A 12KV Solid State High Voltage Pulse Generator for a Bench Top PEF Machine

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Abstract– *High voltage pulsed electric field (PEF) is increasingly used for nonthermal food processes. This paper presents a design of IGBT based 12KV solid state high voltage pulse generator. A simple main circuit topology is employed in this pulse generator to reduce the cost and meanwhile still to meet specified requirements for PEF food processing. Intelligent IGBT modules, rating at 1200V and 1200A, are used as power switches in the inverter circuit. A sophisticated grounding system is implemented to solve EMI caused by high integration of the equipment. In order to shape output pulse voltage wave, a dedicated DC bus work for the inverter is developed to minimize stray inductance in the current loops. Experimental results are shown in this paper.*

Keywords: high voltage, pulsed electric field, EMI

1. Introduction

Many areas, such as high energy physics, commercial semiconductors, particle accelerators, and metal treatment processes, require reliable, high power, variable pulse-width, variable repetition rate, variable polarity, flat top, high voltage pulses at high power [1]. New processes for food sterilization, waste treatment, pollution control, and medical diagnostics and treatment are being developed which also require high voltage pulsed power.

Pulsed electric fields (PEF) is a promising technology for the nonthermal pasteurization of foods. It is a sound complement or replacement to traditional thermal pasteurization that inactivates bacteria and other harmful microorganisms, but also degrades color, flavor, texture and nutrients. Foods can be pasteurized with pulsed electric fields at ambient or refrigerated temperatures for a short treatment time of seconds or less and the fresh-like quality of food is preserved [2]. The following are basic electrical requirements to PEF equipment for effective food processing:

- Electric field strength: 35KV/cm.
- Repetition rate: 0 - 10,000PPS.
- Duration time: 1μS - 20μS.
- Polarity: bipolar and positive or negative mono-polar.
- Flat top.
- Rise and fall times: < 1μS.

In addition, good electrical isolation should be provided for personal safety.

Historically, vacuum switch tubes or thyratrons, alone, or in combination with Pulse Forming Networks (PFNs), have been used for this purpose. The problems with these conventional switches include a large effective voltage drop, limited current and speed capability, high maintenance, and complex driving and protection circuitry. Nevertheless, they have provided a nearly exclusive solution to the problem of high-voltage switching because no cost-effective alternatives were available.

Generally, solid state devices are low voltage devices. But, recent advances in IGBTs have improved the voltage and current handling characteristics. Devices having voltage ratings from 1,200V to 3,300V and current ratings from 50A to 1,200A are available today. There are two major topologies to reach high voltage pulse using IGBTs. One is to cascade many devices in series to obtain a high voltage switch. This approach provides the flexibility for a modular design with no inherent limit to voltage handling. However, it has been known that it is a formidable task to ensure that the load is shared equally between devices so that no single device sees harmful or destructive voltages. Also, to accomplish this the gate drives must be highly synchronized. Another choice is to use a step-up pulse transformer to raise low voltage pulses up to an expected voltage level. One advantage of this method is that the power converter works at low voltage levels. However, IGBTs must be connected in parallel for high power applications, which is technically much easier than that in series.

As shown in Fig. 1, a bench top scale PEF machine with an IGBT based 12KV solid state pulse generator has been developed for food processing. Regardless of slightly reduced efficiency and little longer rise and fall times, the topography with a step-up transformer is selected for the bench top scale equipment because of its small size and low cost. The traditional AC-DC-Pulse structure is employed in the power conversion circuit. A capacitor charger functions as a controllable rectifier by charging a capacitor bank. An H-bridge serves as DC-Pulse inverter in which two intelligent IGBT modules, rating at 1200V and 900A, are employed. Except for control units for pulse generator and pumping system, all power units and treatment chambers are enclosed in a chassis (40cm× 80cm×100cm). Crowding so many parts into such a small space certainly increases the probability of EMI.

Therefore, one major challenge in the system design is how to eliminate, suppress or reduce EMI.

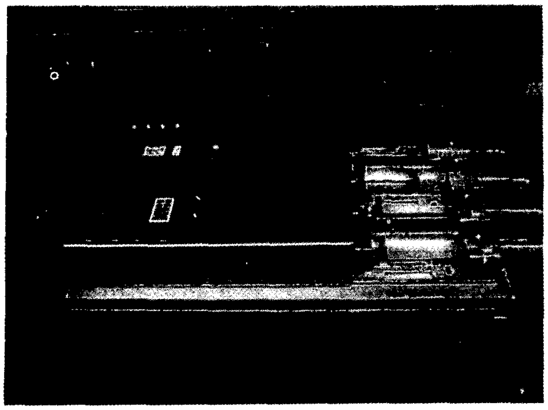

Fig. 1 Bench top PEF machine with a 12KV solid state high voltage pulse generator

In this paper, we will first introduce the system design. Then, major functional units will be described. Afterward, the issues associated with EMI will be discussed. At the end, voltage and current waveforms will be illustrated.

