Inductance Effects in the High-Power Transmitter Crowbar System

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The effective protection of a klystron in a high-power transmitter requires the diversion of all stored energy in the protected circuit through an alternate low-impedance path, the crowbar, such that less than 1 joule of energy is "dumped" into the klystron during an internal arc. A scheme of adding a bypass inductor in the crowbar-protected circuit of the high-power transmitter was tested using computer simulations and actual measurements under a test load. Although this scheme has several benefits, including less power dissipation in the resistor, the tests show that the presence of inductance in the portion of the circuit to be protected severely hampers effective crowbar operation.

I. Introduction

Modern-day high-power transmitters use large and expensive components. For example, a klystron may cost as much as $250,000. The protection of these high-cost items from destructive arcs and overloads is therefore of paramount importance in terms of economy, component life, and reliable operation of the transmitter.

One of the special protection devices in a high-power transmitter is the crowbar unit. When an internal arc in the klystron is sensed, the crowbar is fired within 5 to 10 microseconds, thereby diverting the large stored energy in the power supply system and preventing the disaster that would result if more than 1 joule of the energy were "dumped" into the arc.

In the present DSN transmitter crowbar design (Case 1), a series isolation resistor in the protected portion of the crowbar circuit dissipates power in normal steady-state operation. The disadvantages of this system are that the dissipated power is lost, reducing power to the klystron, and that the series resistor design requires a large amount of physical space. A new scheme was developed (Case 2) that would add a large bypass inductor in parallel with the resistor. DC steady-state current would then flow through the inductor, preventing power dissipation in the resistor. The resistor value was subsequently increased to match the characteristic impedance of the cable.

This article presents data taken from computer simulation and physical measurements under a test load of both the Case 1 and Case 2 schemes (see Fig. 1). The data shows that the presence of inductance in the portion of the system to be protected (klystron/crowbar discharge loop) severely limits the effectiveness of the crowbar.

II. Crowbar Operation and Simulation

A. Crowbar Operation

Observations and simulations were conducted on the DSS-13 S-band klystron high-power transmitter crowbar system to determine the effectiveness of the crowbar when inductance is present in the protected portion of the circuit.

Figure 1 is a simplified schematic of the system that is useful for analyzing various transient loop currents and voltages. The symbols used are defined as follows:

i_f	Fault current flowing through the "1-joule crowbar test wire" when it is shorted to simulate an arc fault
i_c	Crowbar current
E	Power supply voltage
R_F	Discharge resistor
R_1	Crowbar resistor
R_2	Crowbar isolation resistor
L_2 and L_3	Lumped and stray inductance in the crowbar and protected circuit
R_{2M}	Matching impedance to the HV cable
L_{2M}	Steady-state bypass inductance
L_1	Filter inductor
C_1	Filter capacitor
C_2	Energy storage capacitor
C_s	Stray capacitance in protected circuit
r_a	Resistance of the "1-joule crowbar test wire" (this wire is 2.237-inch-long #36 AWG soft copper, which will fuse when 1 joule of energy is passed through it)
t_0	Time at initiation of fault (switch S_a is closed)
t_1	Time when crowbar fires (switch S_a is closed)
t_2	Time when power supply circuit breaker opens (switch S_1 is opened)
Z_o	Characteristic impedance of HV cable
τ	One transit time delay of the cable
R_L	Klystron load equivalent impedance

To make a meaningful analysis of the crowbar system, actual values and, in some cases, estimated values were assigned to the circuit of Fig. 1 as follows:

$E = 40$ kV

$R_1 = 1$ ohm

$R_F = 39$ ohms

$C_1 = 0.2\ \mu F$

$L_1 = 1$ H

$C_2 = 1\ \mu F$

$L_2 = 4\ \mu H$ (estimated stray inductance of the wire)

$L_3 = 6\ \mu H$ (estimated stray inductance of the wire)

$Z_o = 46$ ohms

$\tau = 1\ \mu s$

$R_L = 4$ kohms (estimated klystron normal operating impedance)

$C_s = 1000$ pF estimated stray capacitance

$r_a = 0.077$ ohm

B. Test Cases

Measurements were taken for the following two operational scenarios:

Case 1: Minimal stray inductance in the protected circuit with $R_2 = 10$ ohms.

Case 2: Large bypass inductor, $L_{2M} = 4$ mH inductance; $R_{2M} = 40$ ohms.

