Management of Magnetic Fields in and Around Substations

by

Farrukh Shahzad

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

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This thesis, written by

Farrukh Shahzad

under the direction of his Thesis Advisor, and approved by his Thesis committee, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of

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Thesis Committee :

Chairman (Dr. Farag, Ahmed S. A.)

Co-Chairman (Dr. Bakhashwain, Jamil M.)

Member (Dr. Dawoud, Mahmoud M.)

Member (Dr. Al-Shehri, Abdallah M.)

Dr. Al-Baiyat, Samir A.
Department Chairman

Dr. Ala H. Rabeh
Dean, College of Graduate Studies
Date : 6 5 . 96

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ABSTRACT

Name : FARRUKH SHAHZAD

Title : Magnetic Field Management in and around Substations.

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Over the past decade, the magnetic field issue has become an area of increasing public concern. Utilities have been carrying out extensive projects to characterize and manage the magnetic fields around their substations and other power facilities in an effort to answer public concerns over the possible health hazard associated with these magnetic fields. Research studies in epidemiology, biology, physics and engineering have been conducted extensively, in order to identify the correlation, physical mechanism and technology of magnetic field reduction. The objective of this work is to carry out on-site field measurements and computer simulations to study the magnetic field sources and its management around substations using electrical or/and non-electrical techniques including shielding. Two typical substations are selected; one indoor and another outdoor type. Simulations are done using special software which produce profiles, contours, and 3D maps of magnetic field levels. Different magnetic field reduction techniques are also discussed and simulated. Shielding effect for a small substation is also analyzed.

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خلاصة الرسالة

إســـم الطالب : فرّخ شهزاد

عنوان الرسـالة : تنظيم المجالات المغناطيسية داخل وخارج المحطات الفرعية

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إستحوذ موضـوع المجالات المغناطيسية خلال العشر سنوات الماضية على اهتمام العديد من الهيئـات العلمية وعامة الناس، مما حدا بالعديد من شركات الكهرباء في تنفيذ العديد من المشـاريع والدراسـات لمعرفة خواص هذه المجالات والطرق المثلى لتنظيمها والتحكم بها داخل وخارج المحطات الكهربائيـة وذلك كمحاولة منها للإجابة على الأسئلة المطروحة حول احتمال وجود مخاطر صحية نتيجة التعرض لتلك المجالات المغناطيسية.

ولقد نتج عن هذه الدراسات العديد من الأبحـاث فـي المجـالات الوبائيـة والأحيائيـة والفيزيائيـة والهندسية لمعرفة العلاقة والطرق المختلفة لتنظيم المجالات المغناطيسية وذلك للتقليل من أثرها.

تهدف هذه الرسـالة إلـى إجـراء قياسـات للمجـالات المغناطيسية داخـل وخـــارج المحطـات الكهربائية الفرعية وسيتم محاكاة المجالات على الحاسب لدراسة أثر بعض النظم الكهربائية المستخدمة للتقليل من هـذه المجـالات. ولقـد تـم اختيـار محطتيـن كهربـائيتين فرعيتيـن واحـدة داخليـة والأخـرى خارجيـة وذلـك لإجـراء القياسـات المذكـورة والحصـول علـى طـرق مختلفـة لتنظيـم وتقليـل المجـالات ومقارنتها ومعرفة أثر التدريع على توزيع وخفض المجالات المغناطيسية.

درجة الماجستير في علوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

أبريل، ١٩٩٦

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

Since the mid 60's, concerns have arisen that the electric and magnetic fields from the power system equipment might affect the exposed individual especially utilities working crews and laborers. With the publication of results of different epidemiological studies and the following world-wide research effort on effects of power frequency electric fields, the concerns have shifted from electric field to the magnetic field. The health issue of electromagnetic fields (EMF), more especially, power frequency and low-level magnetic field, has received dramatic attention from the public, utilities, and research institutes in the last decade. Research studies in epidemiology, biology, physics and engineering have been conducted extensively, in order to identify the correlation, physical mechanism and technology of magnetic field reduction. Up to date, no final conclusion has been reached. However, some of the studies did indicate a possible health association [1]-[8]. A two-fold increase in risk of childhood leukemia, breast cancer, as well as brain tumor under long term exposure of milli Gauss (mG) level magnetic field. These findings have stirred concerns of the public.

Utilities are aware that the public's concerns about this issue are widespread and sincere. They recognized and took seriously their responsibilities to help resolve these concerns. Utilities believe that their responsibilities are :

(i) To provide safe and reliable electricity for their customers.

(ii) To provide balanced and accurate information, derived from all sources, to their employees, customers and regulators. This will include providing EMF measurements and consultation to their customers upon request.

(iii) To support all the necessary research to resolve unanswered scientific questions.

(iv) To conduct the required research to develop and evaluate the engineering designs and find ways to reduce the fields generated by electric facilities.

(v) To take reasonable low-cost steps to reduce field exposures from new facilities and continue to consult and advise their customers regarding existing facilities.

(vi) To research and evaluate occupational health implications and provide employees who work near energized equipment with detailed and accurate information regarding field exposures in their work environment

(vii) To encourage agencies such as the Ministry of Health and other appropriate government agencies to provide reasonable and uniform regulatory guidance.

In response to the public concerns, many utilities are being actively involved in EMF-related work. Utilities have been carrying out extensive projects to characterize and manage the magnetic fields around their substations and other power facilities in an effort to answer public concerns over the possible health hazard caused by magnetic fields generated from power system equipment.

Monitoring equipment for magnetic fields has improved considerably in recent years. Use of these equipment for detection and measurement of magnetic flux density has helped utilities characterize exposure to magnetic fields, whether may be caused by utilities installed equipment or customer end-use appliances.

1.1 Magnetic Field Characterization & Management Studies

While the health studies were in progress, it appeared desirable to conduct parallel technical studies related to the electromagnetic fields that can be found in occupational areas. In response to the public concern, many utilities are being actively involved in EMF-related work. Many research-type studies are being or have been funded or supported by utilities. In those studies, both magnetic field characterization and its management in power systems are or were focused [9]-[17].

In the domain of field characterization, magnetic field in the vicinity of power facilities has been surveyed extensively in the past few years. Major sources generating substantial magnetic field have been identified. These major field sources were overhead transmission and distribution lines, underground cables, underground structures, substations and other individual power equipment. The typical value of magnetic field was found in the range of few mG up to a few hundreds of mG in the living and working place. The field levels measured were generally higher than the level identified in epidemiological studies.

As the magnetic field sources in power systems have been identified, the interest of utilities is being shifted to magnetic field management on these sources. Currently, there are many techniques available to manage magnetic fields created by substation's equipment's. All these techniques can be roughly grouped into the following three categories :

(1) increasing the distance between the source and the point of interest,

(2) manipulating source geometry and current (small spacing and low current), and

(3) magnetic field shielding techniques.

The first approach is straightforward, but is limited by physical constraints, such as, space or land availability in the vicinity of the sources. The second category covers source relocating, compacting, re-phasing, return-current control, etc., and the last category includes passive and active shielding.

The theorem of active shielding is not mature yet, and it is still in the phase of development and testing. The passive shielding technique was developed long time ago. It has been considered as an applicable field reduction technique in the phase of both modifying existing power facilities or constructing new power facilities. This approach is expected to reach significant magnetic field reduction. Recently the technique of passive shielding has been practically applied to the magnetic field generated by substations, generators and other power equipment [9],[12]. However, because there were few shielding theories regarding applications in power systems, current shielding designs or implementations are just a practice of experience.

