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Review article

Review of solid-state linear transformer driver technology

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Abstract

This paper is a review of recent developments in solid-state linear transformer driver (SSLTD) for applications to pulsed power generation. It summarizes the technological advances reported by previous publications and interprets the experimental progresses. The application of solid-state LTDs has been proved to be an attractive approach to make compact and repetitive pulsed power generators that have been sought by a variety of industrial applications and scientific researches. Their advantages and disadvantages compared with their alternatives are reported and analyzed in this paper. Future technical trends of solid-state LTDs are also discussed.

PACS codes: 84.30.Ng; 84.30.Jc; 84.70.+p; 52.80.-s

Keywords: Pulsed power; High voltage; Power electronics; Power semiconductor; Discharge

1. Introduction

Power adding using linear transformer driver (LTD) is a relatively new scheme of pulsed power generation, which is an alternative to the traditional concept of pulse compression. The difference between them is illustrated in Fig. 1. Pulsed power generation based on pulse compression achieves high power of short pulse by reducing the time interval during which a certain amount of energy is released [1−8]. In contrast, an LTD generates pulsed power by adding many low-power short pulses together in order to reach the required output power.

An LTD-based pulsed power system consists of many circuit units, each of which is capable of generating a short pulse. The output pulses of all units are added with each other both current-wise and voltage-wise, leading to power multiplication and impedance conversion. The current adding is usually obtained by direct parallel connection while the voltage adding is typically realized by inductive accumulation. An example of LTD equivalent circuit is shown in Fig. 2. Each circuit unit consists of a capacitor and a switch. A number of such units (n units) are connected in parallel to form a module and a number of such modules (m modules) are added in series inductively to form the system. If a single unit can generate an output voltage of v and an output current of i, the output voltage and the output current of the whole system become mv and ni, respectively. Therefore, compared with that of a single unit, the output power of the system is multiplied by nm and the output impedance is converted with a factor of m/n.

The most noticeable advantages of an LTD scheme, over the traditional pulse compression scheme, are in its stress distribution and modular structure. In a pulse compression system, there must be an output switch which handles the peak power of the whole system. This switch usually determines the maximum output power, the repetition rate, and the lifetime, hence it is often seen as the bottleneck of the pulsed power generator. However, no such component is required by LTD, which indicates a theoretical potential of indefinite power adding of LTD systems. In addition, an LTD-based pulsed power generator consists of many identical modules, allowing

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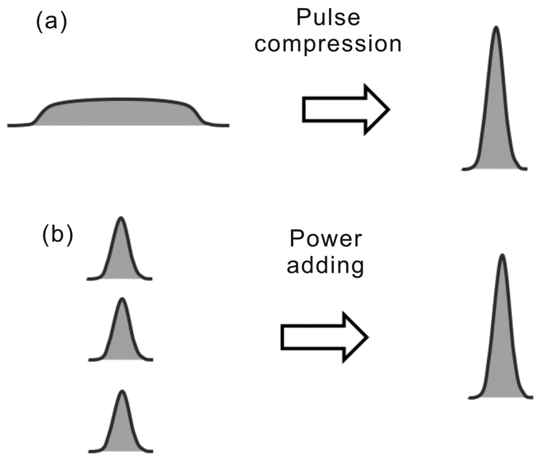

Fig. 1. Alternative pulsed power generation schemes, (a) pulse compression and (b) power adding using LTDs.

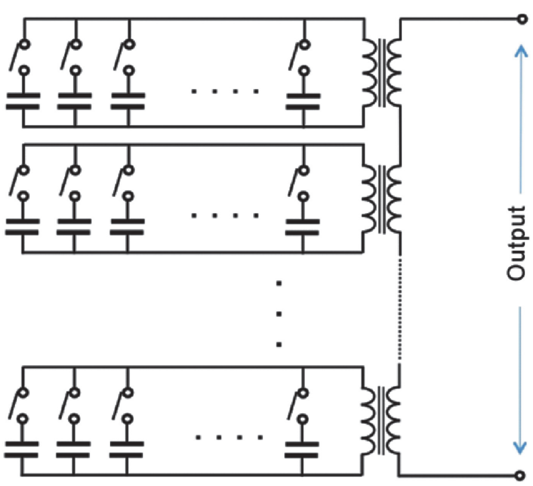

Fig. 2. Equivalent circuit of an LTD-based pulsed power generator.

the possibility of easy maintenance, module recycling, and user reconfiguration.

