Magnetic Fields From Power Lines and Possible Interference with Pacemakers

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***Abstract*—This paper is the final project for EENG386 (Electromagnetics). It will discuss the dilemma of high-power transmission lines and the magnetic fields that could affect people near them. Recently, the implementation of high-transmission lines has been highly debated in the community as people claim it could cause cancer or other possible health issues. In the case of this study, the team chooses to look into whether high-power transmission lines could interfere with the functioning of a pacemaker of someone who is near the lines itself. Through looking at the magnetic properties of the transmission lines itself, down to the distance of the waves to a possible person, and the workings of a pacemaker will draw a conclusion if transmission lines should be so close to humans. Relating this issue back to the "restore and improve urban infrastructure" grand engineering challenge helps provide relevance to the study.**

***Index Terms*—Magnetic Field, Biot-Savart Law, Faraday's Law, Electromagnetic Interference**

I. Introduction

THE implementation of high transmission power lines and its association to health risks were first brought up to concerns back in 1979 through a study relating childhood leukaemia with power lines [1]. With this study being more speculation without any relationships of causal or coincidental being defined, it has not stopped the use of high-voltage power lines in communities. The scientific community declares that there are no detrimental effects because the electromagnetic forces are weak and can be negated. Even though scientists believe there is no correlation between high power transmission lines and health issues like cancer from radiation, what about other medical technologies that have their own magnetic fields that could be interrupted? The team will look into this issue to determine any correlation or causation of a specific case pertaining to pacemakers.

In order to understand the effects of a magnetic field of a pacemaker, it is important to note that the study is not about changing the already existing medical technology implanted in the chests of 1.5 million Americans today [2]. Instead, focusing on the engineering grand challenge dealing with urban infrastructure or the construction of transmission lines itself is the best way to see if there is a need to change the structure of these power lines if found to interfere with pacemakers proper functionality. This is to determine if transmission lines need to be farther away from homes as it is, or the internal structure of the lines itself needs to be changed to a safer level of charge. Through looking at the pacemaker monitor to see how it functions on a regular basis and the possible electromagnetic interference that could impact it in comparison to power lines is beneficial. This will be calculated by using electromagnetic concepts such as Biot-Savart Law and Faraday's laws to see if there are magnetic field interferences and at which distances would cause a disruption in the heart monitor's performance. Considering stakeholders like medical professionals who must deal with faltering heart monitors, people with the pacemakers, and power companies that utilize these power lines are important for this study.

II. Methods

A. *Biot-Savart Law for Transmission Lines*

The electric current carried in a wire induces a magnetic field, mathematically expressed by the well-known Biot-Savart Law. This fact is of particular interest to those living with artificial pacemakers, as magnetic fields can dangerously interfere with the proper function of pacemakers. Manufacturers and medical professionals generally agree that a magnetic field greater than 10 Gauss, or 1 mT, poses a hazard to the proper functioning of artificial pacemakers [3]. As such, our mathematical model seeks to determine the distance at which a common municipal power line may generate a hazardous magnetic field. As discussed, the Biot-Savart law will be used to model the magnetic field as a function of proximity and current. Since the model is concerned primarily with municipal power lines, the Biot-Savart law may be simplified by treating the power line as an infinitely-long wire:

$$B = \hat{\varphi}\frac{\mu I}{2\pi r} \quad (1)$$

In this equation, **B** is the magnetic field vector, μ is the magnetic permeability of free space, I is the RMS current within the wire, r is the radial distance from the wire, and the unit vector φ indicates the direction of the field is given by the right-hand rule. Several simplifications can be made to this equation; our model is only concerned with the magnitude of the magnetic field so the vector component of the equation need not be considered. Second, the air is nonmagnetic so the magnetic permeability variable μ may be replaced by the constant μ_0, the magnetic permeability of free space. With these simplifications in mind, Eqn. (1) simplifies to:

$$|B| = \frac{\mu_0 I}{2\pi r} \quad (1)$$

Since the magnitude of the magnetic field is a function of two variables, a 3D surface plot is necessary to fully model the system. Since the B-field intensity is inversely proportional to the radial distance from the wire, values for r greater than 1m need not be plotted as the magnetic fields generated are negligibly small. The values for current vary from 0A to 2 kA; these bounds were chosen based on manufacturer's ampacity ratings of the ACSR lines used in municipal power transmission [4]. Figure 1 depicts the 3D plot of the magnetic field as a function of these variables, within the discussed bounds.

