Magnetic fields around transmission lines in northeast Arizona — a field study

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with comments by Ragnar Forshufvud

The magnetic fields (EMF) around power lines can be measured up to several kilometers away. The measured levels are higher than would be expected from a simple geometric reduction by distance. This suggests that ground currents or stray voltage are a major factor.

This field study measured the magnetic fields around a set of high-tension power lines in a remote part of the Arizona desert.

Introduction

In the United States, high-tension power lines are Wye (Y) connected. That is, the three phases are run relative to a common neutral wire. The common neutral wire is mounted on top of the pylons, and is directly connected to the pylon without insulators. If the pylon is of steel, which is usually the case, the pylon itself acts as a ground rod through its foundations. In this case, the steel bolts are set in concrete, which are buried in the ground (poles with lower voltages are usually equipped with individual ground rods). The neutral wire is always grounded, and also acts as lightning protection. On some pylon designs (like the one pictured), two neutral wires are used, to ensure good lightning protection.

This neutral wire serves all three phases, which are 120 degrees out of phase from each other. Each phase carries a current of about 1000 amp (twice that for double wires).

Transmission lines use special transformers at each end to balance the phases, so they each carry the same current and there is no current on the neutral wire. If a current were to run on the neutral wire, it would be assumed there is a problem with the line and breakers will trip at the substation or power plant.

This balancing is different from lower voltage distribution lines (69 kV and less in the United States). In distribution lines there are many connections to the line and the current drawn will vary between the phases. Since the current is not the same in the three phases of a distribution line, there will be some current in the neutral wire, some of which may travel in the soil via the ground rods.

Since a transmission line is always fully balanced, there can be no current transmitted to the soil via the ground rods.

In a household, electricity runs to a light bulb through a cable with two conductors (wires). The electricity runs towards the light bulb along one wire and then returns to the outlet along the other wire. A magnetic field is generated along each of the two wires. Because there are two adjacent wires, with electricity running in opposite directions, the fields of the two wires largely cancel each other out.

If one took an electrical cord and separated the two wires, the radiation from each wire would be much greater than if they were adjacent to each other. This is the situation with aerial power lines where the wires are widely separated.

Magnetic radiation diminishes with distance. With a point source, such as a light bulb, the radiation is reduced by all three dimensions. With a doubling of the distance, the radiation will be reduced by a factor of 2 x 2 x 2 = 8 times.

With a long line source, such as a power line, there is reduction by two dimensions. Doubling the distance reduces the radiation by 2 x 2 = 4 times

When the radiation comes from a plane, such as a square kilometer of land, the radiation is only reduced in one dimension — the vertical distance. With a doubling of the vertical distance, the radiation is only reduced by half.

Description of the area

General area at mile marker 34

The general area is a long valley north of Kingman, Arizona. The valley floor is at approximately 3500 ft (1100 meter) elevation and is lined by the Cerbat Mountains on the western side and the Music Mountains to the east. The valley is traversed by the north/south highway from Kingman, named Stockton Hill Road.

The area of measurement does not have any human structures, except for three large transmission lines passing roughly east/west across the area, before turning towards the southeast.

A smaller distribution line (perhaps 15 kV) goes along the road between the villages of Dolan Springs and Meadview, which are both more than a dozen miles away. This line passes the closest transmission line about three miles to the north. To the south, another distribution line follows the highway from Kingman until it terminates about 16 miles south of the southern transmission line (before mile marker 22).

The closest house is near mile marker 25, a couple of miles removed from the road. This house is not grid connected, and probably served by solar panels or a generator.

It is a dry desert with sandy and rocky soil. The water table is very deep and there is little vegetation, mostly creosote bushes, yuccas and Joshua trees (which are not trees).

The area appears very well suited to measure the magnetic radiation from large transmission lines, as outside interference should be negligible.

The transmission lines

500 kV southern line

345 kV and 500 kV northern lines

A total of three transmission lines cross the area. The southern line crosses the highway just north of mile marker 38. It is a 500 kV line (500,000 volt), with double wires which transports power west from the Four Corners plant in New Mexico to Las Vegas or Los Angeles. This line is pictured on the first page.

The other two lines are 1.8 miles (2.9 km) to the north, very close to mile marker 40. These lines are at 345 kV and 500 kV respectively, which connects Las Vegas and Hoover Dam with the metropolis of Phoenix, 250 km to the south. The 345 kV line carries double wires, while the 500 kV line has triple wires. The direction of the power in these lines is unknown, and may vary.

