A TIME-DOMAIN VERSION OF POINT-SOURCE COHERENCE

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ABSTRACT

An exploration of impulsively excited, constant-radius, straight-wire antennas is described. Particular attention is focused on the radiation that results from the continuous reflection of propagating current/charge pulses caused by the wireÕs spatially varying wave impedance and the associated charge acceleration that occurs. When oppositely propagating pulses overlap, their radiation fields become time simultaneous over the entire far-field sphere, analogous to having co-located point sources in the frequency domain. A localized increase in the radiated power results as shown by time-domain FARS (Far-field Analysis of Radiation Sources) and in an increased loss of near-field stored energy.

INTRODUCTION

A well-known phenomenon exhibited by two frequency-domain, constant-amplitude, infinitesimal sources is a doubling of the total power they radiate as their separation distance approaches zero. This happens because the phase coherence of their fields over the far-field sphere systematically increases when the sources are brought close enough together to make their fields become monotonically additive. In the limit of zero separation, the radiated power increases by a factor of two relative to that when the sources are far apart, as demonstrated in Fig. 1. An equivalent phenomenon occurs in the time domain as well, some aspects of which are discussed in the following.

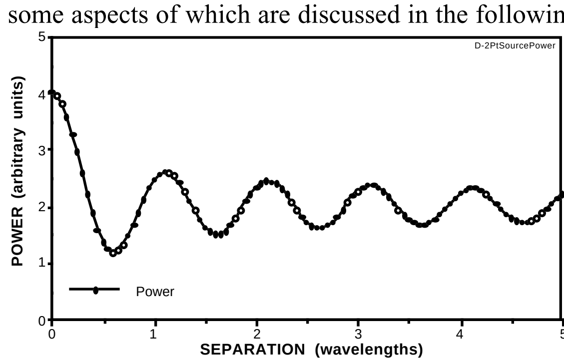

Fig. 1. The total power radiated by two constant-amplitude infinitesimal sources as a function of their separation. When far enough apart, each radiates 1 unit of power for 2 units of total power. However, when brought closer together than a half-wavelength or so, the total radiated power approaches 4 units in the limit of zero separation.

RADIATION PHENOMENA ASSOCIATED WITH A STRAIGHT-WIRE ANTENNA

An impulsively excited, straight, constant-radius, perfectly conducting wire exhibits four different radiation phenomena. Consider such a wire excited as an antenna at its center by a voltage whose time variation is $\exp(-a^2t^2)$. The wire will exhibit two predominant radiation mechanisms, consistent with the Lienard-Wiechert potentials that show the explicit cause of radiation is accelerated of charge. The first of these is due to the exciting voltage that causes an initial charge separation and acceleration by ÒpushingÓ opposite-signed charges out from the source region onto the arms of the antenna. A second, and comparably important, radiation mechanism is the successive reflections of the outward-propagating current/charge (I/Q) pulses at the open ends of the wire antenna. Both of these effects are spatially localized.

Two other radiation mechanisms also occur, not generally as large in magnitude as these, but which extend over longer periods of time [1]. One arises from the ÒextractionÓ of opposite-signed charge from the source region as the I/Q pulses propagate outwards from the point of excitation, a mechanism that is also localized spatially since the associated charge acceleration is confined to the source region. The other mechanism is caused by a low order, but continuous, reflection of the I/Q pulses as they propagate along the antenna, an effect that takes place because the local wave impedance of a constant-radius wire is a slowly varying function of position [2]. Because pulses of opposite-sign charge are propagating in opposite directions and hence experience opposite-sign acceleration, their reflection radiation will be of the same sign. This has the effect of spreading out the continuous-reflection radiation over the entire length of the wire as the propagating pulses move back-and-forth along it. It's this particular phenomenon, especially during the times when the pulses overlap, that will now be considered in more detail.

