Updating Circuit Theory: Answering the Catt Question

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Introduction

Older readers of Electronics World may remember articles by Ivor Catt in which he posed the Question '*When the front edge of a voltage step is propagating along a transmission line, where does the negative charge on the bottom conductor come from*?'

This brought to mind one of the lessons taught to final year students of Electrical Engineering at Glasgow University. It was explained that electrons could not possibly move at the speed of light. Nor did they need to, since there is an abundance of atoms in any copper conductor. If each atom has a free electron, then these entities need only move at a snail's pace to carry the rated current. The question as to how power is transported from Glasgow to London in less time that it takes to blink was left unanswered.

Part of the answer can be found at Wikipedia. '*The photon is a type of elementary particle. It is the quantum of the electromagnetic field including electromagnetic radiation such as light and radio waves, and the force carrier for the electromagnetic force. Photons are massless, and they always move at the speed of light in vacuum*.'

Since photons apply force, they can cause electrons to be ejected from copper atoms. This causes current flow in the conductor, rather like tipping over a pack of cards. Developing this idea allows a mechanism to be postulated; one which provides an answer.

After posing his question to several eminent scientists, Ivor Catt poured scorn on each and every reply. From his point of view, the fact that charges are delivered to the bottom conductor brings the whole science of Electromagnetic Theory into question. Even so, he has made no attempt to provide an alternative explanation.

The Catt Anomaly.

Traditionally. when a TEM step (i.e. logic transition from low to high) travels through a vacuum from left to right, guided by two conductors (the signal line and the 0v line), there are four factors which make up the wave;

- *electric current in the conductors*
- *magnetic field, or flux, surrounding the conductors*
- *electric charge on the surface of the conductors*
- *electric field, or flux, in the vacuum terminating on the charge.*

The key to grasping the anomaly is to concentrate on the electric charge on the bottom conductor. During the next 1 nanosecond, the step advances one foot to the right. During this time, extra negative charge appears on the surface of the bottom conductor in the next one *foot length, to terminate the lines (tubes) of electric flux which now exist between the top (signal) conductor and the bottom conductor.*

Where does this new charge come from? Not from the upper conductor, because by definition, displacement current is not the flow of real charge. Not from somewhere to the left, because such charge would have to travel at the speed of light in a vacuum. (This last sentence is what those "disciplined in the art" cannot grasp, although paradoxically it is obvious to the untutored mind.) A central feature of conventional theory is that the drift velocity of electric current is slower than the speed of light.

Electromagnetic Theory

Books on Electromagnetic Theory usually include a chapter on Transmission Lines. But only after the topics of Static Fields, Conductors and Charges, Voltage and Current, Capacitance, Energy and Forces, Magnetic Field, Magnetic Force, Vector Identities, Amperes Law, Inductance, Maxwell's Equations, and Reflection of Electromagnetic Waves have been fully discussed.

The deductions and analyses recorded in these preceding chapters came about as a result of many experiments and much puzzling as to how the observed results could be explained using scientific reasoning. It was then necessary for other engineers and scientists to review and agree the explanations. The work involved could be measured in terms of man-centuries.

Analysis of transmission lines is based on the knowledge that the currents, voltages and charges in the conductors are the result of the action of the electromagnetic field.

The existence of charges on the bottom conductor referred to in the Catt Question does not disprove Electromagnetic Theory: it is the inevitable result of deductions made during the development of that theory.

Transmission Line

An important feature of Transmission Line analysis is the fact that the return conductor plays an essential role in the propagation of energy. So it is useful to reprise the way it is introduced in the textbooks. Figure 1 illustrates a simple circuit model using lumped components.

