Improvements in Radar Transmitter Performance and Reliability Using High-Voltage Solid-State Modulators and Power Supplies[1]

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Abstract - The operational life of high power radar transmitters that employ microwave VEDs can be extended using high voltage, solid-state modulators and power supplies. Solid-state modulators and power supplies, whether integrated, or stand-alone, can benefit both retrofits and new designs. In this paper, modern solid-state modulator topologies are presented along with the conventional topologies that they replace. Several specific fielded radar transmitters that have been, or could be, retrofitted with "appropriate technology" are identified.

I. Introduction

In 1970, T. Weil wrote "the transmitter is typically one of the largest, heaviest, and most costly portions of a radar system." [1] In the context of new design, he further described the critical nature and complexity of specifying and selecting new RF tubes for radars and concluded: "RF-tube selection has therefore become a vital but hazardous occupation." With a marked decline in the commissioning of new RF-tube based radars, the situation is different today. The term "RF-tube" has been replaced with the term "vacuum electron device" (VED). Transmitters fielded for multiple decades are costly because the traditional modulator vendor base is disappearing. Conventional high-power, high-voltage modulator expertise has diminished, as have the vendors that supported them; exemplified by recent shifts in source and availability of vacuum switch tubes. Cost-effective radar transmitter maintenance has now become the "hazardous occupation."

The name of the game today is not how to select new RF VEDs, but how to extend their lives in radar transmitters that use very old modulator technology. Over the last several decades, those working in the microwave-VED modulator field have learned that the performance and reliability of a radar transmitter is directly dependant upon the performance and protection capability of its power conditioning and switching components. "This comes about because the device [modulator] usually controls more energy than is needed to melt or otherwise destroy it" [2]. Put another way, a poorly designed modulator will very likely destroy microwave-VEDs (and other components) on a regular basis, and it will never be known how long a microwave-VED will actually live. A well-designed modulator maximizes radar mission availability by increasing microwave-VED life, preventing collateral damage, and delivering cost-efficiency over the life of the radar.

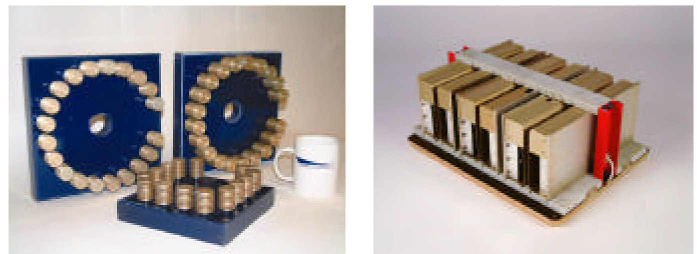

Fig. 1. DTI high-voltage switch modules. Left: Potted, air-insulated 11 kV and 8 kV, 25 A, units. Right: oil-insulated array of 15 kV, 300 A units.

A. *"Appropriate Technology" - Advanced Solid-State Modulators and Microwave-VEDs.*

Klystrons, TWTs, CFAs, and magnetrons are the common microwave-VEDs found in radar transmitters. The two major power subsystems in a radar transmitter are the high-voltage power supply (HVPS) and the pulse modulator. Historically, transmitters at high power used linear HVPSs with both coarse primary and pulse-to-pulse secondary regulation schemes. Examples of conventional pulse modulator switches are triodes, tetrodes, and beam switch tubes, which normally operate in constant-current mode. Thyratrons, SCRs, magnetic switches, and FETs are examples of other prevalent switch devices. Penalties for using such traditional technologies include increased size, weight, and complexity, higher operating voltages than required by the VED, and low efficiency.

Fig. 2. DTI high-voltage, high-power, switching power supplies

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In his paper titled "Modern Microwave Tubes for Radar", R. S. Symons discusses how microwave-VEDs, through the use of "appropriate technology" can play a role in the design of affordable radar [3]. Technological advances in switching power supplies and solid-state switch modules offer "appropriate technology" for radar transmitter modulators. Modern switching HVPSs can provide the performance required for radar at reduced size and weight, and at very high efficiency. Because of their high-frequency operation, these supplies are capable of providing very accurate voltage regulation into dynamic loads, with very low ripple and low stored energy. This, in turn, enables the efficient application of fully saturating, high-current switch devices in the modulator. Coordinated operation of the HVPS regulation circuitry and pulse modulation minimizes inter- and intra-pulse voltage variations. The result is a simple, highly efficient, integrated HVPS and pulse modulator, having the pulse regulation needed for precision phase and amplitude performance in a radar transmitter.

