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A Review of Non-Isolated High Step-Down Dc-Dc Converters

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Abstract

In this paper, a review of the common techniques used for high step-down dc-dc voltage conversion is presented. First, the limitations of conventional buck & synchronous rectifier buck converters used for high step down dc-dc voltage conversion which include narrow duty cycle, high voltage stress, large ripple and low efficiency are briefly discussed. Then various topologies of non-isolated step-down dc-dc converters are reviewed and discussed. The topologies/techniques used for high step down dc-dc conversion are divided into various groups which include interleaved, quadratic, tapped, switched capacitor, switched inductor, coupled inductor, multi level and buck converter with three state switching cells. Each group of converters is briefly discussed, main circuit structure of each topology is given and their features and limitations are given. Finally a comparison of all the discussed topologies is carried out based on some common features.

Keywords: *Buck converter, high step down dc-dc conversion, narrow duty cycle, high voltage stress and current ripples*

1. Introduction

Several applications require high step down voltage conversion. Some of the most common applications are light emitting diode (LED) lamps, voltage regulator modules (VRMS) for microprocessors, telecom equipments and battery operated portable devices such as personal digital assistant (PDA), cellular phones and global positioning system (GPS) etc. For such applications a step down voltage conversion ratio of around 0.1 or even less is required as these applications requires very low dc voltages. Conversely they operate at very high currents [1-3].

The most basic converters used for such type of voltage conversion is a basic buck converter. A basic buck converters and synchronous buck converter are show in Figure 1 [4, 5]. This basic step-down dc-dc converter is not suitable for high step down voltage conversion as it must operate at a very small duty ratio (D=V_O/V_{in}). Such a small duty ratio effects the dynamic performance of the converter and cause asymmetry in the on and off times of the switches. Moreover extremely small duty ratio limits the converters switching frequency and results in severe reverse recovery problem of free-wheeling diode which degrades the converter's efficiency.

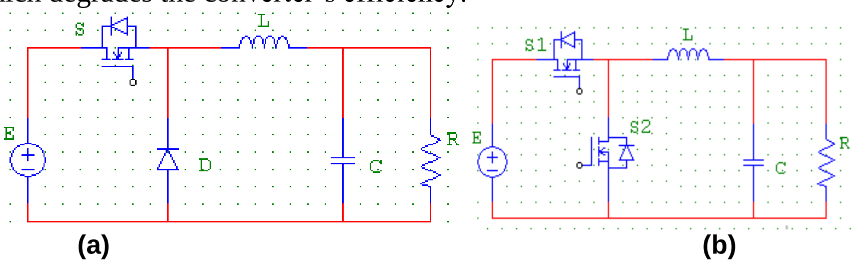

Figure 1. Buck & Synchronous Rectifier Buck Converters: a) Buck Converter. b) Synchronous Buck Converter

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In a conventional buck & synchronous buck converter with high input & low output voltages, there is a very high voltage drop (voltage stress) across the semiconductor switches. This high voltage stress of switches is also a major concern as it increases the ratings of the devices which results in increased size and also increase the switching losses which lowers the converter's efficiency [3, 6]. Another issue related with conventional buck & synchronous buck converters is the large current ripples. These large current ripples results in an increase in conduction losses and lowers the overall efficiency of the converter. Large filter inductors must be used to reduce these current ripples which increase the size and weight of the converter [7].

The conventional buck & synchronous buck converter is not suitable for high step down dc-dc voltage conversion due to its several limitations discussed above. A lot of research has been done on DC-DC converters with high step down voltage gain and a number of methods/topologies have been proposed in the literature to obtain a low voltage conversion ratio without the use of small duty ratios, to lowers the switch voltage stress, to decrease ripples and improve efficiency. No review of these step-down dc-dc converter topologies is available in the literature. The aim of this paper is to review the topologies used for high step down voltage conversion and point out the merits and demerits of each. The techniques/methods used for step-down voltage conversion in the literature are divided into different sub groups and then each sub groups is briefly discussed.

2. Interleaved Buck Converters

To solve the problems of large current ripples associated with conventional buck converters, interleaved buck converter are used by connecting two or more buck converters in parallel. Interleaving technique not only reduces output current ripples but also increase the power ratings [8, 9]. Figure 2 shows the circuit diagram of a two phase interleaved buck converter. This converter uses two same inductors in two parallel phases. There are four states of operation in one switching period and during state-I and state-III, when current in one phase increases the current in the other phase decreases and there is a ripple cancellation effect which results in small output current ripples. The current is shared among the two phase which decrease the conduction losses and improve efficiency and can be used in high power ratings. However, this topology does not lowers the voltage conversion ratio and still suffer from small duty ratio operation for high step down voltage conversion. The voltage gain of a simple buck and interleaved buck converter is same.

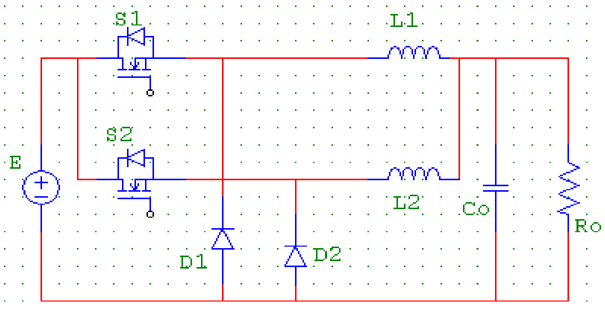


Figure 2. Two-Phase Interleaved Buck Converter

Interleaved buck converters with extended duty cycle have been proposed for high step-down voltage conversion [10-12]. Figure3 shows the circuit diagram of a two phase buck converter with extended duty cycle. One additional input capacitor is used between the two phases for extending the duty cycle and also clamping the voltage stress of switches. The concept can be generalized to more than two phase.

