# A 1MW MAGNETRON RADAR TRANSMITTER UPGRADE USING MODULAR LINE-TYPE SOLID-STATE PULSE MODULATOR

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***Abstract*** – **This paper describes the upgrade of Atlas tracking radar system transmitter at Alcantara Launch Center (CLA), Maranhão, Brazil. The original transmitter installed in the 1980's was equipped with a conventional hard-tube pulse modulator to excite a 1MW C-band magnetron. In order to extend overall system lifetime, improve reliability and introduce new monitoring and command functions the original tube-type modulator and control system was substituted by a modular line-type solid-state modulator and a digital control system.**

***Keywords*** **– Radar upgrade, radar transmitter, magnetron, high voltage solid-state pulse modulator, high voltage pulse transformer, soft failure mode (on-line degradation), switch mode power supply, IGBTs.**

## I. INTRODUCTION

Alcantara Launch Center is an operating space launch facility capable of supporting launches of different types of mission orbits. Its facilities include a 1MW C-band tracking radar system called Atlas. This radar was installed in the 80's and uses a magnetron as the microwave emitter source and a hard tube pulse modulator. With more than 20 years of use, its reliability was becoming questionable due to the lack of availability of its main high-voltage components.

Recent advances in semiconductor devices capabilities have led to the development of many solid-state high voltage pulse modulators topologies suitable for substituting tube-type modulators [1].

In this paper we describe the development of a solid-state pulse modulator and digital control unit designed to substitute the hard-tube modulator of Atlas transmitter. Figure 1 shows the basic configuration of the hard-tube modulator formerly used.

A capacitor is charged by a 50 kV DC power supply. A trigger pulse commands the switching of a tetrode tube. When the tetrode is commanded, the voltage across the capacitor is coupled to the load. The coupling capacitor has a very high capacitance of 0.3 μF and must handle up to 50 kV.

Although very robust, this configuration is bulky and made use of multiple tube amplifier stages (pentode and triode stages) to produce the tetrode trigger. Also, due to its non-modular conception, maintenance was very difficult and monitoring was poor [2].

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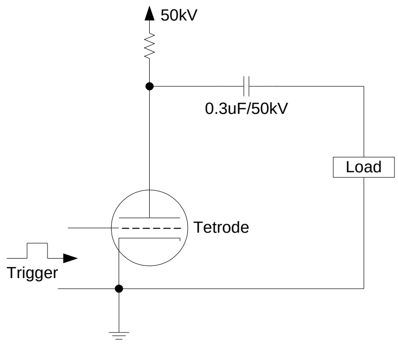


Fig. 1. Basic configuration of a hard-tube modulator

Our purpose was to develop a solid-state modulator with a higher pulse regulation, a more compact assembly, better reliability and maintainability. The main advantages of the proposed topology lay on its modular conception, which maximizes its operational availability and facilitates maintenance. By building the modulator with eight independent identical switching modules connected in parallel we achieve to implement the soft failure mode [3] of operation. That feature enables the transmitter to operate even with the failure of one or two modules. The absence of these modules will only result in a transmitted power reduction, which diminishes the radar range.

## II. SYSTEM OVERVIEW

As it is shown in Figure 2 the presented solid-state modulator is composed by a three-phase non-controlled line-rectifier, a high-voltage and a filament switch mode power supplies, a Clipper circuit, a charging circuit, a modulator unit, a pulse transformer, a shaping circuit and a control unit.

The input voltage for the system is 200 V AC three-phase at 400Hz (radar station conditions). This voltage is rectified to 260 V DC and feeds the high voltage and the filament power supplies.

The magnetron filament power supply is not essentially part of the modulator but is necessary for magnetron proper operation. This circuit was implemented using two cascaded push-pull converters. The output level is regulated to a maximum of 5 V DC 20 A and requires an output isolation of 50 kV. The regulation is made by the first stage and the isolation guaranteed by the second stage.

The high-voltage power supply is a 2.7 kW full-bridge converter with fixed output set to 900 V DC. This voltage is applied to the Clipper circuit, which regulates the charge of the pulse-forming-networks (PFNs) present in the switching modules. The charging circuit is composed by an inductor and sixteen charge diodes (one for each PFN). This configuration allows charging the PFNs with twice the dc supply voltage while isolating the power source and the modulator switches.

