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TH-3 Microwave Radio System:

Power System

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This paper describes TH-3 powering arrangements, particularly the traveling-wave tube dc-to-dc converter.

I. INTRODUCTION

One design goal for the TH-3 radio system was to use or adapt, as much as possible, existing TD-3 powering arrangements. A number of power-related TD-3 facilities, requiring little or no change for TH-3 use, included the −19-volt regulator, the common −24-volt battery plant, and dc distribution and radio-building grounding arrangements. These items will not be discussed here, as they have been detailed in an earlier paper.[1] On the other hand, the 6-GHz, ten-watt, RF output-power objective for TH-3 required a new TWT, coded the 464A,[2] and an associated TWT power supply.

II. TRAVELING-WAVE TUBE DC-TO-DC CONVERTER

2.1 *Circuit Description*

The traveling-wave tube is powered by a dc-to-dc converter which provides all electrode voltages required for the 464A TWT. These requirements, shown in Table I, reflect a general 50-percent increase in electrode high-voltage and current levels over corresponding TH-1 and TD-3 TWTs,[3,4] resulting from a higher unsaturated output-power objective.

The nominal switching frequency of the TWT converter is 23 kHz, whereas 2 kHz is used in TD-3. Concern over possible personnel annoyance and fatigue at the audible frequency, as well as a desire to utilize the existing TD-3 framework and housing to contain the higher-power conversion circuitry of TH-3, required converter operation in the ultrasonic range.

TABLE I—TWT SUPPLY REQUIREMENTS

Electrode	Voltage	Voltage Stability*	Current	Ripple (rms)
Anode	Adjustable, +50 to +850V with respect to the helix voltage	±30V with respect to cathode	0 to 1 mA	25 mV at 40 kHz
Helix	Adjustable, +3600 to +4400V with respect to cathode	±20V with respect to cathode	0 to 4 mA	6 mV at 40 kHz
Cathode	Fixed, −1825V with respect to collector	−1500 to −2000V with respect to collector	59 mA	1.0V
Collector	Connected to ground	—	—	—
Heater†	+7.5V with respect to cathode	±150 mV	0.8 to 0.9A	100 mV
TWT Coil	−24V with respect to ground	−21 to −28V	25 mA	100 mV (p − p)

* Over normal ambient operating range of 55°F to 95°F.
† 9.1 volts during timed, preheat interval.

A block diagram of the dc-to-dc converter is shown in Fig. 1. The nominal −24-volt battery voltage input is regulated and filtered to approximately −17 volts by the heater regulator and applied to the 23-kHz square-wave oscillator. Three square-wave outputs are provided from the 23-kHz oscillator. Of these, two serve as switching transistor base-drive signals to the collector inverter and helix inverter, respectively, while the third output is rectified and filtered to provide 7.5-volt dc heater voltage for the TWT. The heater output voltage is a measure of the voltage impressed on the oscillator, and thus the heater output voltage is regulated. This relationship is used to advantage during the 5-minute cathode preheat interval immediately following supply turn-on, when the heater regulator output voltage is initially held at −20.5 volts, resulting in a heater output voltage of 9.1 volts dc. During this interval, the high heater voltage ensures that (*i*) the TWT cathode is not temperature limited when high voltages are applied, and (*ii*) the high cathode temperature tends to reactivate the surface, thus lengthening the cathode lifetime. At the end of the cathode preheat interval, the electronic time delay relay TD automatically restores the heater regulator output to −17 volts, thereby lowering the TWT heater voltage from 9.1 volts to 7.5 volts. Both heater output voltage levels are adjustable over small ranges, should adjustment become necessary.

The square-wave output voltage from the 23-kHz oscillator cannot be used directly as base drive to the collector and helix inverters. Charge storage in the base region causes power switching transistors to consistently exhibit longer turn-off times than turn-on times. This causes a condition commonly referred to as "switch-through" to occur in an inverter driven by square-wave base drive. "Switch-through" is defined as the overlapping in time of the collector currents of the on-going and off-going switching transistors, and is often the major cause of excessive inverter switching loss and device failure. In order to prevent "switch-through," shaping networks are placed in the base drive paths to the collector and helix inverters.