This topology can perform a high step down voltage conversion along with ripples cancellation feature of simple interleaved buck converter. However, it is not suitable for very high step down applications as it only doubles the duty cycle. Moreover, main switch of phase 2 still suffers from high voltage stress.

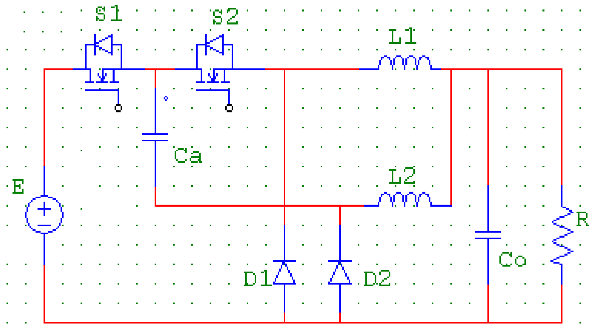


Figure 3. Interleaved Buck Converter with Extended Duty Cycle

A modified form of interleaved buck converters with extended duty cycle is shown in Figure4 [3], this structure use three additional capacitors and two additional transistors to lowers the voltage conversion ratio and obtain a large step down voltage gain. This topology is good for high step down conversion as it uses only a two phase interleaved structure and extended the duty cycle four times and also reduce the stress of semiconductor switches to one fourth of the input voltage. The use of more numbers of active switches and capacitors can be a concern as it can increase cost and size.

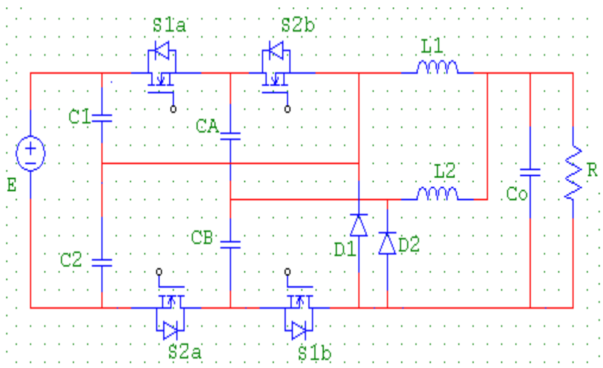


Figure 4. Modified Interleaved Buck Converter with Extended Duty Cycle

3. Quadratic Buck Converters

Quadratic converters are also used for obtaining low voltage conversion ratios [13-15]. The circuit diagram of a quadratic buck converter is shown in Figure 5. This converter uses two buck converters connected in series but employs only one transistor switch. This is a good method for high step-down voltage conversion as it gives a quadratic step down conversion ratio which is equal to the product of the conversion ratios of the two single buck converters. The efficiency is also good as it uses only one active switch. The voltage stress across the switches is high.

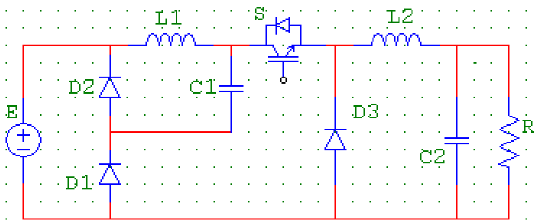


Figure 5. Quadratic Buck Converter

(double, triple) buck converters are proposed to reduce the stress voltage over the switches along with quadratic conversion ratio [16, 17]. A double quadratic buck converter is shown in Figure 6. Double quadratic buck converters has the same step-down conversion ratio as that a simple quadratic buck converter and has an additional advantage of reducing the voltage stress of the switches to half the value compared to simple quadratic buck converter.

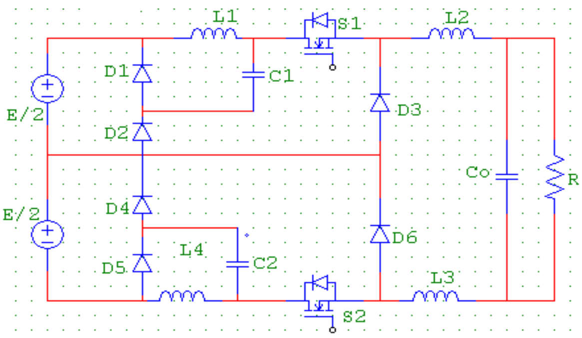


Figure 6. Double Quadratic Buck Converter

A single inductor quadratic buck converters is shown in Figure 7 [18]. Its additional advantage is fast transient response. This converter uses a single inductor to achieve the advantages of double-inductor quadratic buck converter but at the expense of four additional active switches.

