International Journal of Electrical and Computer Engineering (IJECE)
Vol. 10, No. 2, April 2020, pp. 2128∼2138
ISSN: 2088-8708, DOI: 10.11591/ijece.v10i2.pp2128-2138

Asymmetric quasi impedance source buck-boost converter

Muhammad Ado[1], Awang Jusoh[2], Tole Sutikno[3]
[1,2]School of Electrical Engineering, Universiti Teknologi Malaysia, Malaysia
[1]Department of Physics, Bayero Univerity, Kano, Nigeria
[3]Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

Article Info

Article history:

Received Sep 11, 2019
Revised Nov 3, 2019
Accepted Nov 15, 2019

Keywords:

Buck-boost converters
Converters
DC-DC converters
Quasi-Z-source converter
Z-source

ABSTRACT

An impedance source buck-boost converter (BBC) prototype for renewable energy (RE) application in the transportation industry is proposed. Its functions include stabilizing the variable output voltage of the RE sources such as fuel cells and photovoltaic cells. The converter utilized a topology of DC-DC quasi-impedance source converters (q-ZSCs) to achieve the gain curve of the BBC. With BBC gain curve, the converter earned advantages over the two other classes of non-isolated DC-DC q-ZSCs. These advantages include efficient buck-boost capability at the efficient duty ratio range of $0.35 - 0.65$ and continuous and non-zero gain at the efficient duty ratio range. The converter's q-ZSC topology implies using two capacitors and two inductors. These two capacitors and inductors formed two separate LC filters that provides second order filtering compared to the first order filtering in BBC. Its other advantages over the traditional BBC include elimination of dead and overlap-time, simple contol and permitting higher switching frequency operation. The converter is capable of utilizing high switching frequency and asymmetric components to achieve BBC gain by using smaller components to reduce cost, weight and size. Its simulation response and that of a corresponding BBC for some given specifications were compared, presented and analyzed. An experimental scaled-down prototype was also developed to confirm its operation. Analysis of the converters responses confirmed the prototype's second order filtering as against the first order filtering in traditional BBC.

Corresponding Author:

Awang Jusoh,
School of Electrical Engineering,
Universiti Teknologi Malaysia.
Email: awang@utm.my

1. INTRODUCTION

Transportation industry recorded the only sector increase (0.8%) of carbon IV oxide CO_2 emission in 2017 and has been producing the highest since late 1990s [1]. Petroleum and other liquids accounted for the highest energy-related (CO_2) emission by fuel in the U.S. since 1990 and are projected to remain the world's highest source for energy consumption up to the year 2040 [1, 2]. CO_2 emission causes air pollution and 90% of humans breathing polluted air. Polluted air contributes about 43% of lung cancer diseases and deaths [3]. Automobile and aviation industries are integrating renewable energy (RE) sources such as fuel cells and photovoltaic cells in conjunction with batteries and super-capacitors as energy storage systems (ESS) to reduce pollutant emissions [4, 5]. RE sources accounted for 28% of global electricity generation in 2018, of which 96% was produced from the top three RE sources (solar, hydropower and wind) [6, 7]. RE systems require DC-DC converters to regulate their variable output voltage to a given set point because sources like fuel cells and photovoltaic cells have unregulated outputs [8-10].

DC-DC impedance source converters (ISCs or ZSCs) are a class of ISCs [11-15]. ISCs couple converter's main circuit to its power source, thus providing features not obtained in the traditional voltage-source and current-source converters in addition to their advantages [16]. They are immune from shoot-through (ST) effects in voltage-fed ISCs by allowing shorting of output terminals. They are also immune from open circuit (OC) effects in current-fed ISCs by allowing terminal current interruption [17]. ST occurs when complementary switches of a common leg of an H-bridge are both ON while open circuit occurs when they are both OFF. During ST, inductors are used to store energy to be released during non-ST state [18]. ZSCs are controlled by PWM with or without ST. Q-ZSCs [19] were proposed in four variations to solve constraints in Voltage-Fed ZSCs (VF-ZSC) and Current-Fed ZSCs (CF-ZSCs). These Problems include the requirement for inductors to sustain high currents in (CF-ZSCs), sustenance of high capacitor voltage during boost mode in (VF-ZSCs) and discontinuous input current [19].

Reference [14] extended ZSC and q-ZSC concepts to DC-DC application. Transformer-based impedance ISCs were proposed to increase gain and isolation at the expense of increased size, cost and weight [20-22]. Reference [11, 12] proposed DC-DC q-ZSCs with BBC gain. These converters utilized the topologies of DC-DC q-ZSCs to achieve the voltage gain of traditional BBC. The converters usage of q-ZSC topology implies using two capacitors and two inductors connected in such a way that each capacitor-inductor pair (C_1L1) and (C_2L_2) form an LC filter. The two separate LC filters provided second order filtering in these converters as against the first order filtering in traditional BBC. Traditional BBC topology is shown in Figure 1.

