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Simulation and Modelling of Switching High-Voltage Power Supply

Vladislav I. Kalinchuk[a,*], Artem M. Zhuravlev[a], Aleksey G. Goryunov[a], Indira Zh. Khassenova[b]

[a]Department of Electronics and Automation of Nuclear Plants, School of Nuclear Science and Engineering, National Research Tomsk Polytechnic University, Lenina avenue 2, Tomsk, 634050, Russian Federation
[b]Department of Applied Physics, School of Nuclear Science and Engineering, National Research Tomsk Polytechnic University, Lenina avenue 2, Tomsk, 634050, Russian Federation
alex1479@tpu.ru

A key problem in providing more affordable health care with sufficient quality is in the field of X-ray computed tomography. The provision of high-voltage precision power supplies is of utmost importance to solving this task. The current paper evaluates the previous work done in this field and proposes a model for evaluating possible system designs. The presented study solved some of the problems that arose when studying the operation of a voltage multiplier. Choosing the number of the multiplier cells were taken into account weight and size, and current-voltage characteristics of capacitors and diodes.

1. Introduction

High prime cost of elements is one of the most common types of X-ray computed tomography (X – CT) production problems. The HVPPS is the one of these elements. Under conditions of low competition, HVPPS industry is dominated by a small number of large manufacturers. Development of domestic high-voltage precision power supplies (HVPPS) becomes currently relevant and will solve the problem of monopoly on the world market. X-ray tube is a specific element that is causing the complexity of HVPPS' construction and operation. Power electronics is one of few areas of technology where new schema solutions are in demand. Using simple circuit techniques allows to create different devices with new capabilities. It is impossible to achieve high stability of HVPPS' output signal using the base scheme. The development of such supplies is for those reasons changing. High voltage power supplies are a key component in many analytical instruments. By the nature of analytical applications, test equipment, methods and data must show consistent results. In addition, since analytical instruments are being introduced into the management of production processes, high-voltage indicators such as reliability and stability are very important.
Power supply requirements for analytical instrumentation are very different. The input power source may have a wide range of input voltage characteristics (from 3 to $3*10^5$ V). Often, instead of serially produced products, specialized high-voltage power supplies are needed. In such areas as: mass spectrometry, spectroscopy, X-ray diffraction, X - ray fluorescence, and many others.
Depending on the purpose, the power supplies of electronic facilities perform the functions of inverting, straightening, protecting, stabilizing, filtering, or, and more often, a combination thereof.
X-ray machine power supply is a set of technical means for supplying the electric energy of the X-ray tube. The main feature is the presence in the machine of a mode of blending and images. Blending mode requires continuous operation, for several minutes, at low power (up to 500 W). In a different mode, the tube is switched on for a short time, from 10^{-3} s to 5 s, in modern machines power up to 100 kW.
The primary power source is an electrical grid (electric power distribution network) (single-phase or three-phase). Considering various X – ray tubes power supply schemes, it is possible to identify the main circuit of the feeding device in the form of an adjusting element, an inverter, a high-voltage transformer and rectifiers. The main difference for choosing the circuit and the methodology for calculating the main circuit is the duration of the X-ray research and the sensitivity of the X-ray receivers.

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The main characteristics of devices for powering X-ray diagnostic equipment:

- power 1 – 10^5 Wt
- output voltage 1 – 3*10^2 kW
- instability 0.01 – 1 %
- high voltage ripple 0.1 – 1 %
- modes of operation (blending and images)

All over the world, many scientists are considering the problem of creating a high-voltage power supply. For example, Červinka and Novotná (2018) are developing a supply for cellular electroporation with an intermediate isolated DC link. This is done for the purpose of patient safety. In Jang et al. (2012), development and optimization of high-voltage power supply system for industrial magnetrons are considered. Its construction is based on a series of resonant converters in discontinuous conduction mode. The projected power supply consists of an input rectifier and an inductive filter, a capacitor, a three-phase resonant half-bridge inverter, three step-up transformers, voltage multipliers and a divider circuit for high-voltage measurement. In Li et al. (2015), high-voltage power supply for the electron beam of an electron microscope is developed.

High voltage conversion is realized by means of input mains voltage (AC), low voltage rectifier, medium frequency converter, insulating step-up transformer, high-voltage filter and high-voltage protective resistance. Here, a PI controller is implemented that changes the duty ratio of the PWM signal, and then the inverter executes this change. The developed scheme made it possible to verify that the shape of the output signal coincides with the theoretical one.