1.2 Objectives of the Study

The main objectives of this study are to:

- Carry out detailed measurements of magnetic fields in and around different substations using magnetic field meters with special attention given to field measurements near major magnetic field sources such as transformers and LV cables.
- Plot line profiles, contour and 3D maps of measured magnetic field at different

locations in the substations.

- Develop magnetic field model of substation's energized buses and equipment from given electrical and geometrical data to compute the magnetic fields in substations and its vicinity.
- Analyze and compare the measured and simulated field values using comparative profile plots along different lines.
- Based on the analysis and comparison of measured and simulated magnetic field, try to overcome any discrepancies by better measurement, modeling and simulation methodology.
- Identify and verify important sources of magnetic field in substations.
- Simulate and analyze the magnetic fields produced by various substation designs and develop alternative substation designs aimed at minimizing magnetic fields (magnetic field management).
- Study the effect of shielding of major magnetic field sources.

In this study, two typical Substations, an indoor type (69 / 13.8 kV) and an outdoor type (115 / 13.8 kV) are studied in terms of their measured and simulated magnetic fields. In addition, application of magnetic field management techniques is also highlighted. Simulations are performed, using SUBCALC, to determine the magnetic field distribution in and around the power facilities in the substation. SUBCALC is relatively simple to use and provide magnetic field distribution if physical dimensions of substation and amplitude and phase angle of all the currents are known.

On-site measurement of magnetic fields in and around substations are done using EMDEX II and Field Star 1000 magnetic field meters. These measurements are usually performed at one meter above ground levels (sometimes at the ground level also). The contours and 3D profile of the magnetic field are plotted using available interactive graphics packages such as DeltaGraph and GraphTool.

A typical residential area substation is used to verify the magnetic field shielding techniques. The substation is located within the vicinity of KFUPM.

CHAPTER 2

CHARACTERISTICS OF MAGNETIC FIELDS IN SUBSTATIONS

2.1 Magnetic Field Fundamentals

Electric and magnetic fields are generated by the combination of electrical charges and movements of electric charges (electric currents). When the rate of change (frequency) of these fields is sufficiently low, as is the case for power system fields, electric and magnetic fields (EMF) can be separated into electric (related to voltage) and magnetic (related to current) fields and the word EMF should be defined as "Electric and Magnetic fields", as opposed to "Electromagnetic" which implies that electric and magnetic fields are coupled together as in high frequency radiating fields.

The magnetic field is defined by the magnitude and direction of the force exerted on a moving charge. If an electrical charge is moving into a magnetic field, or if a field moves past the charge, the charge will be subjected to a force. If the unit electrical charge, one Coulomb, moves at a unit velocity, one m/s, perpendicular to a magnetic field of a unit flux density, one tesla, it will be subjected to a unit force, one Newton, in a direction orthogonal to both the direction of the charge motion and the direction of the magnetic field. The quantity described is the magnetic flux density, which, in a region with magnetic flux, is the magnetic flux in the unit area perpendicularly traversed by the flux.

Consider a single wire carrying a current (I), as shown in Figure 2-1. The magnetic flux density in the surrounding air at a distance (R) from the wire is equal $2\times10^{-7}\ I/R$. The magnetic flux density is a vector quantity. In this example, the direction of magnetic flux density is tangential to the unit circle with radius (R). Magnetic flux density is usually denoted by letter B, which is the magnetic flux per unit area.

$$\phi = B.A \qquad \text{Equation 2-1}$$

The unit of B is weber/meter^2 or tesla. There is another quantity called "magnetic field strength", usually indicated by letter (H) and measured in ampere per meter (A/m). B and H are related through the permeability of the medium (μ) as,

$$B = \mu H \quad (\text{weber/m}^2) \qquad \text{Equation 2-2}$$

Where for free space/air, $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m.

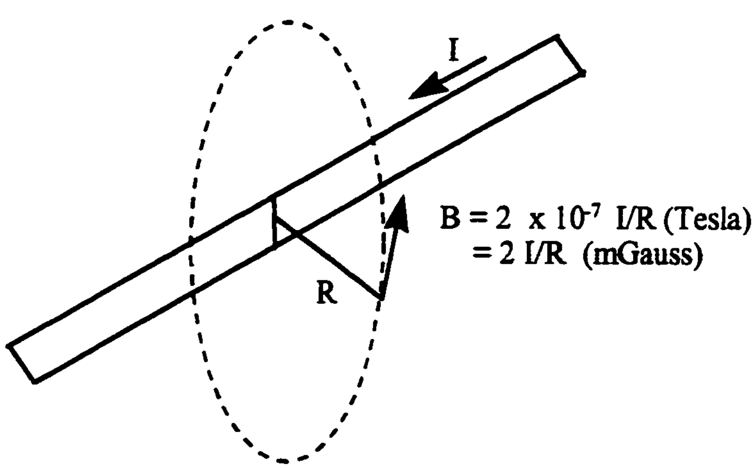


Figure 2-1: Relation between current and Magnetic flux density (B).

The magnitude and direction of AC magnetic fields constantly change and is typically represented at a point in space by a vector whose direction represents the direction of the field and whose length represents its magnitude. A vector representing the changing magnitude and direction of a magnetic field would appear to rotate around the point in space and follow an outline of an ellipse with major axis *a* and minor axis *b*. Such a field is said to be *elliptically polarized*, is typically produced by 3-phase distribution and transmission lines. There are two special cases of elliptical polarization:

- *Linear polarization*, occurs when the minor axis of the magnetic field ellipse is zero.
- *Circular polarization*, occurs when the minor axis is equal in magnitude to the major axis of the field ellipse.

2.2 Purpose of the Substation

Purpose of substations can be summarized as follows:

- Terminate transmission and/or distribution lines,
- Receive bulk power,
- Transform voltage,
- Control power flow in the event of a system disturbance,
- Regulate voltage through regulators and capacitor banks,
- Point of indication (Measurement of data), and control,
- Provide redundancy for maintenance and/or equipment failure,
- Serve the customer.

Substation can be divided into four groups based on services it provide:

a) Switching Station,

b) Receiving Station,

c) Distributing Station, and

d) Customer/Industrial Station.

2.3 Sources of Magnetic Fields in Substations

There are three areas of concern relative to the magnetic field exposure generated by substations : The public, employees, and equipment. Usually the public is less exposed to EMF from substations than they are to fields from transmission and distribution lines except for urban areas and in high-rise commercial and residential buildings. Because of their nature of work, employees of utilities are more subjected to exposure to EMF fields in substations. The concern for equipment exposed to EMF fields is more easily quantified. By field measurements on the equipment, the substation facilities can be designed to limit the fields to a level that the equipment can tolerate.

Magnetic field related measurements are more complicated and demanding than electric field related tests because the magnetic field varies with current fluctuations (I.e. load variations). Furthermore, the magnetic fields generated from substations are more complex and more difficult to measure than the fields near power lines or homes. The line currents passing through substation buses and equipment produce magnetic fields within the substation which have much the same attributes as magnetic fields beneath the lines themselves. The close proximity of substation equipment and the grounding mat complicate the field attributes especially the spatial variability to some measure but do not inherently change the nature of magnetic field.