C. Crowbar Measurements

The crowbar and the arc currents were measured using Pearson Model 101 current probes. The currents were recorded using an HP 1631AD logic analyzer. To simulate an arc, the "1-joule test wire" was shorted to ground, paralleling the 4-kohm equivalent klystron resistive load. The crowbar ignitron switch was fired 10 microseconds later.

D. Computer Simulation

SPICE,[1] a general purpose circuit simulation program for nonlinear dc, nonlinear transient, and linear ac analysis, was used to analyze the crowbar model.

For the purpose of simulating a fault condition (arc), S_a is closed at some time t_0, paralleling the klystron load with a low resistance path ("1-joule test wire"). At time t_1, 10 microseconds later, switch S_c is closed to simulate the crowbar action. Although the trigger pulse is 150 microseconds, the switch S_c can cease conduction early if the voltage reverses across it during the crowbar discharge (underdamped crowbar discharge loop) or if current through it falls below the value necessary for continued conduction (normally less than 10 amps).

III. Results

SPICE-simulated waveforms of arc current through "1-joule test wire" and crowbar current are shown in Fig. 2

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[1] SPICE Version 2.0, Intusoft, P.O. Box 6607, San Pedro, CA 90734.

for Case 1. Figure 2a shows a time scale of 50 microseconds, and Fig. 2b shows a time scale of 1 millisecond.

Physically measured results for Case 1 are shown in Fig. 3. The results are plotted using the same time scales as the SPICE-simulated waveforms in Fig. 2.

SPICE-simulated waveforms for Case 2 are shown in Fig. 4 with time scales of 50 microseconds (Fig. 4a) and 1 millisecond (Fig. 4b).

Physically measured results for Case 2 are shown in Fig. 5. The results are plotted using the same time scales as the SPICE-simulated waveforms in Fig. 4.

From the figures it can be noted that:

(1) Experimental results closely match the computed results.

(2) For Case 1, the arc current decays to zero within 5 microseconds after the crowbar fires (Figs. 2a and 3a), and the crowbar current initially builds up as the ignitron (switch S_c) starts conducting and diverting the energy in the high-voltage cable and in C_2. As C_2 discharges, the crowbar current starts decaying. About 300 microseconds later, the stored energy in L_1 and the follow-on current from the power supply kick in, and the crowbar current starts rising again (Figs. 2b and 3b) until switch S_1 disconnects the power supply.

(3) For Case 2, the arc current drops initially as soon as the crowbar is fired. However, the stored energy in L_{2M} sustains the arc current at a much lower value (Figs. 4a and 5a). Unfortunately, the presence of this large L_{2M} in the protected circuit produces an underdamped voltage condition in the ignitron (Fig. 6) and turns it off. Rather than flowing through the crowbar, which is now turned off, the undissipated energy in C_2 and the inductive energy in L_1 continue to flow through the arc, building the current (Figs. 4b and 5b) until the power supply is turned off.

IV. Discussion

In most applications, the actual energy that a klystron can safely dissipate during an internal arc is an unknown quantity. However, the consensus in the industry is that this dissipated energy should be no more than 1 joule.

The crowbar circuit is tested by substituting a "1-joule test wire" for the klystron. The test wire is purposely shorted through switch S_a to simulate an arc. The energy dumped in this wire is then the resistance of this wire times the square of the arc current times the length of time the arc current continues to flow.

When the crowbar was tested for both Case 1 and Case 2, the 1-joule wire survived in Case 1, indicating less than 1 joule of energy in the arc. The wire was completely fused (evaporated) in Case 2, indicating more than 1 joule in the arc.

In Case 2, as discussed above, the energy stored in L_{2M} and its actual inductance can be considered the driving force that opposes the quenching of the arc. At the same time, the reverse voltage turns off the crowbar, thus adding the rest of the energy from the power supply system into the arc.

V. Conclusions

The information obtained from the tests and computer simulations described above gives conclusive proof that inductance in the protected portion of the circuit severely limits the effectiveness of the crowbar. The inductance increases the total charge that flows through the arc (fault) and impedes the quenching of the arc. Therefore, inductance in the protected portion of the circuit should be kept to the minimum dictated by the physical layout.

Also, the total energy that flows into the fault will be reduced if the delay time to fire the crowbar is kept to a minimum, preferably less than 1 microsecond. Increasing the R_2 (isolation) series resistance would help reduce the energy dissipated in the arc. It would also keep the discharge loop either critically damped or overdamped, thus preventing the ignitron from shutting off. However, R_2 cannot be increased beyond 5 to 10 ohms, since these elements dissipate power during normal klystron operation, resulting in reduced efficiency of the system.

