A Critical Review on Open Loop Analysis of Single-Phase Non-Isolated AC-DC Buck Converters

Istiak Ahmed and Muhibul Haque Bhuyan

Abstract**—**In this paper, we have reviewed a family of power electronic single-phase, non-isolated ac-dc buck converters based on the open-loop analysis. From the literature survey, we have found numerous types of ac-dc buck converter topologies. Among these, a few important topologies are discussed and compared with various parameters like voltage gain, efficiency, switching frequency, total harmonic distortion, and the number of component counts. The comparison shows that the Input switched buck converter maintains an impressive power factor of 0.97 under frequency variation. In terms of the Total Harmonic Distortion (THD) of input current, both the input switched buck converter and switched capacitor buck converter provide much fewer values of THD than the conventional buck converter over the variation of duty cycle and frequency.

Keywords**—**Buck converter, total harmonic distortion, switching frequency, voltage gain, renewable energy.

I. Introduction

With the advancement in the new technological era, reliability, efficiency with compact size, and quality of voltage conversion has become essential whether it is AC-AC, DC-DC, AC-DC, or DC-AC converter. Proper designs for these converters have an important aspect [1].

A buck converter or also called a step-down converter is usually a kind of DC-DC converter that steps down the voltage level by stepping up the current level from its input or supply voltage to its output voltage level at the load or receiving end. It falls in the category of the Switched Mode Power Supply (SMPS). Such types of circuits contain at least two semiconductor devices, such as a diode and a transistor. However, the modern buck converter circuits use another transistor instead of the diode which is used to obtain synchronous rectification. The buck converter circuits also contain at least one energy storage element like either a capacitor or an inductor, or in some cases the amalgamation of both. To diminish the ripples in the supply voltage, filter circuits are normally used both at the input and output sides of the converter circuits. Filter circuits are made of using either a capacitor or an inductor or both. When the filter circuit is used at the input and output terminals then they are called the supply-side and load-side filters respectively [2].

Any DC-DC switching converter like the buck converter can convert the power with higher efficiency than that of the linear regulator. However, the linear voltage regulator circuits are simpler than the buck converter circuits since the linear regulator does not need to step up the current level at the output side by lowering the voltage level at the cost of electrical power dissipation as heat energy [3].

Due to the higher efficiency (sometimes greater than 90%) of the buck converter circuits, it is suitable to step down the main supply voltage of 12V to different smaller voltage levels required by several parts of the computer, such as Universal Serial Bus (USB), Dynamic Random Access Memory (DRAM) and Central Processing Unit (CPU) (usually 1.8V or less). Besides, the DC-DC buck converters are desirable when the conversion of voltage from 24V to 12V DC to operate a radio, transceiver, or mobile phone or from 12V to 3V DC to run a personal CD player or from 12V to 5V DC to run a modern CPU chip.

On the other hand, AC-DC converters are being utilized to deliver a regulated variable DC voltage for different application areas. Usually, AC-DC converters are popularly recognized as rectifiers. This circuit is implemented in two stages utilizing diodes and thyristors to deliver uncontrolled and controlled DC power through unidirectional and bidirectional power flow respectively. But these types of converters suffer from low power quality due to the harmonic injection in current and hence it causes the power factor to degrade, the supply voltage to distort, and the crest factor to rise.

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Due to the increasing number of application areas of such circuits, these are being implemented in single-stage to enhance the power quality and efficiency and at the same time to shrink the number of components used.

There is an austere prerequisite of maintaining the power quality at AC mains and to comply with that, numerous harmonic mitigation standards, such as IEC 1000-3-2, IEEE 519 (USA), AS 2279, D.A.CH.CZ, EN 61000-3-2/EN 61000-3-12, and ER G5/4 (UK) are being applied to restrict the distortion level at the common coupling point if power electronic circuits and nonlinear loads are in use [4]. To improve the power quality at AC mains if the filters are used in the existing connections then it is done by sacrificing the cost, size, weight, and losses of the system [5]. However, these problems can be eradicated by the use of input current shapes [6-7], high power factor single-stage converters, Power Factor Correction (PFC) converter [8-10], etc. In the recent past, various types of systems are being evolved that uses DC supply for their operation and such types of systems are growing in numbers [11].