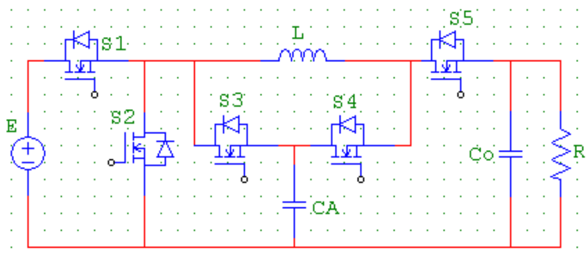


Figure 7. Single-Inductor Quadratic Buck Converter

4. Tapped-Inductor Buck Converters

Another method used for obtaining high step-down voltage conversion is the tapped-inductor buck converter [19, 20]. Figure 8 shows a common diode tapped inductor buck converter. This converter uses a tapped inductor with one primary and one secondary winding. Tapped-inductor buck converter permits the duty cycle to be adjusted at a proper value for high step-down voltage conversion by controlling the tapped winding ratio. This technique is also useful in reducing the switching & conduction losses. The main drawback is the appearance of a high voltage spike across the main switch due to the leakage inductance between the two coupled winding. The leakage energy is dissipated and results in additional power loss.

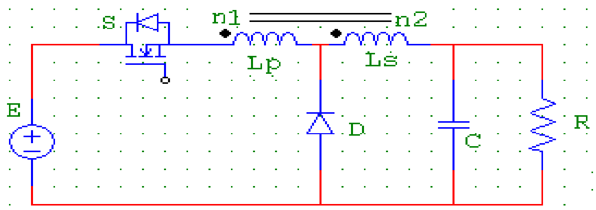


Figure 8. Tapped-Inductor Buck Converter

The voltage spike across the switch of taped-inductor buck converter is recovered by using additional lossless clamp circuits as shown in Figure 9 [21, 22]. The lossless clamp circuit is made of two diodes and a capacitor. This lossless clamp circuit can remove the high voltage across the switch and can also recover thee leakage energy as it is stored in the clamp capacitor and is recovered to the output.

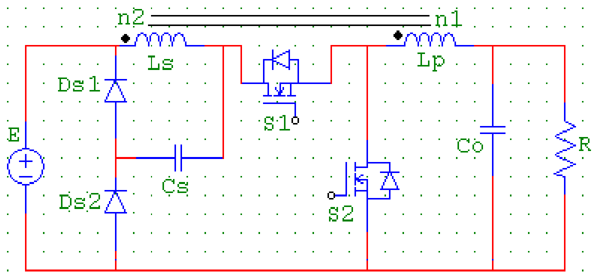


Figure 9. Tapped-Inductor Buck Converter with Lossless Clamp

Tapped inductor buck converter with a series clamp capacitor is shown in Figure 10. [23, 24] This converter uses an active clamp circuit for voltage spike problem with clamp capacitor connected in series with tapped inductor winding. This converter provide a higher step- down voltage gain as compared to a traditional tapped inductor buck converter and also minimizes the magnetic core size of the tapped inductor

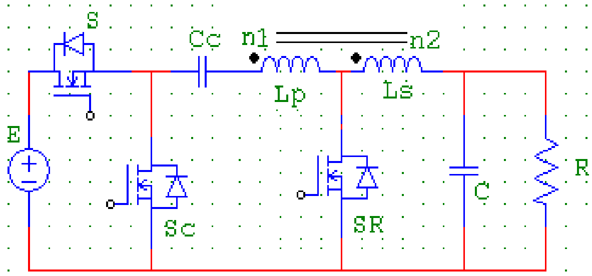


Figure 10. A Novel Tapped-Inductor Buck Converter

5. Switched-capacitor step down converters

Inductors-less switched capacitor step-down converters have been proposed that uses only switches and capacitors to obtain a high step down voltage conversion [25, 26]. Figure 11 shows a switched capacitor step-down converter with three switched capacitor cells, each cell consists of a capacitor and three switches. The operation is such that each capacitor charges from the source or other capacitor and then discharge to the load or other capacitor, thus a very high step-down voltage conversion can be achieved with high efficiency. However, the input current is pulsating and voltage regulation is poor.

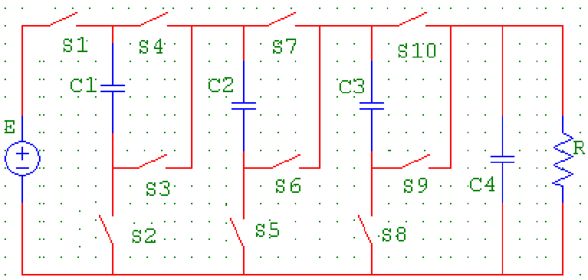


Figure 11. Switched Capacitor Step-Down Converter

Hybrid switched capacitor step-down convertor have been developed to solve the problem of conventional switched capacitor step down converts [27-32]. A hybrid switch capacitor converter made of first stage switched capacitor convertor followed by a second stage traditional buck convertor is shown in Figure 12. The first stage switched capacitor convertor is used for the purpose of voltage transformation by converting the input voltage to a very low unregulated voltage and the second stage buck converter performs voltage regulation. Thus high step-down voltage conversion with a high efficiency is possible.

