HIGH POWER TRANSISTORS FREQUENCY CONVERTER FOR SUPPLY UP TO 500 KW DC ELECTRON ACCELERATORS

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Abstract

In this work, the generalized experience in the development of powerful (500 kW) frequency converters based on JGBT modules designed for feeding industrial electron accelerators of the transformer type is presented. The problems related to the matching of the converter output with the primary winding of the high voltage transformer are considered and recommendations on the converter design are given.

INTRODUTION

The industrial electron accelerators of ELV type are constructed on the base of the cascade generator with a parallel feed of cascades. These accelerators are manufactured in the Budker Institute of Nuclear Physics.

A many tens of accelerators of this series are being operated successfully at the industrial and research institutions of various countries around the world. They are mainly used for the treatment of cable products, for producing thermoshrinkable tubes and films, for waste water treatment and many other technological processes.

The electron beam power for ELV-type accelerators is up to 400 kW. Beam energy range is 0.3 MeV…2.5 MeV.

The design and parameters of the ELV-accelerators are given in many publications (see, for example, [1]).

DESIGN OF ELV-12 ACCELERATOR

Schematically configuration of the high-voltage rectifier of accelerator ELV-12 is shown on fig. 1. The source of a high voltage consists of a primary winding of transformer PW and a column of high-voltage rectifier HVR. The column of the high-voltage rectifier consists of several tens consistently connected rectifying sections. Everyone section contains a secondary winding, rectifying diodes and filtering capacitors. The primary winding feeds by AC voltage of the increased frequency (400 … 1000 Hz).

Distinctive features of configuration of accelerator ELV-12 (400 kW) are as follow: the presence of two primary windings and two columns of the high-voltage rectifier. Columns of high-voltage rectifiers are installed one above another so the high potential applied to accelerating tubes, appears in the center.

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ELV-12 accelerator has three accelerating tubes and three extraction devices: one tube is located inside bottom rectifying column, and two another tubes are installed in remote modules. The high voltage for remote tubes are passed through a gas high-voltage feeder.

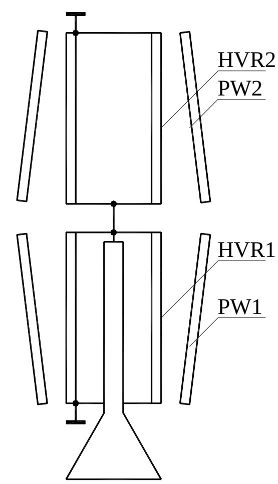

Fig. 1: Configuration of the high-voltage rectifier of accelerator ELV-12

As against the usual transformer the given configuration has essential differences. Extremely simplified linear equivalent circuit is shown on fig. 2.

For ELV-type accelerators inductances L_S and L_μ are approximately the same.

It is related to the fact that the gap between the primary and secondary windings (designed for the total accelerator voltage) is large. The large value of the scattering inductance leads to «sagging» of the output voltage under the load and to the change in the resonance frequency of the power supply-accelerator system.

In addition, inductance values are small (typical value is of 0.4 mH). It means that the primary winding current is high (it may reach a kiloampere and higher). The primary winding voltage can reach 1 kV.

These facts force to insert the circuit for the compensation for the reactive power between the frequency converter and the primary winding of the high voltage transformer.

On fig. 2 the linear equivalent circuit of the high-voltage rectifier together with the circuit of compensation of reactive power is shown.

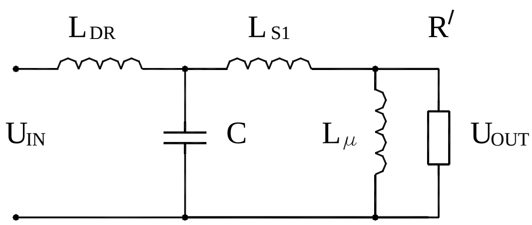

Fig. 2:
L_{S1}- transformer leakage inductance;
L_{μ}- magnetizing inductance;
R- load resistance reduced to the magnetizing;
L_{DR}, R, C – compensation circuit

The analysis of amplitude-frequency characteristics of an equivalent circuit allows us to define values of parameters of the circuit of compensation (L_{DR}, C). It is obvious, that the given circuit provides maximal coefficient of efficiency if the phase of an input current is equal to zero.

Graphs of amplitude-frequency characteristics of an equivalent circuit are shown on fig. 3.