B. Modern Switch Modules, High-Voltage Power Supplies, and Opening Switches.

Recent efforts in the development of high-power, high-voltage commercial and military transmitters have resulted in a variety of modern tools to replace conventional modulator technology. These include solid-state modulators and high voltage power supplies for application in radar transmitters. For example, a new hybrid solid-state / beam switch tube modulator retrofit can be applied to at least three fielded radar transmitters. Because the pulsed-switches open rapidly (<1µs), they also function as a protective opening switch when faults are sensed. Fault-current is quickly interrupted at limited-amplitude, allowing only a controlled amount of energy into a fault. Operation can be resumed on the next pulse if desired and fault-energy can be optimized for VED "self-conditioning", an important aspect of long-life operation. For example, to protect a CW klystron, a 100 kV, 20 A DC opening switch is currently being designed to replace a conventional crowbar. All solid-state mod-anode modulators and HVPSs are being developed for single or multiple microwave-VEDs in radar applications at W-, X-, and Ku-band. This paper will expand on these examples in later sections.

1) Solid-State, High-Voltage Modulator Switches

Fig. 1 shows examples of two types of DTI switch modules used in radar modulators. On the left are three air-insulated, switch-module variations that can be arranged in series to provide 50 kV, 30 A pulses. Unpotted versions for use in oil extend the operating voltage capability. These switch modules are controlled at ground with a simple magnetically coupled loop and are easy to operate in floating high voltage circuits. The modules require no ancillary high-voltage isolated power and operate fully on or fully off. This greatly eases high-voltage management when compared with conventional floating decks and ancillary circuitry. On the right is an array of switch modules used for higher voltages and currents. These modules have been arrayed for use at 300 A and 15 kV in pulse modulators.

2) Switching High Voltage Power Supplies

Fig. 2 shows examples of DTI's switching HVPSs used in radar transmitters. DTI has designed and delivered HVPSs from 10 kV to 120 kV, and greater than 100 kW average power. HVPSs rated for 220 kV and over 200 kW are in production. High-efficiency (>90%), very-tight voltage regulation (< 0.01%) with low-ripple (zero contribution from regulation circuitry), and high-stability in a compact enclosure, are the performance requirements for modern radar transmitters. For over ten years, switching HVPSs have been available up to 50 kV and modest average power levels.

High average power (50 kW to >200 kW) is now conventionally available. Operating costs are minimized by the high efficiency of the design. The remaining aspects of total life-cycle costs, acquisition cost and maintenance cost are critical components. The acquisition cost of a high-voltage, high average power, power supply must be compared against the total cost of the linear version, which includes T/R set, prime voltage adjustment and coarse regulation scheme, and post-regulation circuit requirements.

II. Overview Of Conventional Modulators In Fielded Radar Transmitters

This section describes cathode pulsed and mod-anode pulsed transmitter modulator schemes and examples of specific fielded radars in which they are used (detailed descriptions of these schemes can be found in references 1 and 2).

A. Cathode-Pulsed Modulators

Fig. 3 and Fig. 4 illustrate four cathode-pulsed modulators commonly employed in VED transmitters. Table I lists examples of radar transmitters that use them.

"Cathode pulsers must control the full beam power of the RF tube, either directly or through a coupling circuit." [1] The switches shown in Fig. 3 must open and close with full-control. The clear advantages of cathode pulsers are pulse width agility and pulse shape. Maximum pulse width is limited by the droop tolerable on the energy storage capacitance, and by pulse transformer restrictions. Line-type pulsers like those shown in Fig. 4 are generally restricted to a predefined pulse width and use closing switches to initiate the cathode pulse. The pulse shape is fully determined by the PFN and pulse transformer characteristics.

1) Directly-Connected.

Fig. 3 (left) shows a directly connected modulator with a pre- and post-regulated HVPS, typical of systems requiring well-regulated modulator pulses. High-voltage adjustment and coarse regulation are usually provided by an Induction Voltage Regulator (IVR) or by a variable tap transformer.

