Theoretical Notes

Note 314

April 1, 1981

Soil Breakdown Model For Long Pulse at Moderate Level

Kenneth C. Chen

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Abstract

A Simple Soil electrical breakdown model for millisecond pulses is proposed for describing breakdown behavior near a wire. The model is relevant to the MX power line Resistive link isolation problem.

1. INTRODUCTION

The resistive link isolation scheme to protect the MX shelter from the source region EMP induced powerline current has become the prime consideration for implementation to the MX system. Let us assume a fireball being attached to the powerline at a distance of 800 meters from the MX shelter, an estimate of powerline current, imbedded in a soil with $\sigma = 10^{-3}$ S/m, at the input of a 50 ohm and 250 meter resistive link is about 60 Kamp peak, a risetime of 400 μs, and a decay time of 1 ms. The corresponding voltage to distant ground is approximately 2 Megavolts peak with the same waveform as the current. With this level of electrical stress on the resistive link, it is possible that the resistive link may not stop the stress from penetraing the shelter. Possible physical processes which can defeat the resistive link have been envisioned to be as follows: One, the voltage stress along the resistive link results in the soil breakdown in the direction of the resistive link, which effectively shunts the resistive link and results in large shelter current. Two, the joule heating at the input end of the resistive link is large enough to break a small section of the resistive link, then the large voltage across the broken down section of resistive link creates a low impedance arc through the soil, and the process continues along the resistive link until the large current arrives at the shelter. Three, the arc can jump from the input end of the resistive link to the air-soil interface and then jump to the shelter. Four, the dielectric jacket of the powerline and/or the resistive link can experience breakdown.

To address these four and other possible failure mechanisms, we have to review the state of the art of current technology. First of all, the physics of soil breakdown is not well understood. Second, the available pulse power source is not large enough to conduct a threat level test on the resistive link. Therefore, we have to perform the experiment at a smaller physical size, but at the same electrical stress level, to determine whether each piece of physics would lead to a failure mode. Let us use the four possible failure mechanisms for illustration. The pivot physical process is the breakdown along the resistive link, called longitudinal breakdown. If one could convincingly demonstrate that the catastrophic longitudinal breakdown can not occur in a realistic test configuration, then this failure mechanism ceases to be our concern. Our purpose for experiment II is to investigate this problem. The second failure mechanism described above is more complicated. However, it requires enough energy in the electrical pulse to break the line; it also requires the arc through the soil to have a low impedance. The objective of the experiment I is partly to address the arc impedance of the soil breakdown at a realistic level and waveform. Experiment I also addresses the third and fourth failure mechanisms discussed.

2. MX RELATED GOAL

Let us formulate this in logic language. Let any failure mechanism for the resistive link be X. In order that X can occur, it is necessary that A, B, C, and D have to be true. If we can prove that A is not true, then X can not happen. This is the logic for performing Experiments I and II.

A word of caution is given here. There is an important limitation in this approach. The intrinsic inhomogeneous nature of the soil and the stochastic aspect of the soil breakdown can not be accounted for in this approach.

3. LIMITATION OF EXPERIMENTS I AND II

The most important limitation is the stress level and the pulse duration which are required to stress the small section of the resistive link and its neighboring soil. Present McAir Lightning facility can provide appropriate stress for the electric field, but not the magnetic field and current. Since the soil breakdown is caused by the high electric field stress, the limitation in the current level and magnetic field level is not considered critical. However, the effect of the current and magnetic field level on the arc impedance can be ascertained at a number of levels up to one-half of the threat level. An important limitation for Experiment Ib, the air-soil interface breakdown study, is the absence of the electrons in air. At the late time, 1 ms from the detonation of the bomb, the air electron density is about 10^9 cm^{-3}, which is too large to be ignored.

Finally, the effect of vaporizing wire due to the presence of large current can result in important change in the nature of the soil breakdown near the wire. However, this effect may be very dependent on the precise configuration of the wire.

4. OBJECTIVE OF THIS MEMO

The objective of this write-up is to show what the soil breakdown behavior of the MX powerline and the resistive link can be without the effect of the large current. It also serves as the pre-test planning and post-test analysis of Experiment II.

5. SOIL BREAKDOWN MODEL FOR BURIED CONDUCTOR

The basic assumptions for this model are:

1. The pulse is slowly varying compared to the streamer setup and decay time, i.e., the pulse has a 400 μs risetime, and has a 1 ms decay time,
2. The electrical field and source capacitance are not large enough to create large streamers, and
3. The transient effect of charging the soil is negligible.