Conventional AC-DC converters exhibit low quality in input current. Therefore, there is a requirement for the rectifiers that can provide high quality in input current to comply with the international standards. Researchers have developed numerous approaches to alleviate the power quality problem and still these efforts are going on. The passive filtering technique is such a technique to eradicate the problems of low THD and low input power factor (PF). However, this technique utilizes a large-sized capacitor and inductor [12]. On the other hand, the active filtering technique needs a smaller-sized component than that of passive filtering but is followed by a DC-DC converter [13-16]. Thus, the solid-state switch mode AC-DC converters are used to improve the power quality in terms of Power Factor Correction (PFC) at AC main supply and hence the problems of low THD and low PF at input current are assuaged and thus precise DC output voltage regulation is possible to achieve [17-18]. This technique is widely used in Adjustable Speed Drives (ASDs), Switch Mode Power Supplies (SMPSs), Uninterrupted Power Supplies (UPSs), telecommunication equipment, battery charging for smartphones and laptops, induction heaters, measurement, and testing equipment, etc.

II. TOPOLOGIES AND OPERATIONS OF THE AC-DC BUCK CONVERTER

One of the first families of AC-DC converters is AC-DC Buck converters. They mainly perform two tasks. One is to transform the input AC to output DC. The other task is to step down the input voltage signal. There are many applications where it is needed to change the input AC voltage to a lower value of the output DC voltage. AC-DC buck converters are used in such applications. There are many topologies of single-phase non-isolated AC-DC buck converter. Apart from conventional topology, other circuits are introduced to obtain better performance. In this part, we present an analysis with a comparative review of three different topologies of single-phase non-isolated AC-DC buck converter. In the following sub-sections, we will discuss various topologies and operation of various types of AC-DC buck converters.

A. *Conventional AC-DC Buck Converter*

The schematic diagram of a conventional buck converter is presented in Fig. 1 [15]. The conventional circuit topology of the AC-DC Buck converter uses a bridge rectifier in front of a DC-DC Buck converter. Full-wave rectification is done by the bridge rectifier. Here, the inductor, L_2 works as the buck inductor. C_o and R_o are the output capacitor and the load resistance respectively. A passive filter circuit at the input side of the converter comprising an inductor, L_1, and a capacitor, C_1 is used to reduce the harmonics.

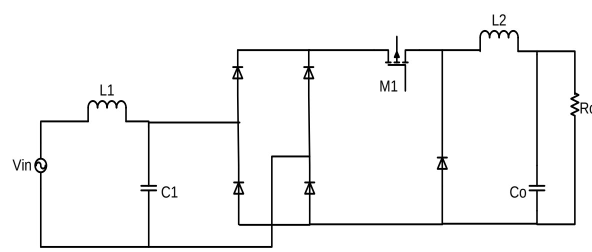

Fig. 1. Schematic of conventional AC-DC buck converter [15]

The open-loop analysis of the circuit is done using software simulation. MOSFET has been used as the switching element. Input voltage (V_{in}) peak is selected as 300 V. Switching frequency, f_s is set at 10 kHz. The values of inductances for L_1 and L_2 are chosen as 5 mH and 1.5 mH respectively. The values of capacitances, C_1 and C_o, and the load resistance, R_o are chosen as 1 μF and 220 μF and 100 Ω respectively.

