Coaxial-type water load for measuring high voltage, high current and short pulse of a compact Marx system for a high power microwave source

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A coaxial-type water load was used to measure the voltage output from a Marx generator for a high power microwave source. This output had a rise time of 20 ns, a pulse duration of a few hundred ns, and an amplitude up to 500 kV. The design of the coaxial water load showed that it is an ideal resistive divider and can also accurately measure a short pulse. Experiments were performed to test the performance of the Marx generator with the calibrated coaxial water load.

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I. INTRODUCTION

High power microwaves can be used to neutralize electronic equipment and systems with a wave that is concentrated in space and time and that has the greatest possible output power. Therefore, a high power microwave source requires a high-voltage, high-current pulse-power generator such as a Marx system, which has a typical pulse duration of ~ 100 ns [1,2]. To characterize this kind of pulse-power generator, one needs a matched load that has sufficiently broad bandwidth and that can withstand high voltage (several hundred kV) and can handle large current (kA). Therefore, we have designed a matched load which can be perfectly matched with the impedance of the Marx generator and can function as a probe for measuring the high voltage generated by the Marx system.

A water load that uses an aqueous resistive solution can function as both a matched load and a probe. In dc or in low frequency generators, a balanced water load [e.g., Fig. 1(a)] has been used to handle high voltage and high current [3]. The “water” is a solution of CuSO_4 or NaCl of a concentration that is adjusted to match the impedance of the generator. The solution also functions as a balanced resistive divider because the electric field in the water is uniform along the length of the resistor. However, this type of water load has too much stray capacitance and too much stray inductance at high microwave frequencies; thus the pulse shape becomes distorted as the pulse duration decreases.

To improve the rise time characteristics of a pulse, another type of the water load made of two concentric columns has been suggested [Fig. 1(b)] [4–6]. The outer column provides a return path for the current, which reduces the stray inductance and capacitance. In addition, the skin effect can be eliminated using a thin water tube, and

this elimination improves the response characteristics of the water load. However, this structure is difficult to compensate for reactance from the self-inductance and the self-capacitance.

We have developed a coaxial-type water load, illustrated in Fig. 1(c), in which the center conductor is the resistive element. With the resistance matched to the reactive impedance of the coaxial line, pulse shape distortion is minimized. The transient behavior of this load has been extensively analyzed using the electromagnetic field code MAGIC [7]. We built a coaxial water load based on this design and measured the characteristics of a short pulse with an amplitude of 500 kV, a pulse width of a few hundred ns, and a rise time of 20–30 ns.

This paper is organized as follows: The study and analysis on coaxial water load is described in Sec. II. Calibration and performance measurement of the Marx generator are described in Sec. III. A summary and conclusion are given in Sec. IV.

FIG. 1. Water load type: (a) balanced water load; (b) two tube water load; (c) coaxial water load.

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FIG. 2. Schematic of a coaxial water load combined with the Marx generator.

II. DESIGN OF WATER LOAD

We have designed a matched load to characterize a Marx generator whose pulse duration is typically the order of a hundred nanoseconds. The matched load (Fig. 2) has a coaxial structure that can compensate for the capacitance and inductance of traveling waves. Also, to avoid breakdown at the generator with an amplitude of 500 kV, the length of the water column is adjusted to ~ 1 m, which is less than the maximum electric field strength of several tens of kV/cm.

The voltage output from the Marx generator had a rise time of 20–30 ns, a pulse width of 200 ns, and an amplitude ≥ 500 kV. The Marx generator was connected with the water load in the form of a coaxial bending structure to make a more compact system having short length (Fig. 2). The coaxial water load is composed of a water column that functions as the inner conductor, and an outer column made of a conductor. The water column is filled with an aqueous resistive solution having a high dielectric constant, which enables the electric field to concentrate along its axis and makes this field uniform. Furthermore, it can be used with pressurized SF_6 along with the Marx generator, because it is capped by the end conductor (Fig. 2). An intermediate grid on the inner water solution resistor at a distance of 5 cm from the end conductor is used to divide the water column into two resistors. Therefore, the water column becomes an ideal resistive divider and the division ratio is given by the ratio of the lengths of the two resistors. The output voltage pulse from the grid point is further fed to a second dividing stage (Fig. 2).

