THE S-BAND TRANSMITTER DESIGN FOR THE INSTITUTE OF ACCELERATING SYSTEMS AND APPLICATIONS RACETRACK MICROTRON

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Abstract

A high-power CW (continuous-wave) source, at 2380 MHz, for the IASA (Institute of Accelerating Systems and Applications), (Athens, Greece), Microtron (see Table 1.) is based on the CPI (Communications and Power Industries) type VKS-8270 multi-cavity klystron. The high-level DC power conditioning for the klystron uses an existing high-voltage transformer-rectifier (HVPS) and variable-voltage transformer (VVT), designed to operate from 60 Hz power, whereas the local power is at 50 Hz. Other features include a new electronic crowbar system and high-speed primary-power disconnect.

1 INTRODUCTION

To transplant the Microtron RF source to its new venue, making use of its iron-cored components, adjustments are made for the use of 50 Hz primary power instead of 60Hz. In addition, a more effective electronic crowbar and surge-current limiting, for protection in the event of a klystron gun arc, is provided. A simplified schematic of the system is shown in Figure 1.

Table 1: The main characteristics of the IASA Cascade RaceTrack Microtron.

	Injector	RTM I	RTM II
Injection Energy [MeV]		6.5	41
Gain per Turn [MeV]		1.32	8
Number of Recirculations		26	25
Max Output Energy [MeV]	6.5	41	240
Max Current [uA]	600	100	100
Incremental Number ν		1	1
Magnets Field [Tesla]		0.22	1.34
Spacing [m]	8.8	3.25	8.7
RF Power Consump. [kW]	117	29	168

2 Effect of 50 Hz Line Frequency

The VVT and the HVPS were designed to operate from 13.8 kV, 3-phase, 60 Hz power. With 50 Hz power the voltage must be reduced by a factor of 50/60 for the volt-time integrals to be the same to avoid iron-core saturation. The maximum line voltage is thus 11.5 kV. The local power is at 20 kV L-L, which must be stepped down to 11.5 kV. This is done with a "bucking" transformer, T1, whose primaries are across the 20 kV and whose 8.5 kV secondaries are in series-opposition with the 20 kV line, yielding 11.5 kV L-L with only 74% of the kVA rating of a 20kV/11.5kV transformer.

3 AC to DC Converter

3.1 Variable-Voltage Transformer (VVT)

The VVT is of dry construction, air cooled, and housed in an enclosure 8.8' x 7.5' x 9.1', weighing 15,000 pounds. At its simplest, the VVT, T2, is a linear-format version of a variable autotransformer. The advantage of linear is increased contact surface area. The disadvantage is increased leakage inductance of the magnetic circuit. The VVT circumvents leakage inductance by means of a transformer with a multiple-tapped secondary winding. The multiple taps are connected to points along the linear winding, short-circuiting the leakage reactance. The E-70381 VVT is far more complicated than just three ganged variable transformers however. Each phase has two linear commutating windings and a transformer whose primary winding bridges the incoming line and which has dual secondary windings, each with 14 taps. There are two sets of dual brushes on each commutating winding, one at each end, motor driven in opposite directions. The brushes are connected to the primary of each phase of a "buck-boost" output transformer. One side of each secondary winding is connected to a tap on the input transformer secondary, which establishes the mid-point of the adjustment range. With the brushes opposite each other, the primary voltage is zero and the output is the midpoint voltage. As the brushes are driven away from each other in one direction, the primary voltage increases in the "buck" direction reducing the output. When driven in the opposite direction, the primary voltage increases in the "boost" direction increasing the output. With 13.8 kV, 60 Hz input, the minimum voltage is 6.2 kV, and the maximum, no-load, is 14.1 kV, 28% buck and boost. With the 11.5 kV, 50 Hz input the corresponding values are 5.2 and 11.75 kV.

3.2 High-Voltage AC-DC Converter (HVPS)

The E-18645 HVPS is oil-insulated, self-cooled, housed in a steel tank 5.25' x 7.1' x 8.8', and weighs 28,600 pounds.

