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HIGH VOLTAGE DC POWER SUPPLIES FOR RF-KLYSTRON-TRANSMITTERS IN ACCELERATORS AND STORAGE-RINGS

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Summary

For klystrons operating in high duty-cycle or cw-modes, the power supplies must meet specific requirements beyond ordinary power supply characteristics. Typical klystron beam voltages range between 40 and 80 kV. Capacitor banks are necessary to avoid rf-phase fluctuations related to beam voltage fluctuations. Hence the stored energies are very high, typically around 20000 Joules. In case of arcing the klystrons can withstand only energies of up to approx. 20 Joules. Therefore crow bar systems are of vital interest in klystron transmitter power supplies. This paper describes design of the PETRA storage ring klystron power supplies and the operational experience.

Introduction

The nominal voltages of the rectifier plants installed at DESY for the klystron transmitters increased from 50 kV in 1963 to 75 kV in 1981 in adaptation to the klystron data. The rectifier power increased from 800 to 2700 kW per installation. Klystrons arc through from time to time and therefore they have to be protected from short circuit current by fast klystron protection equipment. These short circuit requirements determine the design of the installations. - All our 17 transmitter power supplies work as twelve pulse systems. The voltage variation is done on the ac side either by a step transformer at 10 kV or by a symmetrical thyristor ac power-controller in a special intermediate circuit.
Table 1 shows the main data for four available installation types. The design of the installations is briefly described in the following section. Some design details of the main components of the PETRA klystron power supplies are presented.

Brief Description of Plants

DESY

The DESY 55kV-plant was enlarged from 16 to 32 A. Each of two equal phase rectifier bridges connected in series for 16 A are connected with by 30° phase shifted transformer windings to obtain a 12 pulse system. It may be operated in a 6 pulse mode with half power in the case of minor load or faults in parts of the plant. The output voltage may be varied by 41 % of the nominal voltage with a thyristor ac power controller in a low voltage intermediate circuit connected to the bridges near ground. The neutral points of the transformer intermediate circuit windings are connected with each other. This kind of circuit allows thyristors to be used very efficiently[1]. But the transformer windings have to be designed for a $\sqrt{3/2}$ higher rms current. Nowadays semi-conductors are so inexpensive that in general it is avoided to install the heavy load carrying neutral wire. The filter capacitor of 120 μF, designed for 50 Hz pulse load, is of special evidence. The klystrons are protected by crowbar spark gaps against the 150 kWs stored in the capacitor. Not only the klystron but the high voltage rectifiers too have to be unloaded quickly from the short circuit current. This is done by short circuit switches connected to tertiary windings of the rectifier transformers.

DORIS

DORIS has 6 plants which are symmetrically controlled by thyristor ac power controllers in a low voltage intermediate circuit. The transformer neutral points are connected to each other. Detailed information is given in[2].

PETRA Stage I of Construction

The first four PETRA transmitter power supplies were designed for two klystrons with an rf power of 600 kW each at $\eta \geq 0.55$. This resulted in rated dates of 60 kV, 40 A. The voltage ripple had to be limited to $\leq .02\ U_N$. The overshoot voltage was not allowed to exceed the nominal voltage when switching on the nearly undamped filter and the surge current on the 10 kV side must not exceed the nominal current. These restrictions could be met with a step transformer on the 10 kV side. The range of voltage is 0.46 to 1.0 U_N and its step voltage 0.04 U_N. The transformer must be set down to the lowest step before switch-on. The short circuit voltage of the transformers was designed to ≥ 16 %. As a result of this there are voltage differences of 8 % when changing loads. Transformers, rectifiers and chokes are installed in oil tanks in the open air. (Fig. 1). Filter capacitors, protection equipment and modulator were installed in a high voltage room in the neighbourhood of the klystrons. Cable connections, fittings, insulators and distances were designed according VDE 0111 Reihe 45 standards. Fig 2 in[3] shows the schematic circuit diagram of the installations.

Fig. 1 Open air equipment PETRA I - power supply (SR)

PETRA II-, 1 GHz- and 500 MHz-Test Transmitter

2 power supplies with each 75 kV, 18 A for these installations allow the operation of two 800 kW klystrons with $\eta \geq 0.60$ and voltages up to 75 kV. With this high nominal voltage no overvoltages due to sudden load decrease may be tolerated. A constant voltage is advantageous for reliable transmitter operation. In a view of the high power involved semi-conductors and the 10 kV-system have to be protected from short circuit stresses. Therefore we decided on symmetrically controlled ac power controllers in a low voltage intermediate circuit. The transformer neutral points were not connected. Short circuits are quickly switched off by blocking the thyristors, so that the short circuit current may not reach its full value. For this reason there are smaller and shorter voltage drops in the whole system. The phase control system causes higher harmonic contents in the output voltage; therefore the filter must be larger than that for the plants without ac power controllers. The ac power controllers are installed in containers near the transformers to get short cable connections. Each two transformers of a 6 pulse-system are in one tank. Fig. 2 shows the schematic circuit diagram of the plant without the dc load circuit.

