Journal of the Korean Physical Society, Vol. 49, December 2006, pp. S309∼S313

High-Power Pulse Transformer for a 1.5-MW Magnetron of KSTAR LHCD Microwave Application

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(Received 29 August 2005)

The microwave heating system of KSTAR consists of ECH and LHCD. ECH and LHCD offer reliability of operation at the beginning of plasma formation and non-inductive current drive for long-time steady-state operation, respectively. LHCD demands a C-band microwave system with a frequency of 5 GHz. A pulse generator with a power of 3.6 MW, 4 μs, 200 pps is required to drive a high-power magnetron. The high power pulse transformer has the function of transferring pulse energy from a pulsed power source to a high-power load. A pulse transformer producing a pulse with a peak voltage of 45 kV is required to produce a 5 GHz microwave source in a 1.5 MW magnetron. We have designed the high-power pulse transformer with 1 : 4 step-up ratio. The peak power handling capability is 3.6 MW (45 kV, 90 A at load side with 4 μs pulse width). In this paper, a system overview and test results of the high power pulse transformer are presented.

PACS numbers: 84.70.+p
Keywords: LHCD, Pulsed power modulator, Pulse transformer

I. INTRODUCTION

The microwave heating system of KSTAR consists of ECH and LHCD. ECH and LHCD offer reliability of operation at the beginning of plasma formation and non-inductive current drive for long-time steady-state operation, respectively. LHCD demands a C-band microwave system with a frequency of 5 GHz [1]. A pulse generator with a power of 3.6 MW, 4 μs, 200 pps is required to drive a high-power magnetron. The modulator system for LHCD system relies on a pulse transformer to step the peak pulse voltage up to 45 kV. The high-power pulse transformer has the function of transferring pulse energy from a pulsed power source to a high power load. A pulse transformer producing a pulse with a peak voltage of 45 kV is required to produce a 5 GHz microwave source in a 1.5 MW magnetron. We have designed the high power pulse transformer with 1 : 4 step-up ratio. The peak power handling capability is 3.6 MW (45 kV, 90 A at load side with 4 μs pulse width). This paper shows a system overview, the relations of equivalent circuit and transformer parameters to pulse performance, design procedure and test results.

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II. DESIGN CONSISERATIONS

1. Equivalent circuit analysis

A pulse transformer and its associated pulse generator and load can be represented by an equivalent circuit. Fig. 1 shows the equivalent circuit of a pulse generator, step-up pulse transformer and load [2,3].

By analyzing the behavior of each of the simplified equivalent circuits for a given pulse width (τ) and load (R_L, C_L), transformer parameters such as primary inductance (L_p), leakage inductance (L_L), and distributed capacitance (C_D) can be determined and thereby optimized for the best pulse response.

These transformer parameters are a function of coil geometry and winding configuration, dielectric constant of the insulation, and permeability of the core material. Fig. 2 shows the coil geometry and winding configuration of the pulse transformer.

Transformer parameters such as shunt inductance (L_p), leakage inductance (L_L), and distributed capacitance (C_D) are given by equations (1), (2), and (3), respectively [3]. The best design is one having the lowest LC product, providing it has the proper L-C ratio to match.

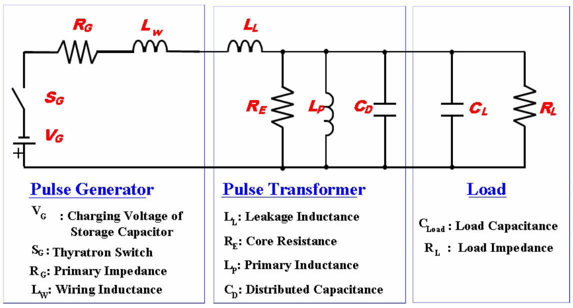

Fig. 1. Equivalent circuit of pulse transformer.

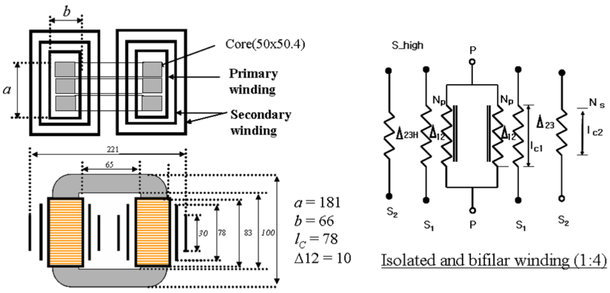

Fig. 2. Coil geometry and winding configuration.

$$L_L \cong 2\pi(a + b + 4\Delta_{12})N_s^2 \left(\frac{\Delta_{12}}{l_c}\right) \qquad \text{[nH]} \tag{1}$$

$$C_D \cong \frac{1}{2}\left(\frac{8.854\varepsilon_r U_c l_c}{\Delta_{12}}\right)\left(\frac{n-1}{n}\right) \qquad \text{[pF]} \tag{2}$$

$$L_p \cong 4\pi\mu_e N_p^2 \frac{A}{l_m} \qquad \text{[nH]} \tag{3}$$

where, N_p is the number of turns in the primary coil, is the insulation distance between layers, U_c is the average circumference of the layers in cm, l_c is the winding length in cm, ε_r is the relative dielectric constant of the insulating material between the layers, μ_e is the relative pulse permeability of the core, A_m is the cross-sectional area of the core, l_m is the mean magnetic path length of the core, and n is the step-up ratio.

