A Buck-Boost Converter-Based Bipolar Pulse Generator

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Abstract

This paper presents a buck-boost converter-based bipolar pulse generator, which is able to generate bipolar exponential pulses across a resistive load. The concept of the proposed approach depends on operating the involved buck-boost converters in discontinuous current conduction mode with high-voltage gain and enhanced efficiency. A full design of the pulse generator and its passive components is presented to ensure generating the pulses with the desired specifications (rise time, pulse width, and pulse magnitude) for a given load resistance and input dc voltage. In case of moderate pulsed output voltages (i.e. few of kV), one module of the presented bipolar generator can be employed. While in case of high-voltage pulsed output, multi-module version can be employed, where each module is fed from an isolated dc source and their outputs are connected in series. Simulation models for the proposed approach are built to elucidate their performance in case of one-module as well as multi-module based generator. Finally, a scaled-down prototype for one-module of buck-boost converter-based bipolar pulse generator is implemented to validate the proposed concept.

Key words: Pulse generator, Pulsed power system

I. INTRODUCTION

Repetitive pulse generators are commonly used in modern pulsed power applications [1]-[3]. Recently, power electronics-based pulse generators are preferred to avoid the main disadvantages of the classical pulse generators, [4]-[6], as the lack of compactness and reliability, high cost, low repetitive rate and short operational lifetime.

Different types of power electronics-based pulse generator have been presented in the literature [1]-[19], such as solid-state Marx generator [7], [10], modular multilevel-based pulse generators [12], H-bridge based pulse generator [11], [13], and dc-dc converter-based pulse generators [14]-[19].

In [14], [15], a positive buck-boost dc-dc converter is employed to generate high voltage pulses. In this configuration,

the inductor is charged to a certain current level. Then, inductor is shorted to keep its current level. When it is desired to generate an output voltage pulse, the current is released to feed the load. In [16], [17], a boost converter array has been employed to generate high voltage pulsed output from a low voltage dc source without high voltage pulse transformer. The circuit has n number of switches, capacitors, inductors and diodes to get n times of input voltage, and additional switch can be used to block the discharging current of the boost voltage of capacitors through the load. In [18], boost and buck-boost dc-dc converters are employed in conjunction with Capacitor-Diode Voltage Multipliers (CDVMs) to elevate the voltage of a relatively low input dc voltage into a high output dc voltage. Then a high-voltage solid-state chopping switch/H-bridge output stage is used to generate unipolar/bipolar pulse output, respectively, which increases the system complexity and negatively affects the system cost. In [19], a boost converter-based ringing circuit for unipolar pulse generation employing the discontinuous current conduction mode has been presented. In this configuration, the load is differentially connected between the input and output terminals, and only unipolar pulses are achievable.

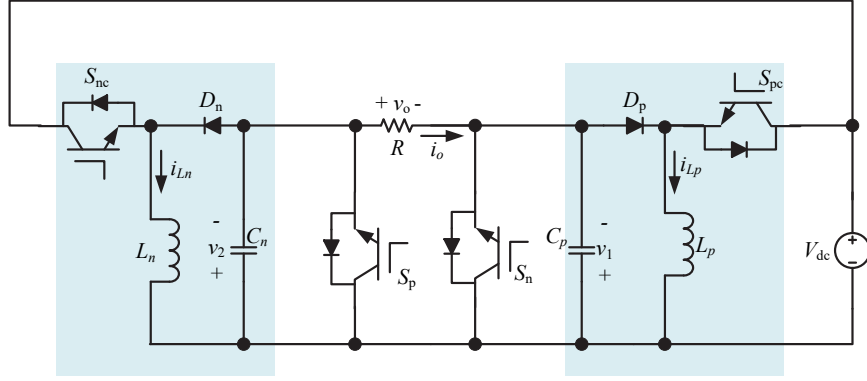In [20], boost inverter based bipolar pulse generator has been

Fig. 1. The buck-boost converter based bipolar pulse generator module.

proposed. This configuration is effective only for loads with high resistances.

In this paper, the single-stage single-phase buck-boost inverter presented in [21] is employed, but with different perspective to ensure the generation of bipolar output pulses. The main advantages of the proposed configuration are:

(i) operating with high output-input voltage gain, i.e. relatively low input dc voltage level can be employed to generate high-voltage pulses,

(ii) operating with enhanced efficiency by operating the involved buck-boost converters with Discontinuous Current Conduction Mode (DCCM), since no current flows in the converter components continuously, i.e. as most of the time; the circuit is in idle mode with no current.

(iii) Unlike [20], the suggested configuration is valid for loads with low as well as high resistances with the same number and rating of the involved controlled semiconductor devices.

On the other hand, the main limitation of the proposed generator is that the passive components are selected to get a pulsed output voltage with certain specifications (rise time and pulse width), i.e. having other pulse specifications necessitates replacing the generator passive components.

In case of moderate pulsed output voltage (<4 kV), one module of the buck-boost based bipolar pulse generator can be employed, while in case of high-voltage pulsed output, multi-modules with isolated input voltages and series-connected outputs can be employed to ensure employing semiconductor devices with a moderate-voltage rating. Both versions are presented with detailed analysis and design to achieve the desired pulse specifications (pulse magnitude, rise time, pulse width, and repetition rate).

Finally, a scaled down prototype for one module of the presented buck-boost converter-based pulse generator has been implemented to validate the suggested operational concept.