B. *Input Switched AC-DC Buck Converter*

The circuit diagram of the input switched AC-DC buck converter with improved power quality is presented in Fig. 2 [16]. There are nine diodes (D_1 to D_9), two capacitors (C_1 and C_2), three inductors (L_1 to L_3), and a switching device, basically a transistor (M_1). Here, inductors L_1 and L_2 are used for the buck operation inductors. Inductor, L_3, and capacitor, C_2 are used as the passive filter at the input side of the circuit. Besides, the capacitor C_1 is used as the output capacitor and resistor R_1 is used as the load.

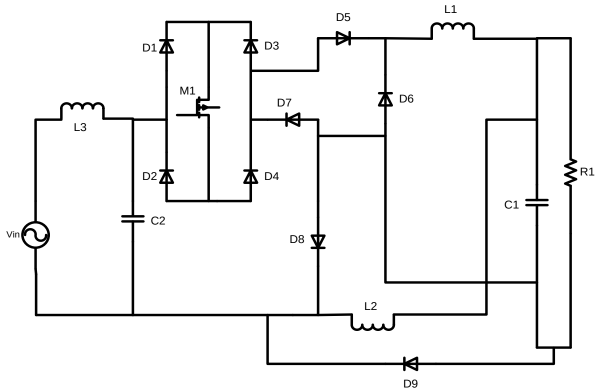

Fig. 2. Input switched AC-DC buck converter [16]

The open-loop analysis of the circuit is performed using software simulation. An IGBT is used as the switching device. The peak input voltage (V_{in}) is chosen as 300 V and the switching frequency is selected at 10 kHz. The values of inductances for L_1, L_2, and L_3 are chosen as 25 mH each. The values of capacitances for C_1 and C_2 are chosen as 3 μF each. The value of the load resistance for R_1 is set at 100 Ω.

C. Switched Capacitor AC-DC Buck Converter

The circuit diagram of a switched capacitor AC-DC step-down converter is presented in Fig. 3 [18]. The circuit comprises two stages. In the first stage, there exists a single-phase full-wave bridge rectifier. The second stage is a switched capacitor DC-DC converter. There are eight diodes (D_0 to D_7), four capacitors (C_f, C_0, C_1, and C_2), two inductors (L_f and L), and a switch Q_1. Inductor L is used as the buck inductor. Inductor L_f and capacitor C_f constitute the passive type filter at the input side of the converter circuit to inhibit the harmonics as it creates harmful effects on all types of converters [19-20]. Capacitor C_0 is used as the output capacitor and resistor R as the load of the buck converter circuit.

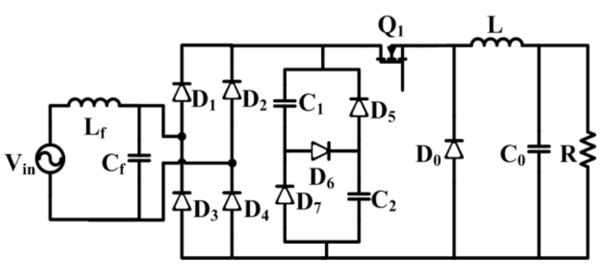

Fig. 3. Switched capacitor AC-DC buck converter [18]

The open-loop analysis of the circuit has been performed using software simulation. MOSFET is used as the switching device. Input voltage (V_{in}) peak is selected as 300 V and the switching frequency has been set at 10 kHz.

III. Performance Comparison

Based on the open-loop analysis of different topologies of single-phase non-isolated AC-DC buck converter, a performance comparison has been made among three different buck converters. Table 1 provides a general comparison of three different topologies of buck converter (BC).

TABLE I
GENERAL COMPARISON OF DIFFERENT TOPOLOGIES OF AC-DC BUCK CONVERTER (BC)

Topology	Figure #	Ref. #	Switch/ Capacitor Count	Diode/ Inductor Count
Conventional BC	1	15	1/2	5/2
Input Switched BC	2	16	1/2	9/3
Switched Capacitor BC	3	18	1/4	8/2

A. Performance comparison by changing the duty cycle

The open-loop performance comparison on different topologies of the AC-DC Buck converter is done based on duty cycle variation. The overall efficiency, input power factor, total harmonic distortion (THD) of the input current, and the converter voltage gain at the output side are analyzed with the variation of the duty cycle. A load of all the converters is chosen as 100 Ω and the switching frequency has been fixed at 10 kHz. The data is provided in Table 2. For a better understanding of the comparison, a column chart and a line chart are provided.

