Power Electronic Pulse Generators for Water Treatment Application

A Review

Guo, Xiaoqiang; Zheng, Dongpo; Blaabjerg, Frede

Published in:
I E E E Transactions on Power Electronics

DOI (link to publication from Publisher):
10.1109/TPEL.2020.2976145

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

Power Electronic Pulse Generators for Water Treatment Application: A Review

Xiaoqiang Guo, *Senior Member, IEEE,* Dongpo Zheng, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*- Water treatment is one of the most important issues for all walks of life around the world. Different from the conventional water treatment technology, the advanced power electronic pulse technology has unique features and advantages for the modern water treatment. Unfortunately, there is no literature reported to describe them in a comprehensive and systematic way. To fill this gap, an overview of modern power electronic pulse generators (PPGs) for water treatment is presented. This paper, for the first time, classifies the different types of PPGs from the viewpoint of pulse formation. Each of them is discussed, and the advantages and disadvantages are compared and summarized. Aside from that, this paper presents the development and trend of the pulse generators suitable for the specified water treatment processes such as electrolysis, sterilization, and discharge degradation. Finally, a list of more than 100 relevant technical papers is also appended for a quick reference.**

***Index terms*: power electronic pulse generator (PPG), electrolysis, sterilization, water treatment, discharge degradation**

Nomenclature

BL– Blumlein Line
CDVM – Capacitor-Diode Voltage Multipliers
CES – Capacitive Energy Storage
EC – Electro- Coagulation
EF – Electro-Flotation
HV – High Voltage
IES – Inductive Energy Storage
MBL – Multilevel Blumlein-Line
MMC – Modular Multilevel Converter
MPC –Magnetic Pulse Compressor
MS – Magnetic Switch
PEF –Pulse Electric Field
PFL – Pulse Forming Line
PFN – Pulse Forming Network
PPG – Power Pulse Generators
PPVM – Parallel-Parallel Voltage Multiplier
PT – Pulse Transformer
SOS – Semiconductor Open Switch
SSVM – Series-Series Voltage Multiplier
SPVM – Series-Parallel Voltage Multiplier

I. INTRODUCTION

Water treatment has become an urgent and significant environmental protection project around the world. The traditional water treatment methods mainly use a chemical therapy to sterilize or degrade insoluble substances, but often produce by-products which are harmful to humans, animals and plants during the treatment. Also, chemotherapy is not able to degrade certain organic matters. The recent research reveals that power electronic pulses can achieve the sterilization and organic degradation, meanwhile not produce the harmful substances [1-5]. The unique advantages of the power electronic pulses in water treatment make it attractive and promising in practical applications. Therefore, the PPG for water treatment engineering receives more and more attentions in both academic and industrial fields. In this paper, the PPGs applied in different water treatment technologies (electrolytic treatment, pulse electric field (PEF) treatment and pulse discharge treatment) are discussed and summarized. Before discussing PPGs, it is necessary to introduce their application background.

The earliest application of power electronic pulses in wastewater treatment is electrolysis, electrolysis, which is a low-voltage high-current process technique. It has many advantages, especially the simple implementation of electrolytic equipment. It can be divided into electro-coagulation (EC) and electro-flotation (EF), and their operating parameters (reactor design, current density, time and electrode type and arrangement) have impacts on these processes [6]. Among the electrochemical processes, the EC process is the best choice. It can achieve a satisfactory removal, and its process is cost-effective. Typically, the EC uses the iron as the anode. Under the action of direct current, the anode of iron is continuously dissolved, and the ferrous ions produce the precipitation of ferrous hydroxide and ferric hydroxide in a weakly alkaline and neutral medium. Both of these deposits act as flocculants to remove the inorganic and organic contaminants. Because the electrical conductivity of waste water has an impact on the treatment process of electrolysis, it is generally applicable to saline wastewater. Nowadays, as a relatively mature technique for water treatment, electrolysis is common used to deal with the wastewater containing cyanide and chromium. The typical application is the treatment of printing and dyeing wastewater, tannery wastewater, papermaking wastewater and so on [7, 8].

The PEF is a relatively new water treatment technology. The PEF across the water to be purified can cause irreversible electroporation of cells to achieve water sterilization. It is superior to the heat or radiation treatment. And it prevents the electrodes from being electrolyzed due to the use of a PEF instead of a continuous electric field [9, 10]. The PEF sterilization has been developed for a long time and has been mostly used in the disinfection of liquid food (such as juice, milk, etc.) since the 1960s. In the 1980s, Hflsheger and Zimmermann developed an experimental equipment to investigate the mechanism of sterilization [11, 12]. And they attempt to use the PEF sterilization technology for industrial production. In the 90's, with the development of power electronics, a new type of pulse electric field sterilization

X. Guo, D. Zheng are with the Department of Electrical Engineering, Yanshan University, 066004, China, (email: yeduming@163.com).
Frede Blaabjerg is with the Department of Energy Technology, Aalborg University, Aalborg DK-9220, Denmark.

equipment is developed. The researchers start to investigate the bactericidal effect of a variety of pulses (exponential decay pulse, square pulse wave, oscillation pulse, etc.) and put forward more sterilization mechanism. By the end of 2000, PEF technology is used for commercial applications. In 2001, the Diversified Technologies, Inc in the United States developed the first industrial PEF sterilizing equipment [13]. After that, the PEF technology is commercialized in food sterilization and water treatment. But the high cost of the high-voltage pulse equipment limits the practical application of PEF technology in water treatment at that time [14]. So the research of PEF pulse power generator is important.

Basically, the PEF can only kill microorganisms in the water. However, the organic matter is difficult to degrade in the waste water in practice. The strong pulse discharge in water can degrade these insoluble organic matters. The pulse discharge in water generates many active species which are the Ozone and OH radical, ultraviolet rays and shock wave[15, 16]. All of them can rapidly and non-selectively degrades the organic compounds in wastewaters into the smaller and less toxic organic compounds, even inorganic compounds. Simultaneously these active radicals are able to destroy the harmful wastewater ingredient [17-20]. The main forms of discharge for wastewater treatment are the gas discharge, underwater discharge and water-gas mixed discharge [21, 22]. The gas discharge mainly occurs on the surface of the liquid. It is easy to form the plasma in the gas discharge device, and there is no electrode corrosion problem. But the plasma region and the active radicals are far away from the target and the treatment is uneven. The water-gas mixed discharge requires a very complicated reactor, which can generate non-equilibrium plasma in the gas on the water surface and corona discharge in water [21]. In [23], it is concluded that the water-gas discharge is better than the gas discharge, while the voltage of the water-gas discharge is lower than the voltage of underwater discharge. There are two main forms of underwater discharge, namely pulse streamer and pulse arc discharge. The characteristics of these two different forms are listed in Table I [24]. In the streamer discharge process, the decomposition of water is impossible. And the streamer does not propagate to another electrode due to the large resistance of water. The water resistance can be considered constant and the value of water conductivity depends on the amount of dissolved salt. Table II shows the conductivity of different types of water [25]. However, The arc discharge creates a conductive channel between two electrodes, which generates a high current (higher than 1 kA) to make water broken down [26]. The arc discharge requires a lot of energy, but its sterilization and degradation of organic matter is the best. Although the instantaneous pulse energy of the streamer discharge is less than the arc discharge, it is able to kill the bacteria and other microorganisms, and degrade organic matter [27].

Based on the abovementioned techniques, the topologies of PPGs used in water treatment will be summarized and discussed. First of all, the features of PPGs in water treatment are briefly introduced in section II. In order to help the readers clearly understand the PPGs for water treatment, the categorization and analysis of PPGs are presented in section III. To obtain the most suitable PPGs solution for the specified water treatment, the PPGs applied in three kinds of water treatment (electrolysis, sterilization, and discharge degradation) are discussed in section IV. Finally, the conclusions are drawn in section V.

II. Features of Water Treatment PPGs

The PPGs in water treatment is similar to the general pulse power generators. It consists of a DC voltage source, an energy storage unit, a pulse forming unit and a load, as shown in Fig. 1. The parameters to evaluate the PPGs performance generally include the output voltage, rising time, pulse width, fall time, repetition rate, peak power and average power. In water treatment applications, the PPGs with long life, high reliability and repeatability are needed. In this section, several important features of PPGs in water treatment will be discussed.

TABLE I
CHARACTERISTICS OF PULSE STREAMER AND ARC DISCHARGE.

Parameter	pulse streamer	Pulse arc
Pulse frequency	10^2 - 10^3 Hz	10^{-2} - 10^{-3} Hz
Pulse voltage magnitude	10^4 - 10^6 V	10^3 - 10^4 V
Load current magnitude	10 - 10^2 A	10^3 - 10^4 A
Rise time	10^{-7} - 10^{-9} s	10^{-5} - 10^{-6} s
Pressure wave generator	Weak to moderate	Strong
Pulse energy	~1 J	~1 kJ

TABLE II
CONDUCTIVITY OF DIFFERENT TYPE OF WATER

Water type	Conductively
Distilled water	1us/cm
Tap water	100-500us/cm
Sea water	>10000us/cm

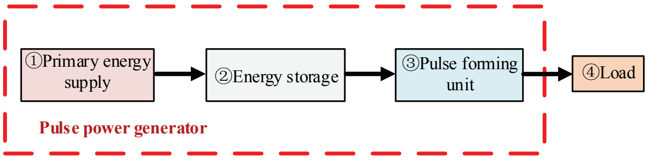


Fig. 1. The PPGs system diagram in water treatment

A. Storage unit

The energy storage unit is generally divided into two forms, one is the inductive energy storage (IES), and the other is the capacitive energy storage (CES). In general, the energy storage density of an inductor is several tens of times that of a capacitor [28]. Although the capacitor's energy storage density is not as high as the inductor, the high-voltage capacitor is still the main energy storage device of most PPG systems. This is because many of the switches used in the capacitor store PPGs are relatively stable, repeatable, and fast. While there are few switches that can be used in the inductance store PPGs. In addition, the IES circuit could output higher voltage than that of the CES circuit, but its energy efficiency was lower than that of the CES circuit. However, the IES circuit realized the higher output voltage and the high energy transfer efficiency by the adjustment of the load impedance [29].

B. Switch

The switch is a vital device for PPGs in water treatment, and its performance directly affects the reliability of the PPG and its pulse output characteristics. The switches of the PPG in water treatment often have gas switches, semiconductor switches, and magnetic switches. The gas switch is usually spark gap switch that is not only suitable for high power pulses, but also triggered more accurately [30-32]. However, it has the disadvantages of complicated design, high cost and short service life. The magnetic switch is often used in MPC PPGs [33-35]. It utilizes the inductance saturation characteristics to achieve switching state changes, so they have certain advantages in high power, high repetition rate and long life. However, it has the disadvantage that the core must be reset and the loss of magnetic material is large. Semiconductor switches used in water treatment PPG typically have thyristors, IGBTs, and semiconductor open-circuit switches. Thyristors and IGBTs are controllable devices with high reliability, long life and simple control, which greatly improve the performance of PPGs [36, 37]. The semiconductor open-circuit switch (SOS) is a diode with a very short reverse recovery time. It is generally used in the IES circuit, and acts as an open switch that cuts off currents of tens of kA [38]. Fortunately, with the advent of wide-band semiconductor devices, the performance of solid-state PPGs using them has been further improved, and it has become a trend in the development of water treatment PPGs [39-41].

C. Load

The water to be treated is the load of the PPGs. Its circuit model can be represented as a resistive load in parallel with the capacitor[4]. The value of this resistance depends on the conductivity of the water, i.e., on the amount of salt dissolved in the water, and the capacitance depends on the relative dielectric constant of water, which is about 81. In water treatment, the electrical equivalent circuit depends on the conductivity of the water. And when the capacitance is very small, it can be ignored. Their load model is shown in Fig. 2. Among the three types of water treatment, the load of arc discharge type water treatment is special. It needs to simulate the breakdown process by adding a parallel branch that consists of an arc resistor in series with the switch. When the switch is closed, the total resistance seen by the load is approximately equal to the arc resistance.

D. Reactor

Electrolytic water treatment and PEF water treatment require only two plates (anode plate and cathode plate, respectively) without a reactor. Pulse discharge water treatment requires a more complicated reactor. Further, the structure of the reactor module was investigated. The main reactors are 3 types, i.e., discharge on the water surface, discharge in bubbles in water, and water droplets spray into discharge space in gas. The water droplets spray type is the highest energy efficiency [29], but itis extremely complicated, and its structure is shown in Fig. 3.

III. Categories of Water Treatment PPGs

The pulse forming unit is the core of the PPG, which directly determines the output characteristics of the PPG. The water treatment environment is more complicated, so it is necessary to study the PPG for water treatment from the pulse formation, and explore the PPGs of different water treatments. In this section, the PPGs for water treatment will be divided into two types according to the pulse formation method for the first time, which are called classical PPGs and solid-state PPGs, as shown in Fig. 4. In following subsections, the details of each class of PPGs for water treatment will be discussed and compared.

A. Classical Generator

1. Chopper circuit

The chopper circuit that is a PPG for capacitor storage, is the simplest way to achieve high-voltage pulses [42, 43]. The basic chopper circuit is shown in Fig. 5. It boosts the alternating current through a transformer, then obtains the high-voltage DC through a rectifier and then charges a large-capacity capacitor. Finally, a high-voltage switch is used to generate a high-voltage pulse. When a PPG requires a relatively large energy pulse, such as from several hundred joules to several tens of thousands of joules, it generally uses multiple capacitors in parallel operation. The gas switches are commonly used in switching devices for chopper circuits[44]. It is suitable for conducting high-current, large-charge pulses and can also accurately trigger. However, it has poor reliability and short life. It directly affects the life

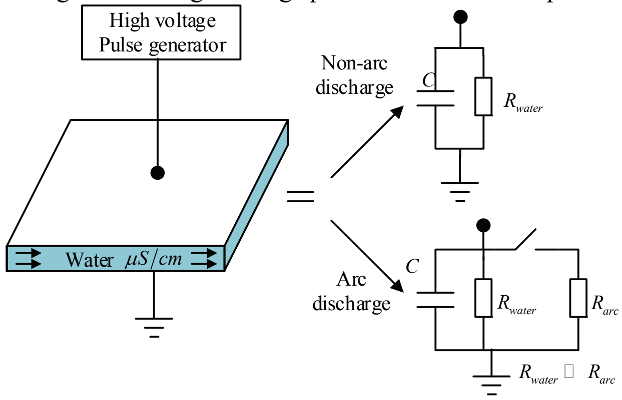


Fig. 2. Electrical equivalent circuit of the water sample in different treatment methods

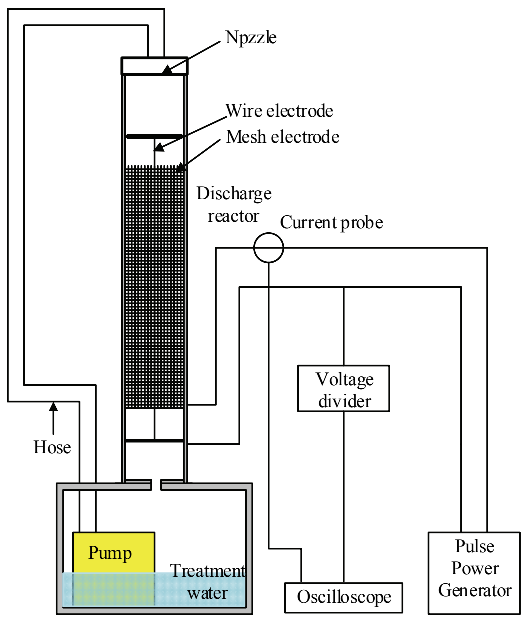


Fig. 3 Reactor for the water treatment using pulsed discharge generated in air by spraying water droplets

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

and reliability of PPGs. In addition, the circuit is bulky because it contains transformers. Although this type of PPG has become unsuitable because of too many shortcomings, its mechanism still permeates other PPGs.