II. Buck-Boost Converter-Based Pulse Generator Module

The buck-boost converter-based bipolar pulse generator module is shown in Fig.1. The circuit passes through six different modes to generate bipolar pulsed output voltage, namely (I, II, III) for positive pulse generation and (IV, V, VI) for negative pulse generation as shown in Figs. 2 and 3. The detailed illustration of each mode can be summarized as follows:

Mode I: In this mode, the positive-side inductor, namely, L_p, which is the inductor that will generate positive output voltage pulse, is charged to a certain current (I_o). This can be done by turning on the switch (S_{pc}) only for a suitable time interval (t_L) as shown in Fig.2a. During this time interval, the load voltage is zero ($v_o=0$), while the inductor is charged via turning on the switch (S_{pc}). As a result, the inductor current increases linearly as in (1);

$$i_{Lp}(t) = \frac{1}{L_p}V_{dc}t \tag{1}$$

At $t=t_L$, the inductor current is given by,

$$I_o = \frac{1}{L_p}V_{dc}t_L \tag{2}$$

Mode II: After charging the positive-side inductor, the inductor energy is released by turning off the switch (S_{pc}) and turning on (S_p). It is safe to turn-on S_p in this mode as the voltage across the capacitor C_n is zero in the previous mode [Fig. 2(a)]. It has to be noted that by turning on the switch S_p, the capacitor C_n is shorted, i.e. $v_2=0$ in this mode, and the load resistance becomes connected in parallel to capacitor C_p, which are fed from the inductor (L_p) through the diode D_p (i.e. $v_o=v_1$) as shown in Fig. 2(b). Therefore, the resultant circuit in this mode is a second order parallel RL_pC_p circuit, and a positive output voltage pulse appears across the load terminal. Equation (3) represents the Kirchhoff's current law in mode II circuit (where $t'=t-t_L$);

$$i_{Lp} = i_{Cp} + i_R = C_p\frac{dv_1}{dt'} + \frac{v_o}{R} = -C_p\frac{dv_{Lp}}{dt'} + \frac{-v_{Lp}}{R}$$
$$= -L_pC_p\frac{d^2i_{Lp}}{dt'^2} + \frac{-L_p}{R}\frac{di_{Lp}}{dt'} \tag{3}$$
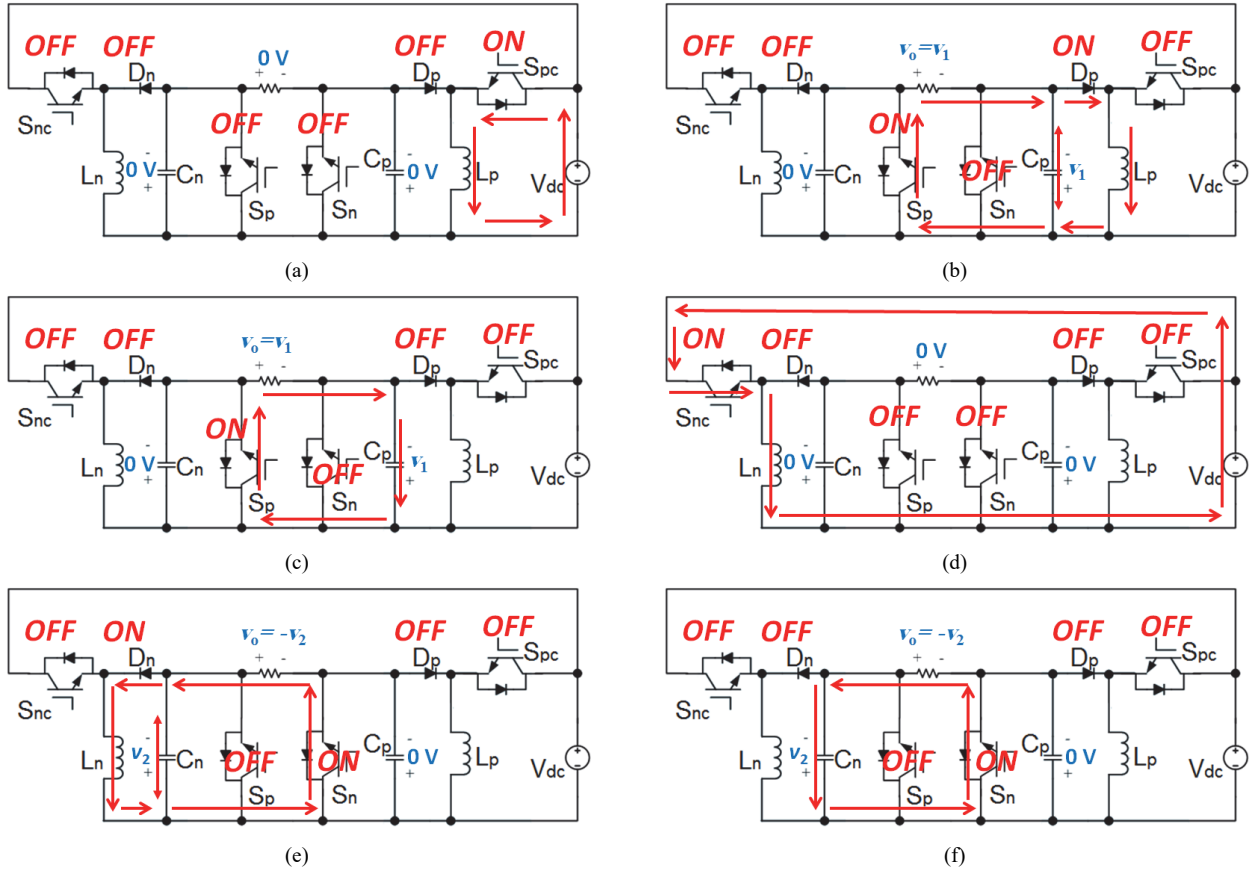
Rearranging (3) leads to (4).

Fig. 2. The operational modes of the buck-boost converter based bipolar pulse generator. (a-c) modes I-III, (d-f) modes IV-VI respectively.

$$\frac{d^2 i_{Lp}}{dt'^2} + \frac{1}{RC_p}\frac{di_{Lp}}{dt'} + \frac{1}{L_p C_p} i_{Lp} = 0 \qquad (4)$$

where; $i_{Lp}(0) = I_o$, and $\frac{di_{Lp}}{dt}(0) = 0$ are the corresponding initial conditions.