Finally, a note on computer simulation. A crowbar system is a large and expensive piece of equipment. It is not easily modeled on the laboratory bench with smaller components, and yet it must be modeled and more fully understood to ensure reliable operation. Since these simulations and experimental measurements agree quite well, we now have a tool that allows us to try out new concepts rapidly by giving us considerable insight into how the circuit will behave before expensive components are built.

Acknowledgment

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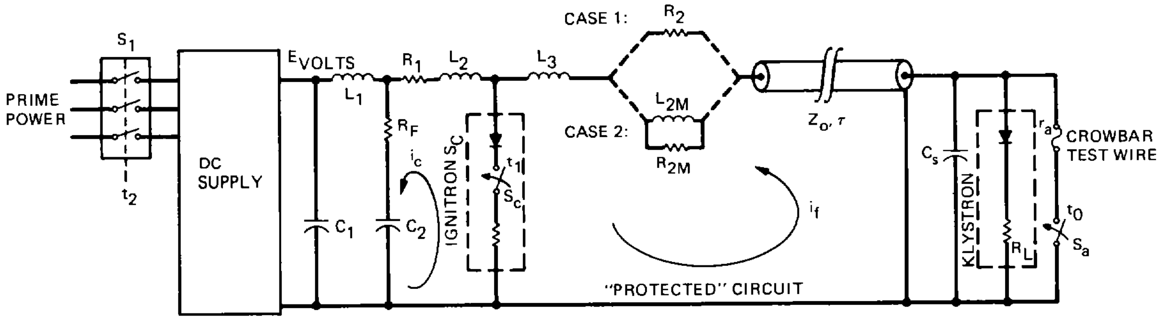

Fig. 1. Crowbar system, simplified schematic diagram

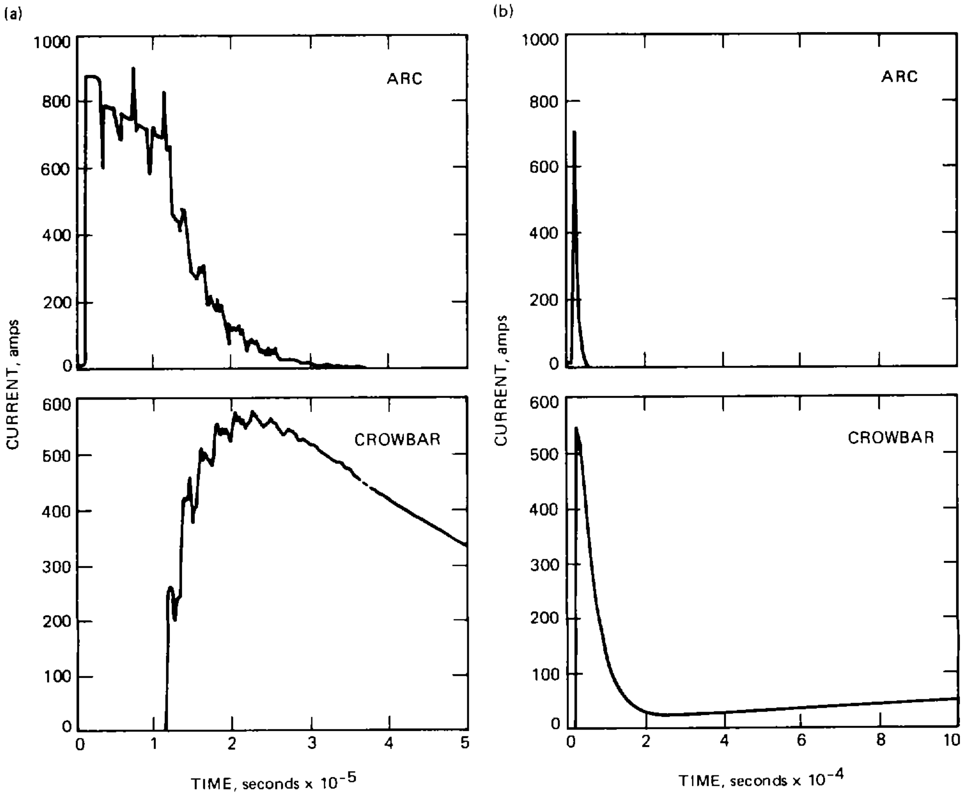

Fig. 2. SPICE-simulated waveforms for Case 1: (a) 50-microsecond time scale; (b) 1-millisecond time scale

