A SEPIC Fed Buck Converter

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Abstract—A new patented topology – the SEPIC fed buck converter [1, 2] – addresses two critical issues confronting the power electronics field today: efficiency and transient response. A buck converter is integrated into a SEPIC to receive energy from the SEPIC inductors and the outputs of both deliver energy to the load in parallel. When the controlling switch – shared by both converters – is ON, the buck portion delivers energy to the load while the SEPIC portion stores energy in the magnetic element and feeds the buck portion. When the controlling switch is OFF, the stored energy is delivered to the load through both the buck and the SEPIC portions. The new converter has a voltage transfer ratio of $E_{OUT}/E_{IN} = D/(2-D)$ and complementarily combines the characteristics of both buck and SEPIC converters, resulting in reduced voltage and current levels in the magnetic and switching devices and leading to reduced conduction and switching losses. Additionally, an inherent gate-charge-extraction mechanism facilitates extremely fast turn-off of the control switch, essentially eliminating its turn-off loss. Furthermore, a new volt-second structure on the magnetic element significantly improves transient response of the power stage.

INTRODUCTION

The power electronics field is increasingly faced with two major issues today – efficiency and transient response, especially as the output voltage trends below 1V and load current continues to climb. As an example, the synchronous buck converter that dominates the Point-Of-Load (POL) application features a current magnitude on the order of the full output current throughout the power stage. All the conduction related losses are proportional to the square of the output current (I^2_{OUT}), whether they are in the inductor, the switches or the wiring structure. During switching transitions, the control switch has a switching loss proportional to Iout*Ein and the duration of the switching transition. Furthermore, gate turn-off speed is limited by the parasitic source inductance [3] in MOSFET packages. Various improvements in device $R_{DS(on)}$, switching characteristics and drive mechanism have pushed the efficiency envelope to a very mature degree such that quantum step improvements are difficult. On transient response, the buck converter is dominated by the integrating inductance, and by the low Eout during load release. Various digital and nonlinear control methodologies have permitted enhanced transient response while modestly improving efficiency. Some alternative topologies that affect the down converter integrating inductor function include 1) auto transformation of the integrating inductor applied voltage [4], 2) inter-phase coupling of the integrating inductor in multi-phase topologies [5], 3) the distributed EMF (tapped-inductor) topology [6]. Alternatives 1) and 2) are characterized by multi-phase complexity while 3) is burdened by the associated leakage inductance.

The foregoing discussion makes it very clear that a POL converter topology with significant improvements in power loss and transient response would find great utility.

THE SEPIC FED BUCK CONVERTER

The SEPIC Fed Buck (SFB) topology [1, 2] is invented to fundamentally improve power conversion efficiency and transient response, while retaining the simplicity and low cost of the synchronous buck converter. Both conductivity losses and switching losses are addressed. To overcome the issue of $I^2_{OUT}R$ losses in the buck converter, multiple energy delivery paths are made available to split the load current. To address the significant turn-off loss issue in the buck, the SFB topology features an extremely fast controlled turn-off commutation of the control switch, made possible by a gate-charge extraction (GCE) mechanism [7, 8] inherent in the topology. Due to the lower voltage and current stresses on the power switches, their turn-on losses are significantly reduced as well. On transient response, the reduced current level on the integrating inductors and increased reset voltage brings fundamentally faster response from the power stage, as will be discussed later.