2. Marx generator

The Marx generator, invented by Erwin Marx in 1924 [45], is a capacitive storage PPG. Fig. 6 shows the circuit diagram of a simple Marx generator. The basic principle of the Marx generator is that: at the beginning, the switch is not triggered, the capacitors are charged in parallel, then they are connected in series to discharging across the load, creating the required high-voltage (HV) pulse. As a result, the amplitude of the

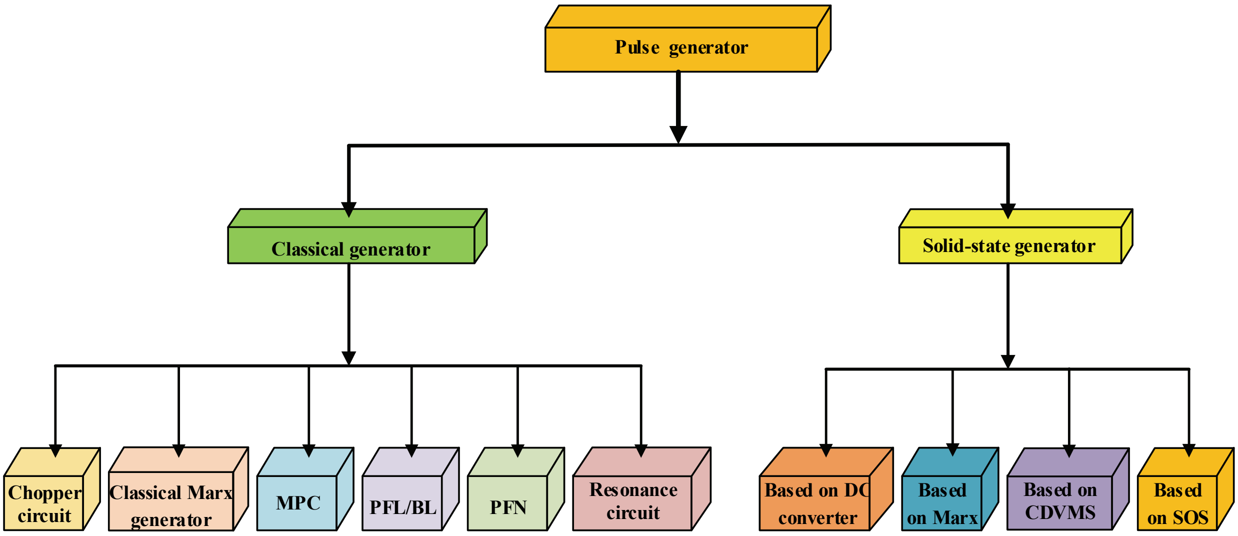


Fig. 4. Categorization of pulse power generator

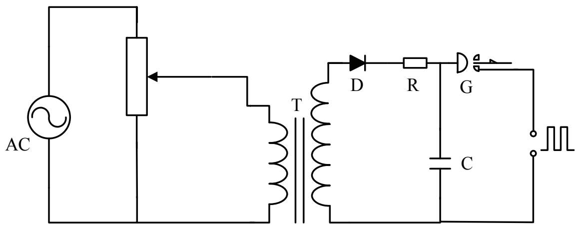


Fig. 5. The PPG based chopped circuit

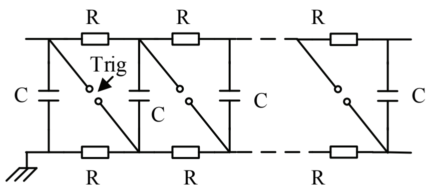


Fig. 6. The circuit diagram of a simple Marx generator.

output voltage is the product of the capacitor voltage and the number of capacitors. The spark gap switch is often used in this circuit. But because the spark gap switch is easily damaged, the reliability of the traditional Marx generator is poor. In addition, traditional Marx circuits are bulky. However, semiconductor switching devices have the advantages of flexible and convenient control, reliability, and small size, many researchers have applied them to Marx circuits, greatly improving the performance of Marx generators [1, 2, 45]. After that, the idea of charging the capacitors in parallel mode and discharging in series mode has been widely used.

3. MPC converter

The MPC converter was invented in 1951 and applied to a 13kV pulse width of 250ns radar power supply [46]. Due to its advantages such as high repetition rate, high power and long lifetime, the MPC system has been extensively researched and developed in the last decades [47-51]. The magnetic switch (MS) is a key component of the pulse formation in the MPC system. The switch performance directly affects the characteristics of the pulse. The magnetic switch with a high repetition rate, high power, and high reliability has been developed in the 20th century. And its high-speed switching features enable it to enhance the performance and development of the MPC system [52].

Fig. 7(a) is a circuit diagram of an n-stage MPC, where each stage consists of a storage capacitor and a magnetic switch. When the capacitor starts to be charged, the magnetic core coil has a large inductance, and the magnetic switch is open. When the core saturates due to the leakage current flowing through the coil, its inductance drops to the initial value $1/\mu$, where μ is the relative permeability of the core material. This change makes the magnetic switch closed. At this moment, a large current flows through the magnetic switch and the current is amplified. This process is shown in Fig. 7(b). Obviously, the saturated and unsaturated states of the MS act as the on and off states of the switch. In order to efficiently transmit energy, the energy transfer time of the (n-1)th stage should be equal to the saturation time of the magnetic switch core of the (n)th stage. The following equation is the energy transfer time of each stage.

$$t = \pi\sqrt{L_{sn} \times C_n} \tag{1}$$

$$\tau = \frac{2 \times \Delta B \times A \times N}{V_p} \tag{2}$$

where L_{sn} is the saturation inductance of the (n)th MS , and C_n is the capacitance of the (n)th stage. ΔB is the difference between the saturation magnetic flux and the remnant flux, A is the cross-sectional area of the magnetic material, N is the number of turns of the MS, and V_p is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

the maximum input voltage to the magnetic switch.

Although it has many advantages, high repeatability, high reliability and high power, it has its own limitations. Due to the loss of the magnetic switch, the loss of the MPC system increases as the number of cascades of circuit increases, thereby reducing overall efficiency. In addition, because the output pulse width is related to the capacitance and magnetic switching parameters of the circuit, the generated pulse width is fixed. In order to improve the performance, the new MPC system is developed by removing the external

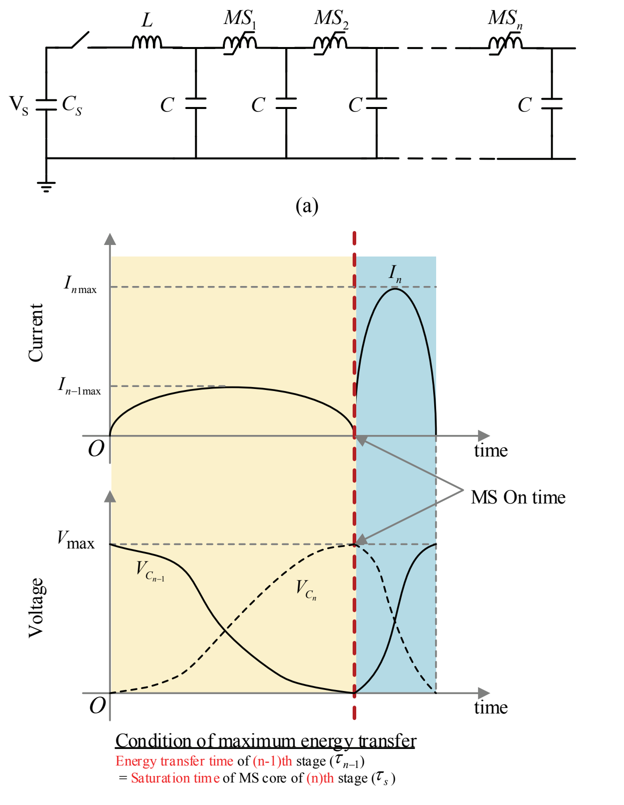


Fig. 7. Schematic of MPC. (a) The basic circuit of n-stage MPC. (b) Ideal concept design.

degaussing circuits [53]. Also, the adjustable magnetic switch in [54] is developed to further enhance the performance of the MPC system.

4. Pulse forming line (PFL) and Blumlein line (BL)

The PFL is an important method to generate the short pulses. It is widely used to generate high power pulses of 1-10^2 ns pulse width [55]. It is based on two characteristics for generating high voltage nanosecond pulses. Firstly, under certain conditions, the pulses can be easily transmitted along the transmission line. Secondly, the impedance of a transmission line is often Ohm level within the appropriate load or transmission time, resulting in the loss of the transmission line with smaller. In practical applications, the PFL generators often use the coaxial or ribbon transmission lines, where the coaxial line is usually water and oil as an insulation medium.

The basic parameters of the transmission line are inductance of per unit length L_0 and capacitance of per unit length C_0, characteristic impedance Z, and wave velocity v. Fig. 8(a) is the schematic diagram of PFL with a single transmission line. S is the main switch, and R is the load. When the characteristic impedance and the load impedance match perfectly, i.e. $R = Z$, the pulse width of $\tau = 2l/v$ can be obtained at load, where l is the length of the transmission line, and $v = 1/\sqrt{L_0 C_0}$. If the loss on the transmission line is not taken into account, the pulse amplitude is only half of the charge voltage $U_o/2$. In practice, the impedance should be

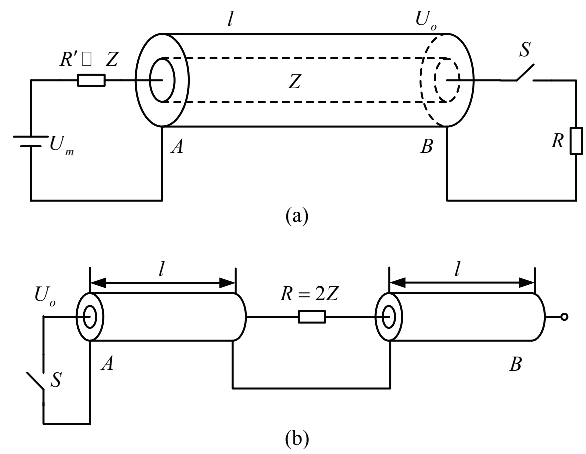


Fig. 8. Schematics of PFL and BL. (a) PFL (b) BL.

matched perfectly for operation with high performance.

In order to solve the technical limitation of the PFL, which only generates a pulse whose amplitude is only half of the charge voltage, the BL was proposed in 1948. It is a series connection of two same single transmission lines, which can produce pulses with an amplitude equal to the input voltage value. The schematic is shown in Fig. 8(b). Its impedance exactly matches, e.g. $R = 2Z$, and the generated pulse width is $\tau = 2l/v$ [56, 57].

The shape of the output pulse of the Blumlein transmission line is closely related to the quality of the switch S. Therefore, in order to obtain a rectangular pulse, the limitation of the switch should be taken into account. In practical applications, the high voltage laser switches with short rise time, low resistance, and low inductance are used. In practical applications, the impedance is difficult to match completely because the load impedance may vary, especially the impedance of the sewage. In addition, the pulse width is related to the circuit parameters, so the pulse width is not able to be flexibly adjusted. In order to solve the technical issue, the PPGs based on the multilevel Blumlein-line (MBL) is proposed to reduce the size and increases the power density, as well as the flexibility [56, 58].

5. Pulse forming network (PFN)

As for generating rectangular pulses with the pulse width greater than 500 ns, the above-mentioned PFL is not suitable anymore. In this case, the PFN is a choice. It is essentially an open-ended PFL consisting of discrete capacitance and inductance. Fig. 9 shows a simple PFN circuit, where the values of each capacitor and each inductor are equal, i.e. $C_1 = C_2 = C_3 = \cdots = C_n$, $L_1 = L_2 = L_3 = \cdots = L_n$. For an n-stage PFN, its pulse width is $\tau = 2n\sqrt{LC}$, and the characteristic impedance is $Z_0 = \sqrt{L/C}$ [59-61]. L and C denote the inductance and capacitance of each cell. The rising time and falling time of the matched load pulse can be

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

estimated as [62].

$$\tau_{rise} = 0.8\sqrt{LC} \quad (3)$$

$$\tau_{fall} = 0.8\sqrt{nLC} \quad (4)$$

The advantages of the PFN are the limited stored energy and simple structure. A typical application is the PFN-Marx

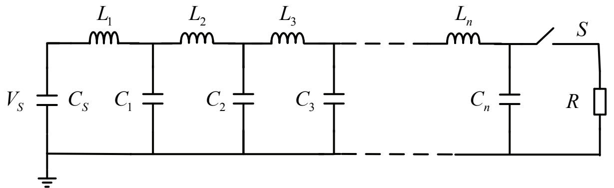


Fig. 9. Schematic of the PFN

generator [63]. However, their drawbacks, such as the poor pulse quality, fixed pulse width and narrow range of the load impedance, limit their applications [64]. Similar to BPFL, in order to overcome the shortcomings of PFN, which is the output voltage pulse amplitude is only half of the input voltage, BPFN was also found.

6. Dual resonant circuit

Basically, the dual resonant circuit is equivalent to a dual resonant transformer[65]. It does not use magnetic cores and is also named as the Tesla transformer [66]. Fig. 10 shows the Tesla transformer circuit. It has two coils. The outer coil is the primary coil L_1, and the inner coil is the secondary coil L_2. The coupling coefficient is k. The primary coil is connected to a capacitor C_1, and the secondary coil is connected to a capacitor C_2. When the loop parameter satisfies the double-resonance condition $1/\sqrt{L_1C_1} = 1/\sqrt{L_2C_2}$, a dual resonance occurs in the circuit, and the secondary can output a high-frequency voltage with high amplitude. Because it uses the circuit resonance to generate the required microsecond pulses, it can operate at different voltages as long as it is properly tuned. In addition, compared with the Marx generator, its structure is compact and the operation stability is relatively good because there is only one switch connected to the primary of the Tesla transformer. It is suitable for small and medium power PPG with a frequency of no more than 1000Hz. In addition, due to energy loss and inaccurate tuning, the output voltage is actually less than the design value. It also has some problems. The circuit is difficult to achieve. The pulse width is also related to the circuit parameters and is difficult to adjust.

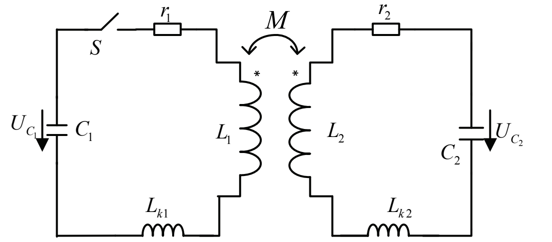


Fig. 10. Dual resonant circuit

B. Solid-state PPG

The solid-state PPG is using solid-state switches to generate specified pulses. It has features such as small size, high repeatability, long lifetime and high reliability. Therefore, it has been widely used in pulse circuits. The solid-state switches include transistor, diode, MOSFET, IGBT, semiconductor open switch (SOS), and so on. Compared with the classical PPG, the solid-state PPG design and control are flexible and convenient. The following will present the general structure and feature of these kinds of PPGs.

1. Based on DC converter

A DC converter is required during the pulse generation process. There are two forms of converting direct current into pulses. One is to apply a single switch or multiple switches in series to generate a pulse by chopping, as shown in Fig. 11(a), but it can only produce unipolar pulses. The other is the H-bridge circuit, which can produce both unipolar and bipolar pulses as shown in Fig. 11(b). In water treatment applications such as electrolysis, it requires low-voltage high-current pulses. However, some applications require high voltage pulses. The high voltage PPG has a boosting section. So high-voltage PPGs have two types of transformer and transformerless.