TABLE II
PERFORMANCE COMPARISON ON DIFFERENT TOPOLOGIES OF SINGLE-PHASE NON-ISOLATED AC-DC BUCK CONVERTER BASED ON DUTY CYCLE VARIATION

Duty Cycle	Topology	Efficiency (%)	Power Factor	THD (%)	Voltage Gain
	Conventional BC	2.29	0.68	8.27	0.168
0.1	Input Switched BC	99.98	0.097	17.27	0.09
	Switched Capacitor BC	75.15	0.089	34.4	0.08
	Conventional BC	8.134	0.77	15.45	0.314
0.2	Input Switched BC	99.28	0.38	3.3	0.18
	Switched Capacitor BC	88.24	0.21	7.67	0.18
	Conventional BC	14.29	0.73	21.56	0.312
0.3	Input Switched BC	98.93	0.69	5.07	0.27
	Switched Capacitor BC	91.34	0.33	7.00	0.25
	Conventional BC	25.43	0.73	35.67	0.406
0.4	Input Switched BC	98.28	0.86	5.89	0.36
	Switched Capacitor BC	92.63	0.41	9.01	0.33
	Conventional BC	8.95	0.72	59.7	0.504
0.5	Input Switched BC	97.42	0.94	5.48	0.45
	Switched Capacitor BC	93.28	0.47	10.48	0.45
	Conventional BC	43.62	0.69	72.35	0.599
0.6	Input Switched BC	96.37	0.97	5.39	0.54
	Switched Capacitor BC	93.66	0.51	11.4	0.64
	Conventional BC	51	0.66	83.7	0.690
0.7	Input Switched BC	95.16	0.98	5.93	0.63

	Switched Capacitor BC	93.89	0.53	12.08	0.72
	Conventional BC	56.72	0.63	88.1	0.773
0.8	Input Switched BC	93.81	0.99	6.86	0.72
	Switched Capacitor BC	94.08	0.55	12.28	0.87
	Conventional BC	60.79	0.60	89.45	0.86
0.9	Input Switched BC	92.32	0.99	8.04	0.81
	Switched Capacitor BC	94.50	0.57	12.00	0.96

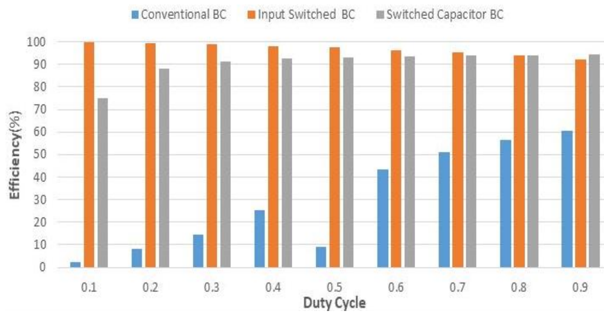

Fig. 4. Comparison of efficiency among the different topologies of single-phase non-isolated AC-DC buck converter under duty cycle variation.

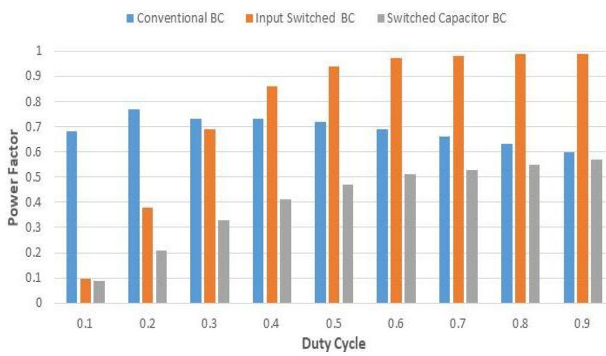

Fig. 5. Comparison of power factor among the different topologies of single-phase non-isolated AC-DC buck converter under duty cycle variation