Eight identical modules in parallel compose the modulator unit. The modulator output is connected to the primary side of a step-up pulse transformer that matches the impedance of the load and to the PFNs, resulting in maximum energy transfer. In the secondary side of the pulse transformer a shaping circuit is necessary in order to adjust the rate-of-rise of voltage of the pulse to the value required by the magnetron (90 – 120 kV/µs).

To excite the 1 MW C-Band magnetron tube [Model TV313 Thales] used at Atlas radar at maximum peak and average power, the modulator shall provide 1.7 µs pulses of 37 kV and 65 A at a pulse repetition frequency (PRF) of 585.5Hz.

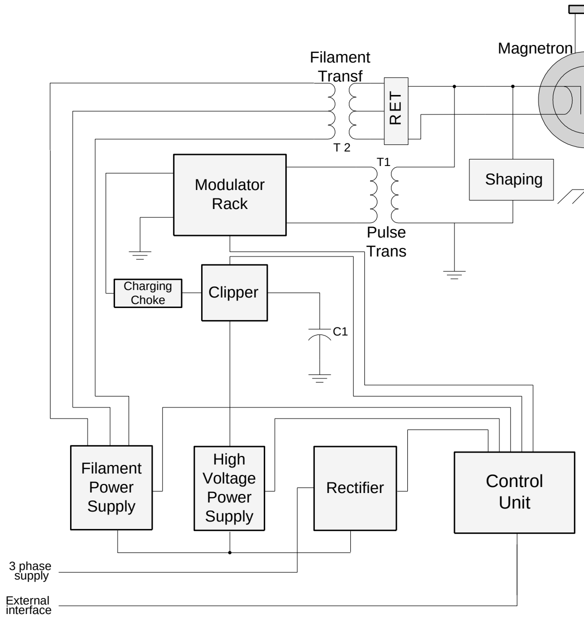


Fig. 2. Schematic diagram of the modulator system

## III. MODULATOR TOPOLOGY

Figure 3 shows a schematic diagram of the pulse modulator. The modulator is composed of eight identical modules, each of them containing a fuse, two charge diodes (D1 and D8, Part Number VMI K25UF), two interconnected Guillemin E-type PFNs of 0.85 µs, two IGBTs with internal reverse diodes (SWA and SWB, Part Number BSM 300 GA 170 DLC), two IGBTs protection diodes (D3 and D7), two line interconnection diode (D4 and D6), a backswing protection diode (D5) and a driver circuit for the switches (the part number used for diodes D3, D7, D4, D6 and D5 is APT2X100D120J with its two diodes connected in series).

By controlling the switches, the modulator can provide three operation modes: long-pulse (1.7 µs), short-pulse (0.85µs) and bipulse (two pulses of 0.85µs separated from 3 to 12µs). For short-pulse operation, switch A must be driven in order to discharge only PFN A, since diode D4 blocks PFN B discharge. For long-pulse operation, switch B must be driven. In this case, both PFNs (A and B) will be discharged forming a pulse with double the width of the first case. Finally, for bipulse operation, switches A and B must be driven in sequence one after the other. In this case PFN A will discharge first and then PFN B will discharge in sequence, with a controlled delay.

Figure 4 shows a schematic diagram of the Clipper circuit. The power source is set to a constant 900 V DC output and it regulates the charge level of the PFNs. When IGBT SW1 is turned-on the charging procedure starts and there will be a resonance between L1 and the total PFNs capacitances, which will tend to duplicate the supply voltage at $V_{L1B}$. The Clipper control compares a reference voltage with the charging voltage and when they equal, SW1 is turned-off and, at the same time, IGBT SW2 is turned-on. Together with diodes D9 and D2 of the Clipper circuit, it is formed a path for the energy stored in L1 returns to the power supply. The charging diodes are used to prevent discharge of the PFNs once they are charged. The value of L1 determines the charging period; its value must compromise the maximum pulse repetition frequency, protection sensibility in case of failure and regulation accuracy.

The Clipper circuit also controls the charging current. If the current measured through R2 is higher them the reference value the Clipper will turn SW1 off and turn SW2 on. This protects the system from short-circuit on the modulator or load malfunctions.

