Thesis Title: Investigation of Electromagnetic Field Radiation from High Voltage Transmission Lines. (Part 02: 2D Model Analysis - 400 kV Double Circuit System)
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Executive summary
This report presents a comprehensive 2D computational analysis of electromagnetic field (EMF) radiation from a 400 kV double-circuit high-voltage transmission line. The study employs the Charge Simulation Method (CSM) with the Method of Images for electric-field calculations and the Biot-Savart Law for magnetic-field calculations. Part 2 will focus on a 400 kV double-circuit transmission line using a 2D cross-sectional analysis perpendicular to the line direction. Instantaneous electric and magnetic field values are evaluated for a 50 Hz AC system. Measurements are taken horizontally from 0 to 50 meters. This report provides a comprehensive 2D computational analysis of electromagnetic field (EMF) radiation from a 400 kV double-circuit high-voltage transmission line. The study uses the Charge Simulation Method (CSM) with the Method of Images for electric-field calculations and the Biot-Savart Law for magnetic-field calculations.

Primary Works are:
1. To develop a 2D computational model of electromagnetic fields around a 400 kV transmission line.
2. To calculate electric field strength (V/m) at various distances and heights.
3. To calculate magnetic flux density (Tesla) in the vicinity of conductors.

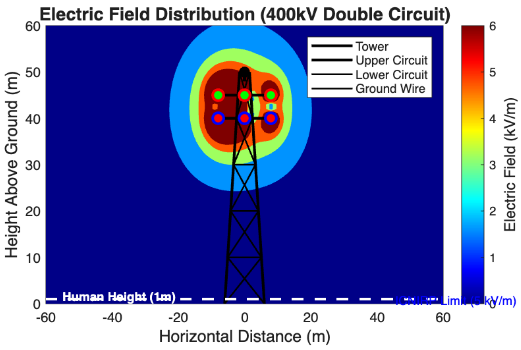
Transmission Line Parameters

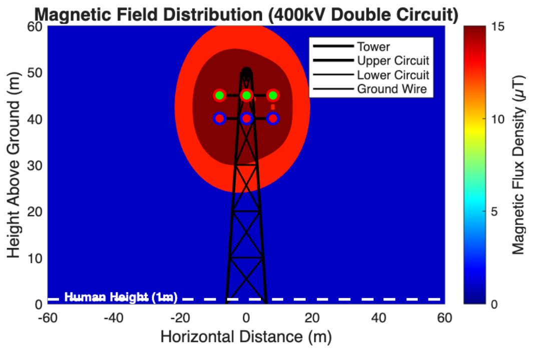
The 400 kV double-circuit transmission line considered in this study operates with a line-to-line voltage of 400 kV and a corresponding phase voltage of 230.9 kV, carrying phase currents of 500 A, 750 A, and 1000 A at a standard system frequency of 50 Hz. The line employs six ACSR-equivalent conductors, representing three phases per circuit, arranged in a vertical double-circuit configuration. Each conductor has an equivalent bundled radius of 15 mm, selected to balance electrical performance with mechanical strength. The towers supporting the line are self-standing lattice steel structures with an overall height of 50 meters, designed with a tapered profile that narrows from a 12-meter base width to a 3-meter width at the top. The upper and lower circuits are placed at heights of 45 m and 40 m above the ground, respectively, maintaining a vertical clearance of 5 m between them. Both circuits adopt a symmetrical horizontal phase spacing of 8 m, with Phases A, B, and C positioned at −8 m, 0 m, and +8 m on each cross-arm. A ground wire is installed at the peak of the tower at a height of 50 m to ensure adequate shielding from lightning. This configuration provides a balanced and reliable structural–electrical arrangement suitable for high-voltage transmission applications.

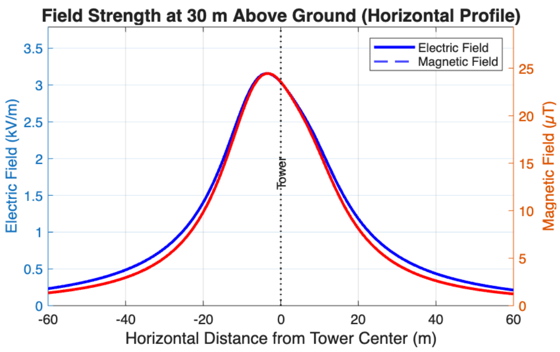
Graph Coordinate System: In this setup, the transmission line layout is described using a simple two-dimensional coordinate system. The starting point, or origin, is placed on the ground directly under the center of the tower. From there, the vertical **Y-axis** goes upward to show how high different parts of the structure are above the ground, while the horizontal **X-axis** extends to the left and right to show how far each conductor is from the tower's center. Positions to the right are marked as positive, and those to the left are marked as negative. This straightforward system facilitates visualization of tlocationshe visualize of each conductor and tower element.

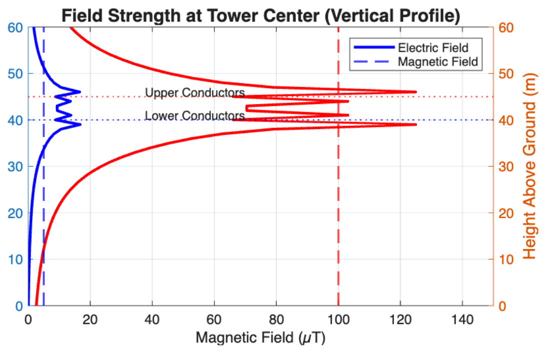
Comparative Analysis

At height 30m, 1000A:







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----------------------------------------
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 1000 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 30m height (center): 3.04 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 245.90 µT
  At ground (center): 2.60 µT
  At 30 height (center): 23.56 µT
  ICNIRP Limit: 100 µT
========================================
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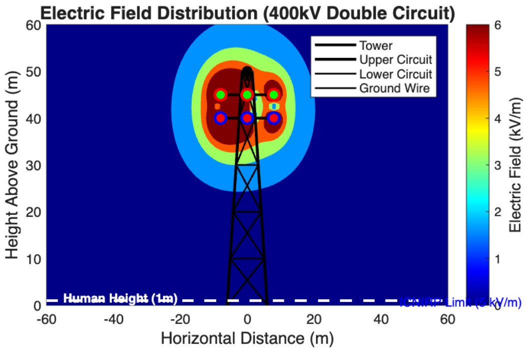
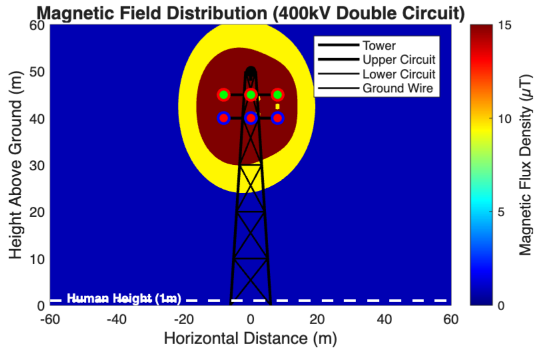
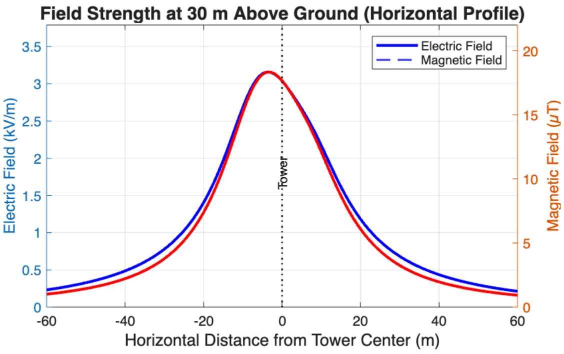
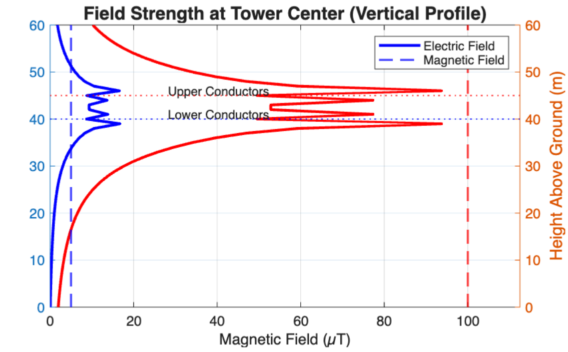
These results describe the electromagnetic environment around a 400 kV double-circuit tower with 1000 A per phase, using both heatmaps and line profiles. The top heatmaps show how the electric and magnetic fields surround the tower in 2D: the colored “bubbles” around the conductors indicate where the fields are strongest, with colors changing from blue (low) through green/yellow to red (high) as the field increases. In the electric-field heatmap the maximum value, about 33 kV/m, occurs very close to the phase wires, while at ground level under the tower the field is only about 0.04 kV/m, far below the ICNIRP public limit of 5 kV/m. In the magnetic-field heatmap the peak is roughly 246 µT near the conductors, but the field falls to about 2.6 µT at ground and 23.6 µT at 30 m height, both well below the 100 µT public limit. The horizontal profile at 30 m height and the vertical profile at the tower centre confirm what the heatmaps suggest: fields rise sharply near the conductors and then drop off quickly with height and horizontal distance, so typical human exposure near ground remains very low.