The extra wires are used to carry more current and improve the cooling in this hot climate and thinner air. A 500 kV line with single wires can typically carry 800 megawatt of power at sea level. The ratings for these lines are not known to the author.

Method

A series of measurements were taken over a two-month period in early 2008. Measurements were taken using a gaussmeter placed on the ground near several mile markers on the highway that runs roughly perpendicular to the transmission lines. Since the lines cross the road near two mile markers (0.2 miles north of MM 38 and 0.1 mile north of MM 40), this gives a decent measure of the distance from the lines to the points measured (one mile is 1.61 km).

Measurements were also taken while driving very slowly under the transmission lines. The instrument was held out the window to minimize disturbance and shielding effects from the car. The highest measurement was recorded in each case. The northern set of power lines were always highly loaded, producing a field slightly beyond the range of the meter. The number was estimated.

Measuring the transmission lines themselves gives a rough idea of the relative current they were carrying at the time. The measurements at the nearest mile markers (38 and 40) also serve this purpose.

The instrument used was a TriField meter from Alpha Labs in Utah, which was factory modified with a 100x external directional probe. This instrument is factory calibrated for power frequencies (50/60 Hz), and is only sensitive to frequencies in the 30 Hz-100 kHz range. With the 100x probe it is capable of measuring levels down to 0.001 milligauss / 0.1 nanoTesla. Since the probe is directional, three measurements must be taken at each location: two perpendicular horizontal measurements and one vertical one. The highest reading was recorded.

The probe is so sensitive that it must be steadied or placed on the ground, as slight movements of the hand will influence the reading due to the earth's magnetic field.

The probe was not used when passing under the power line, as currents were too strong there. The movement of the car did not influence these readings.

The measurements at each mile marker were taken at least twenty feet (7 meters) from the vehicle, to avoid influences from the vehicle.

The instrument is low cost and not highly accurate, but it should provide a fair estimation of the levels and the extent to which the field reaches.

An alternative measuring method is to insert two round rods into the soil and measure the voltage difference. Standard ground rods are 8 ft (2.5 m) long in this area, due to the poor contact with the dry sandy soil. Installing these long ground rods would have been expensive and difficult to obtain permission for. This method is probably also less accurate, as it assumes any current induced in the soil is uniformly distributed vertically, which is highly unlikely.

Results

A total of seven series were recorded on different days over a two month period. No series were closer together than a week. The measurements were always started at mile marker 25, with the whole series taking about 45 to 60 minutes to complete.

The ground currents can be measured for several kilometers south of the transmission lines, most with readings at the edge of the meter's sensitivity. On the north side, the readings drop off more rapidly and reach zero within 3 km (2 miles).

One would have expected a more uniform reach of the ground currents on either side of the power lines. Perhaps the distance difference depends on geological differences, such as the water table, or the fact that the three transmission lines turn south along the eastern edge of the wide valley.

Date	**2/14/08**	**3/3/08**	**3/17/08**	**3/24/08**	**4/1/08**	**4/10/08**	**4/18/08**
MM 25	0	0	0	0.2	0	0.2	0.2
MM 30	0	0.1	0	0.2	0	0.2	0.4
MM 33	0	0	0	0.2	0.2	0.2	0.4
MM 34	0.2	0.2	0	0.2	0.2	0	0.3
MM 35	0.2	0.1	0	0.2	0.2	0-3.0	0.2
MM 36	0.2	0.1	0	0.4	0.2	0	0.2
MM 37	0.4	0.4	0.5	0.5	0.6	0.4	0.7
MM 38	30	30	13	40	6.0	11	11
below line	10,000	8,000	10,000	9,000	6,000	8,000	8,000
MM 39	1.4	0.6	1.2	1.0	0.8	1.2	1.3
MM 40	130	40	50	60	50	80	100
below lines*	11,000	12,000	12,000	12,000	12,000	12,000	12,000
MM 41	0.4	3.5	3.5	3.0	2.8	3.0	3.3
MM 42	0.2	0.2	0	0.2	0	0	0.3
MM 43	0.2	0	0	0	0	0	0.2
Comment			wet soil, morning			variable at MM 35	

** Estimated values*

All numbers in nano tesla (nT). 1 nT = 0.001 uT = 0.01 milligauss.

The ground currents from the local distribution line (between Dolan Springs and Meadview) three miles to the north may simply negate the fields from the transmission lines. This could possibly happen if the two sets of ground currents happen to be out of phase by 180 degrees, or nearly so. Or if the current runs in opposite directions, as they may do in this case.

The three transmission lines are also unlikely to be in phase with each other.