The corresponding roots are given by (5) assuming under-damped response,

$$S_{1,2} = \frac{1}{2}\left(-\frac{1}{RC_p} \pm j\sqrt{\frac{4}{L_p C_p} - \left(\frac{1}{RC_p}\right)^2}\right) = \alpha \pm j\beta \qquad (5)$$

By solving the aforementioned second order differential equation, the inductor current expression is given by (6);

$$i_{Lp}(t') = I_o e^{\alpha t'}\left(\frac{-\alpha}{\beta}\sin(\beta t') + \cos(\beta t')\right) \qquad (6)$$

The corresponding load voltage during mode II is given by,

$$v_o(t') = v_1(t') = -v_{Lp}(t') = -L_p \frac{di_{Lp}}{dt'}$$
$$= I_o L_p e^{\alpha t'}\left(\frac{\alpha^2 + \beta^2}{\beta}\sin(\beta t')\right) \qquad (7)$$

The time at which the voltage reaches its peak (i.e. the rise time, t_m) can be obtained using (8),

$$\frac{dv_o(t')}{dt'} = 0 \rightarrow \beta\cos(\beta t_m) + \alpha\sin(\beta t_m) = 0 \qquad (8)$$

$$t_m = \frac{1}{\beta}\tan^{-1}\left(\frac{\beta}{-\alpha}\right) \qquad (9)$$

The corresponding peak value of load voltage (V_{peak}) can be obtained by substituting in (7) with the value of the rise time (t_m) given by (9), i.e.

$$V_{peak} = I_o L_p e^{\alpha t_m}\left(\frac{\alpha^2 + \beta^2}{\beta}\sin(\beta t_m)\right) \qquad (10)$$

After reaching the peak value of the output voltage, the capacitor/load voltage decreases while the inductor current continues decreasing till reaching the zero current level. An expression for the time ($t'=t_x$) at which the inductor current hits the zero level, which represents the end of mode II, can be obtained with the help of (6) as in (11),

$$t_x = \frac{1}{\beta}\tan^{-1}\left(\frac{\beta}{\alpha}\right) \qquad (11)$$

When the inductor current hits the zero current level, the capacitor voltage will be at a certain voltage level V_x (see Fig. 3). This voltage level is given by,

$$v_1(t')_{t'=t_x} = v_o(t')_{t'=t_x} = V_x \qquad (13)$$

As the diode will turn off at ($t'=t_x$, i.e. at the end of mode II), the circuit will be switched to a simple RC circuit. The voltage V_x given in (13) will be initial condition for the upcoming operational mode (mode III).

Mode III: When the positive-side inductor current reaches zero, the converter diode (D_p) will turn off, and the circuit will be switched to a first order RC_p circuit as shown in Fig. 2(c). These results in continued exponential decrease of C_p
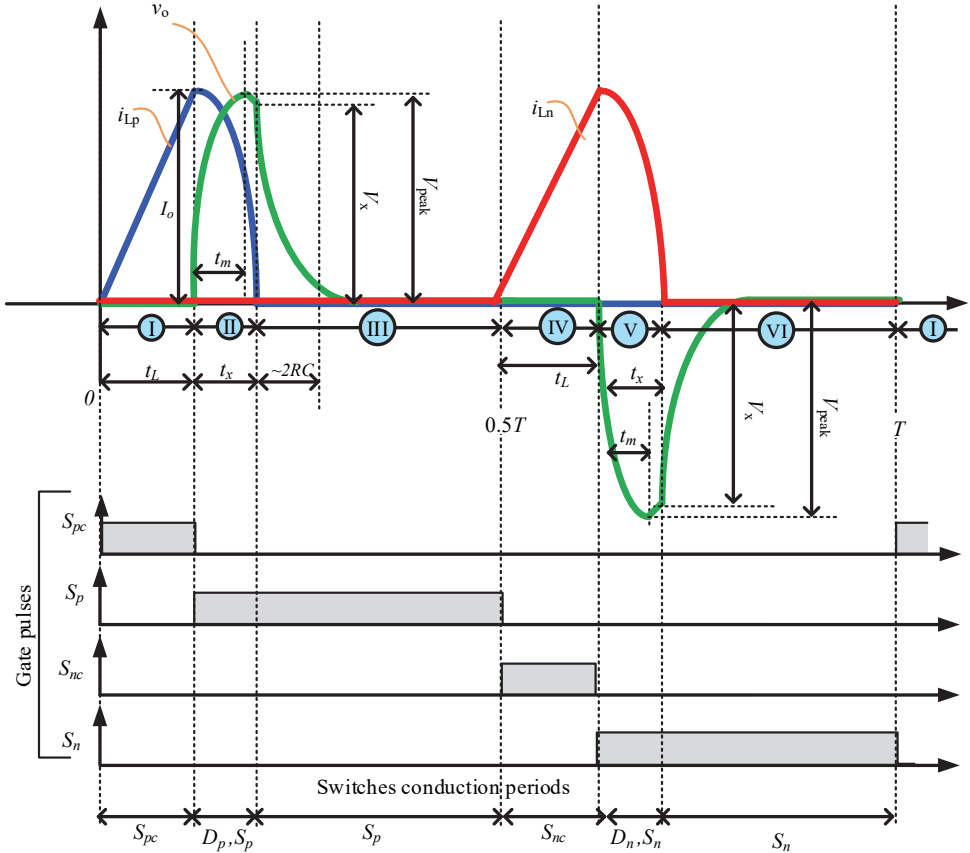
Fig. 3. The corresponding waveforms of the buck-boost based bipolar pulse generator.

voltage till zero, i.e. the repetition rate should be selected carefully to ensure reaching zero capacitor voltage at the end of this mode. The reason for that is the capacitor (C_p) will be shorted during the negative pulse generation, i.e. to ensure a safe short circuit across the capacitor with no high inrush currents.

The voltage of the capacitor C_p in this mode is given by,

$$v_1(t'') = v_o(t'') = V_x \, e^{-t''/RC} \tag{14}$$

where $t'' = t - t_L - t_x$. The corresponding pulse width (mode II + mode III) is given by (15);

$$t_p \approx t_x + 2\tau \approx t_x + 2RC \tag{15}$$

where; τ is the time constant in mode III ($\tau = RC$). It has to be noted that equation (16) shows the condition that should be achieved to ensure successful operation.

$$0.5T > t_L + t_p \tag{16}$$

where; T is the periodic time of the pulsed output voltage.

The end of mode III is the end of positive pulse generation period, while modes IV-VI are the modes for negative pulse generation. Due to the circuit symmetry ($L_p=L_n=L$ and $C_p=C_n=C$), the same aforementioned equations are valid in the negative pulse generation period, but the load voltage will have a reversed polarity.