Once the PFNs have been charged, by triggering SWA or SWB switches, they will be discharged generating pulses of approximately 790 V and 2700 A. Each switch must hold a maximum of 1700 V and drive 340 A to deliver pulses of less than a microsecond.

Diodes D4 and D6 have the function of interconnecting PFNs A and B to operate with long-pulses. Diode D5 is necessary to give a path to the charging current and to pulse-transformer demagnetizing current.

Diodes D3 and D7 protect the IGBTs from reverse voltage. Diode D3 has also the function of avoiding that the end of PFN A is connected in parallel to the IGBT module internal diode. In case SWB is driven, SWA internal diode gets directly polarized and would tend to conduct if D3 is not used.

The pulse-transformer is necessary to step-up pulse voltage generated at the modulator unit output. It has also the function to match the impedances between the switching modules PFNs and the load. The pulse-transformer was designed to minimize leakage flux and it has four primary winding in parallel.

The magnetron parasitic capacitance produces a voltage tail at the end of the pulse. In order to damp out this remnant voltage and also allow the demagnetization of the pulse transformer, a 10 kΩ resistor (R) is connected in parallel with the magnetron.

### *A. High-Voltage Power Supply*

The basic configuration chosen for the power supply is the full-bridge circuit due to its capability to provide high power and voltage output with fair transformers efficiency.

The input is 260 V DC, provided by a three phase non-controlled rectifier. The output voltage is set to 900 V DC. The clipper circuit regulates the output current. The converter operates with pulse width modulation at 30 kHz,

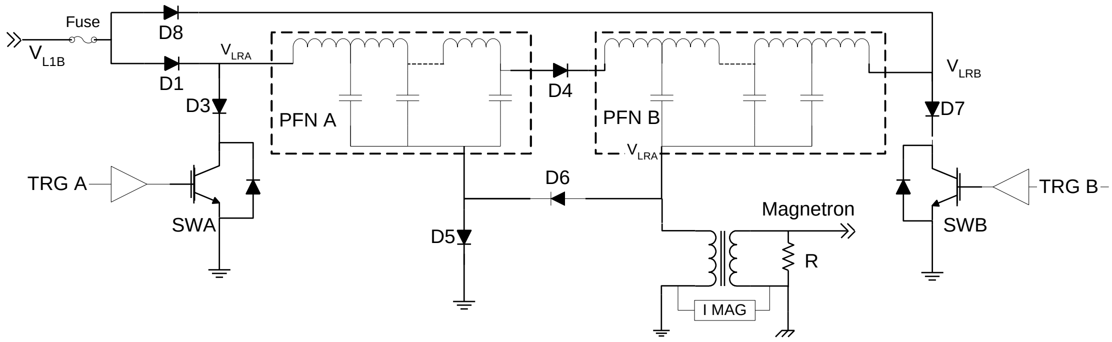


Fig. 3. Modulator topology diagram (indicated voltages are referenced to ground)

with voltage feedback.

The power supply implements the following functions or circuits. Soft start: the control circuit implements a soft start every time the power supply is activated. Short circuit protection: this circuit disables the power supply's output if a current above 150% of the nominal value is detected. The circuit, once disabled, must be manually reset to restart operation. Current monitor: the power supply has a current transformer that detects the output current waveform, useful for the operator to check for anomalies in the output of the power supply. Over-voltage protection: once the power supply output must be regulated in a fixed value, if it is detected a voltage superior to the specified value; the power supply output is disabled, requiring manual reset to restart operation. Input voltage failure: the power supply control circuit monitors the input voltage coming from the three phase rectifier, if this voltage is out of specification the power supply is also disabled. Output voltage and current monitor: the power supply furnishes output voltage and current monitor to the modulator control unit.

### *B. Clipper Circuit*

Clipper circuit has the function of regulating the charging voltage of the modulator PFNs and, additionally, it implements over-current and over-voltage protections. Clipper control system has voltage and current feedbacks. Current feedback acts only in case of short-circuit in the modulator, while voltage feedback is used to control the charging period of the PFNs by controlling the conduction of switch SW1. The PFNs charging voltage defines the pulse peak power.

