

TWO-INDUCTOR BOOST CONVERTER START-UP AND STEADY-STATE OPERATION

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Abstract - In this work, an isolated DC/DC two-inductor boost converter is proposed. The topology is able to start up and operate in steady-state at any output level within 0V to 400V. The current and voltage characteristics make this topology suitable for applications where the relationship between input current and output voltage is too long, such as applications in hybrid electric vehicles (HEVs). In order for its operation to be possible at any output level, two auxiliary windings were added. These auxiliary windings were included to ensure that the start-up current does not rise to a higher level, as opposed to other isolated boost converters where the start-up current level is high. The design of the converter and a detailed analysis are given; an experimental 200W prototype is presented to validate the converter operation and its design.

Keywords – Automatic transition, Boost-Flyback effect, Normal mode, Start-up mode.

I. INTRODUCTION

The boost converter with two inductors and isolation is shown in Figure 1. The use of this topology is not popular; however, some authors have proposed it to be used in some applications. Reference [1] presents a study that performs an integration of the magnetic component to this topology, for high input current and low output voltage; in [2] and [3], the addition of an auxiliary transformer is provided, this transformer connects the coils currents and, through this connection, the output voltage is improved to manage a wide range of loads. With the addition of this auxiliary transformer, the topology is able to reach a high relation between the input and the output voltages, making of this topology an ideal one for applications in which there is a great difference between these voltages. In [4], the author proposes the converter as an attractive alternative to work in those situations where this relation of input and output voltages is required. Reference [5] is a comparative study between the Push-Pull fed current converter and the Two-Inductor Boost converter with a Push-Pull output, calling it Dual Inductor Converter (DIC). In [6], the addition of a resonant circuit to the topology to improve its performance with high currents and low input voltage is presented. Finally, [7] compares the topology shown in Figure 1 against a converter that contains a center tap transformer with a low input voltage and high current.

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However, in all the works previously mentioned, there are no designs that use duty cycles lower than 50% in steady-state form, a task which is performed by the topology presented in this paper. In [8] and [9], a full bridge fed current converter is presented; the author proposes the addition of an aid winding in order to start-up the converter and mentioned that this kind of start-up can be applied to the other isolated boost converters. In this paper, an analysis of the two-inductor boost converter with two aid windings is made in order to propose the operation of this topology not only to start-up. Steady-state operation with duty cycles lower than 50% can be obtained if the designs of the transformers and inductors are adequately.

II. PROPOSED CONVERTER

In Figure 2, the isolated two-inductor boost converter that operates as a boost converter is presented. This topology is integrated by two switches MOSFETs M5 and M6, a full bridge rectifier (D1-D4), two diodes (DF1 and DF2), a transformer TR, two inductors L1 and L2, two auxiliary windings —each one placed in one of the inductors— that conform a Flyback transformers (TF1 and TF2).

In order to analyze the operation of this converter in steady-state, it is recommended to do it in two parts: one, when the duty cycle is between 0% and 50% (Start-up), and the other when the duty cycle is between 50% and 100% (Normal). In spite of being called ‘start-up’, the converter can also operate in steady-state in this mode, with the aid of the auxiliary windings.

It is important to mention that the proposed converter operates exactly in normal mode, as in Figure 1, when it is not using the auxiliary windings in this operation mode. Auxiliary windings operate only when the duty cycle is lower than 50%.

Characteristics like high current capability, galvanic isolation and small component count, make from this topology a good candidate to be utilized in applications where a great relation between input and output voltage are necessary. Operation modes of this DC/DC converter can be seen in Figure 3. The equivalent circuit that is operating in each area is also shown.

A. Operation modes

MOSFETs M5 and M6 control the output voltage regulating the duty cycle d . In order to analyze the operation principle of this converter, it is necessary to split it in two parts: One considering the duty cycle between 50% and 100% (called *Normal*), and other one considering the duty cycle between 0% and 50% (called *Start-up*).

1) Normal operation

When the duty cycle is between 50% and 100%, then the

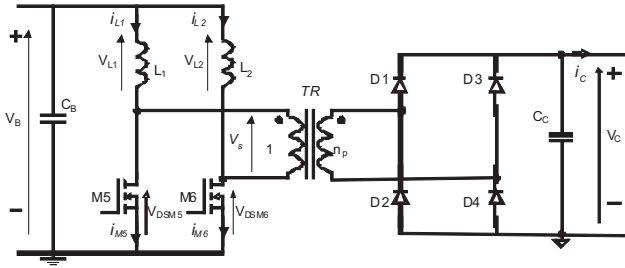


Fig. 1. Isolated two-inductor boost converter.