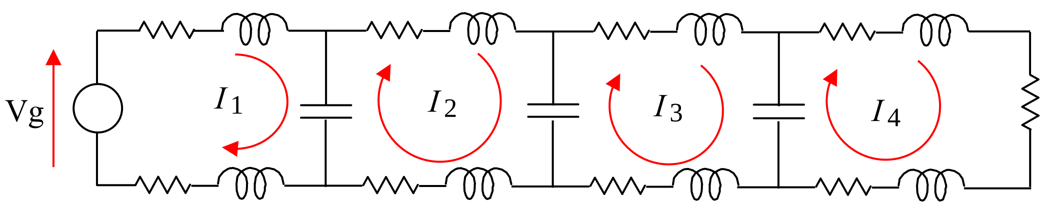

Figure 1 Lumped-Parameter model of a twin-conductor line

Developing this model further, the line is assumed to consist of a series of minute sections, where the components are defined in terms of the length of the section, as illustrated by Figure 2.

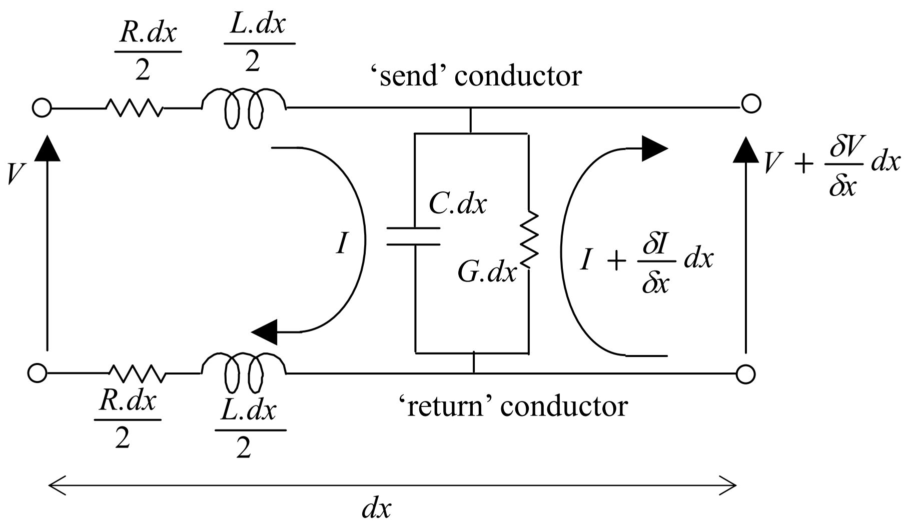

Figure 2 Circuit model of a single segment of the line

In Figure 2, *R* is defined as ohm per metre, *L* as Henry per metre, *C* as Farad per meter and *G* as Siemen per metre.

Mesh Analysis gives the equations;

$$\left(R + j \cdot \varpi \cdot L\right) \cdot dx \cdot I = V - \left(V - \frac{\delta V}{\delta x}\right) \cdot dx \qquad (1)$$

$$\left(R + j \cdot \varpi \cdot C\right) \cdot dx \cdot V = I - \left(I + \frac{\delta I}{\delta x}\right) \cdot dx \qquad (2)$$

Since these equations are the starting point of all subsequent analysis of transmission lines, it is important to note that they have been derived from Figure 2 and that inherent in this figure are unstated assumptions. These are:

Current flows across the gap, from the send conductor to the return conductor.
Current flows back, from the return conductor to the send conductor.
Current flows in a series of tiny loops, as indicated by Figure 1.
Current consists of the flow of charges.

In books on Electromagnetic Theory, the deductions emanating from equations (1) and (2) lead to the conclusion that charges propagate at a speed of light in the medium. That is, they propagate along each conductor at a velocity slightly lower than that of light in a vacuum. They also propagate through the insulation.

These deductions are supported by the results of many tests conducted over the last century. The equations of transmission line analysis are used in the design of every piece of electronic equipment in existence. That is the justification for the above assumptions.

Since both conductors play an active role in the forward propagation of energy, the replacement of the return conductor with a surface at zero volts will eliminate any hope of visualising the mechanisms involved. This may be the basic reason for the Catt Anomaly.

Charges, Electrons, and Photons

It has been shown in this series of articles that, by invoking the relationships derived by Electromagnetic Theory, the analytical tools of Circuit Theory can be used to simulate all the mechanisms involved in the propagation of Electromagnetic Interference (EMI).