Large LTDs have been studied for many years for applications to particle accelerators and fusion-related researches [9−12]. These LTDs use spark gaps as switches so that a single module consisting of 40 units can drive a current as high as 1 MA. However, since a gap switch cannot be turned off, the typical output waveform is that of an RCL circuit and, in case of impedance matching, the output voltage is about half of the capacitor charging voltage.

Recently, solid-state LTDs using semiconductor power devices have also been developed [13−15]. They have been developed specifically for industrial applications, with an aim of replacing existing solid-state pulsed power generators based on other schemes. They are characterized by compactness and high repetition rate. In addition, since the semiconductor switches can be turned off, the output waveform to a resistive load can have a certain flatness and the peak output voltage can approach the charging voltage, if the capacitors are large enough. Furthermore, it has been proved that, if the switch timings of different modules are controlled separately, the output waveform can be shaped with a wide range of variation and variety [16,17].

This paper presents a review of recent solid-state LTD (SSLTD) research and development. It provides a relatively comprehensive description for the principle and circuit structure of SSLTD. It summarizes typical experimental efforts aimed at demonstrating SSLTD characteristics. In addition, it also discusses the future development issues and trends.

2. Basic principle and structure of SSLTD

The basic principle of an SSLTD is the same as that of large LTDs, except for the fact that the switches here can be turned off before the storage capacitors are completely discharged. In the SSLTD case, relatively large capacitors are usually used so that the RC circuit behavior dominates the discharge process instead of the RCL behavior in large LTDs. As a result, the output voltage of a module equals approximately the capacitor voltage and voltage droop during the pulse can be relatively small if the capacitance is large enough.

A typical module design is shown in Fig. 3. An LTD module consists of 24 circuit units. Each circuit unit consists of a film capacitor and a power MOSFET. The cross-sectional structure of the module is shown in Fig. 4 and its equivalent circuit is shown in Fig. 5. The essential operation principle is explained as follows.

The capacitors are initially charged up to a certain DC voltage. When the MOSFETs are turned on, the capacitors discharge in the circuit loop through the MOSFETs and the upper case of the module, as shown by the solid arrows in Fig. 5. At the same time, the large inductance of the magnetic core induces a secondary current in another circuit loop through the whole outer case containing the module and the load, as shown by the dashed arrows in Fig. 5. It is important to note that, for an ideal core, the primary and the secondary currents should be nearly identical and the net current through

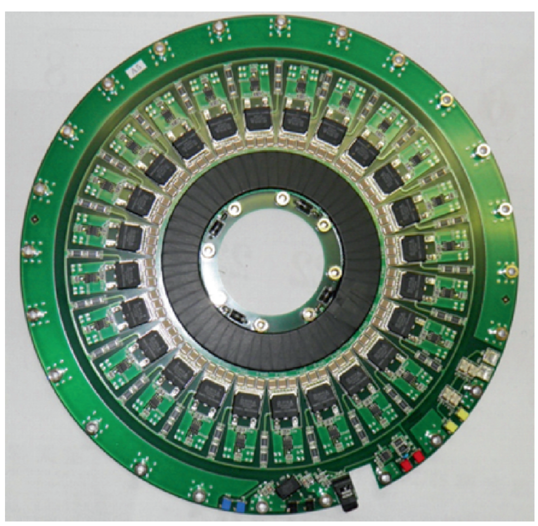

Fig. 3. An example of SSLTD module.

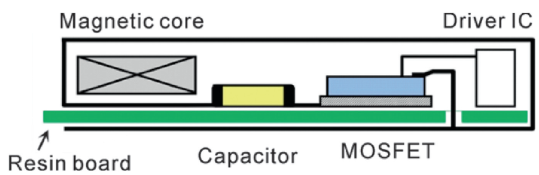

Fig. 4. Cross-sectional structure of solid-state LTD module.