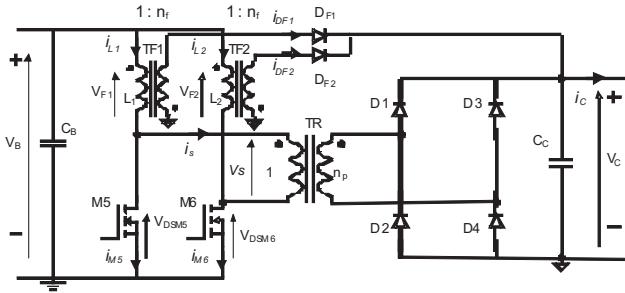


Fig. 2. Proposed converter with two aid windings.

converter works as a boost converter. Figure 4 shows the typical waveforms in this operation mode. In continuous conduction mode (CCM) the equation that defines the gain of the converter, based on duty cycle d and turns ratio n_p , is:

$$k_N = \frac{V_C}{V_B} = n_p \frac{1}{1-d}, \quad 0.5 \leq d \leq 1. \quad (1)$$

2) Start-up operation

The conventional converter topology (Fig. 1) cannot operate by itself with duty cycles lower than 50%. The reason is that the energy that is stored in the inductors L_1 and L_2 for this duty cycle cannot be transferred to the output after being turned off. It is necessary to look for an additional path for the current in order to avoid a high voltage that can damage the MOSFETs. Two additional windings with two diodes (DF_1 , DF_2) are placed to transfer the energy to the output. Figure 2, shows the additional windings in the inductors and diodes.

Additional windings and diodes make of this topology an alternative to operate in steady-state with duty cycles lower

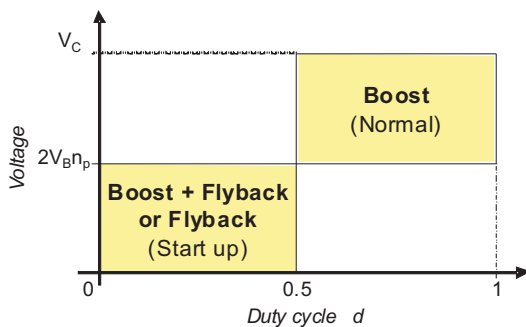


Fig. 3. Equivalent circuit in each operation mode in the proposed converter.

than 50%. With these additional windings and diodes, two patterns can be used to start up the converter from 0V to any output voltage called *Start-up I* and *Start-up II*. These two start-up operation modes take advantage of the inductors that have auxiliary windings and they use them like transformers (TF_1 and TF_2). Start-up I uses these two transformers to transfer the energy to the output as two Flyback transformers, whereas Start-up II uses them in an alternate way: Main transformer TR as boost converter, and transformers TF_1 and TF_2 as Flyback transformers.

- **Start-up I (Flyback)** In this start-up method, M_5 and M_6 are switched on at the same time. In this way, the energy is stored in each transformer (TF_1 and TF_2) and later it is transferred to the output through DF_1 and DF_2 . This operation mode is equivalent to place two Flyback converters in parallel. In this method, once that the 50% in duty cycle is reached, the sequence of control in the MOSFETs changes to normal operation and it continues working as a boost converter through the main transformer (TR). Control signals change from being in phase to being shifted 180° . In order to do this change in the control signals, it is necessary to use a circuit that detects when the 50% in duty cycle has been reached and, at the same time, changes the operation sequence of the control pulses. In CCM, the equation that defines the gain of the converter applying volts balance in one flyback transformer (TF_1 or TF_2) of the converter in one switching period is:

$$k_{S1} = \frac{V_C}{V_B} = n_f \frac{d}{1-d}, \quad 0 \leq d \leq 1, \quad (2)$$

where n_f is the turn-ratio in auxiliary windings.