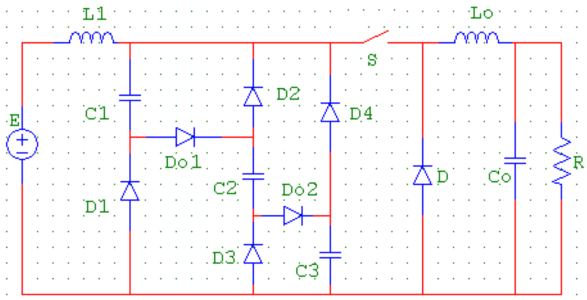


Figure 12. Hybrid Switched Capacitor Converter

Switched capacitor and hybrid switch capacitor step-down converters uses a large number of driven switches for very high step down conversion. An exponential step-down switched capacitor is proposed which uses fewer switches [33, 34]. Figure 13 shows the topology of exponential step down switched capacitor converter. This converter offers a very high step down voltage conversion and high efficiency. The step down conversion ratio can be further lowered exponentially. However, it lacks voltage regulation. The combined application of exponential switched capacitor with a second stage buck converts can provide a very high step down conversion with good regulation.

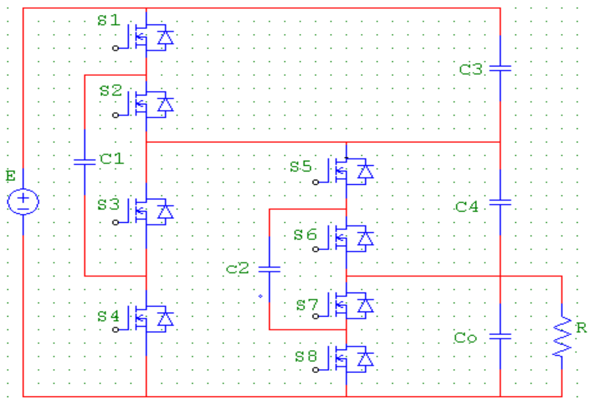


Figure 13. Exponential Step-Down Switched Capacitor Converter

6. Buck Converters with Switched Inductor Cells

Buck converter with switched inductor cells shown in Figure 14 is proposed to achieve high step down voltage conversion [35]. In this topology the inductor of the buck converts is replaced by an L-switching cell. This L-switching cell is made of two similar inductors and two diodes. Switched inductor cells can lower the voltage conversion ratio to same extent as by a switched capacitors cell.

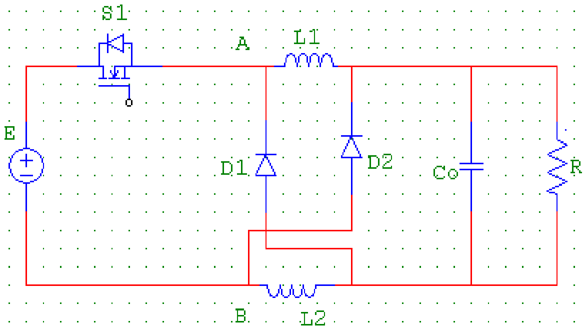


Figure 14. Buck Converter with Switched Inductor Cell

For obtaining much higher step down voltage conversion, buck converts with both switched inductor/ switched capacitor have been proposed [36,37]. Figure 15 shows a switched inductor/switched capacitor buck convert with one switched L and one switched C cell. This convert can provide much lower voltage conversion ratio at reasonable efficiency. The voltage stress of the transistor is slightly higher for high ratio between the input and output voltage. Also output current ripple is high due to L switching cell.

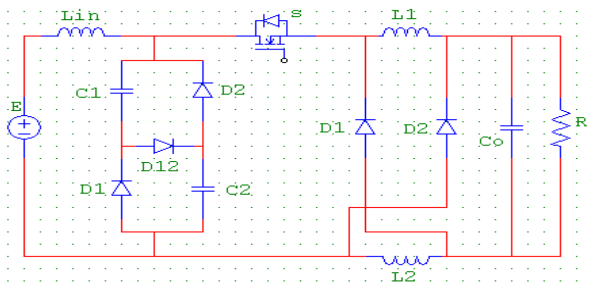


Figure 15. Switched Capacitor/Switched Inductor Buck Converter

7. Coupled inductor buck converters

Buck converts employing coupled inductors are proposed for obtaining small current ripples with smaller inductors [38-43]. Fig .16 shows a buck converts with two coupled inductors. Interleaving technique reduces output current ripple but cannot reduce inductor current ripples. Coupled inductors helps in decreasing the output current ripples as well as inductor current ripples depending on the value of co-efficient off coupling K and duty ratio D. The inductor can be directly or inversely coupled. However, this topology does not lower the voltage conversion and will work at narrow duty cycle high step down voltage conversion.

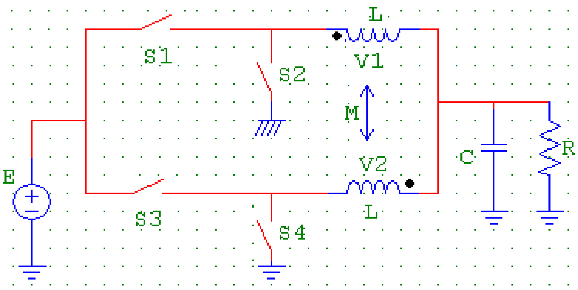


Figure 16. Coupled-Inductor Buck Converter

Buck converts with coupled inductor and extended duty ratio is shown in Figure 17 [44]. This is a four phase interleaved buck convert with inductors of four phases coupled with each other. This topology also uses two input capacitors to extend the duty ratio. The extended duty ratio mechanism divides the input voltage and thus high step down voltage conversion is possible. The capacitors also clamp the voltage stress of switches. The four interleaved coupled inductors in this topology reduces both the inductor and output current ripples and allow small filter inductors to be used. Thus overall size is reduced and efficiency is improved by decreasing both the conduction and switching losses.