The base-drive shaping network appearing within the dashed box of Fig. 2 operates in the following manner: Assume that transistor Q1 is off, that Q2 is on, and that the polarity of base-drive winding 5-6-7 on transformer T1 has just commutated, with terminal 5 now positive with respect to terminal 7. A load current, I, will begin flowing as indicated on Fig. 2. Since the core of L1 is not saturated at this time, windings 1-2 and 3-4 are magnetically coupled as a one-to-one transformer. Hence, a current equal to $2I$ must simultaneously flow

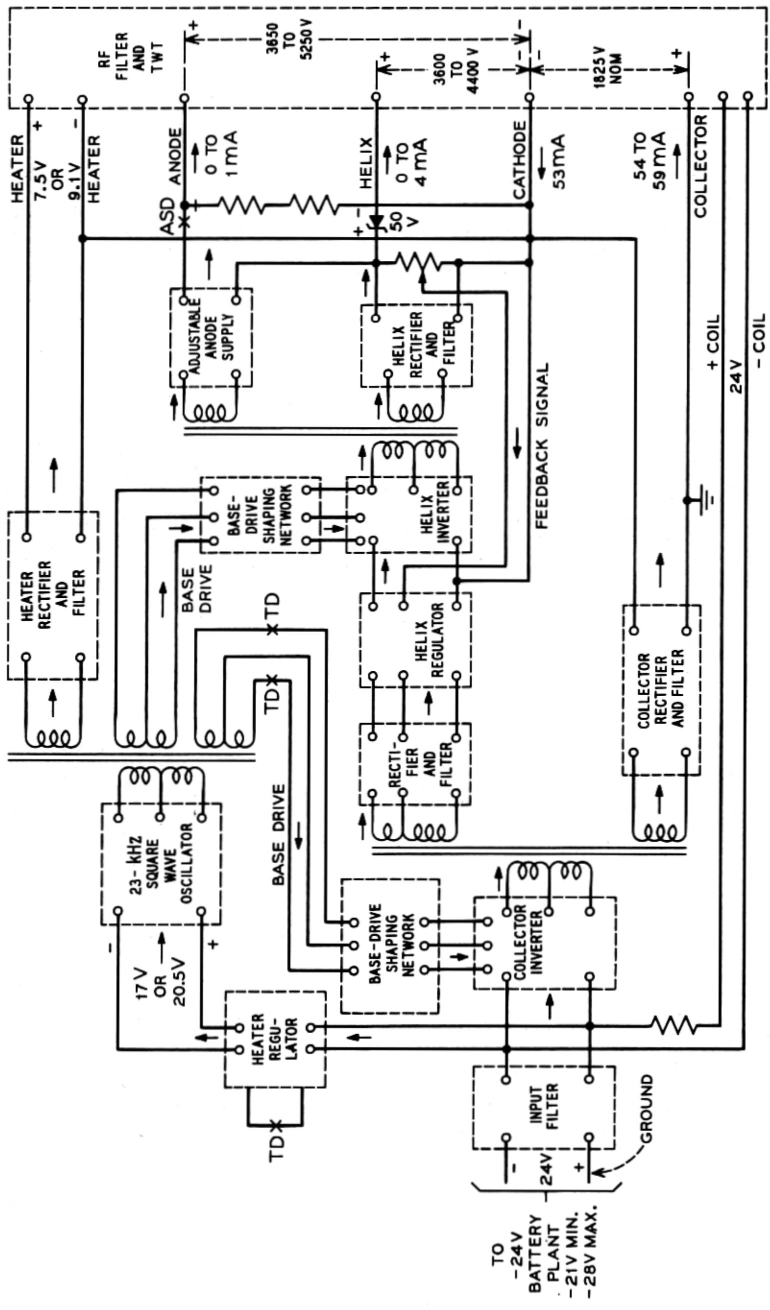

Fig. 1—Block diagram of TH-3 dc-to-dc converter.

