TENS KILOWATTS POWER SUPPLY BASED ON HALF-BRIDGE INVERTER WITH ZERO CURRENT COMMUTATION

A.V. Akimov#, A.A. Pachkov
The Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

The 40 kW power supply prototype based on half-bridge inverter with zero current commutation has been developed. The power supply is to be used for VEPP-5 modulators pulse forming networks charge up to 45 kV with repetition rate up to 50 Hz. The inverter operation algorithm provides IGBT switching with zero current condition. The power supply test results are presented. The design of the step-up power transformer operating at frequency up to 30 kHz is described.

INTRUDUCTION

At present time in BINP the linear accelerator of the injection complex VEPP-5 is prepared for the full-scale operation. The RF-power supply of the accelerating sections is provided by the 3 GHz klystrons produced in SLAC designed for the 60 kW mean power operation. For the pulse power supply of the klystrons the 40 kW, 50 kV modulators are used. The modulators design has been developed almost 20 ears ago and it has not been considerably upgraded till now [1, 2]. The long term modulators operation has proved the reliability of the present pulse system and at the same time some drawbacks has been discovered. First of all the modulator power supply (PS) has to be upgraded. Today the modulator's pulse forming network (PFN) charge is provided by the resonant charging scheme which comprises such bulky parts as the step-up mains transformer (25 kV), the filter capacitor (9 μF, 25 kV), the charging inductor (20 H). As a result this charging system takes approximately 1.5x1.5x1.5 m^3 of the modulator space. The huge volume is not the only disadvantage of the present PS, it also complicates the modulator exploitation while the PFN charge voltage depends on the repetition rate of the modulator. At the repetition rate 1 Hz the voltage on PFN decreases to the 70-80 % of the nominal level, it occurs because of the discharge through the leakage resistors of the scheme elements. This reasons induced the work on the PS upgrade.

PS CIRCUIT PROPOSAL

Today the most developed and widespread system providing the capacitive storage devices charge up to the voltages of dozen kilovolts at the power of dozen kilowatts are the power supplies based on the full-bridge serial resonant inverters. The manufacturers of such the power supplies (Maxwell Laboratories Inc. and Electronic Measurements Inc.) estimate they efficiency at the level 85-92% at the different output power [3]. The main features of the full-bridge serial resonant inverters are:

- partial charge of the capacitive storage device with the small energy doses which are supplied at the frequency of dozen kilohertz;
- application of the step-up transformer leakage inductance together with the additional capacitor as the elements of the serial resonant circuit;
- use of the four IGBT switches for the full-bridge inverter;
- application of the IGBT's embedded free-wheel diodes as the essential inverter circuit elements;
- zero current switch turning-on;
- nonzero current switch turning-off at low switch voltage;
- high precision charge stabilization at wide voltage range.

There is not so widespread but at the same time quiet perspective PS which can be build on the basis of the half-bridge inverter [4]. Figure 1 presents the half-bridge PS circuit with taking into the account the constructional parameters of the step-up transformer: Ls, Lμ, Ctr – leakage, magnetizing inductances and the transformer capacitance respectively (W1, W2 – primary and secondary transformer windings). This topology allows to achieve both the turning-on and turning-off of the switches at the zero current condition. Also the half-bridge inverter seems to be preferable due to the only two switch equipment, it lowers both the inverter costs and the switching loses. And finally the half-bridge inverter operation in the proposed regime does not need the free-wheel diodes employment. In other respects the half-bridge inverter is similar to the full-bridge inverter.

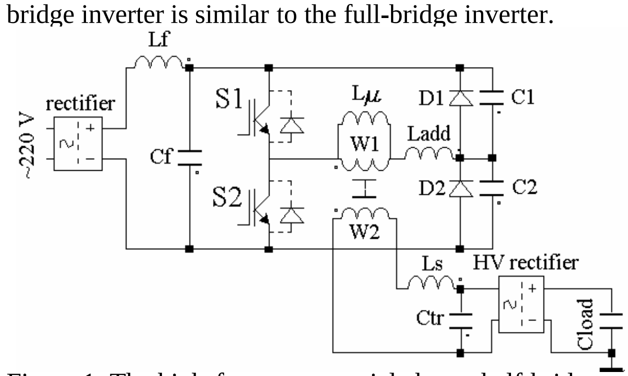

Figure 1: The high-frequency partial charge half-bridge based inverter scheme with taking into the account the parasitic parameters of the transformer.