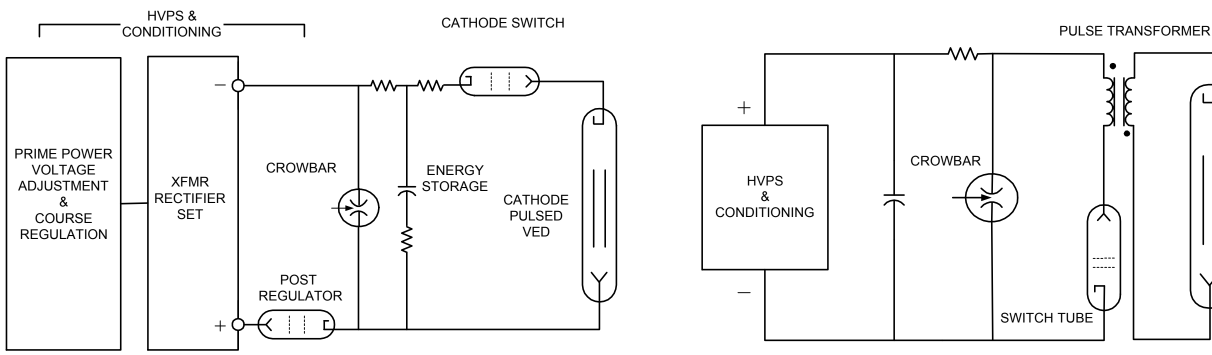

Fig. 3. Simplified examples of hard-tube cathode modulator configurations used in high-power radar transmitters. Left: Pre and post regulated HVPS and directly connected switch. Right: Transformer-coupled.

Next is a transformer-rectifier (T/R) set that may have passive filtering in addition to the post regulator tube shown. A crowbar protects the VED and cathode switch. When the load arcs, a properly designed crowbar system will divert and dissipate destructive energy stored in the capacitor and in the HVPS. Because it can take tens of milliseconds for the prime power contactor to open, the crowbar must also ensure that follow-on current from the HVPS does not cause damage. Crowbars often cause collateral damage when they fire, because the need to react quickly often requires that many kiloamps of peak current be conducted in hundreds of nanoseconds. It is hard to find a crowbar system that protects the load, addresses the follow-on current issues, and does not leave the fault/logic system senseless after firing.

The cathode switch is typically operated in the constant-current mode. The HVPS voltage must include the plate voltage necessary for linear operation of the switch-tube, and the anticipated capacitor bank droop at the end of the longest pulse. Examples of these modulators are found in the AEGIS, ALCOR, TRADEX S-band, and FPS-6 radar transmitters [6-8]. AEGIS uses a tetrode switch to provide constant pulse current into the dynamic cathode impedance of the CFA and to provide regulation against HVPS voltage fluctuations. The ALCOR, TRADEX S-band, and FPS-6 transmitters all use paralleled, beam switch tubes (BST) as constant-current switches.

2) Transformer-Coupled

Fig. 3 (right) shows this arrangement with the switch tube cathode connected to ground, allowing the grid, screen, and filament circuitry to also be ground-referenced. However, the pulse transformer windings must be fully insulated for the full DC HVPS voltage. The original AN/SPG-60 klystron modulator used this transformer-coupled arrangement [9,10]. Another example, at very-high average power, is the Land Based Air Surveillance radar. This transmitter uses off-line SCR phase control for primary voltage regulation and a T/R set for its HVPS. A high-power tetrode is used to provide klystron beam pulse regulation. Transformer coupled systems often present difficulties because the pulse transformer adversely affects pulse shape.

3) Conventional Line-Type

Shown in Fig. 4 (left), a pulse-forming network is resonantly charged from the HVPS energy storage capacitor during the interpulse period. A closing switch, shown as a thyratron, discharges the PFN through the pulse transformer. For efficient power transfer, the pulse transformer is designed to "match" the PFN primary impedance to the VED

TABLE I

EXAMPLES OF RADAR TRANSMITTERS USING CATHODE-PULSED MICROWAVE VEDS

ModulatorType	Radar	Microwave VEDs	Nominal Cathode V-I	Modulator Switch Type
Directly-Connected	AEGIS	CFA	17 kV, 25 A	Tetrode
	ALCOR	Klystron	120 kV, 80 A	Beam Switch Tube
	TRADEX S-band	Klystron	95 kV, 65 A	Beam Switch Tube
	FPS-6	Klystron	---	Beam Switch Tube
Transformer-Coupled	Land Based Air Surveillance	Klystron	85 kV, 50 A	Tetrode
	SPG-60	Klystron	12 kV, 2 A	Tetrode (Original) / Solid-State (Upgrade)
Line-Type	ASR-9	Klystron	68 kV, 30 A	Solid-State RBDT Stack
	TDWR	Klystron	---	Solid-State SCR Stack
	ASR-7	Magnetron	28 kV, 43 A	Thyratron
	NEXRAD	Klystron	---	Solid-State RBDT Stack
SCR-Magnetic Line-Type	ASR-8	Klystron	79 kV, 40 A	SCR-Magnetic
	GPN-20	Magnetron	32 kV, 35 A	SCR-Magnetic