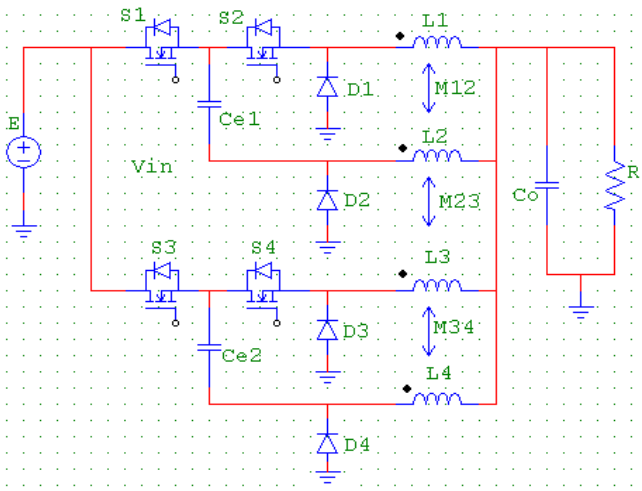


Figure 17. Four winding Coupled Inductor Buck Converter with Extended Duty Ratio

Buck converters with multi-winding coupled inductors are proposed for obtaining large step-down voltage conversion along with the advantage of decreasing inductor current ripples [45, 46]. The circuit diagram of multi-winding coupled inductor buck converter is shown in Figure 18. This converter uses two additional coupled windings in each phase to allow high step-down voltage conversion along with minimizing the inductor current ripples. The coupled windings has a turn ratio of n and by using proper turn ratio a high step down voltage conversion is possible. A lossless clamp circuit is used to recover the leakage energy of coupled inductors.

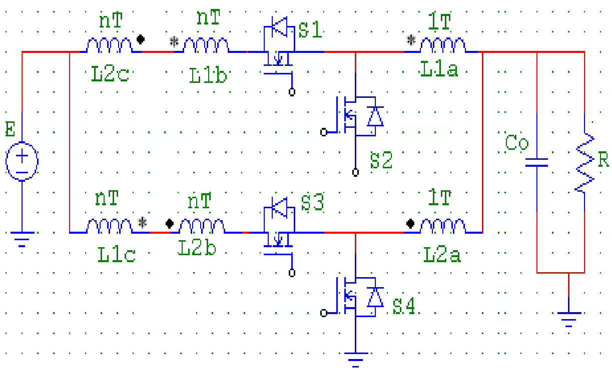


Figure 18. Multi Winding Coupled Inductor Buck Converter

A buck converter employing switched-coupled-inductor cell is shown in Figure 19 [47]. The filter inductor of buck converter is replaced by a cell of two inversely coupled inductors and a diode. This method can achieve high step down voltage conversion & also avoid the voltage over stress caused by leakage inductance. The leakage energy is recovered without using additional clamp circuit.

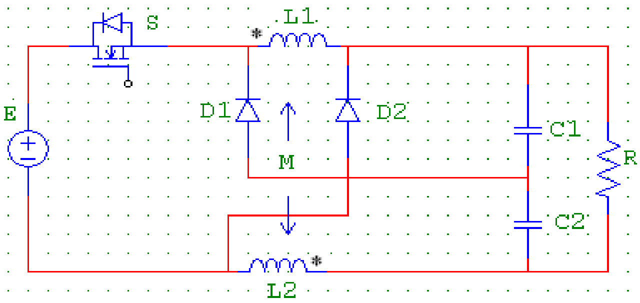


Figure 19. Buck Converter with Switched Coupled Inductor Cell

A two stage buck converter with coupled inductors is shown in Figure 20 [48, 49]. This is a single phase multi stage buck converter with the inductor of first and second stage coupled with each other. This method reduces the ripple currents and also the voltage conversion ratio is nearly quadratic.

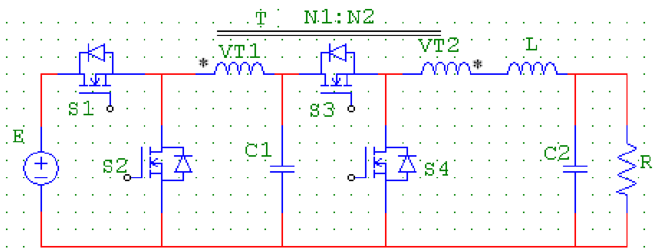
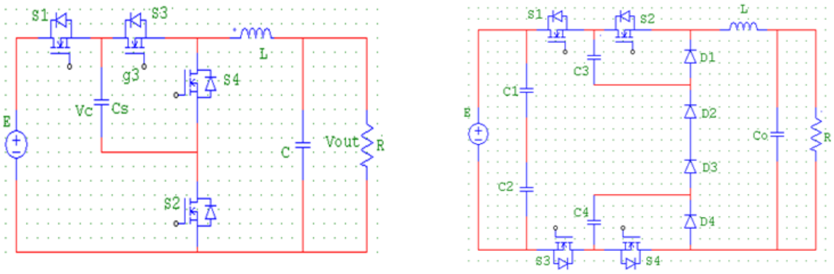


Figure 20. Two Stage Coupled Inductor Buck Converter

8. Multilevel buck converters

Multi level (2-level, 3-level, and 5-level) buck converters are proposed for decreasing the current ripples and voltage stress of the switches [50-52]. Figure 21 shows the circuit diagrams of 3-level and 5-level buck converters. Flying capacitors along with additional switches are used to get the same characteristic of interleaving buck converter in minimizing switching ripples and an additional advantage of reducing the switch stress.