2. Power Converter of Solid State High Voltage Pulse Generator

The functional block diagram of the pulse generator is shown in Fig. 2.

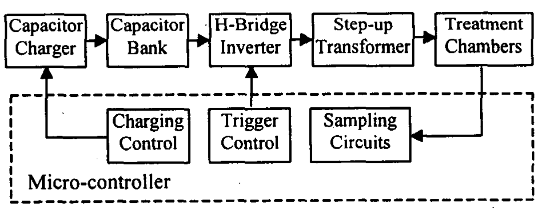

Fig. 2 Functional block diagram of high voltage pulse generator

A capacitor charger is selected in place of a diode rectifier to achieve:

- Controllable DC bus voltage;
- High DC bus voltage up to 1,000V.

The capacitor charger charges the capacitor bank to the desired voltage level. In the high voltage design, it is usually required to minimize the stored energy for the personnel safety. Thus, the capacitance value of the capacitor bank should be limited in a reasonable range. In addition, low inductance (<20nH) capacitors should be chosen to suppress unwanted oscillation involved in DC bus voltage during turning on or off power switches. Two intelligent IGBT modules are employed to form the H-bridge inverter. Fig. 3 shows the schematic diagram of the main circuit of the pulse generator.

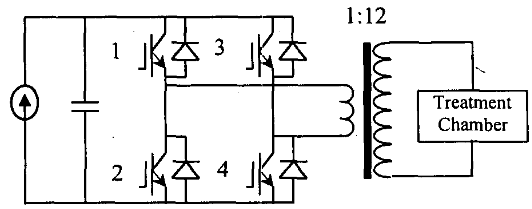

Fig. 3 Schematic diagram of the main circuit for the pulse generator

The step-up transformer provides high voltage pulsed electric fields to the food flowing through the treatment chamber. Electrically, food usually behaves as a pure resistor load. In our situation, the resistance value ranges from 200Ω through 1,200Ω. Thus, when 200Ω load is processed, IGBTs in the inverter should be able to handle 720A current due to 1:12 voltage ratio of the step-up transformer. Each switch of the inverter contains three IGBTs in parallel to enhance the current capability. The whole system is monitored and controlled by a dedicated controller.

3. Functional Units of high Voltage Pulse Generator

The proposed high voltage pulse generator is comprised of different functional units.

3.1 Capacitor Charging Power Supply

Fig. 4 shows the block diagram of the capacitor charging power supply. This switching power supply incorporates a new high-frequency IGBT parallel resonant inverter topology for efficient generation of the output power.

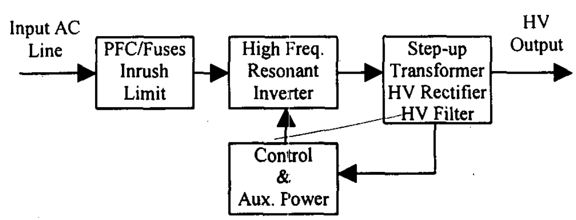

Fig.4 Block diagram of capacitor charging power supply

A high-performance control module precisely regulates the output voltage, automatically compensating for line, load, temperature, and repetition rate variations. Normal external fault conditions such as line dropout, open or short circuit load, HV arc and over-temperature will not damage the unit. The development in the parallel resonant inverter topology and control circuitry also drastically improves pulse-to-pulse repeatability by reducing the ripple or "bucket effect" even at very high pulse repetition rates. The output voltage is fully adjustable.

When the capacitor is discharged, a high peak current may flow out of the power supply as a result of voltage reversal. This occurs in a system that is under-damped in order to clear the high voltage switch after each pulse. The average value of the peak current added to the normal output current may exceed the rating of the HV diodes in the power. A series terminating resistor (or series inductor or clamp diode) must be added as shown in Fig. 5 if the average value of the peak current exceeds 110% of the normal ouput current as shown by the dotted block in Fig. 5.

