On Current Flow through Magnetized Iron Rods

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1. Introduction.

Current flowing through iron rods is of interest because this is the unusual feature of Coler's Stromerzeuger. This paper examines the *internal* inductance and resistance of iron rods using Hallen's book "Electromagnetic Theory". Hallen uses the plane-wave field equations within materials to establish the skin effect that plays its part in both the internal resistance and the internal inductance. Hallen uses the propagation constant γ for these waves, which can be expressed as having real and imaginary components that are respectively the attenuation (α) and phase (β) constants ($\gamma = \alpha + j\beta$). Although Hallen mentions the phase constant β in the case of pure insulators (where $\alpha = 0$), it is found that he ignores the phase constant in the case of waves in metals, even though $\beta \neq 0$. For the present work this could be a serious omission, since for iron β is found to be considerable even at low frequencies.

2. Field Propagation in Materials.

For periodic variations, the propagation constant for plane waves is

$$\gamma = \sqrt{j\omega\mu_R\mu_0(\sigma + j\omega\varepsilon_R\varepsilon_0)} \tag{1}$$

where μ_R is the relative permeability, ε_R is the relative pemittivity, σ the conductivity and μ_0 ε_0 the free-space permeability and permittivity. For pure insulators where $\sigma = 0$ this becomes purely imaginary, $\gamma = j\omega\sqrt{\mu_R\mu_0\varepsilon_R\varepsilon_0} = j\beta$, which then defines the phase constant β. However for metals the terms in (1) containing $\omega\varepsilon_R\varepsilon_0$ may be neglected in comparison with the conductivity for all technical frequencies, including microwaves, hence (1) becomes

$$\gamma = \sqrt{j\omega\mu_R\mu_0\sigma} \tag{2}$$

Using the known relationship $\sqrt{j} = \sqrt{½} + j\sqrt{½}$ we can write (2) as

$$\gamma = \sqrt{\frac{\omega\mu_R\mu_0\sigma}{2}} + j\sqrt{\frac{\omega\mu_R\mu_0\sigma}{2}} = \alpha + j\beta \tag{3}$$

Thus it is seen that the attenuation constant α (Nepers/m) and the phase constant β (radians/m) have the same magnitude. Hallen chose to use $\gamma = x + jx$ where

$$x = \sqrt{\frac{\omega\mu_R\mu_0\sigma}{2}} \tag{4}$$

then called x the attenuation constant.

3. Internal and External Impedances.

Hallen derives an exact formula for the internal impedance of a wire of circular cross section as

$$R + j\omega L_i = R_0\frac{\gamma a}{2}\frac{I_0(\gamma a)}{I_1(\gamma a)} \tag{5}$$

where L_i is the internal inductance, R_0 the d.c. resistance given by $R_0 = \dfrac{l}{\pi a^2\sigma}$, a the wire radius and $I_0(\gamma a)$ and $I_1(\gamma a)$ are Bessel functions. For large magnitude of γa, which is the case for the iron rods in question, the Bessel functions can be evaluated to give

$$\frac{R + j\omega L_i}{R_0} = \frac{\gamma a}{2} + ¼ = \frac{xa}{2} + ¼ + j\frac{xa}{2} \qquad (6)$$

where x is given by (4). At very large values of γa the numerical term (¼) in (6) may be neglected hence

$$R + j\omega L_i = R + jX = (1 + j)\frac{xl}{2\pi a\sigma} \qquad (7)$$

Thus both the resistance R and the reactance X have equal magnitudes and increase with frequency being proportional to $\sqrt{\omega}$. The current then lags by 45° the potential drop across the rod irrespective of frequency. Skin depth $\delta = 1/x$ is small which means the current becomes more a surface flow rather than volumetric.

4. Iron Rod as a Transmission Line

Although the above analysis doesn't allude to the phase constant β, its effect in regard to radial propagation is included in that 45° angle. The large ($\beta = x$) phase constant causes the phase of the current to vary with penetration depth from the surface, the inner currents lagging the outer currents considerably. The net result is the 45° angle for the *total* current. However, here no account has been taken of any internal propagation delay *along* the rod. If, as seems likely, there is a delay proportional to the length of the rod, it must then be considered as a transmission line. The propagation constant for propagation along the rod cannot be x else there would also be large attenuation along the rod, but there could be a smaller value associated with the high permeability. The important thing to note is that the transmission line delay would apply to both the resistance R *and* more importantly the reactance X. It has recently been shown that a finite length of transmission line having *reactive* impedance, when terminated with a capacitor, can exhibit a negative value of input resistance, and an iron rod is such a reactive line. This insight could bring a new dimension into the workings of the Coler Stromerzeuger.

