Effects of Back Corona on Rope Waveforms

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1. Introduction

The purpose of rapid onset pulse energization (ROPE) is to bring the potential of the corona wire in an electrostatic precipitator to its maximum value before localized corona discharges (hot spots) can develop along the wire. The result is a distinct improvement in the distribution of the corona discharge throughout the system. There may also be some benefit in reducing back corona, since there should be a reduced tendency for regions of exceptionally high current density to occur on the surfaces of the plate electrodes. Nevertheless, it should be recognized that back corona can occur with ROPE energization, even though it may begin at a higher value of average current than can occur with conventional energization.

The onset of back corona occurs when the current density passing through the accumulated dust layer on the plate results in an electric field strength in the dust layer that exceeds its breakdown strength. This condition can happen with virtually any kind of energization. If the breakdown strength of the dust layer is E_b, and the resistivity of the dust is ρ, the current density i_b required to set off back corona is derived simply from Ohm's law:

$$i_b = \frac{E_b}{\rho} \qquad (1)$$

Although the onset condition is well defined, the *magnitude* of the back corona current is not generally predictable from first principles. This quantity depends on the distribution of dust on the plate and the number and character of the individual sites at which back corona eruptions occur. It can be anticipated, however, that the magnitude of back corona will vary with applied voltage in much the same way that the primary corona does. Increasing the voltage will increase both the rate of ion production and the ion drift velocity across the space between electrodes. To a first approximation, then, we can define a back corona coefficient β such that for a primary corona current i, the back corona current is $i_\beta = \beta i$. This coefficient is zero if no back corona is present, and for the effect on the waveform to be detectable, it would be a large fraction of 1. There is, in fact, no theoretical reason that β should be limited to values less than 1.

Since back corona does not occur until the current through the dust layer exceeds the stated criterion, it is necessary for ions produced in the primary corona zone to traverse the interelectrode space before back corona can start. The mobility of the ions is such that the transit time is of the order of 1 ms. The rise time for ROPE is typically an order of magnitude less than that, so it can be expected that no back corona will occur during the voltage rise, and there will be a small delay during the trailing part of the waveform before it starts. Consequently it can be expected that back corona will have no effect on the voltage during its rapid increase.

In an appendix to a previous report the theory of electrical conduction in an esp with ROPE was developed, but without reference to any effects of back corona. Since present experience with this mode of energization is inadequate to provide empirical information about suspected cases involving back corona, we will explore the theoretical problem to derive predictions about the shapes of ROPE waveforms in the presence of back corona, and the expected effects on average values of voltage and current with back corona. The following section of this report repeats the previously developed theory, augmented by a modification to take back corona into account. Finally, a graphical comparison of ROPE waveforms with and without back corona will be presented.

Theory of ROPE waveforms

The requirement for the leading edge of the waveform is only that it be fast enough to prevent the development of hot spots on the corona discharge electrodes. At the peak applied voltage V, the capacitance C associated with the electrode arrangement is charged to a value Q =CV. The rate of decrease in the potential across the electrodes is determined by the corona current and any additional current through parallel resistances.

The primary corona current i_p as a function of applied voltage is given by White, in terms of the system geometry for a wire-duct esp as [1]

$$i_p = \frac{4\pi\varepsilon_0 LkV(V - V_0)}{b^2 \ln\left(\dfrac{4b}{\pi a}\right)} \qquad (2)$$

In this expression (transposed to MKS units from the esu expression given by White), a is the radius and L is the total length of the corona wire, and b is the distance from wire to plate; k is the ion mobility. The corona inception voltage V_0 may be estimated by Peek's formula [2].