These converters are not suitable for high step-down conversions but are good for high voltage applications.



(a) **(b)**

Figure 21. Multi-level Buck Converters; a) Three-Level Buck Converter; b) Five-Level Buck Converter

9. Buck Converters with Three State Switching Cell

A buck converter based on three state switching cell is proposed for high current & voltage step down applications as shown in Fig .22 [53, 54]. The three state switching cell consists of two transistors, two diodes and two coupled inductors. This arrangement do not extends the duty ratio but helps in reducing the peak current through the active switch to half the value and minimizes the ripples. Moreover, a part of the power is transferred to the load through transformer instead of the active switches. Thus conduction losses are reduced.

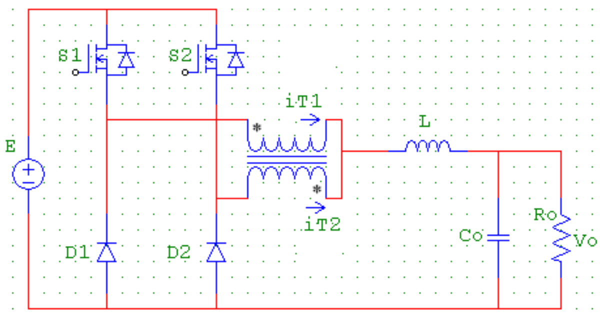


Figure 22. Buck Converter with Three State Switching Cell

10. Comparison

Table below shows the comparison of different topologies discussed above in relation to step down conversion ratio/voltage gain, switch stresses, output current ripple and no of components used.

Table 1. Comparison

Topology	**Voltage Gain (M)**	**Voltage Stress of Transistors (V_S)**	**Voltage Stress of Diodes (V_d)**	**Ripple in output current (Δi)**	**No. of transistors**	**No. of Diodes**	**No. of inductors**	**No. of capacitors**	**Power (P)**	**efficiency**

interleaved Buck converter	D	V_{in}	V_{in}	$\frac{V_{in} D(1-2D)}{L F_S}$	2	2	2	1	400W	97% Aprx.
Interleaved Buck converter with extended duty ratio	$\frac{D}{2}$	V_{in} & $\frac{V_{in}}{2}$	$\frac{V_{in}}{2}$	$\frac{V_{in} D(1-2D)}{2 L F_S}$	2	2	2	2	240W	94% Aprx.
Modified interleaved Buck converter	$\frac{D}{4}$	$\frac{V_{in}}{2}$ & $\frac{V_{in}}{4}$	$\frac{V_{in}}{4}$	$\frac{V_{in} D(1-2D)}{4 L F_S}$	4	2	2	3	400W	94% Aprx.
Quadratic Buck converter	D^2	$D V_{in}(1-D)$	$D V_{in}$ & $D^2 V_{in}$	$\frac{V_{in} D^2 (1-D)}{L F_S}$	1	3	2	2	9W	93% Aprx.
Double Quadratic Buck converter	D^2	$\frac{3V_{in}}{4}$	----	$\frac{V_{in} D^2 (1-D)}{2 L F_S}$	2	6	4	3	500W	----
Single inductor quadratic Buck converter	D^2	----	----	$\frac{V_{in} D(1-D)}{L F_S}$	5		1	1	----	----
Tapped inductor Buck converter	$\frac{D}{D+n(1-D)}$	$\frac{n V_{in}}{D+n(1-D)}$	$\frac{V_{in}}{D+n(1-D)}$	$\frac{n^2 V_{in} D(1-D)}{\{D+n(1-D)\} L F_S}$	1	1	1	1	28W	----
Tapped inductor buck converter with lossless clamp	$\frac{D}{D+n(1-D)}$	$\frac{n V_{in}}{D+n(1-D)}$	$\frac{V_{in}}{D+n(1-D)}$	$\frac{n^2 V_{in} D(1-D)}{\{D+n(1-D)\} L F_S}$	2	2	1	2	75W	90% Aprx.
Novel tapped inductor buck converter	$\frac{D}{n}$	V_{in} & $\frac{V_{in}}{D}$	----	----	3		1	2	45W	90% Aprx.
Switched capacitor step-down converter	$\frac{1}{a+2}$	----	----	----	10			4	70W	70% Aprx.