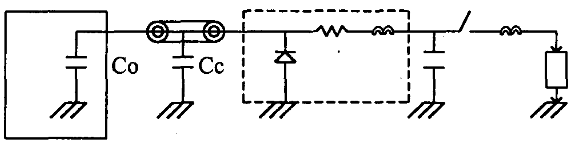

Fig. 5 Repression of peak current against reverse output voltage

3.2 Capacitor Bank

For personnel safety, low capacitance value should be required to reduce the stored energy. There are two capacitors working in parallel. One is a general purpose DC capacitor of 30 μF. Another is a set of low-inductance (<20nH) snubber capacitors of 2μF to

- Reduce or eliminate voltage or current spikes;
- Limit dI/dt or dV/dt;
- Shape the load line to keep it within the safe operating area (SOA);
- Reduce total loss due to switching;
- Reduce EMI by damping voltage and current ringing.

In practice, these snubber capacitors should be installed close to IGBT modules.

3.3 Intelligent IGBT Modules

The selected intelligent IGBT modules are featured with improved electrical and thermal performance, as well as increased reliability. This module integrates IGBT switches, heatsink, driver circuit, protection circuit, and monitoring circuit together. It is also equipped with closed loop current sensors and temperature sensors. The sensed current signals are used in the integrated driver circuit for short circuit and overcurrent protections. Normalized analog signals of output current, DC bus voltage, and temperature are all available for the user control system. The assembly of the module is based on pressure contact technology, which allows for the most compact design. Also, a significantly higher DC bus voltage can be achieved because of the extreme low inductive layout in internal structure.

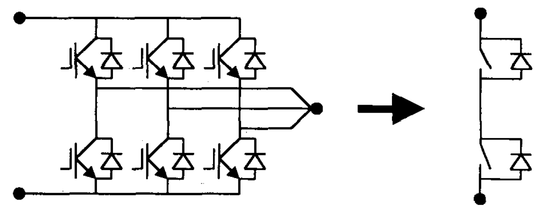

Fig. 6 Integrated IGBT module

Specially, the homogeneous transistors with features of high input impedance, high switching speed, and automatic current sharing (no derating necessary) are used in this module. And, paralleling of big number of IGBT is very easily achieved, because the positive temperature coefficient of V_{Cesat} and switching losses are nearly independent of temperature, as shown Fig. 6.

3.4 Step-up Pulse Transformer

The 1:12 pulse transformer allows operation at a reduced charging voltage while still producing the full output voltage to the load. The reduced primary voltage has several advantages. The maximum charging voltage can be reduced to about 1kV, allowing IGBTs to operate under their voltage rating. Otherwise, it is necessary to use stack of IGBT switches. Stacking semiconductor switches to operate at high voltage becomes increasingly difficult as the voltage increases, requiring more semiconductors in series and also possibly producing more damaging switching transients along the stack.

The pulse transformer primarily accepts a 1kV pulse and steps it up to 12KV on the secondary. The primary is floating so that either terminal may be pulsed positive, allowing an output pulse of either polarity to be produced. The secondary has one terminal at ground and the other at high voltage, polarity depending on the primary polarity. Alternating the polarity on every other pulse allows the full flux swing of the core to be utilized, reducing the transformer size and weight. Secondary impedance ranges from 200 to 1200 ohms.

3.5 Monitor Unit

It is desired to measure the load voltage and current. Being different from DC measurements, high voltage pulse measurement usually have strict requirements for bandwidth of sensors.

A. Voltage Monitor

Building a simple resistor divider using appropriate HV resistors is straightforward for DC high voltage measurement. It should be noted that all HV resistors exhibit a negative voltage coefficient, changing by up to 4% from zero to maximum voltage. When such an approach is used for a pulsed measurement, there are the following problems:

- voltage efficiency;

- damage to resistors due to high electric field gradients;
- stray capacitance to nearby objects which could alter the pulse response.

For a high-performance, a commerical high voltage probe is selected for monitoring the output voltage, which is provided with a standard sensitivity of 1000:1. One major feature of this probe is the use of 50-ohm coaxial cable to connect it to oscilloscopes. Extremely low temperatrure and voltage efficient resistors and capacitors are used in the probe design to provide measurement accuracy of 0.1% and rise time less than 5 nanoseconds.

B. Current Monitor

A commercial current transformer is selected as the current monitor in the system. The output of the current transformer is electrically isolated from the circuit being monitored. This isolation avoids the problem of ground loops, provides protection to both equipment and personnel and guarantees minimal impact on the current being measured. Toroidal construction provides protection against signal contamination by stray magnetic fields. The shield which encloses the core and winding eliminates the effects of stray electric fields; therefore these devices are remarkably noise immune even in hostile environments. They can be connected to oscilloscopes and a variety of other measuring instruments.