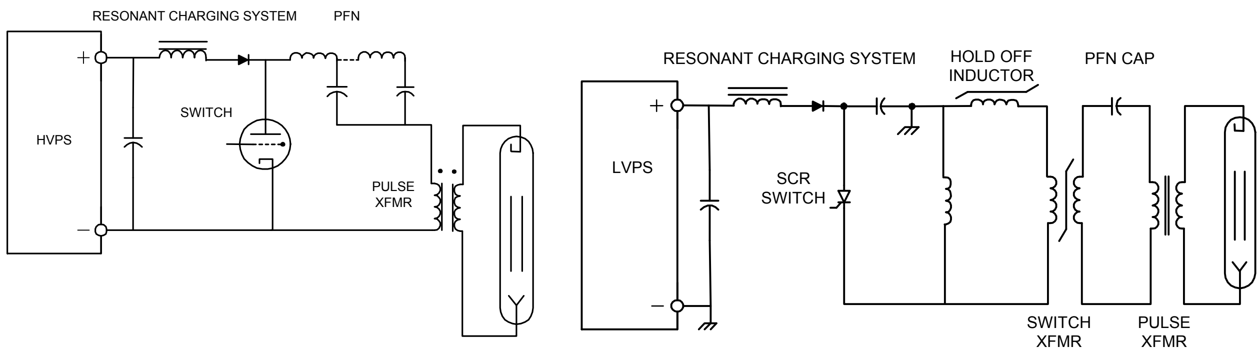

Fig. 4. Simplified examples of line-type modulators used in radar transmitters. Left: Thyratron-switched line-type. Right: SCR-magnetic switched.

secondary load impedance.

Two examples of radars that use line-type modulators are the ASR-7 and the ASR-9. The ASR-7 uses a thyratron-switched PFN with a conventional magnetron. The ASR-9 uses a similar topology with more modern technology: the PFN is charged by a flyback system and the solid-state switch is an RBDT stack [11].

4) SCR-Magnetic

Of the four general cathode pulse types, this scheme is least employed in radar. A low voltage power supply (≈ 300 VDC) is used to resonantly charge a storage capacitor. The SCR switch is commanded "on" and when the magnetic hold-off inductor saturates, the switch transformer primary conducts full current, resonantly charging the PFN capacitor. At the end of this charge cycle, the switch transformer saturates, discharging the PFN capacitor through the switch transformer saturated inductance (the equivalent of a one section PFN). This voltage pulse is translated to the cathode-pulsed load by the pulse transformer.

The ASR-8 and GPN-20 air traffic control radars use the same basic SCR-magnetic modulator scheme as shown in Fig. 4 (right). In the case of the GPN-20 the load is a coaxial magnetron operating at 32 kV and 35 A, and in the case of the ASR-8 the load is a klystron operating at 79 kV and 40 A.

B. Mod-Anode Pulsed Modulators

Some microwave and switch VEDs provide a "modulating-anode" (mod-anode or MA) to turn the cathode beam current on and off, and to adjust beam current, independent of beam voltage [12]. The required MA switch voltage is relatively high, but the MA switching power is low because the intercept current and inter-electrode capacity are low. Microwave VEDs with mod-anodes have DC high voltage applied continuously to their cathodes. Those discussed in this paper typically operate with pulsed MA voltages between 80% and 100% of cathode voltage. Mod-anode pulsed beam switch tubes, in contrast, operate at a much lower percentage of cathode voltage.

Fig. 5 shows two simplified examples of active switched ON and OFF mod-anode modulators. Table II lists examples of radars that use these modulators. Full-control mod-anode switches (active ON and OFF) are prevalent at higher duties to reduce power dissipation. Mod-anode switches can be considerably smaller than cathode switches because they usually carry much less peak current and do so only during the rise and fall times.

1) Directly-connected, active switched.

Fig. 5 (left) is a basic directly connected active-switched mod-anode modulator. During the interpulse period the OFF switch is turned "on", biasing the mod-anode to a few kV below cathode to fully cut off the beam current. To initiate a beam pulse, the OFF switch is turned "off", and the ON switch is turned "on", charging the mod-anode up to the clamp power supply voltage. Two examples of radar transmitters using this type of mod-anode modulator are the SPS-49 and TRADEX L-band. Both are klystron modulators

TABLE II

Examples Of Radar Transmitters Using Mod-Anode Pulsed Microwave-VEDs

MA ON Voltage [% Beam]	Radar	Microwave-VED	Nominal Cathode V-I	Switch Type
100%	SPS-49	Klystron	42 kV, 25 A	Tetrode
100%	TRADEX L-band	Klystron	95 kV, 65 A	Beam Switch Tube
90% (adj.)	Cobra Judy X-band	Two Parallel TWTs	45 kV, 10 A each	Tetrode
---	LRIR	Four Parallel TWTs	42 kV, 10 A each	Tetrode
---	HAX	Two Parallel TWTs	50 kV, 10 A each	Tetrode
---	MMW	TWT	48 kV, 6 A	Tetrode