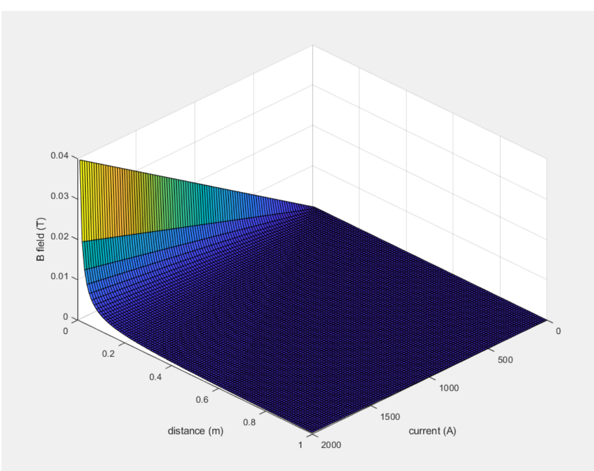

Fig. 1. The intensity of a magnetic field as a function of current within, and distance from, a current-carrying wire. Note that the highest reported value of the magnetic field is approximately 0.04T or 40 mT, much greater than the minimum dangerous magnetic field intensity.

While the data shown here reports a maximum B-field of 40 mT, this occurs at a very small radial distance from the wire. To better depict the potential dangers, we plot the magnetic field in the "worst-case scenario." That is, we chart the magnetic fields for a 2 kA current at distances very near the wire. For the sake of visual clarity, the data is plotted on logarithmic axes. Figure 2 depicts the results of this analysis.

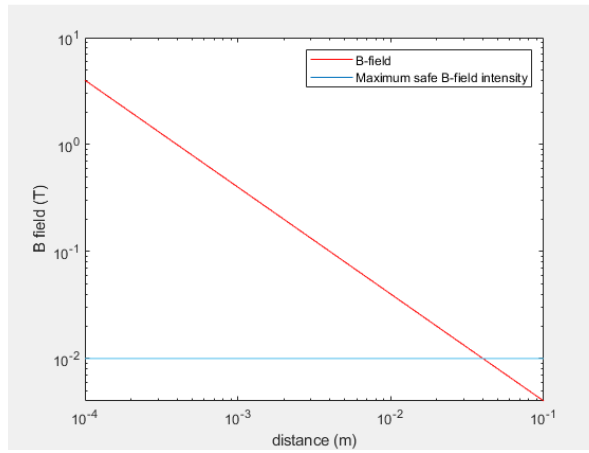

Fig. 2. Logarithmic plot of the intensity of the magnetic field generated by a wire carrying 2 kA of current. From this data, we see that a 2 kA current is hazardous to the function of a pacemaker at a distance of approximately 4 cm.

B. Pacemaker Functionality

Moving on from the transmission line, the pacemaker is an important part of the model. A pacemaker is a stimulator for one's heart and delivers electrical impulses to restore a normal rhythm. A pacemaker is a small machine with two parts where one consists of a small, metal battery-operated computer that is inserted into the soft tissue beneath the skin. This is connected with wires that have electrodes that are implanted into the heart [3]. Therefore, electromagnetic interference (EMI) should be looked at for pacemakers to see if high-transmission power lines could affect it.

In order to minimize the possibility of EMI, electromagnetic compatibility efforts like shielding are used to reject electric fields above 2 MHz. In addition, there are low pass filters to reduce interference and a feedthrough capacitor filter to reduce EMI from mobile frequencies. Even though the pacemaker is protected with filters to reject frequencies outside of the range of interest, if the frequencies are between 0 to 60 Hz it can overlap the cardiac signal range [3]. So if the filters were to reject this frequency range it would affect the proper pacemaker function and possibly lead to asynchronous pacing issues.

This all pertains back to high power transmission lines because the operating frequency is around 60 Hz. This radiation or the low-frequency non-ionizing radiation would affect the semiconductor that could build up charge and the leakage current within the circuit, thus it could affect programming, diagnostic results, and overall circuit failure. Thus, it could affect people with pacemakers so there needs to be a closer look at the transmission lines itself.