Tamuri et al. (2010) describes the development of a high-voltage power supply for electro-optical research. The power supply consists of a driver MOSFET, voltage multiplier circuit and a microcontroller. One timer generates square pulses at a frequency of 1.3 kHz to control a power MOSFET that is connected to a pulse transformer. Using the voltage multiplier, the signal from the secondary winding of the step-up transformer is increased. As a result, the constructed supply power has an output signal with parameters: voltage up to 4 kV, current up to 70 mA, which is suitable for an electro-optical device.

In Kolmogorov et al. (2002), high-voltage power supply system was developed for a diagnostic injector of neutral atoms. Such a supply makes it possible to get a modulated or unmodulated stabilized voltage in the entire required range, with an output current of up to 8 A. This source uses the principle of dividing a high-voltage part, enclosed in a sealed vessel and filled with gas, from a low-voltage part consisting of a multiphase converter operating at a high conversion frequency. The high-voltage rectifier consists of eight rectifying cells connected in series. Each cell in turn consists of a step-up transformer, a diode rectifier and a capacitor filter.

In Petrenko et al. (2016), a high-voltage power supply with improved thermostability for a xenon gamma spectrometer is presented. This supply consists of a control module, switches, a transformer, a voltage regulator and a voltage multiplier. At the output necessary to receive 15 kV and 20 kV DC. The essence of stabilization that the current is supplied to field effect transistors, each field-effect transistor has a feedback with a bipolar transistor. Thus, the resistors in the feedback circuit determine the maximum current flowing through the transformer.

This literary analysis shows, that the majority of high-voltage power sources are developed under the typical scheme. Many developers who are currently creating their own unique device, innovate in a specific node, while not changing the whole core of the device.

2. Methodology for modeling a high-voltage power supply

The basic scheme is compiled by generalizing the schematic variants listed in the literature, it combines most sources with a high output voltage. The result is shown in Figure 1.

The power factor correction is necessary to avoid distortion of the shape input signal and to stabilize the supply voltage of the inverter. The active corrector consists of a power switch – an IGBT-, field-effect, MOSFET- or MOSFET with a built-in diode; a high-speed diode, for example a Schottky diode; buffer capacitor and RF choke, as of an inductor. The input stage is the synchronizer of the input signal. Parameters of the primary source are the values of the electrical supply: frequency 50 Hz, voltage 380 V for a three-phase supply or 220 V for a single-phase supply. This input circuit serves as a rectifier and filter. The input stage is in the form of a strip RC filter.

The inverter is required to feed a high-frequency signal to the step-up transformer. In this regard, a number of problems arise, such as the occurrence of parasitic capacitance, insulation breakdown (sparking), and noise sources. There are a number of different schemes for the hardware implementation of the inverter, such as a bridge circuit, a half-bridge circuit, a resonant circuit. The bridge circuit is used in devices with high power consumption and high voltage. A half-bridge circuit is used in devices where the power consumption is lower, and also to reduce the mass-dimensional parameters. Resonant inverter is used, most often, in the field of electrothermy, where they are used to power induction heating plants. To implement any of these schemes, you need power switches that perform on MOSFET, IGBT-, field-controlled transistors.

The main role in the high-voltage source falls on a high-voltage transformer, where the basis is taken: the large value of the voltage on the secondary winding and the large number of turns. These two parameters, to a greater extent, determine the geometry and technology of cores, as well as winding technology.