Mode IV: In this mode, the negative-side inductor, namely, L_n, which is the inductor that is responsible for generating

negative output voltage pulse, is charged to the current (I_o) by turning on the switch (S_{nc}) only for the time (t_L) as shown in Fig. 2(d).

Mode V: After charging the negative-side inductor, the inductor energy is released by turning off the switch (S_{nc}) and turning on (S_n).It has to be noted that by turning on the switch S_n, the capacitor C_p is shorted. This is a safe short circuit as the voltage of capacitor C_p is initially zero (from the end of Mode III).

As a result, the load resistance becomes connected in parallel to capacitor C_n, which are fed from the inductor (L_n) through the diode D_n (i.e. $v_o=-v_2$), i.e. the resultant circuit is a second order parallel RL_nC_n circuit, and a negative voltage pulse appears across the load.

Mode VI: When the negative-side inductor current crosses zero, the converter diode (D_n) turns off, which switches the circuit to a first order RC_n circuit, and the C_n voltage decreases exponentially to zero (i.e. exponential pulse generation).

The repetition rate should be selected properly to ensure zero C_n voltage at the end of this mode, to ensure a safe short circuit across C_n during the upcoming positive pulse generation interval.

By repeating the aforementioned modes, a train of bipolar exponential pulses can be generated successfully.
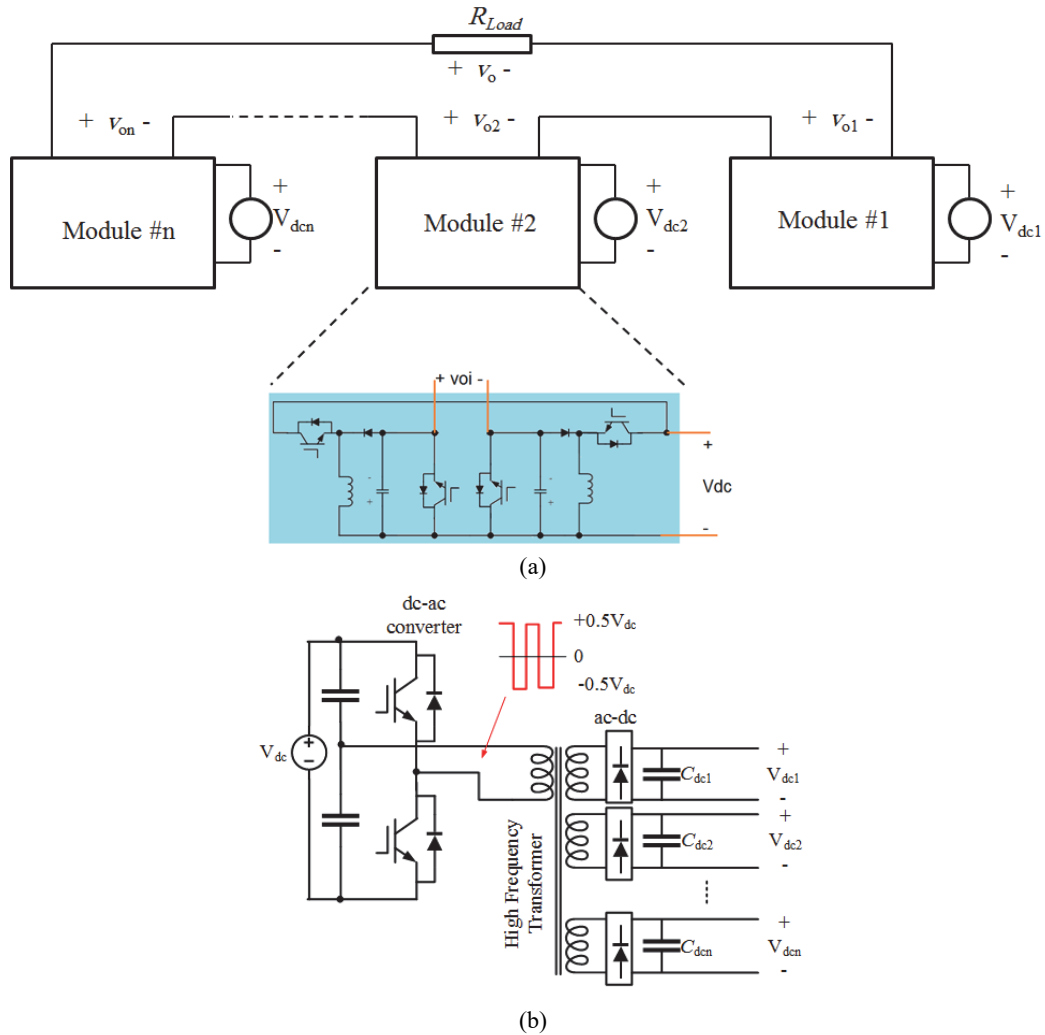
Fig. 4. Multi-module version of buck-boost converter based bipolar pulse generator. (a) Circuit architecture.(b) Isolated dc sources circuit.

III. MULTI-MODULE BUCK-BOOST CONVERTER-BASED PULSE GENERATOR

In case of moderate pulsed output voltage (up to few kVs), one module of buck-boost based bipolar pulse generator (Fig.1) can be employed, as the voltage rating of the involved semiconductor switches will be reasonable and available. Generally, in the conventional buck-boost converter, the involved semiconductor devices are rated at the sum of input and output voltages, i.e. semiconductor devices (S_{pc} and S_{nc}) should have voltage rating above $V_{dc}+V_{peak}$. On the other hand, the bypass semiconductor devices (S_p and S_n) are connected across the outputs of the buck-boost converters, so their voltage rating should be above V_{peak}. When the desired pulsed output voltage peak is moderate, it is easy to implement one module based pulse generator, as the semiconductor devices will be available.

While in the case of high-voltage pulsed output voltage, it will be difficult to implement one module-based converter as high-voltage switches will be needed, which necessitates series-connection of a number of semiconductor devices with

static and dynamic voltage sharing. To avoid that, stacked modules can be employed with isolated dc sources and series-connected outputs as shown in Fig.4a for n modules.

