ENERGY TRANSFER

ELECTRONICS & WIRELESS WORLD NOVEMBER 1984

Once more *Wireless World* gives space to Ivor Catt's views on EM theory. It would help his efforts to overthrow the current position (the 'establishment view') if he showed more evidence that he knew what it was.

His article in the September issue of WW contains at least six major errors, any one of which is sufficient to destroy his thesis.

- Sinusoids and pulses are convenient ways of analysing waves mathematicly, be they electric, water or acoustic. The 'mistake' attributed Einstein and 'the modern physics community' just cannot exist.
- He constantly confuses impedance and resistance, leaving his transmission line analysis without value. EM energy is turned into heat by a resistance. When flowing in a transmission line or free space the energy is not changed into heat by the impedance but can be fully recovered as electrical energy. It is rubbish to say that modern physics ignores the impedance of free space, antenna theory and practice is based on it.
- He persists with his view that modern physics somehow requires electric charge to move with the speed of light in conductors. This is nonsense. It is helpful to regard a conductor as a pipe full of water, water flows in one end and out the other when pressure is applied. Naturally water flow is not the same as charge flow but those 'disciplined in the art' do not think, as Mr Catt would have us believe, that electrons have to rattle down some empty tube of a conductor, filling it up at the speed of light. A conductor already has lots of free electrons in it, all ready to start moving under the influence of a passing wave, it is this that distinguishes it from an insulator.
- He carries his conception of a capacitor as transmission line only so far and fails to complete the analysis. He shows it as an unterminated transmission line, but an open line is always terminated by free space with an approximate impedance of 377 ohms so every time a pulse travels down the line some

C.A.M.

energy is radiated and some reflected. Ivor Catt's mistake is to imagine that there can be some sort of permanent wave oscillating back and forth. Capacitors (and inductors) are only approximations, there can be no exact analysis of a capacitor without including inductive, resistive and transmission line effects. It is worth noting that it is a common v.h.f. and u.h.f. technique to use a transmission line to approximate a capacitor or an inductor.

D.J.O.'Reilly
Antwerp
Belgium

Reference the "Catt Anomaly", there is no anomaly to thoroughgoing Practising Electrician who really believes in charges, currents and fields, since to him it is obvious that a conductor is not just an empty tube. Space does not guide a TEM wave, and intrinsic semiconductors do not either and suffer from space charge effects etc. Conductors are materials that have a high density of mobile carriers, far in excess of the induced charge that moves at "the speed of light". There is no reason why a charge shoukd not move at the speed of light or even more. A charge is a local imbalance between the two polarities of particle. An electric current is the slow drift of the mobile ones. Consequently, where the drift velocity changes, there is a charge build up. The location of a charge can therefore be changed at any geometrical velocity. (A location is neither mass nor signal — thus keeping relativity happy.) Since the drifts are caused by the penetration of the external fields of the TEM wave, the actual velocity with which the drifts rearrange themselves is limited to the phase velocity of the TEM wave with the prevailing boundary conditions. In the case of a step pulse the drifting region elongates at the propagation velocity (nominally c), whilst charge pours into the moving transition region where the drifting carriers "collide" with the stationary ones. As it sweeps along, it leaves the surplus charge behind as a region of enhancement. Where does the charge come from? Nowhere. It was there all the time. All that has happened is a slight compression of the carrier density, made up at the driving end by the earth return current.

D.H. Potter
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Devon

Ivor Catt implies yet again that it is impossible for those "disciplined in the art" of conventional electromagnetic theory to understand the propagation of a current-voltage pulse or step along a twin conductor transmission line. Specifically he implies that the rapid progress of the two electrically charged zones along the conductors, terminating the electric lines of force looped between them, cannot be accounted for ("the Catt anomaly"), since the drift velocity of conduction electrons in metals is known to be small compared with the speed of light.