Using MAGIC code, we have analyzed load behavior. Based on the design, we fabricated a working model and tested its performance experimentally. In this section, we describe in detail the procedure used to model the coaxial water load and the results obtained with MAGIC code. Results of the performance measurement are shown in Sec. III.

A. Transient behavior

The water of a coaxial-type water load exhibits the transient behavior of TEM waves because of its high dielectric constant. Because this transient behavior causes unwanted pulse distortion, the distortion must be minimized by properly designing the load.

Because of the three-dimensional shape of the inner conductor (Fig. 2), pulse distortion may arise due to the bending structure. To examine this geometrical effect on the propagation of TEM waves inside the coaxial transmission line, we simulated two different geometries, i.e., with bending structure [Fig. 3(a)] and straight [Fig. 3(c)]. Voltages of these two cases [Fig. 3(b)] were modeled with MAGIC2D for the straight structure, and MAGIC3D for the bending structure. In both cases the distance from the interface between the inner conductor and the position at which voltage was read in the simulation was the same as the distance when the bending structure is straightened. The effect of the bending structure is negligible [Fig. 3(b)]; this is because the total length of the inner conductor including the bending structure (~ 1 m) is too short compared to the pulse length (100 ns) to cause an effect on the transient behavior of the incident wave. Therefore, all the simulation results in this section were obtained by applying MAGIC2D code to the straight structure [Fig. 3(c)].

The simulated output voltage overshoot the target [Fig. 3(b)]. To determine why this occurred, we first examined the output voltages at three locations in the water load [Fig. 4(a)]. During wave propagation along the interface between the end of inner conductor and the water solution, incident waves on the interface from the input port can be reflected due to the impedance mismatch. The reflected voltage can be obtained by subtracting the injection voltage from the output voltage. The magnitudes of the reflected voltages at the three locations are equal but their phases are different because the locations are at different distances from the interface.

To determine the cause of the reflected voltage which can be generated as a result of field distortion due to the discontinuity at the interface, we compared output voltages at the interface (A), near the conductor (A2), and near the water (A1) [See Fig. 3(c)]. These voltages are nearly equal [Fig. 4(b)], and this suggests that the electric fields near the interface are uniformly distributed without any distortion.

The reflected voltage occurs because the impedance of the water changes over time. This can be seen by examining the electric flux line inside the water load when the

FIG. 3. (Color) Geometry of the water load and simulation result: (a) water load with bending structure; (b) comparison of output voltages for (a) and (c); and (c) water load without bending structure. B0, A: the interface between the inner conductor and the water solution; A1, A2, B, B1: positions of the voltage reading in MAGIC code.

propagation waves penetrate the water (Fig. 5): the electric flux lines initially concentrate on the surface of water, gradually penetrate the water, and finally become uniform. This process changes the load impedance. When the current flows through the water, the cross-sectional area through which the current is flowing is small initially. This area gradually increases over time until the current finally flows through the whole cross-sectional area of the

water column. Because the load impedance is inversely proportional to the cross-sectional area, it is high initially, decreases over time, and converges to a constant value.

The water load acts like a transmission line, and therefore the reflected voltage V_{ref} can be written as

$$V_{\text{ref}} = \frac{Z_L - Z_S}{Z_S + Z_L} V_{\text{in}}, \quad (1)$$

FIG. 4. The amplitude of the output voltage versus time (a) at interface A, B, and C and (b) at A, A1, A2 in Fig. 3(c); superscript, “-”: reflected voltage.

FIG. 5. Electric flux lines in the water load when the propagation waves are penetrated into water.

where V_{in} is the injection voltage, Z_L is the load impedance, and Z_S is the source impedance.

Near the interface between the conductor and the water, an incident wave is reflected because initially $Z_L > Z_S$; the reflection ceases after Z_L has decreased to equal Z_S [Eq. (1)]. Therefore, this process can cause the observed overshooting. However, this transient behavior of traveling waves occurs only briefly (~ 10 ns) [Figs. 3(b) and 5].