All modules should be operated simultaneously to make their pulsed outputs synchronized and identical, which results in having high pulsed output voltage across the resistive load (R_{load}) given by (17). Fig.4b shows a method for generating isolated dc sources from single dc source, where the dc source is fed to dc-ac converter followed by high-frequency transformer with multi secondary windings. Then the secondary windings are fed to uncontrolled rectifiers to extract the isolated dc sources. It has to be noted that the insulation level of the transformer windings should be high due to operating the modules with series-connected outputs.

$$v_o = v_{o1} + v_{o2} + \cdots + v_{on} = n\, v_{o1} \qquad (17)$$

The aforementioned equations (i.e. the one-module version equations) are valid in the multi-module version, but the load resistance seen by each module is given by,

$$R = R_{Load}/n \qquad (18)$$

In the multi-module version, the involved switches are

approximately rated at the total pulsed output voltage divided by number of the involved modules.

IV. DESIGN STEPS FOR THE BUCK-BOOST BASED PULSE GENERATOR

A. Design

In this subsection, the design steps of the buck-boost based pulse generator are presented with the help of the preceding analysis to ensure generating pulses with the desired specifications. First, for a given load resistance, rise time, and pulse width, the inductance and capacitance can be selected as follows: Based on (5), the following condition should be fulfilled,

$$\frac{4}{LC} - \left(\frac{1}{RC}\right)^2 > 0 \qquad (19)$$

Where $L=L_p=L_n$, $C=C_p=C_n$ and R is the load resistance in case of one module based generator, while it equals load resistance divided by the number of modules (R_{load}/n) in case of multi-module based generator, i.e.,

$$L < 4CR^2 \qquad (20)$$

To ensure that the inductance can be defined as in (21),

$$L = 4CR^2/h \ ; \text{ where } h>1 \qquad (21)$$

The corresponding α and β constants are given by (22).

$$\alpha = -\frac{1}{2RC} \text{ and } \beta = \frac{\sqrt{h-1}}{2RC} \qquad (22)$$

By substituting in (9) and (11), t_m and t_x can be obtained as a function of h and time constant (RC) as in (23) and (24), where t_m is the rise time of pulsed output voltage which is counted from the beginning of inductor discharging as shown in Fig. 3.

$$t_m = \frac{2RC}{\sqrt{h-1}} \tan^{-1}\left(\frac{\sqrt{h-1}}{+1}\right) \qquad (23)$$

$$t_x = \frac{2RC}{\sqrt{h-1}} \tan^{-1}\left(\frac{\sqrt{h-1}}{-1}\right) \qquad (24)$$

Based on (15) and (24), the pulse width can be expressed by,

$$t_p \approx 2RC \left(1 + \frac{1}{\sqrt{h-1}} \tan^{-1}\left(\frac{\sqrt{h-1}}{-1}\right)\right) \qquad (25)$$

By solving equations (23), and (25), suitable values of h and C can be obtained. Then (21) can be used to get the proper value of the inductance L.

Then for a given pulse magnitude across the load, the proper value of (I_o) for inductors can be estimated with the help of (10) as in (26).

$$I_o = \frac{V_{peak}}{Le^{\alpha t_m}\left(\frac{\alpha^2+\beta^2}{\beta}\sin(\beta t_m)\right)} \qquad (26)$$

where V_{peak} is the pulse magnitude across the load divided by the number of involved modules.

The time needed to reach the current level (I_o) at the end of inductor charging time interval, (i.e. t_L) is given by,

$$t_L = \frac{LI_o}{V_{dc}} \qquad (27)$$

Finally, the sum of (t_L and t_p) should be less than $0.5T$, where T is the periodic time of pulsed output voltage. If this condition is not achieved, a lower pulse repetition rate should be selected.

B. Numerical Example

In this subsection a numerical example for the designing of the presented buck-boost converter based pulse generator is considered. Assume the desired specifications are (rise time of 2.4 µs, pulse width 9µs, and pulse magnitude of 6 kV).

Based on the presented relations in the previous subsection, for load resistance of 200 Ω and a dc supply of 500V, the corresponding h, C, L, I_o and t_L will be 4, 0.01 µF, 400 µH, 55A, and 44 µs, respectively assuming single module-based generator (Fig.1). As a result, the voltage rating of switches should be above 6.5kV which is relatively high voltage rating for single switch.

Alternatively, 2 stacked-modules can be employed with two 250V isolated dc sources. Each module will be responsible for generating pulsed output of 3 kV magnitude, i.e. switches with a voltage rating above 3.25kV are needed which are available. In this case, the resistance seen by each module equals (200 Ω/2=100Ω), so the corresponding h, C, L, I_o and t_L for each module will be 4, 0.02 µF, 200 µH, 55A, and 44µs respectively. A higher number of stacked-modules can be designed with the same concept.

V. PROPOSED GENERATOR VERSUS BIPOLAR MARX PULSE GENERATORS

In this section, a comparison between the proposed bipolar multi-module buck-boost pulse generator and the bipolar Marx generators presented in [2] is held (Table I) to shows the advantages and disadvantages of the proposed approach.

The Marx generators are selected for comparison, as they are the most common pulse generators in pulsed power applications. Marx generator consists of certain number of cascaded stages (or modules), where the capacitors in these stages are charged in parallel then discharged in series. The details of bipolar Marx generators operational concept can be found in [2]. In [2], three different versions of bipolar Marx generators have been presented, where each stage contains k IGBTs (where k=6 or 5 or 4 according to the generator type), one/two diodes, and one capacitor. All components in Marx generators are rated at the input dc voltage. While the total pulsed output voltage magnitude equals the input dc voltage multiplied by the number of stages.

The comparison is shown in Table I, assuming same pulsed output magnitude (V_{peak}) and same voltage rating of the involved semiconductor devices (V_{sw}) in both types.