COHERENCE, OR SIMULTANEITY, IN THE TIME DOMAIN

First note that for the center-excited, straight wire viewed from broadside in the far field, all of the continuous-reflection radiation fields will be time-simultaneous wherever the I/Q pulses are located on the wire. This simultaneity in the time domain is equivalent to phase coherence in the frequency domain, the result of which is time-additive fields that produce commensurately increased power flow. As the observation angle is moved farther away from broadside relative to the pulse width, then time simultaneity will no longer hold, except when the pulses overlap during their propagation in opposite directions along the wire. For the case being considered, at the time of exact overlap, the current density is doubled and the charge density goes to zero. During the time that the pulses partially to completely overlap, their continuous-reflection radiation fields will be additive as well, to a greater or lesser extent, over the entire far-field sphere. The radiated power will then increase, approximately doubling the continuous-reflection radiation relative to times when time simultaneity does not occur, an effect that is exhibited in the results that follow.

Time-Domain Far-Field Analysis of Radiation Sources (TDFARS)

Extension to the time domain of frequency-domain FARS (Far-field Analysis of Radiation Sources) is here referred to as TDFARS [1]. The time-domain version of FARS involves evaluating the far-field power (or energy) flow by computing the dot product of the total electric field (E-field) with the incremental E-field due to a given segment of the numerical model at a given observation angle and time. This quantity is integrated over all observation angles to yield a power-related quantity for each segment for each time step. Upon integrating over all segments, the usual time-varying power radiated by the object is obtained; in either version of FARS, the space and angle integrations are simply interchanged. A subsequent time integration provides the radiated energy up to that particular observation time. Neither version of FARS has been analytically proved to yield power or energy radiated per unit length by a wire. Their results appear to be physically plausible, however, and agree quantitatively with other frequency-domain results for a sinusoidal current filament with respect to the induced-EMF method [3]; in terms of a distributed radiation resistance [4]; and with a spatial derivative of the surface Poynting vector for a wire [5]. Furthermore, TDFARS is found to agree qualitatively with analytically derived results [6] though TDFARS uses a boundary-value solution while those in [6] use a constant-amplitude Gaussian current pulse. Thus, it is assumed for purposes of discussion in the following that FARS results can be interpreted as providing the time-integrated energy density radiated from along the wire.

In order to separate feedpoint and end-reflection radiation from continuous-reflection radiation, a dipole comprised of 201 segments was impulsively excited in various ways, the results being obtained using the TWTD (Thin-Wire Time Domain) computer model [1]. Single Gaussian pulses of 1.414 V were applied at segments 67 and 101 respectively (cases 1 and 2). Two other cases were run, one with segments 67 and 135 excited by Gaussian pulses of +1 V (case 3), and the second with these same segments excited by pulses of -1 V and +1 V (case 4). These excitation voltages were chosen so that the total source-supplied energy would be the same for all four cases. The TDFARS results for these four cases at time step 1,000, a point at which the current and charge have decayed nearly to zero, are shown in Fig. 2. For the center-excitation of case 1, the reflected pulses overlap at the center as well and so the effects of excitation radiation and time simultaneity of the overlapping pulses somewhat obscure each other; this case is included as a reference. But for case 2, after their first, third, etc. end reflections, the I/Q pulses will overlap centered around segment 135; after the second, fourth, etc. reflections they will overlap near segment 67. A maximum in TDFARS can be seen to occur in the vicinity of segment 135 for case 2 as well as at the source location, the latter being similar to the results for case 1.

The TDFARS results for cases 3 and 4 are particularly revealing. For case 3, where positive voltages are applied to segments 67 and 135, a maximum in the radiated energy density occurs at the center of the wire, midway between the sources. Conversely, for case 4 where negative and positive voltages are applied to these segments, a zero is seen to occur at the center. On the other hand, the case-3 results exhibit local minima at about segments 35 and 167 where local maxima are seen for case 4. Why this occurs can be explained as follows.

In case 3, a positive charge pulse propagating to the right is produced by the +1 V source at segment 67, while a negative charge pulse propagating to the left is produced by the +1 V source at segment 135. The continuous-reflection radiated fields of these opposite-sign pulses propagating in opposite directions are additive over the entire far-field sphere upon their overlap at segment 101 relative to their energies being additive when the pulses are spatially separated. This results in an approximate doubling of the energy radiated from the vicinity of the wire center. Alternatively, for case 4, the charges in the initial (and subsequent) pulses propagating towards the wire center from segments 67 and 135 are the same sign, resulting in their reflection-radiation fields canceling and a consequent zero in the radiated energy at the wire center. A similar effect accounts for the local maxima and minima at segments 35 and 167, but the minima is not zero because the outward-propagating charge pulses are meeting reduced-amplitude, inward-propagating pulses that have already lost some energy upon a prior end reflection.