Design Features of the PETRA Power Supplies

Operation Switches

10 kV cricuit breakers with oil have proved to be unfavourable for frequent switching. We now use vacuum circuit breakers. In general we now try to use circuit breakers for protection purpose only. The contactors in the intermediate circuit of the ac power controllers serve as operation switches. It is evident that the contactors have to be able to switch off the short circuit currents originating from the dc side. In case of short circuits in the intermediate circuit, the switch off command is passed

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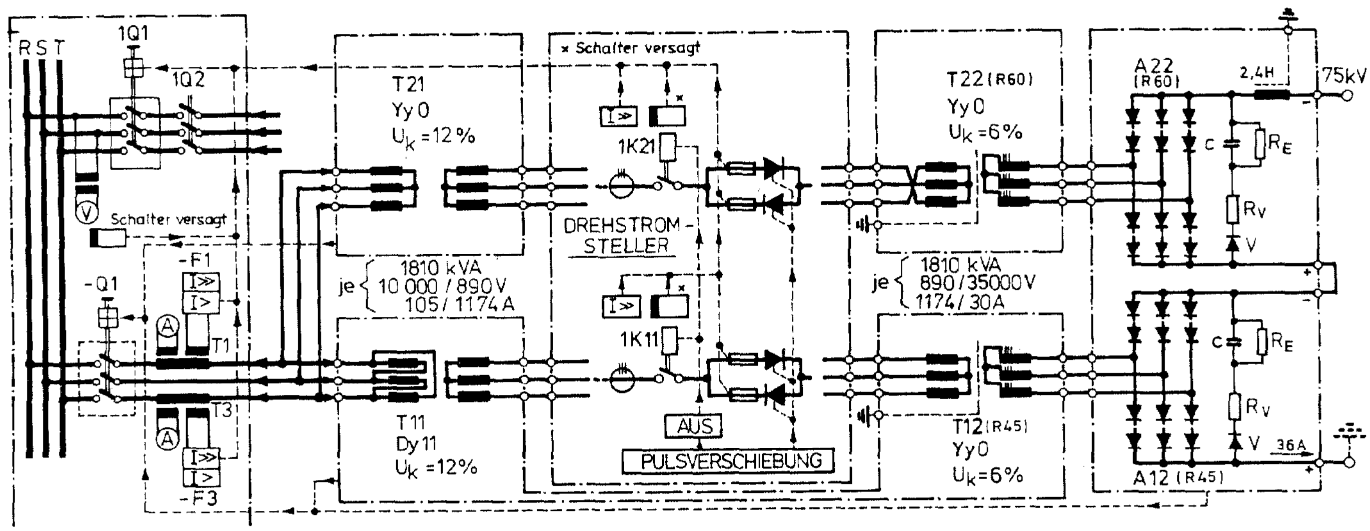

Fig. 2 Principle circuit diagram PETRA II plant (without dc-side)

to a 10 kV breaker which operates several plants. While switching on the thyristors are blocked duringtime required for this procedure. This method decreases the number of switch ons with surge currents and their reactions on the feeding power system. Whenever a switch off is operated the pulses are shifted to the inverter limit. In this manner the contactors, which are interrupting 150 ms later , switch without current.

Transformers

The transformers have to adapt the voltage and the current to the desired values, they have to provide a galvanic separation and shift the phase. Furthermore they have to limit short circuit current. This results in a much higher impedance than usual. Rectifier transformers are designed with reduced induction in order to avoid saturizing caused by quick load changes due to ac controller operation. The adjusting to the allowable klystron voltage is possible in four steps of 7.5 % each by loadless switchable taps on the high voltage side. The additional losses generated by harmonics of higher order on rectifier operation have to be calculated for the design of the transformer tanks.