Since a high transmission line (500 kV to 765 kV) runs at a low frequency of 50 - 60 Hz with a wavelength of around 800 km and produces electric and magnetic fields, it would also be good to look at the waves travelling from the air to a person with a pacemaker [5]. As the frequency is found from one over the time period or the wave speed divided by the wavelength, this would be determined from the power line itself. This is the operating frequency and would not change internally, but it can be analyzed through the magnetic waves it emits through the air. The waves emitted through the air to a pacemaker is important to look at to see if the function could be interrupted from a power line depending on the degree of the wave.

C. Faraday's Law

Distance and environment are two parameters that are necessary to look at when dealing with electromagnetic fields. The energy or strength of the magnetic field decreases as the distance from the source increases. The relationship is proportional to the square of the distance, so for example if one were to double the distance from a transmission line, the strength of the power line would be ¼ of its original value before. So building structures like transmission towers and other environmental factors can influence the amount of electromagnetic interference. The placement of the infrastructure differs like an area of open farmland may not have as much electromagnetic radiation compared to an urban environment with lots of sources with hospitals and other large machinery. This poses a connection to Faraday's law where the induced voltage is proportional to the induction area. So take the distance from the pacemaker to the EMI source and how long is the exposure time. Faraday's law states that the instantaneous electromotive force is induced in a circuit that is proportional to the time rate of change of the magnetic flux. The equation below puts Faraday's law mathematically and the figure below shows a diagram of Faraday's law working in a field [6].

$$\varepsilon = -N\frac{d\phi}{dt} \qquad (2)$$

The emf, ε, produced around a loop of a conductor (N = number of circuit loops), is proportional to the rate of change of the magnetic flux, ϕ through the area of the loop. Note that the magnetic flux is equivalent to the area that the wire encloses multiplied by the magnetic field in Teslas.

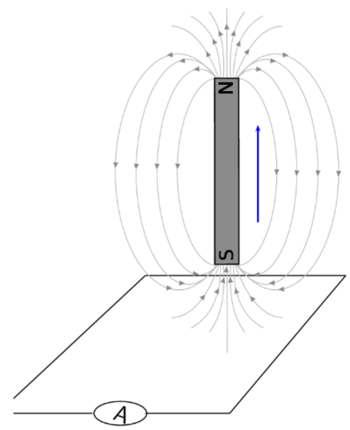

Fig. 3. Faraday's law diagram in the case of the transmission line to the pacemaker.

As Faraday's law has a negative sign in the equation to indicate the direction that the induced emf opposes in relation to the magnetic flux, it is important to keep in mind that induced current will oppose any change. Fig 3, shows the case where the South pole is moving away, thus the field from the magnet grows weaker in strength. This supports why the magnetic field grows weaker in pertaining to distance away, so it could lead to a distinction that high powered transmission lines may not pose a hazard to individuals with pacemakers that are far away.

A way to apply Faraday's law is through data on the magnetic field strength in Teslas to the distance in ft from the transmission lines. Assuming that a person is directly below the transmission line with no obstacles and starting with the minimum government-regulated distance of 60 ft, and an original magnetic field of 6.7E-7 T, an excel table was created showing the doubling of distances to the strength of the magnetic field.

TABLE I. Distance vs. Magnetic Field Strength

Distance (ft)	Magnetic Field (T)
60	6.70E-07
120	1.68E-07
240	4.19E-08
480	1.05E-08
960	2.62E-09
1920	6.54E-10
3840	1.64E-10

This data was then run into Matlab to see the correlation between doubling distance and ¼ the magnetic field strength every step. The correlation coefficient was also calculated and found to be around -0.44 where a correlation coefficient of -1 would define a negative relationship to the data. This isn't as close due to the large drop from the initial magnetic strength while as the data went on, smaller numbers were divided into smaller numbers. The figure below shows the exponential decay graph of the distance vs. magnetic field strength to show that the magnetic field strength gets closer to zero as distance progresses.

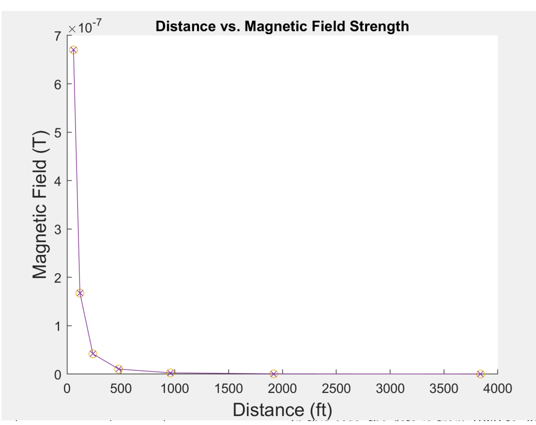

Fig. 4. Matlab plot showing how the magnetic field strength from the transmission line decays as the distance grows.