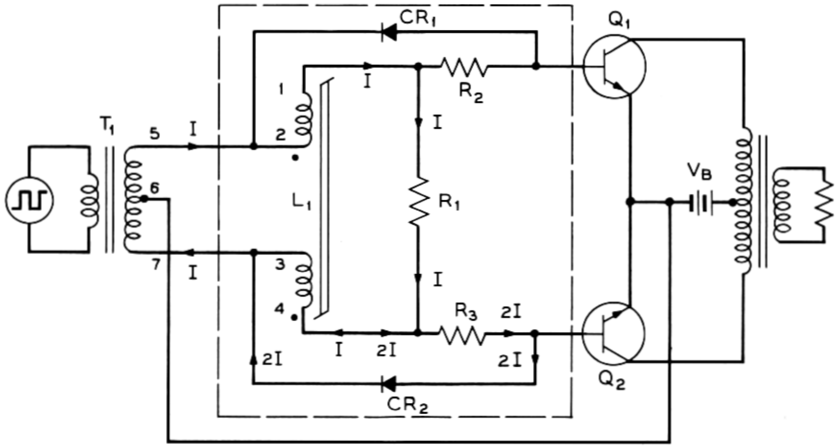

Fig. 2—Base-drive shaping network.

as shown. By transformer action, the sum of the voltage drops across R3 and CR2 appearing across winding 3-4 of L1 will also appear across winding 1-2 of L1, with terminal 2 positive with respect to terminal 1. The polarity of this voltage is such as to reduce the forward voltage appearing across the base-emitter junction of Q1, and in fact, proper choice of circuit parameter values permits this forward voltage to be made less than that necessary to turn Q1 on. In this manner, base-drive current to Q1 can be withheld as long as the core of L1 remains unsaturated, thereby withholding the turn-on of Q1 until after the turn-off of Q2. Upon saturation of L1, however, transformer action ceases and Q1 is driven on, its base drive current level being constrained by resistor R2. To further aid in the prevention of "switch-through," the base region of the off-going transistor is quickly swept free of stored charge by the immediate application of a reverse-bias voltage to its base-emitter junction through a low-impedance path. In Fig. 2, this sweepout current leaves terminal 6 of T1, enters the emitter and leaves the base of off-going transistor Q2, passes through CR2 in the forward direction, and returns to terminal 7 of T1. On alternate half-cycles, the base drive shaping action is reversed, delaying the turn-on of Q2 and accelerating the turn-off of Q1.

As seen in Fig. 1, the −24-volt battery voltage is inverted to yield two 23-kHz square-wave outputs from the collector inverter. The first output, after rectification and filtering, results in the unregulated TWT collector-to-cathode voltage of 1825 volts dc, nominal. Since the TWT collector electrode is operated at ground potential, this collector supply effectively biases the TWT cathode electrode −1825 volts dc from ground. The second square-wave output, after rectification and filtering, results in an unregulated dc voltage which is isolated from the supply input by virtue of the collector inverter transformer. As such, this dc voltage can be referenced to and precisely regulated above the −1825-volt cathode potential by means of the helix regulator, after which it is inverted by the helix inverter to yield two 23-kHz square-wave outputs.

The first of these is rectified and filtered to produce a nominal helix output voltage of 4000 volts dc, measured with respect to the TWT cathode. Automatic regulation of this voltage is effected by returning a fraction of it to the helix regulator. A potentiometer, accessible from the front panel of the converter, permits continuous adjustment of the returned voltage fraction thus permitting continuous adjustment of the helix output voltage over the range 3600 to 4400 volts dc.

The second 23-kHz output from the helix inverter is delivered to the anode supply which yields a continuously adjustable output voltage between zero and 800 volts dc. This voltage is varied by means of an adjustable auto-transformer accessible from the converter front panel and operated at dc ground in the interest of safety. By stacking this adjustable voltage upon another point clamped at 50 volts dc above the helix output voltage, the anode output voltage is produced. This voltage is continuously adjustable between 50 and 850 volts dc above the helix output voltage, measured with respect to the TWT cathode.