The conductors and the surrounding fields represent intimately coupled systems, both essential in the type of transmission system described by Catt. According to the elementary theory of metals the conduction electrons in a circuit behave much as the molecules of a gas contained in a loop of pipe. The current source, such as a cell, behaves as a circulation pump for the gas, sucking electrons in at the positive pole and ejecting them at the negative pole. The metal also contains positive ions, equivalent to obstructions in the pipe, and due to the associated frictional effects (equivalent to resistivity on the metal) the gas can indeed only be circulated at comparatively low speed. Catt continually overlooks the fact that *variations* in electron gas pressure and density generated by the electron pump may be propagated much faster, in the same way as sound propagates through air or a train of coupled wagons quickly jerk successively into motion when the locomotive pushes or pulls them. The zone with increased density generated, say, by a compression stroke of a pump extends to a range equal to the velocity of sound multiplied by the stroke duration. It is this principle which allows a loudspeaker to generate wavelengths much longer than the amplitude of vibration of the cone itself. The combination of the rapidly moving fluctuations in electron gas density and the background of positive ion charge yields the necessary, rapidly moving positively or negatively charged zones in the metal. The analogy with sound propagation is not quite exact, since the extra charge prefers to collect on the surface of the metal to reduce energy, much as cream floats to the surface of milk. Also, the electromagnetic interaction between the electrons equivalent to gas pressure or wagons colliding with each other, is transported principally through the

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surrounding dielectric medium into which the electromagnetic fields penetrate deeply in lines with typical geometry. In the gas filled pipe analogy this is equivalent to the transport of a signal via the material of the pipe itself, which one generally seeks to minimize in practical acoustics. The speed of propagation of electron density variations is accordingly limited by the speed, and in typical lines the relevant speed is that for the dielectric medium. As Catt states, the energy ultimately delivered to the load is most economically regarded as transported by the fields, the conductors acting essentially as a guide for the energy. Contrary to Catt's claim, libraries well-used by "the modern physics community" contain many texts on the transient response of transmission lines. The authors naturally assume that elementary notions of wave generation etc. were well-assimilated by the reader at an early age, and make little reference to very basic ideas.

N. Morton
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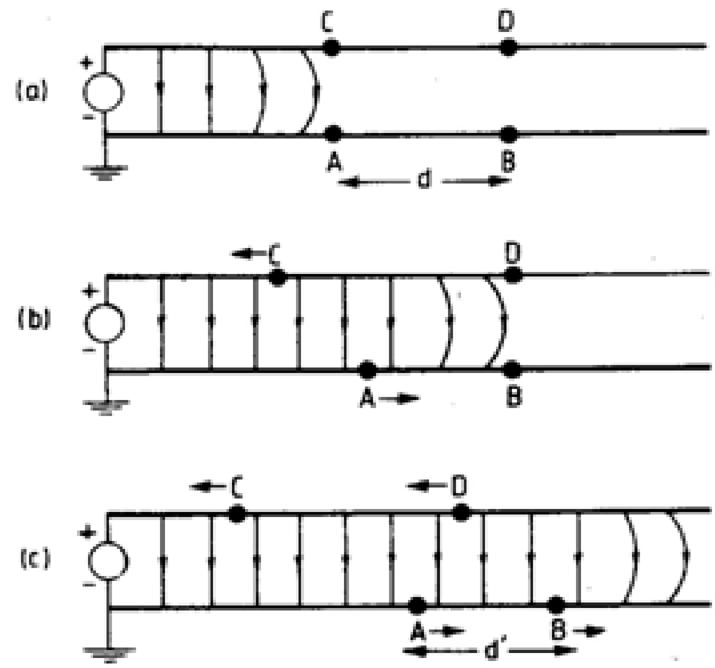
I would like to make two comments on Mr Catt's article on energy transfer.

First, I remember being taught as an undergraduate about the passage of stepwaves and pulses along a transmission line, as well as sinewaves. That was forty years ago, long before t.t.l. and e.c.l. were dreamed of. Yet we were interested in pulses even in those days (remember when radar was still called radiolocation?). So perhaps it would be unwise to assume that everybody else has been taught as badly as, apparently, was Mr Catt.

Second, the Catt anomaly, the details of what happens when a step-wave passes along a transmission line, need more discussion than perhaps Mr Catt felt able to give them in a short article. The figure shows a step-wave passing from left to right. In (a) it has not yet reached two electrons A and B in the earthy wire, which are still at rest a distance d apart. The electric field at the wavefront is bowed outwards, convex in the direction of motion (remember that "lines of force" are supposed to repel each other sideways). Hence at the surfaces of the wires there are components of the field along the wires. Therefore when the wavefront passes electron A the

Fig.1



latter experiences a momentary force (an impulse) which sets it moving relatively slowly — drifting — along the wire. In (b) is shown the situation when the wavefront has passed A, but has not yet reached B. On a truly loss-free system A does not need any further force to keep it moving, so behind the wavefront the electric field is strictly normal to the wires. The important point to notice is that the distance between A and B is decreasing.

