Voltage collapse in low-power low-input voltage converters - A critical comparison

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Abstract- Low power converters with low input voltage are investigated in this paper. Analysis and design of these converters are today of quite importance because of their widespread applications. A key point in such applications is the need for converters with specific features that is small size, high efficiency, and low cost. Furthermore, in such converters we are usually concerned with some other important issues regarding the converter's operation that is the startup regime and the voltage collapse phenomena. In this paper we mainly focus on voltage collapse issues, a concept recently introduced to the literature. In this regard, besides providing comparative studies between Boost, Buck-Boost, and Flyback converters, a new topology improving voltage collapse is proposed. Extensive simulation results are also presented to compare and prove the superiority of the suggested topology.

Key Words: Voltage collapse, Fuel cells, Low power converters, dc/dc converters, Boost converter

1 Introduction

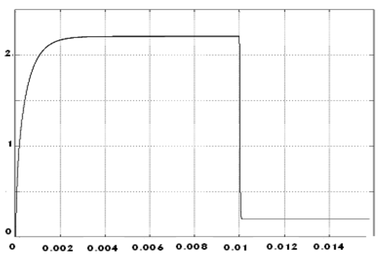
Nowadays, low power converters are widely used in various portable electronic devices such as mobile phones, calculators, portable media systems, etc. In some cases, due to economical issues, the main supply of the converter is either a single fuel cell (or single solar cell), or a single thermoelectric device. Owing to high price of the thermoelectric devices, when used, they are usually implemented as a single element as well. Individual fuel cells naturally yield a low voltage, typically with peak voltage less than 1v for no load and around 0.4v for full load conditions. That of course results in very lower input voltage for the converter in use. In almost all cases we usually must consider some additional important issues that are efficiency, size, weight, and cost. As for efficiency, considering the fact that the range of the output power in such devices is usually low, even a low rate of loss is crucial. As for size and weight, both obviously need to be minimized for any smart design. The last issue refers to minimum cost requirement that requires a design with minimum number of switches and complexity.

The main function of a DC-DC convener in such applications is to produce a stiff output voltage from a non-regulated and low input voltage. Low voltage converters have recently found much attention in the literature [1]-[6]. There are some well-known basic topologies such as Boost, Buck-Boost, and Flyback converters can potentially be used for such applications thanks to their simplicity and ability to boost the input voltage. So far, many topologies have been investigated for low voltage applications [1],[5],[6],[3]. For example, in [3] application of a thermoelectric device with output voltage around 300 mV is introduced. On the other hand, the voltage collapse concept is fairly new to the field, and only few papers have addressed the subject in the recent years. In [1] voltage collapse in a Boost Converter has been introduced. In that reference an analytical approach to predict the voltage collapse was also presented.

In this paper we present an extensive comparative study on various basic topologies such as Boost, Buck-Boost, and Flyback converters. The same method appeared in [1] is extended to evaluate the other topologies in terms of voltage collapse problem. An enhanced Boost topology with improved safe operating region preventing collapse, suitable especially for low power applications, is also presented and investigated.

2 Voltage Collapse Phenomena

This concept has recently been addressed in the field of low power dc/dc converters [1]. In simple words, when the load of dc-dc converter supplied by a low voltage source, is significantly high (excessive output power), it naturally increases the input current of the converter. That in turn can increase the conduction loss of the converter dramatically. Having a low efficiency under such output power situations, results in significant reduction of the output voltage. That ultimately causes voltage collapse. In practice, because of the excessive current, the output voltage reduces too much that cannot even drive the control circuit of the converter. As an example, Figure 1 depicts the voltage collapse phenomena for a typical Boost converter when the normal input voltage 0.6 V is reduced to 0.3 V at the time t=0.1 s and causes significant drop in the output voltage. As an initial study, we assume that the synchronous Boost converter shown in Figure 2 is operating under Continuous Conduction Mode (CCM) condition. The input current always flows through the inductor and one of two



Time (s)

