KLYSTRON CATHODE HEATER POWER SUPPLY SYSTEM BASED ON THE HIGH-VOLTAGE GAP TRANSFORMER

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Abstract

The power supply system for klystron cathode heater, based on the high-voltage gap transformer, has been developed to transfer 800 Watts up to 130 kV. Power transfer has been implemented by resonant way on the frequency of 19.5 kHz using coupled LC-circuits with further transformation to DC. Transformer coupling factor is of 0.58, high-voltage gap is 49 mm, and maximum calculated electric field intensity is 35 kV/cm. Primary winding is powered by the full bridge inverter using phase shifted pulse modulation. High stability (0.3%) of the output power has been reached using proportional regulation in the feedback circuit. The achieved power conversion efficiency of inverter is more than 0.95 in the regulation range; efficiency of the whole power system is more than 0.88. In this paper we give an overview of the design and test result of the power supply system.

INTRODUCTION

For the European XFEL project horizontal multi-beam klystrons will be installed in the XFEL tunnel and will be connected to the double wall tanks of the pulse transformers. Both, the gun tank of the klystron and the pulse transformer tank need to be filled with oil for normal operation. In order to avoid possible oil leakage during connection of the klystron and transformer tank inside the tunnel, a connection module (CM) was proposed. The CM will be mounted on the support platform of the klystron. It will be connected through the tube socket to the klystron's gun electrodes outside of the tunnel and will be transported to the tunnel together with klystron. The connection to the pulse transformer tank will be done with only one HV cable, because the CM has the filament transformer inside. To reduce the weight and volume of the oil, the design of filament transformer was done as high frequency coaxial transformer. In whole the power supply system consists of CM tank and high frequency power supply (HFPS).

DESCRIPTION AND OPERATION

Basic requirements to power supply developed are presented below:

- The device must provide galvanic isolation for 130 kV potential. Maximum electric field intensity inside the gap should not exceed 35 kV/cm.
- The device must provide the following nominal power supply parameters for three types of klystron:
  Thales TH1801 – 8.5 V, 40 A;
  Toshiba E3736 – 23 V, 27 A;
  CPI VKL8301 – 24 V, 22.5 A
- The power supply stability should not exceed ±0.3% when operating on nominal values.
- Power losses inside the Connection Module should not exceed 120 Watts when operating on nominal values.
- The device should provide the ability to adjust the output power in ±10% limits of nominal values and perform smooth rising of the output power from zero towards nominal value ("heating" mode).

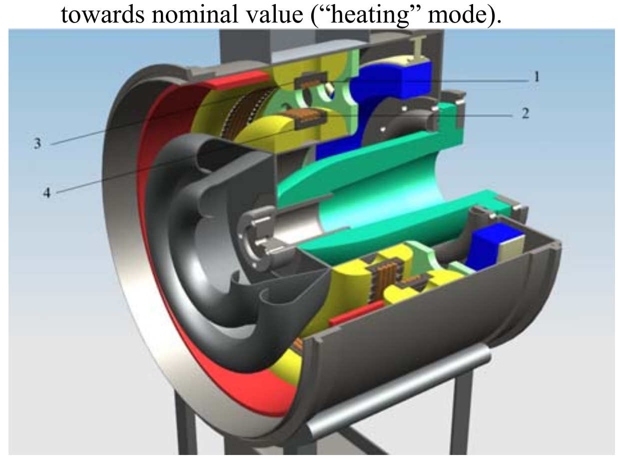

Figure 1: The 3D-model of connection module.

The high-voltage gap transformer design has been determined mostly by the dimensions of connection module – diameter of CM is 642 mm, length of CM is 535 mm (see Fig. 1). High-voltage gap transformer is composed using two annular winding 1 and 2 that are coaxially positioned one inside another with the 49 mm gap. Ferrites cores 3 and 4 increase quality factor and magnetic coupling ratio between windings and reduce leakage fields. When the magnetic coupling ratio between windings $k = M/\sqrt{L1 \cdot L2}$ is significantly less than one, effective power transfer in such a transformer can be obtained using two oscillatory circuits tuned to resonance (Fig. 2). The conditions necessary to get the maximum efficiency for this circuit are the following [1]:

1. Fundamental frequencies of both circuits $f_1 = 1/2\pi\sqrt{L1 \cdot C1}$ and $f_2 = 1/2\pi\sqrt{L2 \cdot C2}$ must be equal to the generator frequency f;
2. Loaded Q-factor of secondary circuit $Q_{2l} = \sqrt{L2/C2}/R_{load}$ should be equal to $1/k$.

The circuit provided on Fig. 2 has the following feature – the current through the load has weak dependence on

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the resistance of load, thus providing current clamping. The load current has the following relation with the load resistance for the resonant tuned circuit:

$$I_{load} = \frac{V_1}{2\pi f \cdot M} \cdot \frac{1}{1 + 1/k^2 \cdot 1/Q_1 Q_{2l}}.$$

Using the formula above for practically values of k~0.5, Q-factor of primary circuit Q_1~100 and changing loaded Q-factor of secondary circuit from 1/k to 100/k the load current increases for 2% only.