In (c) the wavefront has passed B also. B has been set moving, with the same velocity as A, so the pair of electrons drift along together, with a constant but smaller distance d' between them. Applying this result to all electrons in the earthy wire it appears that the moving electrons everywhere behind the wavefront are slightly more crowded together than when they are at rest.

Hence in unit length of the wire there is a larger number of negatively charged electrons than the number of positively charged ions in the parent atoms fixed in the wire. That is, the wire has (as expected) acquired a net negative charge on which the "lines of force" terminate. Conversely, in the live wire the passage of the wavefront causes electrons such as C and D to drift to the left, with an increase in the distance between them. In this wire the mobile (conduction) electrons are less crowded together than normal, and there is a net positive charge from which the "lines of force" originate. To sum up, if in a wire (any wire) the flow of (electron) current is in the same direction as the flow of energy then the electrons are more crowded together than normal; if in the opposite direction, the electrons are less crowded together. This is a detail in the description of the flow of current which admittedly few text books mention.

Nowhere in the foregoing argument has it been demanded that any electron should move with the velocity of light; yet the accumulation of charges, positive and negative, keeps pace with the travelling wavefront. This is because the accumulation are formed by the wavefront itself, from the electrons which are already present at the wavefront. The Catt anomaly does not exist, so any arguments which are adduced to 'explain' it are unnecessary.

In practice the crowding is, relatively, very small. Consider an air-spaced transmission line of characteristic impedance 50Ω, so that its capacitance is (very nearly) 20 pF/ft. For a step wave of amplitude 1V the net charges, negative and positive, are 20pC/ft.

Dividing this by the charge on an electron, 1.6×10^{-19}C, we find that number of excess electronics (or holes) is 1.25×10^{8}/ft. But this is small compared with the number of conduction electrons which in a metal is about 10^{23} per cc. If the wire of which the line is made is 1mm in diameter its volume is 0.24cc/ft, so the relative excess or deficit is $(1.25\times10^{8})/(0.24\times10^{23}) -5.2\times10^{-15}$. This number is so small that Mr Catt, and possibly many other people, may be forgiven for overlooking it.

P.L. Taylor
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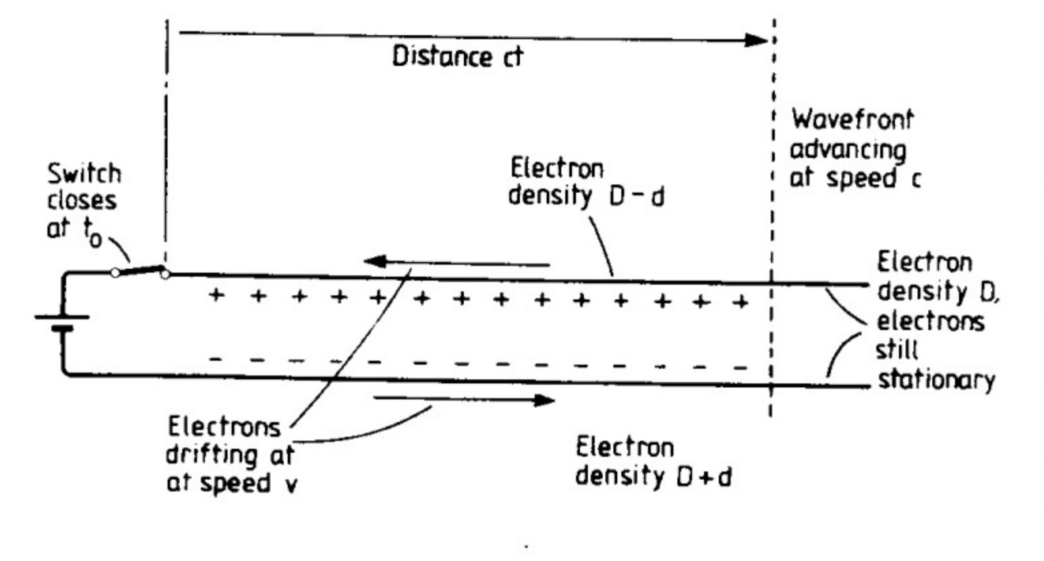
Ivor Catt seems to have repeated a misconception about what happens in transmission lines.