In fact, the current monitor is entirely passive and requires no externally power or circuitry. Its accuracy depends only on the number of turns of the secondary and on the value of the internal terminating resistance. These two parameters are very carefully controlled in manufacture, and the choice of the finest resistive materials assures long term stability. The use of a patented distributed termination technique provides rise time as short as ten nanoseconds. The availability of devices with large inner diameters makes possible the measurement of currents in a broad range of conductor sizes and also enables the measurement of current in high voltage circuits without the risk of voltage breakdown. When a current transformer is used to measure an ideal rectangular current pulse, the output droop will be observed. The use of high permeability materials makes the droop extremely low even with output V/A ratio.

The outputs of voltage and current are connected to BNC connectors located outside of the pulse generator chassis.

3.6 Safety

As always, personnel safety is a critical issue for high voltage equipment. Two approaches are used in our system to ensure safety: reliable grounding of the chassis and installation of an interlock switch.

3.7 Protection

There are mainly the following protections with the system:

- Over current protection
- Short circuit protection
- Over temperature protection
- Open loop protection
- Ground fault protection

The worst case fault condition for the pulse generator is a short-circuited load or arcing. The current flowing through IGBT modules can exceed 125% overcurrent specification in these cases. As mentioned above, IGBT modules can immediately switch off all IGBT devices once the load current exceeds the specification of 125%. Similarly, when over-temperature occurs, all IGBT devices will be switched off. For both over-current and over-temperature, there are error signals generated from IGBT modules. Once accepting these signals, the micro-controller shots down the whole system.

An open circuit will not damage the machine itself. In order to prevent potential damage to items outside the pulse generator, an interlock switch is used to detect the open circuit. In the case of open circuit, the high voltage is inhibited and fault indication is lid on the operation panel.

The circuit breaker for the overall system will have an electrical trip that will be used to remove power from the entire cabinet in the event that a ground fault is detected.

4. EMI Issues with the Pulse Generator

As mentioned in [3], noise is any electrical signal present in a circuit other than the desired signal. Thus, a desired signal in one part of a circuit is considered to be a noise only if coupled to some other parts of the circuit. EMI is the unexpected effect of noise. If a noise voltage causes improper operation of a circuit, it is interference. Noise cannot be eliminated but only reduced in magnitude until it no longer causes interference.

Generally, a severe EMI issue will occur when assembling diverse electrical parts together in a small space. In our case, several functional units operating at different voltage levels, from 5V to 12KV, are integrated together in the pulse generator. Improper grounding, switching of power modules and improper shielding are all potential noise sources that will cause the abnormal operation of the pulse generator. The major noise sources in the pulse generator and a few strategies against EMI are discussed below.

4.1 Noise Sources

A. Capacitor Charging Power Supply

Fig. 7 shows the wave of high frequency output current of the power supply. In order to reduce the risk of electrical shock, strict grounding is required. Thus, the metal cover of the power supply should be connected with the ground of the AC input. In addition, RG58 coaxial cable is used for the high voltage output, and its shield net is also connected to the AC power ground for the same reason.

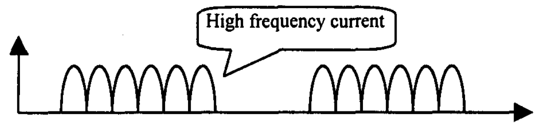

Fig. 7 High frequency output current of power supply

All functional units share the same AC power input in the pulse generator. For safe operation, the chassis of the pulse generator is grounded through the AC power ground. Fig. 8 shows an equivalent circuit for the electrical connection of the power supply. Due to the grounding, there are two paths for high frequency output current of the power supply, which will probably cause EMI.

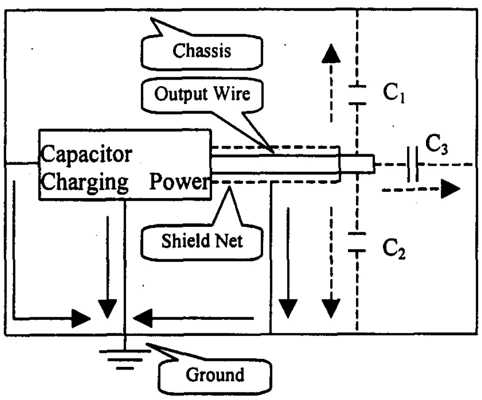

Fig. 8 Electrical connection of capacitor charging power supply

B. IGBT Modules

IGBT is a high-speed power switch. During switching, very high dV/dt occurs on the outputs of the inverter. Fig. 9 is an equivalent electric circuit for the inverter, with grounded return.

