Parallel and Series Configurations of Flyback Converter for Pulsed Power Applications

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Abstract— **Advances in solid-state switches and power electronics techniques have led to the development of compact, efficient and more reliable pulsed power systems. Although, the power rating and operation speed of the new solid-state switches are considerably increased, their low blocking voltage level puts a limits in the pulsed power operation. This paper proposes the advantage of parallel and series configurations of pulsed power modules in obtaining high voltage levels with fast rise time (dv/dt) using only conventional switches. The proposed configuration is based on two flyback modules. The effectiveness of the proposed approach is verified by numerical simulations, and the advantages of each configuration are indicated in comparison with a single module.**

Keywords-pulsed power; flyback converter; parallel and series connection; high voltage pulse;

I. INTRODUCTION

Rapid release of stored energy as electrical pulses into a load can result in delivery of large amounts of instantaneous power over a short period. This strategy is called pulsed power [1]. Generally, a pulsed power system consists of three main parts: energy storage, pulse generator and the load. The most prominent part of a pulsed power system is the pulse generator, which is based on utilized switch and topology. Hence, the switch is the connecting device between the storage and the load. This means that the whole system characteristics such as rise time, repetition rate, voltage rating, efficiency, cost, life time, etc, depend on the employed switch specifications.

Gas-state and magnetic switches have been widely used in pulsed power technology, as they possess a very high electric strength and fast rise time [2]. Gas-state switches require special operating conditions such as high pressure, vacuum equipments and gas supplies. In addition, they are bulky, unreliable, have short lifetime span and low repetition rate. Even with the magnetic switches, which have a higher repetition rate, the problems remain. These conditions limit the mobility, efficiency and increase the cost and the size of the pulsed power system [2], [3]. On the other hand, solid-state switches are compact, reliable, cost effective, and have a long lifetime and repetition rate. The main drawbacks of solid-state switches are their limited power rating and operation speed [2], [3].

Recently, significant advances in solid-state switches (both in peak power and operation speed) and exploiting power electronics techniques and topologies have led to compact, efficient and more reliable pulsed power systems. The new developed solid-state switches such as IGBT (Insulated-Gate Bipolar Transistor) and Integrated Gate-Commutated Thyristor (IGCT) have high power rating [4], but their lower operation speed comparing with the gas-state switches and high cost still put limits in the pulsed power supplies.

One way to increase the pulsed power supply performance and cover the switch limits is to explore alternative circuit topologies. Varieties of circuit topologies such as Marx generators (MG) [5], pulse forming network (PFN) [6], magnetic pulse compressors (MPC) [7] and multistage Blumlein lines (MBL) [8] have been introduced. These topologies have been widely used in pulsed power supplies, but complexity, inflexibility and inefficiency are their main drawbacks [2], [9]. Interest in applying power electronics topologies and techniques to increase power supply efficiency and reliability is growing fast. In the last decade, research and studies designate the advantage of using DC-DC converters in pulsed power applications [3], [9], [10]. However, if one wants to generate extra high voltages, due to components hold-on voltage limits (such as capacitors, solid-state switches and etc), these schemes become ineffective.

In addition to topology, another way is to combine power supplies. Variety of converter configurations have been introduced for improving the power supply specifications such as output ripple, high input voltage, output power ratings, etc [11], [12]. Parallel and series connections are one of the well known combinations. Designing power supplies based on series or parallel connection are widely employed for different applications [11], [12].

This paper proposes parallel and series connections of flyback converter modules to develop power rating and rise time of the pulsed power supply using conventional low voltage switches. Flyback converter is selected due to its unique properties in pulsed power as it is discussed in the next section. The proposed approach is evaluated by numerical simulations, and the advantages of each configuration are indicated in comparison with a single module. The evaluated results indicate the effectiveness and efficiency of the proposed method.