Fig. 2 shows the state of affairs in a transmission line after a voltage step has been applied to its left end. The switch was closed at time t_0, and after a further time t, the wavefront has advanced a distance t, c being the speed of TEM propagation in the dielectric. The left of the wavefront there is an excess of electrons on the lower conductor and a shortage on the top conductor. The right of the wavefront there is no net charge on the conductors. Concentrating on the lower conductor, Catt wants to know where the excess of electrons came from. "Not from somewhere on the left", he says, "because such charge would have to travel at the speed of light in a vacuum", and that this "is obvious to the untutored mind." It is fairly obvious to my untutored mind that somewhere on the left is exactly where the charge came from, that there is absolutely no need for it to travel at anything like to speed of light, and that Catt is wrong.

Perhaps I can illustrate by way of analogy. Imagine a row of coins, all 25mm in diameter, and each separated from the next by 1mm. I begin to push the leftmost coin to the right at 1mm per second. After one second it touches the next coin and this begins to move. After another second this bumps into the third coin. This contact happens 26mm to the right of the first, one second later. After each second elapses, another contact occurs 26mm to the right of the previous one. We can imagine this sequence of contacts to be a "wavefront" running through the coins at

Fig. 2



26mm per second — that is 26 times the speed of the coins themselves. To the right of the wavefront there is one coin every 26mm, but to the left there is a higher "coin density" of one every 25mm.

Returning to the bottom conductor, electrons to the right of the wavefront have the "neutral" density D, but to the left they have a slightly excess density and are drifting slowly to the right. The wavefront itself is moving at the speed of light. Obviously electrons do not "bump into" one another like coins, but the principle is the same. To a first approximation the ratio of c to v is the same as the ratio of D to λ.

In a real transmission line the "neutral" electron density D depends on the geometry of the line and the type of conductor material used. V and λ also depend on these factors, and on the size of the voltage step applied as well. The velocity of propagation of the wavefront though, depends only on the dielectric and has something pretty fundamental about it — which to my mind gives credence to the idea that energy flows through the "insulator", and not the "conductor" which is in fact a barrier to energy flow. After all, metals are shiny because light bounces off them, and I can't ever remember seeing the wires that carry the sun's energy through space to us. I wish Catt would not discredit such (at least potentially) good ideas by throwing in duds of this own.

One final point. On page 47 Catt says "The fact that parallel voltage planes, when entered at a point, present a resistive, not reactive, impedance, was for me an important break-through". Really? If a disturbance is applied at a point in such a pair of planes, a circular wavefront will propagate away from the point. As it moves out, its size will increase, and the impedance of the planes to the wavefront will fall.

As a result of this, energy will be reflected back to the original point of disturbance. This continuous reflection process will present to the disturbance an inductive impedance — won't it?

Alan Robinson
London

FUNDAMENTALS OF ENERGY TRANSFER

It is always refreshing to see a contribution from Ivor Catt even if I do not wholly concur with his conclusions. I am well aware of Heaviside's views that electromagnetic energy leaves a source and enters a load sideways, and he gives an example of a source in London connected by a telegraph wire to a receiver in Edinburgh. Some of the energy from London travels far out into space before converging on the receiver,, but unfortunately I have not been able to find in Heaviside's Electromagnetic Papers any account of how the energy in distant space knows that it is time to start the descent for Edinburgh. However, this is a difficult matter and it is not surprising that the story is incomplete. What is much more difficult to accept is why we should in our theory stumble on the relatively simple matter of a parallel-wire transmission line.

The National Physical Laboratory defines the SI unit of electric current as "The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per metre of length."