Fig.1: Typical voltage collapse in Boost Converter

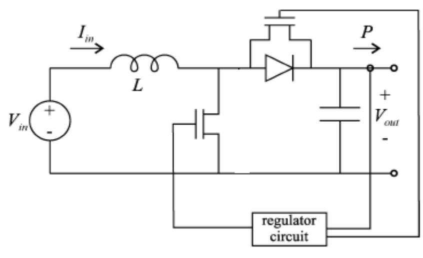


Fig.2: Synchronous Boost converter

MOSFETs as well as part of the printed circuit board traces. This total dc resistance R produces a power loss equals $R.I_{in}^2$. where I_{in} is the input current of the converter. There is also another loss caused by the equivalent series resistance (R_{ESR}) of the capacitor. In this regard, we can approximate the squared rms value of the capacitor current as:

$$I_c^2 = I_{out}\,(I_{in} - I_{out}) \qquad (1)$$

Where I_{out} is the dc output current and I_c is the rms value of the capacitor current. The converter's switching loss can also be approximated as [1]:

$$W_{switch} = \frac{V_{off}.I_{on}.t_{switch}}{2} \qquad (2)$$

Where W_{switch} is the energy loss per switching cycle for each switch and V_{off} is the switch's off- state voltage. Also, I_{on} is the on – state current and t_{switch} is the switching time (the sum of turn – on and turn off times). Hence, the switching loss can be simplified as:

$$P_{lossswitching} = KI_{in} \qquad (3)$$

Where $K = f.V_{out}.t_{switching}$. Based on the above equations, the power balance equation for the circuit is represented as follows:

$$V_{in}I_{in} = P + KI_{in} + RI_{in}^{\ 2} + R_{ESR}I_c^{\ 2} + P_{oh} \qquad (4)$$

P_{oh} is the power loss associated with the control circuit, and P is the converter's output power.

Solving above equation for I_{in} results in the following quadratic equation [1]:

$$RI_{in}^{\ 2} + \left(K + R_{ESR}\frac{P}{V_{out}} - V_{in}\right)I_{in} + P_{oh} + P - R_{ESR}\left(\frac{P}{V_{out}}\right)^2 = 0 \qquad (5)$$

Roots of equation (5) predict the voltage collapse. If the roots are complex, that implies that there is no physical response for the input current and therefore the voltage collapse has occurred [1]. On the other hand, the inductor's loss is usually the major part of the total loss; therefore the inductor design needs significant attention. With a good design of the circuit's layout, it is also possible to reduce the overall value of R. As addressed in [3], most practical converters usually utilize high-power MOSFETs as their main switching devices with low on-state resistance and low gate current. By increasing the switching speed of MOSFETs, the dc Resistance R and its associated loss are decreased. For many applications, the rate of the switching frequency is around 200 KHZ (medium frequency). And it is also possible to find MOSFETs with low dc resistance. Hence, the switching losses for such levels of frequency in not significant, so there is no need to employ soft switching techniques. Soft switching can increase the converter's conduction loss and may even cause voltage collapse. Sometimes, P_{oh} and the loss introduced by R_{ESR} are more significant in compare with other losses. Besides predicting the voltage collapse, equation (5) provides some other useful information on how to choose MOSFETs and Inductors with other passive component. Where a low power DC_DC converter is in use, for example in a mobile phone, the collapse can easily occur at certain low level of the input voltage when the converter's efficiency crashes dramatically as shown in Figure 3.

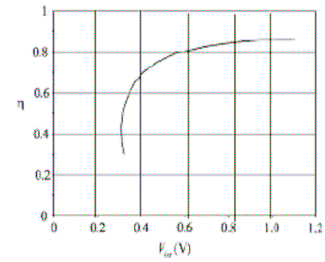


Fig.3: Efficiency versus input voltage

To quantify the voltage collapse prediction, the designer must test equation (5) for its roots [1]. In general, a low enough R is required preventing complex roots for worst cases with highest level of the load power and the lower possible input voltage.

3 Collapse in Buck-Boost and Flyback

In this section, we drive similar equations for Buck-Boost and Flyback converters to make a comparison between them.

A typical synchronous Buck-Boost converter supposed to operate in CCM mode is shown in Figure 4 . In the first subinterval of each switching period, the current I_{in} flows through the inductor together with one of the switches, whereas the current flows through inductor and the other switch in the second subinterval . Similar to the Boost converter we have:

$$I_c^2 = I_{out}(I_{in} - I_{out}) \quad (6)$$

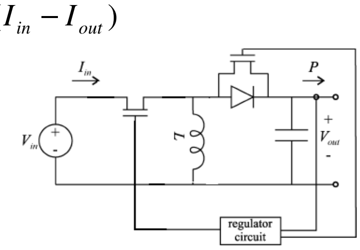


Fig.4: Buck-Boost converter

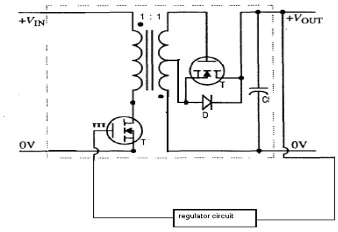


Fig.5: Flyback converter

Using similar equation used for the Boost converter we obtain:

$$P_R = D.R.I_{in}^2 + D'.R.(I_{out} I_{in}) \quad (7)$$

Where $D' = 1 - D$ and P_R is the loss associated with the equivalent resistance R. The corresponding power balance is governed by (8):

$$D.R.I_{in}^2 + (K + (R_{ESR} + D'.R).{}^{P}\!/\!{}_{V_{out}} - V_{in}).I_{in} + P_{oh} + P - R_{ESR}({}^{P}\!/\!{}_{V_{out}})^2 = 0 \quad (8)$$

A similar equation can also be developed for Flyback converter shown in figure 5. If N_1 & R_1 and N_2 & R_2 are the turn numbers and resistances of the transformer windings respectively, then we define:

$$R_2' = R_2 + R_1 N^2 \quad (9)$$

$$N = N_2 / N_1 \quad (10)$$

where N is the transformer's turn ratio. Then, the corresponding power balance is derived as follows:

$$V_{in} I_{in} = DR_1 I_{iin}^2 + D'R_2'(I_c^2 + I_{out}^2) + KI_{in} + P + R_{ESR} I_c^2 + P_{oh} + P_{core} \quad (11)$$

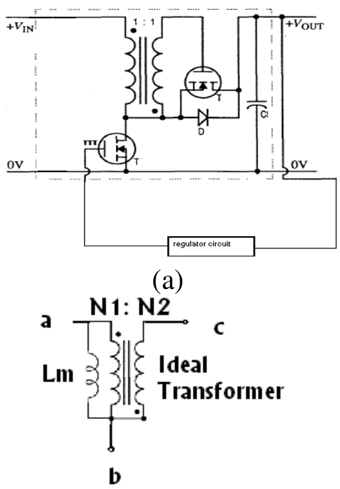
Eq. (11) can be simplified to (12). This equation is used to predict the voltage collapse.

$$DRI_{in}^2 + ((D'R_2' + R_{ESR}){}^{P}\!/\!{}_{V_{out}} + K - V_{in})I_{in} + P + P_{core} + P_{oh} - R_{ESR}({}^{P}\!/\!{}_{V_{out}}) = 0 \quad (12)$$

As appears, the turn ration N incorporates in coefficients of (12) and so affects the voltage collapse risk It is also worth mentioning that as because the Boost converter is an intrinsically unstable topology, using Flyback topologies can relief the problem with just proper designing the duty cycle and the turn ratio N.

4 An Enhanced Boost Topology

Noting the advantages of the Flyback topology in terms of voltage collapse and stability as addressed in the previous section, a new Boost type topology equipped with transformer is proposed. Figure 6.a



(a)

(b)

Fig.6: Boost converter with self-drive
a) Circuit b) the transformer's model

shows the proposed topology. The operation on this circuit is quite similar to the classic one. In addition, its self-drive feature can significantly reduce the switching and therefore total loss of the converter. It also retains most advantages of the Flyback including the stability features. That is because it can usually operate at lower duty cycles in compare with the classic Boost Converter. Figure 6.b shows the circuit equivalent of the transformer used where L_m is the magnetizing inductance. It is easy to show that the equivalent inductance seen between terminals a and c, which exactly take role in the converter's operation is:

$$L = (\frac{N + N_2}{N_1})^2 * l_m \tag{13}$$

A similar approach gives the relation between the input and output voltages in steady-state as governed by (14). That equation clearly describes how for any given D, the converter's gain is greater than the classic one. Hence, it can be set for lower duty cycles.

$$\frac{V_{out}}{V_{in}} = (\frac{1}{D'})(1 + \frac{N_2}{N_1} D) \tag{14}$$

Steady–state operation of this topology is similar to the conventional boost converter. I_{in} flows through R_1 in the first subinterval, and then through R_2' in and next subinterval, where $R_2' = R_2 + R_1 N^2$, and R_1 and R_2 are the primary and secondary resistances of the transformer's windings respectively. With adequate selecting the turn ratio N, it is possible not only to boost the input voltage up to the required level, but also to educe the loss. For this converter, the power balance equation can be presented as follows:

$$P_R = (DR_1 + D'R_2 (N1/N2)^2 + D'R_1) I_{in}^2 \tag{15}$$

Substituting P_R by $R_{in} I_{in}^2$ in equation (5) results in :

$$(R_1 + D'R_2 (N1/N2)^2) I_{in}^2 + (K + (P_{out}/V_{out})) R_{ESR} - V_{in}) I_{in} + P_{oh} + P + P_{core} - R_{ESR} (P/V_{out})^2 \tag{16}$$