1) With transformer. The high voltage transformer plays an important role in the field of power pulse technology. The transformer is used to amplify low-voltage pulses. Therefore, it is called as the pulse transformer (PT) [67]. Fig. 11(c) is the PPG with a PT. Since the voltage rating of the semiconductor switch is small relative to the pulse amplitude,

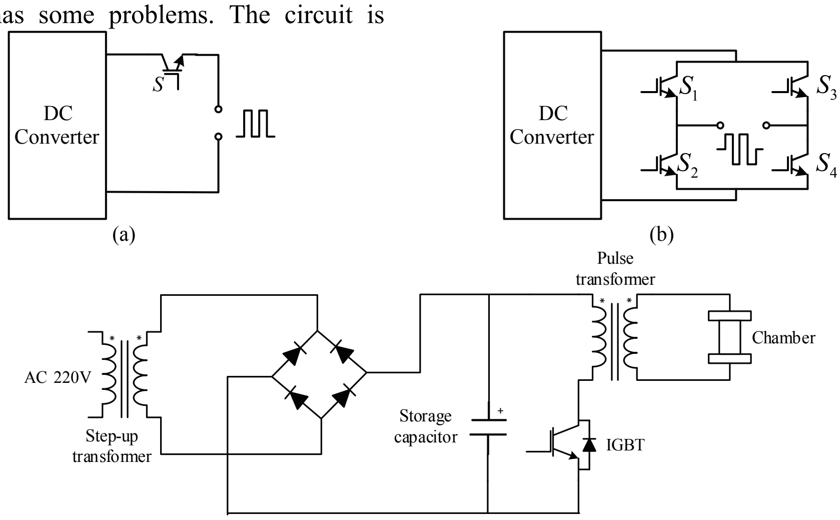


Fig. 11. PPGs based on DC converter. (a) The unipolar PPG. (b) The bipolar PPG. (c) The unipolar PPG with a PT.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

the switch is generally placed in the low-voltage side of the transformer. However, in practice, the leakage inductance and distributed capacitance of the PT affect the pulse waveform [68, 69]. Also, the PT increases the size and weight of the PPG system. Therefore, there is a tradeoff among the cost, weight, pulse waveform, and so on.

2). Without transformer. The step-up converter is needed to generate the high voltage pulse without transformers. The boost and buck-boost converter presented in [55-57] is used to generate the high voltage pulse, as shown in Fig 12. In Fig. 12(a), the circuit is composed of n-stage boost cells connected in series [70]. The input voltage is amplified every time it passes through a boost cell. Finally, the high voltage DC is converted to the required pulse by a high voltage switch. Since the entire circuit does not require a transformer, its size and weight are small. However, the stress of the switch at the latter stage is greater than that of the previous one, and the stress of the last switch is close to the required pulse amplitude. So the voltage rating of the switch will limit the pulse voltage amplitude. If the switches are applied in series in this circuit, it will require a large number of switches, and has to deal with the voltage balance problem, resulting in a complicated control. The circuit in Fig. 12(b) is evolved from a buck-boost converter [71, 72]. Its operation is similar to the buck-boost circuit. First, S_s is turned on, the low voltage power supply charges the inductor, and then S_s turns off and S_i turns on. The inductor charges the capacitor C_i. Then S_L turns on and the capacitor discharges the load. The advantage of this circuit is that both S_s and S_i are low-voltage switches. The capacitors and diodes ensure the voltage balance of the switch S_i and it can be modularized. But it needs a high voltage switch to generate pulses.

The PPG based boost converter with capacitor-diode voltage multipliers (CDVMs) is shown in Fig. 12(c-d). it has two types of circuit topologies based on boost-CDVMs [73]. One of them is that the CDVM fed from the DC-DC boost converter from one end while the load is connected to the other end as shown in Fig. 12(c), and it is used in [74]. Another is that the CDVM centrally fed from the DC-DC boost converter while the load is connected across the CDVM ends as shown in Fig. 12(d), and it provides lower stresses on the CDVM components. The latter is used in [67] for water treatment sterilization. The DC-DC booster converter is in the middle of CDVMs to supply the power. It improves the heat loss distribution by reducing the current variation in each stage of the CDVM. And the proportional integral (PI) controller is used to control the duty cycle to track a certain reference voltage. The output voltage can be expressed as

$$V_{out} = (2m+1)V_b = \frac{2m+1}{1-D_b}V_{dc} \qquad (5)$$

where V_{out} is the output voltage, V_b is the output voltage of the boost circuit, m is the number of the CDVMs, D_b is the duty cycle of the boost circuit, V_{dc} is the input voltage. The advantages of this circuit are lightweight, efficient, reliable and modular. But it also has drawbacks. It requires a high voltage switch. And the pulse repetition rate is limited by the charging time of the capacitor. In summary, Table III lists the features of PPGs based on DC converters.

TABLE III
FEATURES OF PPGS BASED ON DC CONVERTERS

Category	Topology	Features
With transformer	Fig. 11(c)	• With transformer and a DC power. • High power • Bulky
Without transformer	Boost array Fig. 12(a)	• Need a high-voltage switch and a DC power. • Small and medium power • Voltage rating of switches and capacitors increase step by step
	Buck-boost array Fig. 12(b)	• Need a high-voltage switch and a DC power. • Small and medium power • Voltage rating of switches and capacitors is the same • But the ratio of step-up is not high
	Boost-CDVMs Fig. 12(c-d)	• Need a high-voltage switch and a DC power. • Light • Small and medium power • Voltage rating of switches and capacitors is the same • High ratio of step-up

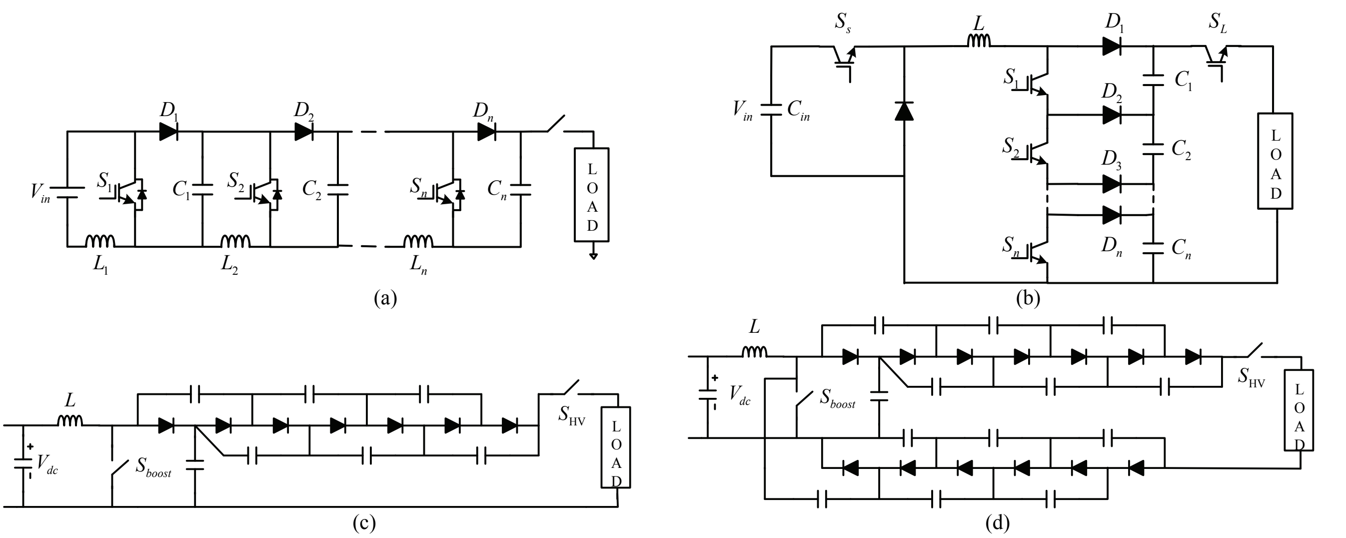


Fig. 12. PPGs based DC converter without transformer. (a) Multilevel boost converter.(b) Multilevel buck-boost converter (c) The first PPG based boost converter with capacitor-diode voltage multipliers (d)The second PPG based boost converter with capacitor-diode voltage multipliers

2. Based on capacitor-diode voltage multipliers (CDVM)

The typical capacitor-diode voltage multipliers are shown in Fig. 13. As shown in Fig. 13(a), it can be used to generate the high voltage, while in Fig. 13(b), it can generate a high current [75]. Many PPGs can be obtained by slightly changing circuit topologies in Fig. 13(a) and Fig. 13(b), which are shown below.

Fig. 13(c) shows the PPG as an n-stage topology of series-parallel voltage multiplier (SPVM) [75]. In this circuit, when T_{Ci} is turned on and T_{pi} is turned off, the ac power supply charges all the capacitors. In positive (negative) half a cycle, odd (even) diodes are in forward bias and lower (upper) capacitors will be charged. When T_{pi} is turned on and T_{Ci} is turned off, the odd capacitors are connected to each other through T_{pi} and discharge to the load. Therefore, output voltage can be solved as follows.

$$V_o = V_{in} + 3V_{in} + 5V_{in} + \cdots + nV_{in} = \left(\frac{n+1}{2}\right)^2 V_{in} \quad (6)$$

where n is odd. In this circuit, the voltage of the switch is equal to the corresponding capacitor voltage and increases step by step. Therefore, this circuit has a disadvantage that each odd capacitor and each switch have different voltage stresses, making it difficult to be modularized. And as the stage of the capacitor-diode increases, the stresses of the capacitors and switches will increase.

Fig. 13(d) shows the PPG as an n-stage topology of parallel-parallel voltage multiplier (PPVM) [76]. In the circuit, all capacitors discharge the load. The output voltage is expressed as follows.

$$V_o = V_{in} + 2V_{in} + 3V_{in} + \cdots + nV_{in} = \frac{n(n+1)}{2} V_{in} \quad (7)$$

where n is the odd index of last stage capacitor. The number of switches increases as the output voltage rises. Similar to the SPVM PPG, the rated voltage and rated current of the switches in each stage of the circuit are different. And it is also not suitable for the modular design. In order to solve the technical issue, the modular solution is presented in [63], as shown in Fig. 13(e). The amplitude of the output pulse is the sum of voltages of the odd capacitors.

$$V_o = 1V_{in} + 3V_{in} + 4\times(2n-3)V_{in} = 8(n-1)V_{in} \quad (8)$$

Compared with the solutions in Fig. 13(c) and Fig. 13(d), the topology in Fig. 13(e) reduces the stress of capacitors and switches at the cost of additional switches.

Fig. 13(f) shows the PPG as an n-stage circuit topology of series-series voltage multiplier (SSVM) [76]. It needn't a high voltage switch. In this circuit, each odd capacitor is parallel to one controllable switch, and they are connected by two diodes which solves the problem of switches voltage balance. When the switch S_i turns off, the capacitor is charged, and when S_i turn on, the odd capacitors discharge in series to the load. The repetition rate of the pulse is the switching frequency. For most switches and capacitors, their voltages are equal. Therefore, it is easy to achieve modularity. However, the number of switches and cost will increase as the output voltage rises.

An interesting solution is presented in [64], as shown in Fig. 13(g). It is an improved version of the circuit in Fig. 13(f). The output voltage is:

$$V_o = V_{in} + 2V_{in} + 2V_{in} + \cdots + 2V_{in} = (2n-1)V_{in} \quad (7)$$

where n is the odd index of last stage capacitor.

It can be easily found that the voltage of capacitors C_1 and switch S_1 is V_{in}, while the other capacitors and switches voltage are $2V_{in}$. So it is easy to achieve modularity. Through careful observation of the circuit in Fig. 13(g), it can be seen that the subunit circuit can be simplified and the diode removed, as shown in Fig. 13(h). Its operating rules are the same as those in Fig. 13(g). However, the number of switches and cost will increase as the output voltage rises. The pulse repetition rate is limited by the charging time of the capacitor, the number of cascades, and the turn-on and turn-off time of the switching device. Therefore, it is not suitable for pulses of ns and ps levels. It should be noted that an appropriate high frequency ac power supply is needed to reduce the charging time of the capacitor. Table IV presents a comparison of PPGs based on CDVM.

TABLE IV
COMPARISON OF PPGS BASED ON CAPACITOR-DIODE VOLTAGE MULTIPLIERS

	Voltage Gain Ratio(V_{out}/V_{in})	No. of Switches	Switch voltage	No of diode	Diode voltage	Minimum charging time
Converter in Fig.13(c)	$\left(\frac{n+1}{2}\right)^2$, (n is odd)	2n	(1,3,5,7 $\cdots$ n) V_{in}	n	1V_{in} and 2 V_{in} (NO.n-1)	n half cycle
Converter in Fig.13(d)	$\frac{n(n+1)}{2}$, (n is a natural number)	2n	(1,3,5,7 $\cdots$ n) V_{in}	n	(2,2,3,4,5 $\cdots$ n) V_{in}	n half cycle
Converter in Fig.13(e)	$8(n-1)$, (n is a natural number)	$\frac{(n-1)}{2}+(n-3)$	1 V_{in}, 2 V_{in}, 3 V_{in}, and 4 V_{in} (No. n-3)	n	2 V_{in} (No.n-1) and 4 V_{in} (the last one)	n half cycle
Converter in Fig.13(f)	$2n-1$, (n is a natural number)	$\frac{n+1}{2}$	1 V_{in} and 2 V_{in} (No. n-1)	n	2 V_{in} (NO. n)	n half cycle
Converter in Fig.13(g)	$2n-1$ (n is odd)	2n	1 V_{in} and 2 V_{in} (No. n-1)	n	2 V_{in} (NO. n)	n half cycle
Converter in Fig.13(h)	$2n-1$, (n is natural number)	2n	1 V_{in} and 2 V_{in} (No. n-1)	n	2 V_{in} (NO. n)	n half cycle

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

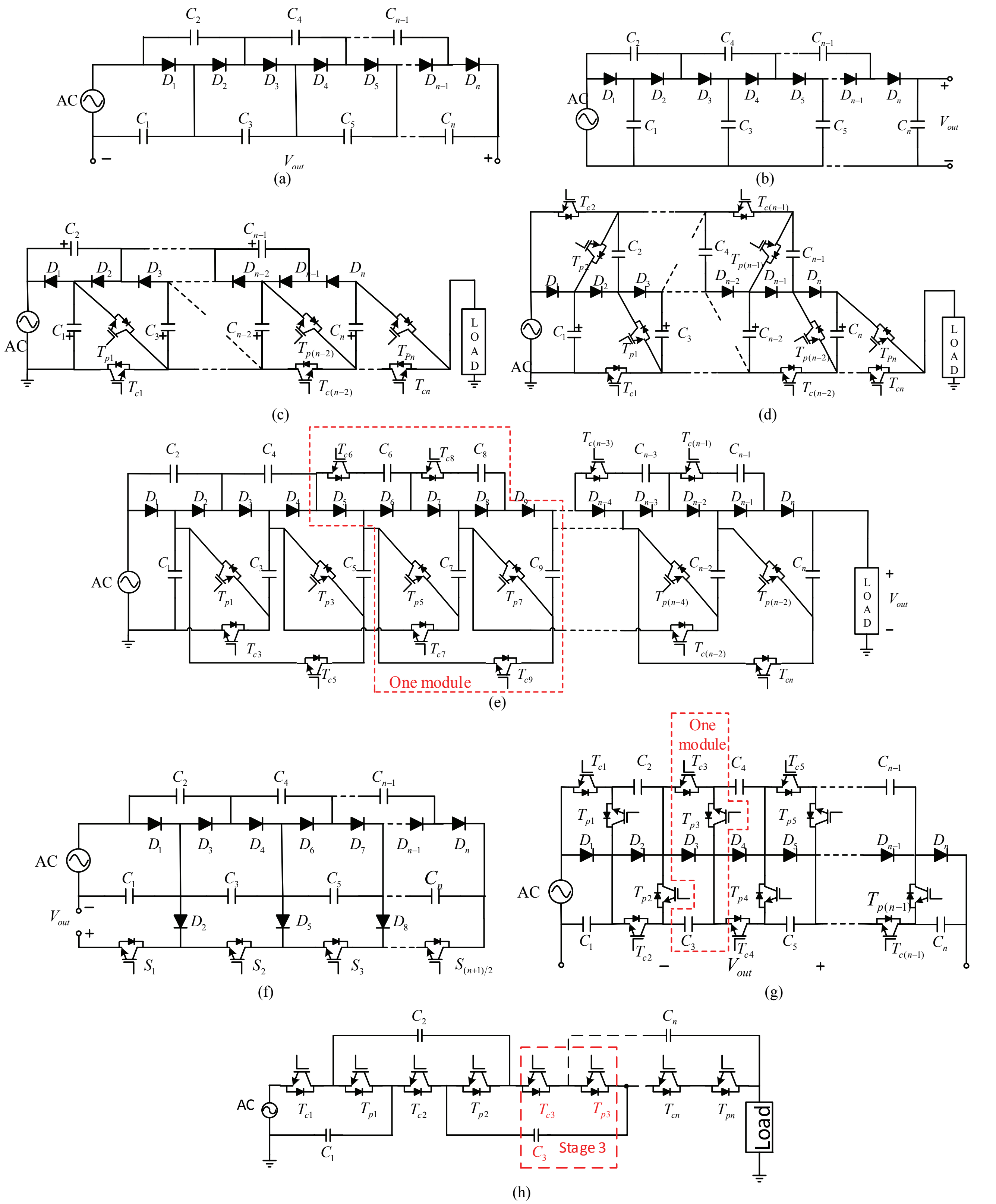


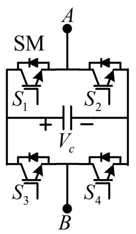
Fig.13. PPGs based on CDVM. (a) The first CDVM topology. (b) The second CDVM topology. (c) The PPG of series-parallel voltage multiplier. (d) The PPG of Parallel-Parallel voltage multiplier (PPVM). (e) The n-stage modulation SPVM circuit topology. (f) The PPG of series-series voltage multiplier (SSVM). (g) The improved topology of the circuit in (f). (h) The simplified topology of the circuit in (g).

