Design, Construction and Characterization of a Line-Type Pulse Modulator for Driving High Power Magnetron

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Abstract — **In this work, the results of design, construction and characterization of a line-type pulse modulator for driving high power magnetron are reported. The sub-assemblies of modulator are: a high voltage supply, a charging reactor, a diode blocking, a pulse-forming network (PFN), a hydrogen thyratron model 5C22 and a pulse transformer. The PFN design approach is based on the Guillemin network synthesis theory, Foster´s and Cauer´s theorems. Using this approach, a 31 Ω of impedance level and 11.4 nF of capacitance PFN was simulated and then assembled to supply 9 kV and 0.7 μs voltage pulses in a pulse transformer primary circuit, at a pulse recurrence frequency (PRF) of 2 kHz. The pulse transformer was designed to impedance matching and d-c isolation between the PFN to magnetron, with transformation ratio 1:7, supplying 30 kV voltage pulses with 93% of efficiency and 9A of filament d-c current through of a bifilar winding.**

Index Terms — **Line-type modulator, magnetron, PFN, pulse modulator, pulse transformer.**

I. INTRODUCTION

Microwave radars require pulse modulators to produce short duration pulses in order to drive microwave tubes, such as pulsed magnetrons. The modulators usually used in radar systems are line-type pulsers. These modulators are referred to as "line-type" because the energy storage device is essentially a lumped-constant transmission line, commonly known as pulse-forming network (PFN). The basic sub-assemblies of a line-type modulator are: a high power supply, a charging reactor, a diode blocking, a PFN, a hydrogen thyratron and a pulse transformer (see Fig. 1).

The PFN consists of a set of inductors and capacitors which may be put together in any one of a number of possible configurations. The values these elements can be calculated to give an arbitrary pulse shape, when the PFN configuration, duration pulse, impedance level, and load characteristics are specified [1].

The pulse transformer is one of the most critical elements of modulator. The transformer leakage inductance L_L and the distributed capacitance C_D are often limiting factors of design, so they can cause undesirable oscillations in output pulse. However, L_L and C_D can be controlled by geometrical quantities of the core and coil. Furthermore, the core and the coil materials must sustain the high voltage through out them. A pulse transformer is capable to supply differents voltage levels to load, to effect d-c isolation between the source and the load, and to match the impedance level (source and load) in order to transfer the maximum energy from PFN to magnetron [1]. In addition, the secondary circuit transformer is used not only to produce high voltage magnetron pulses, but also to bias the magnetron filament through a bifilar winding (Fig. 1).
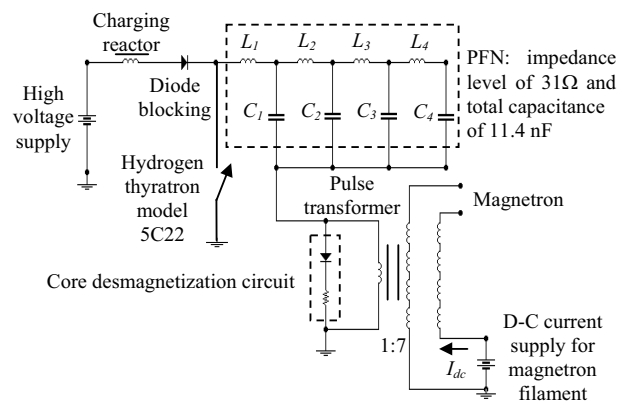

Fig. 1. Typical circuit of the line-type modulator with pulse transformer secondary bifilar winding.

This paper is organized as follows. Section II describes design considerations of charging reactor. Section III presents PFN construction. Section IV describes pulse transformer design. Section V presents experimental results and discussion. Section VI relates conclusion.

II. CHARGING REACTOR DESIGN

In line-type modulators, all energy stored in the PFN is, normally, dissipated during the pulse; hence it is necessary to recharge it in the interpulse interval. For this purpose, a reactor is used as the charging element. This element allows that the PFN to be charged at peak with double of voltage of power supply [1]. This effect occurs because the PFN capacitance C_{PFN} together with the charging reactor inductance L_C work as an oscillatory circuit, so the charging voltage through the PFN reaches a power supply double voltage at $T_C = \pi\sqrt{L_C C_{PFN}}$, where T_C is the charging period.