The 464A TWT is provided with a coil in the vicinity of the cathode structure to aid in the improvement of tube noise figure. An unregulated −24 volts, derived from filtered battery, powers this coil.

2.2 *Equipment Design Requirements for TH-3 TWT Converter*

The physical design of the TH-3 TWT converter, shown in Fig. 3, is similar to that of the TD-3 radio system TWT converter (see Ref. 1) despite higher TH-3 voltages and greater heat dissipation. The TH-3 converter design incorporates mechanical operating techniques and dual unit mounting arrangements similar to those of the TD-3 converter.

Several physical design similarities between the TH-3 and TD-3 converters include:

2.2.1 *Use of Die-Cast Panels*

The front panel die castings, which provide for unit latching, component mounting, and carrying, have common usage in present Western

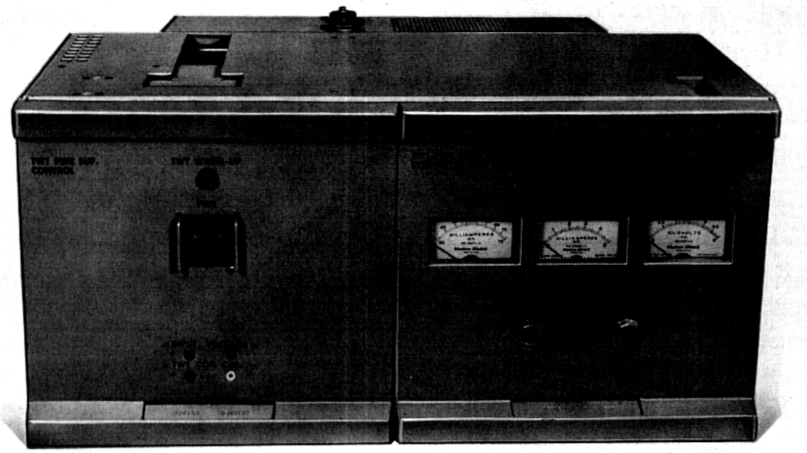

Fig. 3—TH-3 dc-to-dc converter.

Electric production of TD-3 and TH-3 units. The commonality of the front-panel appearance between TD-3 and TH-3 is readily apparent (see Fig. 3 and Ref. 1).

2.2.2 *Placement of High-Voltage Components*

All high-voltage components are mounted on insulated boards or epoxy printed wiring boards. The board and component placement considers not only voltage levels but lead dress for proper circuit operation.

2.2.3 *Personnel Protection Features*

Because of the high potentials present, the mechanical configuration of the supply must ensure personnel protection rather than simply relying on operating instructions. Removal of the left-hand unit will shut down the converter and provide the necessary access to the TWT and supply interconnections. The left-hand unit overlaps the right-hand unit and prevents its sole removal, thereby providing a positive interlock.

Further interlocking is provided by means of a wired interlock loop passing through the associated connectors of the left- and right-hand units and the TWT; consequently all conditions necessary for safety must be fulfilled before the supply can be energized.

Several equipment design requirements unique to the TH-3 TWT converter include:

2.2.4 *New High-Voltage Components*

High-voltage, glass, oil-filled capacitors provide additional output noise suppression and reduce volume requirements. New mica capacitors are used to provide main-unit high-voltage filtering. A miniature high-voltage vacuum relay is used to provide shutdown sequencing.

2.2.5 *Interconnection Grouping Between TWT and Supply*

A single plug-in type connector as used on TD-3 is not appropriate for TH-3 use because of the higher output voltages. The high-voltage outputs of the TH-3 converter are segregated into two voltage groups and the voltage level difference within each group is minimal. Two commercially available quick-disconnect connectors are, therefore, adequate for the application.

2.2.6 *RF Filtering Required to Reduce Converter-Generated Noise*

RF filter components, which are enclosed in a mu-metal housing inside the TH-3 converter framework, provide additional filtering in the converter outputs to the TWT. The leads from the RF box to the TWT are shielded by a mu-metal cover to minimize noise pickup.