- **Start-up II (Boost+Flyback)** This start-up method is a combination of the Boost converter and a Flyback converter. Start-up II occurs by default when the auxiliary windings are placed in the inductors of the converter, as long as the duty cycle in the control signals of M_5 and M_6 vary from 0% to 50% and are 180° delayed. With the addition of these auxiliary windings in the inductors, it is possible for the converter to work in steady-state for any duty cycle lower than 50%. With this method, the converter changes automatically to normal operation as a boost converter when duty cycle reaches 50%, without the need of a circuit to make this transition like in Start-up I. In addition, with this new structure, the output voltage can be controlled for duty cycles lower than 50%. Figure 5 shows the key waveforms for this method. This operation mode is quite different from the classical solutions. If the converter operates in CCM, making a volts balance in any of the inductors (TF_1 or TF_2) of the converter in one switching period, the equation that defines the gain of the converter based on duty cycle d and turns-relations n_p and n_f is:

$$k_{S2} = \frac{V_C}{V_B} = \frac{2d}{\frac{1-2d}{n_f} + \frac{d}{n_p}}, \quad 0 \leq d \leq 0.5. \quad (3)$$

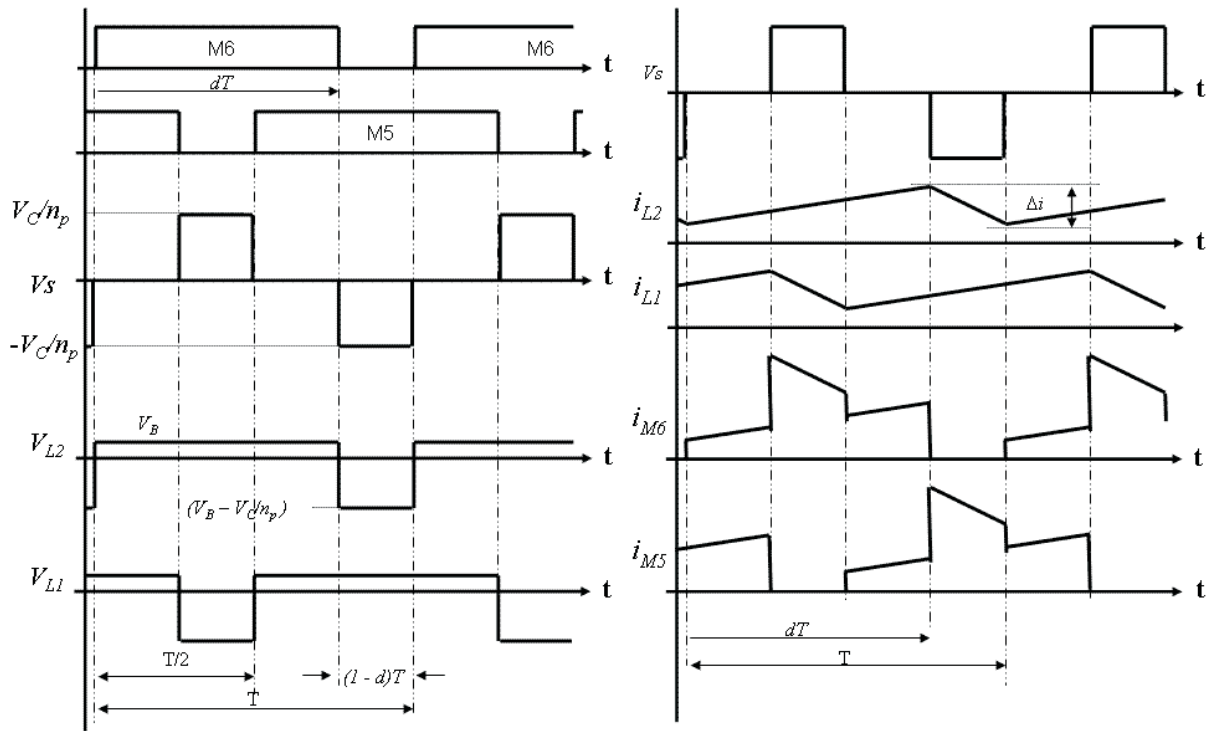


Fig. 4. Waveforms in Normal operation.