The most prevalent sources of magnetic fields in substations are:

I. High and low voltage buses and lines

   A. Low voltage side transformer network,

   B. Bus work segments within the racks which due to loading, are forced to carry high currents.

   C. Pot-heads (underground cable termination), and

   D. Underground cables entering or leaving the station.

   E. Circuit breakers (CB's) and Disconnecting switches (D/S).

II. Currents in connections to the ground mat from structural steel, fences, transformers and other metallic structures in the substation.

III. Air core Reactors.

IV. Capacitor Banks.

V. Battery Chargers.

VI. Wave Traps.

2.4 Factors affecting the Magnetic Field

Magnetic fields from substation's electrical equipment are generally affected by a number of variables including :

I. *Magnitude of phase current* - at power frequency, the magnetic field is proportional to the phase current magnitude. Line currents on substation buswork, vary widely in both their magnitudes and phase angles, so utilities normally calculate magnetic field levels using estimated current magnitudes. Differences in the current magnitudes between each phase (current unbalancing) also effect magnetic field strength and slows the rate at which the magnetic field decreases at distances far from the conductor,

II. *Neutral/shield wire currents*- In an unbalanced power system, the return current flows through the neutral, shield and / or through the ground path. If all of the return current flows back through the neutral, this will tend to decrease the overall magnetic field,

III. *Height of conductors above/below ground* - increasing the height of the current-carrying conductors will reduce the magnetic fields at or near ground level. The opposite is true in high-rise buildings where substations are underground,

IV. *Conductor configuration* - the magnetic field level in substation is the sum of the fields produced by the currents in all conductors and is dependent upon the distance between the observer and each current-carrying conductor. Placing the three conductor as close together as possible creates greater field cancellation and the magnetic field at or near ground level is reduced,

V. *Lateral distance from substation or above substation* - magnetic field strength decreases with the lateral distance from the source of the magnetic field, which is the current in each conductor in the substation. The magnetic field can have $1/r$, $1/r^2$ or a $1/r^3$ decay rate, where r is the distance from the magnetic field source, depending on the line or substation design and the degree of current unbalance. Most three phase power lines and substation buswork produce magnetic fields that decay as $1/r^2$. The $1/r$ rate occurs when the currents on a power line are not balanced. The $1/r^3$ decay rate occurs when using an optimal phase configuration on a double circuit line with phase currents of equal magnitude. Magnetic fields from major substation equipment, such as three phase transformers and reactors decay as $1/r^3$,

VI. *Proximity of magnetic materials and conducting objects* - Magnetic fields are not generally affected by building walls and sections. This also leads to the conclusion that magnetic field shielding is difficult to achieve. To do this, it is necessary to use materials which either have high conductivity or are magnetic (iron or steel). In general, the application of magnetic shielding through use of high conductivity or magnetic materials is limited in an electric power system due to the complexity of obtaining a practical design and associated costs.

2.5 Magnetic Field Modeling of Substation

In the range of low frequency, magnetic field is mainly generated by electric currents according to Maxwell's equations. Since the current in power systems are usually confined to straight conductors (e.g. lines or buses), magnetic field can be calculated by the Biot-Savart equation:

$$\bar{B} = \frac{\mu_o}{4\pi}\int \frac{id\bar{l} \times \bar{a}_r}{r^2} \qquad \text{Equation 2-3}$$

Where, i represents the current flowing through conductors, r represents the distance between an observation point and an integration point on the conductors, and a_r represents a unit vector directed towards the observation point. Given current information as well as geometric information of current carrying conductors, magnetic field is uniquely determined by Equation 2-3. Basically, there are two significant models of sources in the analysis of magnetic fields. These models are a point source and a long-conductor source.

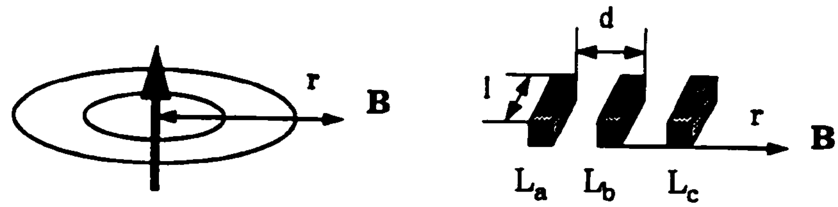
- *The Point Source*: Current-carrying conductors can be modeled as a point source if length l of conductors is much less than distance r, as well as conductor spacing d is much less than r as shown in Figure 2-2(a). Since r does not change much over the whole conductor, a simplified formula of magnetic can be derived from Equation 2-3. Assuming currents in conductors are balanced and have an equal magnitude I_o, its magnitude is given by

$$B = \frac{\mu_o I_o}{4\pi r^2} l$$
$$B = \frac{\mu_o I_o}{2\pi r^3} dl \qquad \text{Equation 2-4}$$
$$B = \frac{\mu_o I_o}{2\pi r^3} \sqrt{3} dl$$

for a single conductor, double and triple conductors respectively.

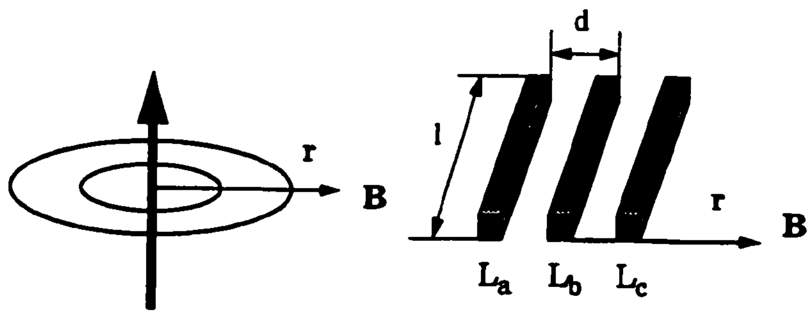
- *The Long-Conductor Source*: Current-carrying conductors can be modeled as a long-conductor source if conductors are much larger than distance r, as well as conductor spacing d is much less than r as shown in Figure 2-2(b). By evaluating Equation 2-3, the magnitude for a single conductor, double and triple conductors respectively, is given by

$$B = \frac{\mu_o I_o}{2\pi r}$$
$$B = \frac{\mu_o I_o}{2\pi r^2} d \qquad \text{Equation 2-5}$$
$$B = \frac{\mu_o I_o}{2\pi r^2} \sqrt{3} dl$$



Decreasing function $=1/r^2$ Decreasing function $=1/r^3$

(a) Point Source(s)



Decreasing function $=1/r$ Decreasing function $=1/r^2$

(b) Long Straight Conductor(s)

Figure 2-2: Source arrangement and their decreasing functions.

In power systems, substations are one of major power facilities creating substantial magnetic field. They serve to distribute electric power either from a low voltage systems or vice versa. The basic elements in substations are buses, cables, transformers, circuit breakers, capacitor banks, etc. From the perspective of magnetic field, these elements can be grouped into two distinct categories: conductor-type element (e.g. buses) and equipment-type elements (e.g. transformers). The major difference is that equipment-type elements have additional metallic parts besides conductors, which might affect magnetic fields around these elements.