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II. TOPOLOGY

The proposed approach utilized flyback topology, which is one of the well known topologies in the power electronics [13]. Conventional flyback converter is usually preferred as it is simple, has only one switch and magnetic component, is able to generate high voltage, can provide multiple outputs, isolation, etc [13], [14]. But when it comes to pulsed power applications, in addition to the mentioned features, it has some more advantages which make it more suitable. Main features of a flyback converter for pulsed power applications are:

- The transformer, in addition to electrical isolation and energy storage also steps down the reflected voltage across the switch; therefore lower voltage rate switches are needed comparing with other topologies.
- Fault tolerant, as the switch is in the off-state during the output pulse.
- High voltage output with low input DC voltage.
- As the pulsed power applications mostly have R-C characteristics [9], a current source topology (such as flyback) is a suitable candidate.

Considering above mentioned features the current source topology is selected for the proposed method. Here basic principle and operation modes of this converter are briefly described.

The behaviour of a flyback converter can be realized by modelling the transformer with a simple equivalent circuit consisting of an ideal transformer, magnetizing inductance (L_m) and leakage inductance (L_l). Fig.1 shows a flyback converter including the simple model of the transformer connected to a load. In this figure C_o is the converter equivalent output capacitance. This capacitance can get affected in the case of an R-C load. It is to be mentioned that, to keep the analysis simple, following assumptions are made:

1. The switch and diode are ideal (voltage drop across them is zero).
2. The switch and diode output capacitances are zero.
3. Conduction and switching losses are negligible.
4. The transformer stray capacitances are negligible.

Basically a flyback converter transfers energy from a source into the transformer magnetizing inductance when the switch is on, and then transfers the stored energy to the load while the switch is off. The proposed approach operates in the DCM (Discontinues Conduction Mode). The operating modes are briefly summarized for 4 different modes (illustrated in Fig. 2) below:

- Mode 1: In this mode the switch is in the on-state. As Fig. 2 depicts, the current flows through L_m and, during this stage, the energy is stored in the inductor. This mode lasts depending on the duty cycle of the PWM signal. The relationship between L_m and V_s can be expressed as:

$$V_s = L_m \frac{\Delta i}{\Delta t} \longrightarrow V_s = L_m \frac{I_m - 0}{D.T_s - 0} = L_m \frac{I_m}{D.T_s} \qquad (1)$$

where V_s is the dc supply voltage, I_m is the maximum current, D is the duty cycle and T_s is the switching period.

- Mode 2: When the switch is turned off the magnetizing current circulates through the primary side of the transformer and the diode in the secondary side is turned on. As the switch is turned off the current flowing through L_l is decreased to zero, which induces voltage spike across the switch according to $v_l = L_l \, {di}/{dt}$. This voltage may damage the switch if it exceeds the switch break down voltage level. A snubber can provide a path for this current and damps the spike to protect the switch [15].
- Mode 3: The diode is turned on and the current stored in the magnetising inductance flows to the secondary side. The maximum voltage across the switch at this stage is:

$$(v_{switch})_{\max} = V_s + \frac{1}{n} v_{o\,\max} \qquad (2)$$

where, V_o is the maximum output voltage level and n is the transformer turns ratio.

- Mode 4: As the converter operates in DCM in this mode, all the stored energy in L_m is completely transferred to C_O, causing the diode to get turned off.

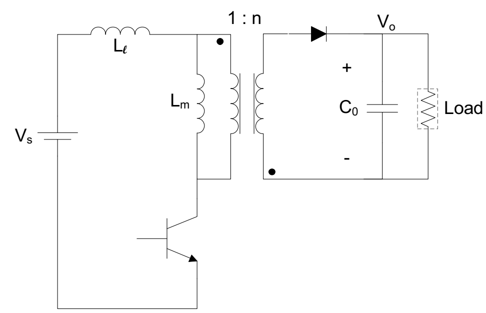

Figure 1. Flyback converter circuit with transformer equivalent circuit model.