The period of measurement was very dry. Rain fell eleven days prior to the first measurements on February 14. The only precipitation during the period was on March 16, the evening before one series of measurements was taken. A light snowfall took place that evening. The snow still covered some parts of the area the next day, from mile marker 36 to the northern transmission lines at mile marker 40. The snow was melting and the soil was wet during the measurements on the morning of March 17.

The wet soil appears to make the ground currents drop off much more rapidly, both on the north and south sides of the transmission lines. However, one has to be very careful with any conclusions, since there is only one case series. This series was also the only one done in the morning, while the rest were done in the afternoon. It was done in the morning as the soil might have become dry by the afternoon.

A curious and unique observation was made at mile marker 35 on April 10, between 5:30 and 5:40 p.m. All other measurements in this entire study had shown a steady reading, but in this single instance the reading varied greatly.

The meter showed a slow increase from zero to a high point, then a very rapid fall back to zero again, before again slowly rising. The entire cycle lasted a couple of seconds, reaching a maximum value of between 1 nT and 3 nT. The most common max value was 1 nT.

The author spent extra time at the next locations (mile markers 36 and 37), but no fluctuations were observed. Nor was this fluctuation observed at any other time, including at mile marker 35.

Mile marker 35 on the western edge of Red Lake, a dry lake.
[Picture not taken on April 10]

The instrument was in perfect condition. There were no observable changes in the area, nothing that could be seen to explain the readings. It is unlikely to be an artifact, though these measurements were the only ones conducted so late in the afternoon.

Discussion

The measured values do not show the rapid drop-off that could be expected from a simple line source. Instead of the expected reduction to ¼ when the distance is doubled, a more linear reduction is observed when further away than a couple of kilometers.

Currents running in the soil itself must be a part of the explanation, as ground currents (also called stray voltage) can travel widely from the source. Radiation from a plane also falls off much more slowly, with just a factor of 2 with a doubling of the distance.

It does not appear possible that the currents originate from the power lines' neutral wires, as they should never carry a current (unlike distribution lines). Instead, the current must be induced in the soil by the high voltage lines.

The method used is very simple and only gives a snapshot of what can vary over time. It took nearly an hour to complete a series, during which the loading of the power lines could have changed, though the readings passing under them were rather stable. The time of day may influence the readings some, as the electrical consumption does vary across the day. The measurements were taken in the early spring which probably does not see as great a daily variation as the hot season does, when the air conditioners are run hard in Phoenix and California.

Higher readings would possibly be observed during hot summer afternoons, when the annual power consumption would be at its annual high.

A change in the depth of the current can affect the readings on the surface, making the actual readings an unreliable method to determine the actual amount of electricity running in the soil.

The EMF levels recorded are far below those typically found in cities, and below ambient levels in rural areas with standard grid connections.

Only one incidence of precipitation occurred during the measurement period. More such incidents will be needed to look at the effects of wet soil on the ground currents, though the one incidence suggests a dramatic effect. The conductivity of the soil is probably improved, perhaps causing the electricity to run closer to the pylons.

The author cannot venture a guess as to the nature of the curiously varying field at mile marker 35. This event would possibly not have been observed had automated equipment been used, unless the resolution in time was very fine.

Automated equipment would otherwise produce a more rich set of information about the variations of the ground currents over time, and perhaps over the daily cycle. However, this study does show that induced ground currents do consistently travel at great distances on both sides of transmission lines, at least in dry sandy and rocky soil. It would be interesting to repeat the study in other climates and soils with different conductivity.

The author does not see that other sources could have produced these readings, such as the earth's static field, distant radio transmitters or solar storms. The static field is eliminated by keeping the probe stationary. Solar storms would have affected readings at all locations. There were no thunderstorms in the area during any measurements. There were no radio transmitters of any kind for at least a dozen miles from any of the locations, and the meter is not affected by those frequencies.

The author has observed similar readings around a pair of 500 kV lines in a rural area in northeastern Arizona. They pass through areas with no other power lines, though the area is lightly populated with households producing their own electricity using solar panels.

Conclusion

The measured values show magnetic fields several kilometers from large transmission lines, much further than was expected. There were no other sources that could explain the readings, which also were consistent over time.

The conductivity of the soil appears to be very significant in how far away the magnetic fields can be measured.

The measured values were very low at distances of more than a mile from the lines. Here, the readings were almost always below 1 nanoTesla (0.01 milligauss). This compares with a common ambient reading of 10 nanoTesla in suburbia (measured in yards, away from all wires, lines, etc.).

The author is an engineer and lives in rural Arizona.