Three Phase Thyristor AC Power Controller

The intermediate circuit voltage was designed considering the equipment and thyristors available on the market. It was not permissible to connect the thyristors in series. They are fuse protected. But the fuses are only allowed to melt in case of of failures in the intermediate circuit. Short circuits on the dc voltage side, which can be expected frequently, must not influence the characteristics of the fuses, except in case of failure of the pulse blocking and a short circuit current time of more than 50 ms. The result of this is that the fuses - not the thyristors - must be designed in accordance with the expected short circuit current. The thyristors have to be selected so that they are fully protected by the fuses. Overcurrents are measured on the dc-side as well as in the intermediate circuit. Except for the pulse shift to the inverter limit, they activate the contactors in the intermediate circuit or the common 10 kV breaker depending on the amplitude. In case of contactor failure the 10 kV breaker is cut off after 100 ms. The thyristor fuses, provided with indicators each, disconnect directly the 10 kV breaker.

Rectifiers

There are two three-phase current bridges connected in series which are designed for a no load dc voltage of 47 kV each. They are installed in an coil cooled tank together with an overvoltage damping and a smoothing choke. Each branch contains 64 series connected avalanche diodes for U_{RRM} = 1600 V. Each diode is provided with a parallel resistor and capacitor to make sure that the voltage is equally distributed in case of static as well as in case of dynamic operation. The parallel resistors and capacitors - not the diode reverse current or capacity distribution against earth - determine the distribution of the total voltage. The diodes must withstand the short circuit current six consecutive times running with intervals of 1 minute. The permissible junction temperature should not be exceeded. From calculations of the manufacturer it is seen that the design is determined by the first half wave of the asymmetric short circuit current. Each pair of diodes of Type DSA75 - 16 is connected in parallel for economic reasons. 6 diode pairs are installed in series with their wiring in a module. Each 11 modules stacked one over the other form a bridge branch. -After installation of the diodes and the other equipment no further access is possible to the completed unit. Therefore they have been carefully examinated before. Lateron check must be possible. In addition to the usual tests such as insulation, no load operation, warming up with rated current, inductivity measurement, the test of each diode and its wiring, completely mounted, was required before its installation in oil. Furthermore the forward current per bridge branch was measured at constant dc-voltageand temperature. This measurement had to be repeated at each of the six bridge branches with up to three short circuited diodes in each bridge. Measurement of forward current may be repeated in the completely installed plant to check for defect elements after breakdowns. The zinc coated tanks for the rectifiers are provided with radiators in the same way as those for the transformers . The distribution of heat, however, is different from that in the transformers. Furthermore the maximum permissible oil temperature is limited to 75° C by diodes and capacitors. This has to be considered too, when the plant is switched off for regenerating of the oil.

Filter

The filter resonance frequency of 37.5 Hz has been chosen by taking into consideration the 50 Hz interferences which are nearly unavoidable in circuits of such dimensions. In cases of short circuit the current rise time is decreased by high inductivities. Furthermore 1 H at 75 kV is cheaper than 1µF. This consideration determined the choice of 2.4 H and a capacity of 7.5 µF with a stored energy of 21 000 Ws at 75 kV. Two 42.5 kV capacitor groups are connected in series. In case of arcs in the klystron the capacitor is discharged aperiodically by a 20 Ohm resistor. Capacitors have to withstand short circuit currents. This is taken into special considertation when they are tested. Clophen-paper or castor-oil-paper is used as dielectric. The air gap choke must accept the total voltage in case of short circuit. The choke is provided with grounded screen and constructed for small capacity (disc winding).

Klystron Protection

In case of inner arcing in the klystron the energy which concentrates on one point of the tube body must be kept small, so that no roughness or melting pearls can form. Therefore the manufacturer of klystrons usually demand a limitation of the converted energy in the klystron to $W_{Kl} \leq 20$ Ws. The energy W_C stored in the filter capacitor C is by some orders higher. Most of this energy fortunately is dissipated in the series resistor

R_v of the discharging circuit. If the remaining energy is higher than the permissible value $W_{KI\,zul}$, then a klystron protection has to be provided. Calculating the time necessary for reaction of this protection equipment the approx. result is, when neglecting the unavoidable inductivities, and with R_{KI} inner resistance of a klystron in short circuit, and with $T_E = (R_v + R_{KI}) \cdot C$,

$$t_{max} = \frac{T_E}{2} \cdot \ln \{ 1 - \frac{W_{KI\,zul}}{W_C \cdot R_{KI}/R_v} \}; \quad \frac{R_{KI}}{R_v} \ll 1$$

Our values for this: $W_C = 21\,000$ Ws; $R_{KI} = 0.1$; $R_v = 24\Omega$; $T_E = 180\ \mu s$; $T_{max} = 23\ \mu s$.