The generator of square pulses (inverter) has been used as power supply V_1 (Fig. 2) in practical realization of the system. The input resistance of resonance circuit with serial primary circuit for main frequency harmonics appears highly inductive; therefore there is no need to clamping the current peaks when the inverter voltage rises or falls. The scheme with parallel primary circuit would require such clamping due to capacitive nature of input impedance at high frequencies. Moreover, such circuit doesn't provide internal limiting of current when the short circuit of load occurs.

Optimal parameters of resonance circuits for power transition have been chosen for the most powerful load – Toshiba klystron. The measured values of windings inductance are L1=49 uH, L2=11.7 uH; the measured magnetic coupling ratio is k=0.58; the capacitance of circuits are C1=1.42 uF и C2=5.8 uF. The measured

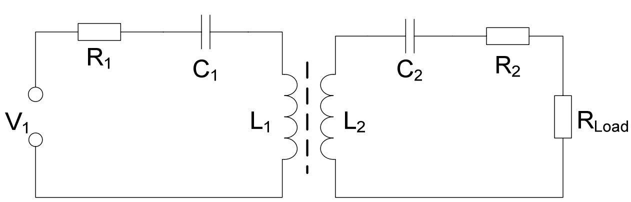

Figure 2: Resonance circuit of loosely coupled transformer.

unloaded Q-factors of circuits are $Q_1 \approx 130$ and $Q_2 \approx 100$ for operating frequency 19.5 kHz. The calculated efficiency for these parameters is equal to 96%.

The inverter with phase-shifted pulse modulation (PSM) scheme [2] has been used as a power supply for transformer resonant circuit. The inverter is based on high-frequency full-bridge circuit implemented on IGBT-switches (IRGB4061DPbF) as shown on the figure below (Fig. 3).

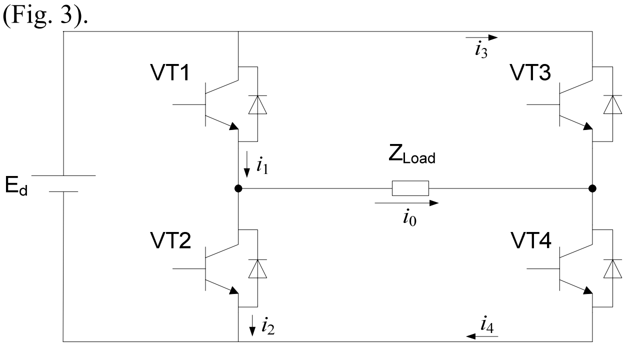

Figure 3: Phase-shifted pulse modulation inverter.

The regulation of inverter output power is carried out using the delay dT between switches VT1-VT2 and VT3-VT4 as shown on the figure below (Fig. 4).

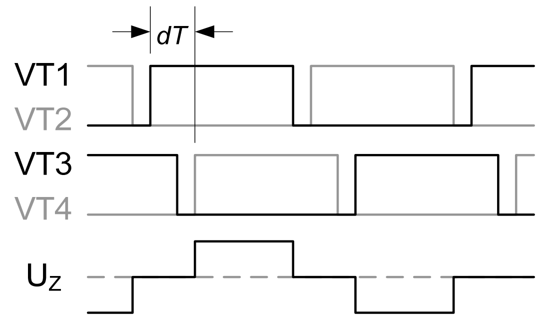

Figure 4: The duty cycle of PSM scheme.

Changing the delay dT allows adjusting the output power from 0 to Wmax. The dependency of output power has cosine form and IGBTs switching is performed with low current through the switches in wide range of delays (soft switching operation). The switching losses are minimal in these conditions therefore a maximum of efficiency is achieved.

The inverter control has been implemented using AT91SAM7X microcontroller (ARM7TDMI core). This microcontroller working on 45 MHz core frequency allows generating 19.5 kHz control pulses with shifts from 2 us to 23 us that corresponds to fill rate from 8% to 92%. The regulation step in these conditions is about 0.2% of regulation range.

The stabilization of output power in this supply system is performed using the feedback loop signal taken from primary resonance circuit of the transformer; therefore the actual stabilized value is the input power of loosely coupled transformer. However, taking in consideration that the resonance circuits and the transformer are linear elements; and diode rectifier used in secondary circuit to obtain DC voltage has losses that change weakly, this stabilization approach has proved to satisfy the klystron cathode heater power supply system requirements.

Also, the hardware protection of power supply has been realized for inverter overvoltage and overcurrent, oil overheat and oil leak conditions. External lockout of the HFPS has provided in a case of vacuum failure. The hardware protection signals are processed by CPLD Altera MAX3000 series.

