66.5	67.1

Table 5. Traditional SEPIC converter Performance at constant duty ratio of D=0.5 for different switching frequencies.

Parameters \ fs / kHz		10	20	30	40	50	60	70
Δi_{L1} / A	Calculation.	1.414	0.707	0.4714	0.3535	0.2828	0.2357	0.2020
	Simulation	1.411	0.7062	0.4712	0.3532	0.2825	0.2467	0.2137
	$\Delta i_L/I_{Lmax}$	67%	76%	74%	62%	54%	47%	42%
Δi_{L2} / A	Calculation.	2.828	1.414	0.942	0.707	0.5656	0.4713	0.4040
	Simulation	3.217	1.444	0.9524	0.7209	0.5879	0.4948	0.4283
	$\Delta V_o/V_o$	135%	119%	109%	95%	85%	77%	70%
ΔV_c/ V	Calculation.	30.3	15.15	10.10	7.58	6.06	5.05	4.329
	Simulation	100.8	21.39	10.66	8.371	7.272	6.313	5.641
	$\Delta V_c/V_o$	99%	32%	19%	15%	13%	11.3%	10%
ΔV_o/ V	Calculation.	2	1	0.6667	0.5	0.4	0.33	0.2857
	Simulation	5.334	1.542	0.8202	0.6184	0.5165	0.4543	0.4098
	$\Delta V_o/V_o$	5.3%	2.3%	1.5%	1.1%	0.92%	0.81%	0.73%
Gain (G)	Calculation	1	1	1	1	1	1	1
	Simulation	1.81	1.18	1.0	0.999	0.998	0.997	0.996
Efficiency (η) / %		92.2	99.4	88.9	90.6	95.3	95.6	96.9

The consideration design parameters of the converters are explained for the converter duty cycle of D=0.5, at which the current ripple becomes maximum [24].The input (inductor) ripple current is considered to be approximately 40% of the maximum input current [28]. As the average input current is higher than the average output current for a step-up converter, the volume of 2nd inductor $L_2$is lower than the volume of 1st inductor L_1, meaning that the value of L_2=50% L_1as stated in table 3.

The maximum capacitor voltage ripple of C_1equals to nearly 7% of the output voltage for traditional and modified SEPIC converters [28, 29].The output voltage ripple of the output filter capacitance Co is considered equal to 1% of the average output voltage.

The relationship between the efficiency at constant duty cycle (D = 0.5) and switching frequency for different converters are displayed on Fig.4, 5 and 6 for modified MSEPIC, traditional TSEPIC and Buck-Boost (BB) converters respectively taking into account the calculated and simulated results stated in accordance with tables 4, 5 and 6.

Table 6. Traditional SEPIC converter Performance at constant duty ratio of D=0.5 for different switching frequencies.

Parameters	fs / kHz	13	20	30	40	50	60	70
Δi_{L1} / A	Calculation	1.088	0.707	0.4714	0.3535	0.2828	0.2357	0.2020
	Simulation	1.113	0.7109	0.4715	0.3574	0.2941	0.2524	0.2236
	$\Delta i_{L1}/I_{L1max}$	22%	16.9%	12%	9.3%	7.8%	6.7%	6%
ΔiL2 / A	Calculation	2.176	1.414	0.9428	0.707	0.5656	0.4713	0.4040
	Simulation	3.326	1.598	0.9872	0.7479	0.6411	0.5757	0.5361
	ΔiL2/IL2max	114%	81%	56%	47.5%	42%	39%	37%
ΔVc1 / V	Calculation	115.8	57.95	35.58	25.53	19.65	18.64	15.68
	Simulation	114.8	54.21	32.48	24.24	20.50	18.20	16.79
	ΔVc1 /Vo	61%	31%	19%	14%	12%	10.8%	9.98%
ΔVo/ V	Calculation	4.615	3	2	1.5	1.2	1	0.86
	Simulation	5.238	3.122	2.03	1.526	1.239	1.051	0.9213
	ΔVo /Vo	2.8%	1.8%	1.2%	0.9%	0.7%	0.62%	0.55%
Gain (G)	Calculation	3	3	3	3	3	3	3
	Simulation	3.35	3.11	3.04	3.02	3.01	3.01	3.01
Efficiency (η) / %		98.3	97.8	97.8	98.2	98.8	98.7	98.9