At height 30m, 750A:









Command Window

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ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 750 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 30m height (center): 3.04 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 184.43 μT
  At ground (center): 1.95 μT
  At 30 height (center): 17.67 μT
  ICNIRP Limit: 100 μT
========================================
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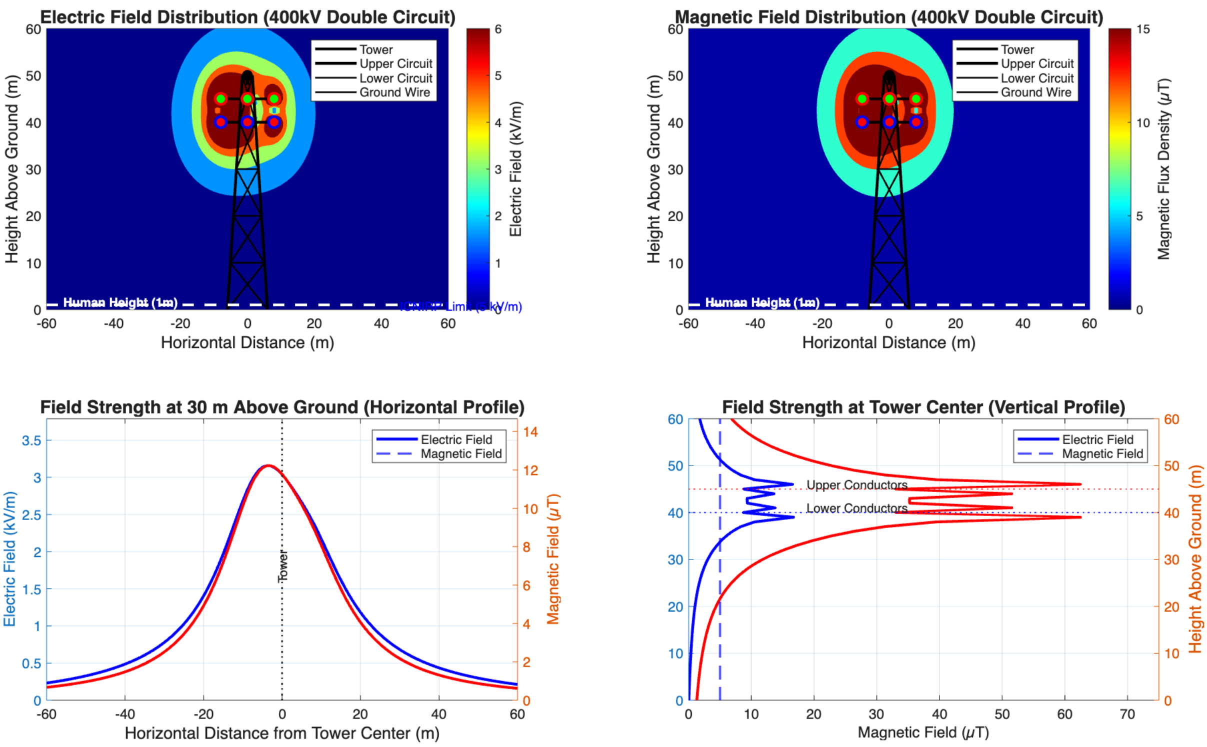
This figure and output summarise the electromagnetic fields for a 400 kV double-circuit line when the phase current is 750 A. The top heatmaps show the 2D distribution of electric and magnetic fields around the tower: in both cases the strongest fields form a coloured “halo” around the conductors between about 40 and 50 m height, while the ground region remains dark blue, indicating very low field levels . The analysis reports that the maximum electric field anywhere in the domain is about 32.95 kV/m, very close to the conductors, but at the tower centre it is only 0.04 kV/m at ground and 3.04 kV/m at 30 m height, compared with the ICNIRP public limit of 5 kV/m . Similarly, the maximum magnetic flux density is about 184.43 µT near the conductors, while at the tower centre it drops to 1.95 µT at ground and 17.67 µT at 30 m height, all well below the 100 µT ICNIRP public limit . The lower plots—horizontal profile at 30 m and vertical profile at the tower centre—confirm what the heatmaps show: both fields peak in the conductor region and decay rapidly with height and horizontal distance, so typical human exposure near ground remains far under international guideline values.