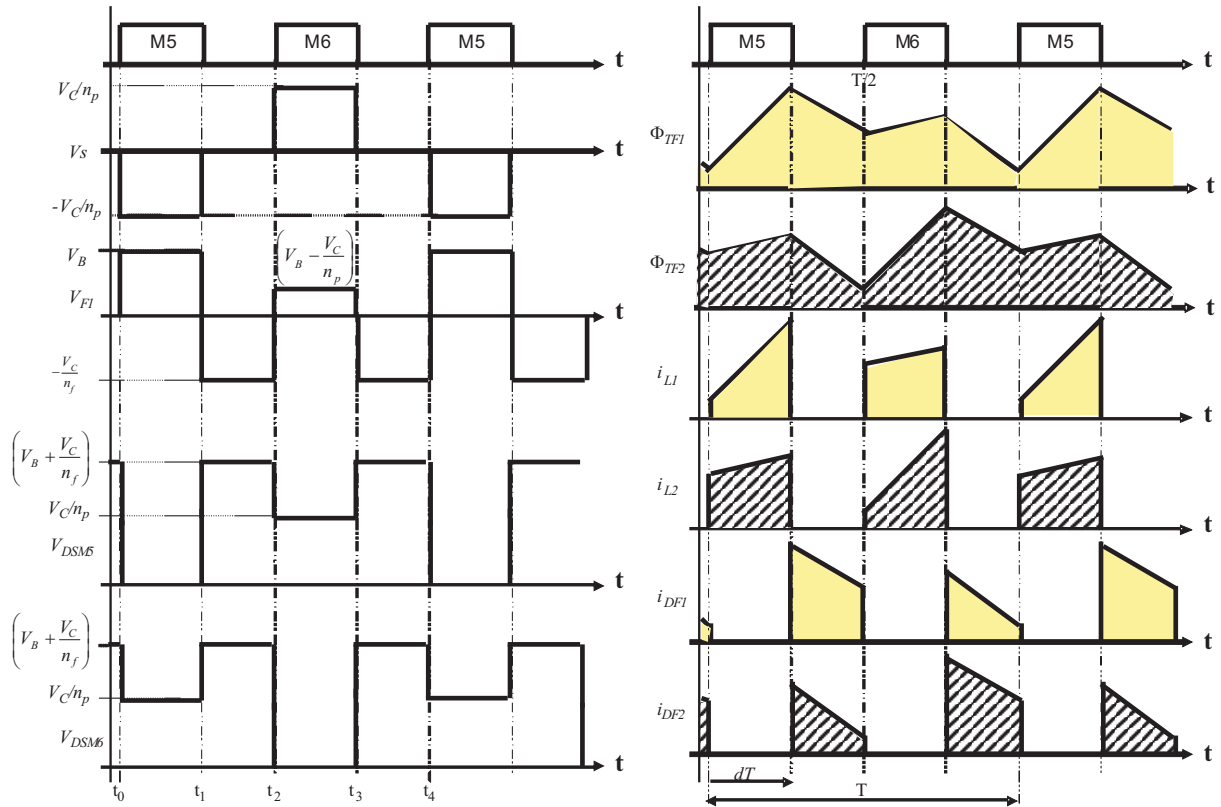


Fig. 5. Waveforms in Start-up II.

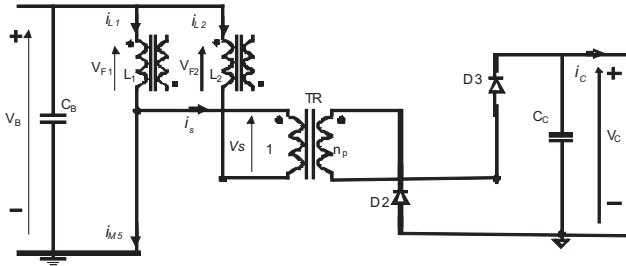


Fig. 6. Equivalent circuit for $t_0 - t_1$.

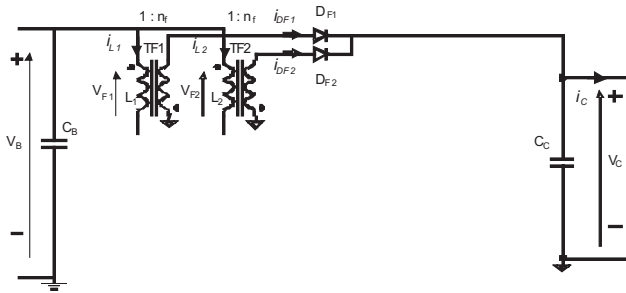


Fig. 7. Equivalent circuit for $t_1 - t_2$.