Other advantages of these DC-DC q-ZSCs over the traditional BBC include higher frequency operability and elimination of dead-time and overlap-time, but their two capacitors and two inductors increased components count when compared with the traditional BBC. However, the use of asymmetric capacitors and inductors in q-ZSCs could enhance performance and reduce weight, cost and size [23, 24]. Also, the two inductors could be coupled together to decrease weight and size, provide isolation or/and increase voltage gain [20,22,25-36]. BBC has advantages over the Z-source and quasi-Z-source converters proposed in [14] because

(a) It has a continuous and non-zero ideal gain at duty ratio (D) of 0.5 while the the Z-source and quasi-Z-source converters proposed in [14] have either a discontinuous or zero ideal gain at $D = 0.5$.

(b) It has buck-boost capability at the efficient duty ratio range. This is against the boost only or buck only capability of the other two classes [37].

(c) When compared with the ZSCs and qZSCs with single gain [14], it has higher gain magnitude at boost mode [11].

Although the q-ZSCs with discontinuous gain have higher gain magnitude during boost mode than the BBC, their discontinuous gain, buck mode limitation, lack of buck-boost capability at efficient duty ratio range (0.35 to 0.65) and abrupt change in polarity are disadvantages [16,37-39].

This paper proposes a BBC based on the asymmetric DC-DC q-ZSC. The proposed converter is shown in Figure 2. A potential application of the converter is in the renewable energy based transportation. Its capable applications include regulating the variable output voltages from fuel cells or other RE sources to a given reference, charging and discharging of ESSs etc. [40,9].

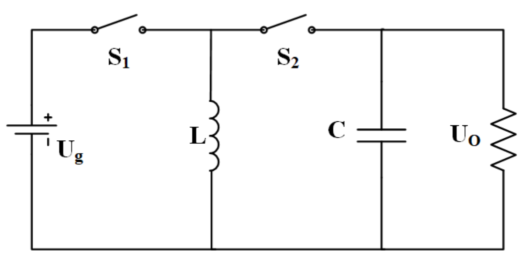

Figure 1. Traditional Buck-Boost Converter Topology

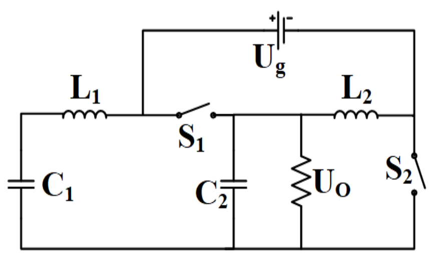

Figure 2. Proposed Converter

The proposed converter's response and that of a corresponding BBC were compared by simulation for buck and boost modes at two different switching frequencies. Its performance was experimentally verified using a mini prototype at 50 kHz switching frequency. Results obtained from both the simulation and experimental verifications confirmed that its response and that of a corresponding BBC are similar.

This paper also confirmed that the additional capacitor and inductor in the converter provides additional filtering. Thus, the converter provides second order filtering as against the first order filtering provided by the traditional BBC. Second order filtering permits the use of smaller reactive components than in first order filtering, thus saving more weight and cost.

2. CIRCUIT ANALYSIS

The converter's operation was analyzed using ideal components to derive the gain equation from (1) to (7). Mode I: S_1 is ON while S_2 is OFF as shown in Figure 3 with duty ratio D.

$$U_{L1} = U_O - U_{C1} \tag{1}$$

$$U_{L2} = U_g \tag{2}$$

Mode II: S_1 is OFF while S_2 is ON as shown in Figure 4 with duty ratio $D' =$ 1-D.

$$U_{L1} = U_g - U_{C1} \tag{3}$$

$$U_{L2} = U_O \tag{4}$$

Applying volt-second balance on L_1 and L_2 yields

$$\bar{U}_{L1} = DU_O + U_g - U_{C1} - DU_g = 0 \tag{5}$$

$$\bar{U}_{L2} = DU_g - U_O(D-1) = 0 \tag{6}$$

Simplifying (6) yields

$$U_O = -\frac{D}{1-D} \times U_g \tag{7}$$

Equation (7) shows that the output voltage is inverted and can be less than or greater than the input voltage. This output equation is the same as that of the traditional non-isolated BBC. It implies that it could be used to achieve the operation of the BBC.

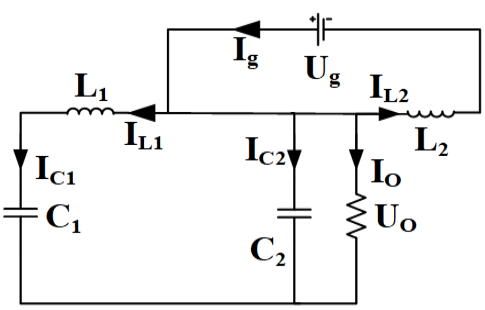

Figure 3. Proposed converter's operation in Mode I

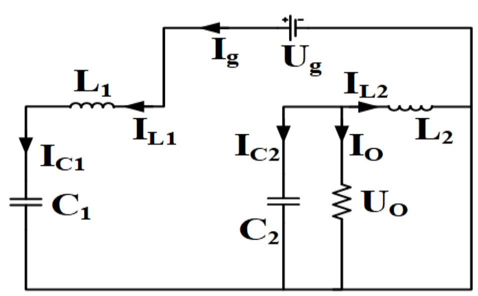

Figure 4. Proposed converter's operation in Mode II

3. VERIFICATION

First, the responses of the proposed converter were compared with those of corresponding BBC by simulation. A corresponding BBC was obtained by making its capacitor and inductor identical with the converter's output capacitor (C_2) and inductor (L_2) respectively. A mini-prototype was also developed and its responses are presented.

