Modular pulsed generator for kV and kHz applications based on forward converters association

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Keywords

Pulsed power converter, High Voltage power converters, High frequency power converter, MOSFET, Transformer.

Abstract

The operation of a modular generator topology, developed for kHz and kV pulsed applications, is presented. The proposed generator uses individual modules each one consisting of a pulse circuit based on a modified forward converter topology, with the secondary windings series connected, delivering a fraction of the total voltage. A laboratorial prototype with three 5 kV modules, 800 V semiconductor switches and 1:10 step-up transformers has been assembled. The first experimental results of this modular generator are presented and discussed. The circuit has 80 % efficiency and is capable of delivering, into resistive loads, -15 kV / 1 A pulses with 5 μs width, 10 kHz frequency, with less than 1 μs pulse rise time.

Introduction

Recently, new industrial processes were developed, which require high voltage pulses [1-3]. These pulses are further produced from pulsed power supplies based on solid-state switches, due to the improved volt-ampere performance of these devices, as well as the new pulsed topologies brought from power electronics converters. In recent years considerable effort has been made in developing a new variety of semiconductor-based high voltage pulse generators, able to provide high-voltage pulses suitable for pulsed power applications [4-6]. To achieve the needed high voltages, different techniques were brought into practical circuits to overcome the high voltage limitations of the solid-state devices. The most common approaches use either series connected semiconductors to directly switch a high-voltage power supply into the load [7, 8], or pulse transformers, single or series connected, to further increase the voltage of the output pulses [9, 10].

One of the major concerns for designers of magnetically cored pulse transformers is the lengthening of the pulse rise-time and overshoot caused by transformer parasitic elements (leakage flux and distributed capacitance the pulse transformer). This problem is exacerbated in transformers with a high secondary to primary turns ratio, where the voltage gain is high [11, 12]. Although the careful physical design of the pulse transformer can minimise the parasitic parameters, other considerations, such as the windings insulation, limit the extent to which the parasitics can be reduced. An alternative method for reducing their effect is to build transformer associations with series connected secondary windings [13-14].

In this paper, a modular pulsed generator developed for kHz and kV pulsed applications is presented. The proposed circuit uses individual stacked modules, each one consisting of a modified forward converter driving a step-up transformer. The secondary of each step-up transformer is series connected with the following module, each step-up transformer delivering a fraction of the total voltage. Experimental results are presented and discussed, showing the operation of a laboratorial prototype, with three 5 kV modules, 800 V semiconductor switches and 1:10 step-up transformers, delivering -15 kV / 1 A pulses into resistive loads, with 5 µs width, 10 kHz repetition rate and less than 1 µs pulse rise time.

Transformer association

The non ideal behaviour of the transformer makes the construction of a single high voltage pulse transformer with a high turns ratio (N=N_2/N_1>>1) complex, leading to significant parasitic effects as the output voltage rises. To solve this problem, it is possible to associate in series several pulse transformers with lower turn's ratio, in order to have only a fraction of the total voltage in each one. With a careful design, the leakage inductance of the equivalent circuit is reduced as compared to one single equivalent transformer, leading to a better rise-time performance.[25]

The most common way to associate pulse transformers is shown in Fig 1. Where three transformers with the secondary windings in series are presented, each one designed for one third of the output voltage v_0. In the primary side, windings are in parallel, supplied by v_{in}, and referenced to ground. Hence, the isolation voltage between windings of each transformer is different.