<u>At height 30m, 500A:</u>



Command Window

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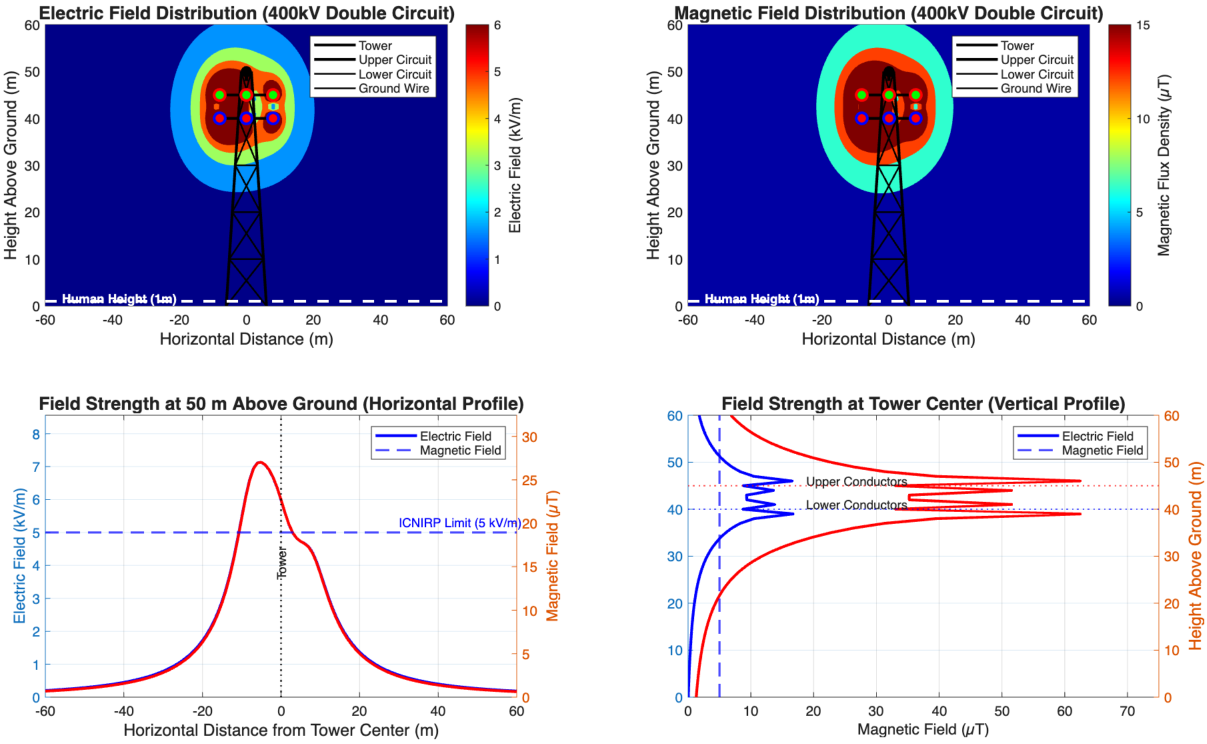
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 500 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 30m height (center): 3.04 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 122.95 µT
  At ground (center): 1.30 µT
  At 30 height (center): 11.78 µT
  ICNIRP Limit: 100 µT
========================================
```

This figure shows the electromagnetic field results for the same 400 kV double-circuit tower when the phase current is reduced to 500 A. The two heatmaps again display how the electric and magnetic fields surround the tower in space: the coloured halos around the conductors mark the strongest regions, while the area near the ground stays dark blue, indicating very low fields. The command-window output quantifies this. The maximum electric field anywhere in the domain is still about 32.95 kV/m, because it depends mainly on the 400 kV voltage and conductor geometry, not on current. At the tower centre the electric field is only 0.04 kV/m at ground and 3.04 kV/m at 30 m height, comfortably below the 5 kV/m ICNIRP public limit. The magnetic field, which scales with current, is lower than in the previous higher-current cases: the maximum value near the conductors is about 122.95 µT, while at the tower centre it is 1.30 µT at ground and 11.78 µT at 30 m height, all well under the 100 µT ICNIRP limit.

Lowering the current from 750–1000 A down to 500 A leaves the electric-field pattern unchanged but reduces all magnetic-field values roughly in proportion to the current, further increasing the safety margin for public exposure.

At height 50m, 500A:

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Command Window
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 500 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 50m height (center): 5.99 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 122.95 µT
  At ground (center): 1.30 µT
  At 50 height (center): 22.72 µT
  ICNIRP Limit: 100 µT
========================================
```
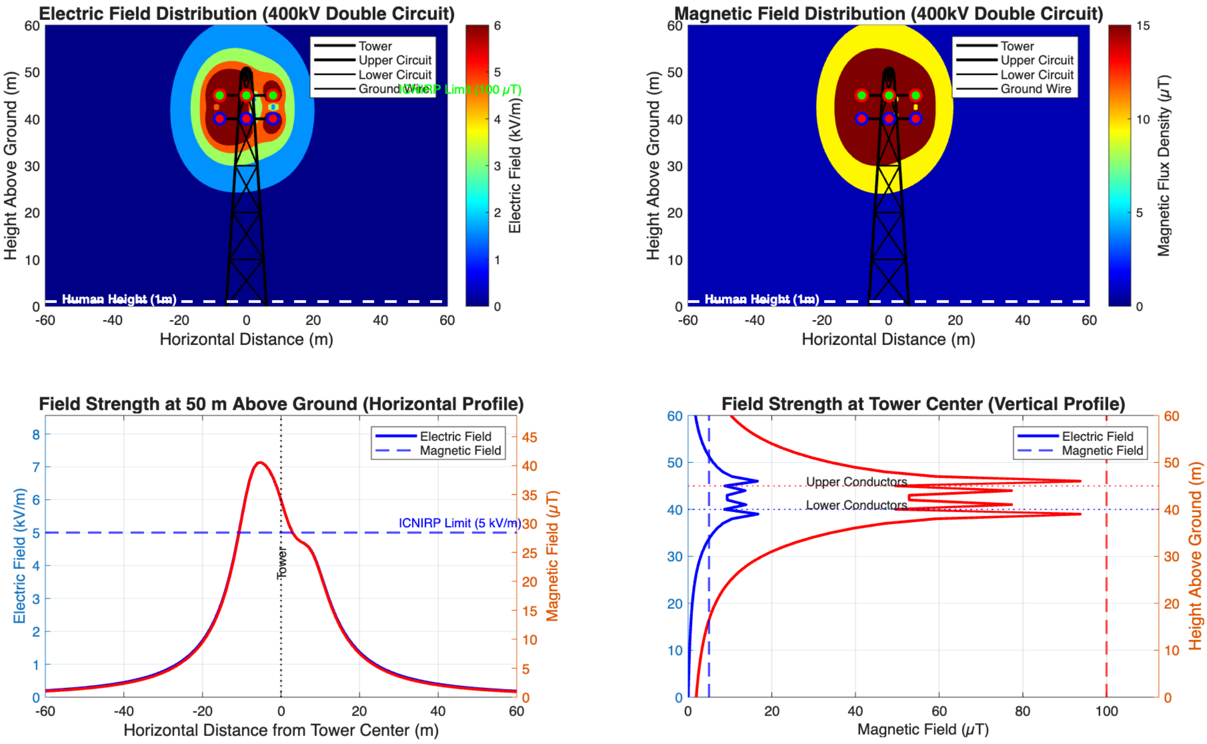

This figure shows the electric and magnetic fields around the 400 kV double-circuit tower at a phase current of 500 A, with a focus at a height of 50 m. The top heatmaps again display where the fields are strongest: both electric and magnetic fields form bright halos around the conductors between about 40 and 50 m height, while the ground region remains dark blue, meaning very low field levels. In the bottom-left plot the horizontal profile is taken at 50 m above ground, which passes slightly above the upper conductors, so the fields reach their maximum here: the electric field peaks at roughly 7 kV/m at the tower centre and the magnetic field at about 25–30 µT, then both decay rapidly as you move laterally toward ±60 m. The dashed horizontal line marks the ICNIRP public electric-field limit of 5 kV/m; the curve crosses this only in a narrow region very close to the tower, indicating that even at 50 m height the exceedance is small and confined near the conductors. The bottom-right vertical profile at the tower centre shows the same behavior with height: the magnetic field rises smoothly from near zero at ground to a maximum around the conductor region and then decreases above, while the electric field has sharp local peaks close to the upper and lower conductor levels and remains low at ground and well above the line.

At height 50m, 750A:

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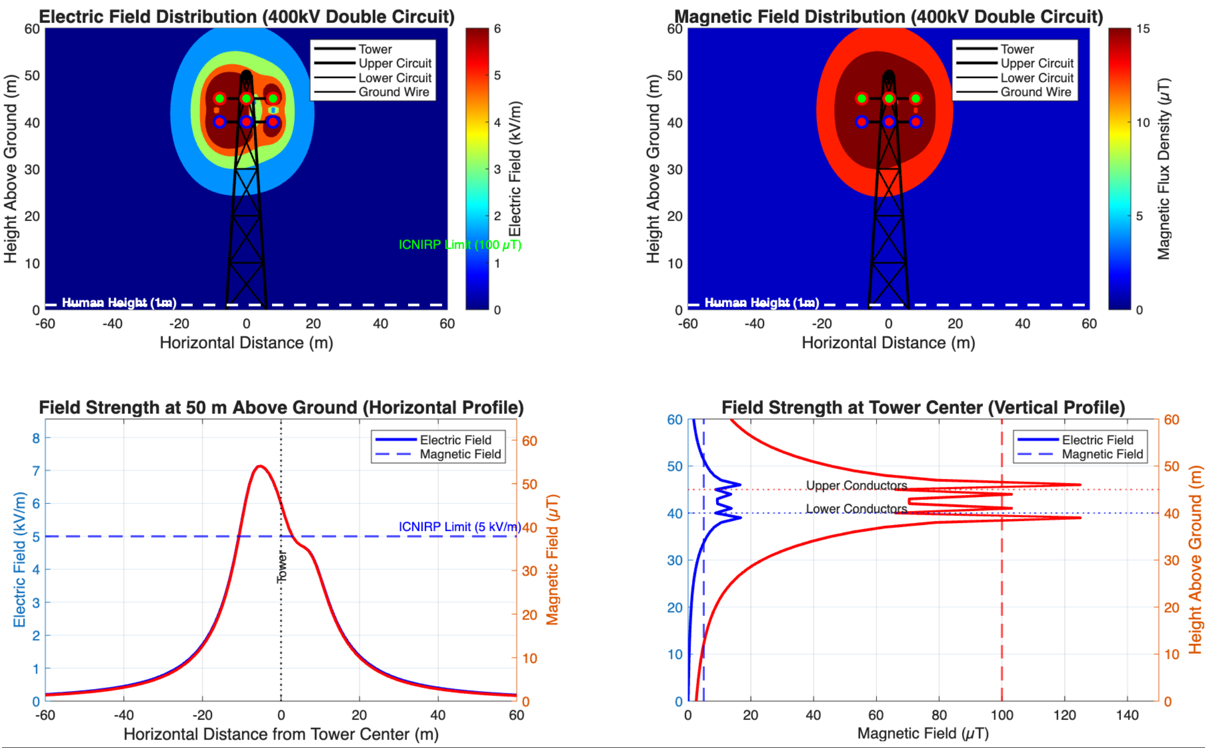
Command Window
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 750 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 50m height (center): 5.99 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 184.43 µT
  At ground (center): 1.95 µT
  At 50 height (center): 34.08 µT
  ICNIRP Limit: 100 µT
========================================
```

This figure presents the 400 kV double-circuit tower results for a phase current of 750 A at a height of 50 m (near the conductor region). The heatmaps at the top show that both electric and magnetic fields are concentrated around the phase conductors between 40–50 m above ground, while the fields near ground remain very low. Numerically, the maximum electric field in the domain is about 32.95 kV/m, occurring close to the conductors, but at the tower centre it is only 0.04 kV/m at ground and 5.99 kV/m at 50 m height, slightly above the 5 kV/m ICNIRP public limit in a narrow region close to the line. For the magnetic field, the maximum near the conductors is about 184.43 µT, whereas at the tower centre it is 1.95 µT at ground and 34.08 µT at 50 m height, well below the 100 µT ICNIRP limit. The lower horizontal and vertical profiles confirm this behaviour: both fields peak around the conductor heights and drop off rapidly with horizontal distance and with height above the line, so significant exceedance of the electric-field limit occurs only very close to the conductors, while typical ground-level exposure remains far within safety guidelines.

<u>At height 50m, 1000A:</u>

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Command Window
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 1000 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 50m height (center): 5.99 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 245.90 µT
  At ground (center): 2.60 µT
  At 50 height (center): 45.44 µT
  ICNIRP Limit: 100 µT
========================================
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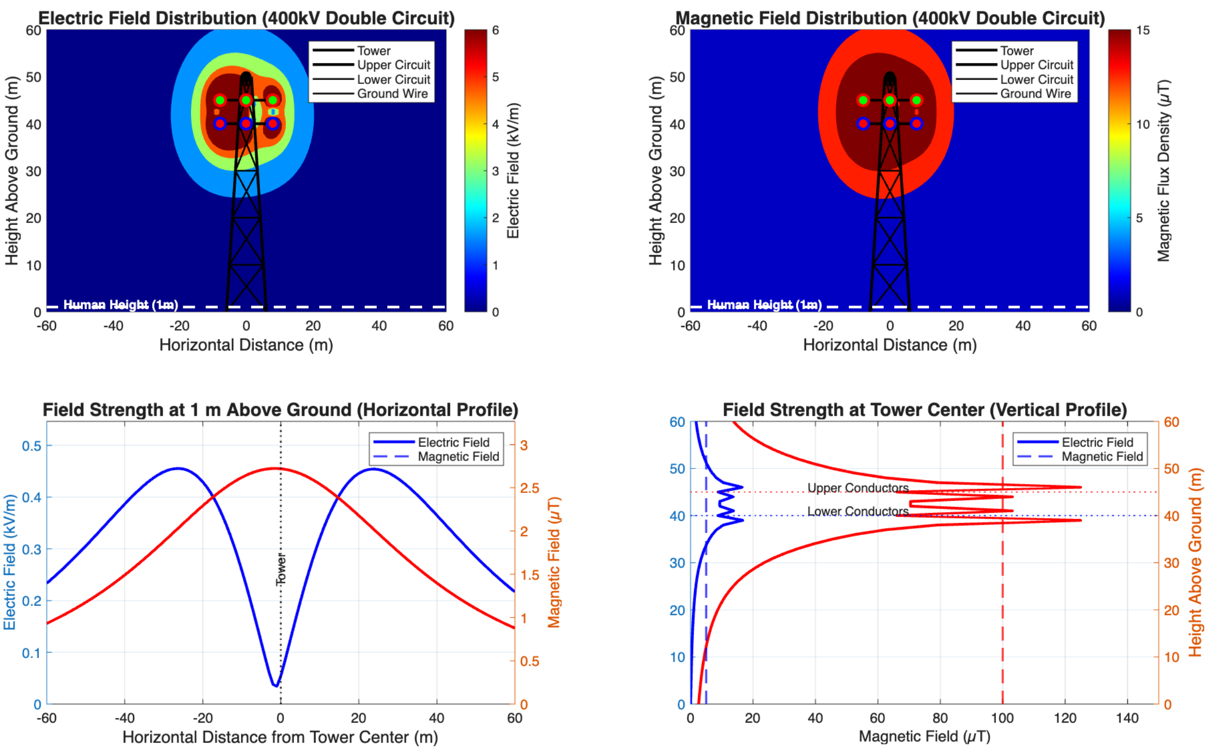
At 50 m height (just above the upper conductors) the fields around the 400 kV double-circuit tower are strongest, and the three cases (500 A, 750 A, 1000 A) mainly differ in the magnetic field, which scales with current. For 1000 A, the heatmaps show the same electric-field pattern as before, with a maximum of about 32.95 kV/m near the conductors and only 0.04 kV/m at ground, but the horizontal profile at 50 m gives about 5.99 kV/m at the tower centre, slightly exceeding the 5 kV/m ICNIRP limit in a narrow region, while the magnetic field reaches a maximum of about 245.9 µT, with 2.60 µT at ground and 45.44 µT at 50 m, still below the 100 µT limit. For 750 A, the electric field is identical (same 32.95 kV/m maximum; 5.99 kV/m at 50 m centre; 0.04 kV/m at ground), but the magnetic field is lower in direct proportion to current: the maximum is about 184.43 µT, with 1.95 µT at ground and 34.08 µT at 50 m. For 500 A, again the electric field is unchanged, but the magnetic-field maximum drops further to about 122.95 µT, and at the tower centre it is only 1.30 µT at ground and 11.78 µT at 50 m.

In summary: changing the phase current from 500 → 750 → 1000 A does not affect the electric-field distribution (voltage-controlled), but increases all magnetic-field values roughly linearly, while in all three cases ground-level fields remain far below the ICNIRP public limits.

<u>At height 1m, 1000A:</u>



Command Window

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ELECTROMAGNETIC FIELD ANALYSIS RESULTS
======================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 1000 A
--------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 1m height (center): 0.05 kV/m
  ICNIRP Limit: 5.0 kV/m
--------------------------------------
MAGNETIC FIELD:
  Maximum: 245.90 µT
  At ground (center): 2.60 µT
  At 1m height (center): 2.72 µT
  ICNIRP Limit: 100 µT
======================================
```
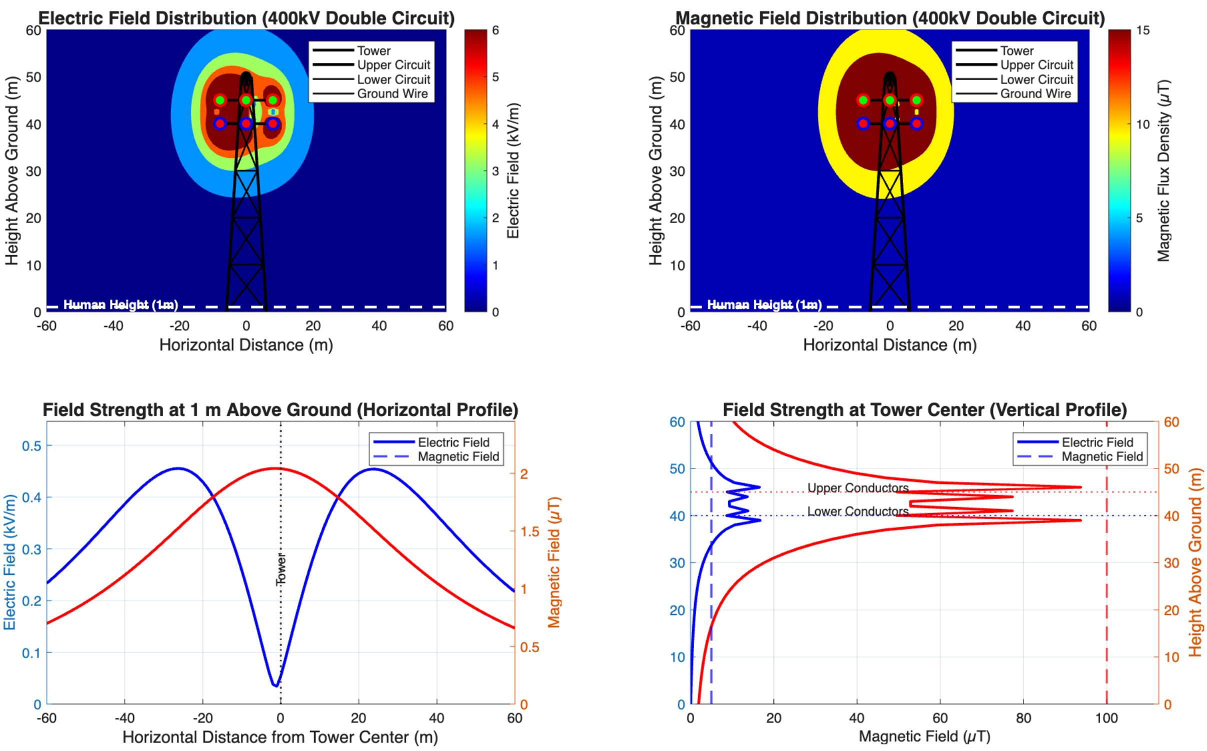