The HVPS, PS1, has a step-up transformer with a single 3-phase delta primary and two secondary windings, one delta and the other wye, having identical line-line voltages. A three-phase, full-wave rectifier (six-pulse) is connected to each set of windings, and the rectifier outputs are connected in series-aiding. There is an inherent 30-degree phase difference between the outputs of the delta and wye windings, which interleaves the conduction intervals of the 6-pulse rectifiers, producing a 12-pulse output with 30-degree conduction intervals. The first theoretical ripple component is the 12^{th} harmonic, or 600 Hz, having a no-load amplitude of 2/143 of the DC component. The average output is 0.9886 times the peak AC input and the peak-valley ratio is 0.97. Line voltage amplitude imbalance, however, produces ripple components at 2, 4 and 6 times the line frequency. Load current produces phase-phase commutation delays in the rectification process because of AC source inductive reactance, primarily leakage reactance. Because of these imperfections an internal ripple filter comprising a 7.5 H voltage across which is proportional to klystron beam current.

4 Protection for the Klystron

The klystron, V1, is prone to breakdown between cathode and body, which short-circuits the DC input. The threats to the klystron are the energy and charge stored in the capacitance and the charge transport produced by short-circuit current before the switchgear disconnects the input line.

4.1 Capacitive Stored Energy and Charge

The energy and charge stored in the 4.3 uF capacitor at 54 kV are 6.3 kJ and 0.23 Coulomb. The fundamental protection against stored energy is current-limiting resistance in series with the klystron cathode. It is optimally effective if it limits current to 1000 A or less.

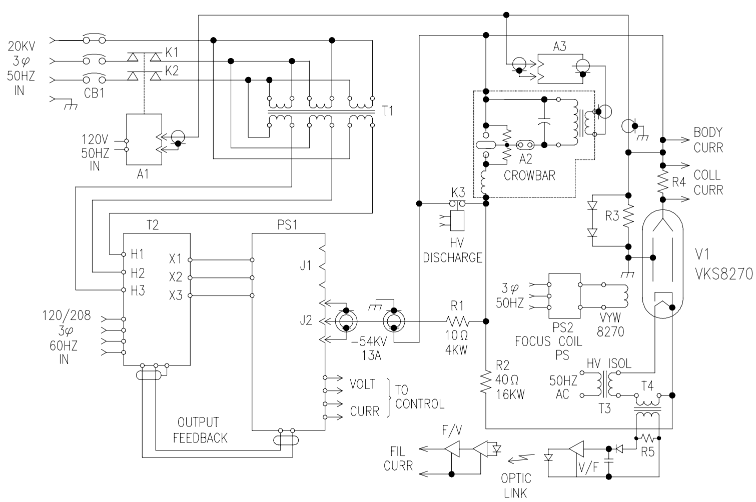

Figure 1: A simplified schematic of the IASA transmitter

series inductor and a shunt capacitor of 3 uF is used.

With 13.8 kV, 60 Hz, the combination of VVT and HVPS produces an output variable from –33 kVDC to –65 kVDC, at 16.5 ADC. With 11.5 kV, 50 Hz input, the output range is –27.5 kVDC to –54 kVDC. In order for the filter to have the same ripple-reduction at 50 Hz as at 60 Hz the shunt capacitance is increased by the square of 60/50, or 1.44, to 4.3 uF.

An internal 65 Megohm resistor is connected to the HV terminal of the transformer-rectifier. At the low end of the resistor is a current meter and an 8.2 kOhm fixed and 5 kOhm variable resistance, in series with the low-voltage return. The voltage across the resistors is fed to the control input of the VVT, for voltage regulation. The current meter output is proportional to output voltage. In series with the low-voltage return to the rectifier is a high-speed current-overload relay and a 20 A. meter shunt, the

At this current vacuum arcs are stable and have voltage drop of 20 Volts or less. This calls for approximately 50 Ohms series resistance. Following an arc, all but 20 V of the capacitor voltage will be across the series resistor. Most of the 6.3 kJ is dissipated in the resistor. With the VKS-8270 operated at 54 kV beam voltage, and corresponding beam current of 11.4 A the resistor voltage drop is 570 V, reducing actual klystron beam voltage to 53.4 kV.

4.2 Short-Circuit Power Supply Current

The second component of charge transport is short-circuit power supply current, limited by the series reactance on the AC side of the rectifier, measured to be a total of 10%. The rated output current is 16.5 A. The short-circuit current will be 165 A. Opening within ½ cycle, 10 milliseconds at 50 Hz, the charge transport, with half-sinusoidal waveform, is 1 Coulomb.

4.3 Klystron Arc Energy and Discharge "Action"

With no protection other than series resistance and ½-cycle primary interrupt, the energy dissipated in an arc, assuming constant arc drop of 20V, is 20 V x charge transport = 20 V x 1.23 C = 24.6 J. Also of importance is the "action" or the time integral of the square of the discharge current, which determines the temperature-rise of a conductor passing the current. The component due to stored energy is 6.3 kJ/50 Ohms = 126 Amp-squared-seconds. The component due to ½-cycle follow current of 165 A peak is 136 Amp-squared-seconds. The total of 262 Amp-squared-seconds is slightly more than the 207 required to fuse an AWG #30 copper wire. This is often the criterion of efficacy of a protection system.

