EVALUATION OF RESISTORS FOR TRANSIENT HIGH-VOLTAGE APPLICATIONS

J.M.Lehr, C.E. Baum, W.D.Prather and J.Hull
Air Force Research Laboratory,
Kirtland AFB, New Mexico 87117-5776

M.C.Skipper and M.D.Abdalla
ASR Corporation, Federal Division
Albuquerque, New Mexico

and
D.V.Giri
Pro-Tech, 1630 North Main Street, #377
Walnut Creek, CA 94596-4609

Abstract

Applications for transient, high-voltage pulsed power technologies are on the increase. High-voltage resistors are an essential component of such systems, especially in the proof-of-concept and prototype testing. We have recently procured and tested certain resistor samples, supplied by Kanthal Globar and HVR Advanced Power Components. Results of a detailed evaluation of the HVR resistors are presented in this paper.

Two types of HVR high-powered resistors have been tested to determine hold-off voltage, frequency variation and resistance to high voltage. The resistors were tested in a coaxial geometry driven by a two stage Marx generator. The voltage and current were measured by calibrated sensors. The high-voltage pulse resistance of each resistor is then determined on a pulse by pulse basis by dividing the maximum voltage by the maximum current in the time-domain.

The two samples (HVR-10, HVR-12 ; washer type) were nominally 10 and 12 Ohms with resistivity of 28 and 80 Ohm-cm respectively. The variations in the low-voltage to pulsed high-voltage resistance were 9% for the HVR-10 and 18% for the HVR-12. With an average applied field of 65 kV/inch or 25.6 kV/cm, the resistors flashed in air, but not in pure SF6 and N2/SF6 mix. These resistors were found to be satisfactory for transient applications.

I. CHARACTERIZATION OF HVR RESISTORS

The resistor samples are the washer type as shown in Figure 1. These resistors are also available in the disc type without the hole in the center. The quoted tolerances are 5, 10 and 20%. Standard metallised contacts are aluminum, although brass, silver, copper and nickel are possible. The resistors can be chamfered or left with square edges for enhanced high-voltage performance [1]. The

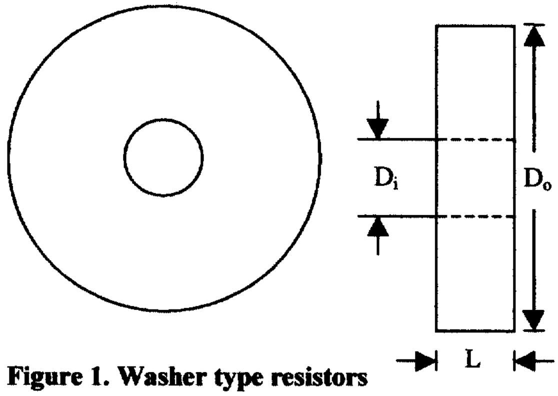

Figure 1. Washer type resistors

resistivity ρ and the conductivity, σ are given by

$$\rho = \frac{R}{L}\frac{\pi}{4}\left(D_o^2 - D_i^2\right) \quad (\Omega - m) \qquad (1)$$

$$\sigma = \left(\frac{1}{\rho}\right) \qquad \left(\frac{S}{m}\right) \qquad (2)$$

Given the relative dielectric constant ε_r of the ceramic material, the relaxation time t_r can be estimated as

$$t_r = \frac{\varepsilon}{\sigma} = \varepsilon_0 \varepsilon_r \rho \qquad (3)$$

and the skin depth δ_s into the resistor can also be estimated using

$$\delta_s = \sqrt{\frac{2}{\omega \mu_0 \sigma}} = \sqrt{\frac{\rho}{\pi f \mu_0}} \qquad (4)$$