With these assumptions, let us consider a powerline cable buried a meter under the air-soil interface. Let us consider a meter-section of this cable. The line voltage to distant ground, e.g., ℓ = 1000 m from the cable is estimated to be 2 Megavolt peak. The radial electric field on the surface of the conductor before the soil breakdown is given by

$$E_{\rho_0} = \frac{V(t)}{\rho_0 \, \ell n \frac{\ell}{\rho_0}} \tag{1}$$

V(t) is the voltage to distant ground ℓ = 1000 m away from the cable, and has a peak of 2 Megavolts.

Let us assume a reasonable electric field level for the streamers to continue is E_c = 100 KV/m. The value for E_c can be different for different soil types [1]. The variation is not expected to be more than a factor of two. Let us assume E_c to be 100 KV/m, the corona radius, which defines a region around the wire where small streamers exist, can be determined to be

$$\rho_c(t) \sim \frac{V(t)}{E_c \, \ell n \, \frac{\ell}{\rho_c}}$$

$$\text{Sup } \rho_c(t) \sim 2 \times 10^6/10^5 \times 10 \sim 2 \text{ meters} \tag{2}$$

We have plotted, for a waveform of V(t) as shown in Figure 1a, the corona radius $\rho_c(t)$ in Figure 1b. The only inaccuracy of Figure 1b is the onset of corona, which is determined by a breakdown initiating field which can be somewhat higher than E_c.

Let us invoke assumptions (1) and (3) that the steady state is set up in microsecond time frame. We can say at $\rho_c(t)$ that a steady state has been established so that the continuity equation has to hold, which gives

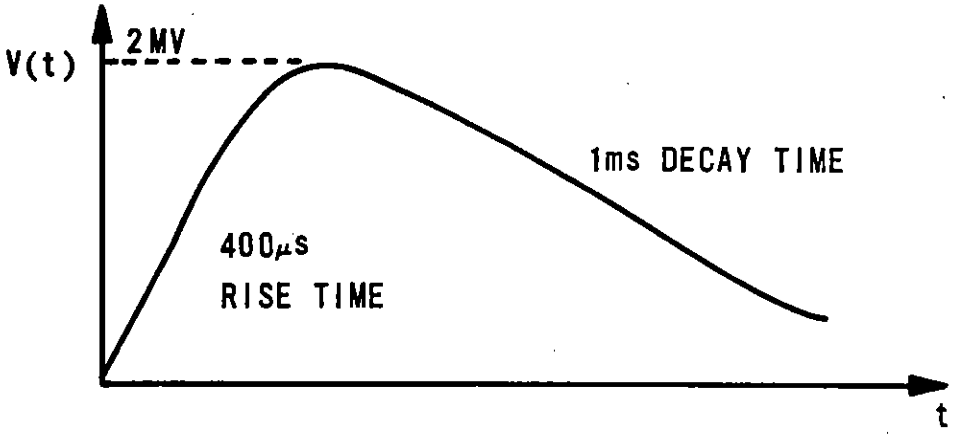
$$J_{\rho_c}(t) = \sigma_0 E_c \tag{3}$$

There is no streamer beyond $\rho_c(t)$; therefore, the relationship between J and E_c has to be the soil conductivity at low level.

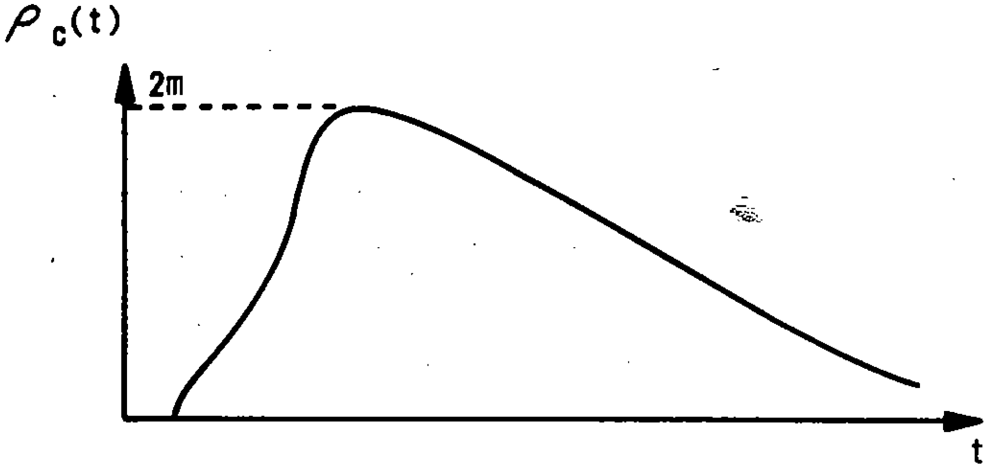
Invoking the continuity equation again we can scale the current density anywhere within the corona region. The result is