Four basic operations modes in a period of commutation can be identified; the equivalent circuits in each mode and explanation are defined next:

- $t_0 - t_1$ In this interval, M6 is off and M5 is on, causing the current i_{L1} to increase linearly with the input voltage V_B and storing energy in the core of transformer TF1 as Flyback (see Figure 6). At the same time, energy that was previously stored in the core of TF2 is transferred to the output through the main transformer TR like a boost converter. This causes that i_{L2} circulate around the primary one of TR. Current i_{L1} and current i_{L2} add up since both circulate in MOSFET M5.
- $t_1 - t_2$ In this interval, M6 is still off and M5 is off, causing the current i_{L1} to circulate through the secondary of TF1 and diode DF1, delivering energy to the output capacitor CC. At the same time, the current i_{L2} changes to circulate through the secondary of TF2 and diode DF2 to deliver energy to the output, too. In both cases the energy is transferred like a Flyback converter (see Figure 7). On the other hand the magnetizing current of

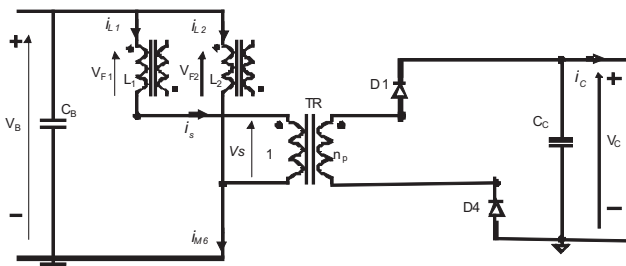


Fig. 8. Equivalent circuit for $t_2 - t_3$.

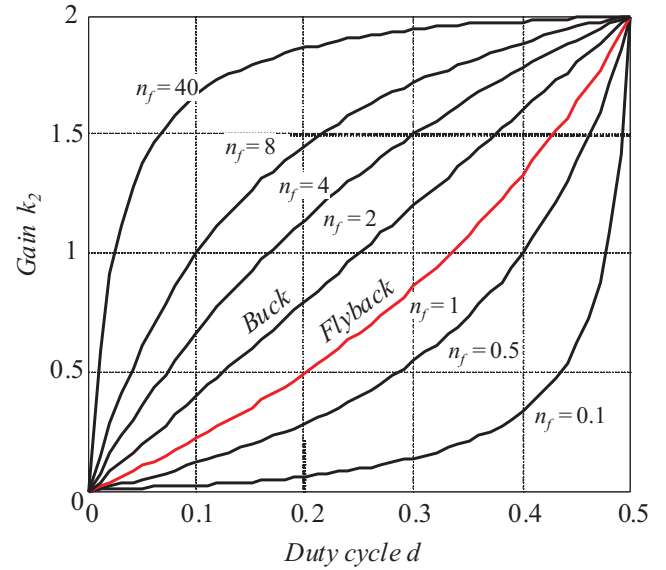


Fig. 9. Gain of the converter varying n_f with $n_p = 1$.

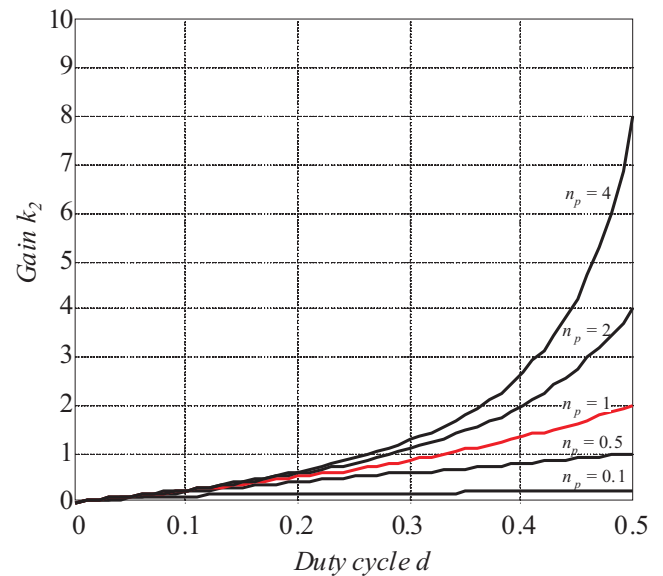


Fig. 10. Gain of the converter varying n_p with $n_f = 1$.

main transformer TR circulates through the diodes D1-D4. This current does not appear in the circuits of Figure 7 due to the fact that it is meaningless when compared to the load currents of the converter, which are significant.

- $t_2 - t_3$ This interval is similar to the interval $t_0 - t_1$ with different components, since M5 is still off and M6 on. In summary, in this interval, part of the energy is stored in TF2, and another part is transferred through TR thanks to the energy previously stored in TF1 (see Figure 8). The slope of the current i_{L1} in this interval can be positive, zero or negative. If the output voltage reflected in primary of TR is smaller, equal or greater than the input V_B , the slope is positive, zero or negative, respectively. In this case, in Figure 5 the output voltage reflected in the primary of TR must be lower than V_B

TABLE I
Voltage stresses in semiconductors

Semiconductor	Start-up	Normal
D1-D4	V_C	V_C
M5-M6	$V_B + V_C/n_f$	V_C/n_p
DF1-DF2	$V_C + n_f V_B$	$V_C + n_f V_B$

since the slope of the current i_{L1} in this interval is positive.