The reactor of modulator is made up of grain-oriented silicon-steel (Hipersil®) type-C (see Fig. 2). The core volume is $3.024 \times 10^{-4} \text{m}^3$, with an average magnetic path of 0.336 m, and a cross-sectional area of $9 \times 10^{-4} \text{m}^2$. In order to obtain a desired degree of linearity during operation of the reactor, an experimental circuit was developed to measure the effective magnetic permeability of the material. The results achieved allowed to design a reactor that works in a linear operation with a coil of 1325 turns and a 4.5×10^{-5}m of airgap. These values were used in order to obtain an inductance of 2.7 H. Thus, using the values of reactor inductance and PFN capacitance, it was possible to obtain a charging period $T_C \cong 500$ μs, that is suitable for a 2 kHz PRF operation.
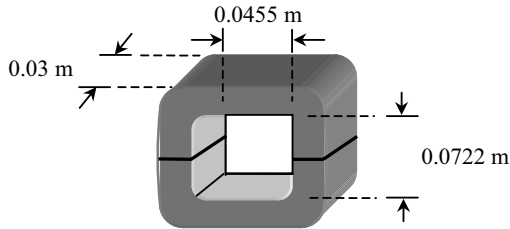

Fig. 2. Sketch of type-C core charging reactor of modulator.

III. PULSE-FORMING NETWORK CONSTRUCTION

The design of the PFN is based on the Fourier-series expansion, techniques used by Guillemin, together with Foster´s and Cauer´s theorems [1]. The PFN was made up using a 0.48 m length and 0.025 m diameter continuous solenoid, assembled around of PVC pipe and four 2.85 nF high voltage mica capacitors. Each capacitor was tapped at the proper points at the tubular solenoid. The solenoid inductance and mutual-inductances values were ajusted using a Hewlett-Packard LCR meter based on results reported in [2]. The PFN was constructed with 31 Ω impedance level, 11.4 nF of total capacitance and 462 mJ of energy, supplying 9 kV and 0.7 μs voltage pulses to the pulse transformer primary circuit at a PRF of 2 kHz.

IV. PULSE TRANSFORMER DESIGN

In order to the pulse transformer transfers the maximum amount of energy of PFN to the load (i. e., maximum efficiency η of pulse transformer), in a given pulse duration τ, a minimum energy must be stored in the coil. This can be obtained if the impedance level of load R_L and τ fulfill the following conditions

$$R_L = \sqrt{\frac{L_L}{C_D}} \,, \qquad (1)$$

$$\tau = \sqrt{2L_P C_D} \,, \qquad (2)$$

where L_P the primary inductance, the L_L inductance and the C_D capacitance are the relevant variables of the pulse transformer design. These elements can be related to the geometrical quantities of the transformer and the core material characteristic according to the equivalent circuit (see Fig. 3), establishing therefore, a tradeoff between these parameters. Hence, the maximum efficiency η in percentage is obtained according to

$$\eta = \left[1 - \left(\sqrt{\frac{2L_L}{L_P}} \right) \right] 100\% \,. \qquad (3)$$

A. Equivalent Circuit of the Pulse Transformer

Figure 3 shows the equivalent circuit of the pulse transformer used in this work. The $v_P(t)$ and $v_S(t)$ are the electric voltages in primary and secondary circuits, respectively. The $i_P(t)$ and $i_S(t)$ are the electric currents in primary and secondary circuits, N_P and N_S are the numbers of primary and secondary turns, M is the mutual inductance, R_I is the primary winding resistence and L_S is the secondary inductance.
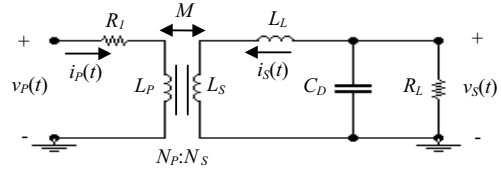

Fig. 3. Equivalent circuit of the pulse transformer.

The circuit elements shown in Fig. 3 are calculated from the geometrical quantities of the transformer, the dielectric constant of the insulation material ε, and the effective permeability μ_e of the core according to the expressions

$$L_P = \left(\frac{N_S^2 A \mu_0 \mu_e}{l_m} \right), \qquad (4)$$

$$L_L = \left(\frac{N_S^2 p_{av} d_{av}}{2l} \right) f_2 \,, \qquad (5)$$

$$C_D = \left(\frac{2 \times 8.85 \times 10^{-12} p_{av} l \varepsilon}{d_{av}} \right) f_1 \,, \qquad (6)$$

where A and l_m are the cross-sectional area and the mean magnetic-path length of the core, respectively, d_{av} is the average gap between layers, p_{av} is the mean perimeter of coil, l is the winding length and μ_0 is the free space magnetic permeability. All quantities are expressed in the MKS system [1,3]. In addition, f_1 is a factor which

depends on the voltage distribution between the primary and the secondary circuits to a given winding arrangement and f_2 is a factor related with step-up voltage ratio.

