Re: MIT's Walter Lewin's twice surprises the EE professors! (fun)

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- *Date*: Sat, 13 Jan 2007 18:33:42 +0000 (UTC)

Cyberkatru wrote:

> But Bill, he actually uses the voltmeter to make the point. He moves the voltmeter without changing where it is connected and gets a different reading? This is puzzling if there is a real scalar function (node voltage) along the wire whose changes around a loop add to zero. This demonstration is in lecture 16. He actually used the physical voltmeter to show that the changes around the loop don't add to zero.

(I looked at the video −− despite the best efforts of RealPlayer to keep me from doing so. I see what you are talking about.) As with any magic trick, there is a misdirection right at the start. In this case, the misdirection is in leading you to believe that different points along a wire represent the same circuit node. In the absence of time−varying magnetic fields, they should be, but the point of Faraday induction is that this is no longer true when the B field changes. To treat this case with circuit theory, we have to make it a distributed circuit, and two points along the wire are no more the same circuit node than two points along the center conductor of a coaxial cable (transmission line) are. Or, for that matter, the two ends of the wire coming out of an inductor coil.

We would analyze the situation the same way we analyze a transmission line: find the equivalent circuit model for a differential length along the wire. In this case there will a resistive element R0 dx where R0 is the resistance per unit length. In series with this will be the Faraday generator, a voltage source of magnitude −dA/dt (dot) dx, A being the vector potential. To include the possibility that the wires are moving in the magnetic field, we should probably take the time derivative of the whole dot product. If we're simply looking at a closed wire loop with induced eddy curent, the Faraday generator raises the voltage a dV and the resistor immediately drops it −dV, leading to V(x) looking like a differential sawtooth pattern until we take the limit dx to 0, where it smooths out into a constant.

For the case Lewin does, the series resistors limit the current in the loop to a value much lower than the full eddy current allowed by the wire. Thus, the Faraday generators can add up to a macroscopic voltage along the length of the wires connecting the two resistors. Despite what the circuit schematic might imply, the two resistors are in no way connected to the same two circuit nodes. If you model the circuit correctly by taking into account the Faraday generation in the wires, there is no violation of Kirchoff's Voltage Law.

Note that you may also need to include induction in the voltmeter leads too.

This explanation in no way contradicts what Lewin writes in his supplement, about charge redistribution in the circuit. The nice thing about circuit theory is that it automatically takes this into account, incorporating such things as the build−up of charges on the contacts to a resistor as required to create the voltage drop across that resistor.

> Another thing that bothers me with your explanation is that you said that the node voltage and the electrostatic potential are related by a constant. How could an additive constant make a difference here? KVL wouldn't be affected by an additive constant would it?

Note that I said they were connected by a constant within a metal of a given composition. In other conductive media, there are more complicated correction factors. (Again, multiply everything that follows by that pesky minus sign due to the electron charge.) In semiconductors, voltage (Fermi level) is equal to the potential energy for an electron at rest (the conduction band edge energy) + kT ln (n/Nc), where n is the electron concentration and Nc is a constant whose origin we don't need to worry about. Now, −k ln (n/Nc) is just the entropy of the electron gas, so we see that the voltage can be interpreted as the Helmholtz free energy per electron. In dilute electrolytes, you have a similar situation, resulting in the Nernst equation. In metals, the electrons are so highly degenerate that we can ignore the entropy correction.

Since the voltage is a measure of free energy, the normal relations like P=VI really do measure do measure the available energy (or power). Thermodynamics have already been taken into account.

> You might have the right explanation but it still not clear to me. It is almost as if you are saying that the line integral \int E \dot dl is not the relevant quantity for circuites. But this seems inconsitent with Jackson's book. I think I ansered that above. E dot dl is very relevant, but it's not the only thing that needs to be considered.
> Is your explanation written in and advanced E&M texts?

In my experience E&M authors have very little interest in the grubby

details of what happens within technological materials. It will
certainly be in a textbook in the future, since I am working on one on
the topic of electron devices. This is obviously sufficiently confusing
that it is worth a section or perhaps an appendix.

(By the way, my mail server seems to be having problems, because I have not
seen my post show up yet. If anyone else responded to my post please email
me directly.)

− Bill Frensley

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