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	-

4. TITLE AND SUBTITLE
Evaluation Of Resistors For Transient High-Voltage Applications

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Kirtland AFB, New Mexico 87 117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Applications for transient, high-voltage pulsed power [l]. The technologies are on the increase. High-voltage resistors are an essential component of such systems, especially in the proof-of-concept and prototype testing. We have recently procured and tested certain resistor samples, supplied by Kanthal Globar and HVR Advanced Power Components. Results of a detailed evaluation of the HVR resistors are presented in this paper. Two types of HVR high-powered resistors have been tested to determine hold-off voltage, frequency variation and resistance to high voltage. The resistors were tested in a coaxial geometry driven by a two stage h4arx generator. The voltage and current were measured by calibrated sensors. The high-voltage pulse resistance of each resistor is then determined on a pulse by pulse basis by dividing the maximum voltage by the maximum current in the time-domain. The two samples (HVR-10, HVR-12 ; washer type) were nominally 10 and 12 ohms with resistivity of 28 and 80 ohm-cm respectively. The variations in the lowvoltage to pulsed high-voltage resistance were 9% for the HVR-10 and 18% for the M-12. With an average applied field of 65 kV/inch or 25.6 kV/cm, the resistors flashed in air, but not in pure SF6 and N2/SF6 mix. These resistors were found to be satisfactory for transient applications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

where μ_0 is the free space permeability and has a value of $4\pi \times 10^{-7}$ *H/m* and *f* is the frequency. The parameters ρ, t_r and δ_s can all be optimally selected for a specific transient application.

II. EXPERIMENTAL CONFIGURATION

The resistors were tested in a conical geometry driven by a 100 kV Marx generator. The Marx is composed of TDK 1.7 nF, 50 kV capacitors and (PI Model # 670) high-pressure switches. The Marx was specifically designed to have an erected capacitance of 3.4 nF and a series inductance of less than 100 nH. The Marx is a two stage design and is charged to 50 kV/stage with a Maxwell CCDS power supply. The 96 nH circuit series inductance limits the maximum voltage to approximately 70 kV.

The resistor voltage and current were measured using in-house manufactured sensors. The sensors were initially calibrated using a 30 kV/30 kA modulator. Calibration reference data were collected using a Tektronix P6015 voltage probe and a Pearson 110 current probe. Transfer functions were developed and used to correct the raw sensor data in the frequency domain. The voltage and current sensors have 17.2 MHz and 707 MHz transition frequencies respectively, These sensor spectral responses are verified using a 20 GHz Tektronix 11801 TDR equipment. The high-voltage pulse resistance of each resistor is then determined on a pulse by pulse basis by dividing the maximum voltage by the maximum current.

The test sequence for each resistor type is as follows:

- Measure the low-voltage resistance value with an HP Model 4262A LCR meter at 1 kHz;
- Measure the average high-voltage pulse resistance over 10 shots at approximately 60 kV in pure SF6;
- Perform the lifetime test in pure SF6 at approximately 65 kV;
- Perform lifetime test in N2/SF6 mixture at approximately 65 kV;
- Perform lifetime test in pure air at approximately 65 kV;
- Repeat high-voltage resistance measurement at approximately 65 kV in N2/SF6 mixture
- Repeat low-voltage measurement

The results of the resistance value testing at low and high-voltages are summarized in Table 1.

TABLE 1. Resistance Value Test Summary

Quantity	HVR 12	HVR 10
Rated Resistance	12 Ohms	10 Ohms
Low-voltage Resistance	13.1 Ohms	10.0 Ohms
Pulsed high-voltage Resistance	14.3 Ohms	11.8 Ohms
Percent Deviation	9%	18%

Table 2 summarizes the results of the high-voltage lifetime tests.

TABLE 2. High-Voltage Pulse Testing

Gas environment	HVR 12	HVR 10
SF6	1,000	1,000
N2/SF6	1,000	1,000
Air	Flashed	Flashed

It is noted that with L = 1" and an applied voltage peak of 65 kV, the average field exposure is approximately 25.6 kV/cm.