This figure presents the electromagnetic fields around the 400 kV double-circuit tower for a phase current of 1000 A, evaluated at 1 m above ground, which represents typical human height. The heatmaps in the top row show that both the electric and magnetic fields are concentrated around the conductors at 40–50 m height, while the region near the ground (highlighted by the dashed "Human Height (1 m)" line) remains dark blue, meaning very low field levels. Numerically, the command-window output reports that the maximum electric field anywhere in the domain is about 32.95 kV/m, occurring very close to the conductors, but at the tower centre it is only 0.04 kV/m at ground and 0.05 kV/m at 1 m height, which is far below the 5 kV/m ICNIRP public limit. For the magnetic field, the peak value near the conductors is approximately 245.90 µT, while at the tower centre it is 2.60 µT at ground and 2.72 µT at 1 m height, again well below the 100 µT ICNIRP limit. The bottom-left horizontal profile at 1 m shows that both electric and magnetic fields have small, smooth variations across –60 to +60 m, with a slight dip in electric field directly under the tower and shallow peaks around ±20–30 m, but all values stay under about 0.5 kV/m and 3 µT. The bottom-right vertical profile confirms that field strengths rise sharply only near the conductor region and remain very low at ground level, demonstrating that public exposure at 1 m height is comfortably within international safety guidelines even for the highest current case.

At height 1m, 750A:

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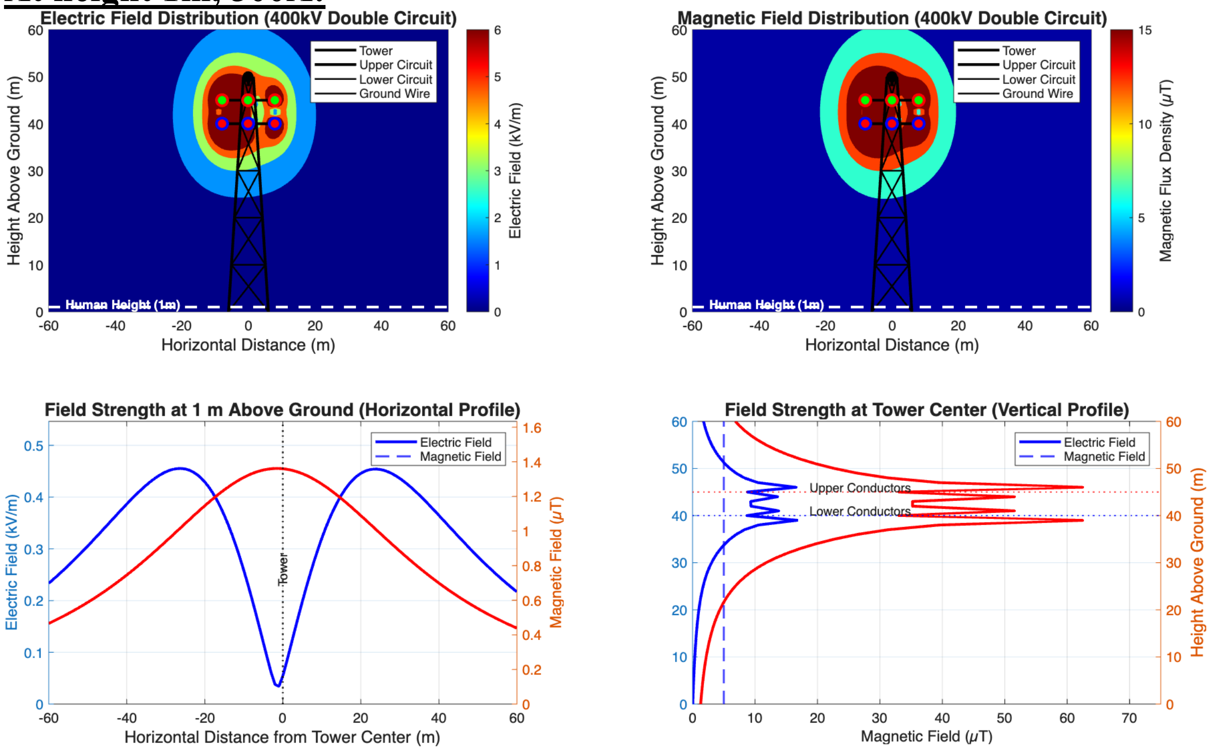
Command Window
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 750 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 1m height (center): 0.05 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 184.43 µT
  At ground (center): 1.95 µT
  At 1m height (center): 2.04 µT
  ICNIRP Limit: 100 µT
========================================
```

his figure shows the electromagnetic fields around the 400 kV double-circuit tower for a phase current of 750 A, evaluated at 1 m above ground, representing human height. The upper heatmaps indicate that both electric and magnetic fields are concentrated around the conductors between 40–50 m height, while the 1 m line along the ground remains in the dark-blue region, meaning very low fields. The numerical results report that the maximum electric field in the whole domain is 32.95 kV/m, but at the tower centre it is only 0.04 kV/m at ground and 0.05 kV/m at 1 m height, which is far below the 5 kV/m ICNIRP public limit. For the magnetic field, the maximum near the conductors is 184.43 µT, while at the tower centre it is 1.95 µT at ground and 2.04 µT at 1 m height, safely below the 100 µT limit. The lower-left horizontal profile at 1 m shows small variations in both fields across −60 to +60 m: the electric field dips slightly directly under the tower and peaks around ±20–30 m at about 0.45 kV/m, and the magnetic field peaks at the centre at about 2 µT and decreases gradually sideways. The lower-right vertical profile confirms that field strengths become significant only close to the conductor region, while they remain very low at human height, demonstrating that public exposure is comfortably within international guidelines for this current level.

At height 1m, 500A:

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Command Window
ELECTROMAGNETIC FIELD ANALYSIS RESULTS
========================================
Transmission Line: 400 kV Double Circuit
Tower Height: 50.0 m
Conductor Height (Upper): 45.0 m
Conductor Height (Lower): 40.0 m
Phase Current: 500 A
----------------------------------------
ELECTRIC FIELD:
  Maximum: 32.95 kV/m
  At ground (center): 0.04 kV/m
  At 1m height (center): 0.05 kV/m
  ICNIRP Limit: 5.0 kV/m
----------------------------------------
MAGNETIC FIELD:
  Maximum: 122.95 µT
  At ground (center): 1.30 µT
  At 1m height (center): 1.36 µT
  ICNIRP Limit: 100 µT
========================================
```

At 1 m above ground, this figure shows that the 400 kV double-circuit line produces very low fields even for the lowest current case of 500 A. The heatmaps at the top indicate that both electric and magnetic fields are concentrated around the conductors at 40–50 m height, while the 1 m “human height” line along the ground remains dark blue, meaning minimal exposure. The numerical results give a maximum electric field in the domain of 32.95 kV/m, but at the tower centre it is only 0.04 kV/m at ground and 0.05 kV/m at 1 m height, which is far below the 5 kV/m ICNIRP public limit. The magnetic field peaks near the conductors at 122.95 µT, while at 1 m height at the centre it is only 1.36 µT (and **1.30 µT at ground), well under the 100 µT limit. The bottom-left horizontal profile shows small variations across the corridor: the electric field has gentle peaks of about 0.45 kV/m at roughly ±25 m from the tower and a shallow minimum under the tower, while the magnetic field peaks at the centre at about 1.3–1.4 µT and decreases slowly with distance.

For the last three cases at 1 m height (500 A, 750 A, 1000 A), the electric field is essentially identical because it depends only on the 400 kV voltage and geometry: in all three, the maximum is 32.95 kV/m, and at the tower centre kV/m at ground and at 1 m. The magnetic field scales nearly linearly with current:

- At 500 A, µT, and µT at 1 m.
- At 750 A, µT, and µT at 1 m.
- At 1000 A, µT, and µT at 1 m.

So increasing current from 500 → 750 → 1000 A multiplies all magnetic-field values, but even the highest case remains far below 100 µT, while ground-level electric fields stay two orders of magnitude below 5 kV/m.

Overall Summary:

Across all graphs and heatmaps, the main message is that this 400 kV double-circuit line creates strong fields only very close to the conductors, while the fields where people can stand remain low and safely within international limits.

At every current level (500, 750, and 1000 A), the electric field pattern is almost the same because it is set mainly by the 400 kV voltage and the tower geometry, not by the load current. The absolute maximum electric field in the model is about 32.95 kV/m right next to the conductors, but this is a region that is not accessible in practice. At the tower centre the electric field is only about 0.04–0.05 kV/m at ground and at 1 m height, around 3 kV/m at 30 m height, and roughly 6 kV/m at 50 m height. This means the public reference level of 5 kV/m is never exceeded at ground level and is crossed only in a narrow zone close to the line around 50 m height.