3. Based on Marx generator

The solid-state Marx generators with controllable semiconductor switches have the advantages of small size, light weight, high reliability, simple control, and modularization, which overcome the technical limitation of conventional Marx generators [77]. Therefore, it is attractive for the PPG. Its principle is that the capacitors are charged in parallel, and then connected in series to produce high voltage pulses [78-82]. In practice, the solid-state Marx generators is a modular multilevel converter (MMC) which is composed of a large number of submodules which is composed of switches and capacitors. The sub-modules (SM) have two types. One is the full-bridge structure, as shown in Fig. 14(a). The other is the half-bridge structure, as shown in Fig. 14(b).

Fig. 15(a) shows a high voltage PPG [83] based on MMC with full-bridge SM is proposed, which can generate unipolar or bipolar high-voltage pulses with different shapes. Each full-bridge SM consists of four low-voltage switches and a capacitor. The generator is supplied with a low voltage DC through a series limiting resistor. The input voltage can be connected or disconnected to the circuit by the switch. Each module has four states, and they are charging, bypassing, discharging in the positive direction and discharging in the negative direction, as shown in Fig. 15(b) to (e). During the charging process, the capacitors are charged sequentially from the input DC supply through an external limiting resistor which is used to limit the inrush current. In general, the i_{th} capacitor is charged when the i_{th} sub-module (SM) operates in charging mode, as shown in Fig. 15(b) and (d), while the other sub-modules are switched to the bypass mode in Fig. 15(c) and (d). During the charging process, the load resistance is bypassed by the thyristor. When all the capacitors have been charged, the rectangular pulse can be generated by switches.

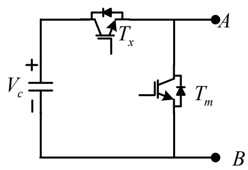
Basically, the MMC PPGs can be divided into two categories. One is the PPG with high-voltage DC input, and the other is the PPG with low-voltage DC input. For the former, the voltage stress on the circuit is high, and it needs to balance the capacitor voltage in each modular by many sensors. The improved solution to balancing without sensors can be found in Fig. 16. The circuit in Fig. 16(a) has two MMC bridge arms, one is a series arm, and the other is a parallel arm[84]. In addition, a diode is connected in series between adjacent SMs in each bridge arm to balance the capacitor voltage in each module. Fig. 16(b) also shows a MMC PPG without sensors [85]. The circuit has two MMC bridge arms. Each bridge arm consists of n SMs and a charging inductor. The circuit is simple in structure and can realize unipolar and bipolar pulses of different shapes. The circuit mainly uses phase disposition (PD) modulation to achieve the voltage balance. The idea of phase disposition modulation is to determine whether the SM in the bridge arm is inserted or idled by comparing the output reference pulse and carrier.



SM switching table

S_1	S_2	S_3	S_4	State
ON	OFF	OFF	ON	Charging
ON	OFF	ON	OFF	Bypassed
OFF	ON	OFF	ON	Bypassed
ON	OFF	OFF	ON	Positive discharging
OFF	ON	ON	OFF	Negative discharging

(a)



SM switching table

T_m	T_x	State
ON	OFF	Bypassed
OFF	ON	Inserted
OFF	OFF	Idle

(b)

Fig. 14. Sub-modules structure (a) Full-bridge. (b) Half-bridge.

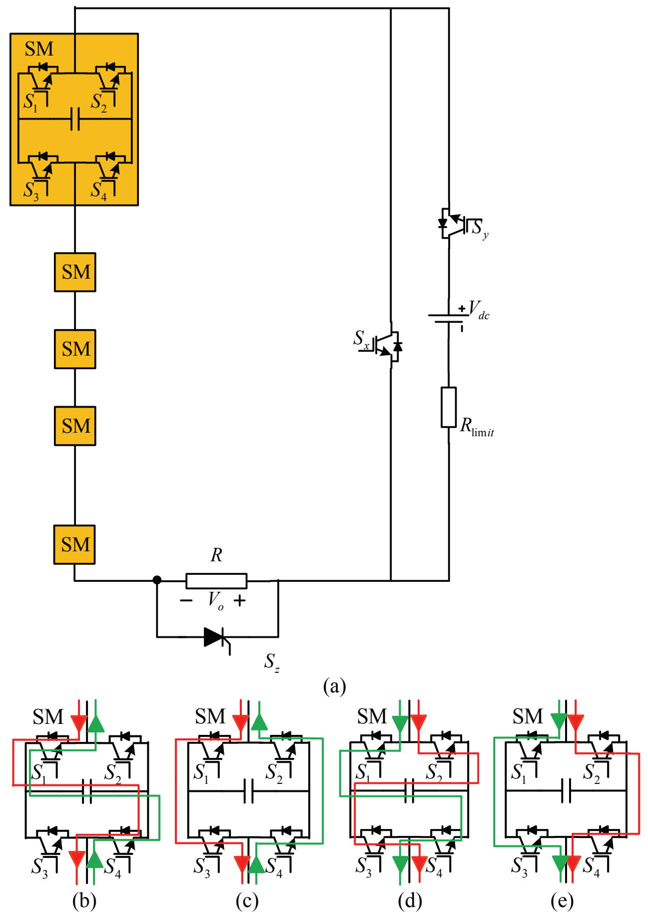


Fig.15. High voltage PPG based on full-bridge module (a) Schematic. (b) Positive Charging mode (red line) or positive discharging mode (green line). (c) Positive bypass mode during charging process (red line) or positive bypass mode during discharging process (green line). (e) Negative Charging mode (red line) or negative discharging mode (green line). (d) Negative bypass mode during charging process (red line) or Negative bypass mode during discharging process (green line).

The circuit in Fig 16(c) is an H-bridge MMC (HB-MMC) [86]. When positive pulses is generated, the bridge arm 1 and the bridge arm 2 are bypassed, and the bridge arm 3 and the bridge arm 4 are inserted. When negative pulses is generated, the bridge arm 1 and the bridge arm 3 are bypassed, and the bridge arm 2 and the bridge arm 4 are inserted. The SM in each MMC bridge arm is simultaneously turned on/off. Therefore, all switches in the MMC bridge arm share the input voltage. The cell capacitor clamps the switch voltage and enforces a symmetrical series voltage distribution. Although this circuit utilizes the full voltage of the input and can operate when an SM is damaged, it requires a large number of switching devices.

Fig.17 shows the low-voltage DC PPGs. Their structures are similar, and there is no voltage balance problem for these circuits. Its operation principle is that the capacitors are charged sequentially, and then discharges in series to generate a pulse. The charging voltage of every capacitor is the supply voltage. The circuit in Fig.17 (a) can only produce the unipolar pulses [3]. The circuit in Fig. 17 (b) require two high voltage switches to connect the power supply and the upper or lower legs, charging the positive MMC arm or the negative MMC arm [2]. The circuit in Fig. 17(c) requires four low-voltage switches to switch the charging and discharging processes [87]. But it also requires two high voltage thyristors to bypass the load when the power supply charges the capacitor. All of them have a common drawback, that is, due to the low input voltage, the charging time becomes longer when the charging resistance is larger so that the pulse repetition rate will be reduced. The capacitor charging time limits the pulse repetition rate and the number of cascades. However, charging time can be reduced to a certain extent by adding an inductance in the charging circuit and making the charging process underdamped. Table V presents the differences of the PPGs based on Marx circuit described in this subsection.

4. Based on semiconductor open switch (SOS)

The semiconductor open switch is also called SOS diode [88]. It has a high current capacity and high voltage rating, and cuts off the current in nanoseconds [89]. It can be scaled up or down to cover a wide range of operating voltages. It is generally used in the PPGs based on IES to cut off the large currents generated by energy storage inductors. The PPGs based on SOS can repeatedly generate 50 kV, tens of kA, nanoseconds pulses. It includes a primary capacitive store with a thyristor switch, a magnetic compressor and an SOS

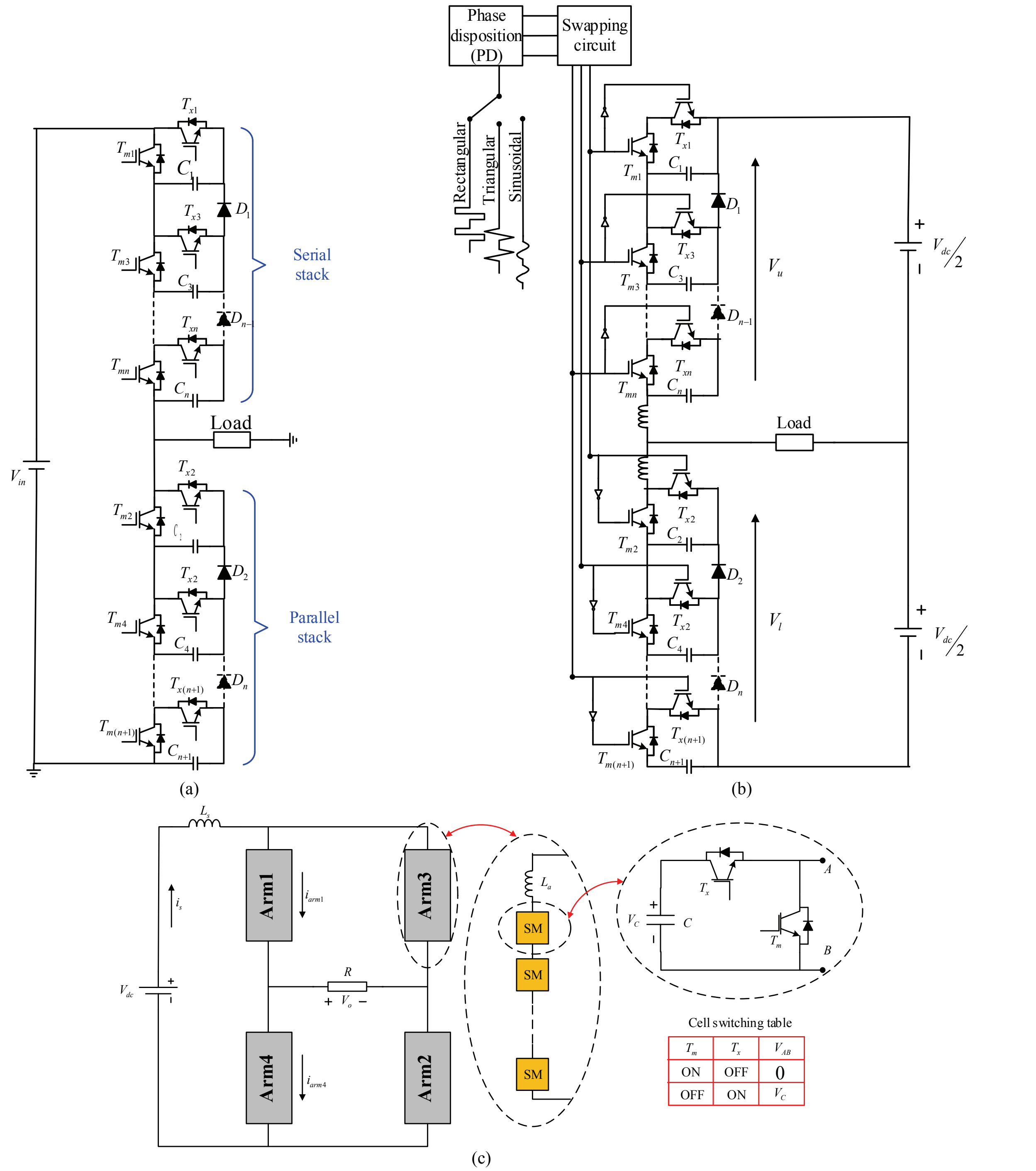


Fig. 16. Solid Marx PPGs with sensorless voltage balancing technique. (a) n-stage MMC-based PPG with diodes (b) n-stage MMC-based PPG with PD control. (c) improved topology[86].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

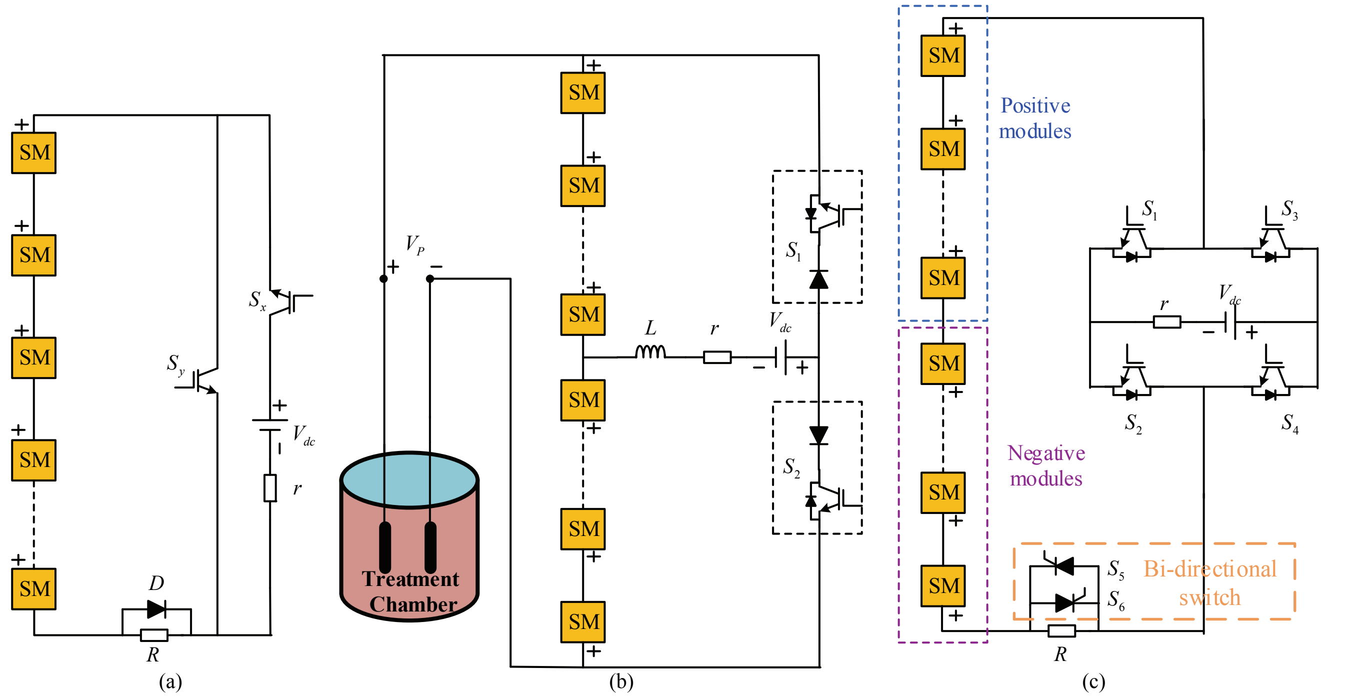


Fig. 17. Solid Marx PPGs based on the low-voltage DC

TABLE V
THE DIFFERENCES OF THE PPGS BASED ON MMC

Feature	High voltage PPG based on MMC						
	LVDC				HVDC		
	Fig. 17(a)	Fig. 17(c)	Fig. 17(b)	Fig. 15	Fig. 16(a)	Fig. 16(c)	Fig. 16(b)
Structure	HB-SM	HB-SM	HB-SM	FB-SM	HB-SM	HB-SM	HB-SM
Polarity	unipolar	bipolar	bipolar	bipolar	Unipolar /bipolar	bipolar	bipolar
Forming pulse	Capacitors is charged in sequence and then discharge in series				Capacitors is charged and discharge in series	PD algorithm	
Capacitor voltage balancing control	Not required and Attained automatically				Required and sensorless		
Auxiliary switch	Two HV switches and one HV diode	Four LV switches and two HV thyristors	Two HV switches	Two HV switches and one HV thyristors	Voltage balancing diodes are needed between adjacent SMs	Needless	Needless
Repetition rate flexibility	Limited by SMs charging time				Limited by ac input frequency and number of converter stages.	Controlled by switch frequency	Limited by number of converter stages.
Operation under failure	Possible, but the output pulse-peak is reduced by the number of failed SMs. No extra voltage stress are expected					Possible without affecting the output pulse peak, but voltage stresses of other SM increases	Its operation deteriorates when one SM is damaged.

diode. The magnetic compressor is required to compress the energy in time since the characteristic time of transmitting the energy through the thyristor is 10-100 us, while the forward pumping time should be no longer than 30-400 ns at the units current density of kA/cm^2. But the largest energy loss of the circuit is the magnetic compressor. For this reason, the overall efficiency of the SOS generator is generally around 40% [89]. It has been shown that a microsecond regime of the SOS pumping can be implemented and the number of the magnetic compressor sections can be reduced

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

by decreasing the current density[90]. And its efficiency can reaches 70%.