3.1. Simulation

For simulating the response ot the converters, MATLAB SIMULINK was used. Table 1 and Table 2 show the specifications used for the simulations. The specifications also include parasitic resistances R_1 and R_2, for the capacitors C_1 and C_2 and equivalent series resistances r_1 and r_2 for inductors L_1 and L_2 respectively. The BBC has a single capacitor C = C_2 and inductor L = L_2. Their response for the switching frequencies of f = 50 kHz and f = 100 kHz were compared. The converters were compared for buck mode at D = 0.3 and boost mode at D = 0.7 for each of the frequencies.

Table 1. BB-qZSC Specification

Variable	Unit	Value
U_g	V	4
R_O	Ω	220
C_1	μF	0.01
C_2	μF	0.9
L_1	μH	22
L_2	μH	470
R_1	mΩ	1
R_2	mΩ	20
r_1	Ω	0.6
r_2	Ω	6

Table 2. BB-qZSC Specification

Variable	Unit	Value
U_g	V	4
R_O	Ω	220
C_1	20	-
C_2	μF	0.9
L_1	μH	-
L_2	μH	470
R_1	mΩ	-
R_2	mΩ	20
r_1	Ω	-
r_2	Ω	6

The simulation response of the converters under these frequencies of 50 kHz and 100 kHz and duty ratios of D = 0.3 and D = 0.7 are presented in Figure 5, Figure 6, Figure 7, and Figure 8.