#a.v.akimov@inp.nsk.su

OPERATION OF THE HALF-BRIDGE PS

For more detailed estimation of the half-bridge inverter operation the 300 W PS for the 200 keV VEPP-5 electron gun power supply was developed [4]. Such PS provides the modulator capacitive storage device charge up to the 3 kV voltage at the 50 Hz repetition rate, it was successfully tested and is being exploited on the gun test stand during three years. Let us consider the operational features of the half-bridge inverter taking for the example the experimental 300 W PS currents and voltages curves.

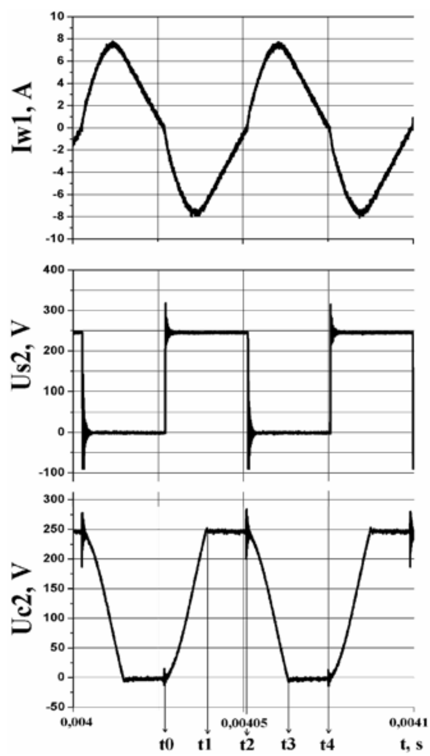

Figure 2: 300W PS current and voltages waveforms.

At the moment t0 (fig.2) the gate trigger voltage of the switch S2 is turned off while the switch S1 is triggered on. After the defined delay the voltage on the S1 switch falls to the minimal level and the S1 switch current starts to flow (negative polarity of the Iw1 current). The rise time of the switch current is limited by the summary inductance Ls + Ladd, where Ladd is the additional inductance which can be used in the case of small Ls value. So the soft zero current IGBT turning-on with the minimal switching losses is provided. When the S1 switch is turned on the discharge of the dosaging capacitor C1 takes place through the serial circuit S1-W1(Ls)-Ladd-Cload, simultaneously the second dosaging capacitor C2 is charged from the rectified voltage supply through the same circuit. At the moment t1 charge-discharge of the dosaging capacitors is over, the supply current is no more consumed and the energy accumulated in the Ls and Ladd inductances starts to dissipate through the serial circuit S1-D1. This process lasts until the inductance current (equal to the switch current) falls to zero. In that moment (t2) the switching of the inverter legs can be done. Due to the minimal IGBT current his turning-off process is taken place in the soft regime with minimal switching losses.

With S1 switch turning-off and respectively S2 switch turning-on there is the analogous process following with C2 capacitor discharge and C1 capacitor charge (t2-t3). So the energy accumulated in the dosaging capacitors and further in the Ls + Ladd inductances is delivered to the storage capacitor Cload through the step-up transformer. The partial charge of Cload capacitance is continued till the specified voltage level is achieved, after that the switches trigger signals are turned off and the charge process is stopped. The Cload voltage stability is defined by the one doze of the dozing capacitor (C1 or C2). At the nominal operation voltage the stability of the 300 W PS did not exceeded 0.5%. The measured PS efficiency is about 90%.

The inverter legs switching driving algorithm is performed with the IGBT current measurement by the ferrite current transformers. The developed algorithm provides the inverter's IGBT turning-on/turning-off at the minimal current value (zero-current commutation) [4].

It is need to be mentioned that the real zero-current turning-off process is hard to achieve due to the transformer magnetizing current [4]. To minimize this current the transformer magnetizing inductance ($L\mu$) need to be heightened. For example, at the attainable $L\mu$ value 4 mH the magnetizing current is about 2 A while the amplitude IGBT current is 500 A.

The successful PS creation experience allow us to start the 40 kW PS development which will charge the PFN storage capacitance of the VEPP-5 modulator up to 50 kV voltage.

Figure 3: Power supply test prototype.

POWER SUPPLY DEVELOPMENT FOR THE VEPP-5 MODULATOR

The test prototype of the power PS was made on the attainable IGBT half-bridge module SKM300GB125D (Semikron) designed for the 300 A (DC current), 1200 V operation (fig.3). For the initial experiments the 10 kW, 40 kV step-up transformer was taken. The low-power load of the PS prototype test stand let us to achieve the 2 kW output power at the 20 kV output voltage. In such regime the IGBT-module operated at the 600 kA amplitude currents and it had not problem with the cooling. The PS driving scheme (fig.3) has been performed on the Altera programmable logical integral circuit.