2.5.1 Conductor-type Elements

- *Bus bars* serve to assemble incoming currents and distribute outgoing currents, and usually carry very high currents. They are made of long conductors with either circular or rectangular cross-section. Current is not uniformly distributed over the cross-section area, due to skin effect. However, since radius or side length of conductors is much less than distance *r*, bus bars can be modeled by equivalent filaments carrying the same amount of current and located at the geometric center of the conductors.
- *Cables* serve to transmit electric power from one location to another location. It could be single underground cable with three cores inside (3 phases) or three cables each with single core inside. Each core is a current-carrying conductors surrounded by insulation layers. In some cases, cable has its own metallic sheath. The sheath is mainly designed for the mechanical protection, however, it might serve magnetic field shielding in some circumstances. The magnetic field generated by cables are effected by three factors: (1) skin effect, (2) proximity effect and (3)

shielding effect. However, these effects might be neglected, since geometry of a cable is usually much less than distance *r*, and cables can be modeled by equivalent filaments centered on their corresponding conductors.

- *Disconnectors* in a substation serve for separation of two circuits, and operate only when the two circuits are deenergized. In the on-switching status, current might flow through this piece of conductor, and it can be replaced by a piece of filament centered at the conductor for the calculation of magnetic field generated by the disconnector.

2.5.2 Equipment-type Elements

- *Power Transformers and Voltage Regulators* has three main parts affecting magnetic field: (1) windings, (2) high-permeability core and (3) metallic enclosure. Due to complex geometry of these parts, as well as nonlinear performance of core and enclosure, the exact modeling of 3-D magnetic field evaluation is much difficult. However, if distance *r* is much larger than geometry of a transformer or a regulator, one approximate model can be used in the magnetic field calculation. In this model, leads of the equipment is replaced with filaments and everything within the enclosure is neglected.
- *Circuit Breakers and Fuses* are devices which are capable of disconnecting energized circuits when it is triggered. They have a pair of outgoing and incoming conductors, as well as other auxiliary mechanical parts. The pair of connectors are connected together at one end, and a current flows through it when it works normally. The conductors and metallic enclosure are two major parts affecting magnetic field. In an approximate model the current-carrying conductors are

simply replaced with filaments by neglecting the enclosure. This model will lead to overestimation of magnetic field by ignoring shielding effect of the enclosure. However, the error will be small if distance *r* is much greater than geometry of a circuit breaker or fuse. -

CHAPTER 3

MAGNETIC FIELD MANAGEMENT

Magnetic field management can be defined as the " *implementation of programs to minimize the impact of possible health effects of power system magnetic fields while maintaining power system reliability, safety, and effectiveness*". These programs may include :

- Communication programs,
- Management programs,
- Research programs,
- Assessment of different design options,
- Application of field reduction techniques.

Magnetic field management results from the commitment of the utility industry to find a solution to any potential problem which is of most benefit to the public. Therefore, magnetic field management also includes programs aimed at reducing unjustified public fears generated by the debate on the issue. For each magnetic field source within the power system, there may be a number of design options that would reduce magnetic field exposure without altering the function for which the system was intended.

The magnetic field strength from the substation alone can be reduced if the physical geometry and/or electrical characteristics, as well as the layout, of the substation are designed to take advantage of various field reduction properties. A classification of the different approaches to substation magnetic field exposure reduction techniques are discussed in following sections.

3.1 Modification of People Activity Patterns

Magnetic field strength levels decrease as the distance from the source increases. One method of reducing the magnetic field strength level at a particular substation would be to increase the distance from the sources at the point of interest. The rate of decrease is dependent on several factors, including substation layout and the current unbalance in the circuit. This approach consists of finding ways to avoid the presence of people at times or at locations of high magnetic fields. It may include:

- Modification of work rules based on limitation of magnetic field exposure,
- Access limitation of high magnetic field areas,
- Installation of facilities and equipment so that magnetic fields are minimized in areas frequently occupied by people.

This can be accomplished in a variety of ways, including:

- Equipment / conductor relocation - locate sources as far away from the public areas and areas of interest as possible,
- Increased/decreased height of substation bus work - increase (decrease for underground substations) the height of overhead sources, within the acceptable limits,
- Increased property boundary lines - increase the amount of site property in order to increase the distance from the substation's electrical facilities and property boundary line.

- Selection of site for the substation - selection of the optimal site for the proposed substations taking into account all the important factors.

3.1.1 Equipment/conductor relocation

The sources should be located within the facility as far from the property line as feasible. In addition, the higher current sources should be located closer to the center of the facility if possible. Any incoming lines to the substation, whether transmission or distribution, should be routed within the property line and as close to the facility as feasible.

The magnetic fields from transformers, reactors and capacitors decay as $1/r^2$ to $1/r^3$. Magnetic fields from most three phase lines and substations buswork decay as $1/r^2$. If placed near the substation fence, high current devices (i.e. transformers, reactors, and capacitors) may significantly contribute to magnetic fields outside the substation property boundary. Magnetic fields resulting from these devices may be neglected when evaluating field levels beyond the property line if these devices are located closer to the center of the substation property and away from the fence.

3.1.2 Increased/decreased Height of Substation Buswork

One way to reduce the magnetic field strength at ground level is to increase (decrease for underground substations as in high-rise buildings) the distances between the current-carrying conductors from the ground or the public. There are two primary methods in which this may be accomplished:

- Raise the height of the substation structure used, height of overhead lines and associated buswork,

- Suspend sources from the existing taller structures. This may increase the cost and aesthetic impact of the substation. This is particularly important for sources located near the fence such as bus conductors, disconnect switches or wave traps. Any resulting impacts to the visual aesthetics of the substation must be considered along with the magnetic field reduction issue.

3.1.3 Increased Property Boundary Lines

Another method of reducing magnetic fields from the substation is to increase the property boundary of the substation to limit the distance of approach. Increasing the amount of site property would increase the distance from the sources to the property line, thereby reducing the magnetic field level at the property line. Land availability for acquisition and the costs associated with the additional property must be taken into consideration when examining this option. In addition, this action will only provide the desired result if the public uses/access within the property line are also controlled.

3.1.4 Optimal Site Selection

The selection of an optimal substation site requires consideration of numerous technical, economical and environmental factors. A study of the existing and projected magnetic field strengths should be performed to investigate how siting considerations may affect magnetic field levels. An analysis of present magnetic fields, computer-generated fields for the proposed alternatives and a discussion of how land uses may be impacted should be included in the study. This may result in siting the substation farther from the load or causing longer line routes. Any resulting impacts to line magnetic fields, environmental concerns or costs must be balanced against the substation magnetic field issue. Environmental issues, safety, maintenance, cost and the magnetic field levels must be considered along with all other siting criteria. Briefly speaking, substations should be located away from the normally occupied areas, to the extent practical.

3.2 Design of Electrical Facilities and Equipment for Low Magnetic Field

This approach consists of modifying circuit currents, or conductor arrangements, or characteristics of magnetic materials of facilities and equipment. This approach offers a large number of engineering solution opportunities, some of which are explained in the following sections.

3.2.1 Bus work compaction (reduce conductor spacing)

The resultant magnetic field strength level is the vector sum of the individual phase vectors at any particular location of the various current-carrying conductors. The closer the conductors of the phases are to each other, the more effective the magnetic field is canceled by the other phases. However, the concern of potential flash-over and other reliability considerations set practical limits to the reduction in conductor spacing. Close phase conductors spacing in substations increases the chances of birds, rodents and other animals coming in contact with live parts. This can cause phase-to-phase bus faults which would result in extended loss of service to customers.