Following the general observations about back corona presented in the *Introduction* section above, we can modify the theory by revising the expression for the current to include a back corona component. The total current i is the sum of the primary corona current i_p and the back corona contribution i_b. Assuming that the back corona current is the product of the primary current and the back corona coefficient β, we will use $i = (1+\beta)i_p$, and substitute that value in equation (2) for the original value of i.

$$i = \frac{4\pi\varepsilon_0 LkV(V - V_0)}{b^2 \ln\left(\dfrac{4b}{\pi a}\right)}[1 + \beta] \qquad (3)$$

Since the current is the rate of change of the charge, and taking C to be the capacitance of the corona system

$$i = -\frac{dQ}{dt} \tag{4}$$

$$= -C\frac{dV}{dt} \tag{5}$$

Now, setting the right-hand side of this equation equal to that of equation (2), and adding a current contribution corresponding to leakage or other ohmic resistance R parallel to the corona current,

$$\frac{dV}{dt} = -\frac{4\pi\varepsilon_0 Lk - V(V - V_0)[1+\beta]}{Cb^2 \ln\left(\frac{4b}{\pi a}\right)} - \frac{V}{RC} \tag{6}$$

If we lump the constants together to simplify the computation, this equation can be written as

$$\frac{dV}{dt} = -AV^2 + BV \tag{7}$$

This is a form of Bernoulli's equation, which can be solved to yield

$$V(t) = \left[\alpha e^{-Bt} + \frac{A}{B}\right]^{-1} \tag{8}$$

Finally, taking $V(0) = V_P$, the peak value of the voltage, then α is determined and equation (8) becomes

$$V(t) = \left[\left(\frac{1}{V_p} - \frac{A}{B}\right)e^{-Bt} + \frac{A}{B}\right]^{-1} \qquad (t<\tau) \tag{9}$$

The constants are

$$B = AV_0 - \frac{1}{RC} \tag{10}$$

and

$$A = \frac{4\pi\varepsilon_0 Lk[1+\beta]}{Cb^2 \ln\left(\frac{4b}{\pi a}\right)} \tag{11}$$

This result applies only for the time during which $V(t) > V_0$, the corona inception voltage. Beyond that point the current is limited to the leakage through resistance R. The time τ at which the voltage reaches corona inception may be found by solving equation (9) for $V(\tau) = V_0$, which results in

$$\tau = \frac{1}{B} \ln\left[\frac{V_0 RC}{V_p}\left(AV_p - B\right)\right] \tag{12}$$

Beyond the time t=τ the voltage falls off as in an ordinary RC circuit, so

$$V(t) = V_0 \exp\left(\frac{\tau - t}{RC}\right) \qquad (t>\tau) \tag{13}$$

Average Quantities

The average value of the voltage can be found by integrating the function V(t) over the period of the wave an dividing by the length of the period, i.e.

$$V_{ave} = \frac{1}{T}\int_0^T V(t)dt \tag{14}$$

Substituting for V(t) from equation (9) results in

$$V_{ave} = \frac{1}{T}\left[\frac{tB}{A} + \frac{1}{A}\ln\left|\left(\frac{1}{V_p} - \frac{A}{B}\right)e^{-Bt} + \frac{A}{B}\right|\right]_0^T \tag{15}$$

which can be written as

$$V_{ave} = \frac{1}{T}\left[\frac{tB}{A} + \frac{1}{A}\ln\left|\frac{1}{V(t)}\right|\right]_0^T \tag{16}$$

Again using $V(0)=V_p$,

$$V_{ave} = \frac{B}{A} + \frac{1}{TA}\ln\left|\frac{V_p}{V(T)}\right| \tag{17}$$

The constant A appears in most of these equations. Its effect is immediately apparent since back corona implies a substantial increase in A. The voltage V(t) as expressed in equation (9) will fall off more quickly in the presence of back corona, since the increased current discharges the system more quickly. The time required to drop below corona inception will also be reduced. The average voltage V_{ave} will decrease in inverse proportion to the quantity (1+β)

Application without back corona

Preliminary tests of ROPE were performed with a laboratory-scale device. The corona electrodes consisted of a single corona wire or other discharge electrode between a pair of grounded parallel plates. Several different kinds of corona discharge electrodes were tested, and voltage waveforms were recorded. For comparison with the theoretical description above, the results for a test done with a conventional 0.109 in-diameter corona wire were plotted. The spacing between plates was 8 in.