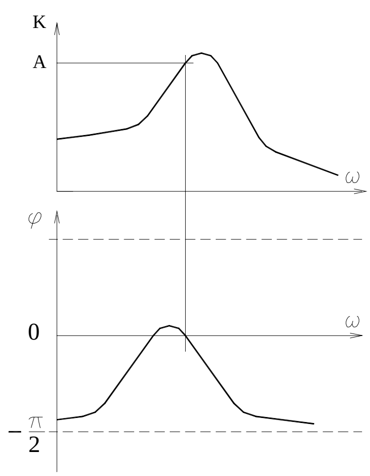

Fig. 3

On the top graph it is the amplitude-frequency characteristic of the circuit, and on bottom - the phase characteristic are shown.

Required value of transfer constant (A) is defined by a necessary a primary winding voltage.

Thus, for a finding values of inductance and capacitor in the circuit of compensation of reactive power we should solve the system of the equations shown below relatively L_{DR} , C. It is necessary to set frequency of the inverter preliminary. The conclusion of these expressions is bulky and not shown here:

$$\begin{cases} \dfrac{k}{\sqrt{(1-T^2\omega^2)^2+(2\xi T\omega)^2}} = \left|\dfrac{U_{OUT}}{U_{IN}}\right| = A \\ \operatorname{arctg}\dfrac{\omega^4 T_1^4+\omega^2(T_2^2-T_1^2-k_1T_1^2)+k_1}{\omega T_2(1-k_1)} = 0 \end{cases}$$

Constants and variables in the given system of the equations can be determined from the expressions shown below.

$$k=\frac{L_{\parallel}}{L_{DR}} \qquad L_{\parallel}=\frac{LL_{DR}}{L+L_{DR}} \qquad T=\sqrt{L_{\parallel}C}$$

$$R=\frac{D^2+M^2}{D} \qquad \xi=\frac{L_{\parallel}}{2R\sqrt{L_{\parallel}C}}$$

$$D=\frac{\omega^2 R^/ L_\mu^2}{(R^/)^2+\omega^2L_\mu^2}$$

$$M=\frac{\omega(R^/)^2(L_\mu+L_S)+\omega^3L_\mu^2L_S}{(R^/)^2+\omega^2L_\mu^2}$$

$$k_1=\frac{L_{DR}+L}{L_{DR}}$$

$$L=\frac{D^2+M^2}{\omega M} \qquad T_1^2=LC \qquad T_2=L/R$$

FREQENCY CONVERTER CIRCUIT

For operation with such loading has been developed a frequency converter based on IGBT half-bridge modules.

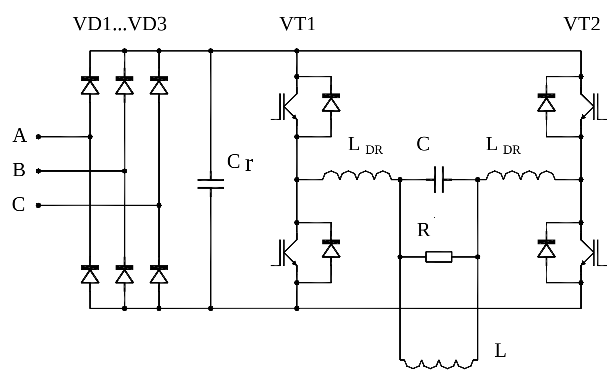

Fig. 4: Simplified power circuitry of converter.
L1, L2, C_P – compensation circuit.

The capacitor bank C_{DC} on the rectifier output composed on film capacitors is installed on the rectifier output. This bank is used for reducing down to acceptable value the overvoltages occurred during reswitching the bridge transistors.

The transistor bridge combines functions of the inverter, output voltage control and also it provides the emergency de-energizing of the accelerator in case of, for example, the high voltage breakdown.

Main Technical Parameters of Converter.

- Accelerator beam power is up to 150 kW;
- For increasing beam power up to 500 kW it is necessary to connect 4 this converters in parallel.
- Coefficient of power efficiency - 95%;

- Output frequency – 400…1000 Hz;
- Range of regulation on the first harmonic of an output voltage of the transistor bridge – 0 … 400 V.

By the operation principle, the frequency converter belongs to the voltage inverters based on the bridge transformer-free scheme with powerful IJBT modules of half-bridges with built-in inverse diodes. The control of primary winding voltage is realized by the variation of the width of output pulse.

Forms of the voltage and current of the primary winding are close to sinusoidal.