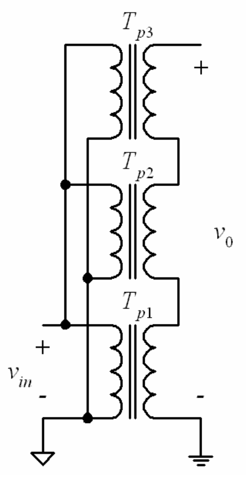


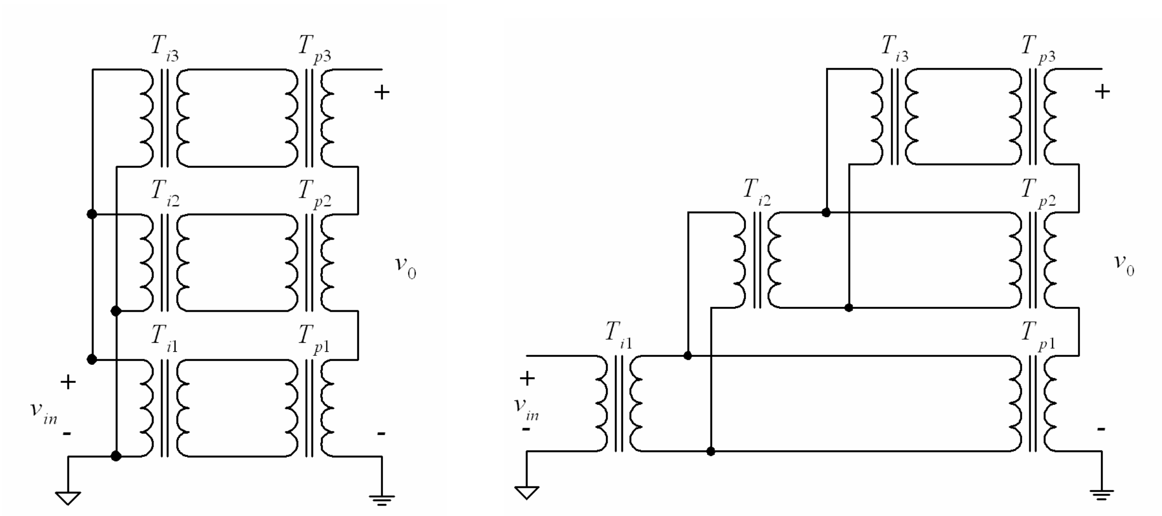
Fig. 1: Simplified transformers association with secondary windings in series and parallel primaries.

Considering Fig. 1, while the secondary winding potential in transformer T_{p2} and T_{p3} is, respectively, increased by $v_0/3$ and $2v_0/3$ through the secondary winding of transformer T_{p1} and T_{p2}, in the primary windings the reference potential stays constant. As a result, each transformer holds a different voltage between windings, depending on the series position of each transformer, which increases towards higher potentials. Thus, transformer galvanic isolation between windings must be designed to $v_0/3$ for T_{p1}, $2v_0/3$ for T_{p2} and v_0 for T_{p3}.

The above drawback sets serious difficulties for pulse applications of the Fig. 1 circuit. Since the pulse transformers placed at higher potentials hold higher voltages, the isolation distance in these is increased. Consequently, the pulse waveform is distorted due to the increase of the parasitic leakage inductance with the isolation. To overcome this problem, it is possible to feed the primary windings of the pulse transformers with galvanic isolated power supplies. This can be achieved with the introduction of isolation transformers, in order to keep the secondary windings of the pulse transformers in series but with the same isolation voltage between windings. This solution has the immediate advantage that all the pulse transformers are similarly built, with the same minimum isolation distance, which helps to reduce the output pulse rise-time. Two configurations can be considered, Fig. 2: *i*) Independent isolation transformers, Fig. 2 (a); *ii*) Cascade connected isolation transformers, Fig. 2 (b).

For both circuits in Fig. 2, the secondary windings of the pulsed transformer are series connected, delivering each one (T_{p1}, T_{p2} and T_{p3}), $v_0/3$ of the total output voltage v_0. In the circuit of Fig. 2 (a) the primary windings of T_{p1}, T_{p2} e T_{p3} are fed, respectively, by the secondary windings of the isolation transformers T_{i1}, T_{i2} e T_{i3}, these ones being fed by the input voltage v_{in}. In this way, the pulse transformers T_{p1}, T_{p2} e T_{p3} can be assembled with the same structure and characteristics, for the same isolation voltage of $v_0/3$. The voltage increase due to the secondary winding series connection of T_{p2} and T_{p3} is sustained by the isolation transformer T_{i2} and T_{i3}. Then, for the worst running condition (considering a high capacitance between primary and secondary of the pulse transformers), the galvanic isolation of T_{i2} e T_{i3} must be predicted to hold, respectively, $v_0/3$ e $2v_0/3$. The isolation transformer T_{i1} is not necessary.