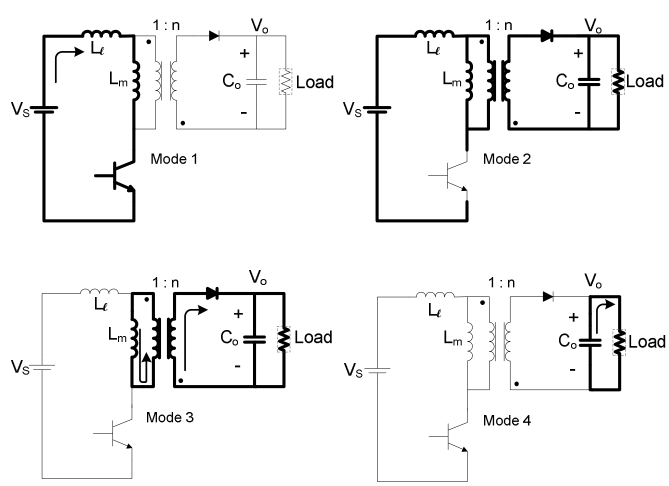

Figure 2. Operating modes in a flyback converter.

III. PROPOSED METHOD

High voltage pulses with fast rise-time are the two main important features of a pulsed power supply [1]-[3]. Fig. 3 illustrates the proposed method, which employs the advantage of parallel and series configuration of the pulsed power modules to increase the voltage level and the rise-time, while using the low-voltage switches. As the figure shows, the parallel and series connections are only considered for the secondary side of the converter.

A. Single Module

To understand and compare the parallel and series configuration, first a single module characteristic is described. As mentioned, a flyback converter can operate as a current source. Therefore, circuit schematic shown in Fig. 1 is simplified as in Fig. 4. Comparing these two figures, the estimation of the output voltage can be summarized as below:

First, as described earlier, the magnetizing inductance is charged by the DC power supply. The charged energy stored in the inductor L_m under ideal situation can be expressed as:

$$E_{pri} = \frac{1}{2} L_m {I_m}^2 \tag{3}$$

This stored energy will be transferred to the output capacitor when the switch is in the off-state. The capacitive stored energy is:

$$E_{\sec} = \frac{1}{2} C_o {V_o}^2 \tag{4}$$

If a lossless system considered, then the stored energy in the primary side, E_{pri}, is equal to the stored energy in the secondary side, E_{sec}. Therefore, the output voltage can be derived based on equations (3) and (4) as:

$$V_o = I_m \sqrt{\frac{L_m}{C_o}} \tag{5}$$

The rise time for the generated voltage is defined as dv/dt. When the switch is turned off, the magnetizing inductance current is at its peak value (I_m). Since the current through a capacitor is proportional to the time-rate of the stored voltage, the rate of rise is:

$$\left(\frac{dv}{dt}\right) = \frac{I_o}{C_o} = \frac{I_m}{nC_o} \tag{6}$$

This equation is valid till the current through the capacitor is approximately constant; otherwise the rate of rise completely depends on the resonant frequency.

The above equations show the effect of stored current level, magnetising inductance and the output capacitor on the generated output voltage and the rise-time. The idea of parallel and series configurations of the pulsed power modules is inspired by both equations (5) and (6).

B. Parallel Modules

Considering Fig. 3(a) and the fact that each transformer is acting as a current source, the stored energy in the primary side is doubled when two modules are connected in parallel. This stored energy will be transferred to the output capacitors; hence considering (3) and (4) the output voltage magnitude and its rate of rise are as follows:

$$V_{o\,parallel} = \sqrt{2} I_m \sqrt{\frac{L_m}{C_{op}}} \tag{7}$$

$$\left(\frac{dv}{dt}\right)_{Parallel} = \frac{2I_o}{C_{op}} \tag{8}$$

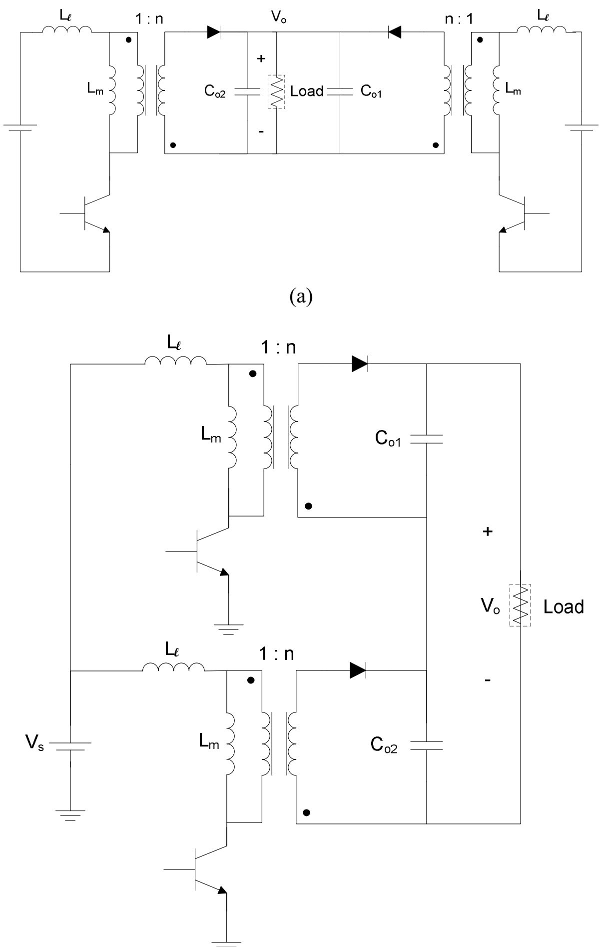

Figure 3. Flyback converter series and parallel connection (secondary side), a) Parallel, b) Series.

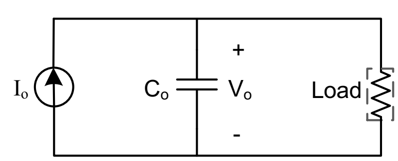

Figure 4. Energy transmission in a single module flyback converter.

where C_{op}=C_{o1}+C_{o2}. Equations (7) and (8) indicate the importance of the output capacitor. Even if the modules are paralleled the output capacitance can affect the output voltage level and rise-time and keep them same as the single module. Therefore, the parallel configuration is beneficial in pulsed power applications when C_{op}=C_o. This happens in the case of R-C load when the load capacitance is much bigger than the power supply output capacitance.

C. Series Modules

Second alternative is series connection of the pulsed power modules, as illustrated in Fig. 3(b). Here, the injected energy to the output is also doubled. But as described, the generated voltage features also depend on the output capacitance. Taking into account the equations (3) to (6), the output voltage magnitude and its rate of rise can be expressed as:

$$V_{o\,Series} = \sqrt{2} I_m \sqrt{\frac{L_m}{C_{os}}} \tag{9}$$

$$\left(\frac{dv}{dt}\right)_{Series} = \frac{I_o}{C_{os}} \tag{10}$$

where C_{os} is $C_{o1}C_{o2}/(C_{o1}+C_{o2})$. Same as in parallel modules, in series modules, the output voltage level and rise time improve as the output capacitance decreases. Here the series modules are beneficial in both level of voltage and its rate of rise when C_{os}<C_o. The influence of N modules and equivalent output capacitor (for two different cases) on the output voltage and rise time are summarized in Tables I and II.

As Fig. 3(b) shows, in the series connection each switch withstands its own module reflected output voltage, while in the parallel connection, each switch should tolerate the whole reflected output voltage.

TABLE I. OUTPUT VOLTAGE AND RATE OF RISE WHEN C_{o1}=C_{o2}=… C_{oN}=C_o.