2. Rise time analysis

The pulse efficiency depends on the detailed design parameters of the pulsing system including a pulse transformer and a load. We can neglect the effect of the shunt resistance R_e and the shunt inductance L_p during the short rise time in the leading-edge analysis.

The normalized load voltage $y(t)$ defined as

$$y(t) = \frac{V_L(t)}{V_G}\left(\frac{1+m}{m}\right) \tag{4}$$

is given by

$$y(t) = \left\{1 - e^{-at}\left(\frac{a}{w}\sin wt + \cos wt\right)\right\} \quad (\sigma < 1) \tag{5}$$

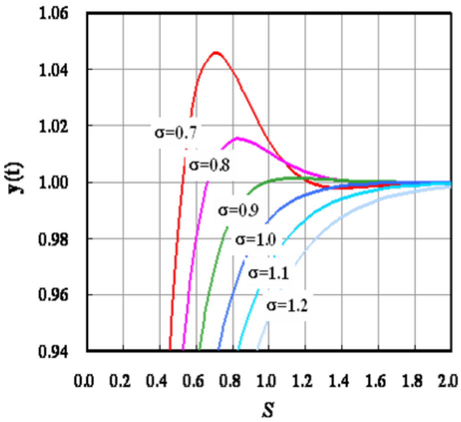

Fig. 3. Normalized rising-pulse waveform for various values of the damping factor.

$$y(t) = \left\{1 - e^{-at}\left(\frac{a}{k}\sinh kt + \cosh kt\right)\right\} \quad (\sigma \geq 1) \tag{6}$$

where

$$a = \frac{2\pi\sigma}{\tau}, \quad k = \frac{2\pi\sqrt{\sigma^2 - 1}}{\tau}, \quad w = \frac{2\pi\sqrt{1-\sigma^2}}{\tau},$$

$$\sigma = \frac{1}{2\pi\sqrt{m(m+1)}}\left(\gamma m + \frac{1}{\gamma}\right),$$

$$\tau = 2\pi\sqrt{\frac{m}{(m+1)}}\sqrt{L_T C_T},$$

$$m = \frac{R_L}{R_G}, \quad \gamma = \frac{Z_T}{R_L}, \quad Z_T = \sqrt{\frac{L_T}{C_T}}$$

$$L_T = L_W + L_L, \quad C_T = C_D + C_L$$

m is the matching parameter between the generator and the load, and γ is the impedance matching parameter between the transformation system and the load; Z_T is the transformation impedance of the pulsing system.

An expanded view of the leading edge of $y(t)$ near the flat top is shown in Fig. 3 as a function of the damping factor σ. In this figure, the normalized time S is defined by $S = t/\tau$. The pulse shape and the rise time are sensitive to the damping factor σ near the flat top. For given values of L_T and C_T, small σ gives fast rise time but generates large overshoot. For a matched load, the rise time is determined by

$$t_r = \sqrt{2}\pi S(\sigma)\sqrt{L_T C_T} \tag{7}$$

where S (σ) is a fitting function to give a rise time from 10 % to 90 % of maximum pulse height.

In general, a pulse flattop with less than ± 0.5 % ripple is required to produce a high-efficiency pulse. The damping factor σ has to be larger than 0.86 to limit the overshoot to less than 0.5 % during the flattop [4].

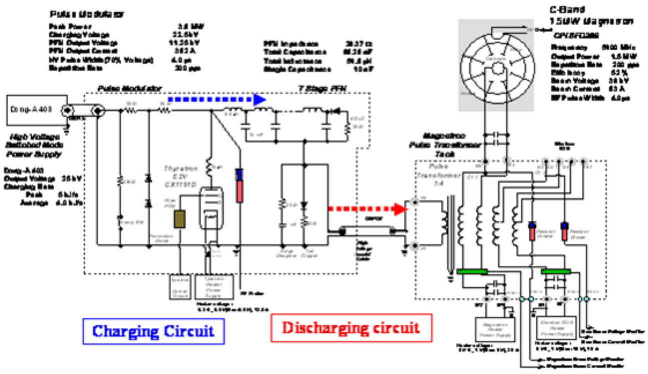

Fig. 4. Main circuit diagram of the pulse modulator for a 5-GHz low power test system.