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Appendix

The magnetic field from a three-phase power line by Ragnar Forshufvud.

If you want to describe the intensity of a magnetic field in air, you generally use the *magnetic flux density* and the unit nanotesla (nT). 1000 nanotesla equal one microtesla (µT), and 100 microtesla equal one gauss, an older unit.

The flux density around a straight wire of infinite length is $200\ I/x$ nanotesla, where I is the current through the wire in amps, and x is the distance from the wire in meters.

The magnetic field under a 3-phase power line is quite complicated, because there is a phase shift of 120 degrees between any two of the three currents. If you walk perpendicularly to the direction of the wires, then amplitude, phase, and direction of the field will all change rapidly. But if you keep walking, away from the power line, the phase will more and more be determined by the current in the nearest wire, the direction of the field will be more and more vertical, and the amplitude will approach B in the following formula:

$$B = 200 \cdot 3^{0,5} \cdot I\, a\, x^{-2} = 346\, I\, a\, x^{-2} \text{ nanotesla}$$

where I is the phase current, a is the distance between wires and x is the distance from the center wire.

To explain how I worked out this formula would require too much space. But to test its validity, I calculated the exact flux density, assuming the current I = 1000 amps and the distance between wires $a = 17$ meters. The error of the approximate formula turned out to be 1.7 percent at $x = 100$ m and 0.2 percent at $x = 1000$ m.

Please note that all calculations are based on the assumption that the currents are sinusoidal (no harmonics).

It is interesting to compare measured values with those calculated theoretically. Minor deviations may be caused by the field from the two northern lines, 2 miles further to the north. **Major deviations, especially far from the line, indicate the presence of a secondary magnetic field from induced currents in the ground.** The values most suitable for comparing with calculations are those measured south of the southern line. The total field produced by the two northern lines cannot be calculated, as the relative phase angles are unknown. If you superimpose two AC fields of the same frequency but with unknown phase difference, the resulting field may be anything between the sum and the difference of the two fields.

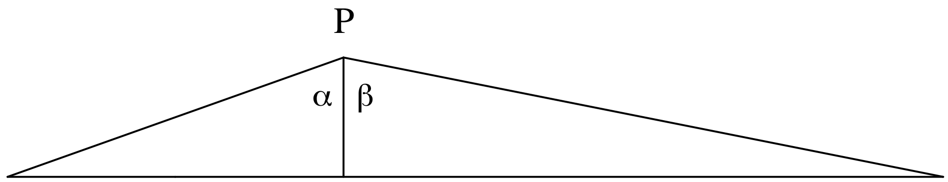
I calculated the flux density right under a 3-phase power line, assuming I = 1000 amps and the height of the wires above the measuring device = 22 meters. The result was 8300 nanotesla, in reasonable agreement with values measured under the southern line. Of course, the current is never exactly 1000 amps and the height probably not 22 meters, but the order of magnitude is right. If the current is 1000 amps, the following flux density values could be expected if there were no currents in the ground:

Measuring point	Distance from power line, miles	Flux density, nanotesla
MM25	13.2	0
MM30	8.2	0
MM33	5.2	0.1
MM34	4.2	0.1
MM35	3.2	0.2
MM36	2.2	0.5
MM37	1.2	1.6

In a medium of good conductivity (and immediately above this medium) induced currents may outbalance the primary field almost completely. This may explain the low magnetic field at the 17th of March, when the soil was wet. When the soil is dry, the current may follow underground streams, which may cause the field pattern to be irregular. In some places the primary field may be outbalanced, in other places the secondary field will add to the primary field. Lenz's law says that an induced current is always in such a direction as to oppose the motion or change causing it, but this does not mean that the primary field will be outbalanced or weakened in every point. When a current is induced in a wire or other narrow conductor, or in a non-homogeneous medium, the field may be magnified locally.

What may the order of magnitude of the ground currents be? If we measure a certain flux density above the ground, what does that tell us about the current density in the ground below? Unfortunately, due to the irregular and unknown distribution of ground conductivity, exact calculations are not possible. But to get a broad idea of the orders of magnitude involved, I calculated the flux density above a plane current sheet, 1 kilometer wide and carrying a current of 1 ampere. I found the flux density to be 0.63 nanotesla.

The horizontal flux density in a point P above a current sheet with current density i amps/meter is 200 i ($\alpha+\beta$) nanotesla, where the angles α and β are expressed in radians. There is also a vertical component, but it can generally be neglected, except close to the limits of the current sheet.



Whenever α and β are both close to $\pi/2$, the horizontal flux density is approximately 200 $i\,\pi$ nanotesla.