In substation, reducing magnetic field strength levels by reduced conductor spacing techniques achieves less field reduction results when compared with increasing the distance to the source. For overhead buses, horizontal or vertical configurations typically has a larger phase spacing and hence, produce higher fields under the bus than triangular or delta configurations. For underground buses, self contained systems, where each phase is placed in a separate duct, generally produce greater fields than pipe-type systems, where all three phases are contained in a single duct. Feeder outlets for distribution can typically be installed underground in a single duct, thereby reducing the overall magnetic field strength. For metal-enclosed bus, as in switchgear and gas-insulated substation (GIS), the phase spacing can be greatly reduced, thereby minimizing the overall magnetic field strength. Switchgear devices and buses that utilize vacuum or gas insulation will significantly reduce the phase spacing compared to oil or air insulation.

3.2.2 Balanced Phase Current

Balanced phase currents produce weaker magnetic field strength level when compared to unbalanced currents. The magnetic field from lines or buses with unbalanced currents decreases less rapidly than the fields from those with balanced currents. In many cases, the ground level component of the magnetic field strength due to unbalance is greater than the component due to the phase currents. Maintaining balanced phase currents will result in magnetic field strength reduction. Balancing phase currents on distribution circuits will result in more balanced phase currents within the substation.

3.2.3 Optimized Phasing

Phase configuration techniques use the phase difference between magnetic fields generated by the individual conductors to reduce or cancel the overall field. The typical substation conductor configuration is horizontal. Other configurations include vertical and delta or a combination/variation of these configurations.

There is a number of different bus configurations available for substation construction. However, the type of bus configuration that should be used in a particular substation is dependent on a number of factors including: reliability, operation flexibility, complexity, land availability, safety, cost effectiveness, and future expansion.

Phasing relationships produced by different bus configurations can be evaluated to determine which one results in the lowest combined magnetic field strength level. However, this type of evaluation is dependent on current loading and direction of current flow through each section of bus which may vary with time. Therefore, there may not be a single optimum low magnetic field phase configuration for substations. Some utilities do not currently construct conductors in delta configuration in substations and some has no immediate plans to do so in the near future. Some of the de-merits of delta configuration are:

- It makes tapping of the bus extremely difficult,
- Increases safety risks to the maintenance personnel.

3.2.4 Minimizing Current (Higher Line Voltage)

The magnetic field strength level is directly proportional to the magnitude of current flowing in the conductor. This is true for the phase conductor current or the unbalanced neutral currents. It is possible to reduce the current component and still provide the same amount of power by increasing the operating voltage. Utilities has been doing this over the years as technology advances in the area of power distribution. The oldest systems are operating at 2.4 kV and 4 kV. Utilities has adapted 12.5, 13.8, and 20.8 kV distribution systems as the technology became available. This significantly reduces the current levels required to transport the same amount of power when compared with 2.4 and 4 kV circuits. As a result, a line operating at the higher voltage will produce a lower magnetic field strength for the same power transfer than a line operating at a lower voltage. The distribution system dictates the operating voltage required at distribution substations. Voltage conversions to higher levels must first take place in the distribution system. Converting system voltage to higher levels is not always practical or even possible. Existing system configuration, reliability, operability and cost factor must be taken into account prior to higher operating voltage conversion.

It is also possible to achieve some reduction in current through Customer Energy Efficiency Programs. Adequate reactive load compensations (capacitors) can be provided to bring the power factor closer to unity at distribution level, thereby minimizing the reactive power flow (and hence the total current) on transmission lines.

3.3 Shielding

Magnetic field exposure is reduced if the areas occupied by people are shielded, either by shielding the subjects or by shielding the source. Basically, shielding methods can be divided into :

- shielding caused by induced currents,
- shielding obtained by modification of magnetic field flux patterns using high permeability and /or high conductivity materials,
- active shielding obtained by actively adding a second magnetic field that tends to reduce the original field.

The various shielding schemes that exist can be separated into two broad categories : shielding subject and shielding source. Shielding a subject means to implement a shielding of some sort to reduce the field in some relatively small, well defined volume, due to sources of field outside the volume. Shielding the source involves placing a shield to reduce the magnetic field in the "outside" world due to some localized source.

In order to evaluate the effectiveness of shielding scheme, it is necessary to define terms which quantify the degree of shielding. The term shielding factor (SF) is defined as

$$SF = B/B_0 \qquad \text{Equation 3-1}$$

Where, B is the rms. value of the magnetic field with shielding,

B_0 is the rms. value of the magnetic field without shield.

Obviously, SF is a function of position. However, in general it can also be function of frequency, field strength, temperature, shielding material, etc.

Another term which is usually used to quantify shielding effectiveness is the shielding efficiency (SE) and is defined as :

$$SE = (1 - SF)\times 100\ \% \qquad \text{Equation 3-2}$$

Recently the technique of passive shielding has been practically applied to the magnetic field generated by substations, generators and other power equipment [9],[12]. However, because there were few shielding theories regarding applications in power systems, current shielding designs or implementations are just a practice of experience. There are many-magnetic field shielding problems that are being currently studied and need further investigations:

- What is the shielding mechanism in power applications ?
- Which one is better, eddy-current shielding or high-permeability shielding ?
- Does high-permeability shielding material create another problem by enhancing magnetic field somewhere ?
- How are design parameters (material, thickness etc.) selected ?

Magnetic field shielding problem in power system has its own distinct characteristics:

- Low frequency (60 or 50 Hz),
- Near field or closeness to magnetic field sources (non-uniform field),
- Large size shields,
- Low-level magnetic field, and others.

Theories developed in areas other than power systems might not be applicable in power applications. Thus shielding theorem, principles and guidelines for applications in power systems need to be studied and developed deeply.

3.3.1 Shielding Models

In substations, bus bars are the major source of magnetic field. The common feature of bus bars in the substation is that they are much longer, and parallel with the floor. In other words, the bus bars can be modeled as 2-D geometry filaments in the shielding problems. Magnetic field shielding in the substation can be viewed to shield magnetic field created by long filaments with conducting shield.

Planar and cylindrical structures are two common shield structures frequently used in shielding magnetic field created by filaments. The planar shield is placed at the location between sources and a shielded subject, and the cylindrical shield is used to separate shielded subjects from sources. The first shielding scheme is called region shielding, and usually applied when geometry of sources is complex and the source-shielding structure is difficult to apply. The second shielding scheme is called source shielding, and usually applied when magnetic field sources are geometrically simple. It is expected that magnetic field in the shielded region will be reduced, and the magnetic field in the source region will be redistributed (might be enhanced in some circumstances) due to the induced current within the conducting shield. Fortunately, the source region (e.g. inside the cylindrical shell) is usually inaccessible to people, will not cause other problems.

CHAPTER 4

MAGNETIC FIELD MEASUREMENT AND SIMULATION PROTOCOL

Monitoring equipment for electric and magnetic fields has improved considerably in recent years. Use of these equipment for detection and measurement of magnetic flux density has helped utilities characterize exposure to these fields, whether may be caused by utilities installed equipment or customer end-use appliances.

On-site measurement of magnetic fields in and around substations are done using EMDEX and Field Star magnetic field meters. These measurements are usually performed on a 1 ft ×1 ft grid near a source and 1 m × 1m (or more) far away from the source; at two different heights, i.e. on ground and on one meter above ground levels. The contours and 3D plots of the magnetic field can be plotted using available interactive graphics packages such as DeltaGraph, GraphTool, etc.