Comparing (16) with (5), reveals that due to decrease in the coefficient of I_{in}^2, we now naturally expect occurring collapse for higher levels of the output power P. That means that the risk of collapse is reduced.

5 Simulation Results and Comparison

To evaluate and compare the topologies presented in the previous sections with respect to voltage collapse problem, a set of low power DC-DC converters for mobile phone application is considered. The converters are supposed to be supplied by a single fuel cell unit.

5.1 Converter's parameters

Most of the converters' parameters are taken based on [1]. The converters' maximum output power is 2.5W and the output voltage must be kept at 4V, while the input voltage ranges between 0.4V and 1.2V (see fuel cell characteristics shown in figure 11). The other parameters are as follow:

-The on-state resistance of the MOSFETs is $14\,m\Omega$

-The switching frequency is set at 200 kHz

-The inductor's capacity for Boost and Buck-Boost Converters is $10\mu H$ with $10m\Omega$ internal resistance

-The capacitor's capacity is $250\mu F$ with a high R_{ESR} exceeding $13m\Omega$.

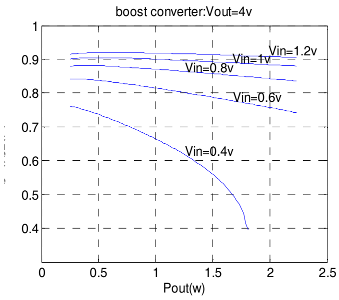
- K is equal to 0.077

- P_{oh} is supposed to be equal to 10 mW which is insignificant for this study.

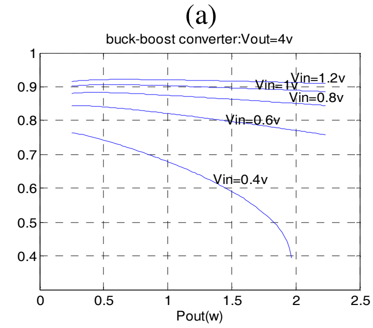
- P_{core} that is the transformer's loss equals 20mW

5.2 Boost, Buck-Boost, and Flyback converters

The efficiency performance of the Boost, and the Buck-Boost Converters under study are presented in figure 7. These curves clearly explore the significant drop in the converter's efficiency occurs under high load situations, which means the voltage collapses. Also, as seen, the Boost topology features a slightly higher efficiency than the Buck-Boost one for high powers and low input voltages. The simulation results of the Flyback Converter for different turn ratios are also curved in figure 8. It can easily be recognized that the voltage collapse risk is improved in compare to the other topologies. Also, the results demonstrate impact of the turn ratio N on the efficiency and



(a)



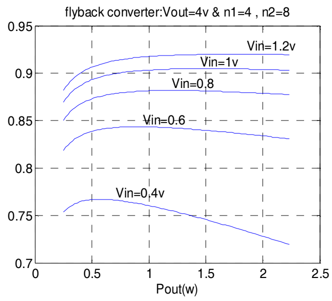
(b)

Fig.7: Efficiency versus output power
a) Boost converter b)Buck-Boost converter

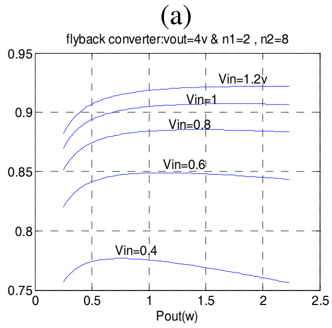
therefore collapse risk. Turn ration N influence both the loss and output voltage of the converter. The figure also explains how the Flyback converter is of higher efficiency with a flatter curve.