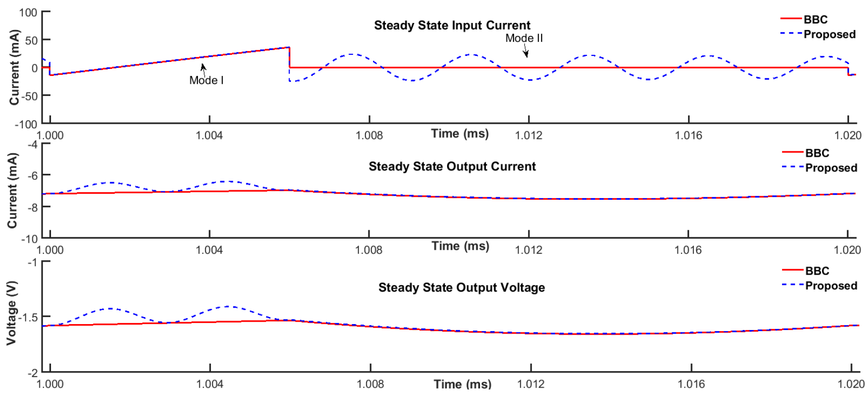

Figure 5. Buck Mode for f = 50 kHz

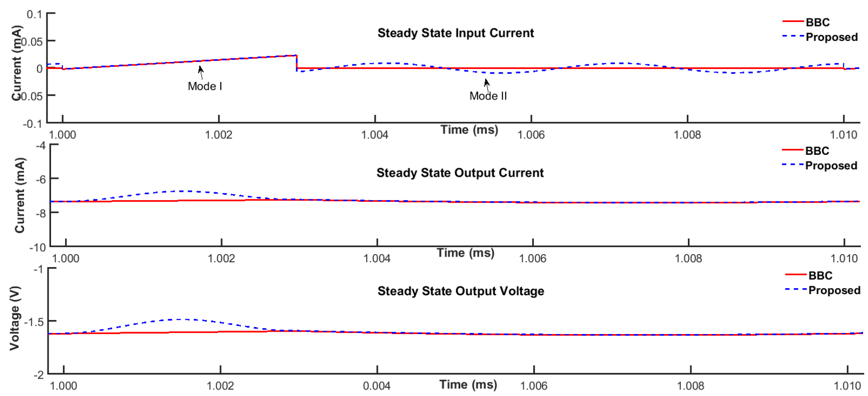

Figure 6. Buck Mode for f = 100 kHz

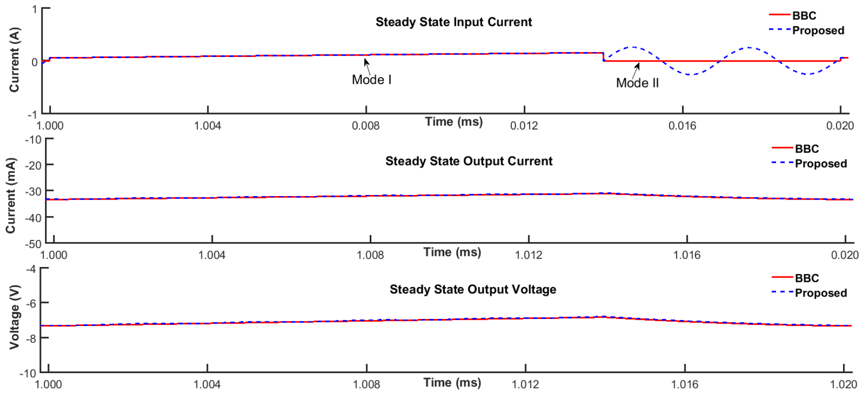

Figure 7. Boost Mode for f = 50 kHz

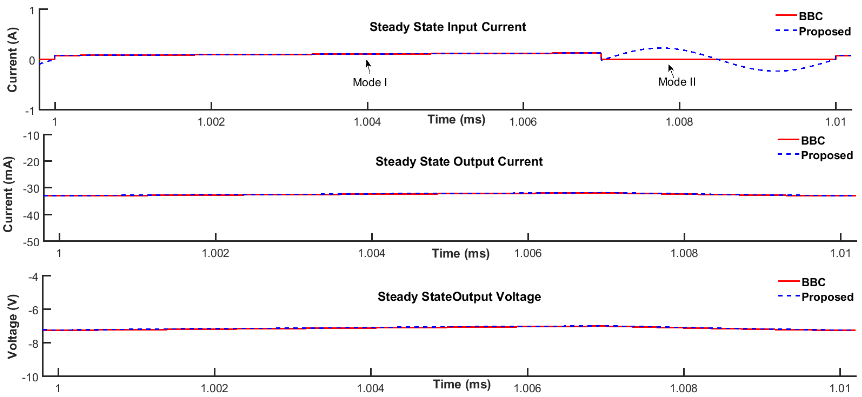

Figure 8. Boost Mode for f = 100 kHz

3.2. Experimental verification

The prototype was developed by using the specifications in Table 1. A switching frequency of 50 KHz was used to switch the transistors of the converter. Similar to conventional BBCs, two complementary pulse width modulated (PWM) gate signals with dead-time of 3 μs split between the pulses were used as switching signals. Its responses for buck mode at D = 0.3 and boost mode at D = 0.7 are presented in Figure 9 and Figure 10. The steady-state output voltage for each mode was measured directly with a voltmeter and their values were found to be 1.55 V for buck and 6.21 V for boost mode.

4. RESULTS AND DISCUSSION

The results obtained from both the simulation and experimental verification are presented and discussed in this section.

4.1. Simulation results and discussion

Figure 5 and Figure 6 show comparisons of the simulation results of the proposed converter's response and a corresponding BBC's response for buck mode at D = 0.3. Figure 5 is a comparison of the two converters' buck mode response at D = 0.3 and f = 50 kHz while Figure 6 is a comparison of their response at D = 0.3 but f = 100 kHz. Figure 7 and Figure 8 show comparisons of the simulation results of the proposed converter's response and the corresponding BBC's response for boost mode at D = 0.7. Figure 7 is a comparison of the two converters' boost mode response at D = 0.7 and f = 50 kHz while Figure 8 is a comparison of their response at D = 0.7 but f = 100 kHz.

The simulation results of Figure 5, Figure 6, Figure 7, and Figure 8 show that the responses of the proposed converter and a corresponding BBC are similar. This similarity is noticed for both buck mode and boost mode. However, some ripples (oscillations) are observed in all the four figures. The oscillations decreased both in frequency and amplitude when the switching frequency was increased from 50 kHz to 100 kHz. This effect of frequency on the the ripples of the proposed converter's response is clearly noticed when Figure 5 and Figure 6 or Figure 7 and Figure 8 are compared together. Comparing Figure 5 and Figure 6 together since they have identical parameters except frequency shows that by doubling the switching frequency, the cycles of the ripples are halved and their amplitudes reduced.

The decrease in oscillation cycles with increase in frequency shows that at higher frequencies the ripples observed in the proposed converter's waveforms diminishes, thus the converter becomes stable. This oscillations are predicted in [23] because:

(a) Complex conjugate pairs exist in all the small signal output capacitor voltage $\tilde{U}_{C2}$ to input small signal transfer functions given by (8), (9) and (10) when (11) holds.