Based on the shown comparison, it is clear that the both

TABLE I
COMPARISON BETWEEN BIPOLAR MARX GENERATORS AND THE PROPOSED BIPOLAR PULSE GENERATOR

	Bipolar Marx Generators [2]	Proposed bipolar multi-module pulse generator
Number of modules (or stages)	$m=V_{peak}/V_{sw}$	$m \approx V_{peak}/V_{sw}$
Number of IGBTs	$mk+1$ k=4 or 5 or 6 (according to generator type)	$4m$
Number of capacitors	$m+1$	$2m$
Number of inductors	-	$2m$
Input dc voltage level	$\approx V_{peak}/m$ (moderate dc voltage level)	$<< V_{peak}/m$ (relatively low dc voltage level)
Number of dc sources	1	m (isolated)
Current stresses of semiconductor devices	Unequal current stresses where the devices of modules ,near from the dc supply, carry higher current	Equal current stresses in all modules' devices

types have almost the same passive components. However, the proposed approach has extra inductors, which insures operating with relatively low dc voltage level to generate high-voltage pulsed output magnitude, i.e. operating with higher output-input voltage gain. It has to be noted that as discontinuous conduction current is associated to the proposed approach, small capacitances and inductances are enough for the proposed concept, which reduces the system cost and volume. In addition, Unlike the Marx generators, the current stresses of the involved devices are equal. On the other hand, the main drawback of the proposed approach is the need for isolated dc sources, which can be extracted from one dc source as described in Fig. 4(b).

VI. SIMULATION

Two simulation models have been built for the proposed approach to validate the presented analysis (one for one module based pulse generator, while the other for the multi-module version).

A. One Module Based Generator

The system parameters in the simulated one module based pulse generator are: input dc voltage, V_{dc}=100V, load resistance, R=100Ω, pulse width of 100 µs, rise time of 25 µs, pulse magnitude of 1kV, and periodic time of 2ms.

Based on the aforementioned analysis, the suitable C, L, I_o and t_L are 0.25µF and 2.5mH, 18A and 458µs, respectively. It has to be noted that the sum of t_L and t_p is less than $0.5T$ which guarantees successful operation. The corresponding simulation results in Fig. 5. Figs. 5(a) and 5(b) show the pulsed output voltage, and its zoom-in figure, as it is clear that output voltage pulses of 1kV magnitude and 100µs pulse width are generated successfully from 100V dc source. Fig. 5(c) shows the variation of capacitors voltages while Fig.5(d) shows inductor currents. Finally, Figs. 5(e) and 5f show the semiconductors currents and voltages respectively.

B. Multi-Module Based Pulse Generator

The system parameters in the simulated multi-module based pulse generator are: input dc voltages, V_{dc}=250V, load resistance, R=200Ω, pulse width of 9µs, rise time of 2.4µs, pulse magnitude of 6 kV, periodic time of 1 ms and number of involved modules is two.

Based on the aforementioned specifications, the corresponding h, C, L, I_o and t_L for each module will be 4, 0.02 µF, 200 µH, 55 A, and 44µs, respectively.

The corresponding simulation results are shown in Fig. 6. In this mode, the modules are operated simultaneously and their outputs are identical, which is clearly shown in Figs. 6(a) and 6(b). Fig. 6(c) shows that the total pulsed voltage is double the output voltage of each module, as two modules are involved in the presented case. The zoomed-in view of the output positive pulse is shown in Fig. 6(d). Figs. 6e and 6f show the inductors' currents for the first and second module respectively. It is clear from the presented results that pulses with the desired specifications are generated successfully from a relatively low-voltage dc supply, i.e. operating with high output/input voltage gain.

C. Effect of Capacitances/Inductances Mismatch

It has to be noted that the mismatch in capacitances (C_p and C_n) causes insignificant difference between the positive and negative pulsed output voltage. Fig. 7(a) shows the negative pulsed output voltage for C_n=1.1C_p, assuming the same aforementioned simulation data of the one-module version. On the other hand, the effect of the mismatch in inductances (L_p and L_n) is noticeable. Fig. 7(b) shows the negative pulsed output voltage for of L_n=1.1L_p. This problem can be mitigated by operating with different t_L in the positive and negative half cycles (i.e. tuning of t_L in each half cycle).

VII. EXPERIMENTAL VALIDATION

A scaled-down experimental prototype has been used for validation of the proposed approach (assuming one module-based generator). The parameters of the experimental setup are given in Table II.