The magnetic field behaves differently: it scales almost linearly with the phase current. Near the conductors the maximum field is about 123 µT for 500 A, 184 µT for 750 A, and 246 µT for 1000 A. However, at 1 m height directly under the line, the corresponding values are only about 1.36 µT, 2.04 µT, and 2.72 µT, which is still far below the 100 µT public guideline. The horizontal profiles show that both electric and magnetic fields are highest directly under, or slightly beside, the tower and then fall away quickly as you move beyond about 30–40 m from the centre. The vertical profiles confirm that the fields rise sharply as you approach the conductor region around 40–50 m and then weaken again above it.

Put simply, the simulations show that even for the highest current case, everyday exposure at ground level (around 1 m height and within 0–60 m of the tower) is much lower than the ICNIRP limits for both electric and magnetic fields. The only locations where the fields come close to or slightly exceed the electric-field limit are very close to the conductors at high elevation, where the public does not have access.

Electric and Magnetic Field Levels at Different Heights and Load Currents (summary):

EMF Analysis Table					
Current (A)	Height (m)	Electric Field (kV/m)	ICNIRP Limit (kV/m)	MAGNETIC FIELD (µT)	ICNIRP Limit (µT)
1000	1	0.05	5	2.72	100
1000	15	0.61	5	6	100
1000	30	3.04	5	23.56	100
1000	50	5.99	5	45.44	100
750	1	0.05	5	2.04	100
750	15	0.61	5	4.5	100
750	30	3.04	5	17.67	100
750	50	5.99	5	34.08	100
500	1	0.05	5	1.36	100
500	15	0.61	5	3	100
500	30	3.04	5	11.78	100
500	50	5.99	5	22.72	100

Final Remarks: The EMF analysis table summarizes how the electric and magnetic fields vary with both height and current for the 400 kV double-circuit line, and compares these values directly with the ICNIRP public reference levels. At all three load currents considered (500, 750, and 1000 A), the electric field depends mainly on the line voltage and tower geometry, so its values are identical for a given height: about 0.05 kV/m at 1 m, 0.61 kV/m at 15 m, 3.04 kV/m at 30 m, and 5.99 kV/m at 50 m, while the ICNIRP limit remains 5 kV/m at every height . This means that the electric field stays well below the guideline up to 30 m, and only slightly exceeds 5 kV/m at 50 m, very close to the conductors, where public access is not expected . In contrast, the magnetic field scales linearly with current: for 1000 A it increases from 2.72 µT at 1 m to 45.44 µT at 50 m, for 750 A from 2.04 to 34.08 µT, and for 500 A from 1.36 to 22.72 µT over the same height range, all compared against a constant ICNIRP reference level of 100 µT . These results show that even in the worst case (1000 A at 50 m) the magnetic field reaches only about half of the public limit, while at typical human heights near the ground it is less than 3 µT for all loading conditions.