The PPG with SOS is shown in Fig. 18 [91]. When the initial switch is turned on, the capacitor C_0, which is initially charged to V_{dc} by the high-voltage DC power supply, discharges through the loop of C_0-L_0-PT-C_1, resulting in C_1 charging at a voltage boosted by the PT. The magnetic switch MS_1 saturates at C_1 maximum voltage, then C_1 discharges through the C_1-MS1-L_1-C_2-SOS loop, resulting in C_2 charging and SOS forward current. Magnetic switch MS2 saturates at the time of maximum C_2 voltage, allowing C_2 to discharge through loop C_2-MS2-L_2-SOS, resulting in SOS reverse current. At the reverse current peak, the SOS diode suddenly recovers, and the inductive stored energy at L_2 and MS2 is released into the load.

In summary, it can be concluded that traditional PPGs such as Marx generators, MPC, PFL, PFN, and Dual resonant circuit are relatively bulky, inflexible, inefficient, and have poor reliability. While the solid-state PPGs are lightweight, flexible, reliable, and efficient. Some of them can be modularized and attractive for high repetition rate, flexibility, and intelligence. For the long pulses or low power aspects, the solid-state generator has its unique advantages. In practice, a suitable PPG should be selected and designed according to the specific requirement in Table.VI.

IV. PPGs FOR WATER TREATMENT APPLICATION

The prospect of PPG application in water treatment is very good, but from the current market research and academic research, it is still in an immature stage. Among the three water treatment applications, the pulsed electrolysis water treatment technology is relatively mature. And there are different voltage, current and power level pulse generator products on the market for electrolytic water treatment. The PEF water treatment and pulse discharge water treatment has a complicated mechanism and a relatively high voltage and power level. At present, PEF is mostly used in liquid foods, and its products used in water treatment are few, and a large number of reports are only present in academic research. Water discharges are also in the research stage of major companies and academic institutions. But their recent research results are worthy of our research and study. It can be obtained from the results that have been studied that the pulse width, amplitude, and repetition rate of the PPGs in the water treatment are different due to different water treatment environments. From the current research results, the PPG in water treatment is only used in a certain application as shown in Fig. 19. In general, the voltage power levels discussed will be used to demonstrate the characteristics of different PPGs in related applications of water treatment.

A. *Electrolysis for wastewater treatment application*

The electrolysis wastewater treatment is based on the electrochemical reaction. It generally requires large currents to provide the free electrons to undergo redox reactions. Therefore, the PPG used in electrolysis is required to be able to generate high current and high power. Meanwhile, its pulse width and the frequency are adjustable. Fig. 20 shows the basic principle of PPG for the electrolytic water. Fig. 21 shows the circuit for the PPG of electrolysis [92]. The electrical indicators of the electrolytic PPGs for water treatment on the market are currently almost the same, their output voltages are adjustable from a few volts to several hundred volts, and the current is adjustable from a few amps to several hundred thousand amps, and pulse frequency is tens Hz to 100kHz, and the pulse width is adjustable, and they can work at around 90% efficiency.

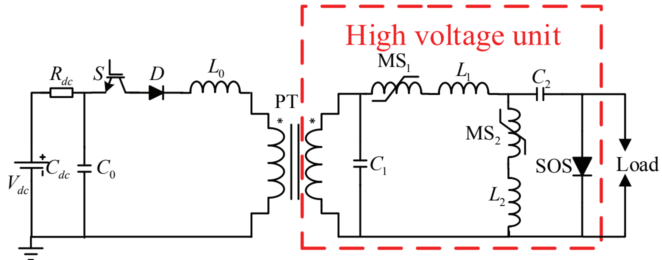


Fig. 18 The PPG based on SOS.

TABLE VI
SUMMARY OF MAIN CHARACTERISTICS OF CLASSICAL PPGS

		Structure	Polarity	Switch	Repetition rate	Pulse width	Reliable	Power	Lifetime
Classical generator	Chopper circuit	Sample But bulky	Unipolar/ bipolar	Spark gaps / gap switch	Small	us	Poor	High	Short
	Marx circuit	Complexity bulky	Unipolar/ bipolar	Gap switch	Small	us	Poor	High	Short
	MPC	Complexity bulky	Unipolar	Spark gaps/ thyristor	Small	ps/ns	Good	High	Long
	PFL/ BL	Complexity bulky	Unipolar	Spark gaps/ thyristor	Small	ns	Poor	High	Short
	PFN/ BPFN	Complexity bulky	Unipolar	Spark gaps/ thyristor	Small	ns/ps	Poor	High	Short
	The dual resonant	Complexity bulky	Bipolar	Thyristor	Larger	ps/us	Good	High	Short
Solid generator	Based on DC converter	Complexity lightness	Unipolar/ bipolar	Thyristor/ MOSFET/ IGBT	Largest	us	Very good	Low	Longer
	CDVM	Sample /lightness	Unipolar/ bipolar	MOSFET/ IGBT	Largest	us	Very good	Low	Longer
	Solid Marx	Sample /lightness	Unipolar/ bipolar	IGBT	Larger	us	Very good	Low	Longer
	SOS	Complex /bulky	Unipolar	SOS /IGBT	Larger	ns	Good	Low	Long

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

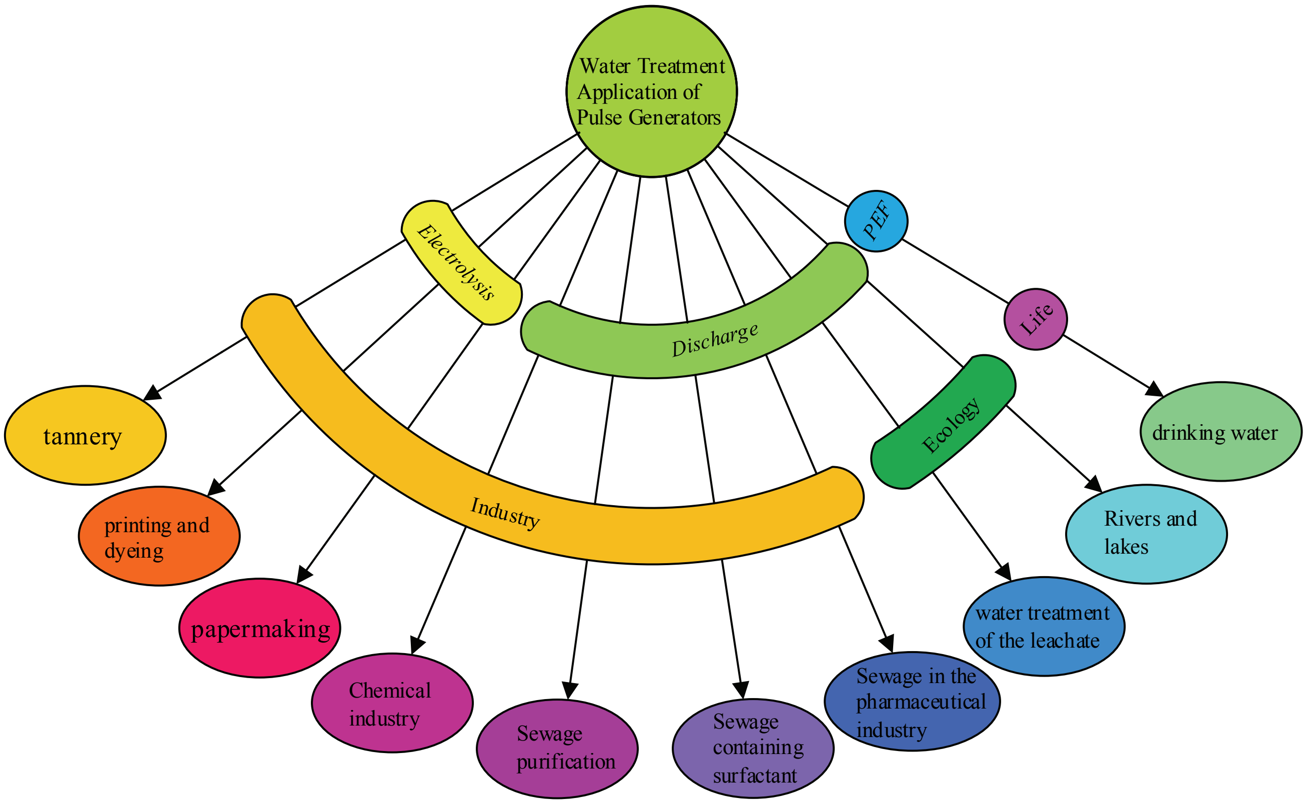


Fig. 19. Illustration of PPGs in a variety of water treatment applications

B. PEF for wastewater treatment application

Pulsed electric fields are mainly used in the sterilization of drinking water. It requires a high-voltage PPG. In PEF sterilization technology, a suitable electric field is 10-40kV/cm. And high voltage PPG used in PEF technology is required to be able to generate a pulse that lasts for duration of tens of nanoseconds to dozens of microseconds [74, 93]. In addition to the Diversified Technologies Inc, (DTI) the product of PPGs for PEF water treatment is difficult to find in the market. DTI's sterilizing equipment used in PEF water treatment can generate pulses of 35kV/350A, and process 10,000 liters / hour of wastewater. Its circuit is shown in Fig. 22. The circuit directly transforms high-voltage DC into bipolar high-voltage pulses by 35KV/350A solid-state switch modules. The average power is 150 kW. DTI claims they have already solved the switching synchronization and voltage balance problems when the IGBTs are in series in solid-state switch modules [94-96]. However, the technology is not publicly shared. Fortunately, in the literature of Mr. Chen, the solution of IGBT switch module was found to be applied in PEF applications [97].It should be noted the fiber-optic driver is used to deal with the switch synchronization and the snubber circuit is utilized to solve the voltage imbalance of series IGBT modules. And a PPG using the series of IGBT modules (composed of 64 isolated IGBTs) is designed to produce pulses of 35.8kV, 44A and pulse width greater than 2.5us.

The PPGs for PEF Water treatment have been heavily studied in the academic field, mostly focusing on DC converters, PFN, CDVMs, and MMC PPGs. The DC converters with PTs do not require high voltage switches and a large number of solid switches [98, 99]. Therefore, they are the good candidates for commercial applications. Their basic circuit structure is shown in Fig. 23. The DC/AC part may generate a unipolar pulse through one switch or a bipolar pulse through an H-bridge structure of four switches. But its output pulse is limited by PT parameters. And the PT will make the whole PPG look cumbersome. There are also some commercial patent that use PFN to generate high voltage pulses in PEF water treatment [100, 101]. In addition, some studies used PFN and PTs to generate high-voltage pulses for PEF water treatment [102], and show that the pulse amplitude can reach several hundred KV, and pulse width is 5-20us. The experimental circuit diagram is shown in Fig. 24. But the output pulse of the PPG with PFN and PT is limited by the circuit parameters.

To overcome the limitation of the PT and PFN, the PPGs based on solid-state Marx and CDVMs can be used in water treatment due to no need of transformers. They have advantages of high power density, high efficiency, light

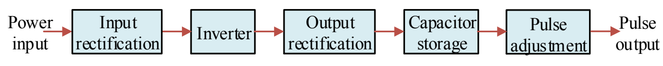


Fig. 20. The Basic principle of PPG for water treatment.

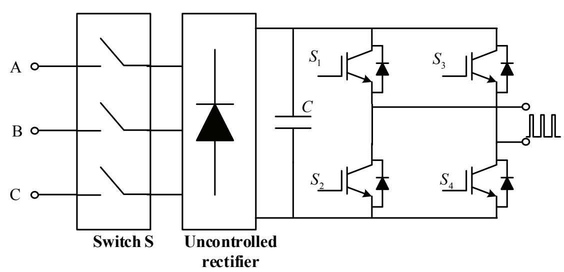
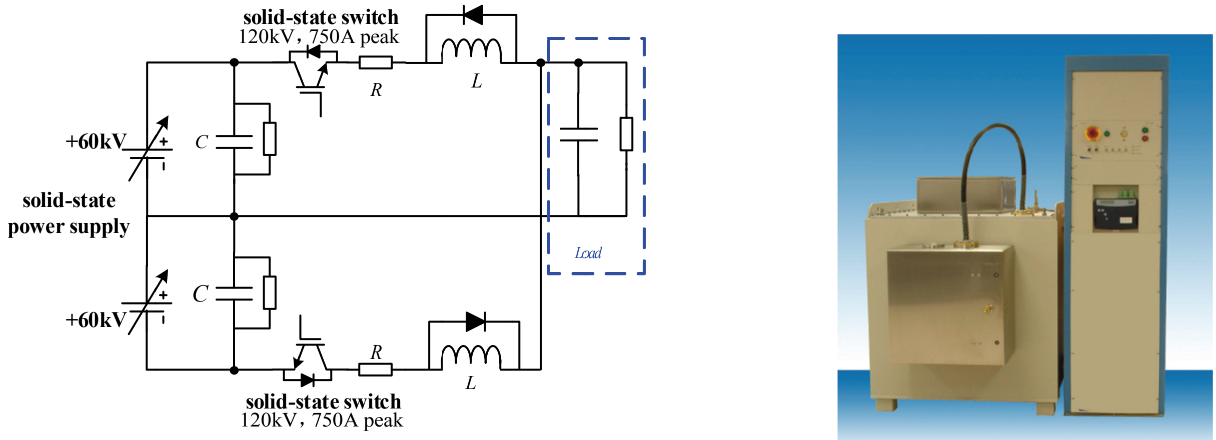


Fig. 21. The Circuit for the PPG of electrolysis.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics



(a) (b)

Fig. 22. Diagram of first commercial pulse electric field system. (a) Schematic. (b) The Photo of product

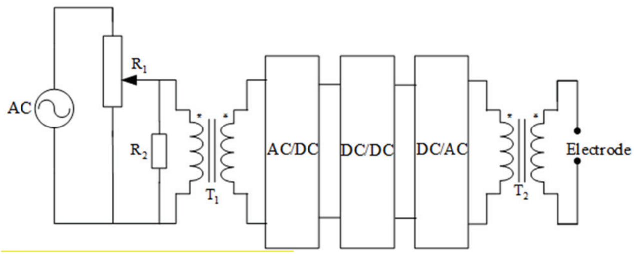


Fig. 23. High voltage PPG in [103].

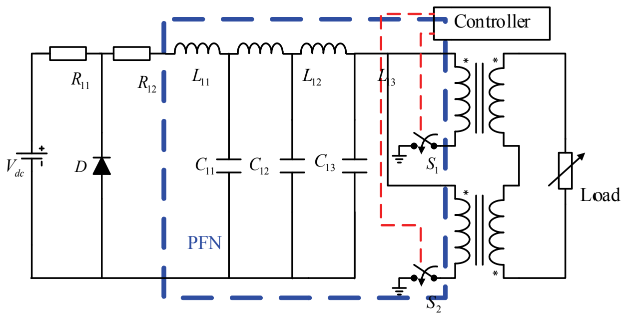


Fig. 24. The bipolar high voltage PPG with PFF

weight, high reliability, flexible pulse regulation, and modularity. That's why they are popular in water treatment applications [86]. Aside from that, another point is the effect of pulse width on sterilization [10, 104]. In [105], the effect of pulse width and pulse repetition rate is also discussed. Therefore, a flexible high voltage PPG with a wide range of adjustment is favorable in practice.