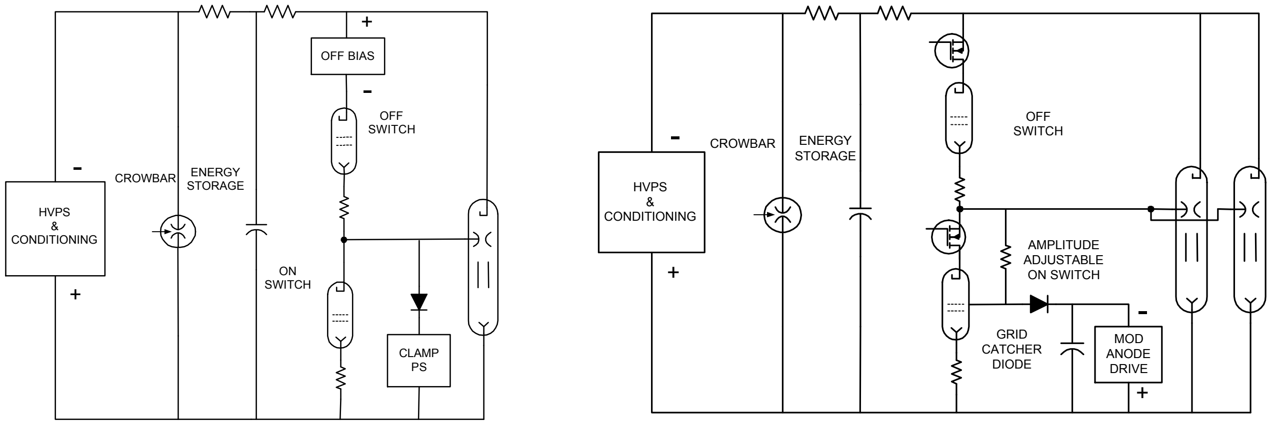

Fig. 5. Simplified examples of mod-anode modulator configurations used in high-power radar transmitters. Left: Active ON and OFF, directly connected. Right: Active ON and OFF, adjustable mod-anode drive, multiple microwave VEDs.

that switch their mod-anodes from cathode bias-voltage to ground, with no provision for mod-anode amplitude adjustment. The SPS-49 klystron operates at 42 kV and 25 A, and the TRADEX L-band klystron operates at 95 kV and 65 A.

2) Directly-connected, active switched, multiple microwave VEDs.

Fig. 5 (right) shows a simplified diagram of an active-switched mod-anode modulator used to pulse two or more microwave VEDs. This basic topology is used in the LRIR, HAX and MMW TWT modulators [4,13]. ON and OFF control is performed by cascode-connected FETs. This allows the ON switch tube grid to be diode-connected to the mod-anode drive power supply. This "grid-catcher" arrangement results in a flattop voltage only marginally different from the mod-anode drive power supply voltage.

III. Solid-State Modulators for Radar Transmitters

Recently, several radar-transmitter modulators have been built using switch modules containing between four and twenty individual transistors (FETs or IGBTs) operating in series. The voltage rating of each module is 3 kV to 12 kV, depending on the module design. These switch modules are available in peak current ratings from 30 A to over 5,000 A. To meet the transmitter's specific voltage requirements, multiple modules are connected in series. An external gate drive controls all modules simultaneously, with risetimes as low as 30 ns. Modular construction leads to flexibility, economy, and ruggedness.

A. SPS-49 Solid-State Cathode Modulator Retrofit

The SPS-49 klystron mod-anode modulator is a 1970 design that uses vacuum tubes as shown in Fig. 7 (left). Due to high failure rates in the switch-tube and low modulator MTBF, the US NAVY sponsored a contract with DTI to design, retrofit, and test a replacement solid-state modulator. Because the mod-anode is 100% modulated (full-swing to ground), the cathode-switch prototype shown in Fig. 6 was chosen for the retrofit design. The retrofit eliminated both vacuum tube switch decks, the bias power supply, the rise time assist network, and the series limiting resistor assemblies. A Phase II effort is underway to repackage, optimize, and environmentally qualify the prototype for full-scale production.

The TRADEX L-band is another example of a radar transmitter using a 100% modulated mod-anode that can be readily retrofitted with a similar solid-state cathode switch. Although the nominal cathode operation is 95 kV, 65 A, the customer requested that the solid-state switch operate at 132 kV, 90 A.