Figure 1 highlights the derivation of the SFB converter from a SEPIC converter and a buck converter. The buck converter in the lower part is integrated into a SEPIC converter to receive energy from the SEPIC portion and the outputs of both converters are combined to deliver energy to the load. The SEPIC control switch (S_{1SB}) is not terminated to the input return as in the original form, but is instead shared with the buck converter. When S_{1SB} is ON, the two commutation switches (S_{2S} for the SEPIC portion and S_{2B} for the buck portion) are OFF, and the buck portion delivers energy to the load while the SEPIC portion stores energy in the magnetic element and feeds the buck portion. When S_{1SB} is OFF, the stored energy is delivered to the load through both the buck and the SEPIC portions. As a result, the buck portion delivers continuous current to the load while drawing current during switch ON time. The SEPIC portion draws current from the source all the time while delivering current during OFF time only, as in the original SEPIC converter. The combined converter integrates the best features of both converters by drawing continuous input current and delivering load current all the time (although the SEPIC portion during OFF time only). As a result, input EMI is minimized and input capacitors can be reduced. The load current I_{OUT} is shared by the two portions and does not fully stress any device.

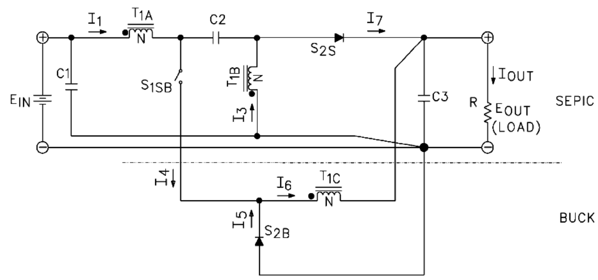

Fig. 1 Derivation of SEPIC Fed Buck Converter

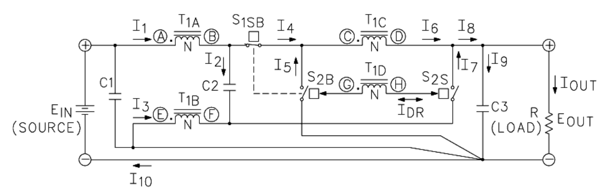

Fig. 2 SEPIC Fed Buck Converter

The SEPIC fed buck converter is redrawn in Figure 2 where the commutation switches are shown as ideal switches and can be implemented as synchronous rectifiers. In this non-isolated implementation, the entire magnetic function in both the SEPIC and the buck is combined into a single coupled inductor to facilitate energy storage and transfer, in which all the windings have the same number of turns. The three power windings are called input winding (T_{1A} with current I_1), SEPIC winding (T_{1B} with current I_3) and output winding (T_{1C} with current I_6). To simplify driving S_{2S}, an additional winding (T_{1D}) is constructed within the same magnetic structure to provide a floating drive signal synchronized to the gate drive for S_{2B}.

STEADY-STATE ANALYSIS

The power stage circuits during control switch ON time and OFF time are shown in Figures 3 and 4.

For ease of analysis, consider the magnetizing inductance L_m to be the total inductance across T_{1A} and T_{1C}. During ON time, the voltage across L_m is:

[1] $$EMF = E_{IN} - E_{OUT}$$

During OFF time, the voltage across L_m is:

[2] $$MMF = -2E_{OUT}$$

By applying the volt-second balance on the inductors, one can readily derive the steady-state output voltage as:

[3] $$E_{OUT} = \frac{D}{[2-D]} E_{IN} = M * E_{IN}$$

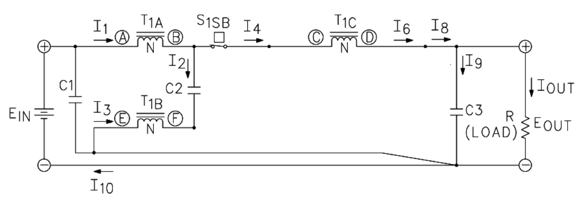

Fig. 3 SEPIC Fed Buck Converter During ON Time

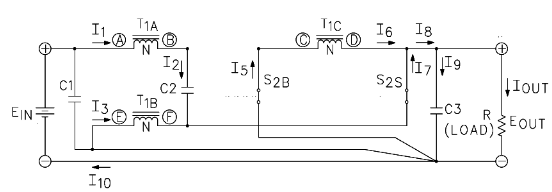

Fig. 4 SEPIC Fed Buck Converter During OFF Time

where M is defined as

[4] $$M = \frac{E_{OUT}}{E_{IN}} = \frac{D}{2-D}$$

The duty ratio D can be expressed as

$$D = \frac{2E_{OUT}}{E_{IN} + E_{OUT}} = \frac{2M}{1+M}$$ [5]