The basic assumptions of Engineers who design circuits and electrical systems are that charges propagate at near-light velocity along conductors and through insulation. This assumption is inherent in the definitions of Voltage, Current and Charge in Circuit Theory and these definitions lead inexorably to the circuit model of Figure 2 and to the deductions of Transmission Line Theory.

On the other hand, Scientists declare that the electron is the smallest particle which possesses the property of ‘charge’. Yet electrons do not move at the speed of light and do not flow through insulating material.

Hence, there cannot be a one-to-one relationship between electrons and charges. Since Scientists conclude that the photon is the *quantum of the electromagnetic field*, it is logical to reason that currents, voltages, charges, electric flux and magnetic flux are manifestations of the interactions between photons and conductors.

What follows is a description of the mechanism involved in the propagation of charges along a transmission line. It is based on the relationships of Figure 2.

Coupling Mechanism

When photons interact with copper atoms, they cause the release of the ‘free’ electrons, which depart in the opposite direction. An atom with an electron missing is positively charged. An atom with an extra electron is negatively charged. Electrons can move in any direction in a conductor, but they cannot depart from the surface of the conductor. The action of stopping at the surface causes the emission of a photon into the environment and for that surface to become positively charged.

When photons arrives at the bottom conductor, they cause that surface to become negatively charged and for photons to be released into the body of the conducting material. The process then continues in the bottom conductor. It can be likened to the movement of the steel balls in Newton’s Cradle or to a pack of cards tipping over. Figure 3 illustrates this.

As well as driving positive charge into the body of the return conductor, photons can also move charged particles back along the surface. In turn, this causes the emission of photons back towards the send conductor. That is, the conducting surface acts as a reflector to some of the incoming photons. Figure 4 illustrates this.

When photons arrive back at the send conductor, the wavefront will have moved forward. This means that they augment the number of photons being driven forward along that conductor. This action is the same as positive feedback.

Current flows in a loop; along the send conductor, across the gap, and back via the return conductor.