***N* Modules connected in**	V_o	$\frac{dv}{dt}$
Parallel	$I_m\sqrt{\frac{L_m}{C_o}} = V_{o\,Single}$	$\frac{I_o}{C_o} = \left(\frac{dv}{dt}\right)_{Single}$
Series	$NI_m\sqrt{\frac{L_m}{C_o}} = NV_{o\,Single}$	$N\frac{I_o}{C_o} = N\left(\frac{dv}{dt}\right)_{Single}$

TABLE II. OUTPUT VOLTAGE AND RATE OF RISE WHEN C_{OP}=C_{OS}=C_o.

***N* Modules connected in**	V_o	$\frac{dv}{dt}$
Parallel	$\sqrt{N} I_m\sqrt{\frac{L_m}{C_o}} = \sqrt{N} V_{o\,Single}$	$N\frac{I_o}{C_o} = N\left(\frac{dv}{dt}\right)_{Single}$
Series	$\sqrt{N} I_m\sqrt{\frac{L_m}{C_o}} = \sqrt{N} V_{o\,Single}$	$\frac{I_o}{C_o} = \left(\frac{dv}{dt}\right)_{Single}$

This fact makes the series connected modules more appropriate for generating high voltage waveforms using low voltage switches. Therefore, (2) can be rewritten as below for N-series module:

$$(v_{switch})_{\max} = V_s + \frac{1}{Nn} v_{o\max} \tag{11}$$

D. Operating Conditions

The above mentioned calculations are correct if three important points are considered in the designing procedure of pulsed power modules. These are:

1) The output capacitor should be completely discharged during each period; otherwise the whole stored energy in the magnetising inductor will not transfer to the capacitor.

2) Synchronization of each switch gate signal is required. Delays between each module gate signal reduce the performance of the system.

3) It is also important to consider the *damping factor* (ζ). As shown in Fig.4, the entire circuit acts as a parallel RLC circuit (the current source is an inductor). Hence, the output voltage and the rise time are the results of the resonance effect of this circuit. The output voltage can be expressed as:

$$V_o(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t} \tag{12}$$

where s_1 and s_2 are given as:

$$S_{1,2} = -\alpha \pm \sqrt{\alpha^2 - \omega_0^{\,2}} \tag{13}$$

here, $\alpha = \frac{1}{2RC}$ is known as *neper frequency* and $\omega_0 = \frac{1}{\sqrt{LC}}$ is the *resonance frequency*. $V_o(t=0^+)=0$ and $I_C(t=0^+) = I_O$ are the primary conditions. I_0 is the stored current in the magnetizing inductor (I_m=nI_o) transferred to the secondary side. The coefficients A_1 and A_2 are determined by the primary conditions as:

$$A_1 = -A_2 = \frac{\omega_0^{\,2}}{-2\sqrt{\alpha^2 - \omega_0^{\,2}}} LI_0 \tag{14}$$

Now depending on the damping factor coefficient can have two different values:

$$\begin{gathered} \textit{Underdamped}\ \zeta < 1 \ \text{or}\ \alpha < w_0,\ \ \zeta = \frac{1}{2R}\sqrt{\frac{L}{C}} \\ |A_1| \cong \frac{I_0}{2}\sqrt{\frac{L}{C}} \end{gathered} \tag{15}$$

$$\text{Overdamped } \zeta > 1 \text{ or } \alpha > w_0$$

$$|A_1| \cong RI_0 \tag{16}$$

Equation (15) shows that if the circuit is in underdamped situation, then the generated voltage amplitude is independent of the load impedance, which is the situation where the proposed method is valid. But under overdamped condition as in (16), the output voltage amplitude depends on the load impedance and the initial current. Hence, in overdamped condition, the parallel connection has better performance.

IV. Simulation Results

To verify the proposed method and the theoretical analysis, simulations under different conditions were carried out. Here the performance of parallel and series flyback configurations (Fig. 3) is compared with a single flyback converter (Fig. 1). The software that was used for simulation was MATLAB 7.10. Table III shows the parameters value used in simulation corresponding to Fig. 1. In order to make the simulation results more close to reality, the transformer core and copper losses (R_c and R_w) are also considered.