When L1 output voltage ($V_{L1B}$) reaches the value determined by the control reference (Vref), switch SW1 is turned-off and SW2 is turned-on, allowing the remnant energy in L1 to be returned to the power supply.

Figure 5 shows the PFN voltage ($V_{LRB}$) and the power supply input current ($I_{IN}$) waveforms for long pulse operation. The long pulse charging period is approximately 600 µs and the charging voltage peak occurs at 1600 V.

The PFNs charging period should be less then the maximum pulse repetition frequency, which is 2x585.5 Hz (twice nominal PRF due to staggering). The bigger the period, the better the pulse power regulation and the short-circuit efficiency. Hence, the charging period should be as close as possible to the minimum repetition period.

Clipper circuit implements also magnetron backswing over-current protection. Internal sparks in the magnetron forces the modulated energy applied to the magnetron to return to the modulator. This phenomenon is common to the operation of the magnetron, thus, it must be considered in the design of the modulator. To reduce the effect of this phenomenon, the Clipper circuit monitors this backswing current and, when it reaches a determined value, the Clipper reference voltage is set to a value 10% lower then the nominal value. This reduces the next pulse power also in 10% and allows the magnetron to recover faster from the undesired spark.

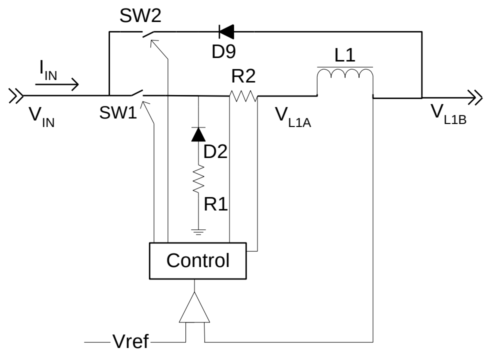


Fig. 4. Clipper circuit diagram (indicated voltages are referenced to ground)

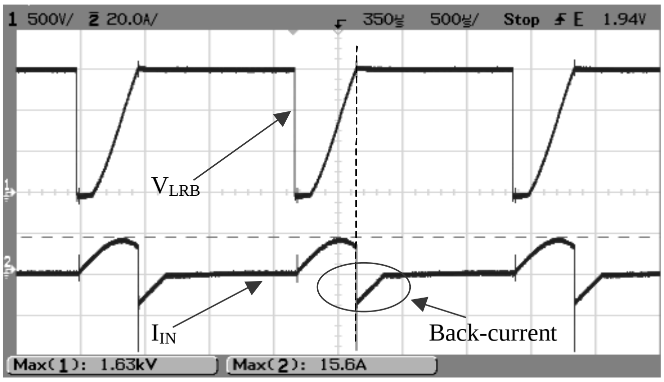


Fig. 5. PFN voltage ($V_{LRB}$) and power supply input current ($I_{IN}$) waveforms for long pulse operation (V: channel 1 – 500 V/div, channel 2 – 20 A/div and H: 500 µs/div)

### *C. Pulse Forming Network*

Each switching module is composed by two interconnected E-type voltage-fed Guillemin networks to generate the desired pulses. This PFN form is particularly convenient since it uses equal-value capacitors and a continuously wound tapped coil whose dimensions are chosen so as to provide the proper mutual physical coupling between tapped sections [5].

Since one of the main objectives is to implement the modulator unit in a modular conception, the design of the PFN parameters should start by the definition of the operation region of the magnetron. Thus, it must be defined the magnetron static impedance to which the modulator will be submitted. Following the magnetron data-sheet we observe that the emission begins at 33 kV and 20 A and goes up an absolute maximum of 37 kV and 65 A. This defines the impedance range from 570 to 1650 Ω, as represented in Figure 6.