For MSEPIC converter with result displayed on Fig.4

$$\eta_{MSEP} = 0.023\, z^5 - 0.026\, z^4 - 0.062\, z^3 + 0.073\, z^2 + 0.037\, z + 0.9 \quad (2)$$

For TSEPIC converter with result displayed on Fig.5

$$\eta_{TSEP} = 0.00057\, z^4 - 0.0021\, z^3 - 0.00015\, z^2 + 0.0058\, z + 0.98 \quad (3)$$

For BB converter with result displayed on Fig.6

$$\eta_{BB} = 0.013\, z^4 + 0.0083\, z^3 + 0.02\, z^2 + 0.014\, z + 0.6 \quad (4)$$

where, $\boldsymbol{z} = \frac{(\boldsymbol{f_s} - \mathbf{40})}{\mathbf{19}}$. (5)

The interpolated efficiency performances of different converters are bundled together and displayed in Fig.7, which shows the distinction of MSEPIC converter's efficiency over the others.

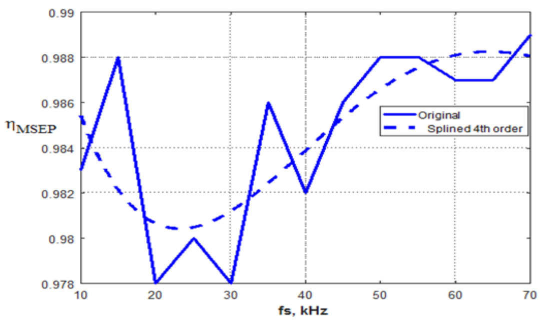


Fig. 4: Efficiency at various frequencies for MSEPIC.

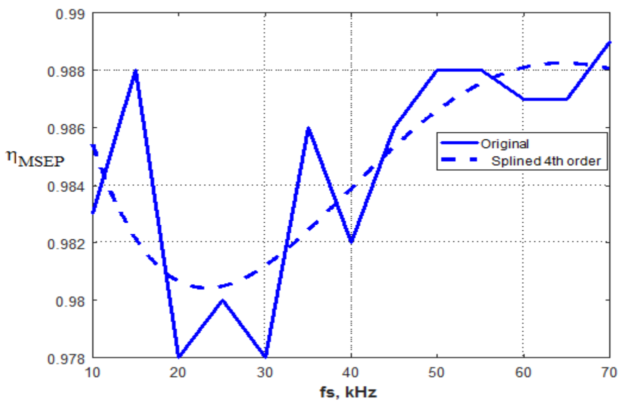


Fig. 5: Efficiency at various frequencies for TSEPIC.

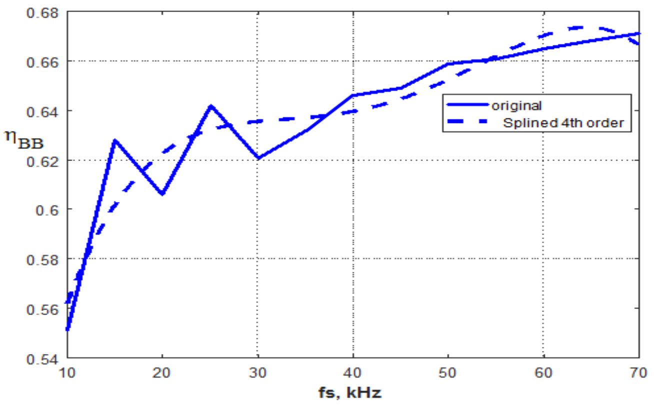


Fig. 6: Efficiency at various frequencies for BB.

