DEVELOPMENT OF A MODULAR LINE-TYPE SOLID-STATE PULSED MODULATOR FOR AN S-BAND MAGNETRON

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Abstract – **This paper describes the design, development and assembling of a pulsed modulator used to excite a 1 MW S-Band magnetron tube [Model PM 110 S of CTL, USA]. The modulator provides 2.0 µs (long) or 0.8 µs (short) pulses of 38 kV and 50 A at a repetition rate of 400 Hz or 1200 Hz, respectively. It consists of seven parallel modulator units driving the three primary windings of a 1:50 ratio pulse transformer. Each unit contains two discrete pulse-forming networks (PFN) and two solid-state switches to generate 790 V and 390 A long and short pulses. This modulator topology was developed to improve reliability and maintainability of solid-state modulators by allowing on-line degradation (soft failure mode) and fully microwave source and modulator protection.**

***Keywords* – High voltage power supply, magnetron, pulse forming network (PFN), pulsed modulator, pulse transformer, soft failure mode (on-line degradation).**

I. INTRODUCTION

The objective of this work is to build a modulator to equip modern weather radars systems and to provide a up-grade alternative for obsolete magnetron or klystron radar transmitters modulators. There are two principal types of pulse modulators: line-type and hard-tube [1]. Thyratrons have been used as the main switch in line-type modulator, while triodes, tetrodes, or pentodes have been utilized in hard-tube applications. Modern solid-state modulator designs have tended to implement hard-tube offshoots topologies.

Compared to traditional modulators equipped with tube-type switches, hard-tube solid-state modulators have presented higher pulse length agility, higher pulse regulation, more compact assemblies, lower operational cost and finally better reliability and maintainability [2]. Our development efforts are aiming to build a modular line-type solid-state modulator which shall present the same pulse performance of modern hard-tube solid-state modulator, but with better efficiency, reliability and maintainability. Our proposal was to develop highly reliable equipment that would maximize its operational availability by its modular conception. Thus, it was implemented the on-line degradation concept [3] by building a modulator with seven modules that can still operate with the failure of two of them resulting only in a transmitted power reduction which impacts in the range of the radar.

II. SYSTEM OVERVIEW

As it is shown in Fig 1 the presented modulator is composed by a three-phase line-rectifier, a high-voltage power supply, a filament power supply, a Clipper circuit, a charging circuit, a modulator rack, a pulse transformer, a corner-cutter circuit and a control unit.

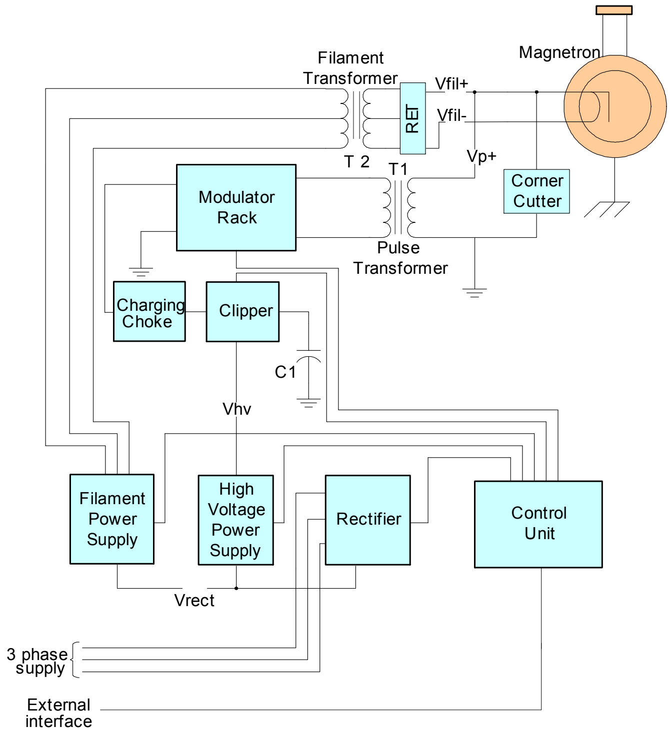

Fig 1. Schematic diagram of the modulator system

The input voltage for the system is 220 V AC three-phase at 50 to 60Hz. The input voltage is rectified to 300 V DC (Vrect) which is the input of the high voltage and the filament power supplies.