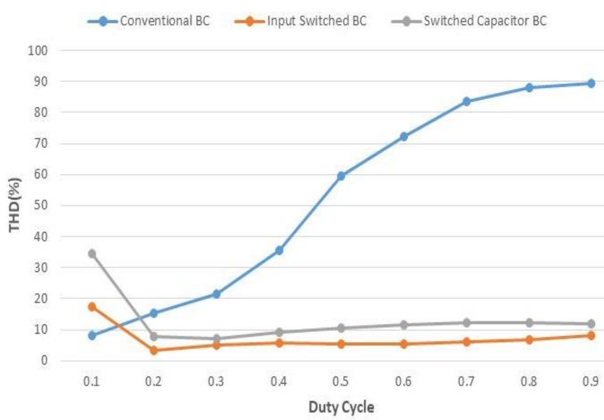

Fig. 6. Comparison of total harmonic distortion (THD) among the different topologies of single-phase non-isolated AC-DC buck converter under duty cycle variation

B. Performance comparison by changing frequency

The open-loop performance comparison on different topologies of the AC-DC Buck converter is done based on frequency variation. The overall efficiency, input power factor, total harmonic distortion (THD) at input current, and voltage gain are analyzed with the variation of the switching frequency. The load resistance value for all the converters has been selected as 100 Ω and the duty cycle has been fixed at 0.6. The data is provided in Table 2. For a better understanding of the comparison, a column chart and a line chart are provided.

TABLE III
PERFORMANCE COMPARISON ON DIFFERENT TOPOLOGIES OF SINGLE-PHASE NON-ISOLATED AC-DC BUCK CONVERTER BASED ON FREQUENCY VARIATION

Switching Frequency (kHz)	Topology	Efficiency (%)	Power Factor	THD (%)	Voltage Gain
	Conventional BC	43.62	0.69	72.35	0.599
10	Input Switched BC	96.37	0.97	5.39	0.54
	Switched Capacitor BC	93.66	0.51	11.4	0.64
	Conventional BC	90.12	0.61	90.27	0.82
20	Input Switched BC	98.05	0.97	4.7	0.54
	Switched Capacitor BC	90.12	0.44	9.24	0.63
	Conventional BC	89.97	0.60	96.13	0.81
30	Input Switched BC	98.65	0.97	4.4	0.54
	Switched Capacitor BC	87.5	0.4	7.39	0.63
	Conventional BC	89.81	0.59	98.97	0.81
40	Input Switched BC	98.94	0.97	4.5	0.54
	Switched Capacitor BC	84.47	0.37	6.96	0.62
	Conventional BC	89.66	0.59	100	0.81
50	Input Switched BC	99.98	0.97	4.5	0.54
	Switched Capacitor BC	84.38	0.35	8.47	0.62
	Conventional BC	89.57	0.59	101	0.81
60	Input Switched BC	99.98	0.97	4.3	0.54
	Switched Capacitor BC	86.86	0.34	8.93	0.61
	Conventional BC	89.51	0.59	102	0.81
70	Input Switched BC	99.27	0.97	4.3	0.54
	Switched Capacitor BC	99.98	0.33	9.21	0.60
	Conventional BC	89.36	0.59	103	0.81
80	Input Switched BC	99.31	0.97	4.4	0.54
	Switched Capacitor BC	88.87	0.32	10.17	0.60
	Conventional BC	89.31	0.59	103	0.81
90	Input Switched BC	99.35	0.97	4.3	0.54
	Switched Capacitor BC	99.98	0.31	10.06	0.59
	Conventional BC	89.06	0.59	103	0.81
100	Input Switched BC	99.28	0.97	4.4	0.54
	Switched Capacitor BC	89.97	0.31	10.52	0.59