The initial experimental results have confirmed the advisability of the high-power high-voltage PS development on the basis of the half-bridge inverter. Today the PS variant designed for the 40 kW, 50 kV operation is being built. The new PS employs the high-current IGBT-modules SKM800GA126D (Semikron). This is the single IGBT-switch designed for the 800 A DC-current, 1200 V voltage.

Figure 4: 40 kW, 50 kV step-up transformer.

The 50 kV step-up transformer is done with the use of the cores made from the 5BDSR alloy (AMZ, Russia). The outer diameter of the cores is 330 mm, the inner is 190 mm, the cores width is 25 mm. The transformer comprises two such the cores. The transformer equipped with the rectifying circuit made of the BYX90G (Philips) diodes (fig.4), the water cooling system will be arranged in the oil tank which has the following dimensions: diameter – 480 mm, height – 230 mm.

The 5BDSR alloy has the following specific power losses at the specified values of the applied voltage frequency and the amplitude magnetic induction (Table 1, in the brackets the power losses properties of the permalloy 50NP is presented for the comparison).

Table 1: 5BDSR/(50NP) power losses dependence.

	Voltage frequency	
Magnetic induction	20 kHz	30 kHz
0.15 T		13.5 W/kg (24 W/kg for 50NP)
0.2 T	13.5 W/kg (25 W/kg for 50NP)	

At the transformer rated duty the amplitude magnetic inductance value is expected to be 0.15 T at the maximal voltage frequency 30 kHz.

The following feature of the transformer design can be mentioned. The figure 5 presents isolator which provides the isolation gap between the primary and the secondary transformer windings. The most part of the gap is filled with the mineral oil, the rest part is occupied with the solid dielectric. The isolator height (h) is 12 mm. It is important to provide the electrical strength along the solid dielectric surface. As mentioned [5] in weakly heterogeneous electrical fields with the boundary between the solid isolation and the oil laid approximately along the electrical field line the presence of the solid dielectric changes the breakdown voltage not significantly. It means that in the quiet homogeneous electrical field (E) (fig.5) the electrical strength along the solid isolator surface is comparable with the electrical strength through the main dielectric body (oil). The proper additional experiment was made and it has proved the mentioned statement. So we decided not to extend the isolator surface but to make it equal to the oil isolation gap height (h). At the windings ends where the electrical field is strong heterogeneous the pure oil isolation is provided.

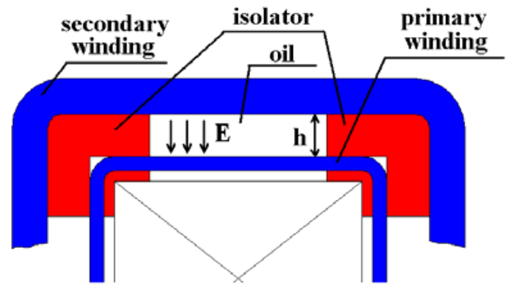

Figure 5: Transformer isolation gap construction.

CONCLUSION

The half-bridge inverter PS prototype test results proved the operation ability of the PS power scheme and the driver board, also it allowed to make precise requirements to the next high-power PS. Today the work on the PS launching on the VEPP-5 modulator is carried on. The next power supply is to provide the 40 kW output power at the voltage 50 kV.

REFERENCES

[1] Pulse modulators for the VEPP-5 injection complex klystron power supply// A.V. Akimov, V.E. Akimov, P.A. Bak et.al. – Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations. 2001, No.3(38), p. 92 - 94.

[2] The VEPP-5 Injection complex modulator revision and operational experience// A.V. Akimov, P.A. Bak, E.A. Gusev et.al. – Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations. 2004, No.2(43), p. 99 - 101.

[3] 240 kJ/s & 120 kJ/s Power Supplies for High Regulation, Minimum Unplanned Downtime Applications /K.W. Harris, F.J. Cathell, B.E. Strickland et. al. *Maxwell Laboratories, Inc.*, San Diego, CA 92123.

[4] The VEPP-5 injection complex 200 kV electron gun modulator power supply// A.V. Akimov, P.A. Bak, I.V. Kazarezov et.al. – Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations. 2004, No.1(42), p. 125 - 127.

[5] High voltage technique// L.F. Dmohovskaya, V.P. Larionov, Yu.S. Pintal et.al. Moscow, Energiya, 1976, 488 p.