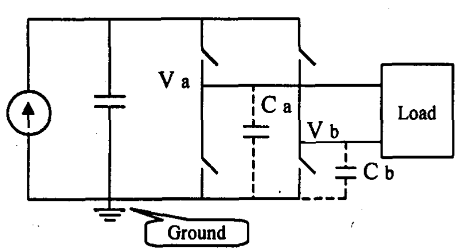

Fig. 9 Stray capacitance for inverter output

There is stray capacitance between the output and ground, as depicted by C_a and C_b. Generally, the bus voltage is around 1 kV, and dV_a/dt and dV_b/dt can reach up to 10 kV/μS, which may lead to conducted currents through the stray capacitance. Apparently, they will pollute the grounding net and generate noise voltages on low voltage electronics circuits.

C. Pulse Transformer

One output wire on the secondary side of the transformer is grounded for safe operation, as shown in Fig. 10. The nominal voltage of the secondary side is 12 kV. All the capacitors connected by dotted lines describe the stray capacitance around the transformer. The stray capacitance not only leads to serious noise voltages, but also alters the characteristics of the transformer.

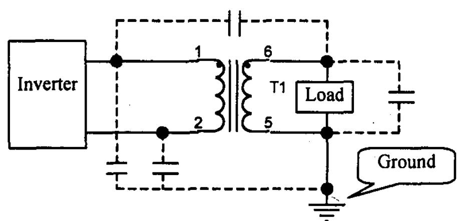

Fig. 10 High voltage pulse transformer

In addition, the secondary side of the transformer generates severe electromagnetic emission due to high working voltage and high voltage varying rate (around 10KV/μS). Thus, proper shielding is necessary for the transformer.

4.2 EMI Elimination

Effective grounding is one of the primary ways of minimizing unwanted noises. Proper grounding can solve a large percentage of all noise problems. In our design, the following grounding approaches are used:

- Chassis is connected to safe ground of AC input power ;
- For low frequency functional modules, like linear DC power supplies, a single-point ground is used;
- For high frequency functional modules, like the capacitor charging power supply, a multi point ground is used;
- Signal ground is isolated from the safe ground;

A. Shielding

For high voltage and high frequency equipment, shielding is usually necessary to protect them from electromagnetic emission. The following shielding is used in our design:

- Shield the step-up high voltage pulse transformer;
- Shield all cables carrying control signals;
- Shield the control unit;

In addition, cable shields that penetrate a shielded enclosure are bonded to that enclosure in order to prevent noise coupling across the boundary.

B. Filtering

Filtering is one of the basic approaches to solve EMI issues. Noises usually span a very wide range of frequency. It is unavoidable that switching noises produced by IGBT modules are always coupled to electronics circuits. Sometimes, it might affect the normal operation of the control unit. In our design, the following filtering is adopted:

- High frequency EMI filters are used in AC power inputs for low voltage functional modules, like control unit and IGBT driver units;
- All interface signals with the control unit are filtered through low-pass R-C filters;
- Digital filtering is used for sampled signals by the controller.

C. Isolation

Electrical isolation is necessary for communication between electronic circuits and controlled functional modules. These are the types of electrical isolation used in our design:

- Fiber optics are used for communication between control unit and IGBT driver units;
- Opto-couplers are used for the interfaces between control unit and knobs on operation panel;
- Relays are used for control signal outputs to capacitor charging power supply and crow bar;
- Isolation transformer is used specially for DC power supply of control unit.

5. Experimental Result and Conclusion

Fig. 11 shows voltage and current waves on a 300-ohm load.

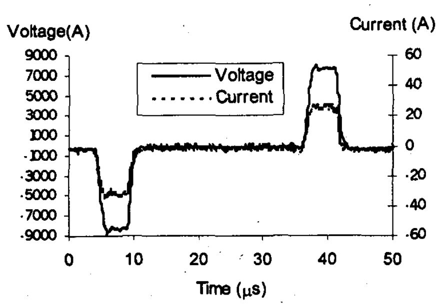

Fig. 11 Output voltage and current on load

It is a new trend to apply the solid state semiconductor technology to pulsed power fields. In this paper, we present our efforts. A few technical keys of the design keys are described in detail. Experimental results have investigated the feasibility of the proposed technical approach.

Reference

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