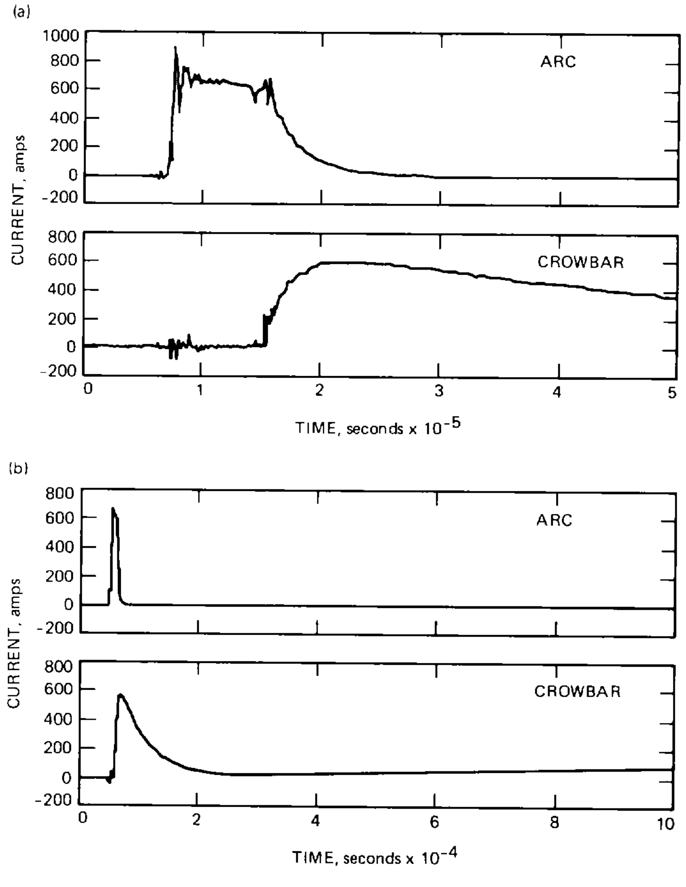

Fig. 3. Physically measured results for Case 1: (a) 50-microsecond time scale; (b) 1-millisecond time scale