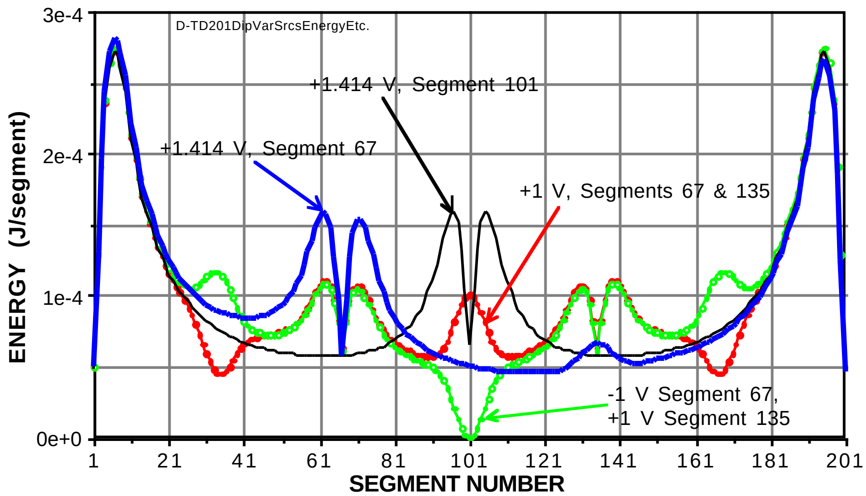

Fig. 2. Results from TDFARS for the four cases discussed in the text after 1,000 steps of the time-domain solution, where the energy radiated to the far field is shown on a per-segment basis. For center excitation (case 1) these results are qualitatively similar to results derived analytically [5], showing most of the radiated energy comes from the ends of the antenna and the source region, but with a non-zero intermediate contribution as well due to continuous-reflection radiation. Moving the source to segment 67 (case 2) produces a Òconjugate Óbump with a peak at segment 135. Further artifacts are produced when two feedpoints are used, with cases 2-4 all demonstrating the effect of time-simultaneity as the I/Q pulses overlap in their propagation along the wire.

Loss in Stored Energy

A measure of the total energy, E(t), stored in the near fields of an impulsively excited, perfectly conducting object is provided by $E(t) = \iint\{[I(s,t)]^2 + [Q(s,t)]^2c^2\}ds$, where the integration is over the objectÕs surface on which I(s,t) is the time- and space-dependent current, Q(s,t) is the associated charge density and c is the speed of light [7] in the medium. Consequently, the time rate of decrease in E(t) yields a measure of the rate at which this stored energy is lost via radiation to the far field. Upon examining the results of Fig. 3, where the current, charge and total energy measures are plotted as a function of time together with the time derivative of the total energy for case 2, it can be seen that this expectation is indeed realized. When the I/Q pulses meet at segment 135 at the time of their first overlap, the current energy is seen to double while the charge energy goes to zero because the plus and minus charge pulses cancel. A corresponding approximate doubling of -dE(t)/dt also occurs, as expected, i.e., the radiation increases when the pulses overlap due to the time-simultaneity of their fields over the entire far-field sphere. Note that the derivative results shown here (and in Fig. 4) are rather noisy appearing due to their being obtained from the subtraction of two nearly equal numbers.

CONCLUDING COMMENTS

An investigation of radiation from impulsively excited straight-wire antennas using TDFARS (Time-Domain Far-field Analysis of Radiation Sources) and a measure of the energy stored in their near fields obtained from spatial integrals of the square of the current and charge density multiplied by light speed has been described. In particular, the radiation caused by a continuous, partial reflection of the current/charge (I/Q) pulses propagating along a constant-radius wire due to its spatially varying wave impedance, has been examined in detail. Four kinds of impulsive excitation have been employed, three chosen to isolate in time the effect on the instantaneous radiated power and total radiated energy of overlapping, oppositely propagating, I/Q pulses. A localized increase (or decrease) of radiation occurs due to the time-simultaneity of the far fields of the overlapping pulses. The effect is analogous to the frequency-domain phenomenon where the power radiated by two infinitesimal, constant-amplitude sources doubles as their separation approaches zero.