In addition, its voltage gain G exceeds the voltage gain of the other converters by three times, as shown in Fig. 8. In order to choose the best switching frequency at high efficiency for different converters, the aforementioned conditions related to voltage and current ripples should be fulfilled, or most of them at least. From the results of table 5 and Fig.9, the inductor current ripple in traditional SEPIC converter is higher than the others.

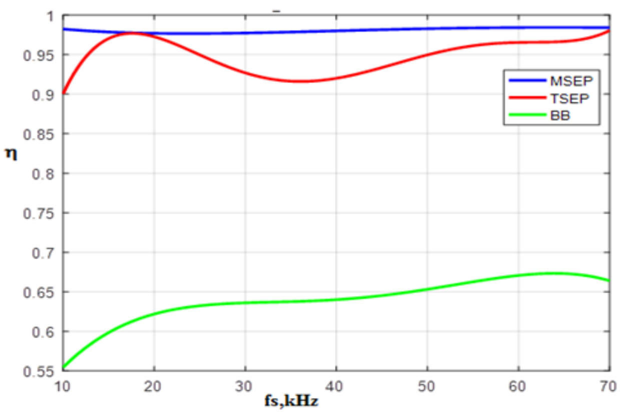


Fig. 7: Efficiency at various frequencies for different converters.

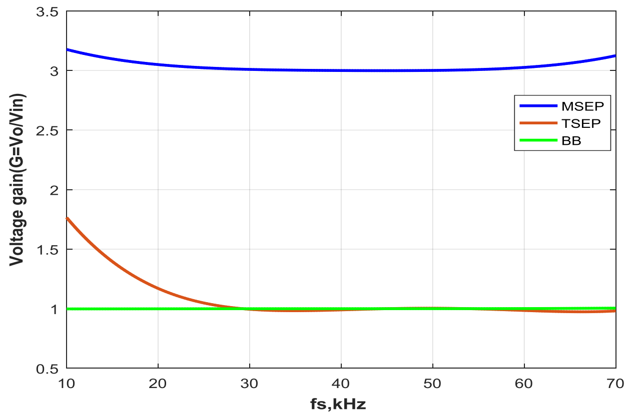


Fig. 8: Voltagegains at various frequencies.

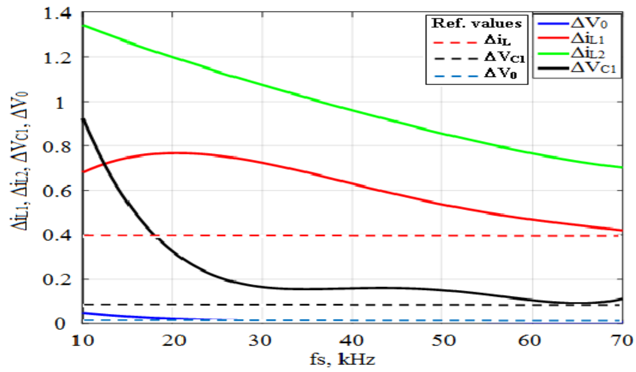


Fig. 9: Continuous performances of TSEPIC. converter

Therefore, the switching frequency of 70 kHz is chosen for this converter because it fulfils the minimum conditions previously mentioned, while the frequency of 50 kHz is sufficient to operate the other converters as shown in Fig.10.

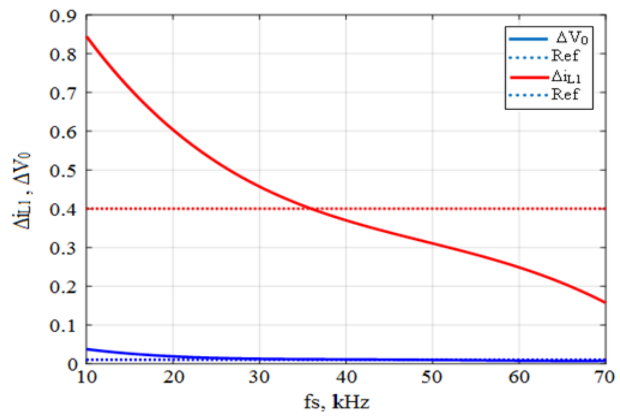


Fig. 10: Continuous performances of BB converter.

