Circuit modification and research of operation modes of high-frequency pulsed resonant converter of the X-ray tube power supply

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Abstract. Despite obvious drawbacks of the resonant converter, such as complicated calculation, increased size and weight of the device, deviations of the circuit parameters from product to product, the resonant converter shows significant advantages in comparison with other. The task was to design the generator, which is built on a resonant topology.

In the modern market of switching power supplies resonant converters find a narrow scope. This is due to the fact that the process of the development of classical PWM converters is relatively well-established and researched. Therefore, apart from the fact that existing knowledge of the processes in the converter and the years of experience of their calculation and design significantly simplify and accelerate the development of modern power source, circuits, based on the PWM control, are simple and therefore more reliable.

However, despite obvious drawbacks of the resonant converter, such as complicated calculation, increased size and weight of the device, deviations of the circuit parameters from product to product (forcing to carry out a manual configuration of each individual power source), the resonant converter shows significant advantages in comparison with other. These include: lower dynamic losses in power switches, reduced electromagnetic interference, increased efficiency in the use of the transformer core and output rectifier or multiplier [1].

The task was to design the generator, which is built on a resonant topology. The first result was a layout, witch tested on a low output voltage (transformation ratio for simplicity, was taken 1). The Converter was based on LC topologies and showed a good result at the load power 320 W, temperature of switches and reactive elements did not rise above 55 °C. A block diagram of the control shown in figure 1, demonstrates the principle of source control. A microcontroller was selected as generator of control signal because it has greatly simplified the operation mode control and debug from a personal computer, but also increased system reliability, simplified the circuit and improved the ability of control the operating mode of the transmitter: adjustment in a wide range of frequency and duty cycle of the bridge circuit to create the possibility of algorithms of automatic tuning of parameters and calibration. The disadvantage of the use of microprocessor-based systems include the inability to stabilize the output voltage with fast transient response. In addition, the microcontroller is a digital system, so the frequency and pulse width adjustment is limited by the discretization of the internal timers of the chip.
As the input source uses a stable source of 24 V. The adjustment was carried out by a frequency method. With increasing frequency LC filter, which has certain resonant frequency, selects all a smaller part of the main harmonic of the primary signal. The voltage drop at switches at the turn-on time is equal to the voltage drop across the diode that eliminates switching losses. The opposite effect is switching at zero current, when the load is capacitive (frequency below the resonance) and transistors turn-on is lossless. The second method has several disadvantages (increased current load on the diodes, the presence turn-on losses because of transistor’s internal capacitance), so the resonant converters typically operate at frequencies above the resonance frequency of the LC circuit. The exception is topologies, built on the current devices, such as IGBT, which has a “current tail”, or the thyristors, which turn-off will happen in a natural way and without losses (the current through the switch itself reaches zero).

When testing circuits on high-voltage transformer (schematic figure 2) the behavior of the scheme has changed its character. First, the spectral composition of the output voltage in the primary coil was significantly reduced in all investigated frequency range (60–120 kHz, the true resonant frequency of the transducer 72 kHz) the output signal was an almost pure sine. Secondly, it changed the load effect on the resonant frequency of the circuit: on low-load resonant frequency is higher than high that were opposite to the results obtained previously. Thirdly, PWM adjustment (the test was conducted in the range of duty cycle 30–95 %) are now not only distorts the output signal (distortion starts only in the region of small fill factor), but almost linearly adjusts the amplitude of the voltage on the primary and, as a consequence, the secondary winding.

![Block diagram of the converter.](image)

**Figure 1.** Block diagram of the converter.

In the case of high voltage transformer, the secondary winding, because of their large number, form a sufficiently large parasitic capacitance (evaluation value varies in the region of tens of nF). This capacity is connected in parallel to the primary winding. On the side of the primary circuit, the capacity is increased in accordance with the transformation ratio. The obtained scheme is another rather famous variant of resonant topology and is called the series-parallel resonant LCC Converter.