B. Division ratio

We have designed water load which functions as a resistive divider with a fixed division ratio. This divider should also closely reproduce the original voltage shape, which has fast rise time. A grid made of metal mesh was inserted between the upper end and the lower end of the water solution (Fig. 2), and the resistance ratio was adjusted and determined by the position of the grid. Therefore, the division ratio of the resistive divider is given by the ratio of the lengths of the upper end and the lower end of the water solution.

The amplitude of the input voltage was measured at various locations, and the output voltage was measured over time (Fig. 6), where the input voltages are those at A, B, and C in Fig. 3(c), and the output voltage is the voltage difference between the grid and the end conductor. Input voltage with an amplitude of 500 kV and a pulse duration

of 100 ns was supplied through the input port [Fig. 3(c)]. The division ratio is 20:1 which is the same as the length ratio. Although the input voltages showed transient behavior initially, eventually all of them converged to 500 kV [Fig. 6(a)]. Also, the output voltage converged to 25 kV [Fig. 6(b)]. Therefore, the designed coaxial-type water load is a resistive probe with a dc-like division ratio.

C. Response characteristics of a resistive divider

To accurately measure the performance of the Marx generator, the resistive probe must regenerate the original injection voltage. The rise time of the injection voltage is an important parameter in the voltage output of the resistive probe which determines the response characteristics of the probe.

The response of the water load was measured at injection voltages with rise times of 10 ns [Fig. 7(a)], 5 ns [Fig. 7(b)], and 1 ns (Fig. 8). The designed water load reproduced the original injection voltage when the rise time was 5 ns, but for injection voltage of 1 ns rise time, the water load's response characteristics were not appropriate.

To improve the response characteristics of the water load, we propose a thin-tube water load (Fig. 9) to reduce the stray capacitance and the skin effect, which are the factors that limit response characteristics of the water load.

FIG. 6. (a) Input voltage and (b) output voltage versus time for injection voltage having rise time of 10 ns [see Fig. 3(c) for the meaning of A, B, and C].

FIG. 7. Response characteristics (a) for rise time of 10 ns and (b) for rise time of 5 ns.

FIG. 8. Response characteristics for rise time 1 ns.

FIG. 9. (Color) A schematic of thin tube water load.

When the tube water load is 1.25 cm thick, the column water has a radius of 5 cm, and the input voltage has a rise time of 1 ns; therefore this tube's output voltage resembles the injection voltage more closely than that of the column water load [Figs. 10(a) and 10(b)]. Therefore, the limiting response characteristic of the tube water load is <1 ns.

III. MARX GENERATOR PERFORMANCE MEASUREMENTS

We built a water load based on our design and then tested the Marx generator's performance in two stages. First, we

calibrated the water load to obtain a precise divide ratio. This ratio is necessary if the load is to be used as a resistive voltage divider which can in turn be used to calibrate a capacitive probe built into the Marx generator. Second, we measured the performance of the Marx generator using the calibrated water load.

A. Water load calibration

Water load calibration is a process which verifies that the water load acts as an ideal resistive divider. It is a natural way to show that an ideal resistive divider both divides exactly the injection voltage and reproduces the shape of the original voltage. So, we tested the water load calibration using pulses with a rise time of ≤ 20 ns, a duration of 100 ns, and an amplitude of a few kV. These pulses were generated by a pulse-forming-line (PFL) generator which is composed of a 4 kV power supply, a coaxial cable with 50- Ω impedance, and a spark gap switch.

Because the impedance of the water load is 100 Ω , a compensated resistor of 100 Ω was connected in parallel to the water load to match the impedance of a coaxial cable. The divider consists of two stages (Fig. 11). The first stage was formed by the water solution column. A grid was inserted into solution near the lower end; this grid functioned as an electrode. The second stage was formed by the compensated resistive divider which was connected to the grid of the first stage. The compensated resistive divider was formed by 25 resistors of 4.7 Ω which were connected in series to achieve a division ratio of 25:1. Also, resistors were connected in parallel to capacitors, to compensate for stray inductance according to the length of the resistor. The measured attenuation of the divider was 500:1.