Simulation studies can be used to determine the electromagnetic field distribution in and around the power facilities in the substation. Advantages of simulation and modeling of substations, where feasible, are as follows:

- It allows an environmental effect related evaluation of substation design,
- It is good complement to full scale studies for both measurement and analysis

techniques,

- It can be used as a design tool that can save money in the development stages of substations,
- Simulation and modeling can be used to accumulate large amounts of data in a short time,
- Ground level magnetic field strength or magnetic flux density mapping can be done,
- Easy change of operating and geometric conditions,
- Development of mitigation techniques, and
- Systematic study of parameters that influence the magnetic field distribution.

Packages are available, which are relatively simple to use and provide magnetic field distribution if physical dimensions of substation and amplitude and phase angle of all the currents are known.

4.1 Substation Magnetic Field Program Protocol

The purpose of the program protocol of investigation is to determine if a three-dimensional modeling program can accurately predict the magnetic fields in and around substations prior to and after construction. This will model the magnetic fields which employees are working in and also the magnetic field levels on adjacent property.

4.1.1 Technique

- Select typical substations and conduct detailed survey of each substation using measuring devices such as EMDEX IIC meter, Field Star 1000, and Wave Capture

Systems,

- Construct a model of the substation using magnetic field programs such as 3D-Fields, MF3D, and SUBCALC, and verify model results against the survey and fine tune the model,
- Perform an additional survey of the same substations, using available records. Observe the results of the model's magnetic fields and compare the results of those recorded on the wave capture systems or other meters, and
- Improve the substation model, taking into account all pervious information gathered during measurement and simulation, and conduct another comparison against measured field.

4.1.2 Anticipated Results

- Determine the error which is probable in modeling a substation using the three dimensional modeling programs,
- Establish areas with sensitivities that impact the reported fields,
- Determine areas where reported results are not consistent with measured values and suggest reasons for deviation,
- Conduct survey using other meters (EMDEX IIC and Field Star 1000), and compare the results of the data collected with the other wave capture system. This will include X, Y and Z axis and the resultant field, and
- Establish a degree of certainty and probable error when using the survey instruments for evaluating substation magnetic fields.

4.2 Information Required for Magnetic Field Evaluation

The following information is necessary for the evaluation and presentation of substation magnetic field calculations, simulations and measurements:

4.2.1 Geometrical Information

- Substation layout plan, description of components,
- Conductor, tower and substation geometry, including configuration, phasing, sag and clearance data,
- Test traverse location, level and direction, and
- Location of test traverse points.

4.2.2 Electrical Parameters

- Line and bus voltages,
- Real and reactive line and transformer loads,
- Individual bus and line currents (magnitudes and preferably phase angles),
- Wave shape, harmonic content (if available),
- Location of electrical measurements, and
- Grounding conditions.

4.2.3 Magnetic Field Measuring Devices

- Types of meters and probes, single-axis or multiple-axis principle,
- Characteristics, and response,
- Calibration information, and correction factors, and
- Height of meter during measurements, positioning and orientation of the meter.

4.2.4 Miscellaneous

- Description of environment,
- Time and duration of measurements,
- Coordinate system,
- Correlation of magnetic field and load variation,
- Verification of Simulation Studies,
- Conducting field measurement on full scale station,
- Develop components in the simulation packages,
- Develop a generic computer program and apply it to the full scale station, and
- Compare results of the full scale model measurements and calculations.

4.3 Magnetic Field Meters

EMDEX IIC and Field Star 1000 meters are used for measuring magnetic field in substations. They are portable magnetic field measurement and analysis system with computer interface [19].

The EMDEX II is a programmable data-acquisition meter which measures the orthogonal vector components of power-frequency magnetic fields through its internal sensors. Measurements are stored in the meter's memory and can be later transferred through a serial communications port to PC for storage, display and analysis. AC magnetic field strength (flux density) is determined by measuring the current induced in three sensor coils mounted orthogonally along the x, y and z axes. The EMDEX II hardware consist of two main operating sections: the on-board digital computer and the signal processing circuitry.

4.4 Magnetic Field Computation using Fields Software

Three-dimensional (3D) computer programs have been developed to model substations. These programs create a 3D replica of all the conductors in the substation, which have been reduced to straight segments and represented by the three coordinates of the beginning and ending points. In addition, the magnitude and phase angle of the current circulating on each conductor is entered into the program. These programs have the capability of showing a graphical representation of the entered data. Once the data are entered, the program calculates the values of magnetic field at any selected point or along any given line or grid. For reasons of simplicity, when modeling a substation, only the high voltage conductors (which are carrying power) are entered. No consideration is given to control cables and low voltage light and power circuits.

When modeling a substation, it is important to keep in mind that all the resultant magnetic fields are being calculated based on one given loading condition. Therefore, it is important to make some logical assumptions as to what these loads and consequent currents will be and to keep these assumptions constant when comparing two or more different cases. The following assumptions are commonly used in the modeling of substations:

- Unless a different loading condition is specified, the substation will be considered loaded as it's nameplate capacity with the load equally balanced among the available transformer banks and distribution circuits.
- All transmission and sub-transmission lines as well as distribution circuits are assumed to have balanced loads. Neutral or ground currents are usually not

considered.

- The substation is considered working under normal operating conditions. No emergency conditions are analyzed. On all switch-racks with operating and transfer bus schemes, the bus tie and the bus parallel breaker (if applicable) are considered open.
- When incoming transmission and sub-transmission lines are located on a double circuit tower or pole, they will be assumed to be phased for maximum field cancellation.
- All distribution circuits located in underground duct banks are assumed to be phased in a fixed pattern which is kept constant throughout the calculations.

4.4.1 SUBCALC

SUBCALC is a computer program for modeling 60Hz magnetic fields from substation conductors. It computes magnetic flux density using the Biot-Savart Law with 3D conductor models. The program assumes the system to be a perfect air model [18].

Currently the types of source objects which can be placed in the drawing area are transmission lines, primary distribution Lines, underground cables, buswork, circuit- breakers, and custom conductors. The user can define objects such as transmission lines and distribution lines and place them in the area of concern simply by drawing them with the mouse.

Magnetic fields will be calculated for the three orthogonal axes, the maximum field and the resultant field. The calculated magnetic fields can be displayed in the form of 3-D graphs, contour plots, and multi-segmented profile plots.

SUBCALC was developed by Enertech Consultants beginning in 1992 under the sponsorship of the Electrical Systems Division of EPRI. This first version of SUBCALC is designed to allow the input of transmission lines, primary distribution lines, underground cables, buswork, circuit-breakers, wave-traps, and custom conductors. The magnetic field from these sources can be calculated and displayed in the form of 3-D graphs and contour plots. The unique feature of SUBCALC is that the user can draw in where the sources go using CAD-like data entry with a mouse. Though primary distribution lines can be drawn, no pole-mounted transformers are modeled in this release. Similarly, no secondary distribution system can be modeled with this version of SUBCALC. However, there is nothing preventing user from using the custom conductors to approximate secondary distribution lines.

Future versions of SUBCALC will contain many additional features for modeling more complex substation systems. Wave-traps, transformers, capacitor banks, a grounding grid, and pipe-type cables will be added as objects to be drawn in using the CAD-like data entry. The ability to read and write .DXF files will provide a link to other CAD modeling software. Human exposure modeling will be added to a future version of SUBCALC. Also some simulation capabilities will be added. For instance, the ability to specify the line load over a period of time from which SUBCALC will produce a series of output at user-defined time increments.