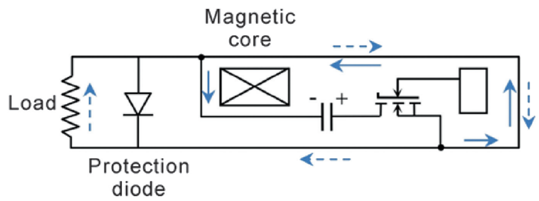

Fig. 5. Equivalent circuit of an SSLTD module. The solid and dashed arrows indicate the directions of primary and secondary currents respectively.

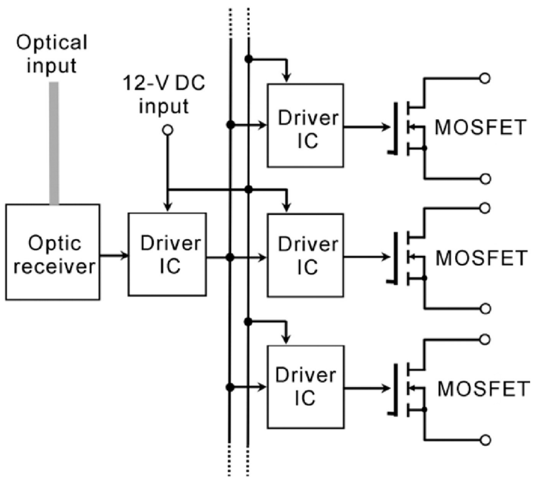

Fig. 6. Diagram of control-signal wiring on each LTD module.

the upper case can be negligible. Therefore, the circuit behavior in the LTD module functions as a 1:1 transformer which efficiently couples the capacitor discharge energy to the output. However, in real situations, the cores are not ideal and, consequently, there is always an issue of output efficiency.

After each pulse, the magnetic flux in the core has to be restored or the core will soon saturate in repetitive operation. We have used a separate winding carrying 2 A of DC current for this purpose.

Fig. 7. Pulsed power generator consisting of 30 solid-state LTD modules. The resistors on the top are dummy loads.

Other than the components mentioned above, an LTD module also contains the MOSFET control circuits as shown in Fig. 6. The switch on/off signal is received by an optical module and is then amplified by a driver IC, before being sent to all drivers of the MOSFETs. The original control signal is primarily binary (logical) while the driver output to the MOSFET gates has issues of rise-time and synchronization.

The circuit components used in the LTD module shown in Fig. 3 are listed in Table 1.

Many such LTD modules can be stacked together to achieve voltage adding as illustrated by Fig. 2. Fig. 7 shows an LTD system consisting of 30 modules. As can be seen from Fig. 4, each module has a conducting sheet (coating) on its bottom surface, so that, when they are stacked on top of each other, the bottom sheet of the upper module serves as the top cover for the module beneath it. Therefore, all module cases are connected to the ground, which is very convenient for charging, controlling, and noise shielding.

Table 1
Circuit components used in the SSLTD module.

Device	Manufacturer	Model	Specifications	Number per module
MOSFET	IXYS	IXFT6N100F	1000 V, 6 A (DC)	24
Driver IC	Microchip	MCP1407	4.5−18 V, 6 A	25
Capacitor	Murata	GRM55DR73A	1 kV, 100 nF	72
Magnetic core	Sichuan Liyuan Electronics	1K107	130 mm (outer dia.) 86 mm (inner dia.) 5 mm (thickness)	1
Optic module	Hitachi	DR9300	DC ~ 50 Mb/s	1
Diode	Vishay	UF5408	1000 V, 3 A (DC)	4

3. Typical operational behavior of SSLTD

All SSLTD modules are controlled through optical fibers. The control signals are generated by using an FPGA (Altera Cyclone IV). The timing sequence measurement results show that the total time delay from the FPGA to the MOSFETs is about 150 ns, mostly caused by the driver ICs. However, the jitter of the delay among all MOSFETs in each module is less than 2 ns.

For the system shown in Fig. 7, a total number of 720 MOSFETs are used. When switch-on signals are sent to all modules, an output voltage summing all 30 modules is applied to the load and, when switch-off signals are sent simultaneously, the load voltage drops to zero. The observed results are shown in Fig. 8, for different capacitor charging voltages. The rise and fall time of the load voltage shown in Fig. 8 were caused by many factors including circuit inductance, device response and its spread. The slight voltage drop during the pulse is caused by the voltage drop on the capacitor. The peak output voltage reached nearly 29 kV for capacitor charging of 1 kV. The peak current through the load resistor of 120 Ω reached ~240 A, approximately 10 A per device if the current was distributed uniformly.