$$G_{\tilde{u}_g}^{\tilde{u}_{C2}} = -\frac{s^2(L_1+L_2)+s(R_1+r_1+r_2)+\frac{1}{C_1}}{s^2C_1L_1+sC_1(R_1+r_1)+1)(sL_2+r_2)s\frac{C_2}{C_1}}DD' \quad (8)$$

$$G_{\tilde{i}_O}^{\tilde{U}_{C2}} = -\frac{s^3+s^2\frac{L_2(D^2R_O+R)+L_1(R_OD^2+r_2)}{L_1L_2}+s\frac{R_OC_1D'^2R+r_2C_1(R+D^2R_O)+L_2}{L_1L_2C_1}+\frac{R_OD'^2+r_2}{L_1L_2C_1}}{s^2C_1L_1+sC_1(R_1+r_1)+1)(sL_2+r_2)s\frac{C_2}{C_1}} \quad (9)$$

$$G_{\tilde{d}}^{\tilde{u}_{C2}} = \frac{s^3L_1L_2I+s^2(L_1r_2I+L_2RI+DL_2V-D'L_1V)+s(Rr_2I+\frac{L_2}{C_1}I+Dr_2-D'RV)+\frac{r_2I-D'V}{C_1}}{s^2C_1L_1+sC_1(R_1+r_1)+1)(sL_2+r_2)s\frac{C_2}{C_1}} \quad (10)$$

$$L_1 > C_1(\frac{R_1+r_1}{2})^2 \quad (11)$$

Substituting the values of parameters from Table 1 into (11) shows

$$22\times10^{-6} > 0.01\times10^{-6}(\frac{0.001+0.6}{2})^2 \quad (12)$$

$$\Rightarrow 22\times10^{-6} \gg 9.03\times10^{-10} \quad (13)$$

From (13), the existence of the ripples could be anticipated due to the oscillation that arise because of the existence of complex conjugate pair. However, the effect of this ripple is reduced with increase in frequency as seen when the frequency was increased from 50 kHz to 100 kHz. This shows that C_1 and L_1 in addition to C_2 and L_2 have effect on the stability of the proposed converter. This is contrary to what is obtained in traditional BBC where the stability is controlled by the lone capacitor (labelled C_2 in this work) and lone inductor (labelled L_2 in this work). This confirms the second order filtering of the q-ZSCs as against the first order filtering of the traditional BBC [15].

(b) Large values of L_1 push the poles of the transfer functions (14), (15) and (16) close to the origin thereby reducing the system's stability.

$$G_{\tilde{U}_g}^{\tilde{I}_{L1}} = \frac{sC_1(1-D)}{s^2C_1L_1+sC_1(R_1+r_1)+1} \quad (14)$$

$$G_{\tilde{I}_O}^{\tilde{I}_{L1}} = \frac{sC_1DR_O}{s^2C_1L_1+sC_1(R_1+r_1)+1} \quad (15)$$

$$G_{\tilde{d}}^{\tilde{I}_{L1}} = \frac{sC_1(U_O-U_g)}{s^2C_1L_1+sC_1(R_1+r_1)+1} \quad (16)$$

The roots of the transfer functions in (14), (15) and (16) are given by (17)

$$-\frac{R_1 + r_1}{2L_1} \pm \frac{\sqrt{(\frac{R_1+r_1}{L_1})^2 - \frac{4}{C_1 L_1}}}{2} \tag{17}$$

Substituting the values of R_1, r_1, C_1 and L_1 given in Table 1 into (17) give the location of the poles as

$$s_{1,2} = -1.3659 \times 10^4 \pm 2.132 \times 10^6 i \tag{18}$$

Equation (18) shows that the poles are negative but have complex conjugate pairs. As seen from (17), the position of the real part of the poles is affected by the value of L_1.

An obvious finding is that, the converter's additional capacitor C_1 and additional inductor L_1 provides additional filtering in the proposed converter. This claim can be verified by testing the validity of the condition given by (19) that for a switched circuit with a resonant network, switching ripples are minimized if switching frequency (f_s) is much higher than the natural frequency (f_o) of the resonator given by (20) [41].

$$f_s \gg f_o \tag{19}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{20}$$

This converter has two resonant (filter) networks as shown in Figure 2. The first filter network is at the output side and is formed by L_2 and C_2. The output filter network is synonymous to the filter network that exists in the traditional buck-boost converter. The second filter network is that formed by L_1 and C_1 and could be called the optimizing network.

The validity of (19) was tested by determining the natural frequency of each of the two filter networks and comparing it with the switching f_s. For the optimizing filter network formed by L_1 and C_1, its resonant frequency f_{o1} is given by

$$f_{o1} = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{21}$$

Substituting the values from Table 1 into (21) shows that,

$$f_{o1} = \frac{1}{2\pi\sqrt{220 \times 10^{-6} \times 0.01 \times 10^{-6}}} = 2.132\ MHz \tag{22}$$

For the output filter network, its resonant frequency f_{o2} is given by

$$f_{o2} = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{23}$$

Substituting the values from Table 1 into (23) shows that,

$$f_{o2} = \frac{1}{2\pi\sqrt{470 \times 10^{-6} \times 0.9 \times 10^{-6}}} = 7.738\ kHz \tag{24}$$

Comparing f_{o2} of (24) with the f_s of 50 kHz and 100 kHz used shows that (19) is valid for both switching frequencies. Thus switching ripples should be minimized. As expected, the switching ripples of the buck-boost converter were minimized since this is the only filter network that existed in this converter and it satisfies the condition. However, some ripples were observed in the q-ZSC. These ripples could be better explained after analysing the effects of the second (optimizing) filter network.