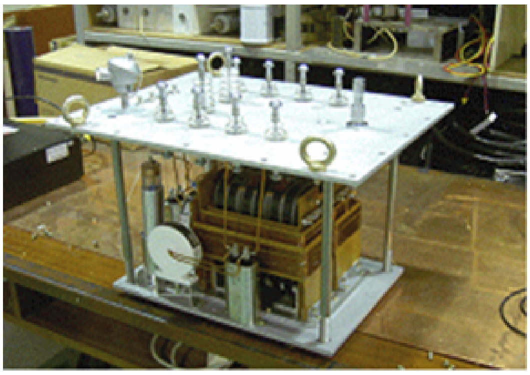

Fig. 5. Photograph of 1:4 pulse transformer.

3. Droop and core size

The pulse magnetization of the core, droop, and core volume are given by (8), (9), and (10), respectively:

$$V_s\tau_w = 10^{-8}\Delta B N_S A_e \tag{8}$$

$$D_r = \frac{R_L\tau_w}{2L_s} = \frac{\Delta B R_L l_m}{2\mu_0\mu_e V_s N_s} \tag{9}$$

$$V_{core} = \frac{2\mu_o\mu_e}{\Delta B^2}P.\tau_w D_r, \tag{10}$$

where ΔB is the average increment of the magnetic flux density of the core in gauss, V_s is the load voltage in volts, and τ_w is the pulse width.

From the above analysis, a fast rise time can be realized by reducing the number of secondary turns, but it produces larger pulse droop and core size. Thus, a tradeoff among these parameters is required to generate the optimum output pulse [5].

III. SYSTEM DESCRIPTION

A line-type pulse modulator is used to drive a 1.5-MW magnetron for a LHCD low power test system. Fig. 4 shows a main circuit diagram of the pulse modulator for a 5-GHz low power test system. Main components of this system are composed of 7 stages of PFN, thyratron tube switch (E2V,CX11910), and a 1 : 4 step-up pulse transformer.

In this system, the pulse energy is initially stored in an artificial delay-line pulse-forming network (PFN) and then periodically discharged into the primary of the pulse transformer by a gaseous discharge switch, or thyratron tube. During the inter-pulse period, the PFN is recharged from the dc supply. The pulse transformer also made it possible to match the impedance of the load to a power source for maximum transfer of energy from the modulator to a microwave electron tube. Table 1 describes the main specifications of a pulse transformer for a 1.5-MW magnetron.

The 1 : 4 pulse transformer has been designed and manufactured. In practice, a negative-polarity pulse is applied to the magnetron's hot cathode. The isolated and secondary bifilar winding technique is used for voltage distribution of the high-voltage pulse transformer [2, 3]. Cathode heater power can be supplied to the cathode by means of a bifilar secondary on the pulse transformer.

Table 1. Specifications of a pulse transformer.

Parameter	Value
Pulse droop [%]	4
Rising time [μs]	0.7
Step-up ratio	4
Primary voltage [kV]	22.5
Primary current [A]	375
Secondary voltage [kV]	45
Secondary current [A]	96
Load impedance [Ω]	470
Flat-top pulse width [μs]	4
Pulse Energy [J]	17.3
Repetition rate, max [Hz]	200

Table 2. Main parameters of a pulse transformer.

Parameters	Designed	Measured
Turns ratio	1 : 4	1 : 4
Primary turns	10	10
Leakage inductance	37 μH	42.2 μH
Distributed capacitance	12.82 pF	38.78 pF
Primary inductance	21.6 mH	19.85 mH
Magnetic flux swing	0.68 T	-
Effective permeability	800	-
Gap length	24 μ m	24 μ m
Effective core cross-section	66 cm^2	-
Mean magnetic path length	50.3 cm	-
Core weight	47 kg	-

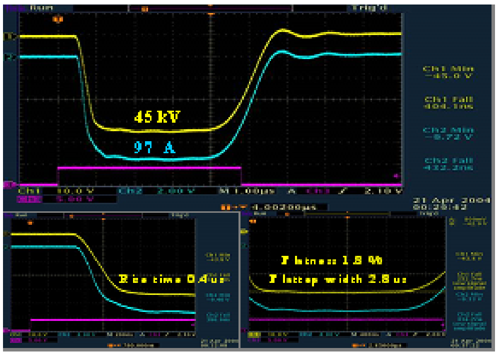

Fig. 6. Load voltage and current waveform with 472 Ω resistor (ch 2 (1000X), ch 2 (10X)).