Fig. 6. Solid-state cathode-pulsed, prototype modulator in SPS-49 transmitter.

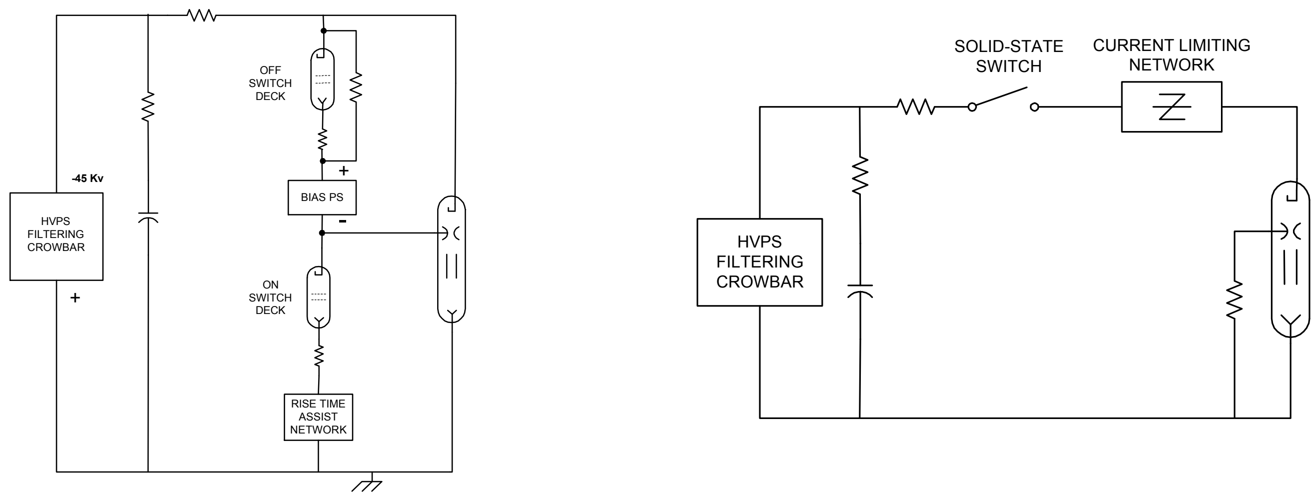

Fig. 7. Left: Existing SPS-49 mod-anode modulator. Right: Solid-state cathode modulator operating in SPS-49 transmitter.

B. Retrofit Options for a Transformer-Coupled Modulator in a Land-Based Surveillance Radar

This radar transmitter, designed and fielded in the 1980's, uses a transformer-coupled cathode modulator as shown in Fig. 3 (right). The klystron is pulsed at 85 kV and 50 A, irregular PRF scheduling is used, and the HVPS average power requirement is nearly 200 kW. In order to reduce maintenance costs, extend the life of the radar, and increase performance, the user contracted with DTI to perform a feasibility study for a solid-state upgrade. The purpose of this study was to identify options for replacing the HVPS and klystron cathode-modulator with DTI's solid-state switching HVPSs and high-voltage switch modules. Three options were identified to allow for various budgeting scenarios. In order of increasing scope, they were:

1. Retain the pulse transformer as-is with ground-referenced primary, replace the tetrode with a floating solid-state switch, and replace the HVPS with a switching HVPS.
2. Rework the PT to a higher turns ratio with ground-referenced primary, replace the tetrode with a floating solid-state switch, and replace the HVPS with a 25 kV unit.
3. Replace the entire modulator with a new 85 kV HVPS and solid-state switch.

In all three options, using a saturating solid-state switch to replace the tetrode moves the entire beam pulse-to-pulse regulation requirement to the new switching HVPS, which it is designed to handle. Because the solid-state switch operates in a "floating" configuration, operating the ground-referenced primary in Options 1 and 2 may reduce the pulse transformer voltage stresses. The crowbar may be eliminated in all three options because the solid-state switch functions as a fast opening switch in the event of an overcurrent fault. Option 3 provides the most improved beam pulse shape, characteristic of directly connected active switch modulators.