It is of interest to note that Coler's machine consists of stacked rectangular copper plates with interweaved flat coils, as shown in Figure 1 which is taken from the Norrby patent. Although this shows two pairs of plates at each layer, this is only for clarity, there is only one pair. Not shown are the iron rods; at each layer there are two rods connected in series at the connection marked P. Thus at each layer there is a transmission line of two iron rods in series terminated by a capacitor plate. Each rod is about 200mm long, hence the total line length is in the order of 400mm. Having plate dimensions of about 1m by 0.25m and separation of about 0.01m the inter-plate capacitance is in the order of 50pF. There is evidence from theoretical work on capacitively-terminated transmission-lines having reactive characteristic impedance that this length of magnetic line terminated in that value of capacitance could produce negative resistance, hence self-oscillation. It is contended this could be the source of the anomalous power generated.

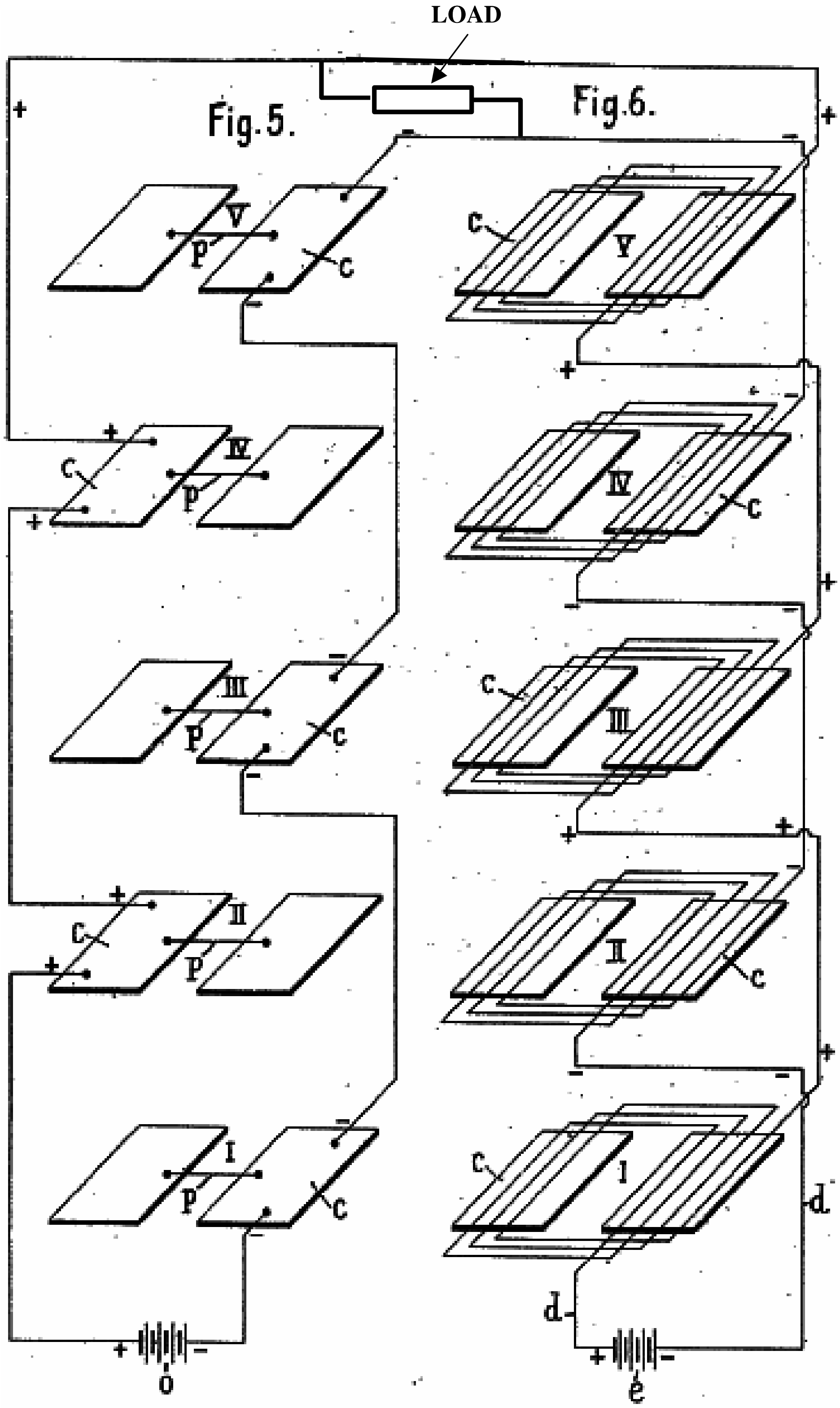

Figure 1. Circuit Diagram taken from Norrby Patent
Each horizontal connection P passes through two iron rods (not shown).