5.3 New Boost converter

Assuming $P_{core} = 20mW$, the new Boost Converter looks to have an overall performance close to the Flyback, the fact is shown by Figure 9. However, Flyback has higher efficiency and so the lowest risk of collapse off course for high output powers, whereas the suggested Boost converter features higher efficiency for low powers. For example, as seen in figures 8 and 9, the Boost topology has apparently higher efficiency than the Flyback one for output powers less than 0.5W. Hence, that is quite an interesting circuit especially for low power applications. For further evaluation, the efficiency versus input voltage for the aforementioned converters including the new Boost topology are represented in figure 10. In this figure, improvement in terms of voltage collapse is apparent. For a given $P_{out} = 1W$ the conventional Boost Converter collapses at input voltage equals 0.3v. It is interesting that the voltage collapse occurs at 0.18 V for the Flyback converter. According to figure 11, the Flyback Converter may look superior at P=1W, as it collapses at lower input voltage. However, it would not be true for sufficiently lower powers as already discussed. Complete comparison of the Flyback and the proposed Boost Converters can be carried out by comparing the corresponding the coefficients appear in equations (16) and (12_).



(a)



(b)

Fig. 8: Efficiency versus output power for Flyback Converter, N2=8 a) N1=4 b) N2=2

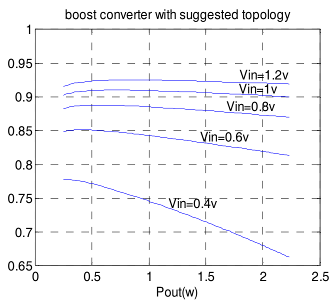


Fig.9: Efficiency versus output power for the Boost Converter with suggested topology

5.4 Fuel cell characteristics

As another issue needs sufficient attention. Considering the V-I characteristics of a typical fuel

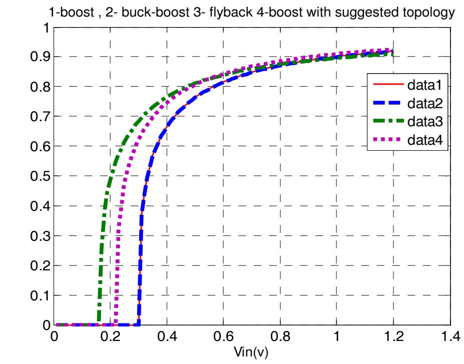


Fig.10: The efficiency versus input voltage for different converters

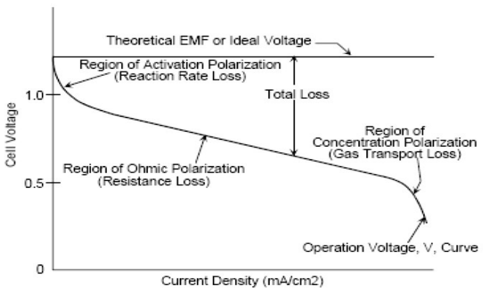


Fig. 11: V-I characteristic of a typical fuel cell

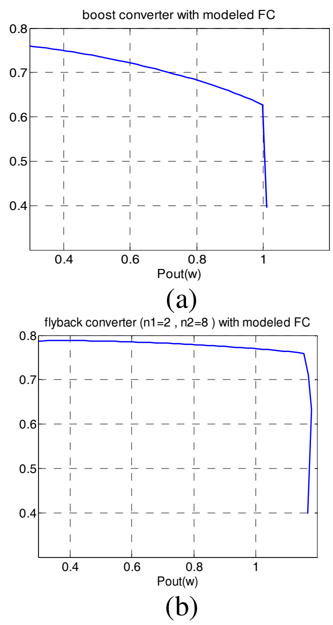


Fig.12: Effect of mismatch between fuel cell and converter. a) Boost b) Flyback

cells (FC) shown in figure 11, there are problems may arise due to significant mismatch between the fuel cell and the converter characteristics. Figure 12 says about a dramatic collapse may occur even at low power levels when the FC is working beyond its resistive region. Therefore, designing an adequate operating point for the fuel cell is quite important.

6 Conclusion

In this paper, voltage collapse issues of some basic DC-DC converters supplied by low voltage fuel cells was analytically studied and compared. It was shown that the Flyback converter potentially demonstrates better performance in terms of voltage collapse when compared to Boost and Buck-Boost converters. A modified self-drive Synchronous Boost Converter comprising higher efficiency and lower risk of collapse was proposed and studied. Through extensive numerical and analytical studies, it was shown that the proposed converter, besides having an improved performance with respect to voltage collapse, provides higher efficiency especially for low powers with a flat curve over a wide range of output power. Further studies can be carried out to improve the existing DC-DC converters with lower risk of collapse and higher efficiency.

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