Consider a typical POL application example with E_{IN}=12V, E_{OUT}=1.2V, M=0.1. The SFB converter has a duty ratio of D=0.1818. In comparison, a buck converter with the same input and output voltages will have a smaller duty ratio of D=M=0.1. The duty ratio in a SEPIC fed buck converter is inherently larger than in a buck, implying much longer on-time. This is a very useful property for low output voltage high frequency applications where the on-time might be close to the minimum switching delays. For example, with a 12V input and a 0.6V output, the buck converter would have a D term of 0.05. For a 500KHz switching frequency, the ON time would be 100ns which is approaching the sum of delays and rise times in the controller, the driver, and the MOSFET, and the converter may have difficulty achieving adequate regulation. In the SFB converter, the D term would be 0.095 and the ON time would be 190ns, which is almost twice as long. Therefore, the SFB converter is inherently easier to achieve good regulation for low duty ratio applications in many low voltage POLs.

The steady-state voltage waveforms are summarized in Figure 5.

By applying charge balance on the capacitors, one can derive the steady-state inductor currents in terms of output current:

$$I_1 = \frac{D}{2-D} I_{OUT}$$ [6]

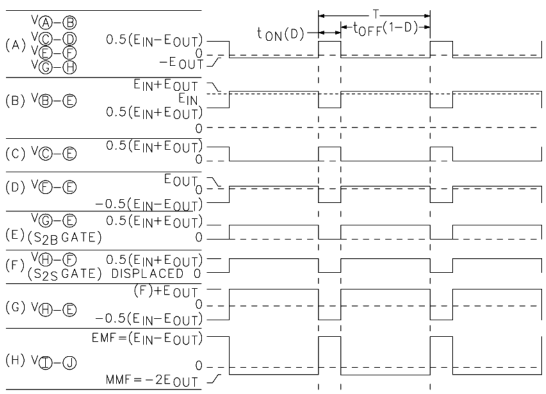

Fig. 5 SEPIC Fed Buck Converter Steady-State Voltage Waveforms

[7] $$I_3 = \frac{1-D}{2-D} I_{OUT}$$

[8] $$I_6 = \frac{1}{2-D} I_{OUT}$$

In practice, it might be more intuitive to express these currents in terms of the output current and M, the voltage transfer ratio:

[9] $$I_1 = M \bullet I_{OUT}$$

[10] $$I_3 = \frac{1-M}{2} I_{OUT}$$

[11] $$I_6 = \frac{1+M}{2} I_{OUT}$$

The steady-state current waveforms are summarized in Figure 6.

The inductor current ripple on winding T_{1C} can be expressed as:

$$\Delta I_{SFB} = \frac{E_{IN} - E_{OUT}}{L_m} DT$$ [12]

$$= \frac{2}{1+M} (1-M) \frac{E_{OUT}}{L_m} T$$

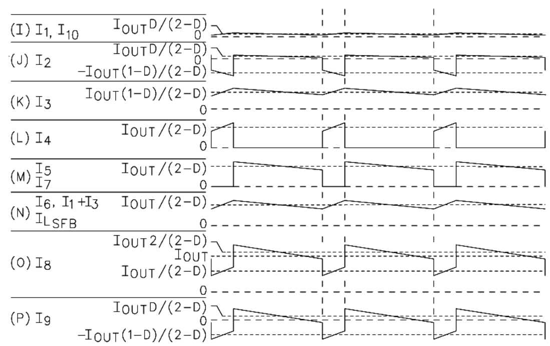

Fig. 6 SEPIC Fed Buck Converter Steady-State Current Waveforms

where T is the switching period. With the buck converter, in comparison, the inductor current ripple is:

$$\Delta I_{BUCK} = (1-M) \frac{E_{OUT}}{L_m} T$$ [13]