The impedance of the water solution was controlled by adjusting the concentration of the salt solution and measured using an LCR meter (Fluke Corp.). During the impedance measurement, the concentration of the salt was affected by a bubble that formed on the surface of the grid when the salt solution was mixed; hence, the measured total impedance was 87 Ω and the division ratio was about 19:1. Because the division ratio of the compensated resistive divider was 26.5:1, the total division ratio was 504:1.

FIG. 10. (a) The response characteristics of the tube water load (B) and the column water load (C) for 1 ns and (b) magnification of (a) during the time from 5 to 6.3 ns.

FIG. 11. (Color) Layout of the water load calibration. Water load V = water load voltage. CT = current transformer.

The PFL generator supplied an output voltage of ~ 4 kV to the water load. To check the voltage of the water load, we measured the voltage of the resistive voltage divider (water load voltage), and at the same time connected a resistive probe (TEK Probe, Tektronic Co.) in parallel to the compensated resistor (Fig. 11). However, the TEK probe voltage is not calibrated for this type of use, because

it is designed for use with long pulses. Therefore, we wrapped its ground in copper tape to reduce stray inductance. We inserted a current transformer (CT) (Stangenes Industries, Inc.) between the PFL generator and the compensated resistive divider, and measured the current to verify the calibration of the water load.

FIG. 12. Results of water load calibration: (a) voltages; (b) current.

FIG. 13. Amplitudes of the voltage (A) and the current (B) of the water load when high amplitude of the output voltage from the Marx generator is supplied to the water load.

The amplitudes of the voltages measured using the resistive divider in the water load and the Tektronix probe were very similar. According to the circuit (Fig. 11), the expected amplitude of the water load voltage was 1.9 kV; the measured amplitude of 1.8 kV (Fig. 12) differed from this expectation by $<8\%$. The TEK probe gave similar results. The pulse shape was also well reproduced. The amplitude of the current recorded by the CT was 0.64 A, which is very similar to the expected value of 0.63 A. However, because the CT is designed to be used to measure long pulses, overshoot occurred at the beginning of current's amplitude wave, even though the CT was adjusted.

B. Capacitive probe calibration and Marx generator voltage test

Using the calibrated water load, we calibrated the capacitive probe in the Marx generator. First, when high amplitude output voltage from the Marx generator was supplied to the water load, we checked the shape and the amplitude of the voltage and of the current. Then we compared these two results to confirm that the water load withstands the high voltage without arcing, and then we calibrated the capacitive probe.

An output voltage of ~ 300 kV amplitude from the Marx generator was supplied to the water load. The voltage shape formed a plateau by using the peaking gap switch because it falls at the beginning of the Marx generator voltage (Fig. 13). These results confirm that the shapes of the voltage and the current agree well, except in the first 25 ns because of the overshoot.

In step calibration of the water load, the amplitude and overall shape of the voltage as measured by capacitive probe completely agree with the measured result in the water load [Fig. 14(a)]. Therefore, the water load divider and the capacitive divider have the same response characteristics. The corresponding simulation results [Fig. 14(b)] agree in shape and amplitude, although a slight overshoot in capacitive voltage occurred, due to the transient behavior observed in earlier simulation results (Figs. 6–8).

IV. CONCLUSION

To measure the performance of a Marx generator's output source of short pulse characteristics, we designed a water load which functioned both as a matched load and an ideal resistive voltage divider. We used computer simulation to more specifically analyze transient behavior effects of the traveling waves using MAGIC code. We built the water load based on this analysis, and tested the performance of a Marx generator with voltage amplitudes ≥ 500 kV, current amplitude of 5 kA, pulse duration of 200 ns, and a rise time of ≥ 30 ns. The measurements agree well with the simulation results.

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FIG. 14. Calibration result for the capacitive probe: (a) measured result and (b) simulation result with MAGIC code.

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