4.4 Series Resistor Characteristics

The resistor must hold off at least 54 kV, dissipating an average power of 6.5 kW, during normal operation, and a total impulse energy of 6.3 kJ, due to stored energy and 6.8 kJ due to short-circuit power-supply current without exceeding a peak temperature of 375 ^{0}C. Resistors of the edge-wound type are custom-designed by Milwaukee Resistor Corp to have sufficient surface area and resistive mass to do this, using special high-mass/Ohm resistive alloys. A total of ten 5-Ohm, 2-kW resistors are used.

4.5 Electronic Crowbar

It is considered prudent to additionally protect the klystron by means of an electronically-triggered low impedance, such as another arc, shunting the high-voltage isolated by a portion of the series resistance. In this case a mid-plane-triggered air-insulated spark gap, of the "infinite-voltage-range" type, A2 is used. It is triggered by the output of the crowbar driver, A3, which is stepped-up to a 200 kV open-circuit pulse by a pulse transformer and applied to the midplane electrode through a sharpening spark gap. The spacings between the midplane electrode and the upper and lower main electrodes are biased so that the trigger arc will be to the electrode having the inductor in series with it, which prevents the arc from short-circuiting the trigger source, allowing the gap between midplane and the other electrode to ionize as well, without the need for external high voltage between main electrodes, hence "infinite voltage range". The 50 Ohm series resistor is divided into two segments, one of 10 Ohms, R1, and one of 40 Ohms, R2. The high-side of the crowbar is connected to their intersection. The 40 Ohms in series with the klystron is much higher in impedance than the fired crowbar, assuring that most of charge is diverted from the klystron. The maximum peak current through the crowbar is 54 kV/10 Ohms = 5400 A.. Having a crowbar means that the 10-Ohm segment in series with the crowbar must meet all of the impulse criteria described in 4.4, since the crowbar protects the remaining 40 Ohms as well as the klystron.

4.6. High-Speed Mains Disconnect

The 20 kV circuit breaker, shown as CB1, has an opening time of 3-5 line cycles, which is too long. At 20 kV line voltage, solid-state SCR-based relays are impractical. Vacuum relays, however, with close-spaced contacts, can achieve opening times as short as 2 milliseconds, or 1/5 cycle, giving ½-cycle clearing time, assuming the post-opening arc extinguishes at the current zero crossing. Only two such relays, Ross Engineering HBF-51-NC, K1 and K2, are required, with normally-closed contacts. They are driven open by the output of an SCR-switched stored-energy driver, type HCB, A1.

5 Klystron RF Amplifier

The VKS-8270 multi-cavity CW klystron amplifier has coaxial RF input, waveguide RF output, electromagnet beam focussing, and liquid cooling. Filament power is from a high-voltage isolation transformer, T3. Filament current is monitored by series transformer, T4, developing voltage across R5, which is rectified, converted to a train of optic pulses with frequency proportional to voltage, and converted back to voltage, at ground level. Focus coil excitation is from PS2. Voltages proportional to body and collector current are developed across R3 and R4. R3 is shunted by high-surge-current diodes to conduct the current resulting from a gun arc. The voltage drop is clamped to 7 V, which is the fault input to the crowbar driver and the stored-energy driver, which have 5 V input thresholds.

Klystron tests, at 2380 MHz, with beam voltage of 65 kVDC and current of 15.1 A showed power output of 490 kW with 1 Watt RF input. With 50 Hz primary power, however, the DC beam voltage available is only 54 kV. Beam current drops as the 3/2 power of voltage and beam power by the 5/2 power. RF output drops even faster than the cube of beam voltage because it is proportional to the square of the fundamental-frequency RF current traversing the output gap, which, at best, diminishes as the cube of beam voltage. As beam voltage is reduced, the spacing between RF cavities is no longer optimum because the beam velocity is lower and bunching effectiveness is diminished, reducing further the RF component of current. The peak RF voltage across the output gap falls more rapidly than beam voltage. Some of the loss in RF power can be regained by means of a properly positioned iris in the output waveguide to effect an increase in the RF impedance reflected into the RF output gap of the klystron, restoring the match between RF impedance and electron-beam impedance, which varies as the ½ power of beam voltage.