In the circuit of Fig. 2 (b) the primary windings of T_{p1}, T_{p2} e T_{p3} are fed, respectively, by the secondary windings of T_{i1}, T_{i2} e T_{i3}, with primary windings fed successively by the secondary windings of the previous transformer (i.e. T_{i3} fed by T_{i2}, which is fed by T_{i1}, which is fed by v_{in}). In this way, the pulse transformers T_{p1}, T_{p2} e T_{p3} can be assembled with the same structure and characteristics, for the same isolation voltage of $v_0/3$. The voltage increase due to the secondary winding series connection of T_{p2} and T_{p3} is held by the isolation transformer T_{i2} and T_{i3}. The isolation transformer T_{i1} is not needed.



(a) (b)

Fig. 2: Simplified layout of series connected secondary windings transformers fed by: (a) independent isolation transformers; (b) cascade isolation transformers.

Taking into account the two circuits of Fig. 2: *i*) In Fig. 2 (a), considering a load power *P*, neglecting the losses in the transformers, each one is assembled for a power of *P*/3 (i.e. the power installed in all the transformers is 2*P*. However, in Fig. 2 (b) the pulse transformers are assembled with a power of

$P/3$ but the isolation transformers have successively powers of P, $2P/3$ and $P/3$. The total power installed in all the transformers is 3P; *ii*) In Fig. 2 (b), all the transformers have the same isolation voltage, while in Fig. 2 (a) the isolation voltage in isolation transformers is different.

Considering only the pulse transformers, the two topologies, in Fig. 2, are equivalent. Hence the choice between the two should be based on the characteristics preferred for the isolation transformers and the features desired for the pulse generator.

Regarding the last, it is considered a great advantage for the high voltage pulse generator to be of modular construction, built upon several equal modules, where each one could occupy any position in the generator. This solution fits perfectly in the modern design techniques used in high voltage systems (HVPS, High Voltage Power Supply), based on the Design for Manufacture and Assembly Principle, which point for the modular approach for high voltage systems [15]. Therefore, we have considered the topology of Fig. 2 (a), and build all the isolation transformers, similarly, for the total series voltage.

Circuit Topology

Fig. 3 shows the simplified layout of the modular pulsed generator used for negative output pulses. If positive pulses are desired, it is only necessary to invert the polarity of the secondary diodes D_{ri}, where $i \in \{1, 2, \ldots, n\}$. Power is supplied to the n modules via isolation transformers (1:1), T_{ii}, with primaries in parallel, connected to a dc-ac-switching converter, as shown in Fig. 3. Capacitor coupling (C_{ci}) is used to eliminate dc components in the insulation transformers. To supply the necessary v_{dci} voltage to each module, voltage multipliers are used allowing low voltage operation of the dc-ac-switching converter in the primary side of the insulation transformers. The low power required for driving the power switches S_i in all the n modules is supplied, via isolated power supplies and the gate control signal is applied via optic fiber, as shown in Fig. 3. To ensure proper operation, accurate synchronization of the drive signals of the S_i semiconductors is mandatory.

The modified forward converter of each module, shown in Fig. 3, consists of a step-up transformer, T_{pi}, with a Resistor-Capacitor-Diode ($R_iC_iD_i$) clamp reset circuit designed to reset the transformer core flux under any load conditions, during the off interval of the power switch S_i. The forward converter does not include the output rectifier, inductor and capacitor, advantageously reducing the maximum voltage on the semiconductor power device, S_i, as described in [4], since the low duty cycle operation enables a low voltage reset circuit of the step-up transformer.

Considering only module 1 (Fig. 3) with ideal components, when S_1 is on, for a time t_{on}, diode D_{r1} conducts and the voltage across R_{d1} is,

$$v_{01} = -v_{dc}N\,, \tag{1}$$

where N is the turns ratio of the step-up transformer, T_{p1}. When S_1 is off, for a time t_{off}, the voltage across R_{d1} is zero. During this time diode D_{r1} reverse voltage is,