5 Simulation Results and Discussion

In order to study the choppers' behaviours as the duty cycle changed D in wide range at given optimized frequency, a simulation circuit is built in SIMULINK platform for MSPEC converter shown in Fig. 11 that can be modified for the other converters.

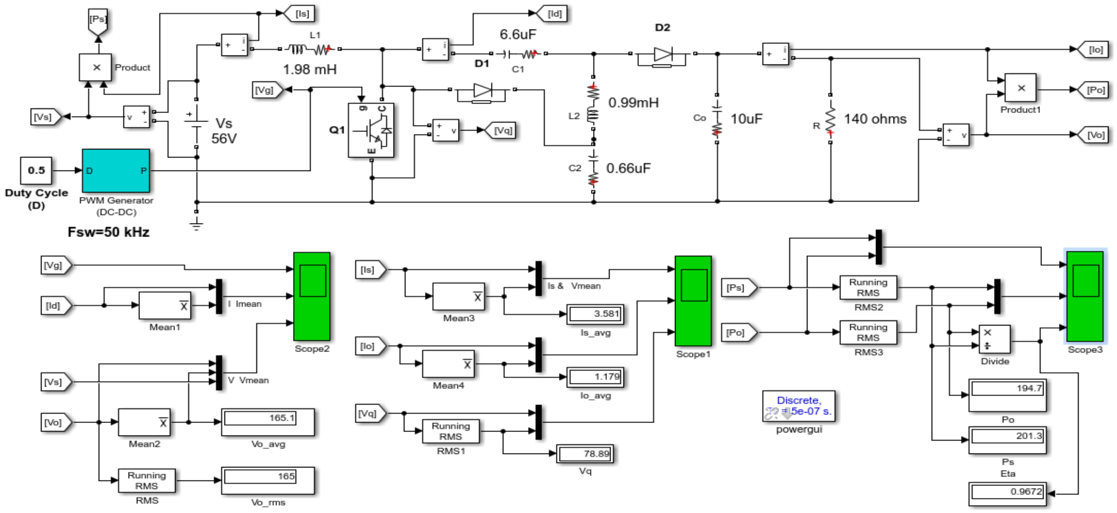


Fig. 11: Simulation platform for MSEPIC converter.

5.1 Voltage Gain Comparison

Fig.12 shows the voltage gains for various converters. It can be seen that the MSEPIC converter outperforms all the other converters in terms of voltage boosting with the gain increasing tremendously at higher duty ratioto about 20 times the input voltage at a duty ratio of D=0.9.However in practice, the efficiency and the life span of a converter become shorter at those high duty ratios [30, 31]. The TSEPIC is seen to have a gain that is closely related to that of inverting BB converter though slightly superior at higher duty ratios.

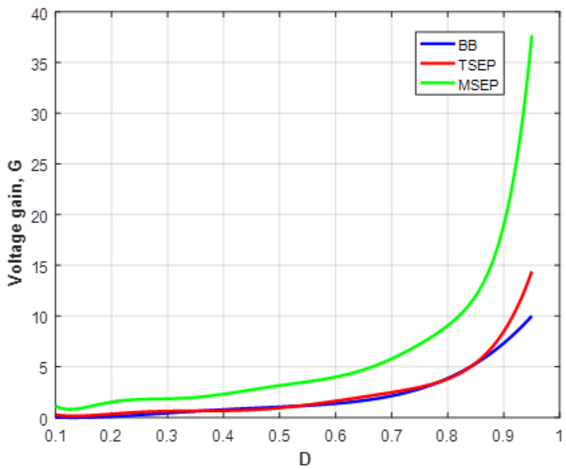


Fig. 12: Voltage gain of different converters for various duty ratios

5.2 Output Voltage Ripple Comparisons

The voltage ripple comparisons of the DC converters at different duty ratio are shown in Fig.13.

The MSEPIC is seen to have very small ripples compared to other converters. This is largely due to it having relatively more filter components than the other converters.