A distinctive feature of the LCC circuit is the increase of the resonance frequency with decreasing load. This is due to the fact that in a resonant circuit contributes to the parallel capacitance, reducing the effective capacity of the LC circuit in accordance with the formula (1):

$$Cr = \frac{Cp \cdot Cs}{Cp + Cs},$$  \hspace{1cm} (1)

where $Cr$ – resulting resonant capacitance, F; $Cs$ – serial capacitance, F; $Cp$ – parallel capacitance, F.

Distinctive features of the LCC Converter are:

- the possibility of voltage gains. At that time, as LC converter operates as a buck converter, a LCC circuit allows to obtain a voltage gain less than or greater than one;

![Electrical circuit of resonant converter.](image)

**Figure 2.** Electrical circuit of resonant converter.
adjustment of \( C_p \) allows to adjust gain and q-factor of resonant LCC circuit: low q-factor allows to simplify the frequency adjustment by reducing the steepness of the gain curve;

LCC Converter provides a cleaner spectral composition of signal on the windings of the transformer, which allows using cores with lower cut-off frequency (and thus greater magnetic permeability);

– in parallel and series-parallel topologies, there is a current flowing through a parallel reactivity and increase the consumption of the scheme: on the one hand, this allows to obtain voltage gain, with another – increases load current [2].

Modification of the power generator to the resonant LCC Converter was carried out. Figure 3 shows a photo of the power board that generates an alternating voltage across the primary winding of the transformer. Since the peak current load on the inductance is about 24 A, it is necessary to take special measures to protect the component from saturation. Magnetic induction in the annular core can be simplistically calculated by the formula (2):

\[
B = \frac{L \cdot I}{N \cdot S} = \frac{A_l \cdot N \cdot I}{S},
\]

where \( B \) – magnetic induction value in the core, T; \( I \) – current through the coil, A; \( L \) – inductance of the coil, H; \( N \) – number of turns, \( A_l \) – specific inductance of the core, H/turn\(^2\); \( S \) – effective cross-sectional area of the core. Thus, to reduce the load on the component (in addition to the protection of saturation the decrease of \( B \) leads to lower losses in the core) reduced the number of primary turns of the transformer. To compensate the additional inductance and reduce a magnetic field in the coil cross-sectional area was increased by combining the three ring cores. In addition, film capacitors of 22 nF was added to reduce dynamic losses when switches turn-off, and external Schottky diodes was added, having the best time and static characteristic than the body diodes of MOSFET transistors. Since the PWM adjustment reduces the load on the transistors and increase the diodes load, diodes in TO-220 package and with a current of 20 A are used in application.

**Figure 3.** Power board of resonant converter and a modified design of high voltage transformer.

A negative consequence of resonant inductance reducing is increased reactive current, especially at high frequencies. This reduces the efficiency of the circuit, therefore the main objective for optimization of efficiency of converter is parallel capacity reduction, i.e. self-capacitance of the transformer’s secondary windings. It is worth noting that in classical PWM generator this capacity has a more destructive effect – it leads to irush current in the switching transistors and, consequently, to serious dynamic losses. The only method of reducing the winding capacitance of the transformer is modification of its design. The main directions in reducing of winding capacitance includes:

– separation of turns with a large potential difference;
– increasing the thickness of the wire insulation;
– separation of the primary and secondary windings.
Also figure 3 shows a photo of a modified design of high voltage transformer. The basically was
taken design with partitioned windings: the winding area is divided into sections [3]. This approach
provides a uniform increasing of potential from one end of coil to the other and, as a result, reduced
capacity. The coil is made of PTFE. After winding the secondary winding (it is wrapped around the
first due to minimal parasitic inductance on secondary side) the PTFE case is put on and the primary
winding is wound. Formed due to the large air gap parasitic inductance is a part of resonant inductance
and does not contribute significantly to the resonance frequency due to the small number of turns
(practical scheme on the primary side used 2–3 turns).

The resonant converter was tested on high-voltage transformer, obtained satisfactory results,
associated with the increasing of the circuit efficiency. It was increased due to the following factors:

– reduced switching losses due to the additional capacitors on the keys;
– body diodes of transistor were replaced by external, more efficient Schottky diodes;
– design of the transformer and the resonant inductance were optimized.

Acknowledgments
Work is performed with financial support and at the expense of a grant of the President of the Russian
Federation for the state support of young Russian scientists MK-1582.2017.8.

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