The corona inception voltage V_0 was determined by making dc measurements of the voltage—current characteristic of this electrode arrangement, and a value of V_0=30.5 kV was used for the calculation. The fit shown by the calculated points in figure 1 was achieved with parametric values of A= $1.91\times10^{-3}\ V^{-1}s^{-1}$ and B=55 s^{-1}. It is assumed that no back corona occurs in this example, i.e. $\beta=0$.

Inclusion of back corona effects

The waveform calculated for the case illustrated in figure (1) is shown as the curve drawn with the dashed line in figure (2). Using the above theory, we have calculated the response of the same system in the case that $\beta=1$; back corona is equal in magnitude to the primary corona current. The most apparent effect is that the trailing edge of the waveform falls off much more rapidly with back corona, which reflects the addition of ionic charge carriers originating at the back corona discharge sites on the plate electrode. Clearly, the average voltage would decrease under these conditions, since the instantaneous values are smaller in magnitude at all points.

Although the average current could be calculated directly from the theory, the general effect can be inferred from the waveform in figure (2). The voltage across the electrodes is the same for both conditions at the peak value of the wave. At the end of the wave, the potential difference is lower when back corona occurs because of the greater amount of charge carried by the combination of primary and back corona current components. The average current during a cycle must therefore be greater with back corona.

If the average values of voltage and current are used to generate an I-V characteristic for the system, the increasing current and decreasing voltage that occur with back corona will produce a slope greater than 90°, qualitatively similar to that observed with back corona in a conventional system. A conceptual sketch of the general shape of such an I-V characteristic is shown in figure (3)