$$J(\rho,t) = \frac{\rho_c J_{\rho_c}(t)}{\rho} = \frac{\sigma_0 \rho_c(t) E_c}{\rho} \tag{4}$$

Let us turn our attention to the electric field within the corona region. Our reasoning is that the electric field in this region is a little bit smaller than E_c; because any electric field intensity greater than E_c will result in the continuation of the small streamers, and there is no reason for streamers to continue when E is less than E_c. Therefore, Sup $E(\rho,t) = E_c$, for $\rho < \rho_c(t)$.



(a) A Typical Long Pulse



(b) An Estimate of Corona Radius

Figure 1.

A simple calculation from (4) and (5) gives the steady state breakdown conductivity

$$\sigma(\rho,t) = \frac{J(\rho,t)}{E(\rho,t)} \sim \frac{\sigma_o \rho_c(t)}{\rho} \tag{6}$$

Figure 2 plots the steady state conductivity for $\rho < \rho_c(t)$.

Based on Figure 2, one can construct the conductance to distant ground as a function of time.

6. APPLICATION TO EXPERIMENT II

The discussion for the electric field around the MX powerline applies to the coaxial test geometry for Experiment II. The soil electric characteristics near the inner conductor are precisely what we have described in Section 5. The only scaling needs to be done is the voltage to appear in the coaxial electrodes. They can be shown to be

$$V_c(t) = \frac{V(t)\ \ell n\ \frac{b}{a}}{\ell n\ \frac{\ell}{a}} \tag{7}$$

where b is the outer conductor of the coaxial structure.

If a probe or grid is inserted near the inner conductor, we expect to observe a waveform as shown in Figure 3. The theory discussed predicts the voltage between the inner conductor to the grid increases, till the arrival of the streamer at the grid, to the value given by $V_{g_{d_1}i} = E_c d_1$. Then as the pulse decays the voltage fields to zero.

It is possible that the streamer formation near the inner conductor is so intense that the radial electric field drops below E_c. However, the steady state electric field increases, as the radius increases, and it eventually equals E_c at $\rho_c(t)$.

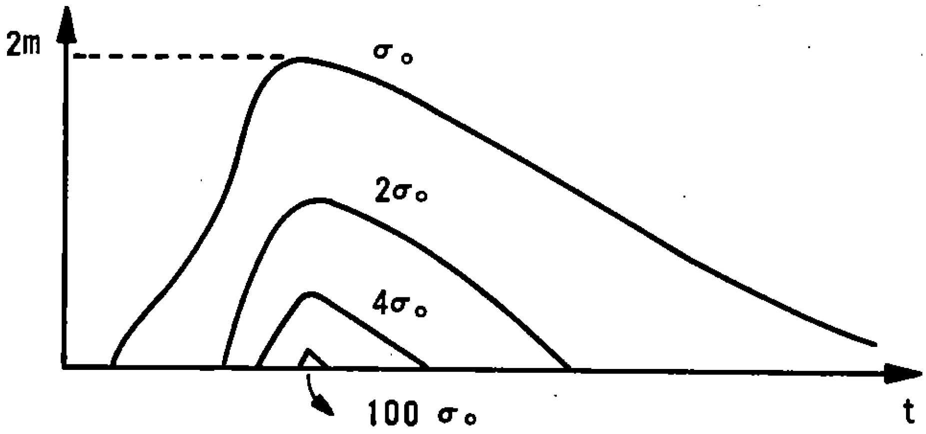


Figure 2. The Steady State Breakdown Soil conductivity.