III. TWT-CONVERTER INTERFACE

3.1 *Tones*

The gain and phase characteristics of the TWT vary with the helix-to-cathode and anode-to-cathode voltages generated by the converter. Therefore, any ripple or noise present on the helix and anode leads will modulate the microwave carrier being amplified by the TWT. The ripple appears in the TH-3 baseband which spans the 0.3- to 10-MHz range and the auxiliary channel which spans the 11- to 12-MHz range. Tones at harmonics of the normal 23-kHz converter switching frequency were initially found throughout the entire baseband and auxiliary channel. The tone requirements are specified at the ouput of the FM receiver and are shown in Fig. 4.

Two basic methods are employed to reduce converter-generated tones to acceptable levels. First, the helix and anode leads are heavily filtered since these leads directly affect TWT gain. Well over 100 dB of filtering loss throughout the entire baseband frequency range is used between each of these leads and the cathode lead. Second, great care is employed to prevent tones from being induced onto the heavily filtered leads. Magnetic shielding is used at both the source and load. Mu-metal cans are used on all transformers. As discussed in Section

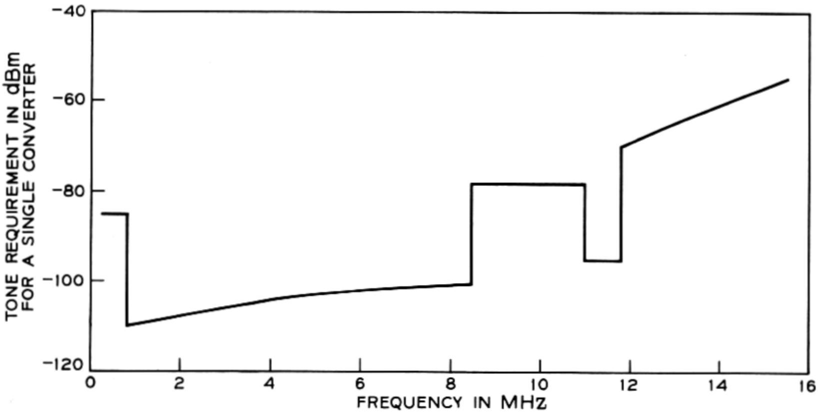

Fig. 4—Tone requirement for a single converter measured at the output of the FM receiver.

2.2.6, the final stages of filtering for all leads are located in a mu-metal box and the output cables which connect to the TWT are shielded with a mu-metal cover. Tests showed that this cover was especially important as tones as high as 16 dB over requirements were found when the cover was removed.

Additionally, induced tones are minimized through the reduction of conducted tones on leads other than the critical helix-to-cathode and anode-to-cathode pairs. While tones on the collector, heater, coil, and interlock leads do not directly modulate the microwave carrier, they can induce tones in more critical leads since they are run in the same cables used for the helix, anode, and cathode leads. For example, rather extensive filtering is required on the interlock loop which is run between the converter and TWT for safety purposes and which carries the timer current. Without this, tones exceeded requirements by as much as 8 dB at 8 MHz, and by as much as 12 dB in the 11- to 12-MHz auxiliary channel band.

3.2 *Negative Resistance Characteristic of the TWT*

The dc-to-dc converter was designed to accommodate the dynamic negative resistance seen looking into the helix-cathode terminals of the TWT. A somewhat typical TWT I-V characteristic is shown in Fig. 5. Instability, resulting in a system oscillation, will occur unless the converter output resistance is less than the absolute magnitude of the TWT's dynamic negative resistance.