The magnetron filament power supply is a two-staged push-pull converter. The output level is regulated to a maximum of 10 V DC and 20 A. The regulation is made in the first stage while the isolation of 50 kV is reached by the second stage transformer (filament transformer – T2).

The high-voltage power supply is a 2.5 kW full-bridge converter with its output set to 900 V DC. This voltage is applied to the Clipper circuit which regulates de charge of the PFNs present in the modulator modules. The charging circuit is composed by a charging reactor and fourteen 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.

The modulator is a rack of eight modules, where seven are switching modulator modules and one contains the trigger circuit. The modulator output pulse is connected to the primary side of a step-up pulse transformer which matches the impedances of the load and the PFNs resulting in maximum energy transfer. In the secondary side of the pulse transformer the corner-cutter circuit is connected, which is used to adjust the rate of rise of voltage of the pulse to the value required by the magnetron. For the magnetron used in this design the requirement is of 30 – 45 kV/μs.

III. MODULATOR TOPOLOGY

Fig 2 shows a schematic diagram of the modulator. The modulator is composed of seven identical modules connected in parallel, each of them containing a fuse, two charge diodes (D1 and D5), two Guillemin E-type PFNs (PFN 2.0μs and 0.8μs), two thyristors (SW1 and SW2), two shunt diodes (D3 and D7), a backswing-protection diode (D4) and two current transformers for measuring charging current (T1) and backswing current (T2).

The output of the charging reactor (L1) connects the charging diodes in parallel. Switches SW1 and SW2 must work alternatively. When the SW1 switches of each module are selected, the long pulse PFNs are discharged and the same happens to the short pulse PFNs when the SW2 switches are selected. Both PFNs of each module have the same impedance but different total energy-storage capacity.

The power source is set to a constant 900 V DC output, and the charge of the PFNs is regulated by the Clipper circuit. When SW3 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_L. The Clipper control compares a reference voltage with the charging voltage and when they equal, SW3 is turned-off and, at the same time, SW4 is turned-on. Together with diodes D9 and D8 is formed a way for the energy stored in L1 return 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, it must be chosen a value that compromises 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 R3 is higher them the reference value the Clipper will turn SW3 off and turn SW4 on. This protects the system from short-circuit on the modulator or load malfunctions.

Once the PFNs have been charged, by triggering SW1 or SW2 switches, respectively, the long pulse PFNs or the short pulse PFNs will be discharged. In both cases, in matched condition, 790V and 2700 A pulses are generated at the modulator's output. Each switch must hold a maximum of 1800 V and drive 390 A to deliver pulses of less than a micro-second. The chosen component was the TF219 20B Dynex fast switching thyristor whose key parameters are: repetitive peak voltage (V_{DRM}) 2000 V and surge on-state current (I_{TSM}) 1200A.

Shunt diodes D3 and D7 are necessary in order to damp out any reflected voltage due to load mismatch. The pulse transformer used to step-up the modulator output was furnished by Stangenes Industries, Inc. Palo Alto – Califórnia – USA; it was built up with three primary windings to reduce leakage inductance and filled up in an oil-tank to guarantee primary and secondary isolation.

One of the problems involved with the operation of a microwave magnetron is the tendency for the tube to oscillate in other than the desired mode [4]. The rate of rise of voltage applied to the tube at the time when the tube initially begins to conduct is a primary factor in determining the tendency of a particular tube-modulator combination to operate stably and in the desired mode. The chosen approach to achieve stable operation was to use a corner-cutter circuit in the secondary side of the pulse transformer.