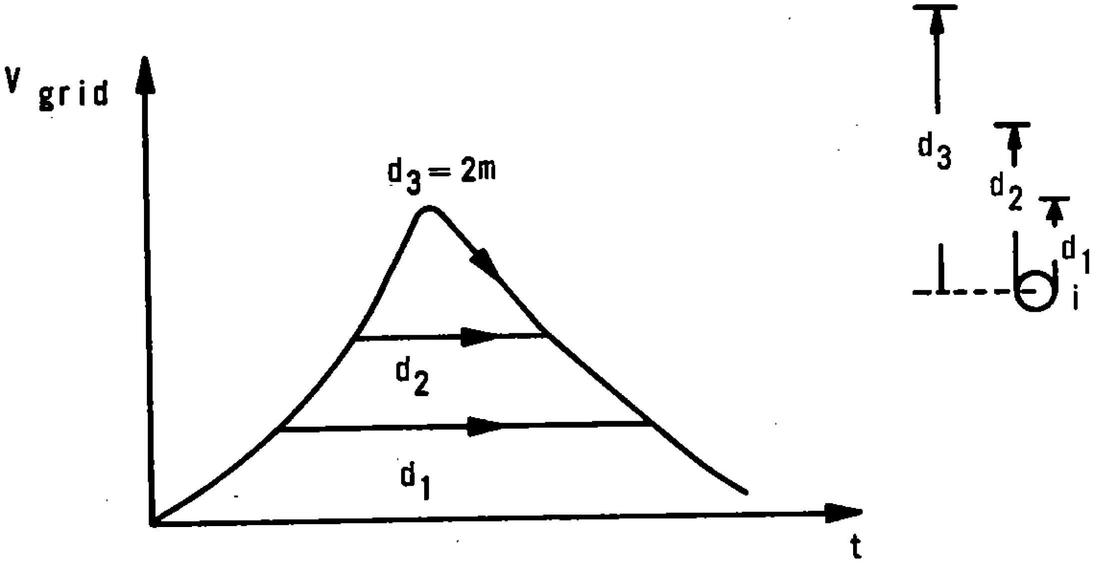


Figure 3. The Voltage from Inner Conductor to Grids Located at Different distances. $d_1<d_2<d_3$

7. CONCLUSION

A steady state model for radial soil breakdown is proposed. It should be used for planning the experiment and for analyzing the post-experiment data analysis.

REFERENCE

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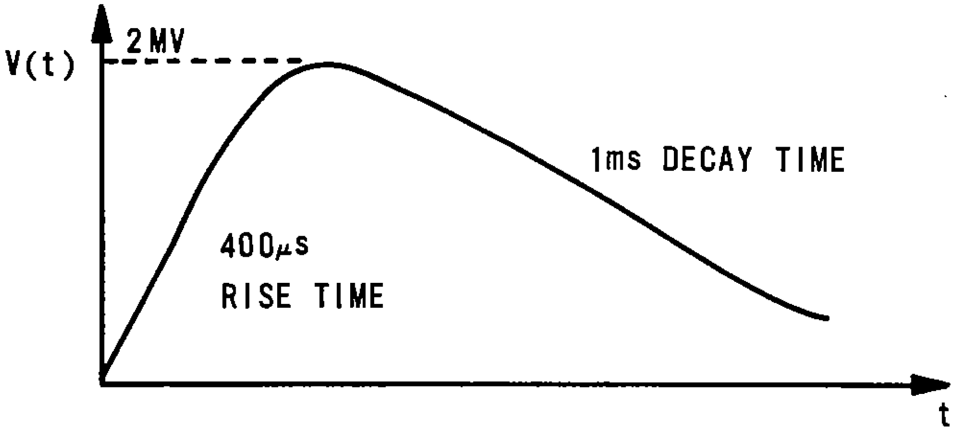