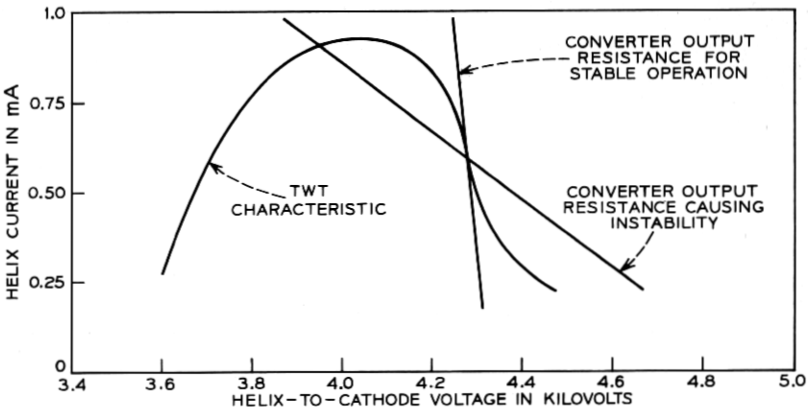

Fig. 5—TWT *I-V* characteristic (with RF drive).

A small-scale linear analysis can be made by defining the reciprocal of the slope of the TWT *I-V* characteristic as a dynamic ac impedance, Z_{HC}. The converter-TWT small-scale linear analysis is made using Fig. 6.

V_R = Reference voltage in helix regulator (8.65-volt voltage regulator diode)
V_{HC} = Helix-cathode voltage at TWT terminals
A = Open-loop gain of helix regulator
Z_O = Open-loop output impedance of the converter
Z_{HC} = AC impedance between the helix-cathode terminals of the TWT

$$B = \frac{R_2}{R_1 + R_2}.$$

Conventional linear feedback analysis of the model shown in Fig 6 yields the following gain equation:

$$\frac{V_{HC}}{V_R} = \frac{A\left(\dfrac{Z_{HC}}{Z_O + Z_{HC}}\right)}{1 + AB\left(\dfrac{Z_{HC}}{Z_O + Z_{HC}}\right)}. \tag{1}$$

By Blackman's Impedance[5] Relationship:

$$Z_{OCL} = \frac{Z_O}{1 + AB}, \tag{2}$$

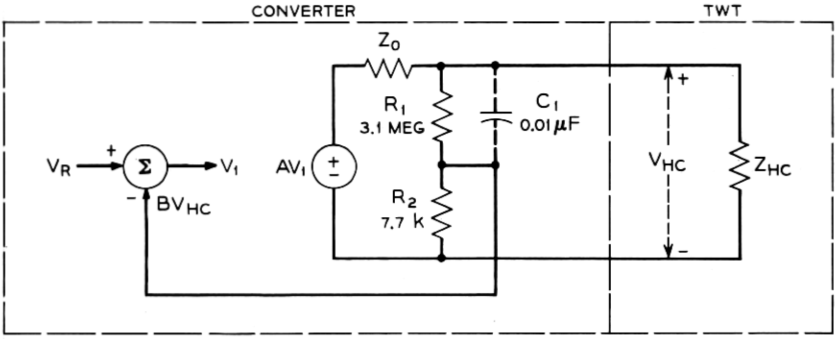

Fig. 6—Linear model of converter-TWT feedback loop (lead capacitor C1 shown with dashed lines).

where Z_{OCL} = closed-loop output impedance of the converter. Substituting (2) into (1) yields, after manipulation:

$$V_{HC} = \frac{AV_R}{(1 + AB)\left(1 + \dfrac{Z_{OCL}}{Z_{HC}}\right)}. \tag{3}$$

Conventional analysis of (3) indicates that if the open-loop gain $AB = -1$, instability results. However, instability also results if $Z_{OCL}/Z_{HC} = -1$, where Z_{HC} is negative in the region of interest. The latter condition occurs when the converter closed-loop output resistance equals the absolute magnitude of the dynamic negative TWT resistance and the reactive components of the two impedances are equal. Both the converter and TWT impedances have practically negligible reactive components in the frequency range where instability would tend to occur.

Instability is particularly undesirable because the helix-to-cathode voltage oscillation causes the system power level to oscillate, or "bobble," as low-frequency oscillations are called. Even less desirable is the increased helix intercept current which often accompanies this condition.

Bobble is prevented by a lead network in the converter feedback loop. The lead network is formed by capacitor C1 in Fig. 6. Typical converter output impedance curves, with and without the lead network, are shown in Fig. 7. The phase angle of the converter output impedance is less than 10 degrees in this frequency range. The lead network adds a "zero" to the feedback loop at about 0.5 Hz. Thus loop gain is increased significantly in the 2- to 4-Hz range.