To evaluate the proposed method in developing the features of a single module pulsed power supply, four distinct cases are considered. Case1 and 2 have been conducted regarding the conditions presented in Table I and II, respectively. In these cases, to simulate a plasma phenomenon, the load gets connected to the output after the output voltage reaches to a certain voltage level (threshold) [9]. The different parameters in each case are indicated in Table IV.

Like all other methods, the proposed method has its own drawbacks under certain conditions. These conditions, mentioned as operating conditions in the previous section, are considered in Case3 and 4. In Case3 the consequence of unsynchronized gate signals on the system performance is described. Finally, in Case4 the effect of damping factor on the generated pulses is examined. Except in Case 4 for all the other cases a 1kΩ resistor is selected as the load.

TABLE III. Simulation Parameters.

V_s (v)	F_s (kHz)	D (%)	L_m (µH)	L_{lp} (µH)	L_{ls} (mH)	R_c (kΩ)	$R_{w1,2}$ (Ω)	n
10	1	8.9	160	2	4	1	0.1	10

TABLE IV. Simulation Parameters in Case 1 and 2.

Parameters Value	Case1			Case2		
	Single	*Parallel*	*Series*	*Single*	*Parallel*	*Series*
Threshold	1000v	1000v	1978v	1000v	1410v	1410v
C_o	4nF	8nF	2nF	4nF	4nF	4nF
C_{o1}=C_{o2}		4nF	4nF		2nF	8nF

A. Case1

In this case the performance of parallel and series connections of two identical power supplies is compared with the single one. Therefore, in this case the output capacitor of each module is equal.

Regarding the capacitor value mentioned in Table IV, 4nF for each module, the equivalent capacitance of the series and parallel modules are equal to 2nF and 8nF, respectively. Fig. 5 shows the obtained output voltage waveform. As can be seen in the series connection, both voltage level and rate of rise are increased with the factor of N, (N=2 is considered here). This has been shown in the analysis of section III and Table I.

Regarding (2) and (11) the reflected voltage across the switches is about 110V for both parallel and series modules. This shows ability of the proposed method in generating high voltages with low voltage switches. So, it is possible to benefit from ultrafast switches, as switch operation speed increases when its hold-on voltage decreases.

As the rate of charging is in terms of a time constant RC; hence, as illustrated in the figure, series connection discharging time is shorter than the parallel and single modules.

B. Case2

If the load capacitance, which is paralleled with the power supply output, is much bigger than the power supply output capacitance, then the entire single, parallel and series modules will have the same equivalent output capacitance. In this case the output capacitance of all modules is considered to be equal to 4nF (see Table IV). As depicted in Fig. 6, both parallel and series modules have same voltage level but the parallel connection shows better performance in the case of dv/dt.

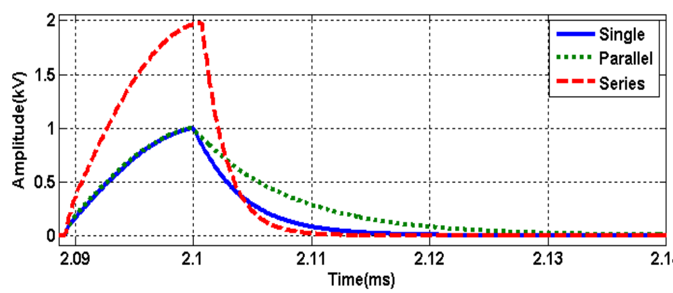

Figure 5. Output voltage waveform of single, parallel and series modules in Case1 (C_{o1}=C_{o2}=C_o).