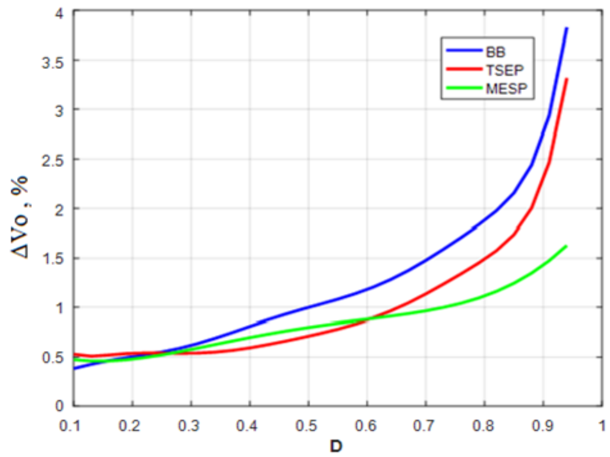


Fig.13: Output voltage ripples.

5.3 Efficiency Comparisons

The comparison of efficiencies of the different converters is shown in Fig.14. From the figure, the MSEPIC is the converter that has the highest efficiency compared to that of the other converters and contains nearly constant at all values of duty ratio. The high efficiency might be due to the added passive components on the MSEPIC converter.

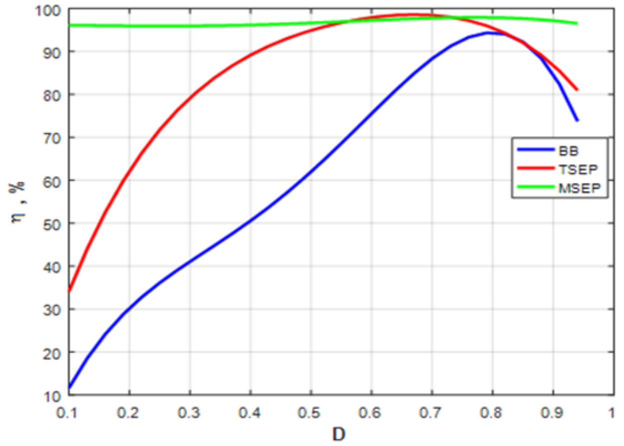


Fig. 14: Efficiency at various configurations.

5.4 Inductor Ripple Current Comparison

From Fig. 15 it can be seen that the MSEPIC is the best in terms of inductor ripple current ΔiL1, which appears much less than its maximum value as stated in the previous conditions during all the values of duty ratio D. While the current ripple values are improved in other converters (less than the permissible limit) after D = 0.5.

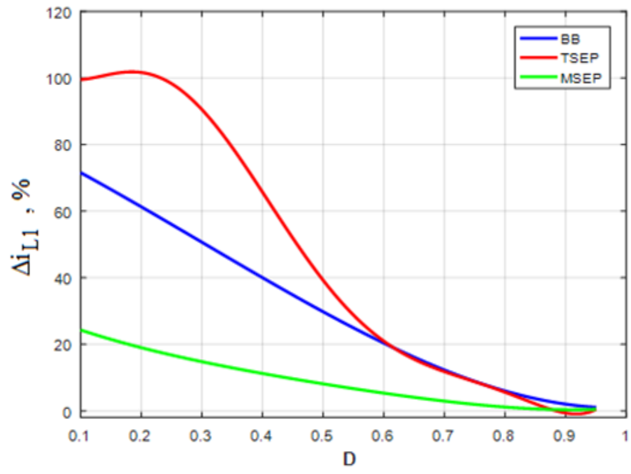


Fig. 15: Inductor current ripples.

5.5 Voltage and Current Time Waveforms

Using formulas stated in table 1 for MSEPIC, if the supply voltage is 56V, then the output voltage at D = 0.1 should be

Vo = [(1+D)/(1-D)] * Vin = (1.1/0.9)*56 = 68.44 V

If at that input voltage and duty ratio the input current is 0.6095 A, then the output current is given by

Io = [(1-D)/(1+D)] * Iin = (0.9/1.1) * 0.6095 = 0.4987 A

The output power at that duty ratio is at its minimum point that is equal to

P_{min} = Io Vo = 68.44 * 0.4987 = 34.13 W.