- $t_3 - t_4$ By symmetry in this interval occurs the same like in $t_1 - t_2$. In summary, in this interval the energy transference becomes from main input to the output by effect of Flyback converter through **TF2** and **TF1** (see Figure 7). This is the last interval of analysis and the process is repeated here.

Two particular behaviors in (3) that define the gain of this operation mode like a Buck and a Flyback converter can be identified varying the turns-relations between n_p and n_f .

If $n_f = 2n_p$, the obtained gain is like the one of a Buck:

$$k_{S2Buck} = \frac{V_C}{V_B} = 4n_p d, \quad 0 \leq d \leq 0.5. \quad (4)$$

In the other case, if $n_f = n_p$, the gain is like the one of a Flyback:

$$k_{S2Flyback} = 2n_p \frac{1}{1-d}, \quad 0 \leq d \leq 0.5. \quad (5)$$

In Figure 9, observe that the gain achieves the same maximum value when the duty cycle achieves 50% for any value of n_f , and $n_p = 1$; the gain is like that of a Buck and a Flyback for $n_f = 1$ and $n_f = 2$, respectively.

When $d = 0.5$, a constant value is achieved in (4). For example, maintaining $n_f = 1$ and varying n_p , yields a total converter gain equal to $2n_p$ (see Figure 10).

III. CONVERTER DESIGN

In order to design the converter, it is important to know some design parameter, like stress voltages and effective currents in the components of the converter. The first things to determine are the turns-relations of the transformer **TR** and the auxiliary windings in the coils.

A. Semiconductor voltage stresses

Table I shows the voltage stresses in each semiconductor of the converter. It shows that **M5** and **M6** are the only stresses that may be penalized, in view that they may actually differ in their values in Normal and Start-up mode.

B. Inductance calculation

As the inductors are placed in the low voltage side of the converter, the minimum number of turns has to be assigned in order to reduce the resistance and minimize the path through which the high currents circulate. Clearly, (6) serves to calculate the value of the inductance of the inductors of the converter with a 100% from peak to peak, in order to ensure that the design will be made with the minimum turns in the

TABLE II
Prototype specifications

Battery voltage range (V_B)	10V \approx 16V
Capacitor voltage (V_C)	0V \approx 420V
Output power (P_o)	200W
Switching frequency (f_s)	100kHz

TABLE III
Magnetics and semiconductors

Element	Description
D1-D4	STP20NM60
M5-M6	HUF75639P3 (3 in each branch)
TR	E/42/21/15-3C85 (1:7) Prim = 6 turns (solid copper 0.75mm), Sec = 42 turns (7 parallel solid copper 0.75mm)
TF1-TF2	L=7.5 μ H Kool Mu 77083A7, (1:7) Prim = 10 turns (3 parallel litz 400x0.07mm), Sec = 70 turns (solid copper 0.75mm)

inductors. Here, P_o represents the output power:

$$L = \frac{2}{P_o} \left(V_B^2 - \frac{n_p V_B^3}{V_C} \right) \frac{1}{f_s}. \quad (6)$$

C. Start-up selection

When the converter has to work with more than 50% in duty cycle, the converter initializes with one start-up (*Start-up 1* or 2); afterwards, it change to Normal operation mode when duty cycle exceeds 50%. In order to do this correctly, some conditions have to be satisfied to select n_p and n_f in each start-up.

1) Start-up I + Normal mode

When duty cycle in Start-up I reaches 50%, then the gain in (2) has to be the same as the gain in (1). Setting both equations equal to each other and solving for n_f , we obtain:

$$n_f = 2n_p. \quad (7)$$

This condition has to be satisfied to ensure that the output voltage in Start-up I be the same in Normal mode, when the duty cycle be 50%.

2) Start-up II + Normal mode

When the duty cycle is 50%, both Start-up II and Normal mode have the same value in their corresponding converter gains. Their values are equal to $2n_p$, which means that in this start-up we can select any value for n_f and the transition will be made without any variation in the output voltage. The only restriction is in the stress voltage in **M5** and **M6**, as shown in Table I.