Hybrid switched capacitor step down converter	$\frac{D}{a-(a-1)D}$	$\frac{aV_{in}}{a-(a-1)D}$	$\frac{aV_{in}}{a-(a-1)D}$ & $\frac{2V_{in}}{a-(a-1)D}$	$\frac{V_{in}D(1-D)}{\{a-(a-1)D\}LF_S}$	1	7	2	4	----	80% Aprx.
Exponential step down converter	$\frac{1}{2^x}$	----	----	----	8	----	----	5	5 W-10 W	85% Aprx.
Buck converter with switched inductor cell	$\frac{D}{2-D}$	$\frac{2V_{in}}{2-D}$	$\frac{2V_{in}}{2-D}$	$\frac{V_{in}D(1-D)}{2(2-D)LF_S}$	1	2	2	1	26 W	----
Buck converter with switched inductor +switched capacitor cell	$\frac{D}{(2-D)^2}$	$\frac{V_{in}(4-D)}{(2-D)^2}$	----	$\frac{V_{in}D(1-D)}{2(2-D)^2LF_S}$	1	5	3	3	----	----
Coupled inductor buck converter	D	V_{in}	V_{in}	$\frac{V_{in}D(1-2D)}{L_KF_S}$	4	----	2	1	500W – 4k W	98% Aprx.
Coupled inductor buck converter with extended duty ratio	$\frac{D}{m}$	V_{in} & $\frac{V_{in}}{2}$	$\frac{V_{in}}{2}$	$\frac{V_{in}D(1-mD)}{mLF_S}$	4	4	4	3	72 W	80% Aprx.
Multi winding coupled inductor buck converter	$\frac{D}{1+n'}$	V_{in} , $\frac{V_{in}}{n'+1}$ & $V_{in}(2-\frac{1}{n'+1})$	----	$\frac{V_{in}D(1-2D)}{(n'+1)LF_S}$	4	----	2	1	37.5W	88% Aprx.
switched coupled inductor buck converter	$\frac{D}{1+n'(1-D)}$	----	$\approx\frac{DV_{in}}{1+n'(1-D)}$ & $\approx\frac{n'DV_{in}}{1+n'(1-D)}$	----	1	2	2	2	5 W	----
Two stage coupled inductor buck converter	D^2	V_{in} & DV_{in}	V_{in} & DV_{in}	$\frac{V_{in}D^2(1-D)}{LF_S}$	4	----	2	2	2.25W	----

Three level buck converter	D	$\frac{V_{in}}{2}$	----	$\frac{V_{in}D(1-2D)}{2LF_S}$	4	----	1	2	----	----
Five level buck converter	D	$\frac{V_{in}}{4}$	$\frac{V_{in}}{4}$	$\frac{V_{in}D(1-4D)}{4LF_S}$	4	4	1	3	5kW	----
Buck converter with three state switching cell	D	V_{in}	V_{in}	$\frac{V_{in}D(1-2D)}{2LF_S}$	2	2	2	1	1kW	97% Aprx.

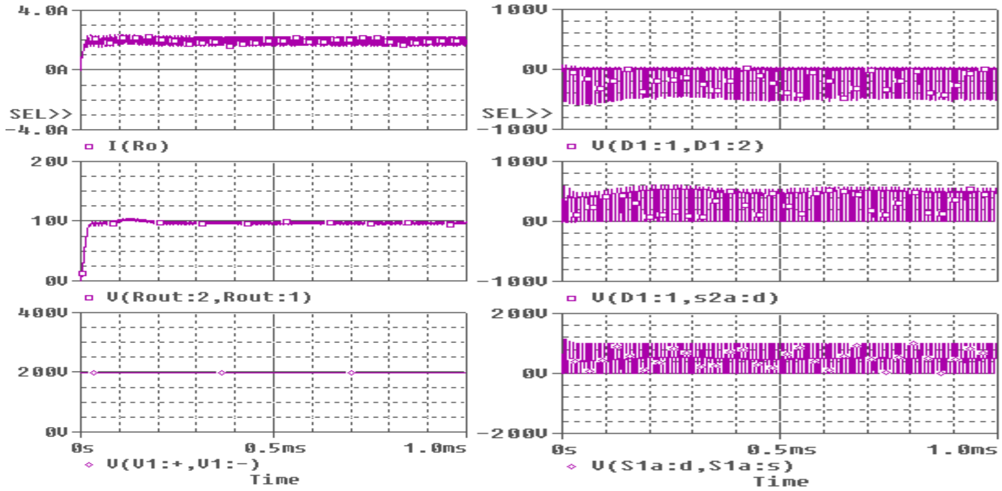
V_{in} is input voltage; V_{out} is output voltage; M is voltage conversion ratio and $M = \frac{V_{out}}{V_{in}}$; D is Duty ratio; L is filter inductor; L_k isLeakage inductance of coupled inductors; f_S is switching frequency; n is turn ratio of tapped inductor windings; a represent number of switched capacitor cells; x represent order number of exponential step down converter ; m is number of extension capacitors; n' is turn ratio of coupled inductors

Table above shows a comparison of different step down converter topologies. Among the interleaved converters modified interleaved is best as it lowers the conversion ratio as well as ripple current considerably and also cuts down the stresses to a quarter value. Quadratic buck converter multiplies the duty ratio and its conversion ratio is equal to the product of conversion ratios of two buck converters. Single inductor quadratic buck converter gives the same advantages with only one inductor. Their efficiency is also good. Tapped inductor gives higher step down voltage gain while using fewer components but raises ripples and switch stress. Switched capacitor converter can achieve very low conversion ratio depending on the number of switched capacitor cells but they hardly achieve a higher efficiency and can be used in very low power ratings. They can be a good choice for the applications that requires high step-down conversion but the efficiency requirements are not strict. Among them hybrid switched capacitor is good as its efficiency is better. Switched capacitor combined with switched inductor has very good performance by lowering conversion ratio as well as current ripples. Among the coupled inductor buck converters, multi winding coupled buck converter is best as it lowers conversion ratio as well as switch stress and current ripples by using appropriate number of turn ratio while utilizing fewer components. Multi level converters are good for giving small ripples and lowering switch stress and buck converter with three state switching cells has the advantage of very small current ripples. The use of those converters which utilizes transformer windings such as tapped inductors and coupled inductor buck converter will not suite high step down voltage conversion applications where efficiency requirements is high due to difficulty of proper coupling and existence of leakage inductance. These converters combined with interleaved structure can give better performance. In this review of various step-down techniques, two best topologies modified interleaved buck converter (Figure 4) and five level buck converters (Figure 21(b)) are further investigated for their performance and their simulation has been carried out in pspice using the same design parameters given below.