In the same manner, the output voltage can be calculated at D = 0.9 as

Vo = (1.9/0.1) * 56 = 1064 V

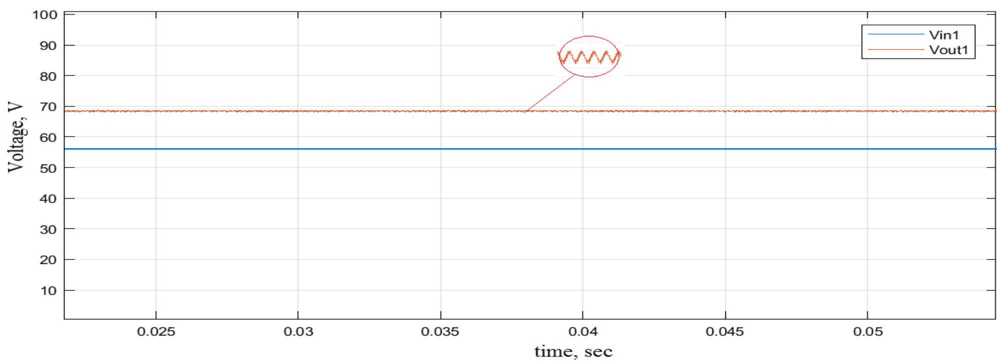
If at that input voltage and duty ratio the input current is 145.2 A, then the output current is equal to

Io = (0.1/1.9) * 145.2 = 7.642 A

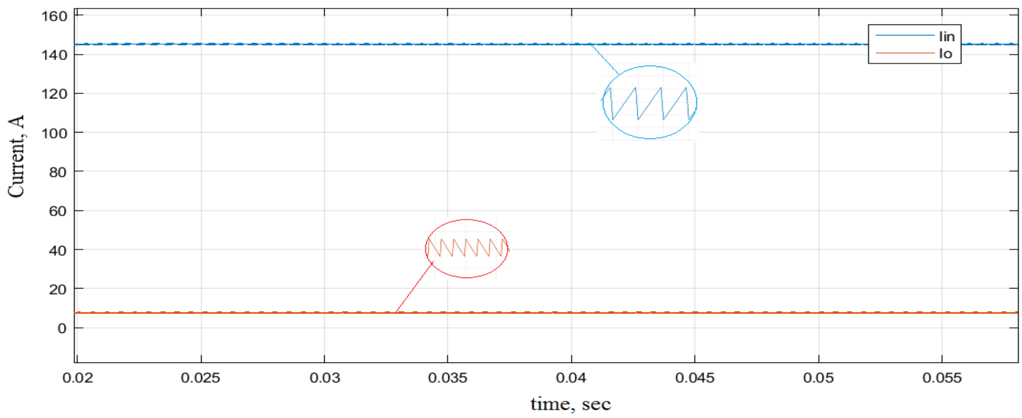
This means that the maximum power delivered to the load is at the maximum duty ratio and is given by

P_{max} = Io Vo = 1064 * 7.642 = 8131 W

These current and voltage values are verified by the voltage and current waveforms obtained at 0.1 and 0.9 that are shown in Fig.15 and Fig.16 respectively.



a) Output voltage



b) Output current

Fig. 15: Simulation results for MSEPIC converter at D=0.1.

6 Conclusions

The present work focuses on the most used various topologies of DC-DC converters for renewable energy applications, charging systems, and regulators, where the existed voltage and current ripples define the chopper effectiveness and reliability. Due to underlined importance of these key factors a detailed investigation was conducted by comparing them for three main configurations of DC choppers: Buck- Boost, Traditional SEPIC, and Modified SEPIC.

By referring to the conducted investigations done by other researchers, we found that there is a lack of research related to determining the optimized switching frequency for these converters. After that, having this frequency it should be maintained at constant value during regulation of the of duty cycle for wide power control range.