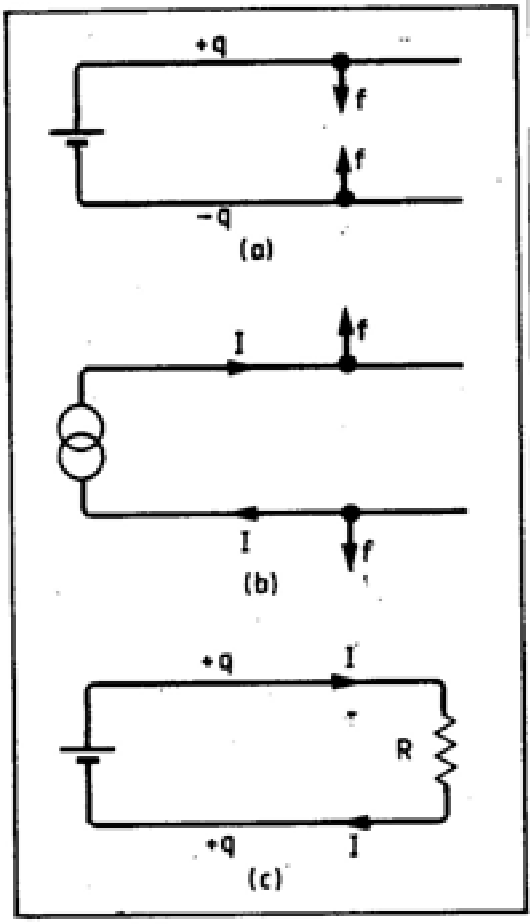
Many text books on electricity, elementary and advanced, use similar wording to define the ampere and indeed the definition is not new. If we substitute centimetre for metre and dyne for newton we have the c.g.s. electrodynamic definition of the ampere that has been used since the beginning of this century, and during this time this piece of scientific nonsense has been for the most part uncritically accepted.

Consider the following relatively short transmission lines:

In diagram (a) the line is open circuit at the distant end hence the conductors experience a mutual electrostatic attraction. In (b) the conductors carry a current and hence mutually repel each other. In (c) we have a combination of electrostatic attraction and electromagnetic repulsion which for some value of R must neutralise each other.

Not very surprisingly the value of R to produce zero resultant force is the characteristic impedance of the line, and that can be achieved by extending the line in diagram (a) infinitely to the right. It seems to have been forgotten

C.A.H.



that if a line has $Z_0 = 100\Omega$ then to establish a current of 1A in the line we need a supply of 100V and the electrostatic attraction because of that cannot be ignored.

Forces on the conductors of a transmission line arise from reflections, and the principal characteristic of an infinite line is that it is free of reflections. Now this absence of force on an infinite line follows almost intuitively from the principal of virtual work so it is all the more surprising that the error should have gone undetected for so long. In an infinite line there is equal sharing of the stored energy between the electric and magnetic fields associated with the line. If we increase the separation of the line conductors by a small amount we need a force to overcome the electrostatic attraction, and that can be calculated from f = dw/dx where dw is the increase in stored energy and dx the displacement. Likewise the force associated with increasing the magnetic field energy is f = dw/dx and because of energy sharing equally, dw is the same in each case, as is dx, and the forces oppose each other, so there is a net resultant of zero. Mr Catt rightly says that nothing travels sideways across a transmission line in the TEM mode and that includes force. Lateral forces on the conductors of a transmission line always arise because of reflections that upset the balance of electric and magnetic energy storage in the line. That is only possible with a line of finite length.

Of course it may be objected that the definition does not specify that the two conductors should be the go and return of a single circuit. They could perhaps be the two go conductors of a circuit with a distant common return. Apart from the added complexity due to the third conductor the problem is the same whether the currents in the specified conductors flow in the same or opposite senses. The twin-beam c.r.o. is an example of two parallel conductors carrying current in the same direction. It can be easily shown for this case that for relatively low anode voltages the beams repel each other electrostatically. As the anode voltage is increased the magnetic attraction of the beams becomes greater and would exactly neutralise the repulsion if the electrons in the beams could accelerate to the speed of light and there, as in the case of inifite parallel conductors, the nett force would be zero. Examination questions on this part of c.r.t. science are not uncommon and take the form of "Show that, no matter how the beam electrons are accelerated, the force between beams can never become attractive". The short answer to that is that we can never get the electron velocity up to the energy propagation velocity of the parallel conductors.

It is quite understandable how the definition of the ampere comes to be as it is. A line of finite length has end effects that we do not know how to take into account, so what could be simpler than to remove them to infinity? Unfortuntely this ploy leaves us with a useless line as far as the measurement of force is concerned.