C. Pulse discharging power for wastewater treatment

According to the current survey results, pulse discharge water treatment is required in the fields of domestic sewage, industrial sewage, pharmaceutical and hospital sewage, and ecological environment treatment. The discharge water treatment includes water-gas discharge and underwater discharge. The water-gas discharge has a lower voltage level than the underwater discharge, but its reactor is complicated. At the same time, experimental data shows that the water-gas discharge is more efficient than the underwater discharge, because some of the energy in the water discharge is lost in the form of heat. The PPG topology types that match these two types of discharge are approximately the same. The only difference is that the PPGs used in underwater discharges (such as the Marx, PFN, MPC PPGs) have a higher number of sub-circuits because the underwater discharge requires a higher voltage level and higher power level.

The water treatment of domestic and industrial sewage mainly includes sewage purification, surfactant sewage treatment, sterilization and the like. They all require a nanosecond pulse of at least a few tens of kilovolts for corona discharge. Generally, MPC, PFN, PFL, resonant transformer PPGs are used more. And PPGs used in actual water treatment applications has achieved good results. For examples, in the literature [106-108], a Living or industrial wastewater containing surfactants uses water-gas discharge technology. These document applies a nanosecond high voltage PPG with a circuit diagram as shown in Fig. 25. Its working principle is that the voltage is amplified by a Tesla transformer, and the pulse is formed by a short PFL and a highly pressurized air gap switch. The water-gas discharge technology has been applied to remove high-phenol and biodegradation in the literature [109]. In this paper, a high-power solid-state compact nanoseconds generator based on MPC is applied. The circuit diagram is shown in the Fig. 26. The output of the PPG is 60kV, 3J pulses. Its pulse repetition rate is up to 500Hz, the rise time is 15ns, and the pulse width is 100ns. Its efficiency is 82% at the impedance load and 62% at the plasma load. In the literature [110], the dual resonance PPG is used for sewage sterilization and has been successfully applied in industrial water treatment. Its circuit diagram is shown in the Fig. 27. The generator can generate high voltage pulses up to 80kV (theoretical 120kV) with an oscillation frequency of up to 2MHZ, a pulse repetition rate of more than 20kHZ, and an average power of 800w. And it can process 10~100L of sewage in one hour.

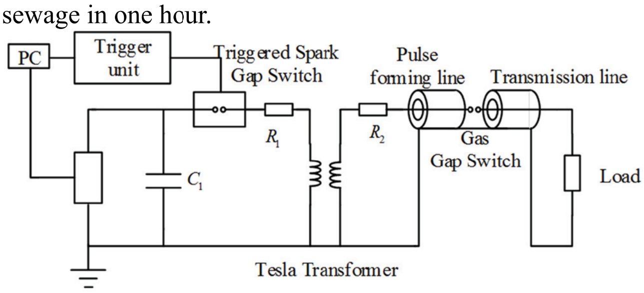


Fig. 25 The schematic diagram of nanosecond pulsed power generator

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

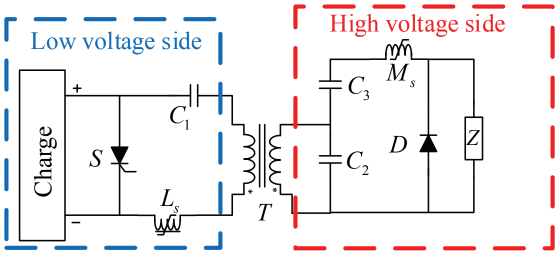


Fig. 26. The circuit of the PPG with magnetic compression

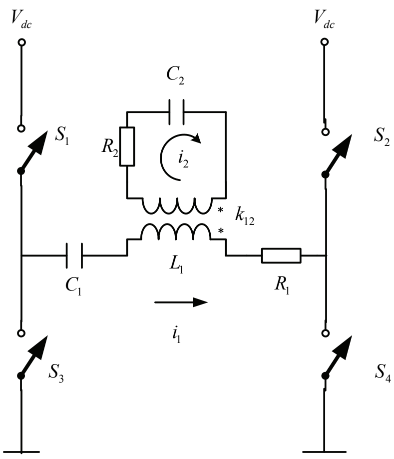


Fig. 27. The Full-bridge dual LC resonant circuit

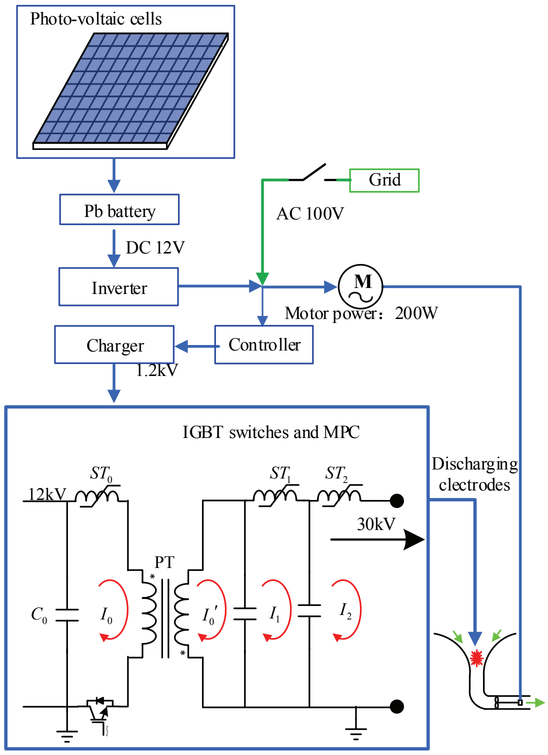


Fig. 28. The pulse power modulator used to treat blooms

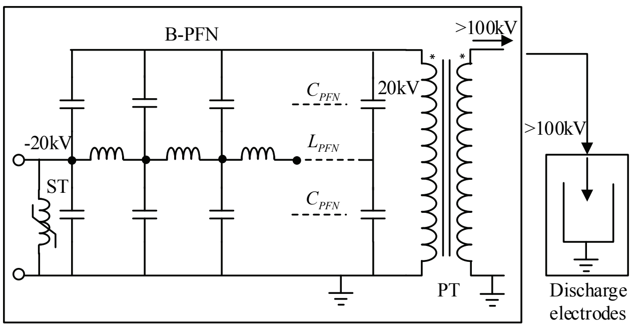


Fig. 29 the circuit Block diagram of with a B_PFN network and a PT for water treatment

The application of water treatment in ecological environment treatment is mainly to control the reproduction of algae in rivers and lakes. This is mainly relying on ultra-high voltage short pulses generated by MPC, PFN, PFL, SOS PPG to produce corona discharge and streamer discharge in water. For examples, in [111], the underwater streamer discharge is used to treat blooms (large-scale blooms may lead to eutrophication of water bodies, damage to water environments, and threats to human safety). It proposes a PPG based on MPC, and the circuit diagram is shown in Fig. 28. The generator can be repeatedly discharged underwater in a pulse mode of 30kV with a pulse width of 4us. Moreover, in [112], the circuit with a BPFN and a PT in the Fig. 29 are added to the circuit in Fig. 28 to boost the pulse voltage to 108 kV and the pulse rise time is 200 ns. The pulse width is 1us and the maximum discharge peak current can reach 5.4kA.

Sewage produced by the pharmaceutical industry or hospital often contains a variety of residual drugs and high molecular organic substances, which generally require high-voltage microseconds pulses to degrade them. It does require a particularly high voltage to allow the water to generate plasma without corona. Generally, DC converter, CDVM, and Marx PPGs can be used to achieve high-voltage pulses of about 10kV. For example, in the literature [113], it uses an all-solid-state Marx generator that produces 7kV pulses with a minimum pulse width of 100ns and rise and fall times of approximately 20ns, depending on magnetic isolation and synchronous drive technology.

At present, there are some application cases of underwater pulse discharge in the experimental stage, which is of great research significance. Rather than putting their PPGs into actual water treatment applications, they used artificially prepared sewage samples as research objects for water treatment. The PPG schemes they use are SOS PPGs [114-116], MPC and BPFN [117], CDVM [4, 118-120] PPGs. Among them, the experimental output pulse voltage of the SOS PPG is 50 kV to several hundred kV, and the current is several hundred amperes to several thousand amperes. The pulse width is in the order of nanoseconds to microseconds. The PPGs consisting of MPC and BPFN has an output voltage of more than one hundred kV. Due to the application of PFN and PFL technology, the pulse width can reach nanoseconds, but their output pulses are fixed because the circuit parameters are fixed. The all-solid-state CDVM and Marx PPGs appears only in conceptual form, and no experiment is seen. But they do not require a transformer, the output pulse is flexible and adjustable without voltage parameters limitation, and are easy to modularize and has high reliability. So they are worth studying and advancing. If solid-state Marx and CDVM PPGs are connected in series and in parallel, they have high voltage and high power output characteristics, and can be applied to high voltage and high power pulse discharge water treatment as shown in the Fig. 30. They will make future water treatment PPG easy to control, and have the advantages of high reliability, high repetition rate, small size, and modularity.

From the whole survey results, the application

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

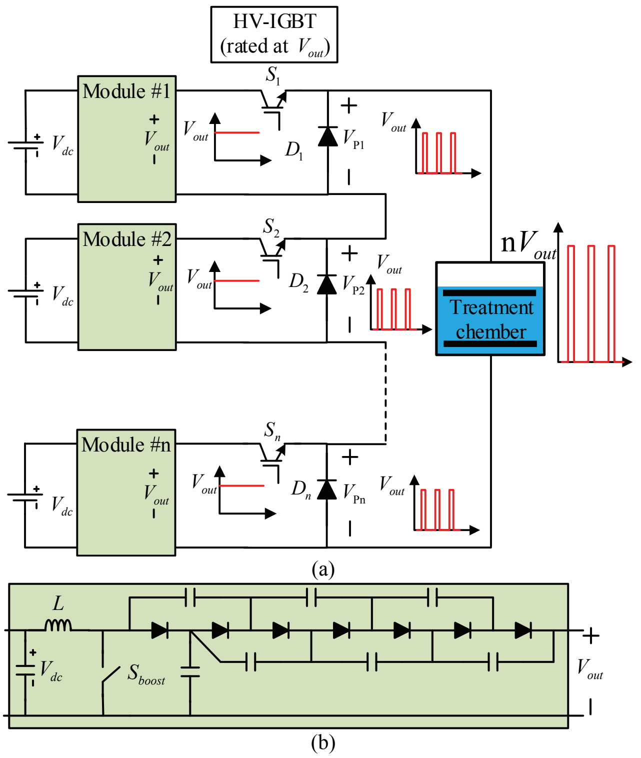


Fig. 30. The circuit Scheme of [121]. (a) The proposed multi-module high-voltage PPG, (b) the construction of each module in the proposed high voltage generator, assuming two-stages CDVM(m=2)

researches of PPGs in water treatment are not enough. The lack of theoretical analysis of the water treatment process and the data research of the actual processing of water treatment make the PPGs unable to optimize and upgrade, improve the processing efficiency, and thus reduce the use of electric energy. The work that needs to be done in the future is to theoretically analyze the water treatment process from the perspective of biochemical physics, and continuously combine the experimental feedback data to obtain the most suitable pulse parameters and pulse working curves for a certain water treatment application. Based on these researches, a powerful and effective PPG can be designed. But the only certainty now is that due to the superior performance of the all-solid-state PPG, it will be the attractive choice for water treatment PPGs.

IV FUTURE RESEARCH

A summary is shown in Tab. VII that uses the PPG on industrial applications. With the development of wideband semiconductor devices such as SiC and GaN [122-124], the power, efficiency, peak voltage and flexibility of high-voltage PPGs will be significantly enhanced. And it would be open a new direction for the super high-frequency PPGs for the water treatment. Compared with traditional PPGs, the solid-state PPGs have advantages in terms of volume, weight, flexibility, repetition rate and reliability. However, the wideband gap semiconductors will be embedded into traditional PPGs for better performance. The application of PPGs in water treatment will also move towards the direction in Fig. 31(b).

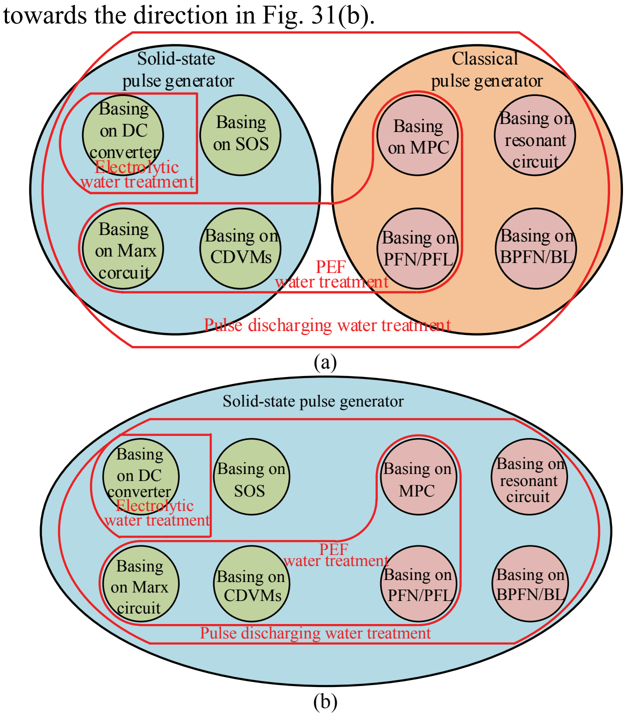


Fig. 31 Applications of PPGs in water treatment.

TABLE VII
SUMMARY OF WATER TREATMENT APPLICATION OF PPGS

	Applications	Types of PPG	Pulse parameters	Company
Electrolysis	Tannery, Printing, dyeing, and Papermaking	DC converter PPG	10-1000V, 0-1kA, 10-100kHz	Changtal Electrical Co. Ltd in China, And College of information & Communication Engineering, SungKyunKwan University
Pulse Discharge	Chemical industry	MC or PFL PPG	20kV, 210A, 10Hz	Propulsion Physics Laboratory, Soreq NRC
	Sewage Purification	resonant circuit PPG	80kV, 20kHz	Electrical Energy Systems Group, Eindhoven University of Technology
	Sewage containing surfactant	PT and PFL PPG	3kV, 50Hz	University of Tokushima
	Sewage in the pharmaceutical industry	Marx PPG	7kV, 30kHz	School of optical electrical and computer engineering, university of shanghai for science and technology in China
	Water treatment of the leachate	DC converter PPG	60kV,300A ,1-300Hz, with 2us-50us pulse width	University of Science & Technology, KERI Campus
	River and Lakes	PT and PFN PPG	30kV with 4us pulse width	School of Science and Technology, Kumamoto University
		PT and PFN PPG	30kV with 4us pulse width	
PEF	Drinking water	Solid-state PPG	35kV,with 350A peak current	Diversified Technologies, Inc.

V CONCLUSION

A comprehensive review of the PPGs for water treatment has been presented in this paper. It provides a summary of applications of PPGs in water treatment. The advantages and disadvantages of different PPG topologies have been analyzed. Each topology has its own characteristics and applications. Many readers might have a question which is the best method. In fact, it is difficult to answer this question, since there is a tradeoff between the efficiency, cost, power density, and pulse peak and repetition rate for most of these methods. Finally, it is expected that this review will serve as a useful reference guide to the researchers working in the area of PPGs for the water treatment.

REFERENCES

[1] M. A. Elgenedy, A. Darwish, S. Ahmed, and B. W. Williams, "A transition arm modular multilevel universal pulse-waveform generator for electroporation applications," *IEEE Transactions on Power Electronics,* vol. 32, no. 12, pp. 8979-8991, 2017.

[2] M. A. Elgenedy, A. M. Massoud, S. Ahmed, and B. W. Williams, "A high-gain, high-voltage pulse generator using sequentially-charged modular multilevel converter sub-modules, for water disinfection applications," *IEEE Journal of Emerging & Selected Topics in Power Electronics,* vol. PP, no. 99, pp. 1-1, 2017.