C. A Solid-State Retrofit for a Shipboard Mod-Anode TWT Modulator.

Fig. 8 shows a simplified diagram of a mod-anode modulator used in a shipboard X-band radar to pulse two microwave-VEDs. The transmitter is nearly 20 years old, and radar availability has been poor due to failing and obsolete modulator hardware. Fig. 9 shows a prototype solid-state replacement design for this transmitter. Three new, 100 kW, 45 kV switching HVPSs eliminate the IVR, T/R set, and vacuum tube post regulator. Two HVPSs are needed for full-power operation of the radar; the third is a standby. A solid-state opening switch, and ON and OFF switches replace the crowbar and vacuum tube floating deck mod-anode modulator. In the interest of further reducing modulator complexity, a cathode-pulsed configuration option will be explored. It may be possible to design cathode-pulsed circuitry which allows the TWT to operate without oscillating during the rise and fall times. In this case, the retrofit modulator uses the opening switch to function as the cathode switch.

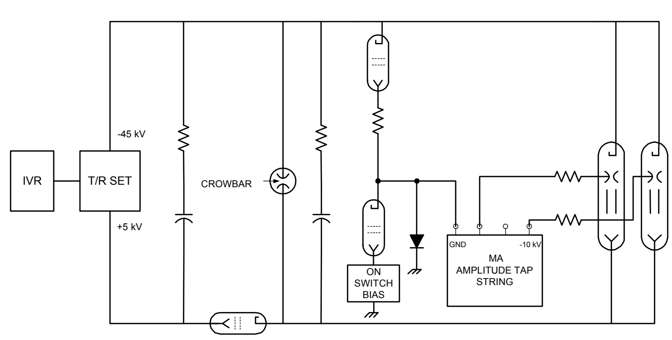

Fig. 8. Existing shipboard mod-anode modulator.

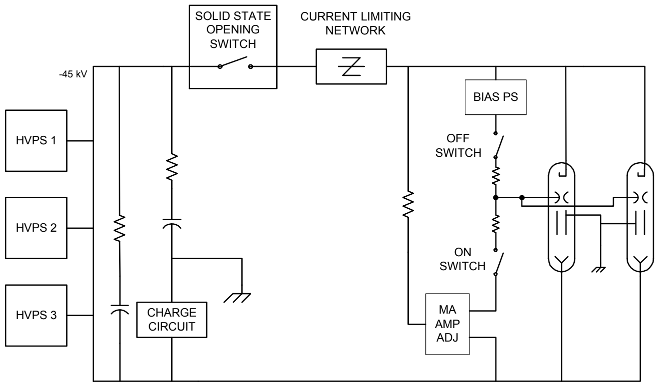

Fig. 9. Solid-state mod-anode modulator replacement for a shipboard TWT transmitter.

D. Hybrid Solid-State / Vacuum-Tube Modulators.

The ALCOR, TRADEX S-band, and FPS-6 transmitters use L-5097 (formerly Litton, now Northrop Grumman ED) beam switch tubes connected in parallel as the active switch to deliver klystron cathode pulse voltages between 90 kV and 130 kV.

Similar S-Band transmitters at MIT-Bates have had their vacuum-tube BST drive circuitry modified [5] using solid-state switch modules and new, highly regulated drive power supplies. The solid-state switch is placed in series with the BST cathode and connected so that, when commanded on, current in the BST (to the klystron cathode) flows proportional to the setting of the new drive power supply. This hybrid arrangement retains and enhances the very-high degree of regulation provided by the BST, greatly simplifies the BST drive circuitry, and reduces overall size and weight of the modulator.

E. NRL 94 GHz Gyroklystron Mod-Anode Modulator.

Limited by the capabilities of their conventional vacuum-tube modulator, the Naval Research Laboratory (NRL) contracted with DTI to build an all-solid-state modulator for their W-band gyroklystron program. The simplified diagram in Fig. 10 illustrates a modulator that provides very high PRF (100 to 400 kHz), pulse width agility, and highly controlled intra-pulse and pulse-to-pulse voltage characteristics. At higher PRFs, average power losses due to capacitive charging and discharging can become intolerably large for conventional active pull-up and pull-down mod-anode modulators. The scheme illustrated in the figure uses solid-state switches in a "quasi-resonant" topology for reactive mod-anode charging and discharging that avoids the resistive losses normally incurred in conventional modulators. To date, switching losses have been reduced by a factor of more than twelve.

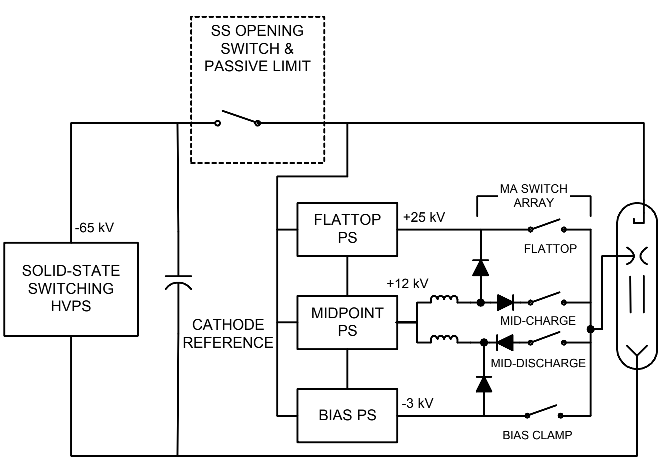

Fig. 10. Schematic of NRL very-high PRF mod-anode modulator.