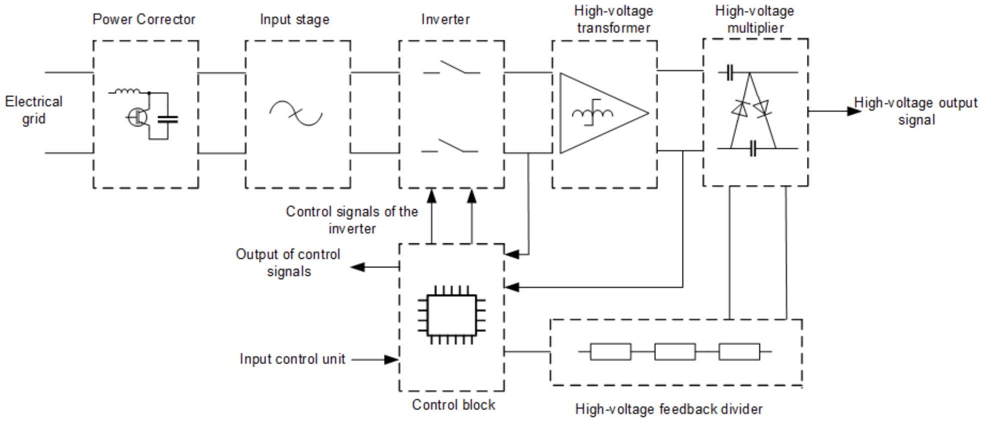

Figure 1: Basic circuit of the source of high output voltage

The high-voltage output stage is a multiplier and a filter of the high-frequency signal received from the secondary winding of the transformer. To implement these functions, high-voltage diodes and capacitors are required, but their switching circuits have different variations. Also, the high-voltage output stage provides feedback and control signals coming in for processing to the source circuit control.
The high-voltage divider of the feedback circuit is necessary for measuring the output voltage, in the general case it is performed in the form of an «ohmic» voltage divider.
The structure of the required model is shown in Figure 2.
The structure of the model fully corresponds to the basic structure of the high-voltage power supply (Figure 1). It is necessary to create mathematical models of the main elements presented in Figure 2.
When designing a model of a precision impulse high-voltage power supply, it is important to take into account the structure of each element. All individual elements of the model are complex electrical and logically programmable devices that perform various functions and use different signals. In this regard, it is necessary to determine the type of each individual element of this model, shown in Figure 2.

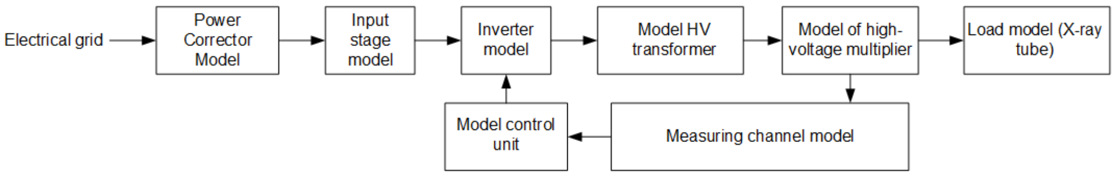

Figure 2: Structural diagram of a high voltage power supply model with load

In order to determine the type of the general model and the elements, it is necessary to find out the type of the signal at the input and output. Signals can be analog, electrical, digital or informational. Analysing the composition of the elements of each block, a functional diagram of this model was obtained (Figure 3)
To implement this model, it is necessary to find out the processes that occur in each of the elements. The main elements of the power factor correction unit are inductance, transistor, diode and capacitance. Therefore processes, which will occur when the corrector is active, are quite simple. When the transistor is opened, a current flowing through the linear law will flow through the inductance, and when closed, the current will begin to drop, charging, through the diode and the capacitor. When the current reaches zero, the transistor will open again. Accordingly, to describe this system, it is sufficient to describe electrical processes.
The input cascade model is a rectifier and a filter. Elemental database devices consist of diodes, resistors and capacitors, as in the previous device you need to describe only electrical processes. All processes occurring in these elements are described in such software tools as Multisim and Proteus.
The inverter model block in the structure has power keys, on IGBT or FETs, controlled by microcontroller signals. As a control signal, current or voltage signals are used. The processes that occur during the operation of this scheme are described in detail in the software tools given earlier.

Pulse high-voltage step-up transformer is the most complicated element in the simulation, since at high voltage there are additional leaks, as well as breakdowns in insulation, which entails various kinds of distortion of the output signal. Considering the fact that a high-voltage transformer must be impulsive and compact in size, it will be necessary to develop a new mathematical model.