The values in Table 2 are the number of shots each resistor was subjected to in the corresponding environment. The resistors were not tested to failure and each was performing well and with no long-term resistance change at the end of the tests. It should be noted that both of the resistors immediately flashed over at 65 kV in air. Each resistor was purposely flashed over approximately 10 times before being retested in the N2/SF6 mixture. Both resistors resumed normal operations in the N2/SF6 environment and no operational degradation was observed. A sample voltage and current measurement for both resistors are included in figures 2 and 3, recalling that the high-voltage resistance is considered as the ratio of voltage to current peaks.

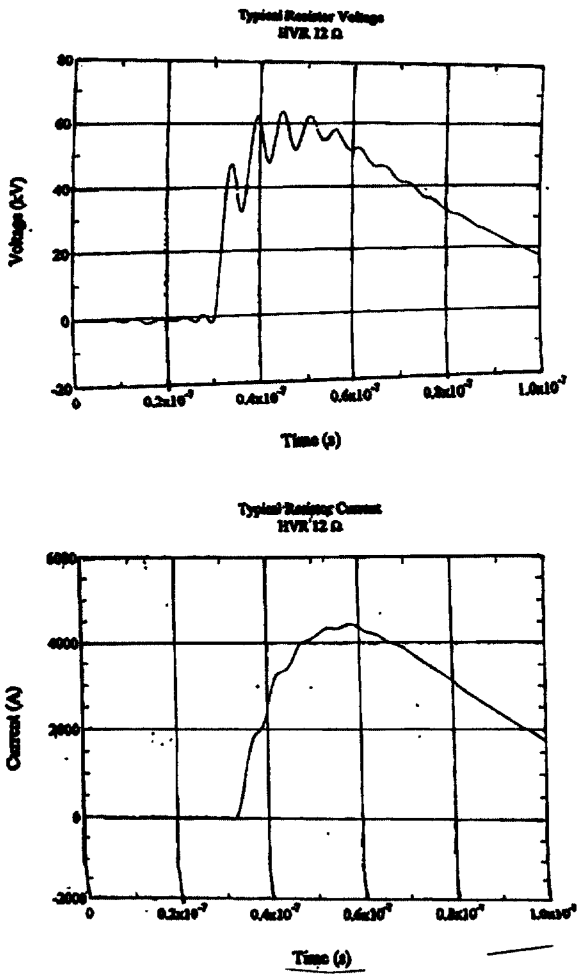

Figure 2. Voltage and current waveforms for HVR12

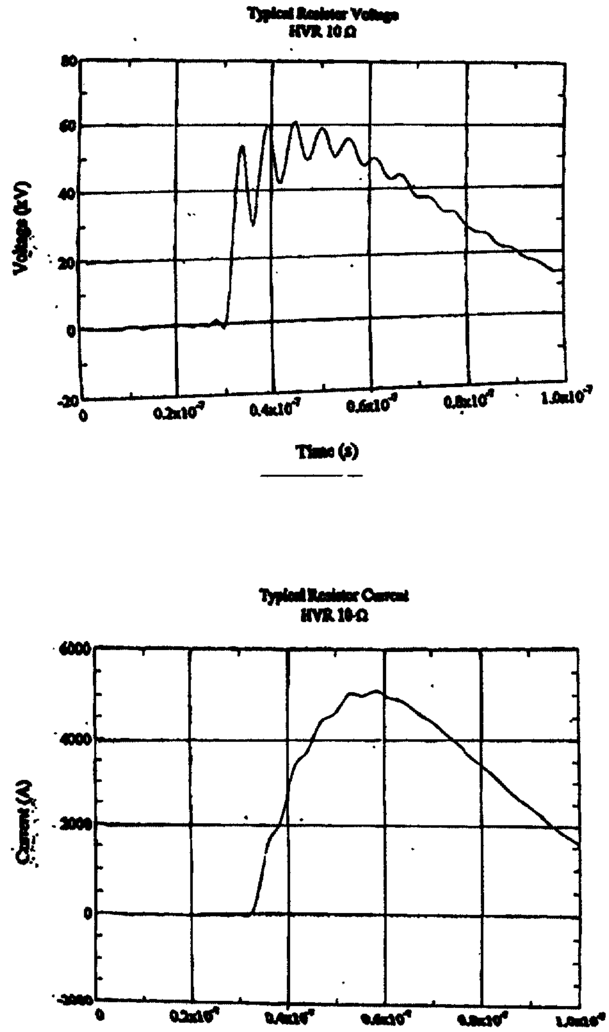

Figure 3. Voltage and current waveforms for HVR 10

III. CAPACITANCE MEASUREMENTS

The two types of HVR high-power resistors have been tested to determine the capacitance of each. The capacitance was measured using an HP 8753C network analyzer with HP 85047A S-parameter set. Each resistor under test (RUT) is then attached to the end of the test cable using a specifically designed, low-inductance fixture, as shown in figure 4.

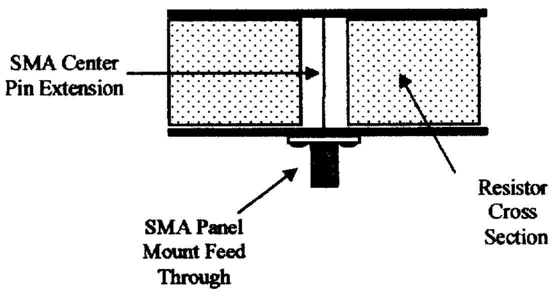

Figure 4. Test fixture for capacitance measurements. The upper and lower electrodes are circular aluminum plates.

The RUT is placed between the circular aluminum plates, which are then tightened against the resistor for good electrical contact using nylon screws (not shown). The SMA panel mount feed through is connected to Port 1 of the HP8753C with the test cable. Such an arrangement provides a low-inductance connection between the HP 8753C and the RUT. The reflection coefficient (ρ) from the RUT is then measured as a function of the frequency using the S11 function of the HP 8753C. From this measurement, we calculate the magnitude of the resistor impedance ($|Z_R|$). The resistor capacitance (C_R) is then calculated as:

$$C_R = \frac{1}{\omega}\left[\frac{1}{|Z_R|^2} - \frac{1}{R^2}\right]^{1/2} \qquad (5)$$

Where R = the resistance of the RUT. Basically each resistor is represented as a parallel combination of R and C_R. R and C_R values for the two types of resistors were found to be 13.1 Ohms and 54.7 pF for the HVR 12, and 10.0 Ohms and 49.9 pF for the HVR 10 resistor. In transient applications, it is desirable to know the parallel capacitance of the resistors.

IV. SUMMARY

The resistors have been tested with a ~65 kV, pulse that has a I ns rise and a 42 ns FWHM waveform. They have been tested in air, in (70/30) (N2/SF^) mixture and in pure SF6.

The HVR 10 resistor has D_0 = 32 mm, D_i = 11 mm, L = 25.4 mm, ρ = 0.28 (Ohm-m) σ = 3.57 (S/m), and t_r = 12.38 ps, with ε_r = 5. The HVR 12 resistor had D_0 = 50 mm, D_i = 19 mm, L = 25.4 mm, ρ = 0.8 (Ohm-m) σ = 1.26 (S/m), and t_r = 35 ps, with ε_r = 5.

The resistors have been tested with a ~65 kV, pulse that These resistors can be oil impregnated, chamfered and coated with anti-tracking material [2]. Previous testing in U.K., has indicated that square edges are better than chamfered edges for enhanced high-voltage performance. The coating was also found to be undesirable, and unnecessary, if the resistors are oil impregnated. The resistors were subjected to fields of the order of 25 kV/cm or 2.5 MV/m and withstood such fields in the gas mixture and in pure SF6, but not in air. They were not tested in an oil environment. The resistors are stackable by using an insulated tie-rod through the hole in the stack of washer type resistors. And are expected to be quite useful in a variety of transient applications.

REFERENCES

[1] A.K.Kidd et. al., "Solid Resistor Tests", Rutherford-Appleton Laboratory, in the United Kingdom, Private communication.

[2] HVR Advanced Power Components, 2250 Miliotary Road, Tonawanda, NY 14150 {Tel: (716) 693-4700}.