This circuit places a large load at the output of the line-type modulator at approximately 75% of the normal operating voltage, slowing the rate of rise of voltage to the tube substantially, and permitting stable operation with reasonably fast rise time, a highly rectangular RF pulse, and rapid fall time.

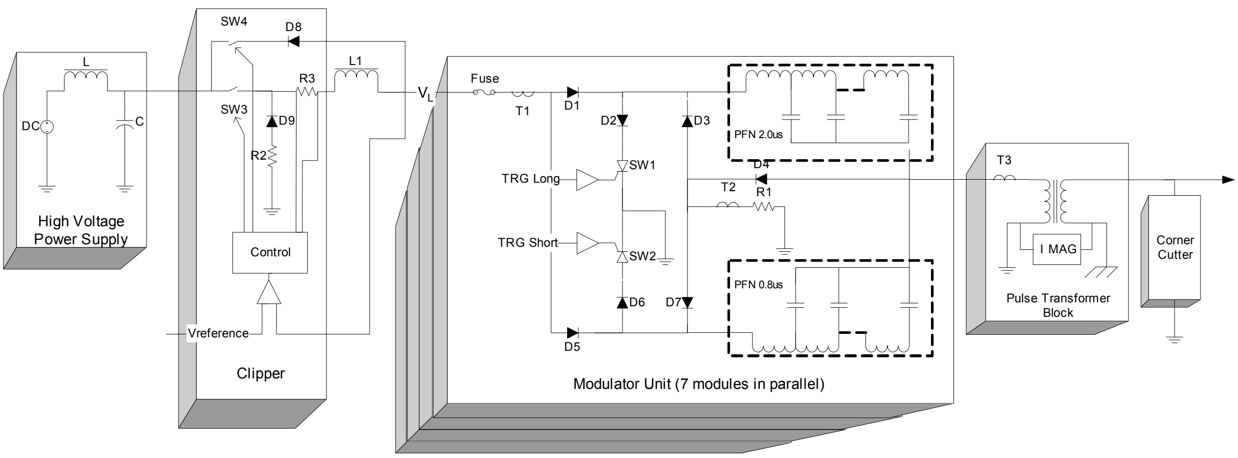

Fig 2. Modulator topology diagram

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 power supply input is a 300 V DC provided by a three phase non-controlled rectifier. The power supply voltage output is set to 900 V DC while its current output is regulated by the Clipper circuit. The control system chosen is the pulse width modulation with voltage feedback and operates at a 30 KHz switching frequency.

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 disable, 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 off 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 to regulate 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 SW3 (Fig 2). The PFNs charging voltage defines the pulse peak power.

When L1 output voltage (V_L) reaches the value determined by the control reference (Vreference), switch SW3 is turned-off and SW4 is turned-on, allowing the remnant energy in L1 to be returned to the power supply (Fig 3).

Fig 4 shows the L1 output (channel 2) and input (channel 1) voltage waveform in long pulse operation. The long pulse charging period is approximately 610μs and the charging voltage peak occurs at 1600V.

The PFNs charging period should be less then the maximum pulse repetition frequency, which is 1200Hz for short pulse operation and 400Hz for long pulse operation. 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 is 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.

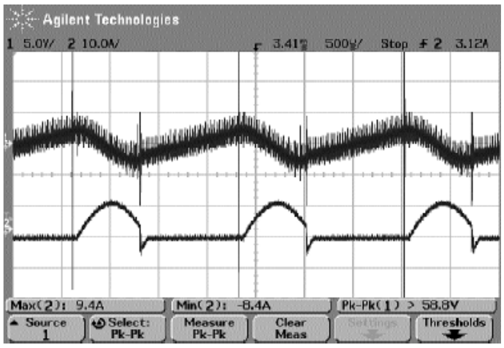

Fig 3. High voltage power supply output waveforms (channel 1 shows output voltage ripple, channel 2 shows output current)