IV. EXPERIMENTAL RESULTS

A prototype circuit with low output power was designed and tested in order to verify each operation mode, Normal ($d > 50\%$) and Start-up ($d < 50\%$). The specifications of the prototype are shown in the Table II. Start-up II was selected due to the fact that, making $n_p = n_f$, results in a Flyback start-up converter with a natural transition from Start-up to Normal mode. The converter was tested in two different output

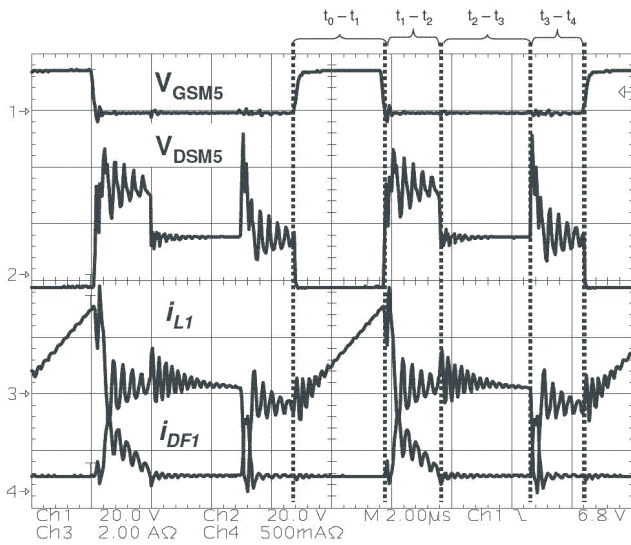


Fig. 11. Waveforms for $V_C = 100V$.

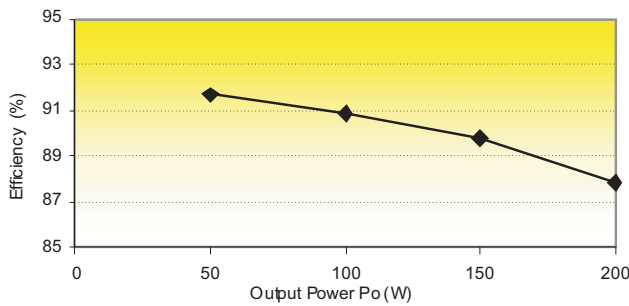


Fig. 12. Efficiency of the converter for $V_B = 14V$ and $V_C = 100V$.

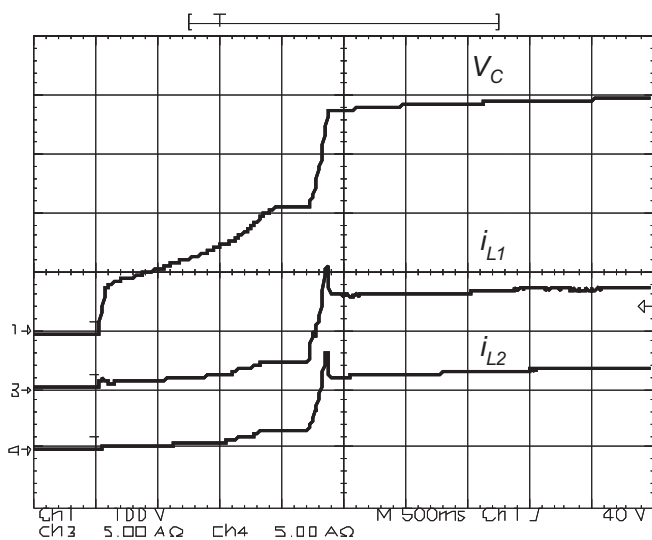


Fig. 13. Output voltage, V_C (100V/div, 500ms/div), current through $L1$, i_{L1} (5A/div, 500ms/div), current through $L2$, i_{L2} (5A/div, 500ms/div).