SUBCALC produces following outputs:

- The *3-D magnetic field map* plots the magnetic field points in an X and Y plane with the field intensity as the third dimension on the Z axis. It looks similar to 3-D topographical maps, but instead of the Z axis representing elevation, it represents the magnetic flux density. The 3-D map can be rotated and viewed from several different angles determined by the user. User can choose to display any of the three individual components of the magnetic field vector (X, Y, or Z), the Resultant field, the maximum field (major axis), or the minimum field (minor axis).

- The magnetic field *contour map* looks similar to topographical contour maps, but instead of the contour lines representing elevation, they represent the magnetic flux density instead. User can choose to display any of the three individual components of the magnetic field vector (X, Y, or Z), the Resultant field, the maximum field (major axis), or the minimum field (minor axis).
- SUBCALC generates a set of *descriptive and order statistics* based on the field calculated at each grid point on reference grid. The descriptive statistics include the minimum, maximum, mean, median and standard deviation for each of the three individual components (X, Y, Z), the Resultant field, and the major and minor axes. The order statistics show the field levels in the calculations below which a certain percentage fall. For example, order statistics show that 90% of the calculations are below 8.3 mG.
- The *profile plot* presents a two dimensional view of the magnetic field strength in one dimension. That is, the strength of the magnetic field is given with respect to the profile line segments. User can choose to display any of the three individual components of the magnetic field vector (X, Y, Z), the Resultant field, the maximum field (major axis), or the minimum field (minor axis).

CHAPTER 5

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EXPERIMENTAL AND SIMULATION STUDIES

Magnetic field measurements and simulations are performed on two typical substations: an indoor type 69/13.8 kV substation and an outdoor type 115/13.8 kV substations. Some magnetic field management (reduction) techniques were also simulated. A small substation used to supply power to a mosque, is also analyzed for shielding effects.

5.1 Measurement Methodology

In order to measure the magnetic field, substations were divided into small sub-areas by means of horizontal and vertical profiles to form a uniquely-spaced grid. A spacing of 2 meters was used throughout. The magnetic field was measured on the points of intersection of the grid at a height of 1 meter above the ground level.

Essentially all measurements were made within four hours window from 9:00 AM to 1:00 PM. The aim was to increase the likelihood of obtaining a set of measurements with little fluctuation in the distribution load.

All the measurements were taken while the instrument is pointing to the same direction as of that we started with at the reference. Secondly, the magnetic fields were measured along similar set of profiles spaced 2 meters apart and running East-West inside the substations. Some difficulties were experienced while taking these measured values. In some cases, an object such as a transformer, breaker, regulator, or structure may block the path of the mapping wheel. In other cases, an access to some locations like the high tension circuit breaker compartment in indoor type substation is impossible for safety reasons. Moreover, a uniform height from the ground level could not be maintained due to level differences between inside building and outside substation in indoor type stations.

These measurements were used to generate contour maps and three dimensional plots of the magnetic fields. An interactive package DELTAGRAPH was used to produce these maps and plots. In the places where magnetic fields can't be measured, a value equal to the highest measured value in a particular location (or zero) was assumed to give an indication of such places. DELTAGRAPH assumed uniform spacing all the time. However, this assumption is ignored in specific areas due to the difficulties mentioned previously.

To have a good understanding of characteristics of magnetic fields, measurement were taken around different substation's equipment like power transformers, auxiliary transformers, circuit breakers, cable trenches, and high voltage buses. For power and auxiliary transformers measurements were conducted just on their borders and 1 meter away from the borders at various height levels. These measurements were fed into DELTAGRAPH to produce the plots.

Another difficulty associated with measurements is related to the three phase bus and feeder currents. Current indicators which were available in the low tension switchgear room were not of great preciseness. Low-value incoming or feeder currents are almost zero as indicated by their corresponding meters. If transformer loading is used to calculate these currents, a fair estimate can be obtained for incoming currents but actual distribution of this current to feeders still represents a difficulty. Moreover, currents were assumed to be balanced just to simplify things although this may not be the real practical situation.

Substation geometry related measurements were highly dependent on the drawings drawn for planned construction which might differ from actual design.

5.2 Simulation Methodology

To calculate the magnetic flux density in the substation, an interactive software SUBCALC is used which is based on closed form solution of the Biot-Savart Law. The program has provision to model major sources of magnetic fields in any substation, namely buses, overhead transmission and distribution lines, underground cables and live tank circuit breakers. It is assumed that the substation current carrying elements can be represented by straight line segment with the current constant for the entire length of each segment. The beginning and ending three dimensional coordinates for each segment have to be specified. In addition, the magnitude and phase angle of the currents passing through all of the segments should be entered. The program has the capability of plotting graphics representations of the following information:

1. Side view of entered data along selected profile lines.
2. Top view of entered data.
3. Contour plot of calculated magnetic fields.

4. 3-D Plot of calculated magnetic fields.
5. Profile plot of calculated fields along selected profile lines.
6. 3-D View of entered data (substation).

The profile lines are drawn either parallel to x-axis or y-axis with point increment of 7 ft. and separated by 7 ft. to make it comparable with the measurement grid. The height of the lines are selected to be one meter (3.28 ft.) above the ground.

Due to the limitations in the software, some common assumptions are used to simplify the modeling process. These assumptions are :

- Balanced loads and normal operating conditions.
- Neutral and ground currents are ignored.
- Transformers, reactor devices and circuit breakers are represented by continuous line segments.
- Underground distribution circuits are phased in a fixed pattern.
- Control cables and low voltage lights are not modeled.
- Tie breakers are considered to be open.
- Incoming transmission lines supplying the substation and outgoing feeders are part of the model.
- Field distortion due to metallic structures and substation equipment is ignored.
- Induced currents in ground wires and ground conductors are not taken into account.
- The effect of finite conductivity of the soil is ignored.
- Cables are considered as buses, therefore cable insulation and phase clearances have not been considered.

Because of all these assumptions, some discrepancies are expected. However, the model still gives, as will be seen shortly, acceptable results.

5.3 Case I: Indoor Substation

5.3.1 Substation Description

The single line diagram of the substation is Shown in Figure 5-1. This substation has two main 69/13.8 kV, 30/40 MVA transformers operating in parallel. The buses are arranged in inverted π-configuration. There are two in-coming and seven outgoing feeders in this substation. The incoming 69 kV lines are installed on double-circuit lattice steel structures. The 13.8 kV outgoing feeders are all three core cables. Two of these feeders supply the station service transformers.

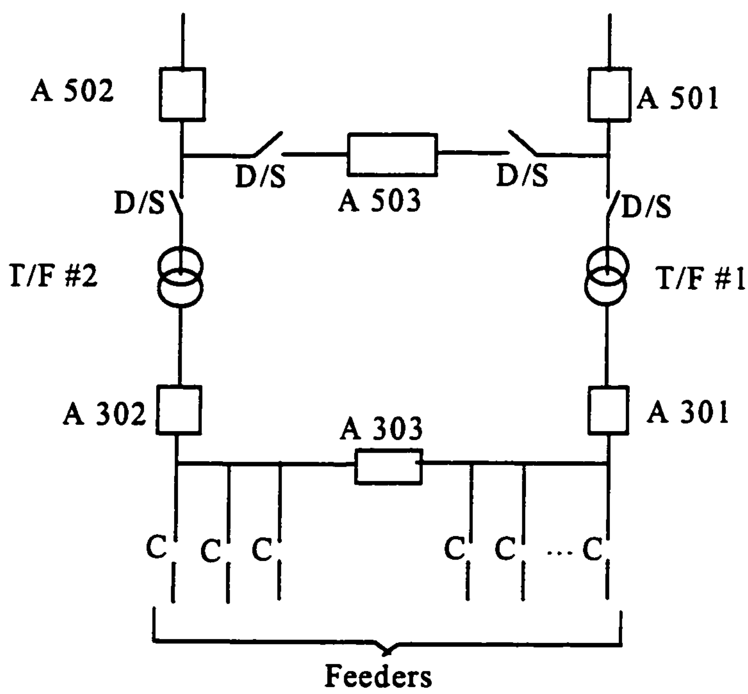

Figure 5-1: Single line diagram (Case I).