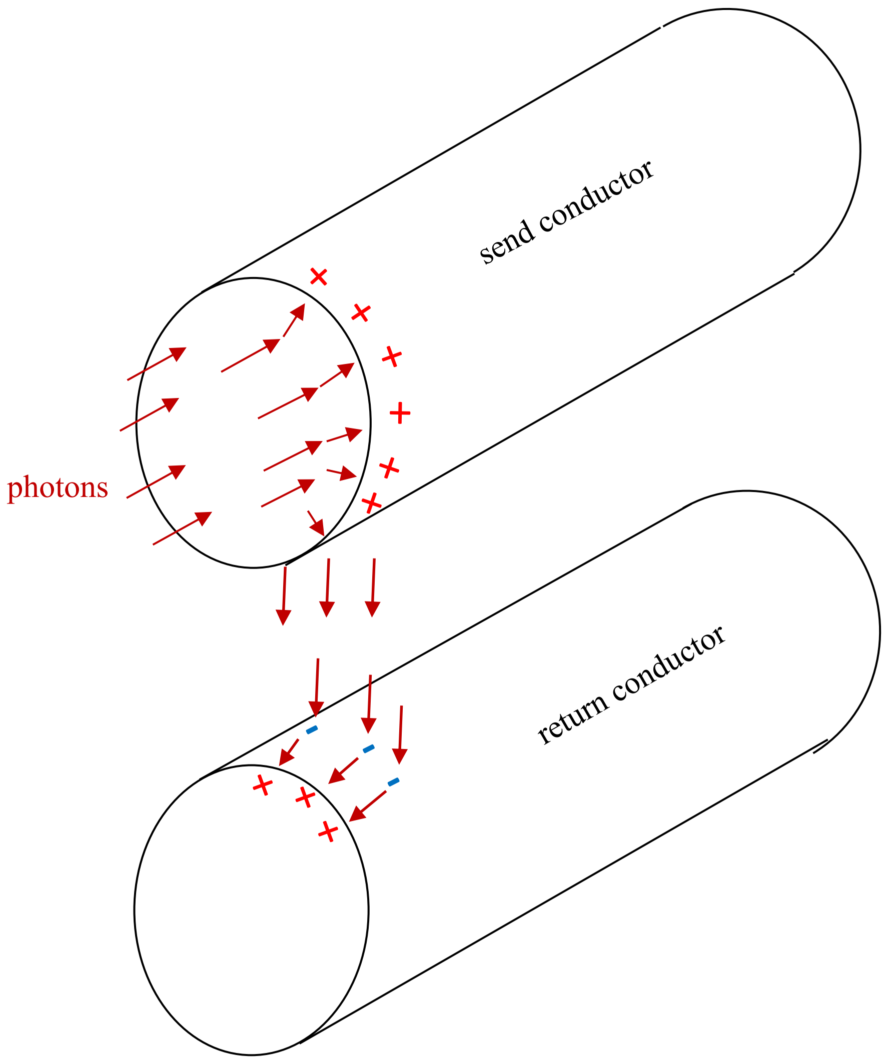

Figure 3 Action of photons in transferring charge between conductors

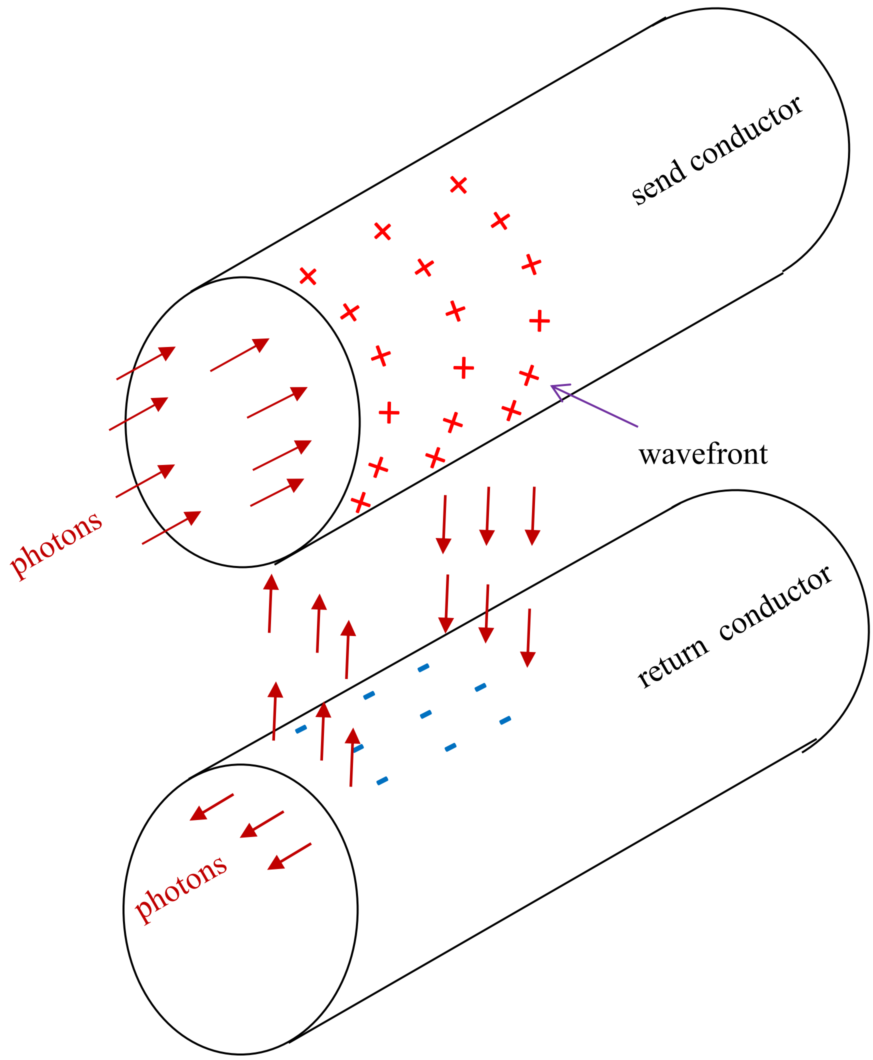

Figure 4 Action of photons in returning energy to the send conductor

Emission Losses

Figures 3 and 4 only show a few of the photons involved. In reality, photons are emitted from every point on each conductor, and depart in every direction. It is possible for many of those on the adjacent surfaces to return to the conductor opposite. The energy used to do this is represented by the voltage developed across the characteristic resistance.

Those which are emitted from the outward facing surfaces depart into the environment. If the cable-under-review is completely isolated, then these photons depart into the environment and constitute a loss of energy. A voltage is developed on these outer surfaces due to the departing photons. As far as Electromagnetic Theory is concerned, current has departed from the system. In doing so it has left trapped charges on those surfaces. The article ‘Updating Circuit Theory: Transient Emission’ describes a way of simulating this type of loss.

Magnetic Field

Inside the body of the material, atoms can move in any direction. As well as moving axially and radially, they can propagate round the circumference of the conductor. This is illustrated by Figure 5. The action can be compared to a slingshot. Since this happens with both conductors, the flow of charges follows a figure-of-eight pattern.

This is possibly the start of an explanation as to how the lines of force in the magnetic field form a series of concentric circles.