The voltage stress on the control switch S_{1SB} is

$$V_{SISB(MAX)} = (1+M) E_{IN}$$ [14]

while its current stress is

$$I_{SISB\,(MAX)}$$ [15]

$$= \frac{1+M}{2} Iout + \frac{2(1-M)}{1+M} \frac{E_{OUT}}{L_m} T$$

The voltage stress on the commutation switches S_{2S} and S_{2B} is

[16] $$V_{S2B[MAX]} = V_{S2S[MAX]} = \frac{1+M}{2} E_{IN}$$

which is only slightly more than half of the voltage experienced by the commutation switch in the buck converter, because M is a very small quantity for typical POL applications. The current stress of the SFB commutation switches are the same as that in the control switch:

[17] $$I_{S2B[MAX]} = I_{S2S[MAX]} = I_{SISB[MAX]}$$

The above analysis quantifies the energy delivery features discussed earlier. In the SFB converter, the input current I_1 is continuous just like the SEPIC; the load current is delivered by both the buck portion and the SEPIC portion. The buck portion delivers load current I_6 all the time while the SEPIC portion delivers load current I_7 during OFF time only, with a quantity equal to the buck current I_6 during OFF time. With a small duty ratio D and correspondingly a small M, each portion only delivers slightly more than half of the load current. From (9), (10) and (11), it can be seen the inductor currents are only a fraction of the load current. For the same POL example mentioned earlier with E_{IN}=12V, E_{OUT}=1.2V and M=0.1, the average inductor currents are I_1=0.1 $I_{OUT,}$ I_3=0.45 I_{OUT}, I_6=0.55 I_{OUT}. It is worthwhile to notice that these currents are only about half of or much less than the load current, unlike the buck converter where the average inductor current is the output current. These lower currents distributed in the inductors, the switches and circuit wiring, lead to much reduced conductivity losses in the form of I^2R which are discussed next.

CONDUCTIVITY LOSSES

In the coupled inductor, it is assumed the three windings are made identical with the same DC resistances (DCR). With first order approximations by using the average currents and neglecting the current ripples, the sum of the inductor DCR losses in the three windings is

$$P_{DCR} = [I_1^2 + I_3^2 + I_6^2]\, DCR$$

$$= \frac{1+3M^2}{2} I_{out}^2\, DCR \quad [18]$$

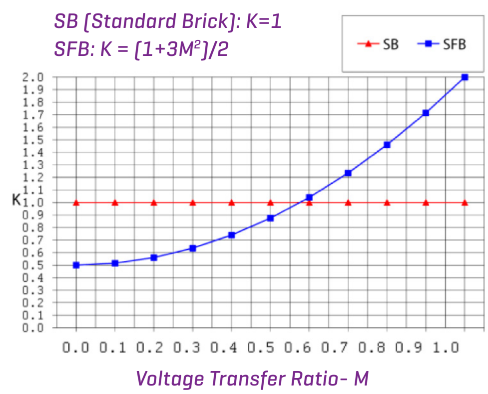

Fig. 7 A First-Order Comparison of Inductor DCR Losses between SFB Converter and Buck Converter

In comparison, a conventional buck converter has an inductor DCR loss of I^2_{OUT}DCR. Figure 7 presents a first-order DCR loss comparison assuming the same DC resistance in both inductors, normalized to the loss of the buck converter. For the preceding POL example with M=0.1, the SFB converter has a scaling factor of 0.515 in inductor DCR loss, which is only slightly more than half of that in a buck converter. This graph clearly illustrates the significant DCR loss advantages in a SFB converter for low voltage POL applications. It is also worth noting that the SFB converter exhibits much higher inductor DCR losses when M>1/√3≈0.577, an important factor to keep in mind in deciding when to use the SFB converter.