As a result of conducted simulation, the following conclusions can be stated:

1- Value each converter has certain optimized switching frequency.

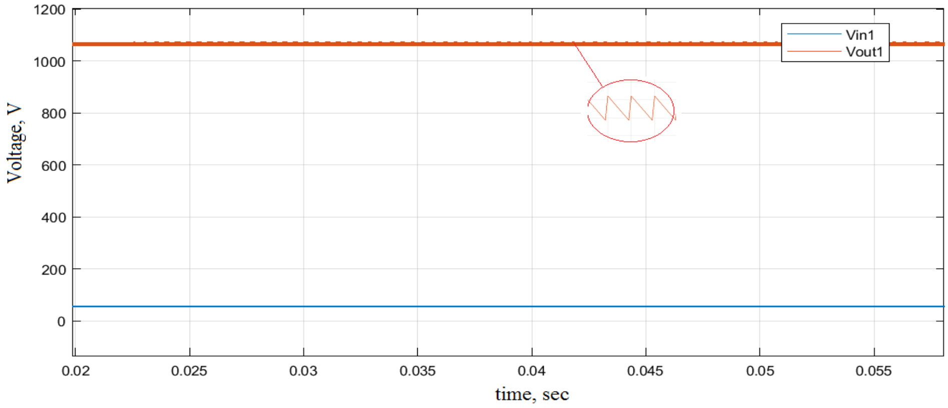
2- At fixed for D=50%, MSEPIC converter has the best performance results occurred at optimized frequency of 50kHz, where the primary inductance ripples are ≤ 7.8% with efficiency of 98.8% and voltage gain factor of 3, while Buck-Boost converter is characterized with gain of unity and efficiency of less than 66%. Furthermore MSEPIC converter is less sensitive to the frequency change keeping the efficiency at high rate approaching 99%. While other converters are much sensitive to the frequency change with significant variation as the frequency changed.

3- With respect to the output voltage ripples MSEPIC indicate voltage ripple of less than 0.65%

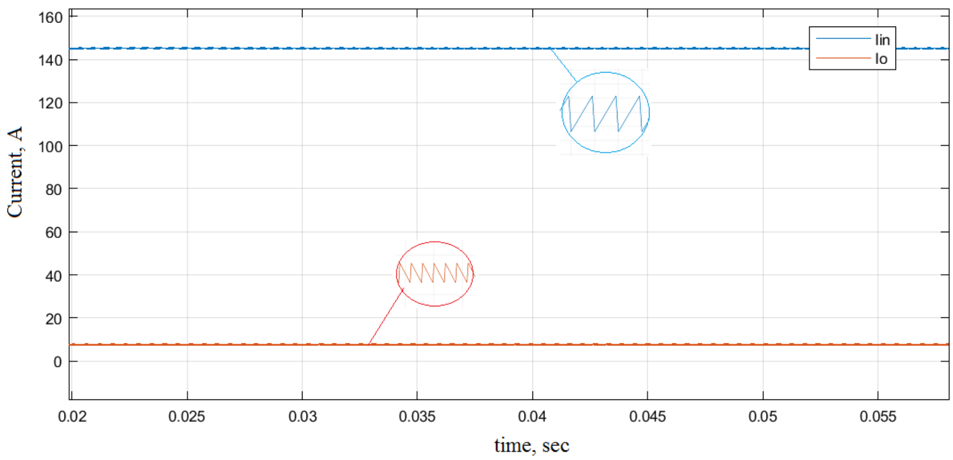
and efficiency of 98.8%, while these factors are ΔVo=1% and η=65% . TSEPIC converters have acceptable performance parameters located between BB and MSEPIC performances.

4- With respect to voltage gain at D=50% , MSEPIC has the greatest value of 3 comparing with TSPEC of and BB of unity and TSEPIC of unity.

5- By comparing the analytically obtained results with those obtained by simulation indicates that there is about 100% matching between both approaches which justify the correctives of proposed research methodology.



c) Output voltage



d) Output current

Fig. 16: Simulation results for MSEPIC converter at D=0.9.

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