Based on the given data, the rise time and pulse width of the generated pulse will be 50µs and 265µs respectively. The
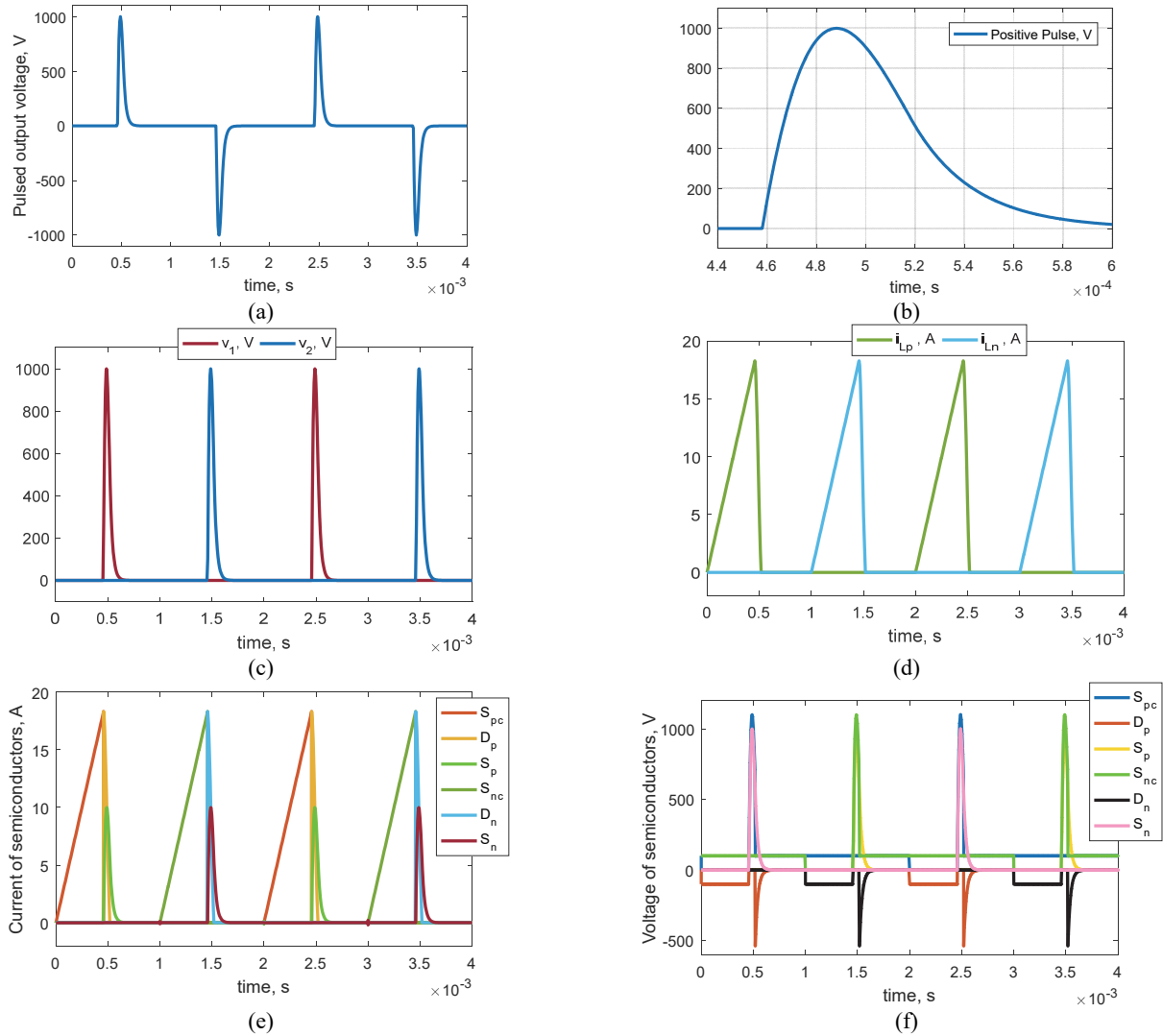
Fig. 5. Simulation results for one module based pulse generator. (a) Pulsed output voltage. (b) Zoomed-in view for the output positive pulse. (c) Capacitors' voltages. (d) Inductors' currents. (e) Current of semiconductors. (f) Voltage of semiconductors.
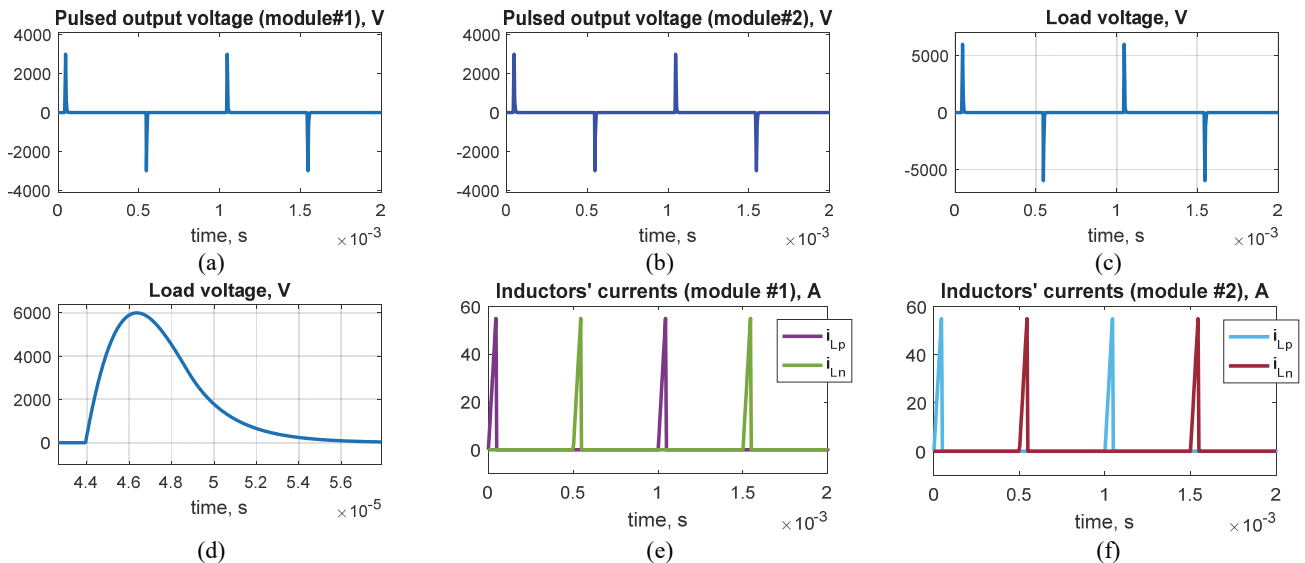

Fig. 6. Simulation results for the multi-module based pulse generator. (a) pulsed output voltage of first module, (b) pulsed output voltage of second module, (c) pulsed output voltage across the load resistance, (d) zoomed-in view of the pulsed voltage across the load resistance, (e) inductors' currents of the first module, and (f) inductors' currents of the second module.
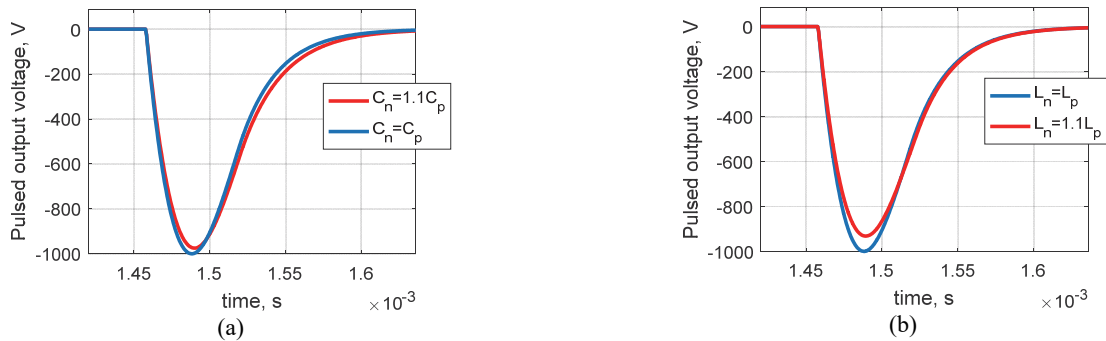
(a)

(b)