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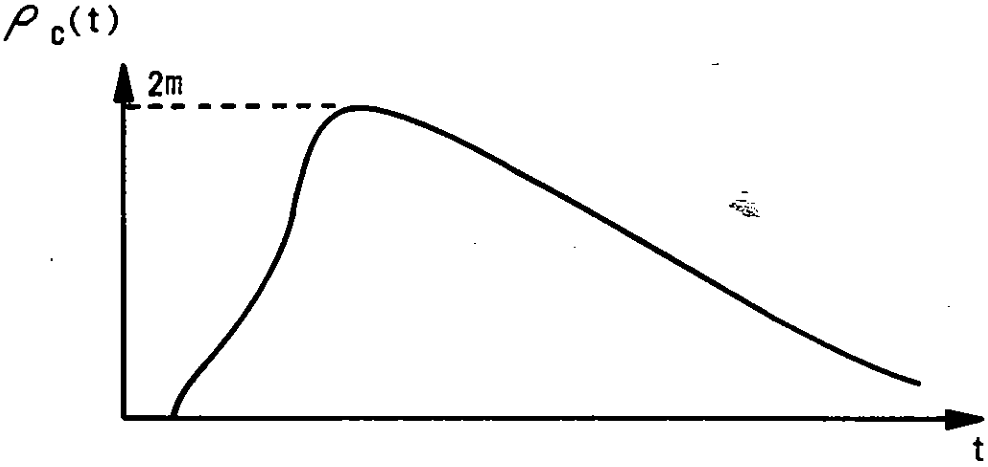

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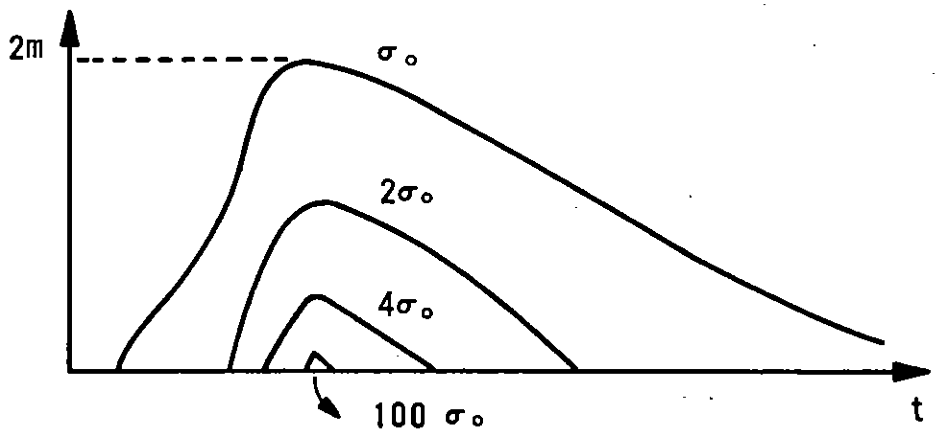

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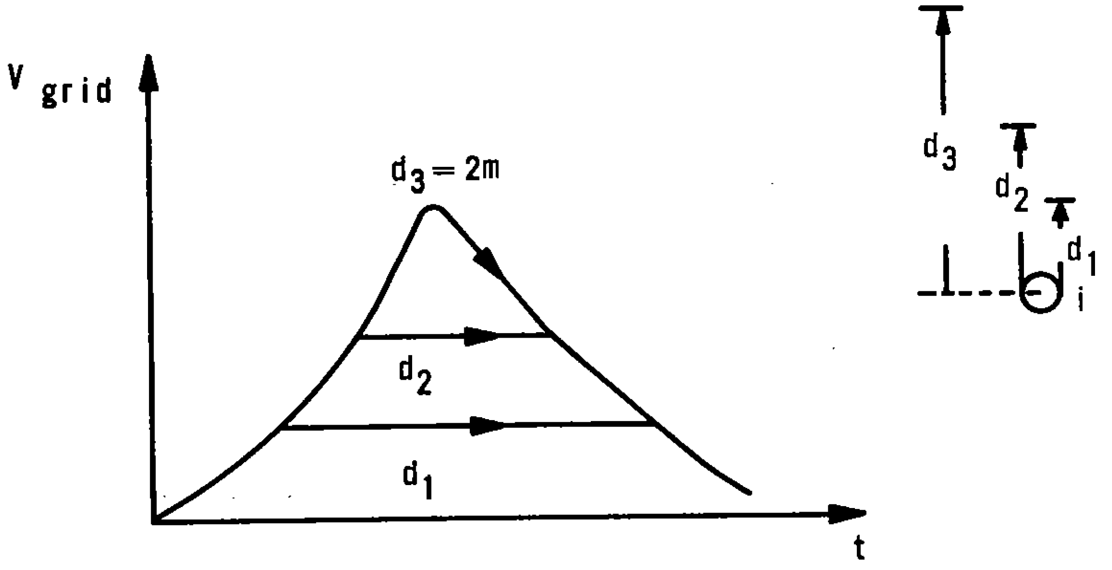

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