For obtaining the maximum voltage on the accelerator primary winding the resonant frequency of the contour formed by the circuit of compensation for the reactive power and the primary winding of the accelerator should correspond to the operating frequency of the converter.

DESIGN OF CONVERTER

Let us note some important moments to be taken into account when designing and arranging the module: rectifier, capacitor bank C_{DC} , transistor bridge VT1, VT2.

In order to provide the switching of the inverter from the short-circuit mode, one should limit overvoltages occurred at the transistor collectors.

At the moment of transistor switching off, the current stored in unductances L1, L2 moves through inverse diodes to the capacitor bank C_{DC}. On the design inductance of wires (buses) connecting C_{DC} with the bridge the voltage increases jumpingly. The computer simulation shows the already of the order of a microhenry the overvoltage pulse value during switching on exceeds much the admissible collector voltages of the transistor bridge, which is inadmissible.

In order to reduce the design inductances to minimum, the inverter design is based on the plane-parallel buses. Capacitors should have very small stray inductance. Calculations show, that the value of capacity C_{DC} should make not less than 10 mkF/kW of output power.

For the beam power more than 100…150 kW one inverter module is not enough for feeding of accelerator. In this case it are possible to use the circuits of addition of power of several modules. The principle of addition of power is shown on fig. 5.

As it was specified earlier the high-voltage power supply of powerful accelerators of ELV type (ELV-6M and ELV-12) has two HV rectifiers. Each of columns has own primary winding. Similar configuration allows, using the biphase inverter to organize a biphase feed for reduction of high voltage pulsations value.

Four described the modules of inverter through reactors DR1 … DR8 are connected in pairs in parallel, forming two independent inverters. Outputs of inverters are connected to the primary windings of high-voltage rectifier PW1 and PW2. Master clock generator G makes two sequences of the rectangular pulses. Shift of phases between these pulses makes a quarter of the period.

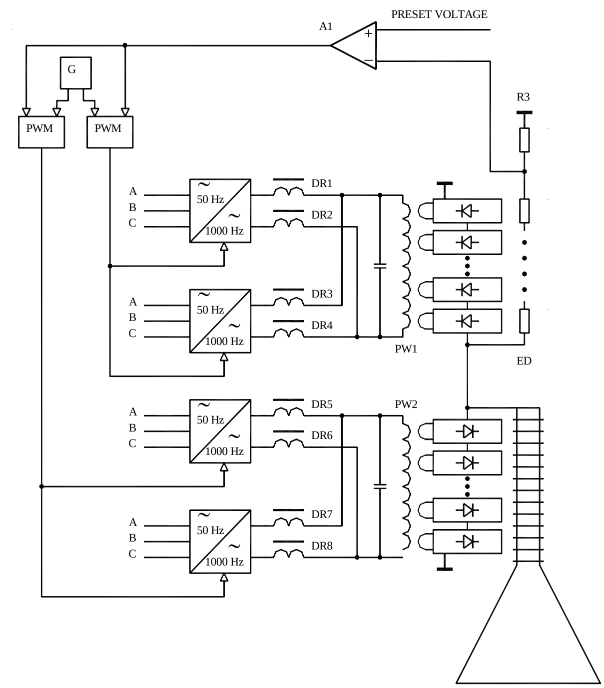

Fig. 5

The energy stabilization system controls the width PWM-signal on an output of the transistor bridge. The loop of a feedback of system includes inverters, high-voltage rectifiers, measuring high-voltage divider ED, the error amplifier A1, pulse-width modulators.

The developed frequency converter was tested together with ELV-12 accelerator for beam power up to 500 kW and has shown high reliability, both at normal operation, and in emergency operation (short circuit on an output of inverter).

If to compare the developed converter with same power electromachine, it is possible to mark, that weight of a transistor converter is tens times less than electromachine one, and its efficiency more than 20% higher in comparing with electromachine one.

Due to small dimensions and weight of a transistor converter all power systems of accelerator are placed in one cabinet. The additional possibilities are opened by simple turning over a wide range frequency of output voltage. The simplicity of the control circuit, high efficiency and convenience of operation allow to hope that the converter will make a worthy competitiveness to the traditional circuits of a power supply of industrial accelerators.

REFERENCES

[1]. Salimov RA, Cherepkov VG, Golubenko JI, Krainov GS, Korabelnikov BM, Kuznetsov SA, Kuksanov NK, Malinin AB, Nemytov PI, Petrov SE, Prudnikov VV, Fadeev SN and Veis ME. Radiat. Phys. and Chem. 2000;57:666.