Comparing f_{o1} of (22) with the f_s of 50 kHz and 100 kHz used shows that (19) is not valid for both switching frequencies. In fact, the reverse occurred where $f_s \ll f_{o1}$. This implies that this filter does not minimize ripples with the current specification. This can be linked with the ripples that existed in the q-ZSC but not in the buck-boost converter at lower switching frequencies.

The effect of the second (optimizing) filter on the converter's performance due to its impact on the ripples in the waveforms confirmed the second order filtering in impedance source converters (ISCs).

This shows that rather than relying solely on the output capacitor C_2 and the output inductor L_2 for filtering, the additional capacitors C_1 and inductor L_1 could be used to augment their functions. The ripples in the simulation results of the output current and output voltage of the converters are less than 10% of their average values. The highest ripples are observed during buck modes. Also, the ripples could be further reduced by using a much higher switching frequency. This is because using a switching frequency (f_s) much higher than the natural frequency (f_o) of L_1C_1 given by (21) minimizes ripples [41]. Since the converter's performance improves with increase in switching frequency, this makes them suitable for application in renewable energy based transportation vehicles. This is because increase in switching frequency permits the usage of smaller reactive components. Usage of smaller reactive components results in reducing weight and saving cost.

4.2. Experimental results and discussion

Figure 9 and Figure 10 show the experimental prototype's response for buck mode at $D = 0.3$ and boost mode at $D = 0.7$. Each of the output voltages displayed by the oscilloscope has to be multiplied by 50 to get the actual reading. The multiplication is necessary because the differential voltage probe used (Tektronix P5200) has a scaling factor and the scaling factor of 1:50 was used. Thus, the approximate output voltages for the buck and boost mode are 33 mV$\times 50 = 1.65V$ and 120 mV$\times 50 = 6V$.

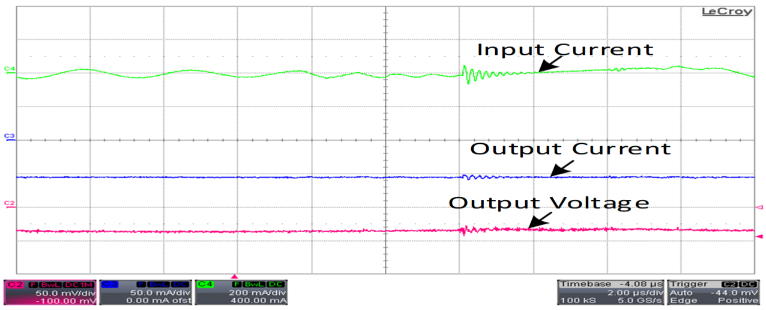

Figure 9. Waveform of experimental verification for Buck mode

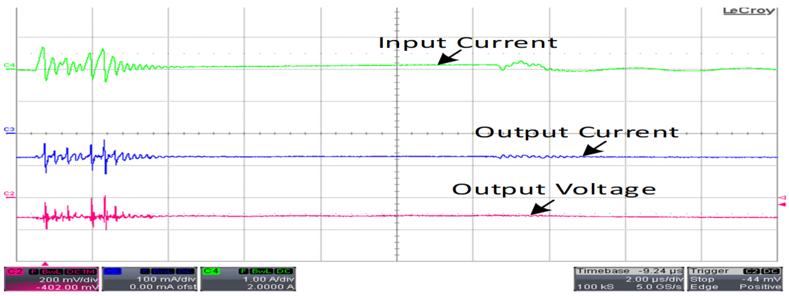

Figure 10. Waveform of experimental verification for Boost mode

4.3. Discussion

In a recent publication [42] the design equations for this converter's components selection were presented. These equations will assist designers in reducing the ripples by choosing the appropriate components for the converter for optimal performance for a given specification. The results in this paper show that the potential of asymmetric q-ZSCs to reduce size, weight and cost make them suitable for RE transportation applications because weight, size and cost are very crucial. The reduction in size was proved by using small capacitors of 0.9 μF and 0.01 μF due to higher frequency and asymmetry. The 0.01 μF capacitor is 1.11 % of the output capacitor thus saving weight and size. Figure 9 and Figure 10 confirmed that by varying D from 0.3 to 0.7, the input voltage U_g could be varied from 1.65 V to 6.00 V signifying 41.25 % to 150 % buck-boost capability.

5. CONCLUSION

An impedance source buck-boost converter (BBC) for renewable energy application has been proposed. It utilized quasi Z-source converter (q-ZSC) to achieve the gain curve of the BBC and earn advantages over other classes of q-ZSCs. Its second capacitor and inductor edge it over a corresponding BBC through second-order filtering, elimination of dead time and permitting higher frequency operation. The capability of q-ZSCs to achieve DC-DC and DC-ac conversion give it advantage over the traditional BBC.

REFERENCES

[1] U. S. EIA "U . S . Energy-Related Carbon Dioxide Emissions , 2017," Tech. Rep. September, 2018.

[2] L. Capuano "International Energy Outlook 2018 (IEO2018)," Tech. Rep., 2018.