V_{in}= 200V, D= 0.2, f_S= 100 kHz, L= 100μH, C= 1uF, P_0= 20W.

Table 2. Results Of Modified Interleaved and Five Level Buck Converters

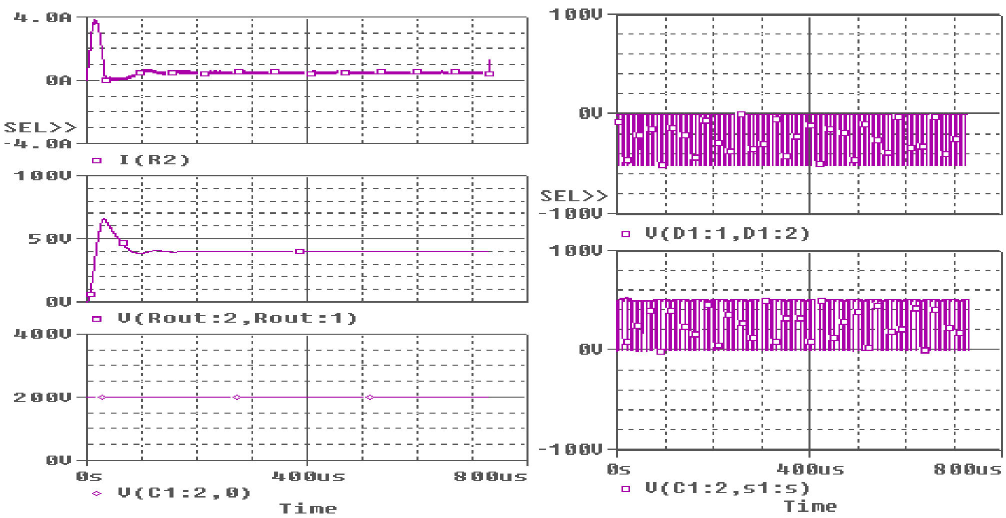
Modified interleaved buck converter	Five level buck converter
Vo= 10V	Vo= 40V
V_{S1a}= 100V	V_{S1}= 50V
V_{S1b}= 50V	V_{S2}= 50V
V_{S2a}=100V	V_{S3}= 50V
V_{S2b}=100V	V_{S4}= 50V
V_{D1}= 50V	V_{D1}= 50V
V_{D2}= 50V	V_{D2}= 50V
……………	V_{D3}= 50V
……………	V_{D4}= 50V
Δi =0.6A	Δi = 0.2A



(a) (b)

Figure 23. Simulation waveforms of Modified interleaved buck converter (a) Input voltage, Output voltage, output current waveforms (b) Voltage stress waveforms of transistors and diodes

As shown in Figure 23 Modified interleaved buck converter generate an output voltage of 10V from 200V input and gives a high step down conversion ratio, The voltage stress of some switches is 50V and that of some are 100V and the ripple in output current is 0.6A. As shown in Figure 24 five level buck converters gives an output voltage of 40V from the same input voltage of 200V and the voltage stress on its all switches is 50V. It also reduces the output current ripples to 0.2A. Modified interleaved buck converter gives a high step down conversion ratio, however the voltage stress on switches and current ripples are less in five level buck converters. For reasonable power and efficiency and low current ripple using interleaved structure and combining any other high step-down technique along with lowered switch stress mechanism of multilevel converters can be a candidate topology for high step-down dc-dc conversion applications.



(a) (b)

Figure 24. Simulation waveforms of Five Level Buck Converter (a) Input voltage, Output voltage, output current waveforms (b) Voltage stress waveforms of transistors and diodes

11. Conclusion

A brief survey of high step-down dc-dc converters is carried out in this study. The limitations of conventional dc-dc converters used for high step-down dc-dc voltage conversion are discussed. Various non-isolated dc-dc step-down converter topologies solving these limitations are reviewed. The circuit diagram of each technique/topology is given and main points are discussed. Interleaving technique is good for reducing ripples: quadratic, tapped & switched capacitor can avoid narrow duty cycle for high step down conversion, coupled inductors can minimize ripple as well as extend duty cycle & multilevel is good for reducing switch stress. A comprehensive review of the published research work on non-isolated dc-dc step down converters is given and around twenty two different techniques used for such type of conversion are briefly explained. A comparison of these topologies is carried out in relation to step down conversion ratio/voltage gain, switch stresses, output current ripple and number of components used. Two best topologies are identified and there simulations results are given. This paper well provides a clear background to the students and researchers who want to do further research on step down dc-dc converters.

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