In practice, the SI definition makes no difference for no one pays any attention to it. The ampere is standardised using an Ayrton-Jones current balance in which the conductors are arranged as circular coils and not as straight lines. In the Ayrton-Jones balance we are dealing with equivalent lines finite length short-circuited at the far end so that all the energy is stored in the magnetic field and none in the electric field, so we have no problems.

However, the definition does make a difference of those of us like Mr Catt and me who have some responsiblity for educating the young in fundamentals of our science. How can Mr Catt persuade his students that nothing traverses a transmission line in the TEM mode sideways, when in all quarters, they see "authoritative" statements to the contrary?

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Mr Catt's article (September 1984) treads some very shaky ground: I consider many of his statements to be rather questionable but I think I can lay the rest the so called 'Catt Anomaly'.

If I understand Mr Catt correctly he is unwilling to accept that a charge pulse can travel down a transmission line at a speed greater than the speed of light local of the copper of the conductors.

In fact, the speed of light in the conductors (or, for that matter, the electron drift speed of some millimetres a minute) has no bearing at all on the speed of an EM pulse travelling down the transmission line. In 1 nanosecond charge does not have to travel 1 foot down the wire: all that is required is for a drift of charges to occur at the leading edge of the pulse, as it moves, so as to leave a net charge on the wire, in the wake of the pulse.

If this does not seem clear, consider the case of a low amplitude sound pressure pulse, travelling down a pipe: the air in the pipe, behind the wavefront travels very slowly indeed, while the pressure front travels forwards at the speed of sound.

I should like to add that I consider the issue of whether EM fields in a waveguide cause currents in the conductors, or vice versa, to be a meaningless, unanswerable question: field and currents are related by the physics of the situation, one does not preceed the other in time, and no wave or pulse travels without both.

There are a great many statements in Mr Catt's article to which I take exception, but I lack the enthusiasm to describe all the fallacies, or research his reference list to isolate their origins.

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DISPLACEMENT CURRENT

Maxwell's displacement current provides a physical mechanism for the thermodynamic concept of entropy.

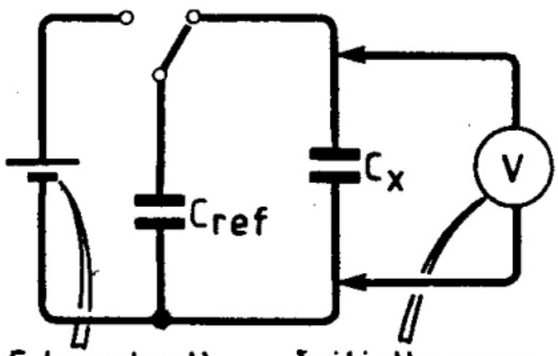
When a capacitor is connected across (strongly coupled with) an e.m.f. the microscopic electronic configuration of the circuit changes as charges are re-distributed around the circuit, The 'information' that any changes in (relative) position of the microscopic elements has occurred propagates out at a finite speed to ('communicates with') distant space (entropy losses), which constitutes the loosely coupled environment (Mach's principle). In other words, the circuit scatters energy to space when it is closely coupled to the e.m.f.

Consider the problem of bucket charge transfer from a virtually infinite source to a finite reservoir

On each cycle of the changeover switch C_{ref} charges to a constant voltage E then shares its charge with the (unknown, say) capacitance C_x, On each switching contact there is energy loss (or 'taxation') from the circuit. It is elementary to calculate the voltage on C_x after n switchings and obtain the assymptotic solution (sent to *WW* Editor in 1982, I believe, and dramatically forgotten as of no significance to the theoretical real world).

How does Mr Catt's theory, based on its fundamental causal concept of 'energy' (whatever that really is), and, no doubt, on the principle of its conservation within any electrical system, account for entropy losses?

P.J. Ratcliffe
Stevenage
Herts



C.A.M.

ENERGY TRANSFER

My article in *Wireless World*, September 1984, entitled Fundamentals of Electromagnetic Energy Transfer led to a large number of comments being published in the November issue.

D.J.O'Reilly complained about my confusing impedance and resistance, "...leaving (my) transmission line analysis without value."

I have for long thought that use of the term 'characteristic impedance' for a transmission line is misleading — it certainly is for a lossless line, because the word "impedance" implies a combination of resistance and reactance, (see for instance "Advanced Physics" by S.M. Geddes, pub. Macmillan 1981, page 189,) whereas a lossless transmission line contains no reactance. It is for this reason that for many years I have wanted to use the term 'characteristic resistance'. (Also note in *Wireless World* Oct, 1984, page 50, the criticism of the repeated LC model for a transmission line. The idea that a transmission line contains alternate L and C is false and destructive.)