The conduction losses in the switches are considered next. During ON time, only the control switch conducts and the current through S_{1SB} is I_6. Assuming the on-resistance of S_{1SB} to be $R_{DS(ON)H}$, the conduction loss is:

$$P_{RDS(on)H} = D * I_6^2 * R_{DS(on)H}$$

$$= \frac{2M}{1+M} * \left[\frac{1+M}{2} I_{OUT}\right]^2 * R_{DS(on)H}$$

[19]

$$= M * I_{OUT}^2 * R_{DS(ON)H} * \frac{1+M}{2}$$

During OFF time, only the commutation switches conduct. The current through S_{2B} is I_6 and the current through S_{2S} is $(I_1 + I_3) = I_6$. Assuming the on-resistance of S_{2S} and S_{2B} to be both $R_{DS(ON)L}$, the total conduction loss is:

$$P_{RDS(on)L} = 2(1-D) * I_6^2 * R_{DS(on)L}$$

$$= 2\frac{1-M}{1+M}\left[\frac{(1+M)}{2} I_{OUT}\right]^2 R_{DS(on)L}$$

[20]

$$= (1-M) * I_{OUT}^2 * R_{DS(ON)L} * \frac{1+M}{2}$$

It is very interesting to note that the power switch conduction losses during ON time and OFF time are both scaled by (1+M)/2 compared to those of a buck converter, respectively, if identical switches are used. Additionally, due to the lower voltage stresses on the commutation switches in the SFB converter, it is possible to use lower voltage devices with potentially lower Rds(on) to lower conduction losses further.

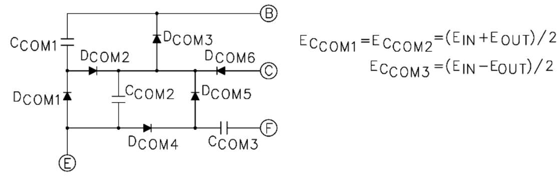

Fig. 8 A Commutation Network for SEPIC Fed Buck Converter

CONTROL SWITCH TURN-ON

The SFB converter achieves significant reduction in power losses due to switching, mostly due to lower switch stresses during turn-on, and due to a gate-charge-extraction mechanism during turn-off. Equations (14) – (17) presented earlier highlights the voltage and current stresses, where all three switches experience a current stress of [(1+M)/2] I_{OUT} if we ignore the current ripples for a first order analysis. The synchronous switches have a voltage stresses of [(1+M)/2] E_{IN} while the control switch has a voltage stress of (1+M) E_{IN}. To improve the converter's turn-on characteristics even further, a commutation network as shown in Fig. 8 is added to the topology in Fig. 2. The commutation network consists of a set of capacitors and diodes and nodes B, C, E and F of the network are connected to the corresponding B, C, E and F nodes of the SFB converter in Fig. 2.

At the beginning of a control switch turn-on sequence, switch S_{1SB} is in OFF state and the voltage on node B referenced to ground E is $(E_{IN}+E_{OUT})$, and node C is at ground level with S_{2B} on. Therefore the voltage across S_{1SB} is also $(E_{IN}+E_{OUT})$. The commutation capacitors CCOM1 and CCOM2 and are charged to $(E_{IN}+E_{OUT})/2$. When switches S_{2B} and S_{2S} are turned off, diodes DCOM1 and DCOM3 are forced to turn on rapidly, which clamps the voltage at node B to $(E_{IN}+E_{OUT})/2$. From that point, the normal turn-on sequence begins to bring the voltage on node C up from 0V to $(E_{IN}+E_{OUT})/2$ and brings the voltage across S_{1SB} down from $(E_{IN}+E_{OUT})/2$ to 0V.