Fig. 7. Effect of capacitances/inductances mismatch on the shape of pulsed output voltage. (a) capacitances mismatch, (b) inductances mismatch.
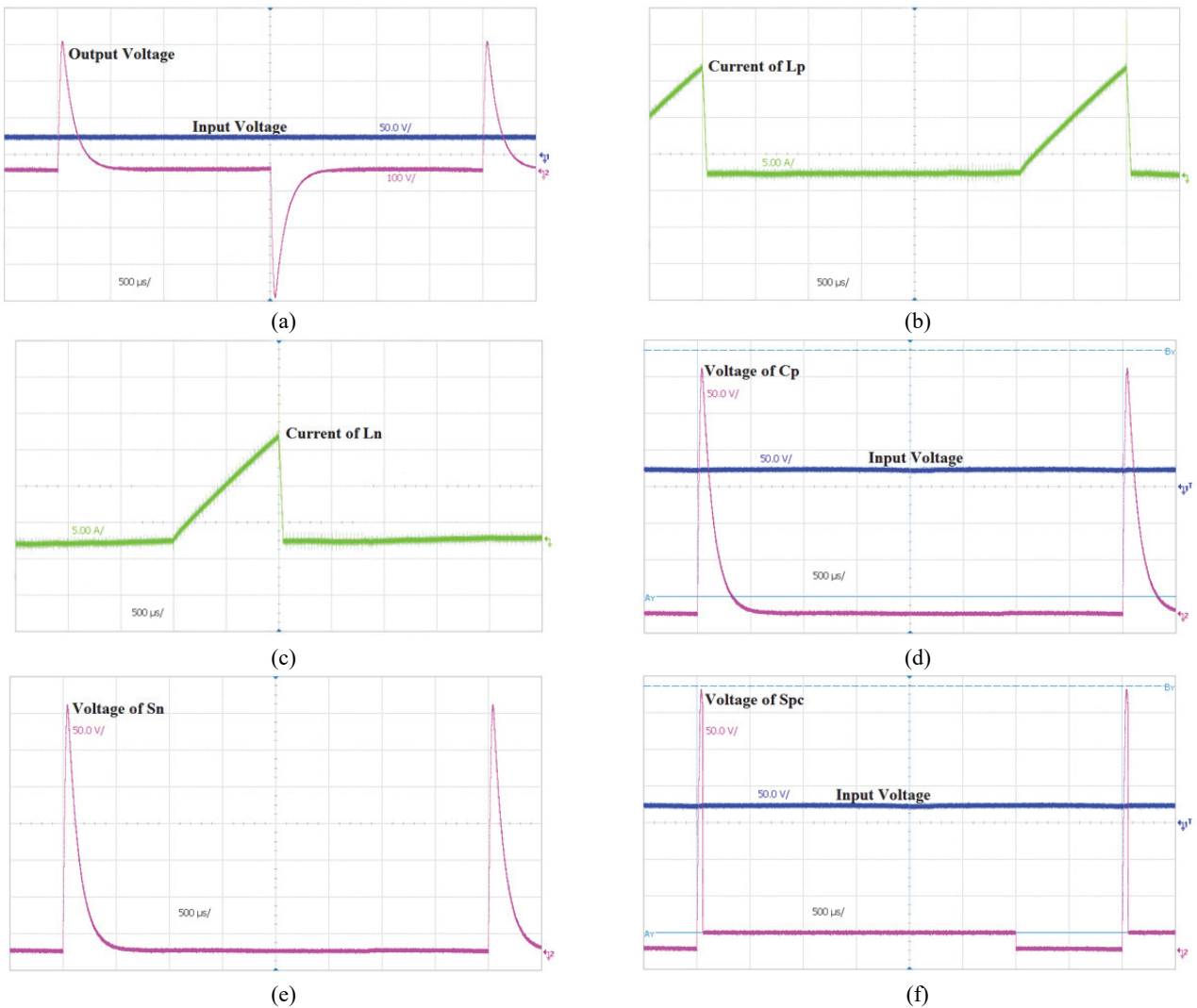

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 8. Experimental results for one module buck-boost converter based pulse generator. (a) Input voltage [CH1: 50V/Div, 500μs/Div] along with pulsed output voltage [CH2: 100V/Div, 500μs/Div]. (b) Positive-side inductor current [5A/Div, 500μs/Div]. (c) Negative-side inductor current [5A/Div, 500μs/Div]. (d) Input voltage [CH1: 50V/Div, 500 μs/Div] along with the voltage of C_p[CH2: 50V/Div, 500 μs/Div]. (e) Voltage of the switch S_n [CH2: 50V/Div, 500 μs/Div]. (f) Input voltage [CH1: 50V/Div, 500 μs/Div] along with the voltage of the switch S_{pc}[CH2: 50V/Div, 500 μs/Div].

corresponding experimental results are shown in Fig. 8. Fig. 8(a) shows the input dc voltage and the bipolar pulsed output voltage. Figs. 8(b) and 8(c) show the variation of positive-side inductor and negative-side inductor current with

operation, respectively.

Fig. 8(d) shows the variation of positive-side capacitor with the operation, while Figs. 8(e) and 8(f) show the voltage of the switch S_n and S_{pc} respectively. It is clear that the voltage

TABLE II

EXPERIMENTAL DATA

Input dc voltage, V_{dc}	≈ 20 V
Pulse magnitude, V_{peak}	≈ 350 V
Periodic time, T	4 ms
Inductor charging time, t_L	1 ms
Inductances, L	1.33 mH (0.2 Ω)
Capacitances, C	1 μF
Load resistance, R	100 Ω

rating of S_n should be higher than the pulsed output voltage magnitude (V_{peak}), while the voltage rating of S_{pc} should be higher than ($V_{peak}+V_{dc}$).

Based on the presented results, it is clear that 20V dc source is used to generate bipolar pulses across the load with amplitude of approximately 350V.

VIII. CONCLUSIONS

In this paper, the buck-boost converter based bipolar pulse generators operating in discontinuous current conduction mode have been presented. The operation under the discontinuous current conduction provides high-voltage gain and enhanced efficiency since the circuit draws current only when it is desired to generate a pulse. Two versions have been presented, single module and multi-module, for moderate and high pulsed output voltage, respectively. This allows operating with semiconductor switches with reasonable and available voltage ratings. Full analysis and design of both versions have been presented. Eventually, simulation and experimental results have been presented to validate the presented concepts.

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