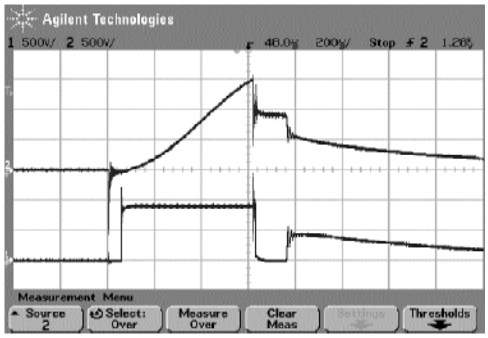

Fig 4. L1 voltage waveforms in nominal power operation (channel 1 shows L1 input voltage and channel 2 shows L1 output voltage)

C. Pulse Forming Network

Each switching modulator module is composed by two independent E-type voltage-fed Guillemin networks to generate the desired pulses. This PFN form is particularly convenient since it is has 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].

The design of the PFN begun by specifying the number of sections, the pulse impedance, the pulse peak power, and the pulse width of the network. The pulse widths are defined to be 2.0μs and 0.8μs. The impedance is specified by the magnetron operation point, the pulse transformer ratio and the number of units connected in parallel.

The capacitor used in the PFN must satisfy a number different criteria, including having low internal inductance and high stability and being able to withstand high applied voltages and to function reliable for extended periods of time at high recharge and discharge rates [4]. The pulse capacitor selected was a high-voltage polypropylene self-healing, non inductive capacitor PP3A2UL type fabricated by Eurofarad, Inc., Paris, France.

The basic relations to calculate the PNF critical design parameters are given by the following equations:

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

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

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

$$\tau = 2\sqrt{L_{n\tau}C_n} \tag{4}$$

Where:

- τ - 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 in our system there are seven modules in parallel, the pulse transformer ratio is 1:50, the magnetron impedance in nominal power operation is given by:

$$Z_{mag} = \frac{V_{peak}}{I_{peak}} = \frac{38KV}{52A} = 730\Omega \tag{5}$$

$$Z_{\text{mod}} = \frac{Z_{mag}}{a^2} = \frac{730\Omega}{50^2} = 0.292\Omega = \frac{Z_o}{m} \tag{6}$$

Where:

- Z_{mag} - magnetron apparent impedance in nominal power operation
- Z_{mod} - magnetron apparent impedance in nominal power operation referenced to the primary of the pulse tranformer
- 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].

$$Z'_{\text{mod}} = 1.1\,\tau Z_{\text{mod}} = 1.1\,\tau 0.292 = 0.3212\Omega \tag{7}$$

$$Z'_0 = m\,\tau Z'_{\text{mod}} = 7\,\tau 0.3212 = 2.24\Omega \tag{8}$$

Now, to calculate Cn that must be taken to account the desired pulse peak power.

$$E = \frac{C_T\,\tau V^2}{2} = P_{peak}\,\tau PW \tag{9}$$

For long pulse network:

$$C_T = 2\,\tau\frac{P_{peak}\,\tau PW}{V^2} = 2\,\tau\frac{2\,\tau 10^6\,\tau 2.0\,\tau 10^{-6}}{1600^2} = 3.125\mu F \tag{10}$$

$$C_n = \frac{C_T}{m} = \frac{3.125\mu F}{7} = 446nF \tag{11}$$

$$L_n = \frac{\tau\,\tau Z_0}{2} = \frac{2\,\tau 10^{-6}\,\tau 2.24}{2} = 2.24\mu H \tag{12}$$

Where:

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

From our requirements of rise time, fall time and flap top of 300ns, 500ns and 1.8μs for the long pulse operation, considering there are losses in the pulse-transformer and in the corner-cutter circuit (5% of total peak power) and the available commercial capacitor values, the optimum number of values of inductances and capacitances turn out to be 0.224μH and 47nF respectively for a PFN with 10 sections.