In a typical implementation with MOSFET as switches, the turn-on and turn-off actions are completed in a finite amount of time, mostly due to the charging and discharging of intrinsic parasitic capacitances. The switching losses are largely determined by the voltage and current stresses and the duration of the transition, in addition to switching frequency, as illustrated in Fig. 9 for the SFB converter and the conventional buck converter. For the buck converter, by ignoring the current ripple, the first-order turn-on and turn-off losses are (where f_{sw} is the switching frequency):

[21] $$P_{SB[on]} = \frac{E_{IN} * I_{OUT}}{2} t_{SB[on]} f_{sw}$$

[22] $$P_{SB[off]} = \frac{E_{IN} * I_{OUT}}{2} t_{SB[off]} f_{sw}$$

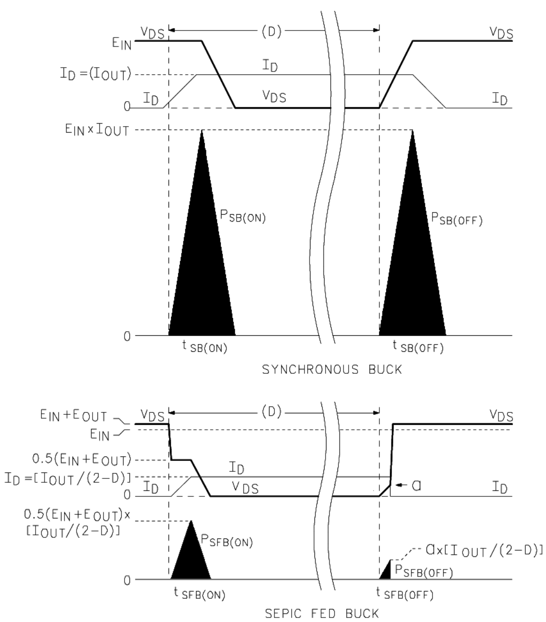

Fig. 9 Switching Transitions in SEPIC Fed Buck Converter and Buck Converter

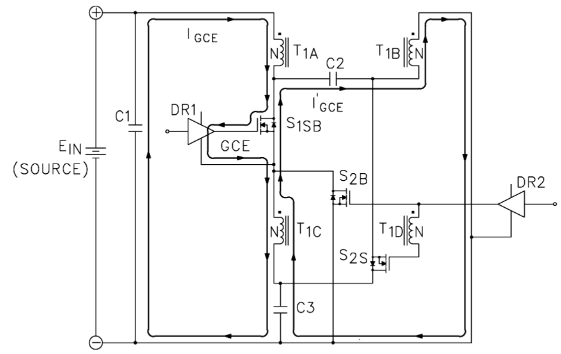

Fig. 10 Gate Charge Extraction During Control Switch Turn-OFF in SEPIC Fed Buck Converter

In the SFB converter, due to the lower voltage and current stresses when the switching transition commences, the first-order turn-on loss is:

$$P_{SFB[on]} = \frac{1}{2}(E_{IN} + E_{OUT})I_6 * t_{SFB[on]} f_{sw}$$

$$= \left[\frac{1+M}{2}\right]^2 \frac{E_{IN} * I_{OUT}}{2} t_{SFB\,[on]} f_{sw}$$ [23]

Compared to the buck converter, assuming identical MOSFETs are used in both applications, the duration of the transition is further scaled down because the current only ramps up to $[(1+M)/2]I_{OUT}$ and the voltage only needs to ramp down from $(E_{IN}+E_{OUT})/2$ which is $[(1+M)/2]\ E_{IN}$. The scaling factor for duration of switching transition is (1+M)/2. Normalized to the turn-on loss of the buck control switch, the loss factor for the SFB converter control switch turn-on is:

$$K_{SFB_{on}} = \frac{P_{SFB[on]}}{P_{SB[on]}} = \left(\frac{1+M}{2}\right)^3$$ [24]

CONTROL SWITCH TURN-OFF

During the turn-off process of the control switch S_{1SB}, a gate charge extraction (GCE) mechanism [7, 8] takes effect to substantially reduce the turn-off switching loss, as illustrated in Fig. 10.