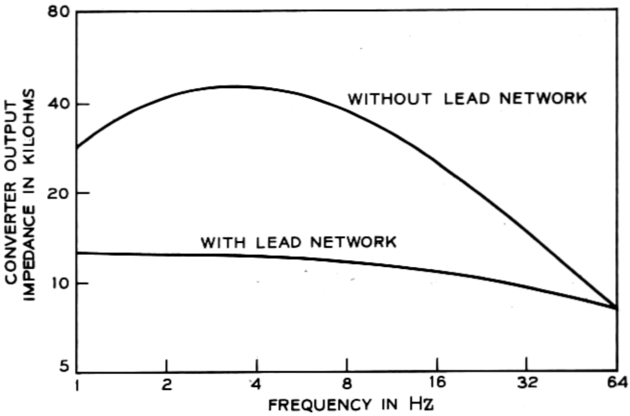

Fig. 7—Typical converter output impedance.

If corrective measures are removed from the converter, a 10-dB peak-to-peak bobble is observed on the RF power meter which monitors TWT output power. The bobble frequency is about 2 to 4 Hz, the frequency range at which the converter output resistance is greatest.

3.3 *Prolonging TWT Cathode Activity*

The 464A TWT is the only vacuum tube used in the TH-3 radio system. As the TWT is the system component with the shortest anticipated lifetime, any improvement made in its reliability will have a corresponding salutary effect on overall system reliability. Since loss of cathode activity is an important cause of TWT failure, several features have been incorporated into the TWT converter to prolong and enhance this activity.

3.3.1 *Cathode Preheat Sequence*

As described in Section 2.1, this 5-minute heater overvoltage interval immediately following converter turn-on is designed to (*i*) prevent temperature-limited operation of the cathode surface, and (*ii*) prolong cathode activity by providing a degree of cathode surface reactivation each time the converter is turned on.

3.3.2 *Automatic High-Voltage Turnup Sequence*

As seen in Fig. 1, timed contact closures, TD, in the base-drive path to the collector inverter insure that no high voltages can be produced until after the electronic timer TD has timed out. When these base-drive contacts close, enabling the collector inverter, the TWT collector-to-cathode voltage appears rapidly. On the other hand, since the power path for helix and anode output voltages includes several additional tandem blocks, these remaining high voltages lag the appearance of the first by tens of milliseconds. This turn-on voltage sequence prevents the formation of a transient helix-intercept current with attendant reduction in cathode activity due to positive-ion bombardment or reaction with outgassing products.

3.3.3 *Automatic High-Voltage Turn-down Sequence*

Electrically keyed to the input power circuit breaker is a fast, high-voltage vacuum relay ASD arranged as an anode-voltage shorting crowbar. This is shown in Fig. 1. Tripping of the circuit breaker, for any reason, is thereby accompanied by a rapid decay of TWT anode voltage and hence, beam current. An anode crowbar time constant of approximately one millisecond assures rapid beam-current decay with no disruptive intercept currents.

3.3.4 *TWT Positive-Ion Trap*

The converter design, as described in Section 2.1, insures that the anode output voltage is at least 50 or more volts higher than the helix output voltage at all times. The resulting potential gradient established between the TWT helix and anode electrodes inhibits cathode damage due to positive ion bombardment.

IV. SUMMARY

Electrical and physical considerations important to the development of the TH-3 TWT converter have been described. The converter design has been optimized to accommodate the particular characteristics of the 464A TWT which it powers. In particular the converter has been designed (*i*) to hold TWT gain constant through accurate helix and anode voltage regulation, (*ii*) to minimize tones through extensive filtering and shielding, (*iii*) to accommodate the TWT negative resistance characteristic through control of the converter output resistance, and (*iv*) to maximize TWT life and reliability through accurate heater regulation and proper sequence of turn-on and turn-off operations.

V. ACKNOWLEDGMENTS

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