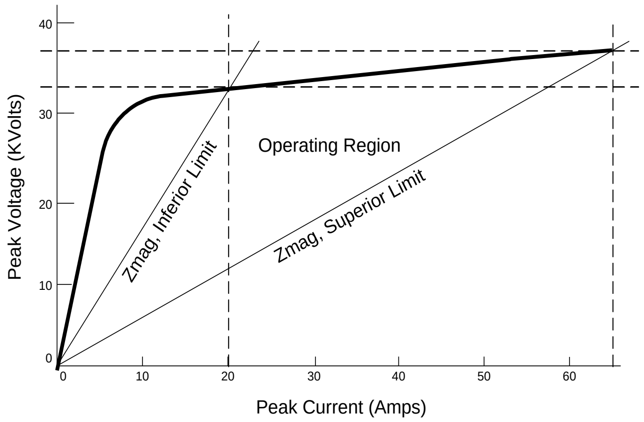

Fig. 6. Magnetron impedance curve

Once the pulse transformer ratio is 1:50, the impedance range referred to the primary side goes from 0.228 to 0.660 Ω.

Having defined the individual PFN characteristic impedance, it is necessary to define how many LC cells each PFN will have and the respective values of L's and C's. In our design we decided to use 10 cells since in type E PFNs each cell represents 1/n of the pulse width. That means we can increase or decrease the pulse width by adding or subtracting cells. As our specified error margin is 10%, in order to be able to adjust the pulse width only by adding or subtracting cells, it is necessary at least 10 cells for each PFN.

The basic relations to calculate the PFN critical design parameters are given by the following equations [5]:

$$C_n = \frac{\tau}{2 \cdot Z_0} \tag{1}$$

$$L_n = \frac{\tau \cdot Z_0}{2} \tag{2}$$

$$Z_0 = \sqrt{\frac{L_n}{C_n}} \tag{3}$$

$$\tau = 2\sqrt{L_n . C_n} \tag{4}$$

Where:

- $\tau$ - output pulse width at 50% points
- $Z_0$ - characteristic impedance of the PFN
- $C_n$ - total network capacitance
- $L_n$ - total network inductance
- n - number of sections
- L - inductance per section $L_n/n$

Since there are eight modules in parallel, and the pulse transformer ratio is 1:50, the magnetron impedance in nominal power operation is given by:

$$Z_{mag} = \frac{V_{peak}}{I_{peak}} = \frac{37KV}{65A} = 570\Omega \tag{5}$$

$$Z_{\text{mod}} = \frac{Z_{mag}}{a^2} = \frac{570\Omega}{50^2} = 0.228\Omega = \frac{Z_o}{m} \tag{6}$$

Where:

- $Z_{mag}$ - magnetron apparent impedance at nominal power operation
- $Z_{mod}$ - magnetron apparent impedance at nominal power operation referenced to the primary of the pulse-transformers
- m - number of switching modulator modules connected in parallel
- a - pulse transformer ratio 1:a

In order to constitute magnetizing current at the end of the pulse, it is recommended to calculate the PFN characteristic impedance 10% higher then the load impedance [4].

$$Z'_{\text{mod}} = 1.1 \cdot Z_{\text{mod}} = 1.1 \cdot 0.228 = 0.251\Omega \tag{7}$$

$$Z'_0 = m \cdot Z'_{\text{mod}} = 8 \cdot 0.250 = 2.0\Omega \tag{8}$$

To operate at the inferior limit of magnetron impedance range ($Z_{mag,prim,\ inf}$) it would be necessary at least three modules ($m$) that defines the modulator impedance ($Z'_{mod,3}$) as:

$$Z'_{\text{mod},3} = \frac{Z_0}{m} = \frac{2.0}{3} = 0.667\Omega \le Z_{mag,prim,\text{inf}} = 0.726\Omega \tag{9}$$

Now, to calculate $C_n$ it must be taken to account the desired pulse peak power, which is given by the stored energy equation.

$$E = \frac{C_T \cdot V^2}{2} = P_{peak} \cdot PW \tag{10}$$

For long pulse network:

$$C_T = 2 \cdot \frac{P_{peak} \cdot \tau}{V^2} = 2 \cdot \frac{2 \cdot 10^6 \cdot 2.04 \cdot 10^{-6}}{1600^2} = 3.19\mu F \tag{11}$$

$$C_n = \frac{C_T}{m} = \frac{3.19\mu F}{8} = 399nF \tag{12}$$

$$L_n = \frac{\tau \cdot Z_0}{2} = \frac{2.04 \cdot 10^{-6} \cdot 2}{2} = 2.04\mu H \tag{13}$$

Where:

- $C_T$ - total line capacitance
- $P_{peak}$ - pulse peak power
- PW - pulse width

Once the long pulse is formed by the junction of PFN A and PFN B, each one with 10 cells, the value of each capacitor should be 20 nF. In order to have the specified power margin, considering the losses, especially coming from the pulse transformer, we have decided to use 22 nF capacitors. The inductive elements were implemented with two solenoid of 0.90 μH each.