At the start of the turn-off, the voltage across the gate and source drops, and the gate current discharges the gate-source capacitance. In the conventional buck converter, the source inductance within the MOSFET package resonates with the gate capacitance to cause the gate current to reduce and even reverse direction, thus significantly slows the turn-off. In the SFB converter as shown in Fig. 10, however, inductor T_{1A} will maintain its current flow and thus causing a current I_{GCE} to flow from the gate to the driver, thereby discharging the gate-source capacitance rapidly and turn-off the channel. Current I_{GCE} is therefore called gate-charge extraction (GCE) current. In the coupled winding T1B, a current I'_{GCE} is induced that flows in a loop in the opposite direction. Currents I_{GCE} and I'_{GCE} combine to cause the drain current I_D to drop to 0A rapidly, leading to low turn-off loss.

The turn-off power loss is given by

[25] $$P_{SFB(OFF)} = \frac{1}{2} I_6 * a * t_{SFB(OFF)} * f_{sw}$$

where "a" is the plateau voltage and $t_{SFB(OFF)}$ is the time needed for V_{DS} to charge up to "a". In comparison, the buck converter takes much longer to turn off the control switch, with the amount of time needed for V_{DS} to charge up to Ein and for I_D to ramp down from Iout to 0A. Normalized to the buck converter, loss factor for the SFB converter's control switch turn-off is:

[26] $$K_{SFB(OFF)} = \frac{P_{SFB(OFF)}}{P_{SB(OFF)}} = \frac{(M+1)\,a^2}{4Ein^2}$$

The turn-on and turn-off losses of the SFB control switch are plotted in Fig. 11 for a typical application of 12V input and 1.2V output. The plateau voltage of the MOSFET for this example is 2V. It can be seen that control switch turn-off is completed with extremely low power loss. The turn-on is also completed with only a small fraction of the buck turn-on loss.

TRANSIENT RESPONSE

The SFB converter achieves improvement in transient response through reduced current in the integrating inductors. During ON time, the applied voltage on the magnetizing inductance L_m (T_{1A} and T_{1C}) is (E_{IN}-E_{OUT}), however the current level is only about half of the load current, implying the load current can rise almost twice as fast as in the buck if its magnetizing inductance is also L_m. During OFF time, the inductor current level is still about half of the load current, but the applied voltage is now $-2E_{OUT}$, implying the load current can ramp down almost 4 times as fast as in the buck. Therefore, the SFB power stage is inherently faster.

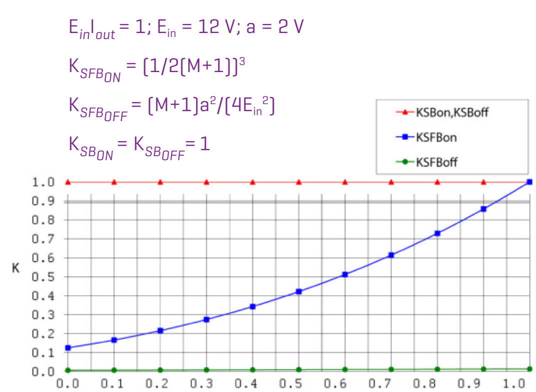

Fig. 11 A First-Order Comparison of Control Switch Turn-on and Turn-off losses in SFB Converter and Buck Converter

CONCLUSION

A new SEPIC fed buck converter has been developed to improve on conduction and switching losses, and at the same time significantly improve transient response. The converter has a new current distribution structure and an extremely fast control switch turn-off mechanism. Its derivation and steady-state analysis were presented, along with examination of conduction loss, switching loss and transient response. A number of benefits can be realized in the SFB converter, including excellent input EMI characteristics, fast transient response and significant efficiency increase. As a result, input and output capacitances can be reduced, power density can be increased and circuit reliability (MTBF) can be measurably increased. Further research directions include study of integrated magnetic element in the SFB converter and high speed control methods to exploit the topology's fast transient response characteristics.

ACKNOWLEDGMENT

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