References

1. White, H. J. *Industrial Electrostatic Precipitation, p. 99*
2. ibid, p. 100

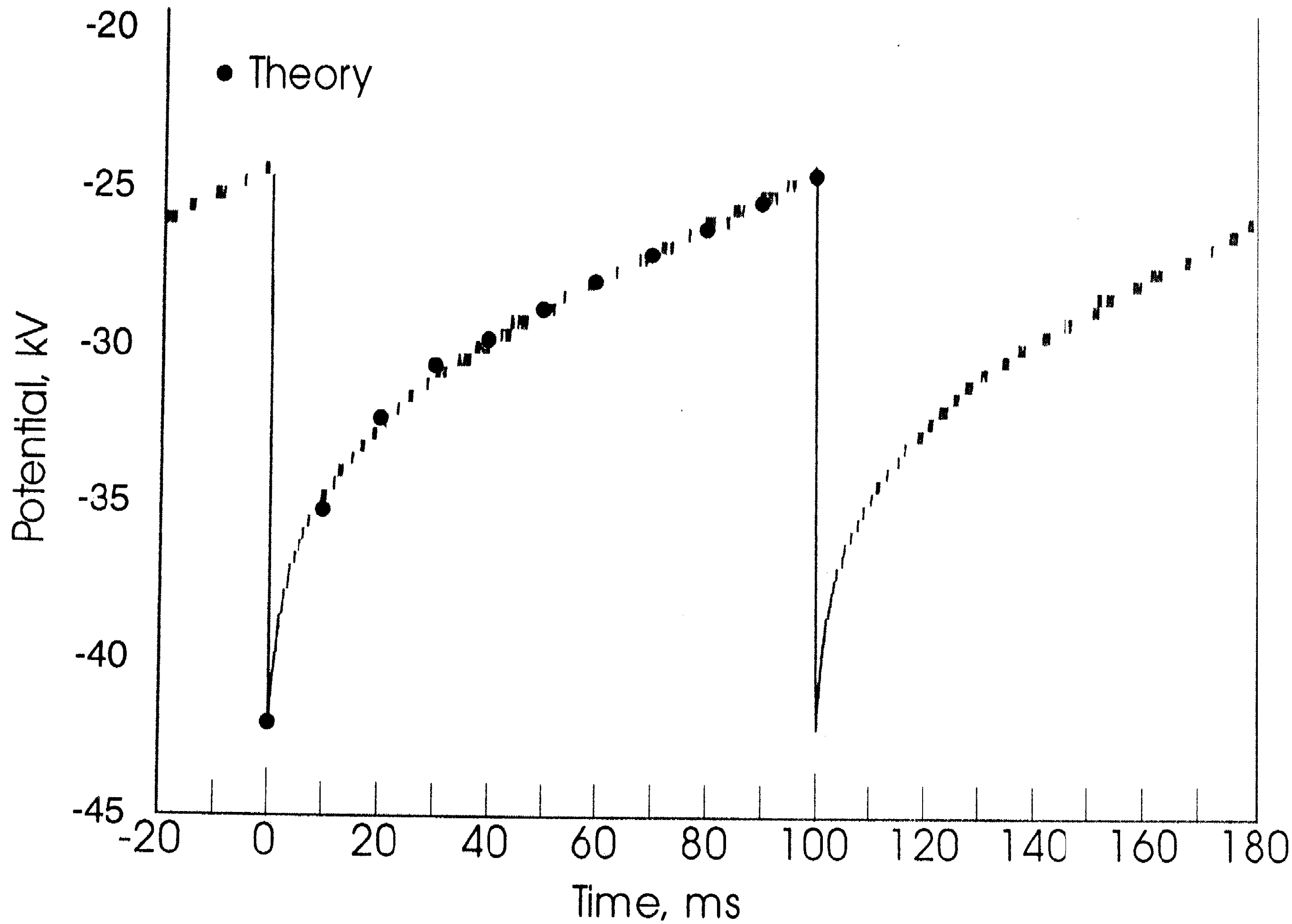


Figure 1. Comparison of the ROPE theory with an experimentally derived waveform (no back corona).