During this time energy feed cannot be interrupted with aid of switches. Currents may be switched on quicker than off. Therefore usually the element to be protected is by-passed until turn off by circuit breaker. The protection system has to by-pass the klystron quickly enough to cut off the not tolerable amount of energy from the klystron. The shunt resistance or the arc voltage respectively, has to be so small that the rest energy in the klystron will be negligible. The PETRA-plants are protected by crow-bar systems[4]. The systems work with main spark gaps in air. The energy for the trigger circuit is stored in a capacitor. The voltage at the main electrodes may be increased so much by this circuit that prompt arcing occurs. The signal for arcing is given by a di/dt-transducer in the positive leg near ground. Triggering is done with spark gap with auxiliary electrode or ignitron. The auxiliary voltage for capacitor loading is surveyed. In case of failure of the auxiliary voltage the energy storing capacitor will be discharged, and consequently there will be an arcing in the crow-bar system and cut off. For safety reasons the capacitor is discharged and the spark gap arcs before each access to the plant. In this way the function of system is easily checked. We had good operation experience with our four installations until now. Many hundred klystron arcs have been taken up. At the present moment the sensibility of the current rise transducer is so high that sometimes the power supply switches off if the klystron current is suddenly blocked. The operation switches are activated by fully insulated di/dt-transducers, which are connected to each klystron. For realizing a true check of the protection equipment a 0.35 mm copper wire is used which short circuits the installation instead of klystrons. If the wire withstands the test the protection is ok. A self testing system, proving function, and measuring a firing delay time of the spark gap, would be desirable. The switch on order should then only be performed if the test was successful. Improvements are planned after completion of the transmitter plant.

Control

It is nearly impossible to go down to the small load range by fast regulating because of the energy stored in the capacitors. The complete blocking of the klystrons is avoided by the modulator. The momentary voltage actual value is derived from a compensated voltage divider. The nominal voltage is given via our DISSY-control-system with sub-controlled DA-converters as used for magnet power supplies. The control system is a DESY development, it is described in[4]. The thyristors are supplied with $180^\circ - \alpha$ pulse chains. The voltage controller gets a "fast window" of about $\pm$ 10 % of the range. The remaining range is traversed slowly. This also avoids saturizing of rectifier transformers.

Operation Experiences

With regard to failures, the switch and control units are at the top of the maintenance and repair list. The protection of the semiconductors of the control system against damage by over-voltages in case of short circuits is difficult. Clear definition of potentials, starlike earthing, avoidance of double earthings - this must be checkable - are absolutely necessary. Whereever possible the main and auxiliary circuits are galvanically separated. A voltage rating of at least 5 kV is recommended for the transducers. The plants have been operated upto now for more than 200.000 hours. Having in mind this figure the number of failures is very small.

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Table 1
Main Data of the Plants

			DESY	DORIS	PETRA Stage I	PETRA Stage II	1 GHz/500 MHz Test-Transmitter
Number of plants			1	6	4	4	2
Transmitter power	P_{WRF}	kW	4 x 125	250	2 x 600	2 x 800	800
Rated active power	P_{WN}	kW	2 x 850	765	2280	2700	1350
Total power	P	kVA	2 x 1220	1298	2500	3620	1800
Nominal direct voltage	U_{dN}	kV	55	45	60	75	
Transformer secondary voltage	U_{2Tr}	kV	20/28,7	21,6/26,6	23,7/23,7	35/35	
Short circuit voltage (I_{Nd})	U_k	%	11,9+ 8,3	9+ 9	16	16	11 + 16
Range of voltage variation	U_{min}/U_N	kV	33/55	10/45	28/60	10/75	10/75
Nominal direct current	I_{dN}	A	16+16	17	38	36	36 18
I_{kd}/I_N (direct voltage side)			5,8	6,4	7,3	6.0	
Filter inductance	L	H	2x 0,75	1,8	0,2	2.4	
Inductor energy (I_N)	W_L	WS	192	260	145	1555	390
Filter capacity	C	µF	120	17	5,6	7.5	
Capacitor energy (U_N)	W_C	Ws	150000	17300	10000	21000	
Klystron protection			spark gap, triggered fr. I_K		spark gap, triggered from di/dt		
Voltage Variation by			ac power controller		step transf.	ac power controller	
Intermediate circuit voltage	U_{ZL}	U_{eff}	865	680		890	
Intermediate circuit current/phase	I_{ZL}	A_{eff}	2 x 333	2x551		2x1360	2x680