$$v_{ka1} = v_c N\,. \tag{2}$$

If the duty ratio (t_{on}/t_{off}) of power semiconductor S_1 is only a few percent and the transformer resetting time extends to almost all the off time of the power switch, diode D_{r1} only blocks a small fraction of the peak output voltage v_{01}, usually less than $0.1v_{01}$ [4]. Moreover, with a step-up transformer (1:10), this topology also enables relatively low voltage semiconductor devices in the primary side (i.e. diodes D_i and power switch S_i). Considering now n modules, in Fig. 3, with switch S_i on in all the modules, diodes D_{ri} are conducting, and theoretically the voltage applied to the load is,

$$v_0 = -(v_{01} + v_{02} + \ldots + v_{0n})\,. \tag{3}$$

For n equal modules, the load voltage becomes,

$$v_0 = -n v_0 N . \quad (4)$$

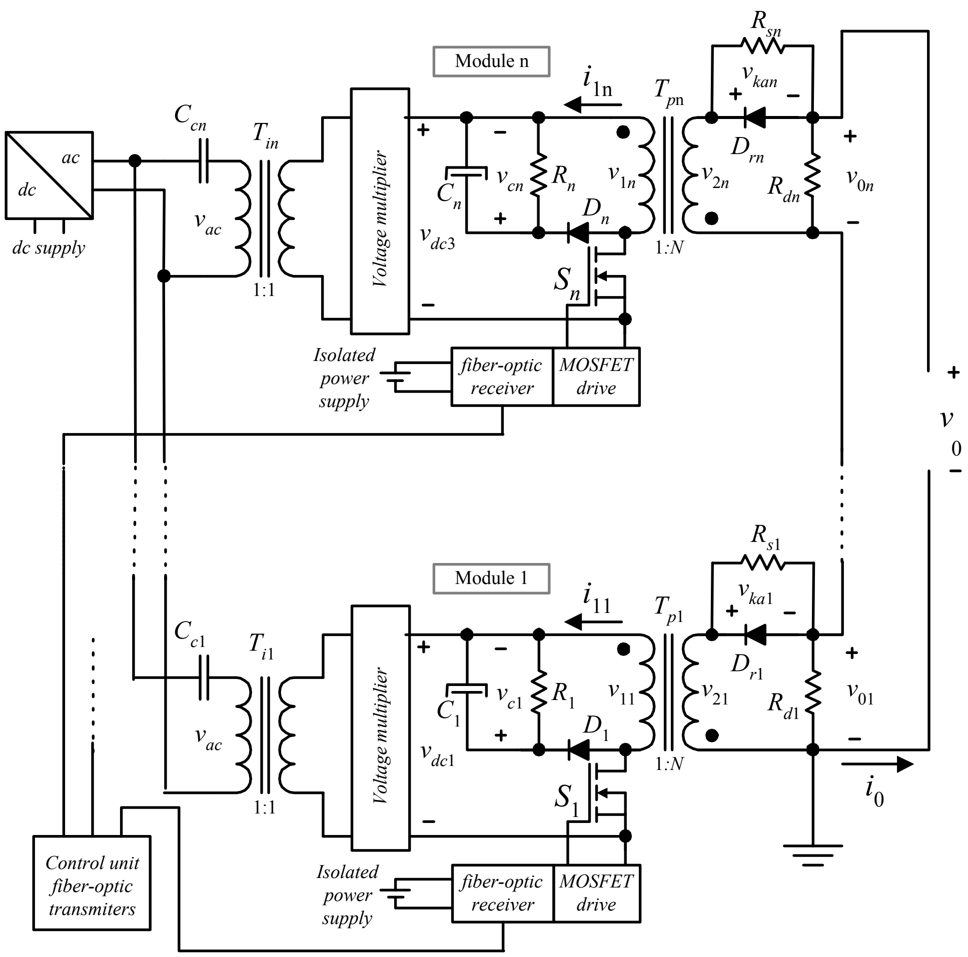


Fig. 3: Simplified layout of the modular pulsed generator for negative output pulses.

During the off time of switches S_i, the voltage applied to the load goes to zero, diodes D_{ri} in each module block only the reset voltage of their respective pulse transformer, which is theoretically equal to (2). Voltage-sharing resistors, R_{si}, are used to equally distribute the reset voltages of each module through diodes D_{ri}. In order to hold the high-voltage potential in each module relative to ground, R_{di} resistances are used.