[3] WHO, "How air pollution is destroying our health," 2018.

[4] H. S. Das, C. W. Tan, and A. H. Yatim, "Fuel cell hybrid electric vehicles: A review on power conditioning units and topologies," *Renewable and Sustainable Energy Reviews*, vol. 76, no. February, pp. 268-291, 2017.

[5] F. Grumm, J. Storjohann, A. Lucken, M. F. Meyer, M. Schumann, and D. Schulz, "Robust Primary Protection Device for weight-optimized PEM-Fuel-Cell-Systems in High Voltage DC Power Systems of Aircraft," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5748-5758, 2018.

[6] A. Demirbaş, "Global Renewable Energy Resources," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 28, no. 8, pp. 779-792, Jul 2006.

[7] E. I. A. U. S., "Today in Energy," Tech. Rep. September, 2019.

[8] B. G. Gang, H. Kim, and S. Kwon, "Ground simulation of a hybrid power strategy using fuel cells and solar cells for high-endurance unmanned aerial vehicles," *Energy*, vol. 141, pp. 1547-1554, 2017.

[9] D. Guilbert, A. Gaillard, A. N'Diaye, and A. Djerdir, "Energy efficiency and fault tolerance comparison of DC/DC converters topologies for fuel cell electric vehicles," in *2013 IEEE Transportation Electrification Conference and Expo (ITEC)*, Detroit: IEEE, 2013, p. 6 pp.

[10] M. S. B. Arif, S. M. Ayob, S. Yahya, U. Mustafa, M. Ado, and Z. A. Khan, "Effect of ZnH2O Nanofluid Back-Flow Channels on the Efficiency and Electrical Power Output of a Solar PV Panel Used in Standalone PV System," in *2018 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, IEEE, 2018, pp. 493–497.

[11] M. Ado, A. Jusoh, S. M. Ayob, M. H. Ali, and G. S. M. Galadanchi, "Buck-Boost Converter with q-ZSC Topology," in *5th IET International Conference on Clean Energy and Techonology*, IET, 2018.

[12] M. Ado, A. Jusoh, M. J. A. Aziz, M. Kermadi, and A. U. Mutawakkil, "DC-DC q-ZSC with Buck-Boost Converter Gain," in *9th IEEE Control and System Graduate Research Colloquium*, 2018, pp. 85–88.

[13] H. Shen, B. Zhang, D. Qiu, and L. Zhou, "A Common Grounded Z-Source DC-DC Converter With High Voltage Gain," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 5, pp. 2925–2935, 2016.

[14] D. Cao and F. Z. Peng, "A Family of Z-source and Quasi-Z-source DC-DC Converters," *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*, pp. 1097–1101, 2009.

[15] F. Z. Peng, "Z-source inverter," *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 504–510, 2003.

[16] A. Chub, D. Vinnikov, F. Blaabjerg, and F. Z. Peng, "A review of galvanically isolated impedance-source DC-DC converters," *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 2808–2828, 2016.

[17] P. C. Loh, F. Gao, and F. Blaabjerg, "Embedded EZ-Source Inverters," *IEEE Transactions on Industry Applications*, vol. 46, no. 1, pp. 256–267, 2010.

[18] Y. Li, S. Jiang, J. G. Cintron-Rivera, and F. Z. Peng, "Modeling and control of quasi-z-source inverter for distributed generation applications," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1532–1541, 2013.

[19] J. Anderson and F. Z. Peng, "Four quasi-Z-Source inverters," in *2008 IEEE Power Electronics Specialists Conference*, 2008, pp. 2743–2749.

[20] M. K. Nguyen, Y. C. Lim, and Y. G. Kim, "TZ-source inverters," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 12, pp. 5686–5695, 2013.

[21] M. K. Nguyen, Y. C. Lim, and S. J. Park, "Improved trans-Z-source inverter with continuous input current and boost inversion capability," *IEEE Transactions on Power Electronics*, vol. 28, no. 10, pp. 4500–4510, 2013.