*D. Pulse-Transformer*

The pulse-transformer is necessary to step-up the voltage pulse applied to it while matching the impedance of the PFNs to that of the magnetron, giving maximum energy transfer. The pulse transformer shall perform a faithful stepping-up of the voltage pulse without causing considerable deterioration of the pulse characteristics.

In order to reduce rise time, the pulse transformer was designed for a low magnetizing inductance. Due to excessively high primary current, the transformer was constructed with four primary winding, which reduces leakage inductance. The values measured of secondary referred leakage inductance and distributed capacitances were 240 μH and 170 pF, respectively.

Figure 7 shows the pulse waveform applied to the input of the pulse transformer and the generated output when driving a matched non-inductive resistive load.

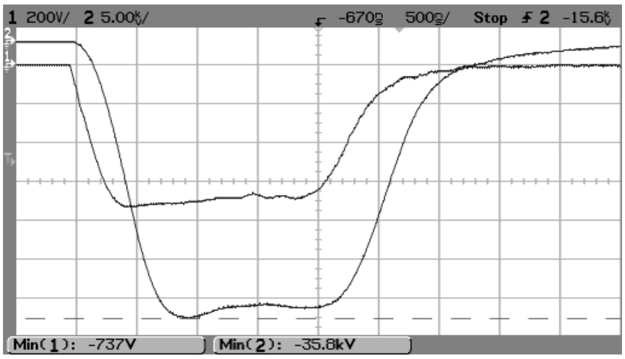


Fig. 7. Channel 1 shows pulse transformer input and channel 2 shows pulse transformer output for long pulse operation

*E. Control and Command Unit*

The control and command unit is responsible for monitoring the security chain signals and to turn the modulator on or off. It also provides the low voltage pulses to drive the modulator.

The main challenge in the development of the control and command unit was to provide a reliable operation despite the presence of high-frequency noise due to magnetron emission and high current pulse modulation. To minimize noise influence in the security chain signals, optocouplers were used, isolating the control circuits from the rest of the transmitter. A Cyclone FPGA from Altera was placed as the core of the command and control circuits, implementing all the needed logic. This programmable logic device was sufficiently fast to allow us to create a “noise filtering” logic, ignoring all the changes in the security signals on the precise instants of noise generation: at the modulator pulse switching and at the enabling of the high-voltage power supply.

Pulse formatting and filtering was also implemented in the FPGA. Three steps are involved in this function. First, the input pulse from the rangefinding system is filtered from spurious pulses, limiting the pulse repetition frequency at a given value (1171 Hz). Then, the pulse is formatted by defining its width to 2.8 μs, independent of its input width. The last step selects which PFN will be driven, depending on the radar pulse width desired by the operator. The formatting function is also responsible for generating a delayed pulse, used in the bipulse operation mode. To reduce the jitter between the first and the second pulse, so to not introduce errors in the rangefinding, we have used a clock of approximately 160 MHz in the FPGA, more than two times the frequency of operation of the rangefinding processor (76.7 MHz).

The human interface of the system can be made by a local control panel or by a remote computer, through a serial communication. This communication is made using a RabbitCore RCM3220 processor and converting its RS232 serial port to a differential RS422 standard, making it more immune to noise. The remote computer can monitor all the security signals of the system and define the operation mode and pulse separation in the bipulse mode. Figure 8 shows the monitoring screen implemented in the remote computer.