Due to the switching stage topology described above, if all the n-1 power switches S_i are on, and the n^{th} semiconductor is off, the power switch in this last module is not destroyed since each power switch only withstands the voltage of its own module.

Experimental Results

To validate the concept presented in Fig. 3, a modular pulse generator prototype was built, consisting of three 5 kV / 1 A individual modules, connected in series with v_{dci}≈500 V. The switching power stage in each module was built using step-up transformers assembled with available ETD49 cores, 3C85 grade material ferrite from Philips. The windings were designed for an output of 5 kV / 1 A with N_1=50 and N_2=500 turns (N=10) and for 10 kHz operating frequency with 5 µs pulse width. An 800 V

MOSFET, IXTH13N80, is used as the power switch, S_i, and 1000 V diode, UF5408, for D_i and D_{ri}. Additional components are R_i=1.1 kΩ, C_i=2.2 µF and R_{di}=R_{si}=10 MΩ.

Fig. 4 (a) shows the experimental waveforms for module 1 of the modular pulsed generator of Fig. 3, considering a resistive load. A –5 kV output pulse is observed, with rise and fall times less than 1 µs, in synchronism with the semiconductor drive signal, v_{gs1}. Fig. 4 (b) shows the experimental output voltage v_0 and current i_0 for the modular high-voltage pulse generator, with three –5 kV stages, delivering approximately -15 kV pulses (1 A peak current in resistive load), 5µs pulse width, with approximately 800 ns rise time, 2000 V overshoot, and a 10 kHz repetition rate.

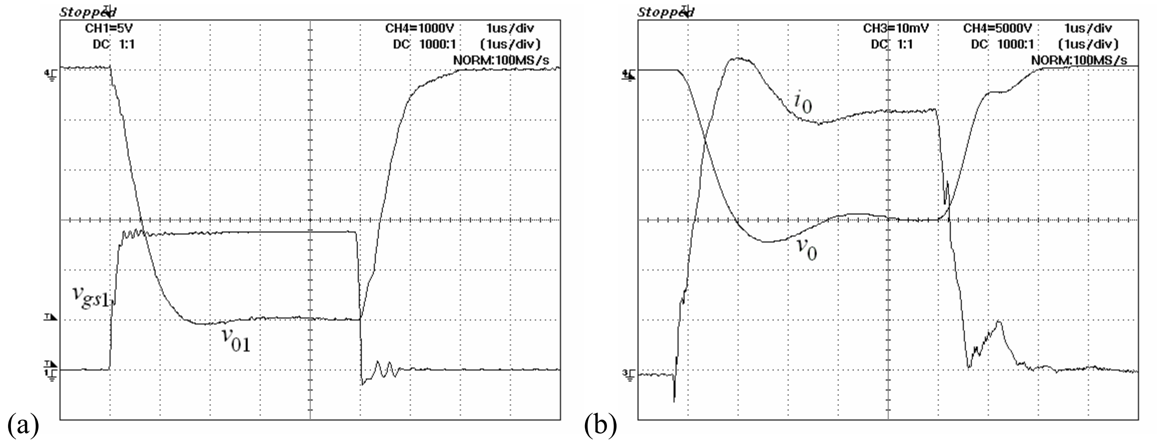


Fig. 4: Experimental waveforms for the modular pulsed generator of Fig. 3, with three -5 kV modules, considering a resistive load. Horizontal scale 1 µs/div, vertical scale: (a) module 1 output voltage, v_{01} (1000 V/div), and switch S_1 drive signal, v_{gs1} (15 V/div); (b) generator output voltage, v_0 (5000 V/div), and output current i_0 (200 mA/div).

The efficiency of the pulsed power generator was determined by measuring the power delivered by the dc power supply to the dc-ac converter, and the power delivered to the load, during the above experimental test, giving nearly 80%.

Conclusion

A modular concept on high-voltage pulse generators was presented. A three 5kV modules prototype was assembled with 800V semiconductor switches and experimentally tested for an output of -15 kV, 5 µs pulse width and 10 kHz repetition rate, with 80 % efficiency, in resistive load conditions, using semiconductor switches with blocking capabilities lower than 1kV.