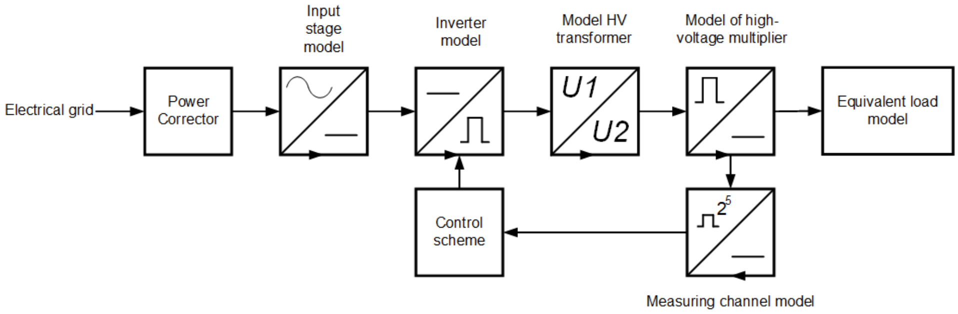

Figure 3: Functional diagram of the model

The voltage multiplier unit consists of diodes and capacitors. These elements, as mentioned earlier, are sufficiently described in software tools as an electrical model, and do not require additional research.
The equivalent load, which is an X-ray tube, is a complex electrotechnical element for modelling, its model will be developed.
The measurement channel model is a complex converter of an electrical signal into a digital signal, which already at this stage introduces enough difficulties. When modelling this block, it is necessary to take into account all its elements, introduced by them inertia and inaccuracy. In addition, the measuring unit must introduce minimal energy losses.
The control unit model is a microprocessor unit that implements a control algorithm based on digital current and voltage regulators. The main functions of this unit are: control of the inverter operation, namely synchronization of switching frequency of power keys due to the supplied output signals in the form of rectangular pulses (control of PWM generators). The model includes an overload protection function that does not allow the elements of the high-voltage power supply to be damaged or damaged. This model also processes the values coming from the real-time measurement model and on their basis converts the error signal into a control signal.
To conduct computational experiments, you need to choose modelling environment. By analysing the possibilities of different media, it turned out that Proteus, Multisim and Simulink are suitable. Proteus and Multisim are environments that focus only on the simulation of electrical circuits, they pay more attention to small electrical components capable of even slightly affecting the results. It is also worth noting that in them it is possible to test the operation of the control algorithm on a specific microcontroller, taking into account its architecture, design, clock frequency, ROM, ADC, etc. The Simulink environment will present a more simplified view of the operation of the control algorithm, which will be sufficient at the initial stages of the power supply simulation. Matlab/Simulink (MathWorks, 2018) is one of the most powerful environments, which has a developed mathematical tool and allows you to set simulation speed and accuracy, Simulink provides ODE solvers with fixed and variable steps, a graphical debugger and a subroutine for estimating the execution time of individual model functions. The program includes convenient tools for building multi-level hierarchical multi-component models, has an extensible library of ready-made blocks, convenient interactive visualization of output signals, means for setting and specifying input effects.
By reason of the high cost and complexity of performing experiments with the high-voltage part of the power supply, it is necessary to perform an experimental simulation of this device with various parameters. Since the device is in itself quite complex, it was decided to conduct various model experiments with some elements of the device, namely a voltage multiplier

3. Simulation of the obtained scheme

To study the multiplier, as a component of a high-voltage power source, with the parameters:

- Input AC voltage 300 V
- Output DC voltage 160 kV
- Output current 0.625 mA

a simplified scheme was used (Figure 4). Input voltage *Uin* - secondary voltage of the step-up pulse transformer, *Uout* - output voltage of scheme.

The first problem that has arisen with the multiplier studies, the number of cells required to obtain an output voltage equal to 160 kV. One cell is the set C1 C2 D1 D2. During the computational experiments on the models of the multiplier, the data were obtained, which are presented at the Table 1.

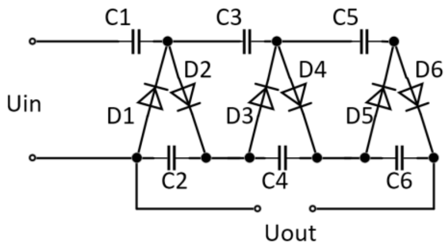

Figure 4: Simplified scheme

Table 1: The data obtained by computational experiments on the models of the multiplier

	Input signal – sinusoidal voltage				Input signal – square pulses			
Experiment No.	1	2	3	4	5	6	7	8
Plate capacity, µF	0.019	0.1	1	6.6	0.019	0.1	1	6.6
Number of cells	440	255	192	192	172	142	135	133

Based on the obtained data, the voltage that each cell of the multiplier adds to the output voltage (160 kV): for the 1 experiment - 363 V; for the 2 experiment - 627 V; for the 3 experiment - 833 V, for the 4 experiment - 833 V; for the 5 experiment - 930 V; for the 6 experiment - 1,126 V; for the 7 experiment -1,185 V; for the 8 experiment - 1,203 V. The second problem in the study of the multiplier was the dependence of the output voltage on the pulse width of the PWM signal, which controls the inverter, the signal from which goes to the transformer and then to the multiplier. To obtain the most complete information, the research was carried out in various software packages and under different conditions.
Software packages:

- Simulink and Multisim

The conditions under which the studies were conducted:

- ideal diodes and capacitors
- Real diodes and capacitors
- Different input frequencies (6, 10 and 14 kHz). The results are shown in Figure 5.