III. Results

From this data, it is reasonable to conclude that those living with artificial pacemakers need to take few if any, special precautions around standard municipal power lines. In the worst possible case, a hazardous magnetic field is not present beyond a 4 cm radius; with this in mind, it would be very difficult to encounter a dangerous B-field without physically touching the wire–a hazardous venture regardless of medical implants. Using the Biot-Savart law for the transmission lines itself makes it mathematically known that it is not hazardous for a person to be walking below a transmission power line.

In addition to understanding the pacemaker itself, there are already shielding efforts in place to deal with electromagnetic interference issues from strong static magnetic fields. The major concern was that pacemakers are susceptible to low frequencies which the power lines frequency fell into that range. However, through using Faraday's law, it was determined that due to the far distance of the transmission line to an individual that the magnetic field strength is weak enough to be negated. At the distance minimum of 60 ft, the magnetic field was 6.70E-7 T whereas pacemaker interference studies state it should not exceed 1 mT, so it can be deemed as safe [3].

In the future, if the infrastructure of the transmission lines itself were to change, it is important to note that it would be best for it to not be any closer than the already regulated 60 ft. Also, it is important to address the stakeholder's concerns about their safety in order to prevent more debates that high voltage transmission lines could pose health risks. Fortunately for those living with pacemakers, our exploration of electromagnetic phenomena show that special precautions are largely unnecessary.

References

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APPENDIX

Fig. 1 MATLAB Code:

```
% 3D Plot of magnetic field as a function of current and distance
% Contributed by Brennen Ward


muNought = 4*pi*10^-7; % defining constant magnetic permeability

[distance,current] = meshgrid(0:1/100:1,0:20:2000); % this model is a function of two variables so we use a 3D plot

BField = (muNought*current)./(2*pi*distance); % Biot-Savart law for a long wire


% Plotting magnetic field as a function of both distance and current and
% adjusting the camera angle for readability
surf(current,distance,BField);
xlabel("current (A)");
ylabel("distance (m)");
zlabel("B field (T)");
view(135,45)
```

Fig. 2 MATLAB Code

```
% Worst-case analysis of magnetic field induced by a current-carrying wire
% Contributed by Brennen Ward

muNought = 4*pi*10^-7;     % defining constant magnetic permeability
current = 2000;             % this model is examining the "worst-case" current value
distance = 0:10^-4:.1;   % this chart will be scaled logaritmically
% to capture the point at which the current generates a dangerous magnetic field
% as such, a high degree of precision is needed

maxSafeBField = 10*10^-3; % 10 mT is equivalent to 10 Gauss, the maximum safe magnetic field for a pacemaker

BField = (muNought*current)./(2*pi*distance); % Biot-Savart Law for a long wire

hold on

loglog(distance, BField, 'r', distance, ones(size(distance))*maxSafeBField), axis([10^-4 .1 0 10]);
% plotting distance vs. magnetic field logarithmically for a constant 2000 A current
xlabel("distance (m)");
ylabel("B field (T)");

legend('B-field','Maximum safe B-field intensity')
```

Fig. 4 MATLAB Code

```
%Scatter plot of Distance vs. Magnetic Field Strength
%Contributed by Zoe Sano

%Import Excel table
dataset = xlsread('distanceToStrength.xlsx','Sheet1','A2:B8');

%Grab data from x and y columns
x = dataset(:,1);
y = dataset(:,2);
format long

%Scatter plot
scatter(x,y)
hold on
plot(x,y,'-x')
xlabel('Distance (ft)', 'FontSize',14);
ylabel('Magnetic Field (T)', 'FontSize',14);
title('Distance vs. Magnetic Field Strength')

%Correlation coefficient
r = corrcoef(x,y)
```

Note of Contribution:

Zoe Sano

1. Abstract
2. Introduction
3. Methods (Part B and C, Figure 4)
4. Part of Results
5. References

Brennen Ward:

1. Mathematical Model (Figures 1 and 2)
2. Methods (Part A)
3. Part of Results
4. References