The purpose of using isolation transformers to supply power for the series connected pulse transformers was to reduce the amount of isolation needed in each pulse transformer to a value needed only to sustain its own secondary voltage v_0. The isolation distance between primary and secondary is the main factor contributing to the increase of the leakage inductance. Hence, with this topology 15 kV pulses were achieved with 800 ns rise time. The isolation transformers in each module were assembled in order to sustain a voltage equal to the maximum output pulse voltage, which is acceptable for isolation transformers. In conclusion, the high-voltage generator proposed can be labeled as modular, considering that identical switched pulse transformer circuits can be connected in series, each one sustaining only its own voltage. The isolation transformers supplying each module ensure this isolation, as they are designed to sustain the series full voltage.

References

[1] Yong-Ho Chung et al, “All solid-state switched pulser for air pollution control system,” presented at the 12th IEEE Int. Pulsed Power Conf., Monterey, CA, June 27-30, 1999 (unpublished).

[2] M.P.J. Gaudreau, T. Hawkey, J. Petry and M. Kempkes, "A solid state pulsed power system for food and wastewater processing," in Proceedings of the Pulsed Power Plasma Science, Vol. 2, pp. 1174-1177, 2001.
[3] M.P.J. Gaudreau, J.A. Casey, M.A. Kempkes, T.J. Hawkey, and J.M. Mulvaney, "Solid state modulators for plasma immersion ion implantation applications," J. Vac. Sci. Technol. B, Vol. 17, pp. 888-894, 1999.
[4] L.M. Redondo, E. Margato, and J. Fernando Silva, "A new method to build a high-voltage pulse supply using only semiconductor switches for plasma-immersion ion implantation," Surf. Coat. Technol., Vol. 136, pp.51-54, 2001.
[5] L.M. Redondo, J. Fernando Silva, P. Tavares and E. Margato, "High-voltage, high-frequency Marx-bank type pulse generator using integrated power semiconductor half-bridges," in Conference Proceedings 2005 EPE 11th European Conference on Power Electronics and Applications", *11-14 September Dresden/Germany*, P1-P8, 2005.
[6] Jong-Hyun Kim *et al.*, "High Voltage-Pulse Power Supply Using IGBT Stacks, " in Proceedings of the 30th Annual Conference of the IEEE Industrial Electronics Society, Busan, Korea, pp. 2843-2847, November 2004.
[7] Marcel P. J. Gaudreau et al, "Solid State Pulsed Power Systems", presented at the Twenty Third International Power Modulator Symposium, Rancho Mirage, June 1998 (unpublished).
[8] Edson Hirokazu Watanabe et al, "Series connection of power switches for very high-power applications and zero-voltage switching", IEEE Trans. Power Electronics, Vol. 15, No. 1, pp. 44-49, January 2000.
[9] O. Maulat, M. Roche, F. Le Coeur, O. Lesaint, Y. Arnal, J. Pelletier, "A new line of high voltage – high current pulse generators for PBII", J. Vac. Sci. Technol. B, Vol. 17, pp. 879-882, pp. 3738-3740, 1999.
[10] J. Klein and M. Padberg, "A modular low-cost, high-voltage pulse generator that is highly effective in terms of pulse energy and repetition frequency," Meas. Sci. Technol., Vol. 6, pp. 550-553, 1995.
[11] L. M. Redondo, E. Margato, J. F. Silva, "Rise time reduction in high-voltage pulse transformers using auxiliary windings," in IEEE Trans. Power Electronics, Vol 17, No. 2, pp. 196-206, March 2002.
[12] Angel Pérez Garcí et al., "Design Criteria for transformers in high voltage output, high frequency power converter applications", EPE Journal, Vol. 4, No. 4, pp. 37-40, December 1994.
[13] Paul W. Smith, Transient Electronics - Pulsed Circuit Technology, (John Wiley & Sons 2002), pp. 163-167.
[14] Yiu-Chung Cheng et al, "Special modulator for high frequency, low-voltage plasma immersion ion implantation", Rev. Sci. Instrum., Vol. 70, No. 3, pp. 1824-1828, 1999.
[15] Carl I. Belnap, John S. Bowers, "Advantages in the development and use of high voltage electronic modules in high voltage power supplies", Presented at the High Voltage Workshop, Newport Beach, CA, April 2000.