For short pulse operation, the values inductances and capacitances turn out to be 0.090μH and 22nF respectively for a PFN with 10 sections.

Fig 5 and Fig 6 show the result of the modulator output pulse driving a matched non-inductive resistive load in long and in short pulse operation respectively. Channel 1 shows the pulse measured directly at the modulator's output, while channel 2 shows the pulse measured at the pulse transformer input. It can be notice that the connection between the modulator and the pulse transformer presents a series inductance to the circuit, slowing down the pulse.

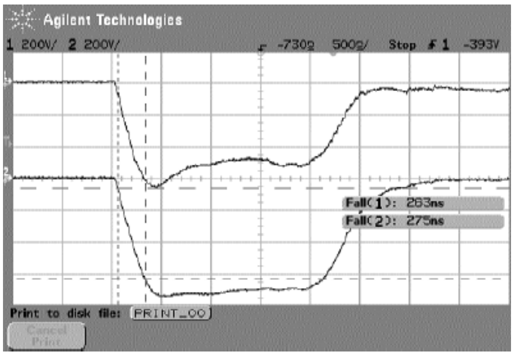

Fig 5. Channel 1 shows modulator voltage output and channel 2 shows pulse transformer voltage input for long pulse operation

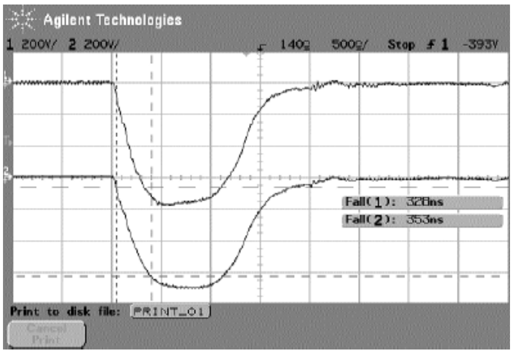

Fig 6. Channel 1 shows modulator voltage output and channel 2 shows pulse transformer voltage input for short pulse operation

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 applied to it 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 three primary winding, this reduces leakage inductance. The values measured of secondary referred leakage inductance and distributed capacitance were 240µH and 170pF respectively.

Fig 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.

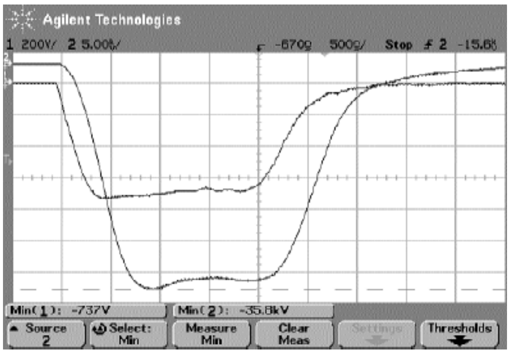

Fig 7. Channel 1 shows pulse transformer's input and channel 2 shows pulse transformer output for long pulse operation

E. Corner-cutter

The corner-cutter circuit is placed in parallel to the magnetron. Its function is to adjust the rate of rise of voltage of the pulse applied to the magnetron.

This circuit was implemented as depicted in Fig 8 where the use of varistors were explored. The varistor behaves as a capacitor when the voltage applied to it is bellow 1200V and as a short circuit when the voltage reaches 1200V. By connecting in parallel four stacks of 27 varistors in series six 47 Ω resistor the circuit places a large load at the output of the line-type modulator at approximately 75% of the normal operating voltage. When the pulse reaches approximately 32 KV the varistors start to behave as a short circuit, the circuit places the 10 series 4.7nF capacitor in parallel to the magnetron, slowing down the rate of rise of voltage applied to it. The 47 Ω resistors placed in series to varistor stack are used to limit the current through to corner-cutter circuit. The 100K Ω resistor placed in parallel to the 4.7nF capacitors discharges them to prepare the circuit to the next recurrence.