[3] A. A. Elserougi, A. M. Massoud, and S. Ahmed, "A Modular High-Voltage Pulse-Generator With Sequential Charging for Water Treatment Applications," *IEEE Transactions on Industrial Electronics,* vol. 63, no. 12, pp. 7898-7907, 2016.

[4] A. A. Elserougi, M. Faiter, A. M. Massoud, and S. Ahmed, "A transformerless bipolar/unipolar high-voltage pulse generator with low-voltage components for water treatment applications," *IEEE Transactions on Industry Applications,* vol. 53, no. 3, pp. 2307-2319, 2017.

[5] A. Abou-Ghazala, S. Katsuki, K. H. Schoenbach, F. C. Dobbs, and K. R. Moreira, "Bacterial decontamination of water by means of pulsed-corona discharges," *IEEE Transactions on Plasma Science,* vol. 30, no. 4, pp. 1449-1453, 2002.

[6] A. K. Chopra, A. K. Sharma, and V. Kumar, "Overview of electrolytic treatment: An alternative technology for purification of wastewater," *Archives of Applied Science Research,* no. 5, pp. 191-206, 2011.

[7] S. Y. Lee and G. A. Gagnon, "The rate and efficiency of iron generation in an electrocoagulation system," *Environmental Technology Letters,* vol. 36, no. 19, pp. 2419-2427, 2015.

[8] A. Deghles and U. Kurt, "Treatment of tannery wastewater by a hybrid electrocoagulation/electrodialysis process," *Chemical Engineering & Processing Process Intensification,* vol. 104, pp. 43-50, 2016.

[9] P. T. Johnstone, "High voltage disinfection of liquids," *Transactions of the Institution of Professional Engineers New Zealand Electrical/mechanical/chemical Engineering,* vol. 24, no. 1, 1997.

[10] K. H. Schoenbach, F. E. Peterkin, R. W. Alden, Iii, and S. J. Beebe, "The effect of pulsed electric fields on biological cells: experiments and applications," vol. 25, no. 2, pp. 284-292, 1997.

[11] U. Zimmermann, J. Vienken, and G. Pilwat, " Development of drug carrier systems: Electrical field induced effects in cell membranes," *Bioelectrochemistry and Bioenergetics,* vol. 7, no. 3, pp. 553-574, 1980/09/01/ 1980.

[12] R. Benz and U. Zimmermann, "Pulse-length dependence of the electrical breakdown in lipid bilayer membranes," *Biochimica et Biophysica Acta (BBA) - Biomembranes,* vol. 597, no. 3, pp. 637-642, 1980/04/24/ 1980.

[13] M. P. J. Gaudreau, T. Hawkey, J. Petry, and M. A. Kempkes, "A solid state pulsed power system for food processing," in *Pulsed Power Plasma Science, 2001. PPPS-2001. Digest of Technical Papers*, 2001, pp. 1174-1177 vol.2.

[14] Z. Yang, Y. Jiang, and L. Xiong, "Study on pulsed electric field application to water treatment system," in *Automation Congress, 2008. Wac*, 2008, pp. 1-5.

[15] B. Sun, M. Sato, A. Harano, and J. S. Clements, "Non-uniform pulse discharge-induced radical production in distilled water," *Journal of Electrostatics,* vol. 43, no. 2, pp. 115-126, 1998.

[16] A. Yamatake, D. M. Angeloni, S. E. Dickson, M. B. Emelko, K. Yasuoka, and J. S. Chang, "Characteristics of pulsed arc electrohydraulic discharge for eccentric electrode cylindrical reactor using phosphate-buffered saline water," *Japanese Journal of Applied Physics,* vol. 45, no. 10B, pp. 8298-8301, 2006.

[17] M. J. K. And and B. R. Locke, "Hydrogen, oxygen, and hydrogen Peroxide formation in aqueous phase pulsed corona electrical discharge," *Industrial & Engineering Chemistry Research,* vol. 44, no. 12, pp. 4243-4248, 2005.

[18] M. A. Malik, "Synergistic effect of plasmacatalyst and ozone in a pulsed corona discharge reactor on the decomposition of organic pollutants in water," *Nucleic Acids Research,* vol. 18, no. 17, pp. 5037-43, 2003.

[19] H. Akiyama, "Streamer discharges in liquids and their applications," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 7, no. 5, pp. 646-653, 2000.

[20] B. Sun, M. Sato, and J. S. Clements, "Optical study of active species produced by a pulsed streamer corona discharge in water," *Journal of Electrostatics,* vol. 39, no. 3, pp. 189-202, 1997.

[21] H. Kusiä, N. Koprivanac, and B. R. Locke, "Decomposition of phenol by hybrid gas/liquid electrical discharge reactors with zeolite catalysts," *Journal of Hazardous Materials,* vol. 125, no. 1–3, pp. 190-200, 2005.

[22] T. Handa and Y. Minamitani, "The effect of a water-droplet spray and gas discharge in water treatment by pulsed power," *IEEE Transactions on Plasma Science,* vol. 37, no. 1, pp. 179-183, 2008.

[23] T. Kobayashi, T. Sugai, T. Handa, Y. Minamitani, and T. Nose, "The effect of spraying of water droplets and location of water droplets on the water treatment by pulsed discharge in air," *IEEE Transactions on Plasma Science,* vol. 38, no. 10, pp. 2675-2680, 2010.

[24] B. R. Locke, M. Sato, P. Sunka, M. R. Hoffmann, and J. S. Chang, "Electrohydraulic discharge and nonthermal plasma for water treatment," *Industrial & Engineering Chemistry Research,* vol. 45, no. 3, pp. págs. 882-905, 2006.

[25] E.P.Management. (Jan.2010). *Theory and application of conductivity*. Available: http://www.emerson.com/resource/blob/68442/7b95542772c37c1415ce2ff0a3c4521a/application-data–theory-and-application-of-conductivity-data.pdf

[26] Y. Yang, "Plasma discharge in water and its application for industrial cooling water treatment," 2011.

[27] A. Elserougi, A. M. Massoud, A. M. Ibrahim, and S. Ahmed, "A high voltage pulse-generator based on DC-to-DC converters and capacitor-diode voltage multipliers for water treatment applications," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 22, no. 6, pp. 3290-3298, 2015.

[28] I. R. McNab, "Pulsed power for electric guns," *IEEE Transactions on Magnetics,* vol. 33, no. 1, pp. 453-460, 1997.

[29] T. Sugai, K. Ogasawara, T. N. Son, A. Tokuchi, W. Jiang, and Y. Minamitani, "Investigation for development of high efficiency water treatment system using pulsed streamer discharge," in *2013 19th IEEE Pulsed Power Conference (PPC)*, 2013, pp. 1-5.

[30] H. Rahaman, J. W. Nam, S. H. Nam, and K. Frank, "Investigation of Spark-Gap Discharge in a Regime of Very High Repetition Rate," *IEEE Transactions on Plasma Science,* vol. 38, no. 10, pp. 2752-2757, 2010.

[31] C. S. Reddy, P. Naresh, A. S. Patel, A. Sharma, and K. C. Mittal, "Voltage recovery characteristics of spark gap using repetitive pulse power system," in *2014 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2014, pp. 512-515.

[32] B. Lee, H. Rahaman, K. Frank, and S. H. Nam, "High repetitive switching of parallel micro-plasma spark gaps," in *2013 19th IEEE Pulsed Power Conference (PPC)*, 2013, pp. 1-4.

[33] J. Rhee, Y. Cho, J. Baek, S. Kim, C. Lee, and K. Ko, "Design of a Low-Stray Inductance Magnetic Switch for High Compression of the Pulse Width in a Magnetic Pulse Compressor," *IEEE Transactions on Plasma Science,* vol. 46, no. 7, pp. 2599-2604, 2018.

[34] S. Kim and M. Ehsani, "Control and Analysis of Magnetic Switch Reset Current in Pulsed Power Systems," *IEEE Transactions on Power Electronics,* vol. 29, no. 2, pp. 529-533, 2014.

[35] J. Rhee, S. Kim, J. Baek, and K. Ko, "Method for Self-Resetting of Magnetic Switches in a Magnetic Pulse Compressor Without Additional Reset Circuits," *IEEE Transactions on Plasma Science,* vol. 46, no. 10, pp. 3708-3712, 2018.

[36] F. J. Wakeman and B. K. Green, "Improved semiconductor switches, for pulse power applications," in *Conference Record of the*

Twenty-Third International Power Modulator Symposium (Cat. No. 98CH36133), 1998, pp. 135-138.
[37] F. Wakeman and W. Findlay, "Press-pack IGBTs, semiconductor switches for pulse power," in *IEEE Conference Record - Abstracts. PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference (Cat. No.01CH37*, 2001, p. 289.
[38] Y. Teramoto, D. Deguchi, S. Katsuki, T. Namihira, H. Akiyama, and I. V. Lisitsyn, "All-solid-state trigger-less repetitive pulsed power generator utilizing semiconductor opening switch," in *IEEE Conference Record - Abstracts. PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference (Cat. No.01CH37*, 2001, p. 480.
[39] X. Ren, Z. Xu, K. Xu, Z. Zhang, and Q. Chen, "SiC Stacked-Capacitor Converters for Pulse Applications," *IEEE Transactions on Power Electronics,* vol. 34, no. 5, pp. 4450-4464, 2019.
[40] L. Collier, T. Kajiwara, J. Dickens, J. Mankowski, and A. Neuber, "Fast SiC Switching Limits for Pulsed Power Applications," *IEEE Transactions on Plasma Science,* pp. 1-8, 2019.
[41] D. Mauch, W. Sullivan, A. Bullick, A. Neuber, and J. Dickens, "Performance and characterization of a 20 kV, contact face illuminated, silicon carbide photoconductive semiconductor switch for pulsed power applications," in *2013 19th IEEE Pulsed Power Conference (PPC)*, 2013, pp. 1-3.
[42] V. V. Peplov, D. E. Anderson, and R. B. Saethre, "New pulsed power supply for the spallation neutron source Linac LEBT chopper system," in *2015 IEEE Pulsed Power Conference (PPC)*, 2015, pp. 1-6.
[43] G. H. Schroeder and E. B. Vossenberg, "A prototype high power pulse generator for the beam abort systems of CERN's proposed 8 TeV collider LHC," in *Nineteenth IEEE Symposium on Power Modulators*, 1990, pp. 104-108.
[44] M. S, "Pulse energization system ofelectrostatic precipitator for retrofitting application," *IEEE Trans. Ind. Appl,* vol. 24(4), pp. 708-716, 1988.
[45] D. K. Sinha, M. S. Ansari, A. Ray, G. Trivedi, A. Chatterjee, and R. D. Schrimpf, "Fast Ionization-Front-Induced Anomalous Switching Behavior in Trigger Bipolar Transistors of Marx-Bank Circuits Under Base-Drive Conditions," *IEEE Transactions on Plasma Science,* vol. 46, no. 6, pp. 2064-2071, 2018.
[46] W. S. Melville, "The use of saturable reactors as discharge devices for pulse generators," *Electrical Engineers, Journal of the Institution of,* vol. 1951, no. 6, pp. 179-181, 1951.
[47] T. Shao *et al.*, "A Compact Repetitive Unipolar Nanosecond-Pulse Generator for Dielectric Barrier Discharge Application," *IEEE Transactions on Plasma Science,* vol. 38, no. 7, pp. 1651-1655, 2010.
[48] Z. Dong-dong, Y. Ping, and W. Jue, "Simulation on a magnetic pulse compression system," *High Power Laser and Particle Beams,* 2008.
[49] D. D. Zhang, Y. Ping, J. Wang, Z. Yuan, and S. Tao, "Dynamic characteristics of magnetic core under micro-second pulse excitation," *High Voltage Engineering,* vol. 35, no. 1, pp. 87-92, 2009.
[50] D. D. Zhang, P. Yan, J. Wang, R. Z. Pan, and T. Shao, "Magnetic component design and circuit simulation for MPC system," *High Voltage Apparatus,* 2009.
[51] D. D. Zhang, P. Yan, J. Wang, Y. Zhou, and T. Shao, "Analysis of one-stage magnetic pulse compression system," *High Voltage Engineering,* vol. 35, no. 3, pp. 661-666, 2009.
[52] S. H. Kim and M. Ehsani, "Control and Analysis of Magnetic Switch Reset Current in Pulsed Power Systems," *IEEE Transactions on Power Electronics,* vol. 29, no. 2, pp. 529-533, 2014.
[53] D. Zhang, Y. Zhou, J. Wang, and P. Yan, "A compact, high repetition-rate, nanosecond pulse generator based on magnetic pulse compression system," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 18, no. 4, pp. 388-390, 2011.
[54] S. Li, J. M. Gao, H. W. Yang, B. L. Qian, and Y. Pan, "An adjustable magnetic switch," *IEEE Transactions on Plasma Science,* vol. 43, no. 8, pp. 2687-2693, 2015.
[55] L. Wang and J. Liu, "Solid-State Nanosecond Pulse Generator Using Photoconductive Semiconductor Switch and Helical Pulse Forming Line," *IEEE Transactions on Plasma Science,* vol. 45, no. 12, pp. 3240-3245, 2017.
[56] S. Romeo, C. D'Avino, O. Zeni, and L. Zeni, "A Blumlein-type, nanosecond pulse generator with interchangeable transmission lines for bioelectrical applications," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 20, no. 4, pp. 1224-1230, 2013.
[57] J. T. Oh, J. H. Rhee, C. J. Lee, and K. C. Ko, "PPC-2015: Numerical analysis and experiment of Blumlein-nonlinear transmission line," in *Pulsed Power Conference*, 2015, pp. 1-3.
[58] Y. Mi, J. Wan, C. Bian, Y. Zhang, C. Yao, and C. Li, "A multiparameter adjustable, portable high-voltage nanosecond pulse generator based on stacked blumlein multilayered PCB strip transmission line," *IEEE Transactions on Plasma Science,* vol. 44, no. 10, pp. 2022-2029, 2016.
[59] P. H. D. Rocha, A. M. De, M, and J. C. A. Dos Santos, "Characterization and implementation of a pulse forming network for a surveillance radar," in *Microwave and Optoelectronics Conference, 2001. IMOC 2001.Proceedings of the 2001 SBMO/IEEE MTT-S International*, 2001, pp. 269-272 vol.1.
[60] J. C. Su *et al.*, "Long pulse electron beam generator based on Tesla transformer and pulse forming network," in *International Conference on High Power Particle Beams*, 2008, pp. 1-4.
[61] C. R. Rose, "Type-E pulse-forming-network theory and synthesis," in *Pulsed Power Conference*, 2015, pp. 1-6.
[62] H. Xiao, L. Li, H. Ding, T. Peng, and Y. Pan, "Study on a Highly Stabilized Pulsed Power Supply for High Magnetic Fields," *IEEE Transactions on Power Electronics,* vol. 26, no. 12, pp. 3817-3822, 2011.
[63] H. Li, H. J. Ryoo, J. S. Kim, G. H. Rim, Y. B. Kim, and J. Deng, "Development of Rectangle-Pulse Marx Generator Based on PFN," *IEEE Transactions on Plasma Science,* vol. 37, no. 1, pp. 190-194, 2009.
[64] S. Mohsenzade, M. Zarghany, M. Aghaei, and S. Kaboli, "A High-Voltage Pulse Generator With Continuously Variable Pulsewidth Based on a Modified PFN," *IEEE Transactions on Plasma Science,* vol. 45, no. 5, pp. 849-858, 2017.
[65] E. M. M. Costa, "High Gain in Double Resonant Systems: Tesla Transformer with Sinusoidal Excitation," *IEEE Latin America Transactions,* vol. 13, no. 8, pp. 2616-2621, 2015.
[66] L. Li *et al.*, "Study on double resonant performance of air-core spiral tesla transformer applied in repetitive pulsed operation," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 22, no. 4, pp. 1916-1922, 2015.
[67] C. Yong-Ho, K. Han-Joon, and Y. Chun-Suk, "MOSFET switched 20 kV, 500 A, 100 ns pulse generator with series connected pulse transformers," in *PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference. Digest of Papers (Cat. No.01CH37251)*, 2001, vol. 2, pp. 1237-1240 vol.2.
[68] J. Biela, D. Bortis, and J. W. Kolar, "Analytical Modeling of Pulse Transformers for Power Modulators," in *Conference Record of the 2006 Twenty-Seventh International Power Modulator Symposium*, 2006, pp. 135-140.
[69] S. Ushkewar, V. Shinde, and V. Dake, "Modeling and analysis of split core pulse transformer for solid state pulse power modulator," in *2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, 2017, pp. 1-6.
[70] B. Ju-Won, Y. Dong-Wook, R. Geun-Hie, and S. Byeong-Mun, "A 2 kV-40 A pulse generator using boost converter array," in *Digest of Technical Papers. PPC-2003. 14th IEEE International Pulsed Power Conference (IEEE Cat. No.03CH37472)*, 2003, vol. 2, pp. 1423-1426 Vol.2.
[71] S. Zabihi, F. Zare, G. Ledwich, A. Ghosh, and H. Akiyama, "A new pulsed power supply topology based on positive buck-boost converters concept," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 17, no. 6, pp. 1901-1911, 2010.
[72] S. Zabihi, F. Zare, G. Ledwich, A. Ghosh, and H. Akiyama, "A Novel High-Voltage Pulsed-Power Supply Based on Low-Voltage Switch–Capacitor Units," *IEEE Transactions on Plasma Science,* vol. 38, no. 10, pp. 2877-2887, 2010.
[73] J. C. Rosas-Caro, J. M. Ramirez, F. Z. Peng, and A. Valderrabano, "A DC-DC multilevel boost converter," *IET Power Electronics,* vol. 3, no. 1, pp. 129-137, 2010.
[74] A. Elserougi, S. Ahmed, and A. Massoud, "High voltage pulse generator based on DC-to-DC boost converter with capacitor-diode voltage multipliers for bacterial decontamination," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, 2015, pp. 000322-000326.
[75] L. M. Redondo, "A DC Voltage-Multiplier Circuit Working as a High-Voltage Pulse Generator," *IEEE Transactions on Plasma Science,* vol. 38, no. 10, pp. 2725-2729, 2010.
[76] M. Rezanejad, J. Adabi, A. Sheikholeslami, and A. Nami, "High-voltage pulse generators based on capacitor-diode voltage multiplier," in *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC)*, 2012, pp. LS3c.4-1-LS3c.4-6.