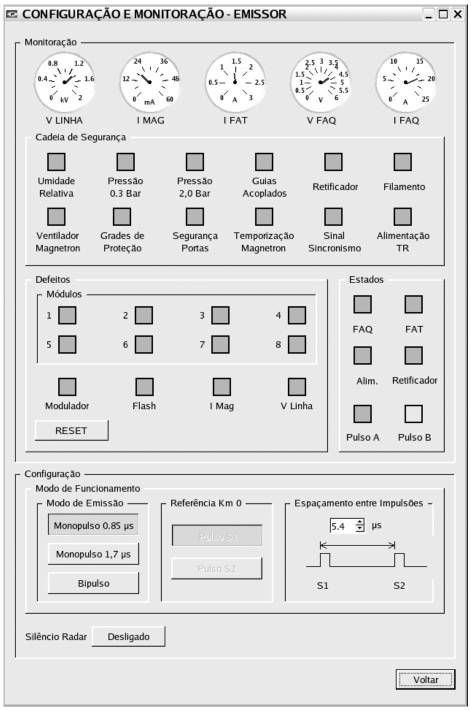


Fig. 8. Remote computer monitoring and control screen

## IV. RELIABILITY AND MAINTAINABILITY

The modulator reliability and maintainability is guaranteed by its modular conception and by its monitoring system that informs status of every equipment module, making it easier to identify malfunctions. All circuits that contain active devices are modular to facilitate substitution.

Once the modulator unit is the critical module of all the equipment, it was made modular to maintain functionality even when same modules are absent or out of work. The transmitter operation is not interrupted for more than one pulse repetition, when one module presents a failure, the only consequence is the lost of 1/8 of the nominal power. In this manner it was introduced the soft failure mode concept, common in solid-state transmitters, used in less expensive microwave tube transmitters.

The position of the modulator module fuse is the key to assure that, in case of failure of the module, it goes out of the circuit without affecting the rest of the system. In the case of a failure in one module, the fuse opens and the module will not be charged in the next cycle.

The operation of the soft failure mode is presented in Table I, which compares the magnetron impedances and the modulator impedance for operation with one to eight modules. The first column shows the number of operation modules, the second column indicates the nominal operation point of the magnetron. The third column gives measured magnetron peak current. Forth column shows magnetron impedance referred to the primary side of the pulse transformer. Fifth column shows total modulator impedance. Sixth column shows the matching ratio ($Z_{mod}/Z_{load}$). Last column shows one module peak current.

Normally, the pulse modulator operates in matched condition with the load. But, in the case of a module failure, the magnetron impedance will be less then the modulator impedance. That will increase modulator current. Thus, if we limit in 115% the maximum matching ratio the average peak current in one module will not surpass 425 A and no more than two modules can be absent.

**TABLE I**
**Magnetron and modulator operating impedance**

| # | V sec. (kV) | I sec. (A) | Z load prim. (W) | Z mod (W) | Matching (%) | I module (A) |
|---|---|---|---|---|---|---|
| 8 | 37.5 | 59.4 | 0.253 | 0.250 | 99 | 398 |
| 7 | 36.7 | 54.4 | 0.270 | 0.286 | 106 | 411 |
| 6 | 35.9 | 48.6 | 0.295 | 0.333 | 113 | 424 |
| 5 | 35.1 | 43.7 | 0.321 | 0.400 | 125 | 444 |
| 4 | 34.3 | 38.1 | 0.360 | 0.500 | 139 | 465 |
| 3 | 33.5 | 30.0 | 0.447 | 0.667 | 149 | 479 |
| 2 | 33.0 | 22.5 | 0.587 | 1.000 | 170 | 504 |
| 1 | 33.0 | 13.7 | 0.964 | 2.000 | 208 | 540 |

## V. CONCLUSION

In this work we have presented a solid-state pulse modulator topology developed to substitute a tetrode hard-tube modulator. We have described the modulator circuits, mode of operation and experimental results. This modulator is already operating in Atlas radar transmitter at Alcantara Launch Center. There are also four other radars in Brazil equipped with equivalent modulators [6].

Compared to the original system, the upgrade gives the following main advantages for radar operator and maintainer: size and weight were reduce for less them a half of the original, facilitating transport and installation, maintenance was facilitated due its modular conception and monitoring system, soft failure mode increased transmitter availability, new command and monitoring function were introduce to help operation and failure detection and, finally, overall system lifetime was extended by making use of up-to-date technology.

## ACKNOWLEDGEMENT

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Fig. 9. Atlas radar transmitter after upgrade

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## BIOGRAPHIES

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