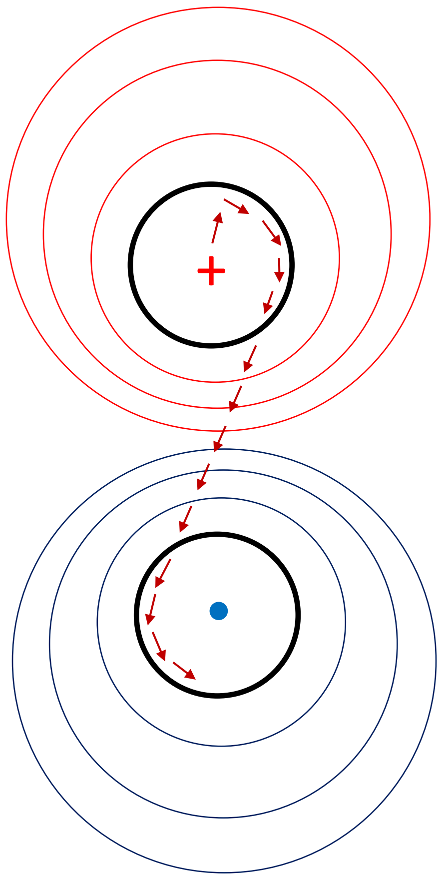

Figure 5 Propagation of photons round the surface creates magnetic fields of force

Electromagnetic Field

The action of the electromagnetic field can be explained in terms of the propagation of photons, both inside and outside a pair of conductors. It correlates with the modelling technique used to analyse the properties of any conducting assembly, as described in the article ‘Updating Circuit Theory: Composite Conductors’.

Charges can propagate in any direction in the body of a conductor; axially, radially and circumferentially. Photons have the same degree of freedom. This correlates with the fact that the analysis of the electromagnetic field emanating from a half wave transmitting dipole has longitudinal, radial, and latitudinal components of both the H-field and the E-field.

Although photons do not carry charge, their interaction with atoms of conducting material allows the flow of these entities to be visualised in terms of moving charges.

Conclusion

This article has described a mechanism whereby photons interact with the atoms of conducting material to cause charges to appear to move at near-light velocity along a conductor, how the departure of photons from the surface of a conductor creates positive charge on that surface and how the arrival of photons at a conductor creates negative charge on that surface.

Such an explanation establishes a clear relationship between Quantum Theory and Electromagnetic Theory; an explanation which can be understood by circuit designers and system designers. It also answers the Catt Question.