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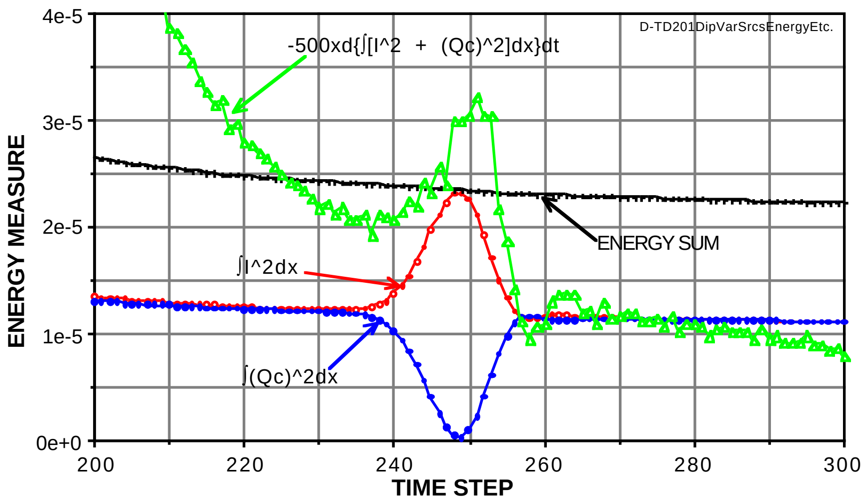

Fig. 3. Energies associated with the current and charge, and their sum, for case 2 where segment 67 is excited, over a window of the time-domain solution together with 500 times the negative of the time-differentiated total energy. The current energy doubles, and the charge energy goes to zero, when opposite-propagating pulses overlap, in this case at segment 135 of the 201-segment antenna. The peak of the excitation occurs at about time step 50, and since $c\Delta t = \Delta x$ where Δt and Δx are the time and space steps while the transit time is 201 time steps, the maximum pulse overlap occurs near time step 250 where a corresponding peak in the differentiated total energy also takes place.

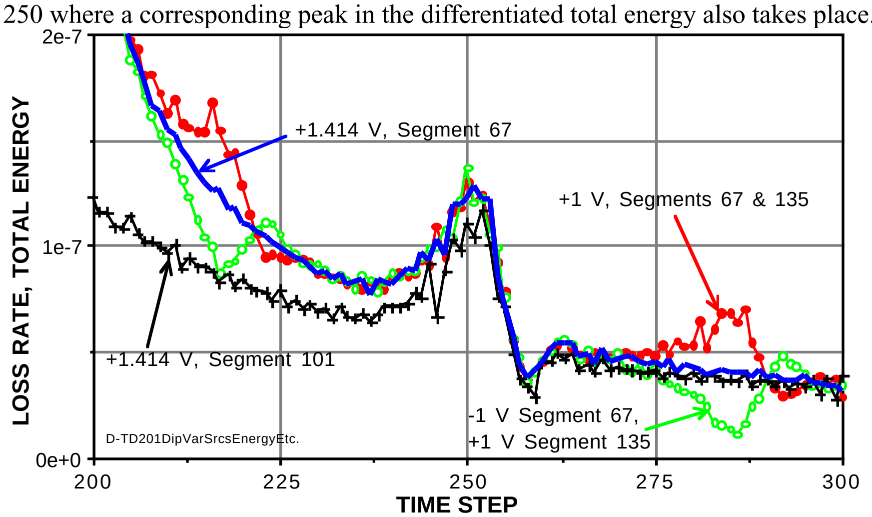

Fig. 4. Negative values of the time-differentiated total energies for the four cases discussed in the text. All exhibit increased radiation loss at about time step 250. Additional extrema of opposite sense occur for cases 3 and 4 around time steps 217 and 287. The latter are associated with extrema in TDFARS results of Fig. 2 in the vicinity of segments 35 and 167, corresponding to increased and reduced spatial radiated energies, respectively. The maxima result when charge pulses of opposite sign overlap while the minima occur with overlapping charge pulses of the same sign.