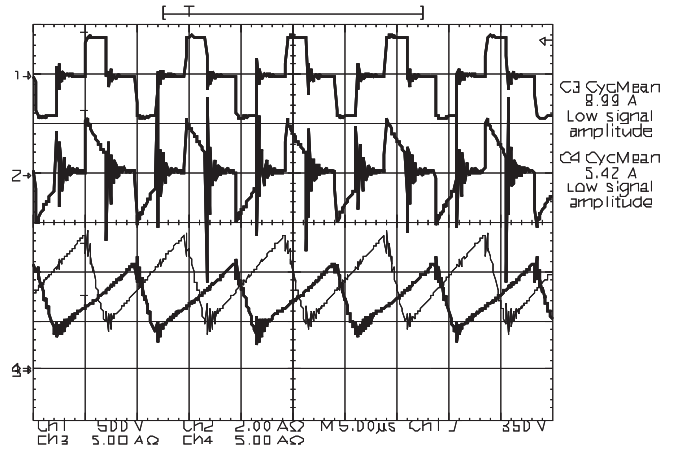


Fig. 14. Voltage of the secondary of transformer TR , V_p (500V/div, $5\mu s$ /div), current of the secondary of transformer TR , i_p (2A/div, $5\mu s$ /div), current through $L1$, i_{L1} (5A/div, $5\mu s$ /div), current through $L2$, i_{L2} (5A/div, $5\mu s$ /div).

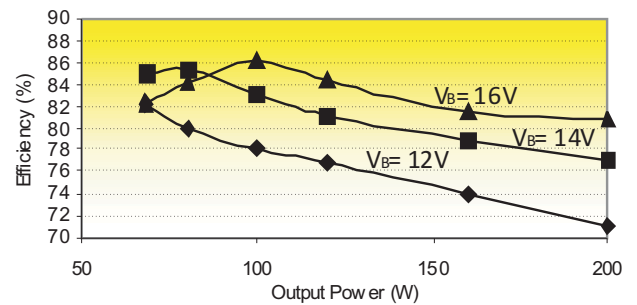


Fig. 15. Efficiency of the converter for $V_C = 400V$.

voltages, $V_C = 100V$ and $V_C = 400V$, with duty cycles lower and higher than 50%, respectively.

Inductors ($TF1$ and $TF2$) were designed with toroidal cores in order to reduce the turns. Several MOSFETs have been placed in parallel to implement $M5$ and $M6$, in order to reduce conduction power losses. Turns-relations n_p and n_f were selected in a 1:7 ratio, in order to use $M5$ and $M6$ to support voltage stresses lower than 100V and the capability to vary the duty cycle appropriately. Synchronous MOSFETs in $D1$ to $D4$ were used in order to reduce the conduction power losses. Table III shows specifications in semiconductor and magnetic elements.

A. Start-up mode

Figure 11 shows, from top to down, the gate signal, the drain source voltage for $M5$ (V_{DSM5}), the current through $L1$ and the current $DF1$. In this operation mode, the converter works with a duty cycle lower than 50% ($V_C = 100V$) and the energy is transferred to the output through TR , $TF1$ and $TF2$. Figure 12 shows the efficiency of the converter in this operation mode.

B. Normal mode

In Figure 13, observe that the output voltage increases from 0V to 400V, and that the currents in both inductors increase without showing excessively high peaks, since the topology can operate correctly with duty cycles lower than 50%. At approximately 2 seconds, the voltage V_C waits before the duty cycle continues to increase; this is because of the design of the control system (in that point, the duty cycle is exactly 50%). Figure 14 shows the waveforms obtained, voltage V_p of the secondary of the transformer **TR**, current i_p of the secondary of the transformer **TR**, and the current in each one of the inductors of the converter (i_{L1} , i_{L2}). These waveforms correspond to the operation in steady-state of the converter for Normal mode.

Figure 15 shows the total efficiency of the converter working with distinct input voltages in V_B (12V, 14V and 16V). Observe that the best efficiency is achieved with the highest input voltage V_B . That is due to the fact that the duty cycle in the MOSFETs increases, causing an increase in the rms currents of the inductors **L1** and **L2** and, also, in the primary and the secondary of the main transformer **TR**. This fact causes that elevated conducted losses are presented in the topology. In order to minimize these conduction losses an optimization of the inductors and the transformer has to be made.

V. CONCLUSIONS

An isolated two-inductor boost converter has been proposed and tested. The converter can be used in those cases where the high voltage bus is held by a bank of capacitors. The voltage may range between 0 and 420V in steady-state conditions, a characteristic improves the capabilities of most of the proposed converters in the references. The converter provides two methods to start up. In one, it operates as two Flybacks working in parallel and, in the second, it operates as Boost + Flyback. The second method was implemented in the prototype and it operates correctly without problems for duty cycles lower than 50%. A test operation with 100V was conducted and it was found that the converter works properly. A 200W prototype has been built and tested. The measured waveforms are in good agreement with the expectations. The results obtained from this topology make it a good candidate to be used in applications where a high relation between input and output voltage is necessary.

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