Appendix:

```
clear all; close all; clc;


% Electrical Parameters
V_line = 400e3;                     % Line voltage (V) - 400 kV
V_phase = V_line / sqrt(3);         % Phase voltage (V)
I_phase = 1000;                     % Phase current (A)
frequency = 50;                     % Frequency (Hz)
omega = 2 * pi * frequency;         % Angular frequency (rad/s)\

% Physical Constants
eps_0 = 8.854e-12;                  % Permittivity of free space (F/m)
mu_0 = 4 * pi * 1e-7;               % Permeability of free space (H/m)

% Tower and Conductor Geometry (400 kV Double Circuit Tower)
tower_height = 50;                  % Tower height (m)
tower_base_width = 12;              % Tower base width (m)
tower_top_width = 3;                % Tower top width (m)

% Conductor positions (x, y coordinates in meters)
h_conductor = 45;                   % Conductor height above ground (m)
h_lower = 40;                       % Lower cross-arm height (m)
h_upper = 45;                       % Upper cross-arm height (m)

% Phase conductor positions (Double circuit - vertical configuration)
spacing_horizontal = 8;             % Horizontal spacing (m)

% Upper cross-arm conductors (Circuit 1)
x_a1 = -spacing_horizontal; y_a1 = h_upper;      % Phase A - Circuit 1
x_b1 = 0;                   y_b1 = h_upper;      % Phase B - Circuit 1
x_c1 = spacing_horizontal;  y_c1 = h_upper;      % Phase C - Circuit 1

% Lower cross-arm conductors (Circuit 2)
x_a2 = -spacing_horizontal; y_a2 = h_lower;      % Phase A - Circuit 2
x_b2 = 0;                   y_b2 = h_lower;      % Phase B - Circuit 2
x_c2 = spacing_horizontal;  y_c2 = h_lower;      % Phase C - Circuit 2

r_conductor = 0.015;                % Conductor radius (m)

% Ground wire position
h_ground_wire = tower_height;       % Ground wire at tower top (m)
x_ground_wire = 0;                  % Center position (m)



% Define calculation grid
x_min = -60; x_max = 60;            % Horizontal range (m)
y_min = 0; y_max = 60;              % Vertical range (m)
grid_spacing = 1;                   % Grid spacing (m)

x_range = x_min:grid_spacing:x_max;
y_range = y_min:grid_spacing:y_max;
[X, Y] = meshgrid(x_range, y_range);

% Initialize field arrays
E_x = zeros(size(X));
```

```
E_y = zeros(size(Y));
B_x = zeros(size(X));
B_y = zeros(size(Y));


fprintf('Calculating Electric Field...\n');

% Phase voltages at time t = 0 (instantaneous values)
V_a = V_phase * cos(0);              % Phase A at 0 degrees
V_b = V_phase * cos(-2*pi/3);        % Phase B at -120 degrees
V_c = V_phase * cos(2*pi/3);         % Phase C at 120 degrees

% Simplified charge calculation (line charge density)
% For infinite line charge: C ≈ 2*pi*eps_0 / ln(2h/r)
q_a1 = V_a * 2*pi*eps_0 / log(2*y_a1/r_conductor);
q_b1 = V_b * 2*pi*eps_0 / log(2*y_b1/r_conductor);
q_c1 = V_c * 2*pi*eps_0 / log(2*y_c1/r_conductor);

q_a2 = V_a * 2*pi*eps_0 / log(2*y_a2/r_conductor);
q_b2 = V_b * 2*pi*eps_0 / log(2*y_b2/r_conductor);
q_c2 = V_c * 2*pi*eps_0 / log(2*y_c2/r_conductor);

% Calculate electric field from each conductor and its image
for i = 1:numel(X)
    x_point = X(i);
    y_point = Y(i);

    min_dist = 0.5;     % Minimum distance threshold (m)

    % Circuit 1 - Phase A
    r_a1 = sqrt((x_point - x_a1)^2 + (y_point - y_a1)^2);
    r_a1_img = sqrt((x_point - x_a1)^2 + (y_point + y_a1)^2);
    if r_a1 > min_dist
        E_x(i) = E_x(i) + q_a1/(2*pi*eps_0) * ((x_point - x_a1)/r_a1^2 -
(x_point - x_a1)/r_a1_img^2);
        E_y(i) = E_y(i) + q_a1/(2*pi*eps_0) * ((y_point - y_a1)/r_a1^2 -
(y_point + y_a1)/r_a1_img^2);
    end

    % Circuit 1 - Phase B
    r_b1 = sqrt((x_point - x_b1)^2 + (y_point - y_b1)^2);
    r_b1_img = sqrt((x_point - x_b1)^2 + (y_point + y_b1)^2);
    if r_b1 > min_dist
        E_x(i) = E_x(i) + q_b1/(2*pi*eps_0) * ((x_point - x_b1)/r_b1^2 -
(x_point - x_b1)/r_b1_img^2);
        E_y(i) = E_y(i) + q_b1/(2*pi*eps_0) * ((y_point - y_b1)/r_b1^2 -
(y_point + y_b1)/r_b1_img^2);
    end

    % Circuit 1 - Phase C
    r_c1 = sqrt((x_point - x_c1)^2 + (y_point - y_c1)^2);
    r_c1_img = sqrt((x_point - x_c1)^2 + (y_point + y_c1)^2);
    if r_c1 > min_dist
        E_x(i) = E_x(i) + q_c1/(2*pi*eps_0) * ((x_point - x_c1)/r_c1^2 -
(x_point - x_c1)/r_c1_img^2);
        E_y(i) = E_y(i) + q_c1/(2*pi*eps_0) * ((y_point - y_c1)/r_c1^2 -
(y_point + y_c1)/r_c1_img^2);
    end
```

```
    % Circuit 2 - Phase A
    r_a2 = sqrt((x_point - x_a2)^2 + (y_point - y_a2)^2);
    r_a2_img = sqrt((x_point - x_a2)^2 + (y_point + y_a2)^2);
    if r_a2 > min_dist
        E_x(i) = E_x(i) + q_a2/(2*pi*eps_0) * ((x_point - x_a2)/r_a2^2 -
(x_point - x_a2)/r_a2_img^2);
        E_y(i) = E_y(i) + q_a2/(2*pi*eps_0) * ((y_point - y_a2)/r_a2^2 -
(y_point + y_a2)/r_a2_img^2);
    end

    % Circuit 2 - Phase B
    r_b2 = sqrt((x_point - x_b2)^2 + (y_point - y_b2)^2);
    r_b2_img = sqrt((x_point - x_b2)^2 + (y_point + y_b2)^2);
    if r_b2 > min_dist
        E_x(i) = E_x(i) + q_b2/(2*pi*eps_0) * ((x_point - x_b2)/r_b2^2 -
(x_point - x_b2)/r_b2_img^2);
        E_y(i) = E_y(i) + q_b2/(2*pi*eps_0) * ((y_point - y_b2)/r_b2^2 -
(y_point + y_b2)/r_b2_img^2);
    end

    % Circuit 2 - Phase C
    r_c2 = sqrt((x_point - x_c2)^2 + (y_point - y_c2)^2);
    r_c2_img = sqrt((x_point - x_c2)^2 + (y_point + y_c2)^2);
    if r_c2 > min_dist
        E_x(i) = E_x(i) + q_c2/(2*pi*eps_0) * ((x_point - x_c2)/r_c2^2 -
(x_point - x_c2)/r_c2_img^2);
        E_y(i) = E_y(i) + q_c2/(2*pi*eps_0) * ((y_point - y_c2)/r_c2^2 -
(y_point + y_c2)/r_c2_img^2);
    end
end

% Calculate electric field magnitude
E_magnitude = sqrt(E_x.^2 + E_y.^2);
E_kV_per_m = E_magnitude / 1000;     % Convert to kV/m

fprintf('Electric Field Calculation Complete.\n');
fprintf('Maximum Electric Field: %.2f kV/m\n', max(E_kV_per_m(:)));


fprintf('Calculating Magnetic Field...\n');

% Phase currents at time t = 0 (instantaneous values)
I_a = I_phase * cos(0);              % Phase A at 0 degrees
I_b = I_phase * cos(-2*pi/3);        % Phase B at -120 degrees
I_c = I_phase * cos(2*pi/3);         % Phase C at 120 degrees

% Calculate magnetic field from each conductor
for i = 1:numel(X)
    x_point = X(i);
    y_point = Y(i);

    min_dist = 0.5; % Minimum distance threshold (m)

    % Circuit 1 - Phase A
    r_a1 = sqrt((x_point - x_a1)^2 + (y_point - y_a1)^2);
    if r_a1 > min_dist
        B_mag_a1 = mu_0 * abs(I_a) / (2*pi*r_a1);
        B_x(i) = B_x(i) + B_mag_a1 * (-(y_point - y_a1)/r_a1) * sign(I_a);
        B_y(i) = B_y(i) + B_mag_a1 * ((x_point - x_a1)/r_a1) * sign(I_a);
```

```
    end

    % Circuit 1 - Phase B
    r_b1 = sqrt((x_point - x_b1)^2 + (y_point - y_b1)^2);
    if r_b1 > min_dist
        B_mag_b1 = mu_0 * abs(I_b) / (2*pi*r_b1);
        B_x(i) = B_x(i) + B_mag_b1 * (-(y_point - y_b1)/r_b1) * sign(I_b);
        B_y(i) = B_y(i) + B_mag_b1 * ((x_point - x_b1)/r_b1) * sign(I_b);
    end

    % Circuit 1 - Phase C
    r_c1 = sqrt((x_point - x_c1)^2 + (y_point - y_c1)^2);
    if r_c1 > min_dist
        B_mag_c1 = mu_0 * abs(I_c) / (2*pi*r_c1);
        B_x(i) = B_x(i) + B_mag_c1 * (-(y_point - y_c1)/r_c1) * sign(I_c);
        B_y(i) = B_y(i) + B_mag_c1 * ((x_point - x_c1)/r_c1) * sign(I_c);
    end

    % Circuit 2 - Phase A
    r_a2 = sqrt((x_point - x_a2)^2 + (y_point - y_a2)^2);
    if r_a2 > min_dist
        B_mag_a2 = mu_0 * abs(I_a) / (2*pi*r_a2);
        B_x(i) = B_x(i) + B_mag_a2 * (-(y_point - y_a2)/r_a2) * sign(I_a);
        B_y(i) = B_y(i) + B_mag_a2 * ((x_point - x_a2)/r_a2) * sign(I_a);
    end

    % Circuit 2 - Phase B
    r_b2 = sqrt((x_point - x_b2)^2 + (y_point - y_b2)^2);
    if r_b2 > min_dist
        B_mag_b2 = mu_0 * abs(I_b) / (2*pi*r_b2);
        B_x(i) = B_x(i) + B_mag_b2 * (-(y_point - y_b2)/r_b2) * sign(I_b);
        B_y(i) = B_y(i) + B_mag_b2 * ((x_point - x_b2)/r_b2) * sign(I_b);
    end

    % Circuit 2 - Phase C
    r_c2 = sqrt((x_point - x_c2)^2 + (y_point - y_c2)^2);
    if r_c2 > min_dist
        B_mag_c2 = mu_0 * abs(I_c) / (2*pi*r_c2);
        B_x(i) = B_x(i) + B_mag_c2 * (-(y_point - y_c2)/r_c2) * sign(I_c);
        B_y(i) = B_y(i) + B_mag_c2 * ((x_point - x_c2)/r_c2) * sign(I_c);
    end
end

% Calculate magnetic flux density magnitude
B_magnitude = sqrt(B_x.^2 + B_y.^2);
B_microTesla = B_magnitude * 1e6;    % Convert to μT