B. Effect of the Circuit Elements in Pulse Waveform

Figure 4 shows an arbitrary pulse with some quantities used to represent the fundamental parts of the waveform.
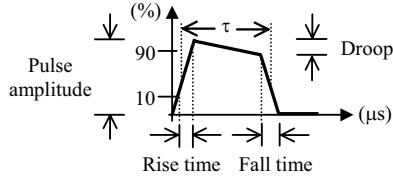
Fig. 4. Fundamental parts of the arbitrary pulse waveform.

In order to obtain pulses with fast rise time t_r and low droop D_r of the top, in a given pulse duration τ, it is necessary to reduce the L_L inductance, the C_D capacitance, and also maintain the L_P primary inductance constant. The expressions which relate these quantities are

$$t_r \propto 1.02\sqrt{L_L C_D} \,, \tag{7}$$

and

$$D_r = \frac{R_L \tau}{2L_P} \,, \tag{8}$$

where, L_L and C_D are obtained by (5) and (6), the 1.02 factor represent 10-90% of rise pulse and L_P is obtained by (4). The quantities t_r and D_r are given in seconds and percentage, respectively. On the other hand, as L_L, C_D and L_P are dependent of the geometrical quantities of coil and core, the rise time and the droop of pulse can be improved using appropriate winding arrangement [1,3].

In order to investigate the effect of L_L and C_D, the circuit of Fig. 3 was simulated using the state variables approach and a fourth order Runge-Kutta algorithm [2]. The results are shown in Fig. 5 for L_L and C_D calculated and measured, respectively. The dashed line represents the primary pulse, the dotted line refers the secundary pulse calculated using (4)-(6), and the solid line is the secondary pulse measured with the experimental set-up.
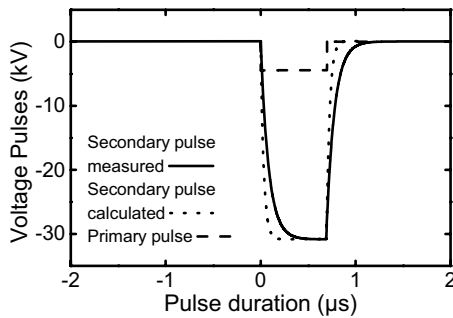
Fig. 5. Effect of L_L and C_D in the secondary pulse of transformer.

Thereby, it is possible to infer that L_L and C_D cause some delay in the rise time and the fall time (solid line), and consequently, an increase in the pulse duration. However, the peak amplitude was mantained in 30 kV and the top of pulse present low droop. The calculated and the measured values used in simulations (Fig. 5) are summarized in Table I. The discrepancy between both values has been investigated.

TABLE I
MEASURED AND CALCULATED ELECTRICAL PARAMETERS
OF THE OUTPUT VOLTAGE PULSE OF TRANSFORMER

Electrical parameters	Units	Calculated values ($\pm$10%)	Measured values ($\pm$10%)
Inductance – L_P	mH	18	21
Inductance – L_L	μH	30	52
Capacitance – C_D	pF	13	23
Rise time – t_r	ns	35	100
Pulse duration – τ	μs	0.7	0.9
Droop – D_r	%	3	4
Permeability – μ_e		472	557
Efficiency – η	%	94	93

C. The Lord-type Winding Arrangement

The Lord-type winding is known as the arrangement which provides the lowest $L_L C_D$-product, and therefore, it allows the pulse produces the fastest rise time and the lowest droop. It is made of two primary windings connected in parallel interleaved between four secondary windings connected in series. Due these features, the Lord-type was used in winding of the coil of transformer in this design [1].

D. Core Material d-c Properties

The PFN voltage pulses with only one polarity are applied on primary circuit pulse transformer, and under this condition, the core material is operated only to the right or to the left of hysteresis *B-H* loops region. Thus, due to pulsed regime, it is necessary to use a desmagnetization circuit for core, made up of a fast diode connected in series with a power resistor of 2 Ω (see Fig. 1). Furthermore, the core material must be capable to hold up 9A the filament d-c current for magnetron through the bifilar winding without saturation, and presents low losses of magnetic energy due to eddy currents. In order to reduce the eddy currents, and consequently, the energy losses, the material must be manufactured with thin lamination. Magnetic materials with thicknesses in the range of 25.4 μm to 127 μm are preferably used in design of pulse transformer [1].