TEST RESULTS OF KLYSTRON CATHODE HEATER POWER SUPPLY SYSTEM

The connection module test runs were performed with dummy loads of Toshiba and Thales klystrons. Load resistances at nominal power were 0.89Ohm and 0.21Ohm respectively. The net voltage during the tests was 240V rms. The ambient temperature was 25°C. Dummy loads were connected to the output of the rectifier through the open end of the connection module tank. Therefore the tank of CM was not sealed and not filled with oil during the tests. All tests were carried out at BINP (Novosibirsk). The test layout is given in Fig. 5.

Load current was measured using current sensor LT100-P (LEM). Load voltage was scaled to the ADC input range by precise resistive divider. Temperatures of the HFPS and CM tank hottest spots were measured by temperature sensors AD22100. All dc signals from sensors were digitized by multichannel precise integrating type ADC with measuring accuracy 0.001%. Temp1 is the temperature of the matching transformer (T1 on Fig. 5) of the HFPS, Temp2 is the temperature of the CM tank output rectifier (D1-D4).

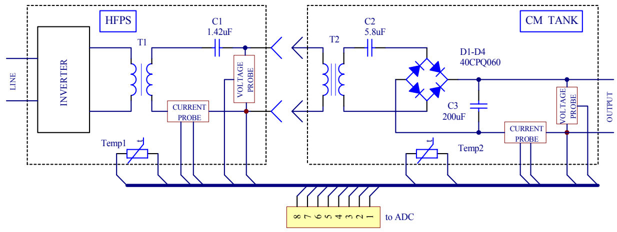

Figure 5: Connection module test run circuit.

Table 1: Test Run Results (Ambient Temperature 27ºC)

Load mode	CM tank Efficiency,%	Stability ,%	Temperature,ºC	
			Temp2	Temp1
Toshiba	92	< 0.3	44	58
Thales	81	< 0.3	54	40

The nominal power test run of the CM lasted 14 hours for each type of dummy load. The obtained results are tabulated in Table 1. During this tests Temp1 temperature did not exceed 58˚C and Temp2 temperature was not more than 45˚C with no forced cooling of the HFPS and CM tank. At the load power 700 W the power losses in the tank did not exceed 64 W. The dependence of the efficiency on the load power is given in the Fig. 6.

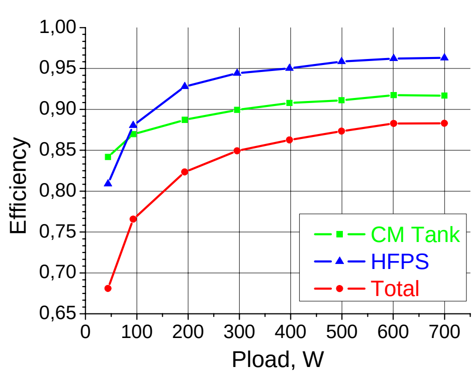

Figure 6: The tank, HFPS and the total efficiency dependence on the output power at Toshiba klystron dummy load.

Figure 7 shows the distribution of the acquired data points during 8 hours test run with Toshiba load. The measured HFPS temperature stability of the output power is not worse than -60ppm/ºC and CM tank temperature stability is less than +140ppm/ºC.

Line regulation test shows that the line regulation is not more than ±0.12% of nominal power over specified input voltage range (240V±10%).

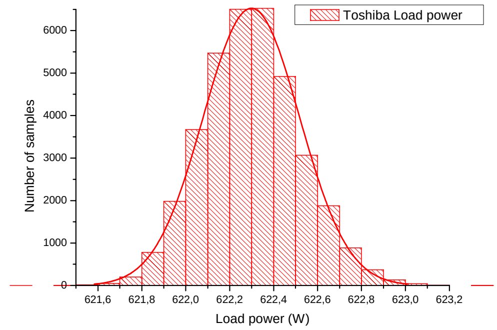

Figure 7: Distribution of the acquired data points during 8 hours test run with Toshiba load.

The inverter switch voltage and current waveforms (Fig. 8) show that soft switching turn-on and turn-off are realized and the inverter main power losses are made up from anti-parallel diode current.

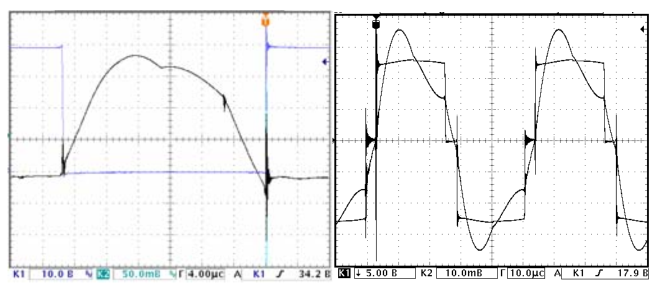
Figure 8: Left – Current and voltage through one of the inverter switches; Right – Interter output current and voltage.

CONCLUSION

The developed klystron cathode heater power supply system complies to all requirements and currently is installed on DESY test stand and is prepared for further tests with horizontal multi-beam klystrons: CPI VKL8301 and Thales TH1801.

REFERENCES

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