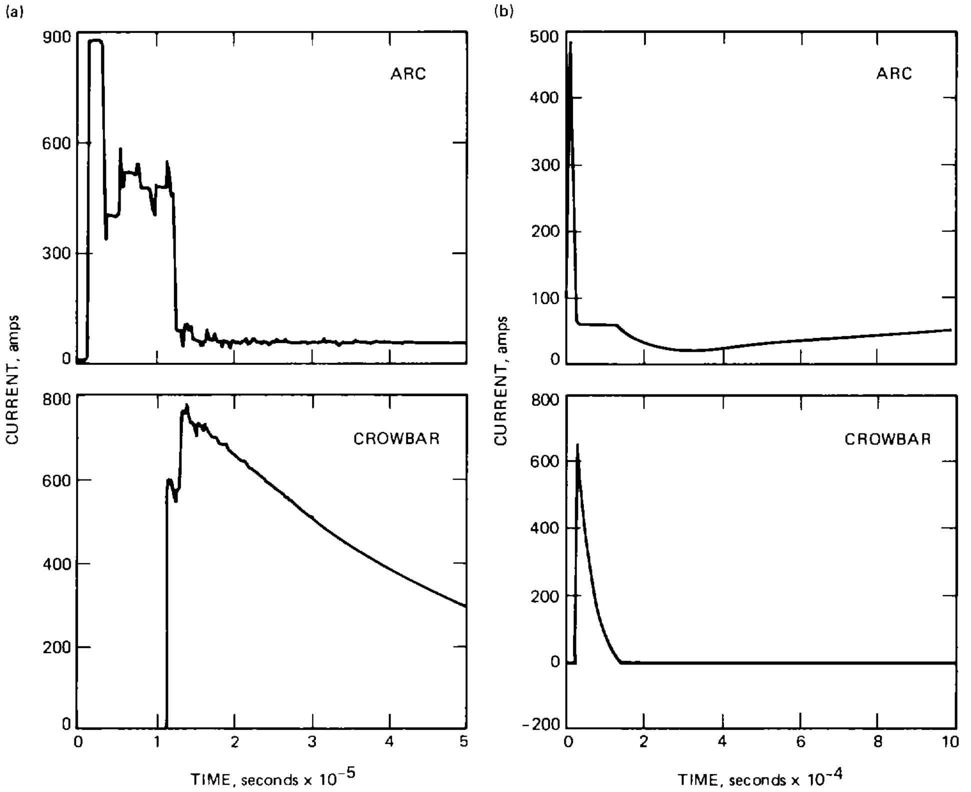

Fig. 4. SPICE-simulated waveforms for Case 2: (a) 50-microsecond time scale; (b) 1-millisecond time scale

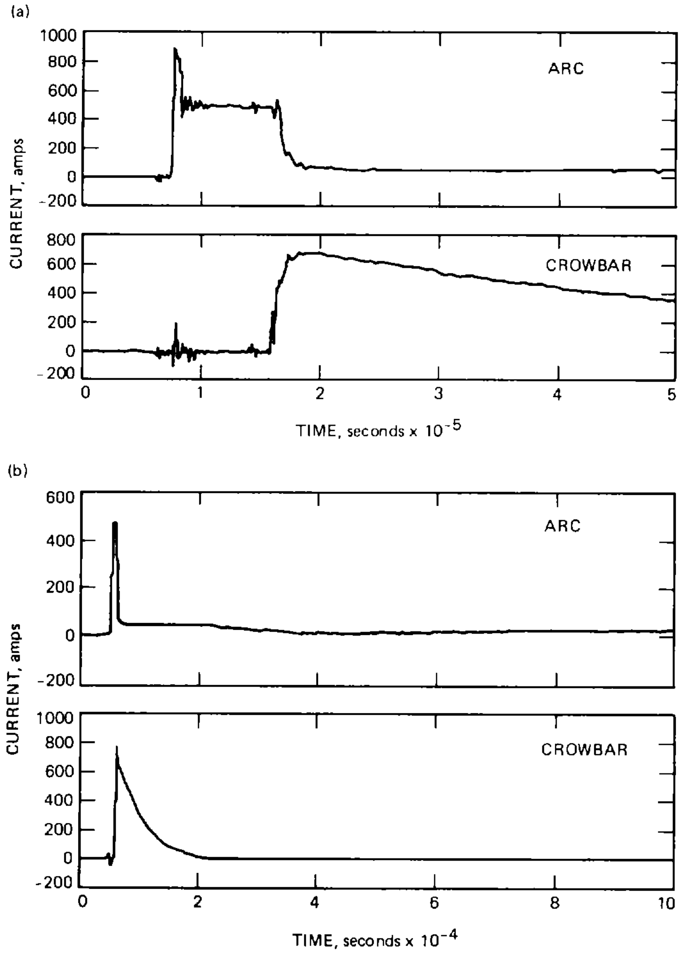

Fig. 5. Physically measured results for Case 2: (a) 50-microsecond time scale; (b) 1-millisecond time scale

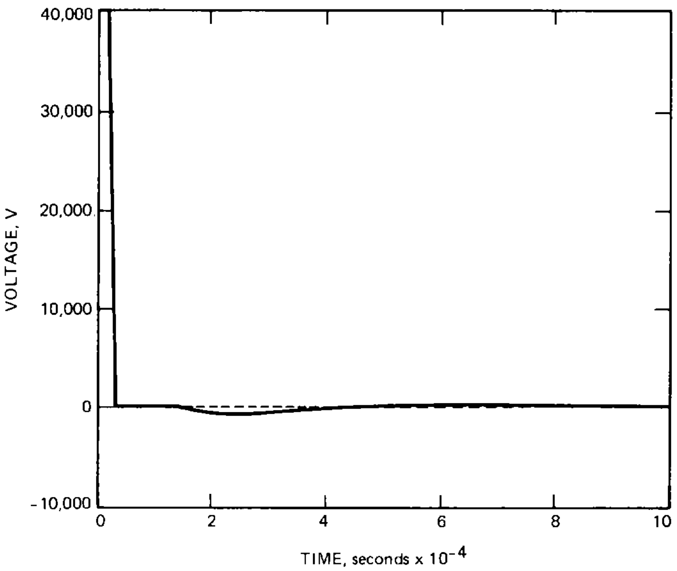

Fig. 6. SPICE-simulated waveform of the crowbar ignitron voltage