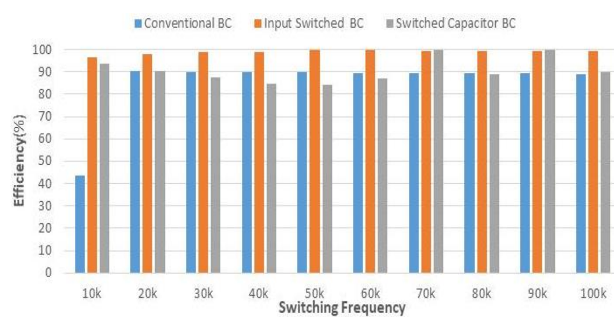

Fig. 7. Comparison of efficiency among the different topologies of single-phase non-isolated AC-DC buck converter under switching frequency variation.

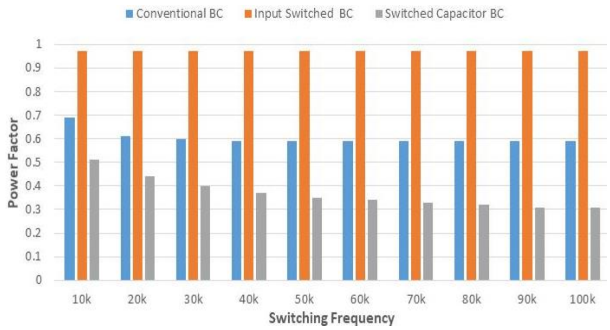

Fig. 8. Comparison of power factor among the different topologies of single-phase non-isolated AC-DC buck converter under switching frequency variation

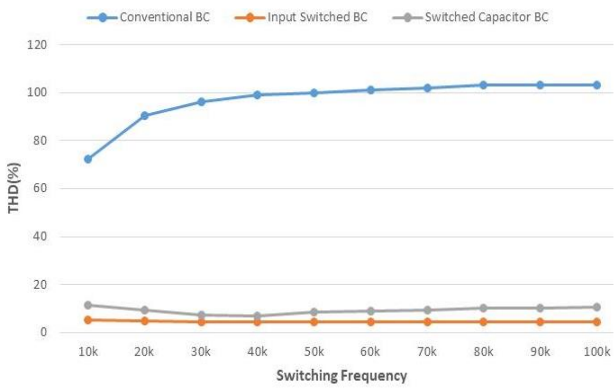

Fig. 9. Comparison of total harmonic distortion (THD) among the different topologies of single-phase non-isolated AC-DC buck converter under switching frequency variation

IV. Conclusion

This paper represents a detailed open-loop analysis on three different topologies of single-phase non-isolated AC-DC buck converter (BC). Performance comparison is performed based on the duty cycle and switching frequency variation. From the analysis, it is seen that both of the input switched BC and switched capacitor BC shows better efficiency than that of the conventional BC upon the duty cycle changes. The conventional BC provides a slightly better power factor than that of the switched capacitor BC upon the duty cycle changes but the input switched BC has a higher power factor over the conventional BC from a duty cycle value of 40% and above. When the THD of the input current is considered it has been observed that both the input switched BC and switched capacitor BC provide smaller values of THD than that of the conventional BC upon duty cycle variation except for duty cycle of 10%. The input switched BC represents higher conversion efficiency than both of the conventional BC and switched capacitor BC upon the variation of switching frequency whereas the overall efficiency of the conventional BC and switched capacitor BC remains quite the same. Both the conventional BC and switched capacitor BC show a lower power factor than that of the input switched BC upon the variation of switching frequency. The input switched BC maintains an impressive power factor of 0.97 under the switching frequency variation. However, again if the THD of the input current is taken into consideration then both the input switched BC and switched capacitor BC provide much smaller values of THD than that of the conventional BC upon the variation of the switching frequency.

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