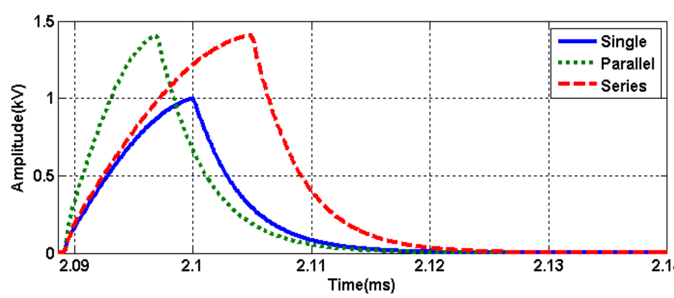

Figure 6. Output voltage waveform of single, parallel and series modules in Case2 (C_{op}=C_{os}=C_o).

C. Case3

Due to differences in semiconductor characteristics and the gate drive circuits, it is quite important to select identical devices and synchronize the gate signals. Here the same situation in Case2 is selected, but 0.2ms delay between gate signals is considered to show the effect. Fig. 7 shows the generated output voltage for parallel and series modules. As can be seen the output amplitude never reached to the threshold value. Therefore the load is not connected, so the capacitors are not completely discharged. This creates another problem since the entire energy in the magnetizing inductor is not fully transferred to the capacitor and the mentioned equations for estimating the output voltage are not valid.

D. Case4

In some applications, the load has low impedance like discharge plasmas in water [3]. In these cases damping factor plays important role in system performance as it discussed in part D of the previous section.

Here the series and parallel modules are considered, same as in Case1, but $R_L = 100\Omega$ is directly connected. This value puts the all three power supplies in the overdamped condition. As Fig. 8 illustrates the parallel modules show better performance, while series module had far better performance in Case1 when the system was underdamped. This means that all the mentioned features about parallel and series connections are valid when the system is underdamped (see (15)). The overdamping effect of the load can be seen as the output voltage levels are dropped tremendously compared to those in Case1. Because when the load resistance decreases, the time constant, $\tau=L/R$, increases, and hence the inductor energy is not completely transferred to the output capacitor. The easiest way to overcome this problem, considering ζ in (15), is increasing the output capacitance.

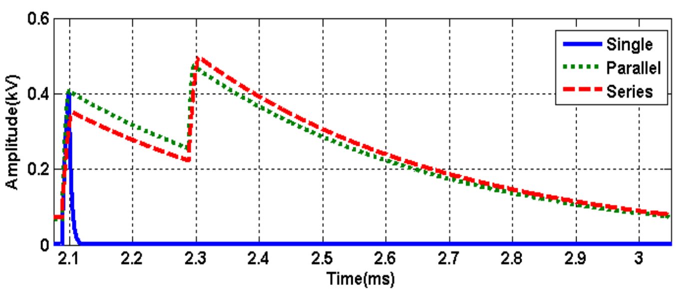

Figure 7. Output voltage waveform of single, parallel and series modules with 0.2ms delay between modules gate signals.

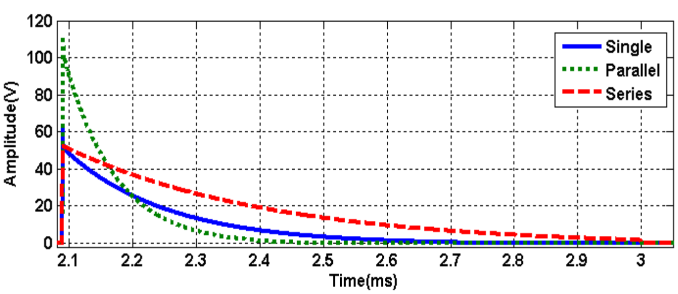

Figure 8. The effect of the load and the damping factor on the system performance.

V. Conclusion

This paper demonstrates the advantages of parallel and series configuration of flyback converters for pulsed power applications. The proposed method aims at increasing the voltage level and rise time of the generated pulses using conventional low voltage switches. In this method the flyback converter topology is employed as it shows beneficial characteristics especially for pulsed power applications. The proposed method is evaluated under different circumstances and obtained simulation results indicate the effectiveness of the approach.

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