When O'Reilly writes, "It is rubbish to say that modern physics ignores the impedance of free space, antenna theory and practice is based on it," he ignores the distinction made earlier in the article between 'modern physics' and digital electronics. Under such classification, antenna theory would certainly not fall within modern physics. Ask modern physics pundits, for instance Professor Paul Davies of Newcastle University or Nobel Prizewinner A.Salam of Imperial College whether they have studied antenna theory. O'Reilly is surely not disputing my point, that modern science is seriously fragmented.

No comment on Messrs. Potter and Morton. Whatever lecturer or text book taught P.L. Taylor that "...the wavefront is bowed outwards, convex...", i.e. that a TEM wave is not TEM? Certainly not Heaviside, see refs. 2 and 3 in my September article.

I agree with Alan Robinson that if a conductor were filled with a row of rigid electrons touching each other, simulating a rigid rod, then an effect could travel at infinite speed even if the electrons (= rigid rod) travelled slowly. This has nothing to do with the theory of the TEM wave, at least as discussed heretofore. Is Robinson inventing the 25mm — 26mm scenario, or will he give us its pedigree?

Referring to Robinson's final point. At the diameter of the wires entering the capacitor, the characteristic impedance of the pair of parallel plates is already very small, and is resistive not inductive. Any reflections resulting from the mechanism he mentions, of a semi-circular flowing out from the entry point to the two plates, can only serve to reduce an already low resistance. This effect does not correlate with the traditional values of series inductance

alleged to be contained within capacitors, (and which are actually a function of something outside the capacitor - its legs;) which are orders of magnitude larger. Robinson has introduced a high quality red herring.

Ivor Catt
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In considering what Ivor Catt has to say, one has, I think, on the one hand to be aware of the situation that existed between the Church and Galileo. Although his findings were of the utmost significance to the world in the end, he was a heretic for propounding them. But on the other hand one is tempted to think that it is just possible that Mr Catt is learning as he goes; that I shall not condemn. After all, this was the great genius of Michael Faraday, noticing happenings he was not in the process of seeking, and then following them up. But one has to be so careful of mistaking what one is learning as one goes, for discovery.

I have been poking pulses out of sources to distant destinations since 1924, whether on wires, down tubes, or just plain flying off into space. And thought processes that have occurred on the way are related to the most incredible mental gymnastics. As early as 1919, when I constructed my first radio set having a valve, a huge affair with massive oak ends for the loose coupler (about 2ft long) at a time of relatively low-frequency operation, I wondered what would happen if wavelengths ever became shorter than the dimension of the tuning condenser. Would the charge get to the outer edge of the plate, before reversal took place and it was on its way out again. I now know that in fact it would have been an unterminated line of non-classic shape. This was to help me in later life, when it came to the contriving of broad-band aerial systems.

Then again, in my mind I would slow down the velocity of a dot on its way over the single-wire telegraph poles, in imagination keeping up with in on my bicycle, waiting for the other dot which had just left the other end. What, I thought, is to be the nature of the collision if the dots are of like polarity? Or the merger if they are unlike? Now that I am very old, using this slowed down technique, I now have a very fair non-mathematical mental image of what goes on.

But the arrival of Ivor Catt on the scene has set me off again. Take the case of a baterry of steady e.m.f. connected to an unterminated line. Wait for the reflections to be absorbed in line resistance, and of course we then have a charged condenser, but no magnetic field in evidence. Now, attempt to change the state of that charge by any means you care to employ, and what have you while charge value is being changed? Why, a magnetic field as long as the state of change exists. It was not there before, so where has it come from. Having charged and stabilised the line, then close it with it characteristic impedance. How does the sending end discern what has happened. One thing that immediately manifests itself is magnetism. Where has it been lurking? Like the heat in unburned fuel. While I have no difficulty in visualising the changes in (dare I use the word) current value when one does this sort of thing, I have not yet got the answer to the appearance and vanishing trick that magnetism can perform. My answer when provided has to be non-mathematical, so visualisation can be communicated. So if Ivor Catt is on the track of this, even by accident, good luck to him.

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