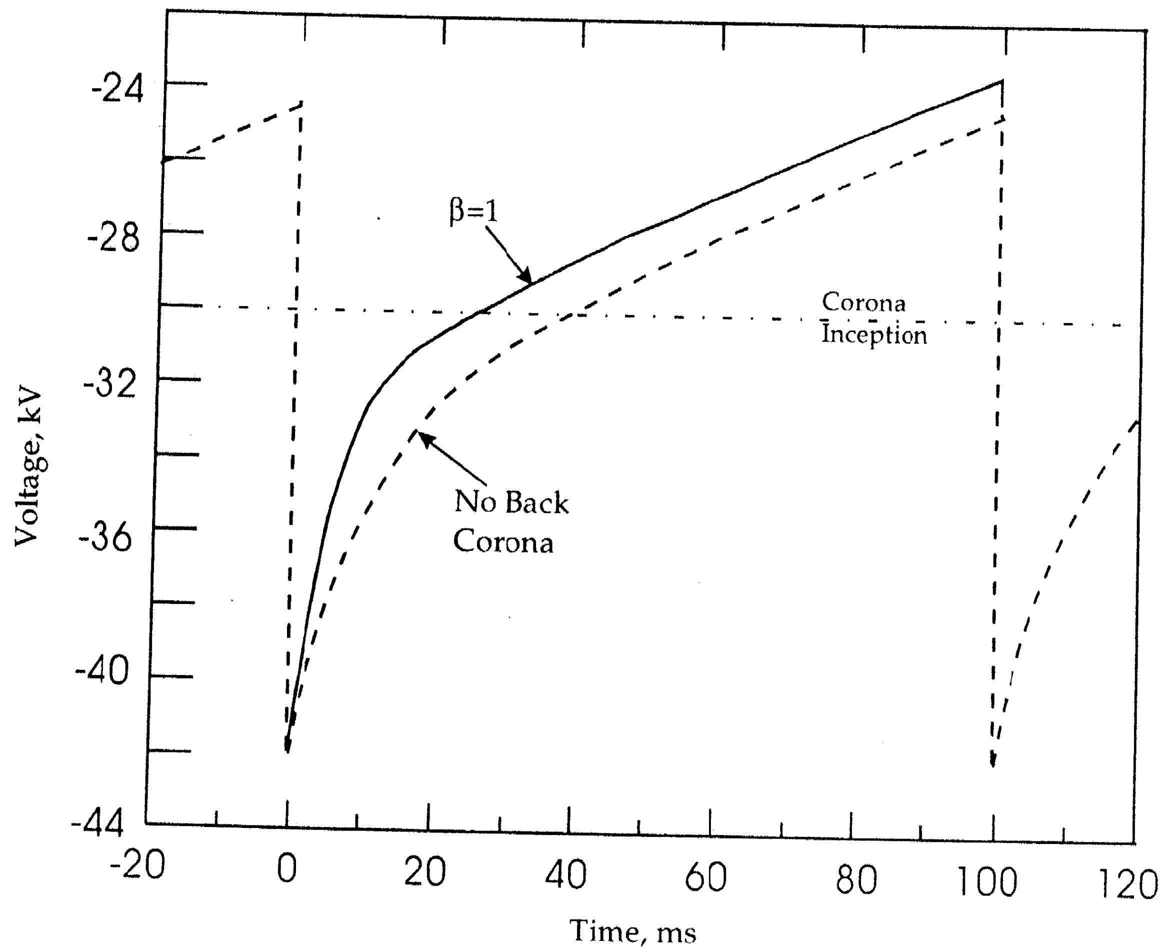
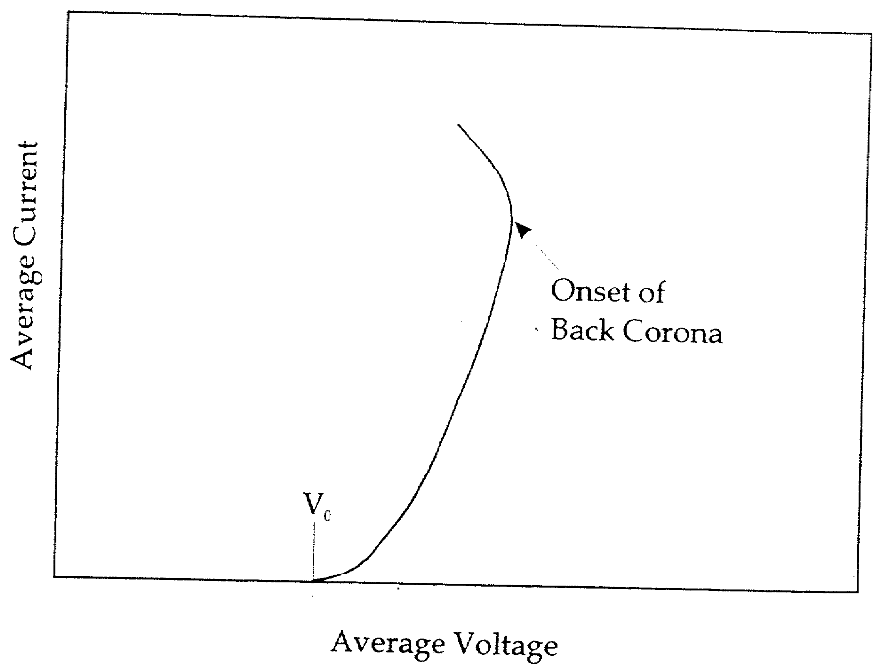


Figure 2. Comparison of Rope waveforms. The dashed line is the same curve derived for figure (1), and the solid line represents the same conditions, but with the addition of back corona, with coefficient β=1.


Average Current
Onset of
Back Corona
V_0
Average Voltage