The time interval between the switch on/off roughly defines the output pulse length. Fig. 9 shows the output voltage waveforms obtained with different time intervals, from 60 to 200 ns. The full width at half-maximum of the output voltage varied from ~50 to ~170 ns, limited by the system rise-time and the core saturation. In other words, the pulse cannot be shorter than the rise-time and cannot be longer than the core saturation.

A very important feature of the SSLTD is that it is not necessary to switch all modules at the same time. The diode that is seen parallel to the load in Fig. 5 is primarily for the protection of the switches, but it also plays the role of bypassing the circuit current in case the local module is not switched on. In other words, only the modules that are switched on contribute to the output voltage and, therefore, the output waveform can be arbitrarily shaped by properly switching on/off a large number of modules.

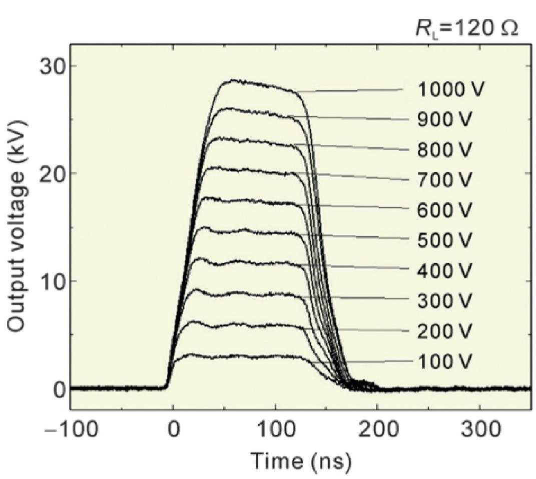

Fig. 8. Waveforms of output voltage obtained with different charging voltages, for control pulse length of 120 ns.

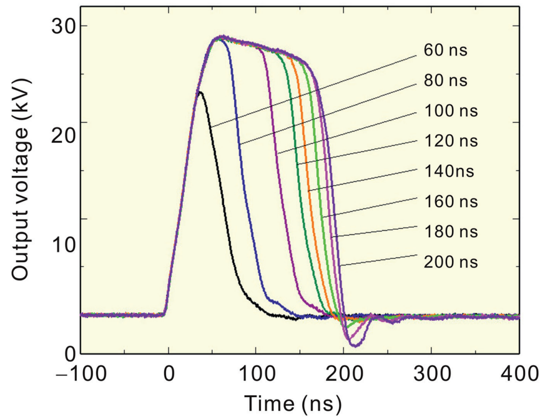

Fig. 9. Waveforms of output voltage obtained with different control pulse lengths, for the charging voltage of 1 kV.

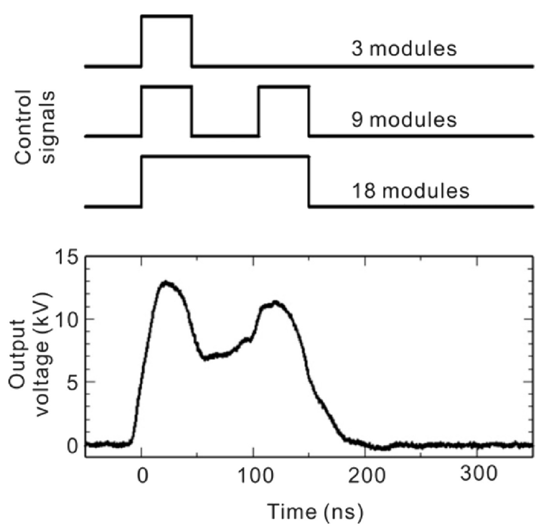

Fig. 10. Demonstration of waveform control by using SSLTD. The upper diagrams illustrate the control signals to different modules and the lower curve is the output voltage waveform.

Fig. 10 is an example of output pulse shaping carried out by using the LTD system described above. The upper diagrams illustrate the timing of the control signals and the lower waveform is the output voltage obtained on the load. An FPGA allows us to program the timing of each module and to change this timing from shot to shot. This method of output control enables a new approach to pulsed power generation, which was not feasible by previous technologies.