[22] W. Qian, F. Z. Peng, and H. Cha, ”Trans-Z-Source Inverters,” *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3453–3463, 2011.
[23] M. Ado, A. Jusoh, M. H. Muda, F. binti Atan, and A. U. Mutawakkil, ”A Prototype of DC-DC Quasi – Z-Source Buck-Boost Converter,” in *10th IEEE Control and System Graduate Research Colloquium*, 2019.
[24] M. Ado, A. Jusoh, A. U. Mutawakkil, and T. Sutikno, ”Dynamic model of a DC-DC quasi-Z-source converter (q-ZSC),” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 3, pp. 1585–1597, 2019.
[25] Y. P. Siwakoti, F. Blaabjerg, V. P. Galigekere, A. Ayachit, and M. K. Kazimierczuk, ”A-Source Impedance Network,” *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8081–8087, 2016.
[26] Y. P. Siwakoti, F. Blaabjerg, and P. C. Loh, ”Quasi-Y-Source Boost DC-DC Converter,” *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 6514–6519, 2015.
[27] Y. P. Siwakoti, F. Blaabjerg, and P. C. Loh, ”New Magnetically Coupled Impedance (Z-) Source Networks,” *IEEE Transactions on Power Electronic*, vol. 31, no. 11, pp. 7419–7435, 2016.
[28] W. Mo, P. C. Loh, and F. Blaabjerg, ”Asymmetrical -Source Inverters,” *IEEE Transactions on Industrial Electronics*, vol. 61, no. 2, pp. 637–647, 2014.
[29] M. Adamowicz, J. Guzinski, and P. Stec, ”Five-phase EV Drive with Switched-Autotransformer (LCCAt) Inverter,” *Vehicle Power and propulsion Conference (VPPC), 2014*, 2014.
[30] Y. P. Siwakoti, P. C. Loh, F. Blaabjerg, and G. E. Town, ”Y-Source Impedance Network,” *IEEE Applied Power Electronics Conference and Exposition*, vol. 29, no. 7, pp. 3250–3254, 2014.
[31] P. C. Loh, D. Li, and F. Blaabjerg, ”Voltage-Type -Z-Source Inverters,” *IEEE Transactions on Power Electronics*, vol. 28, no. 11, pp. 4880–4884, 2013.
[32] D. Cao, S. Jiang, X. Yu, and F. Z. Peng, ”Low-Cost Semi-Z-source Inverter for Single-Phase,” *IEEE Transactions on Power Electronic*, vol. 26, no. 12, pp. 3514–3523, 2011.
[33] D. Vinnikov and I. Roasto, ”Quasi-Z-Source-based isolated DC/DC converters for distributed power generation,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 192–201, 2011.
[34] Y. Tang, S. Xie, and C. Zhang, ”Single-Phase Z-Source Inverter,” *IEEE Transactions on Power Electronic*, vol. 26, no. 12, pp. 3869–3873, 2011.
[35] R. Strzelecki, M. Adamowicz, N. Strzelecka, and W. Bury, ”New type T-source inverter,” *CPE 2009 - 6th International Conference-Workshop - Compatability and Power Electronics*, pp. 191–195, 2009.
[36] Z. Yang and P. C. Sen, ”Bidirectional DC-to-AC inverter with improved performance,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 35, no. 2, pp. 533–542, 1999.
[37] M. Ado, A. Jusoh, A. U. Mutawakkil, and S. M. Ayob, ”Two q-ZSCs with Efficient Buck-Boost Gain,” in *10th IEEE PES Asia-Pacific Power and Energy Engineering Conference*, 2018, pp. 252–256.
[38] V. P. Galigekere and M. K. Kazimierczuk, ”Analysis of PWM Z-source DC-DC converter in CCM for steady state,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 4, pp. 854–863, 2012.
[39] M. Ado, A. Jusoh, T. Sutikno, and M. Ado, ”Extended family of DC-DC quasi-Z-source converters,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 6, pp. 4540–4555, 2019.
[40] D. Guilbert, A. Gaillard, A. Mohammadi, A. N'Diaye, and A. Djerdir, ”Investigation of the interactions between proton exchange membrane fuel cell and interleaved DC/DC boost converter in case of power switch faults,” *International Journal of Hydrogen Energy*, vol. 40, no. 1, pp. 519–537, 2015.
[41] S. Cuk, ”Modelling, analysis, and design of switching converters,” Ph.D. dissertation, California Institute of Technology, 1977.
[42] M. Ado, A. Jusoh, and N. M. Nordin, ”Design Equations for DC-DC Quasi-ZSC,” in *4th IEEE Conference on Energy Conversion (CENCON 2019)*, Yogyakarta, 2019.

BIOGRAPHIES OF AUTHORS

Muhammad Ado is a researcher at Universiti Teknologi Malaysia (UTM) and is currently working towards his Ph.D. He has been a researcher with Bayero University, Kano, Nigeria. He obtained his Bachelor and Master degrees in Electronics from Bayero University, Kano, Nigeria in 2009 and 2016 respectively.His research interests include power converters, modelling, control and semiconductor physics. He is affiliated with IEEE as student member. In IEEE Access, International journal of electronics and other scientific publications, he has served as invited reviewer.

Awang Jusoh was born in Terengganu, Malaysia in 1964. He received his B. Eng. (Hons) from Brighton Polytechnic, UK, in 1988. He obtained his MSc. and PhD. from The University of Birmingham, UK in 1995 and 2004, respectively. Since 1989, he has been a lecturer at Universiti Teknologi Malaysia and is now an Associate Professor at the Department of Power Engineering, School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia. His research interests include all areas of power electronics systems and renewable energy.

Tole Sutikno is an Associate Professor in Electrical & Computer Engineering Department Universitas Ahmad Dahlan, Yogyakarta, Indonesia. He received B.Eng., M.Eng, and Ph.D.degrees in 1999, 2004 and 2016 respectively. He has over 200 publication to his credit. His research interests include power electronics, motor drives, industrial electronics, Industrial application, FPGA application, intelligence control and industrial informatics.