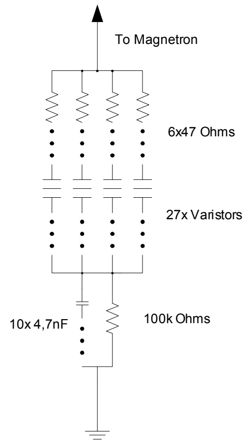

Fig 8. Corner-cutter schematic

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 rack is the critical module of all the equipment, it was made itself modular in a way 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 1/7 of the nominal power. In this manner it was introduced the on-line degradation concept, common in solid-state transmitters, to less expansive microwave tube transmitters with solid-state modulators.

Electrical position of the modulator module fuse is the key to assure that in case of failure the module is out of the circuit without affecting the rest of the circuit. However, when one module is out of the circuit the total PFN impedance goes from 0.32 to 0.37 and to 0.45 when two modules are out. This variation implies in an increasing mismatch with the load as modules are out. As the energy transfer depends upon the matched condition and as there is a limitation to damp reflected power in the modulator, the practical limit of operation is to have at least five modules operating.

V. RESULTS

Fig 9 and Fig 10 show the RF detected pulse for long and short pulse configuration, respectively. Specifications of pulse width, pulse peak power and pulse repetition frequency were achieved in both configurations. However, the RF detected pulses present poor pulse flatness. These oscillations can not be seen when the modulator is driving a resistive load, which indicates that the oscillation is caused by a variation of the magnetron dynamic impedance during the pulse duration and the pulse transformer leakage inductance, distributed capacitance and other parasitic effects.

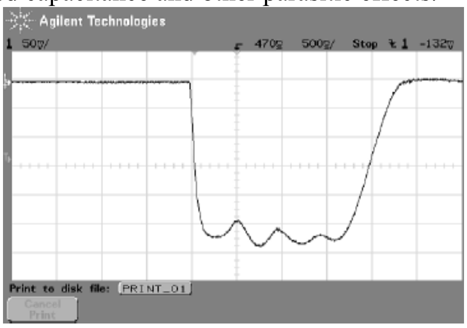

Fig 9. Detected RF long pulse

At the present moment, we are designing a new pulse transformer with four separate primary windings and improved mechanical interface with the modulator, in order to reduce leakage inductance and modulator-to-pulse transformer series inductance.

VI. CONCLUSION

In this article we presented a new solid-state pulsed modulator topology which implements on-line degradation concept. We demonstrated the feasibility of this topology by presenting the experimental results of the development of a 1 MW S-Band magnetron transmitter.

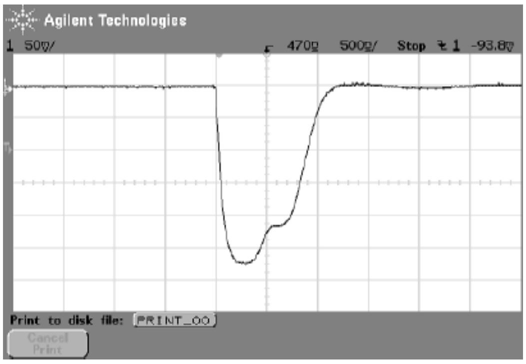

Fig 10. Detected RF short pulse

The results obtained demonstrate that the only specification that was not yet achieved was the RF detected pulse flatness. But since the oscillation present in the RF detected pulse is not present when driving a resistive load, we conclude that the flat-top oscillation is not a limitation of the presented topology but a mismatch between the modulator system and the magnetron load. Nevertheless, the most important requirements of the design, pulse-to-pulse power stability, nominal peak power, stable operation and on-line degradation, were achieved.

ACKNOWLEDGEMENT

In addition to our colleagues at Unicamp and Omnisys, we would like to thank Fapesp for co-sponsoring this work, Cláudio Franca and Múcio Padilha (from Barreira do Inferno Lauching Center – CLBI) for contributing to the success of this work.

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