fprintf('Magnetic Field Calculation Complete.\n');
fprintf('Maximum Magnetic Field: %.2f μT\n', max(B_microTesla(:)));


fprintf('Generating visualizations...\n');

% Create figure with subplots
figure('Position', [100, 100, 1400, 900]);


subplot(2,2,1);
hold on; grid on; box on;
```

```matlab
% Plot electric field contour
contourf(X, Y, E_kV_per_m, 20, 'LineStyle', 'none');
colormap(gca, 'jet');
c1 = colorbar;
ylabel(c1, 'Electric Field (kV/m)', 'FontSize', 11);
caxis([0 min(6, max(E_kV_per_m(:)))]);

% Draw tower structure
draw_tower(tower_height, tower_base_width, tower_top_width, 'k', 2);

% Draw conductors
plot([x_a1, x_b1, x_c1], [y_a1, y_b1, y_c1], 'ro', 'MarkerSize', 8, ...
     'MarkerFaceColor', 'g', 'LineWidth', 2);
plot([x_a2, x_b2, x_c2], [y_a2, y_b2, y_c2], 'bo', 'MarkerSize', 8, ...
     'MarkerFaceColor', 'r', 'LineWidth', 2);
plot(x_ground_wire, h_ground_wire, 'ko', 'MarkerSize', 6, ...
     'MarkerFaceColor', 'k', 'LineWidth', 2);

% Add safety limit line
plot([x_min, x_max], [1, 1], 'w--', 'LineWidth', 2);
text(-55, 1.5, 'Human Height (1m)', 'Color', 'w', 'FontSize', 9,
'FontWeight', 'bold');

% Labels and formatting
xlabel('Horizontal Distance (m)', 'FontSize', 12);
ylabel('Height Above Ground (m)', 'FontSize', 12);
title('Electric Field Distribution (400kV Double Circuit)', 'FontSize',
13, 'FontWeight', 'bold');
xlim([x_min, x_max]);
ylim([y_min, y_max]);
legend('', 'Tower', 'Upper Circuit', 'Lower Circuit', 'Ground Wire',
'Location', 'northeast');

subplot(2,2,2);
hold on; grid on; box on;

% Plot magnetic field contour
contourf(X, Y, B_microTesla, 20, 'LineStyle', 'none');
colormap(gca, 'jet');
c2 = colorbar;
ylabel(c2, 'Magnetic Flux Density (μT)', 'FontSize', 11);
caxis([0 min(15, max(B_microTesla(:)))]);

% Draw tower structure
draw_tower(tower_height, tower_base_width, tower_top_width, 'k', 2);

% Draw conductors
plot([x_a1, x_b1, x_c1], [y_a1, y_b1, y_c1], 'ro', 'MarkerSize', 8, ...
     'MarkerFaceColor', 'g', 'LineWidth', 2);
plot([x_a2, x_b2, x_c2], [y_a2, y_b2, y_c2], 'bo', 'MarkerSize', 8, ...
     'MarkerFaceColor', 'r', 'LineWidth', 2);
plot(x_ground_wire, h_ground_wire, 'ko', 'MarkerSize', 6, ...
     'MarkerFaceColor', 'k', 'LineWidth', 2);

% Add safety limit line
plot([x_min, x_max], [1, 1], 'w--', 'LineWidth', 2);
text(-55, 1.5, 'Human Height (1m)', 'Color', 'w', 'FontSize', 9,
'FontWeight', 'bold');
```

```
% Labels and formatting
xlabel('Horizontal Distance (m)', 'FontSize', 12);
ylabel('Height Above Ground (m)', 'FontSize', 12);
title('Magnetic Field Distribution (400kV Double Circuit)', 'FontSize',
13, 'FontWeight', 'bold');
xlim([x_min, x_max]);
ylim([y_min, y_max]);
legend('', 'Tower', 'Upper Circuit', 'Lower Circuit', 'Ground Wire',
'Location', 'northeast');


subplot(2,2,3);
hold on; grid on; box on;

% Extract horizontal profile at 15 m height
y_profile = 15; % meters (human exposure height)
[~, y_idx] = min(abs(y_range - y_profile));
E_horizontal = E_kV_per_m(y_idx, :);
B_horizontal = B_microTesla(y_idx, :);

% Plot electric field
yyaxis left
plot(x_range, E_horizontal, 'b-', 'LineWidth', 2);
ylabel('Electric Field (kV/m)', 'FontSize', 11);
ylim([0 max(E_horizontal)*1.2]);
% ICNIRP safety limit
yline(5, 'b--', 'LineWidth', 1.5);
text(30, 5.3, 'ICNIRP Limit (5 kV/m)', 'Color', 'b', 'FontSize', 9);

% Plot magnetic field
yyaxis right
plot(x_range, B_horizontal, 'r-', 'LineWidth', 2);
ylabel('Magnetic Field (μT)', 'FontSize', 11);
ylim([0 max(B_horizontal)*1.2]);
% ICNIRP safety limit
yline(100, 'r--', 'LineWidth', 1.5);
text(30, 105, 'ICNIRP Limit (100 μT)', 'Color', 'g', 'FontSize', 9);

% Tower position indicator
xline(0, 'k:', 'LineWidth', 1.5);
text(0, max(B_horizontal)*0.5, 'Tower', 'FontSize', 9, 'Rotation', 90);

xlabel('Horizontal Distance from Tower Center (m)', 'FontSize', 12);
title('Field Strength at 15 m Above Ground (Horizontal Profile)',
'FontSize', 13, 'FontWeight', 'bold');
legend('Electric Field', 'Magnetic Field', 'Location', 'northeast');


subplot(2,2,4);
hold on; grid on; box on;

% Extract vertical profile at x = 0
x_profile = 0; % meters (tower center)
[~, x_idx] = min(abs(x_range - x_profile));
E_vertical = E_kV_per_m(:, x_idx);
B_vertical = B_microTesla(:, x_idx);

% Plot electric field
```

```matlab
yyaxis left
plot(E_vertical, y_range, 'b-', 'LineWidth', 2);
xlabel('Electric Field (kV/m)', 'FontSize', 11);
xlim([0 max(E_vertical)*1.2]);
% ICNIRP safety limit
xline(5, 'b--', 'LineWidth', 1.5);

% Plot magnetic field
yyaxis right
plot(B_vertical, y_range, 'r-', 'LineWidth', 2);
xlabel('Magnetic Field (μT)', 'FontSize', 11);
xlim([0 max(B_vertical)*1.2]);
% ICNIRP safety limit
xline(100, 'r--', 'LineWidth', 1.5);

% Conductor height indicators
yline(h_lower, 'b:', 'LineWidth', 1);
text(max(B_vertical)*0.3, h_lower+1, 'Lower Conductors', 'FontSize', 9);
yline(h_upper, 'r:', 'LineWidth', 1);
text(max(B_vertical)*0.3, h_upper+1, 'Upper Conductors', 'FontSize', 9);

ylabel('Height Above Ground (m)', 'FontSize', 12);
title('Field Strength at Tower Center (Vertical Profile)', 'FontSize', 13,
'FontWeight', 'bold');
legend('Electric Field', 'Magnetic Field', 'Location', 'northeast');
grid on;


fprintf('\n========================================\n');
fprintf('ELECTROMAGNETIC FIELD ANALYSIS RESULTS\n');
fprintf('========================================\n');
fprintf('Transmission Line: 400 kV Double Circuit\n');
fprintf('Tower Height: %.1f m\n', tower_height);
fprintf('Conductor Height (Upper): %.1f m\n', h_upper);
fprintf('Conductor Height (Lower): %.1f m\n', h_lower);
fprintf('Phase Current: %.0f A\n', I_phase);
fprintf('----------------------------------------\n');
fprintf('ELECTRIC FIELD:\n');
fprintf('  Maximum: %.2f kV/m\n', max(E_kV_per_m(:)));
fprintf('  At ground (center): %.2f kV/m\n', E_kV_per_m(1,
round(length(x_range)/2)));
fprintf('  At 15m height (center): %.2f kV/m\n',
E_horizontal(round(length(x_range)/2)));
fprintf('  ICNIRP Limit: 5.0 kV/m\n');
fprintf('----------------------------------------\n');
fprintf('MAGNETIC FIELD:\n');
fprintf('  Maximum: %.2f μT\n', max(B_microTesla(:)));
fprintf('  At ground (center): %.2f μT\n', B_microTesla(1,
round(length(x_range)/2)));
fprintf('  At 15m height (center): %.2f μT\n',
B_horizontal(round(length(x_range)/2)));
fprintf('  ICNIRP Limit: 100 μT\n');
fprintf('========================================\n\n');

fprintf('Program completed successfully.\n');
fprintf('All visualizations have been generated.\n');


function draw_tower(height, base_width, top_width, color, linewidth)
```

```
    % Draws a simplified 2D representation of a lattice transmission tower

    % Tower legs (tapered from base to top)
    base_half = base_width / 2;
    top_half = top_width / 2;

    % Left leg
    plot([-base_half, -top_half], [0, height], color, 'LineWidth',
linewidth);
    % Right leg
    plot([base_half, top_half], [0, height], color, 'LineWidth',
linewidth);

    % Cross bracing (X-pattern at multiple levels)
    num_sections = 5;
    for i = 0:(num_sections-1)
        h1 = i * height / num_sections;
        h2 = (i + 1) * height / num_sections;

        w1_left = -base_half + (base_half - top_half) * i / num_sections;
        w1_right = base_half - (base_half - top_half) * i / num_sections;
        w2_left = -base_half + (base_half - top_half) * (i+1) /
num_sections;
        w2_right = base_half - (base_half - top_half) * (i+1) /
num_sections;

        % Diagonal 1
        plot([w1_left, w2_right], [h1, h2], color, 'LineWidth',
linewidth*0.6);
        % Diagonal 2
        plot([w1_right, w2_left], [h1, h2], color, 'LineWidth',
linewidth*0.6);
        % Horizontal
        plot([w2_left, w2_right], [h2, h2], color, 'LineWidth',
linewidth*0.6);
    end

    % Cross-arms (horizontal beams for conductors)
    arm_length = base_width * 1.2;

    % Upper cross-arm (around 90% height)
    h_upper_arm = 0.90 * height;
    plot([-arm_length/2, arm_length/2], [h_upper_arm, h_upper_arm], color,
'LineWidth', linewidth);

    % Lower cross-arm (around 80% height)
    h_lower_arm = 0.80 * height;
    plot([-arm_length/2, arm_length/2], [h_lower_arm, h_lower_arm], color,
'LineWidth', linewidth);

    % Top peak
    plot([0, 0], [height-2, height], color, 'LineWidth', linewidth*1.2);
end
```