E. Pulse Transformer Modulator Specification

The pulse transformer of modulator holds a core volume of $2.57\times10^{-4}\text{m}^3$, a mean perimeter coil of 0.198 m, a dielectric constant of the insulation material ε of 3.5, a

average gap between layers of 0.002 m, 14 turns primary circuit, 108 turns secondary, 30 kV of secondary voltage, 1.5 kΩ output impedance level. Hipersil® type-C with thicknesses of 270 μm was the magnetic material used in the core. Isopress paper impregnated with mineral oil was used in the core and the coil electric insulation. All system was assembled in a hermetically sealed tank.

V. EXPERIMENTAL RESULTS AND DISCUSSION

In order to check the pulse modulator performance, an experimental set-up was assembled. It consists, basically, of a high voltage power supply that feeds the PFN through the charging reactor and a fast blocking diode. A hydrogen thyratron model 5C22 was used to switch the PFN at 2 kHz. A pulse transformer (1:7) with a secondary circuit winding bifilar, using a power resistor of 0.5 Ω to simulate the magnetron filament, was used to provide energy to a power high voltage, non-inductive, aqueous solution $CuSO_4 \cdot 5H_2O$ resistor. This component was assembled with a glass pipe of 0.25 m lenght and of 0.032 m diameter closed with fenolite material ending, two inner copper electrodes, and two external conectors for load.

Concerning of the behaviour of FeSi-GO type-C material used in core of charging reactor, it is possible to infer that the material operate in linear region of hysteresis *B-H* loop. This is relevant not only to supply the amount of the energy specificated for PFN but also to obtain the output voltage pulse shape satisfactory in the primary circuit of pulse transformer.
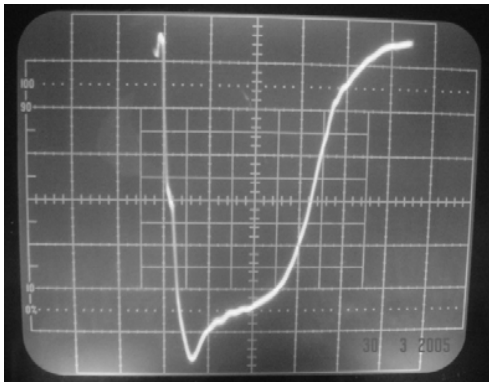

Fig. 6.   Output voltage pulse of secondary pulse transformer. Time scale horizontal: 0.2 μs/div. Time scale vertical: 2 kV/div.

Figure 6 shows output voltage pulses of secondary circuit transformer measured with an oscilloscope. These pulse present, approximately, 30 kV of amplitude, 0.9 μs of duration, 600 kW of peak power with 1.1 kW of average power. Based on in these results, it can be verified a good accuracy in the 1 to 7 ratio between the primary and the secondary circuits with 93% of efficiency. Thereby, it is

also possible to infer the behaviour of the core material FeSi-GO and Lord-type arrangement is satisfactory, even operating with a d-c current of 9 A. Furthermore, the pulse presents a fast rise time t_r (10-90%) of 100 ns, a fall time of 200 ns with a droop of 4%.

The output current pulse, shown in Fig. 7, was obtained using a Rogowski coil and an oscilloscope. This coil was assembled with a magnetic material core in the form of a toroid. It is made up of 0.040 m of inner and 0.078 m of external diameters, respectively, and 96 turns. To produce an output voltage pulse proportional to the output current pulse, it was necessary to use a passive integrator circuit *RC* series. Thus, it was possible to measure current pulses of 100 ns of rise time, 200 ns of fall time, 5% of droop, 0.8 μs of duration with, approximately, 20 A of peak amplitude (see Fig. 7).
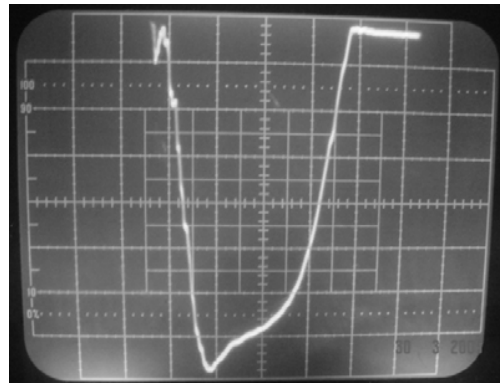

Fig. 7.   Output current pulse of secondary pulse transformer obtained with the Rogowski coil. Time scale horizontal: 0.2 μs/div. Time scale vertical: 2 A/div.

VI. CONCLUSION

In this work, it was reported design, construction and characterization of the line-type pulse modulator. The simulated results showed a good agreement with experimental results. Hence, the modulator designed is suitable for driving high power magnetron.

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