As shown in Fig. 11, this modulator is a turnkey system made up of an oil tank and control/fault logic system. The oil tank contains the mod-anode modulator, and the local and remote computer controls and fault logic are located above the tank. Not shown is the stand-alone 65 kV, 1 A, high-frequency switching HVPS.

F. Current Control Pulse Modulation

A remaining area of investigation is the development of solid-state modulators that operate in current control mode for CFAs and similar microwave-VEDs. DTI has recently developed a modulator design that operates in linear mode to provide current-control operation. This modulator, which will be described in a future forum, provides a solid-state upgrade for VED-based radar transmitters requiring constant-current pulse modulation.

IV. Conclusions

"Appropriate technology" for radar transmitters combines the best features of technically advanced switching HVPSs and solid-state high-voltage pulse modules to produce high-performance, highly reliable modulators that are ideal for microwave-VEDs.

Many microwave-VED radar transmitters can now use switching HVPS and solid-state modulator configurations. For new designs, this configuration provides much higher levels of performance and pulse flexibility than conventional modulators. For existing systems, the decision to upgrade is

Fig. 11. NRL modulator in oil tank and controls.

often driven by reliability, parts availability, and operating cost issues rather than performance improvements. Reliability and performance can be addressed simultaneously. Increased reliability and reductions in operating and maintenance costs are typical for these upgrades.

In this paper, examples of modern solid-state modulator topologies have been presented along with the conventional topologies that they replace. Several specific fielded radar transmitters that have been, or could be retrofitted with "appropriate technology" have been identified.

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References

[1] T. Weil, "Transmitters", in M. Skolnik, ed, *Radar Handbook,* McGraw-Hill, New York, 1970, chap 7.

[2] R. S. Symons, "Tubes - Still Vital After All These Years," IEEE Spectrum, pgs 52-63, April 1998.

[3] R. S. Symons, "Modern Microwaves Tubes For Radar," Tri-Service VED Workshop, Arlington, VA, August 2001.

[4] W. North, "High-Power Microwave-Tube Transmitter," Los Alamos National Laboratory, LA-12687-MS, UC-000, January 1994.

[5] A. Zolfaghari, C. Wolcott, and A. Hawkins, and W. North, "Solid-State Switch Modulator Deck For The MIT-BATES S-Band Transmitter," *Conference Record of the 1998 Twenty-Third International Power Modulator Symposium,* Rancho Mirage, CA, June 1998.

[6] K. Smalley, "AEGIS AN/SPY-1 CFA Constant-Current Hard-Tube Modulator," *Conference Record of the1973 Eleventh Modulator Symposium,* New York City, NY, September 1973.

[7] P. Brown and R. Wilcox, "ALCOR Transmitter - Final Power Amplifier Replacement Program," *Conference record of the 1994 Twenty-First International Power Modulator Symposium,* Costa Mesa, CA, June 1994.

[8] R. Casolaro, "TRADEX S-band Transmitter," *Conference Record Of The 1973Eleventh Modulator Symposium,* New York City, NY, September 1973.

[9] P. Brown et al., "New Directions In Solid-State Compact, High-Voltage Radar Modulators," *Conference Proceedings of the 13th IEEE International Pulse Power Conference,* Las Vegas, NV, June 2001.

[10] Porteus, Matt, "PHD NSWC Introduces New Radar Technology", *CoastaLink*, Nov. 30, 2001

[11] S. Alves, "An all solid-state high-power modulator for a ground-based radar," *Conference Record of the 1998 Eighteenth Power Modulator Symposium,* Hilton Head, SC, June 1988.

[12] A. Staprans et al., "High-power linear-beam tubes," *Proceedings of the IEEE,* vol. 61 No. 3, March 1973.

[13] P. Robinson and W. North, "Compact floating-deck modulator for HAX transmitter," *Conference Record of the 1992 Twentieth Power Modulator Symposium,* Myrtle Beach, SC, June 1992.

[14] M.P.J. Gaudreau, et al., "Compact, Solid-State, High PRF Radar Modulators", *Conference Proceedings of the 12th IEEE Pulse Power Conference,* Monterrey, CA, June 1999.