4. Comparative features and technical issues

SSLTD has undoubtedly been proved to be one of the technical approaches to compact and repetitive pulsed power generation which has found more and more industrial applications in recent years. However, its future depends on its advantages and disadvantages compared with other types of compact pulsed power sources.

There have already been many compact pulsed power supplies commercially available in a wide range of output parameters. The most popular scheme for solid-state pulsed power generation is the magnetic pulse compression (MPC). It was initially developed for pulsed laser pumping and thereafter extended to many other fields such as environmental protection and material modification [18,19]. MPC uses magnetic switch that can operate at repetition rate above kHz level, where spark-gap switches become incompetent. However, MPC belongs to traditional pulse compression category (see Fig. 1) so that it has limitations on modularity and flexibility. In addition, MPC requires intermediate energy storage that may result in relatively large volume and weight.

SSLTD is often compared with solid-state Marx, which is a recently developed method for solid-state pulsed power generators [20−23]. Both circuit methods can achieve vast voltage multiplication and use highly modularized structures. The difference is mainly on whether transformers are used or not. The transformers are the key components in LTDs. They separate the primary circuits from the secondary ones, allowing all modules to be grounded during operation. But the transformers may add inductance to the output loop and the saturation of the magnetic cores limit the output pulse length. In Marx circuits, there are no transformers. The voltage adding is achieved by direct connection of capacitors in series, resulting in different electrical potential of different modules. This fact may lead to problems in insulation management especially for very high voltage cases. But getting rid of the magnetic cores has a lot of advantages in weight, cost, and pulse length. Generally, SSLTDs are more suitable for short pulse output to relatively low impedance load and the Marx system has advantages for cases of relatively long pulse and high impedance.

The pulse-length limitation of LTD is unavoidably caused by the core saturation. For a given operation voltage, the maximum pulse length is proportional to the cross-section area of the magnetic core. Longer pulse requires larger (heavier) cores and this is why LTD is more suitable for short-pulse generation. Magnetic-flux restoration is also necessary in order to avoid core saturation in repetitive operation.

In addition, hysteresis loss occurs in ferromagnetic cores. It depends very much on the material and geometry of the core. For a given magnetic core, the loss is determined by the voltage waveform so that it can be regarded as a leakage resistor connected parallel to the load [11]. Therefore, the lower the load impedance is, the higher the LTD output efficiency becomes. This is why LTD is more suitable for low-impedance load. For the SSLTD system reported in this paper, the core loss dominates the energy consumption in the generator, and it is much higher than the switching loss caused by the MOSFETs.

5. Summary and future trend

This paper has revisited the recent technical developments of SSLTD. Following the remarkable advances recently achieved on large LTDs, the compact and repetitive LTDs based on solid-state switches have also been investigated for the purpose of industrial applications. From the pulsed-power technological point of view, the progress in the small LTDs are equally significant as that in the large ones.

The development of SSLTD technology will continue in the future. The research subjects are expected to be on circuit configuration, device combination, and control method.

Bipolar output will be a very interesting direction for the development of SSLTD circuit configuration. There are many applications that require bipolar high voltage pulses. Bipolar-Marx circuits have been studied and developed in recent years. The modular structure of LTD apparently allows independent control and output of different modules, which, in principle, could provide a relatively easy technical approach to bipolar output from a single stack.

An SSLTD system may use hundreds or even thousands of switching devices. From the cost/performance point of view, these devices do not have to be of the same model. In other words, depending on the load requirement, we can use a combination of different types of switching devices. For example, a gas-discharge load may require a relatively fast voltage rise followed by a relatively high current pulse. In this case, an LTD system consisting of modules using fast switching devices (such as MOSFETs) and high-current devices (such as IGBTs) should be more suitable compared with that using only one type of switches. Another possible combination would be that of silicon devices and silicon-carbide devices.

SSLTD control scenario is still at the beginning for exploration. It covers a wide range of challenges in waveform shaping and feedback response. Because each module of an SSLTD system can be controlled independently, and all controlled signals are delivered through optical fibers, the LTD control can be carried out electronically instead of electrically. Therefore, by using the most up-to-date electronic technologies, the SSLTD control can become more flexible, reliable and smart.

Conflict of interest

The authors declare that there is no conflicts of interest.

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