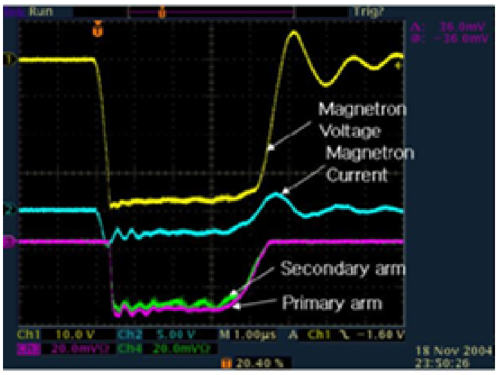

Fig. 7. Waveforms of magnetron cathode voltage and current and RF detector output voltage in two splitting arms.

Fig. 5 shows the fabricated pulse transformer, which is composed of 3 subcores, primary windings, secondary windings, and supporting structures. Each subcore is wound from grain-oriented silicon steel sheet (0.05 mm thickness, Microsil, "ML" cut core) manufactured by Magnetic Metals Corporation. Primary windings are made of Cu wire (ϕ1.6 mm) of 10 turns for each leg of the core, which are connected to the terminal in parallel. Secondary windings are made of Cu wire (ϕ1.8 mm) of 40 turns which are divided into two parts and connected to the terminal in parallel.

IV. DESIGN AND TEST RESULTS

1. Transformer design results

The effective pulse permeability is a very important parameter to design pulse transformers. To estimate droop of load voltage, we need information of primary inductance which is decided by effective pulse permeability, core cross section, magnetic path length and turn number. The effective pulse permeability can be obtained by using load voltage droop. The designed effective pulse permeability of cut core was selected to be 800 from our previous study [7]. The leakage inductance is measured by LCR meter (Hioki 3532) connected across the primary with the secondary shorted and also calculated by Eq. (1). The transformer parameters are measured after the transformer has been assembled. Main designed and measured parameters of the pulse transformer at the secondary side are summarized in Table 2.

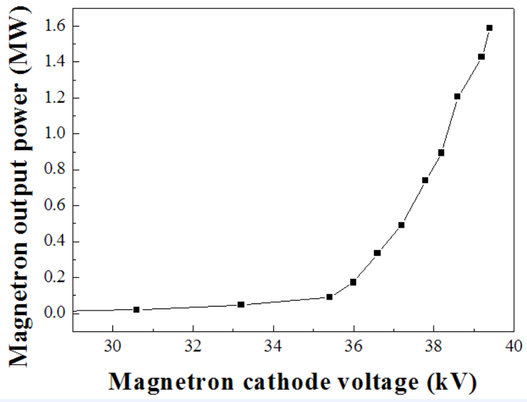

Fig. 8. 5-GHz RF output power *vs.* magnetron cathode voltage.

2. High voltage and high power test

Initially, the PFN modulator was tested with the 472-Ω resistive load for measuring transformer characteristics by using the circuit layout as shown in Fig. 4. In the system, the PFN capacitor was charged to a voltage of 25 kV by using a high voltage inverter power supply [6]. By tuning PFN inductance, the output voltage of the pulse transformer was conformed to the desired risetime and flat-topped pulse.

Fig. 6 shows a set of oscilloscope displays of the final-load voltage and the corresponding current, with an optical trigger waveform obtained in the test circuit of Fig. 4. The peak voltage and current reached 45 kV and 96 A, respectively. The pulse width is 4 μs with a flattop of 2.8 μs, and the voltage rise time is approximately 0.4 μs with a flatness of 1.8 %.

Secondly, the developed PFN modulator was tested for the magnetron, which has 1.5 MW peak power and 4 μs pulse duration for the microwave source of 5 GHz LHCD low power test system. A 3 dB power splitter in the single waveguide channel is tested with the LHCD low power test system. In our test, the matching waveguide is shorted and the splitting arms are connected to the dry dummy loads.

Fig. 7 shows the waveforms of magnetron cathode voltage and current and RF detector output voltage in two splitting arms. From the measurement of RF power by using directional couplers, the 665 kW input power is split into 338 kW for the primary arm and 323 kW for the secondary arm [8]. The power difference in the two arms is just 2.3 %. The insertion loss in 3-dB power splitter is 4 kW.

Fig. 8 shows the magnetron output power as a function of magnetron cathode voltage.

V. CONCLUSIONS

The PFN the modulator to operate the magnetron is designed and developed. The prototype pulse transformer with 1 : 4 turns ratio was developed to drive a 1.5 MW magnetron for a LHCD low power test system. The assembled pulse transformer was studied through parameter analysis and tested at high voltage for the 472 Ω resistive and the 1.5 MW peak power magnetron load for a 5 GHz LHCD low power test system. The test result conforms to the designed one. During the development work, we have established the design procedure and formulas and set up the test method for pulse characteristic measurements.

ACKNOWLEDGMENTS

This work is partially supported by KBSI and KSTAR project by the Korea Ministry of Science and Technology (MOST). The authors would like to thank POSCON and Don-A Tech. for their assistance in the construction of the pulsed modulator.

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