[77] E. Vorobiev and N. I. Lebovka, "Pulsed electric field technology for the food industry. fundamentals and applications," pp. 153-193, 2006.
[78] L. M. Redondo, H. Canacsinh, and J. F. Silva, "Generalized solid-state marx modulator topology," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 16, no. 4, pp. 1037-1042, 2009.
[79] H. Canacsinh, L. M. Redondo, and J. F. Silva, "Marx-type solid-state bipolar modulator topologies: Performance comparison," *IEEE Transactions on Plasma Science,* vol. 40, no. 10, pp. 2603-2610, 2012.
[80] J. P. M. Mendes, H. Canacsinh, L. M. Redondo, and J. O. Rossi, "Solid state marx modulator with blumlein stack for bipolar pulse generation," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 18, no. 4, pp. 1199-1204, 2011.
[81] H. Canacsinh, L. M. Redondo, and J. F. Silva, "New solid-state Marx topology for bipolar repetitive high-voltage pulses," in *Power Electronics Specialists Conference, 2008. Pesc*, 2008, pp. 791-795.
[82] Y. Wu, K. Liu, J. Qiu, X. X. Liu, and H. Xiao, "Repetitive and high voltage Marx generator using solid-state devices," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 14, no. 4, pp. 937-940, 2007.
[83] A. A. Elserougi, I. Abdelsalam, A. M. Massoud, and S. Ahmed, "A Full-Bridge Submodule-Based Modular Unipolar/Bipolar High-Voltage Pulse Generator With Sequential Charging of Capacitors," *IEEE Transactions on Plasma Science,* vol. 45, no. 1, pp. 91-99, 2017.
[84] L. L. Rocha, J. F. Silva, and L. M. Redondo, "Multilevel high-voltage pulse generation based on a new modular solid-state switch," *IEEE Transactions on Plasma Science,* vol. 42, no. 10, pp. 2956-2961, 2014.
[85] A. A. Elserougi, A. M. Massoud, and S. Ahmed, "Modular multilevel converter-based bipolar high-voltage pulse generator with sensorless capacitor voltage balancing technique," *IEEE Transactions on Plasma Science,* vol. 44, no. 7, pp. 1187-1194, 2016.
[86] M. A. Elgenedy, A. Darwish, S. Ahmed, and B. W. Williams, "A modular multilevel-based high-voltage pulse generator for water disinfection applications," *IEEE Transactions on Plasma Science,* vol. 44, no. 11, pp. 2893-2900, 2016.
[87] A. Elserougi, A. Massoud, and S. Ahmed, "Conceptual study of a bipolar modular high voltage pulse generator with sequential charging," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 23, no. 6, pp. 3450-3457, 2017.
[88] I. Grekhov and G. Mesyats, "Nanosecond semiconductor diodes for pulsed power switching," *Physics-Uspekhi,* vol. 48, p. 703, 10/18 2007.
[89] S. K. Lyubutin *et al.*, "High efficiency nanosecond generator based on semiconductor opening switch," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 18, no. 4, pp. 1221-1227, 2011.
[90] P. V. Vasiliev *et al.*, "Operation of a semiconductor opening switch at the pumping time of a microsecond and low current density," *Semiconductors,* vol. 43, no. 7, pp. 953-956, 2009.
[91] T. Yokoo, K. Saiki, K. Hotta, and W. Jiang, "Repetitive pulsed high-voltage generator using semiconductor opening switch for atmospheric discharge," *IEEE Transactions on Plasma Science,* vol. 36, no. 5, pp. 2638-2643, 2008.
[92] D. Minghua, "A double negative pulse high frequency switching power supply for electrochemical wastewater treatment," China Patent CN205610484, 2016.
[93] Ž. MK, D. Hodžić, M. Reberšek, and M. Kandušer, "Combination of microsecond and nanosecond pulsed electric field treatments for inactivation of Escherichia coli in water samples," *Journal of Membrane Biology,* vol. 245, no. 10, pp. 643-650, 2012.
[94] M. Kempkes, M. Gaudreau, T. Hawkey, and J. Petry, "Scaleup of PEF systems for food and waste streams," in *IEEE International Pulsed Power Conference*, 2007, pp. 1064-1067.
[95] M. A. Kempkes, R. Liang, J. E. Petry, and M. P. J. Gaudreau, "PEF Systems For Food And Waste Streams," in *IEEE International Power Modulators and High Voltage Conference, Proceedings of the*, 2008, pp. 73-76.
[96] S. R. Jang, H. J. Ryoo, Y. S. Jin, S. H. Ahn, and G. H. Rim, "Application of pulsed power system for water treatment of the leachate," in *2009 IEEE Pulsed Power Conference*, 2009, pp. 980-983.
[97] X. Chen, L. Yu, T. Jiang, H. Tian, K. Huang, and J. Wang, "A High-Voltage Solid-State Switch Based on Series Connection of IGBTs for PEF Applications," *IEEE Transactions on Plasma Science,* vol. 45, no. 8, pp. 2328-2334, 2017.
[98] E. G. Rocher, R. A. Palomares, and P. B. Sanchez, *A high voltage pulse generator for Pulsed Electric Field pasteurization*. 2010, pp. 276-280.
[99] DANGuo, Z. Yan, C. Yuan, and LIUKai, "Principle of high precise high voltage pulse power and its experimental research," *Journal of Dalian University of Technology,* 2003.
[100] A. H. R. L. Bushnell, San Diego, CA, 92124, US), Dunn, Joseph Edward (3532 Del Rio Court, Rancho La Costa, CA, 92009, US), Clark, Reginald Wayne (12919 Via Esperia, Del Mar, CA, 92014, US), "High pulsed voltage systems for extending the shelf life of pumpable food products," European Patent EP0594566, 1999. Available: http://www.freepatentsonline.com/EP0594566B1.html.
[101] S. A. M. Korenev, IL), "Pulsed electric field system for treatment of a fluid medium," United States Patent US6746613, 2004. Available: http://www.freepatentsonline.com/6746613.html.
[102] Q. H. C. Zhang, OH), Qiu, Xiangxlao (Ottawa, CA), "High voltage pulse generator," United States Patent US6214297, 2001. Available: http://www.freepatentsonline.com/6214297.html.
[103] E. G. Rocher, R. A. Palomares, and P. B. Sánchez, "A high voltage pulse generator for Pulsed Electric Field pasteurization," in *2010 20th International Conference on Electronics Communications and Computers (CONIELECOMP)*, 2010, pp. 276-280.
[104] K. H. Schoenbach, R. P. Joshi, R. H. Stark, and F. C. Dobbs, "Bacterial decontamination of liquids with pulsed electric fields," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 7, no. 5, pp. 637-645, 2000.
[105] C. Yao, X. Hu, Y. Mi, C. Li, and C. Sun, "Window effect of pulsed electric field on biological cells," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 16, no. 5, pp. 1259-1266, 2009.
[106] M. Morimoto, K. Kusunoki, H. Nakai, K. Teranishi, and N. Shimomura, "Development of water treatment system using nanosecond pulsed powers to treat surfactant," in *2013 19th IEEE Pulsed Power Conference (PPC)*, 2013, pp. 1-5.
[107] Y. Shimomura, M. Morimoto, K. Shimizu, K. Teranishi, and N. Shimomura, "Effect of discharge gas on water treatment using nanosecond pulsed power discharges," in *2017 IEEE 21st International Conference on Pulsed Power (PPC)*, 2017, pp. 1-4.
[108] K. Shimizu, M. Morimoto, N. Shimomura, and K. Teranishi, "Effect of solution electric conductivity on surfactant treatment using nanosecond pulsed powers," in *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2016, pp. 625-630.
[109] A. Pokryvailo *et al.*, "High-Power Pulsed Corona for Treatment of Pollutants in Heterogeneous Media," *IEEE Transactions on Plasma Science,* vol. 34, no. 5, pp. 1731-1743, 2006.
[110] A. J. M. Pemen *et al.*, "Power Modulator for High-Yield Production of Plasma-Activated Water," *IEEE Transactions on Plasma Science,* vol. 45, no. 10, pp. 2725-2733, 2017.
[111]T. Sakugawa *et al.*, "A Method of Cyanobacteria Treatment Using Underwater Pulsed Streamer-Like Discharge," *IEEE Transactions on Plasma Science,* vol. 42, no. 3, pp. 794-798, 2014.
[112] T. Sakugawa *et al.*, "All Solid State Pulsed Power System for Water Discharge," in *2005 IEEE Pulsed Power Conference*, 2005, pp. 1057-1060.
[113] J. Rao, Y. Lei, S. Jiang, Z. Li, and J. F. Kolb, "All Solid-State Rectangular Sub-Microsecond Pulse Generator for Water Treatment Application," *IEEE Transactions on Plasma Science,* vol. 46, no. 10, pp. 3359-3363, 2018.
[114] S. Li, S. Hu, and H. Zhang, "Formation of Hydroxyl Radicals and Hydrogen Peroxide by a Novel Nanosecond Pulsed Plasma Power in Water," *IEEE Transactions on Plasma Science,* vol. 40, no. 1, pp. 63-67, 2012.
[115] T. Sugai, W. Liu, A. Tokuchi, W. Jiang, and Y. Minamitani, "Influence of a circuit parameter for plasma water treatment by an inductive energy storage circuit using semiconductor opening switch," *IEEE Transactions on Plasma Science,* vol. 41, no. 4, pp. 967-974, 2013.
[116] T. Sugai, A. Tokuchi, W. Jiang, and Y. Minamitani, "Investigation for optimization of an inductive energy storage circuit for electrical discharge water treatment," *IEEE Transactions on Plasma Science,* vol. 42, no. 10, pp. 3101-3108, 2014.
[117] J. Choi *et al.*, "Feasibility studies of EMTP simulation for the design of the pulsed-power generator using MPC and BPFN for water treatments," *IEEE Transactions on Plasma Science,* vol. 34, no. 5, pp. 1744-1750, 2006.
[118] A. Elserougi, A. M. Massoud, A. M. Ibrahim, and S. Ahmed, "A high voltage pulse-generator based on DC-to-DC converters and capacitor-diode voltage multipliers for water treatment applications," *IEEE Transactions on Dielectrics & Electrical Insulation,* vol. 22, no. 6, pp. 3290-3298, 2016.
[119] A. A. Elserougi, A. S. Abdel-Khalik, S. Ahmed, and A. M. Massoud, "AC-powered multi-module high-voltage pusle-generator with sinusoidal input current for water treatment via underwater pulsed arc

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2020.2976145, IEEE Transactions on Power Electronics

discharge," in *2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, 2017, pp. 163-168.
[120] A. Elserougi, S. Ahmed, and A. Massoud, "Multi-module high voltage pulse generator based on DC-DC boost converter and CDVMs for drinking water purification," in *2016 IEEE International Conference on Industrial Technology (ICIT)*, 2016, pp. 334-338.
[121] A. Elserougi, S. Ahmed, and A. Massoud, "Multi-module high voltage pulse generator based on DC-DC boost converter and CDVMs for drinking water purification," in *IEEE International Conference on Industrial Technology*, 2016.
[122] H. C. P. Dymond *et al.*, "A 6.7-GHz Active Gate Driver for GaN FETs to Combat Overshoot, Ringing, and EMI," *IEEE Transactions on Power Electronics,* vol. 33, no. 1, pp. 581-594, 2018.
[123] J. Rabkowski, D. Peftitsis, and H. P. Nee, "Silicon Carbide Power Transistors: A New Era in Power Electronics Is Initiated," *IEEE Industrial Electronics Magazine,* vol. 6, no. 2, pp. 17-26, 2012.
[124] X. She, A. Q. Huang, L. Ó, and B. Ozpineci, "Review of Silicon Carbide Power Devices and Their Applications," *IEEE Transactions on Industrial Electronics,* vol. 64, no. 10, pp. 8193-8205, 2017.

Xiaoqiang Guo (M' 10-SM' 14) received the B.S. and Ph.D. degrees in electrical engineering from Yanshan University, Qinhuangdao, China, in 2003 and 2009, respectively. He has been a Postdoctoral Fellow with the Laboratory for Electrical Drive Applications and Research (LEDAR), Ryerson University, Toronto, ON, Canada. He is currently a professor with the Department of Electrical Engineering, Yanshan University, China. He has authored/coauthored more than ninety technical papers, in addition to twenty patents. His current research interests include water treatment power supply, high-power converters and ac drives, electric vehicle charging station, and renewable energy power conversion systems. Dr. Guo is a Senior Member of the IEEE Power Electronics Society and IEEE Industrial Electronics Society. He is currently an Associate Editor of the CPSS Transactions on Power Electronics and Applications, Journal of Power Electronics, and IET Power Electronics.

Dongpo Zheng received the B.S. degree in electrical engineering from Xi'an University of Technology, Xian, China, in 2016. He is currently pursuing the M.S. degree in power electronics from Yanshan University, Qinhuangdao, China. His current research interests include renewable energy power conversion system and control of power electronic converters.

Frede Blaabjerg (S'86–M'88–SM'97–F'03) was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he reveived the Ph.D. degree in electrical engineering at Aalborg University, Aalborg, Denmark, in 1995.

He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. From 2017 he became a Villum Investigator. He is honoris causa at University Politehnica Timisoara (UPT), Romania, and Tallinn Technical University (TTU) in Estonia. He has authored or coauthored more than 600 journal papers in the fields of power electronics and its applications. He is the Co-Author of four monographs and Editor of ten books in power electronics and its applications. His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics, and adjustable speed drives.

He was the Editor-in-Chief for the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He has been a Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011 as well as from 2017 to 2018. In 2019–2020 he serves as the President of IEEE Power Electronics Society. He is the Vice-President of the Danish Academy of Technical Sciences too. He was nominated in 2014–2018 by Thomson Reuters to be among the 250 most cited researchers in engineering in the world. He has received 31 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, the Villum Kann Rasmussen Research Award 2014, and the Global Energy Prize in 2019.