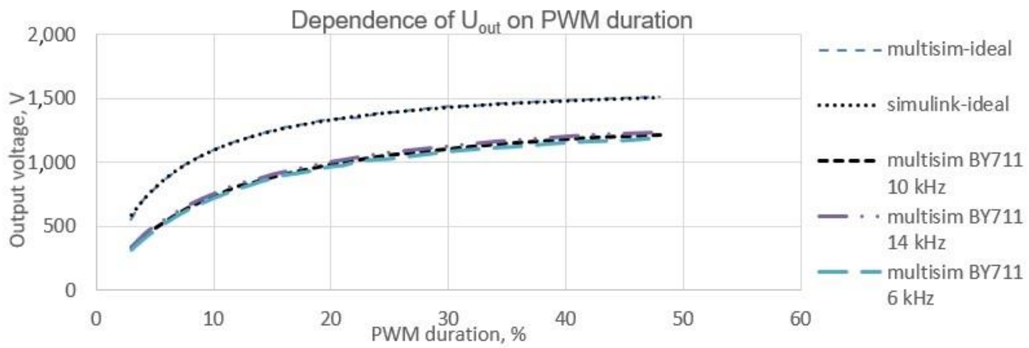

Figure 5: Dependence of U_{out} on PWM duration

As a real diode, BY711 was chosen.
From the obtained graphs it is seen that the characteristic of the multiplier is rather nonlinear, although in the interval from 25 % to 48 %, it is possible to obtain a linear dependence.
When carrying out a computational experiment in various packets with ideal electronic components, it is evident that they are superimposed on this scale, although a slight difference in specific points can be noted.
Analysing the dependencies for real and ideal elements, it can be seen that the real elements have properties under which leakage current exist. Changing the frequency of the PWM signal does not make a big change in

the output voltage, but with increasing frequency, there is a noticeable increase. The next problem was the frequency response of the multiplier pulsations. To study the frequency response of pulsations, a circuit with ideal diodes and 1 k Ohm load resistance was investigated. The result is shown in Figure 6.

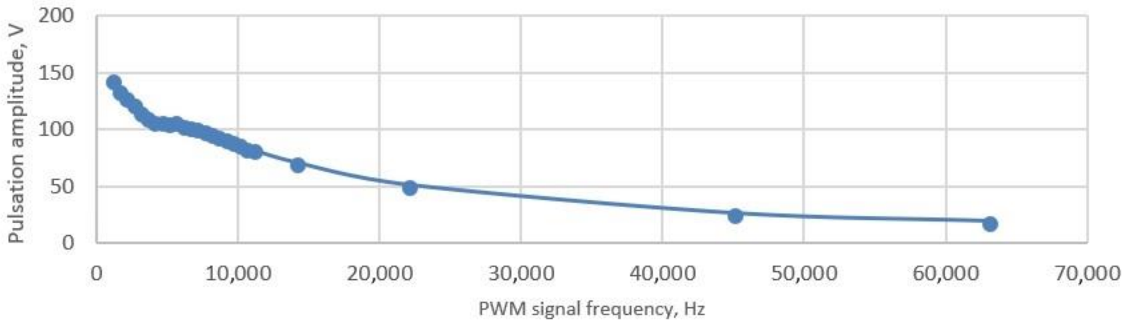

Figure 6: Dependence of the pulsation amplitude on PWM signal frequency

4. Conclusion

Market analysis showed that the development of a precision high-voltage pulse power supply is important. Every state in the world strives to provide citizens with high-quality medicine, but without modern technologies it is quite difficult. Computed tomography is one of the most important methods of studying the human body. High prime cost of elements is one of the most common types of X-ray computed tomography (X – CT) production problems. To these elements high-voltage power supply (HVPPS) must also be added.

At the stage of designing a typical scheme of a precision high-voltage pulse power supply, it was decided to investigate each individual node of this device. In this paper, we solved some of the problems that arose when studying the operation of a voltage multiplier. Choosing the number of the multiplier cells were taken into account weight and size, and current-voltage characteristics of capacitors and diodes. As a result, it was decided to choose capacitors with a capacity of 19 nF. To the next step, the ideal diodes and capacitors were replaced by real ones, in this case BY711 diodes were selected. From the experimental data it can be seen that the real components introduce a voltage drop on the output signal of the multiplier. By solving the following problem, the dependence of the frequency response of the multiplier pulsations on the frequency of the PWM control signal was obtained, from which it can be seen that when the frequency is increased, the amplitude of the pulsations is decreases.

Acknowledgments

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