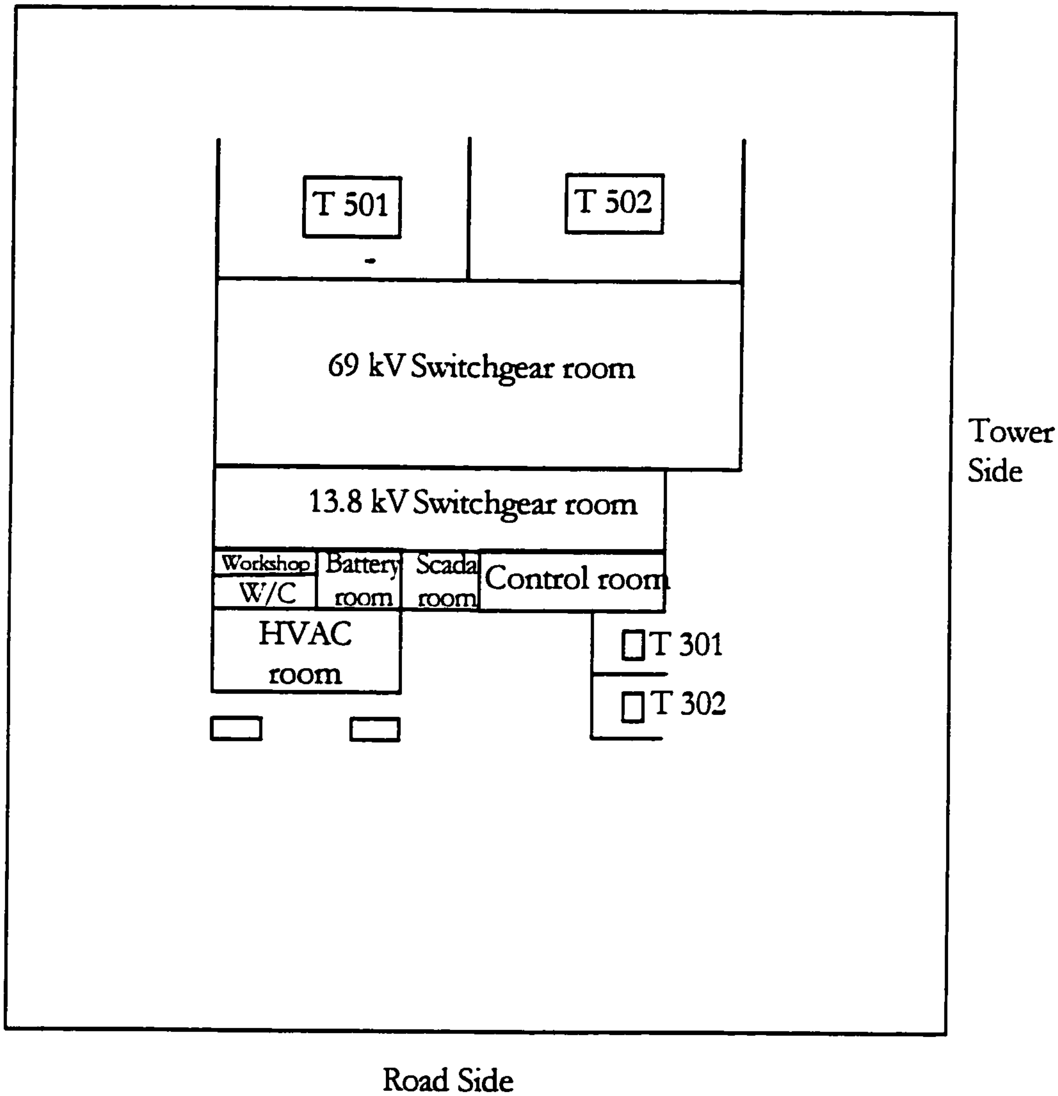

Figure 5-2: Substation Layout (Case I).

5.3.2 Measurement Results

To take the readings of the magnetic field in the whole substation, a grid is drawn in the substation yard. Then the readings are taken at each intersection point of the grid. The substation layout is shown in Figure 5-2.

The magnetic field readings were carefully measured with a particular emphasis on the sources of magnetic field such as main power transformers, station service transformers and the 69 kV and 13.8 kV buses. The magnetic field values in the different rooms of the substation have been measured also. These include the 69 kV and 13.8 kV switchgear rooms, the battery room, the control room in addition to the basement. The contours and 3-D maps of the measured magnetic fields have been plotted using DELTAGRAPH. These are shown in Appendix A in a self explanatory manner. Some comments on the measurement results are given below.

- Usually, the magnetic fields outside the substation building were very small (from 0.1 to 4 mG) as compared to those which are recorded inside.
- In 13.8 kV switchgear room, the highest measured value was near the wall between this room and the control room (i.e. 38 mG) where the DC panels, relay panels, and other control panels are located.
- The magnetic fields in the 69 kV switchgear room were very low (in the range of 3.9 mG to 5 mG), because of the low current in the equipment inside.
- No significant values were measured in the battery room (i.e. max. of 12 mG).
- The highest measured value in the whole substation ground floor was found in the control room (i.e. 88 mG) due to the existence of the control panels.
- For the power (T501, T501) and auxiliary (T301, T302) transformers, high magnetic values (i.e. 1000 mG or more) were recorded in the LV side because of the high current in the secondary side cables.
- In the basement, high magnetic field values (max. 288 mG) were measured due to the presence of LV underground cables. Particularly, these fields are intensified where the cable has bent. This is because of the applied mechanical force on the cable insulation.

5.3.3 Simulation with actual currents

On the day of measurement, the currents in the different conductors were noted. Using these readings of current (40/200 A), entire substation is modeled and the contours, 3-D and profile plots are produced using SUBCALC. Substation layouts and magnetic field plots are shown in Appendix B. The magnetic field descriptive statistics are shown in Table 5-1.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.01	774.48	9.24	47.80	774.48
Y Component	0.01	174.07	4.36	15.46	158.54
Z Component	0.00	318.52	6.69	27.87	81.94
Resultant	0.07	790.71	14.33	56.95	790.71
Major Axis	0.07	778.48	14.25	56.26	778.48
Minor Axis	0.00	138.50	1.26	7.50	138.50

Table 5-1: Case I-Magnetic Field Descriptive Statistics.

To test the validity and the accuracy of the model, profile lines are drawn as shown on the top view of substation model in Figure 5-3. Both measured and simulated magnetic field values were obtained along these profiles as shown in Figure 5-4 to Figure 5-9. It is clear that the model gives a fair estimate of the actual magnetic field values along most of the profiles.

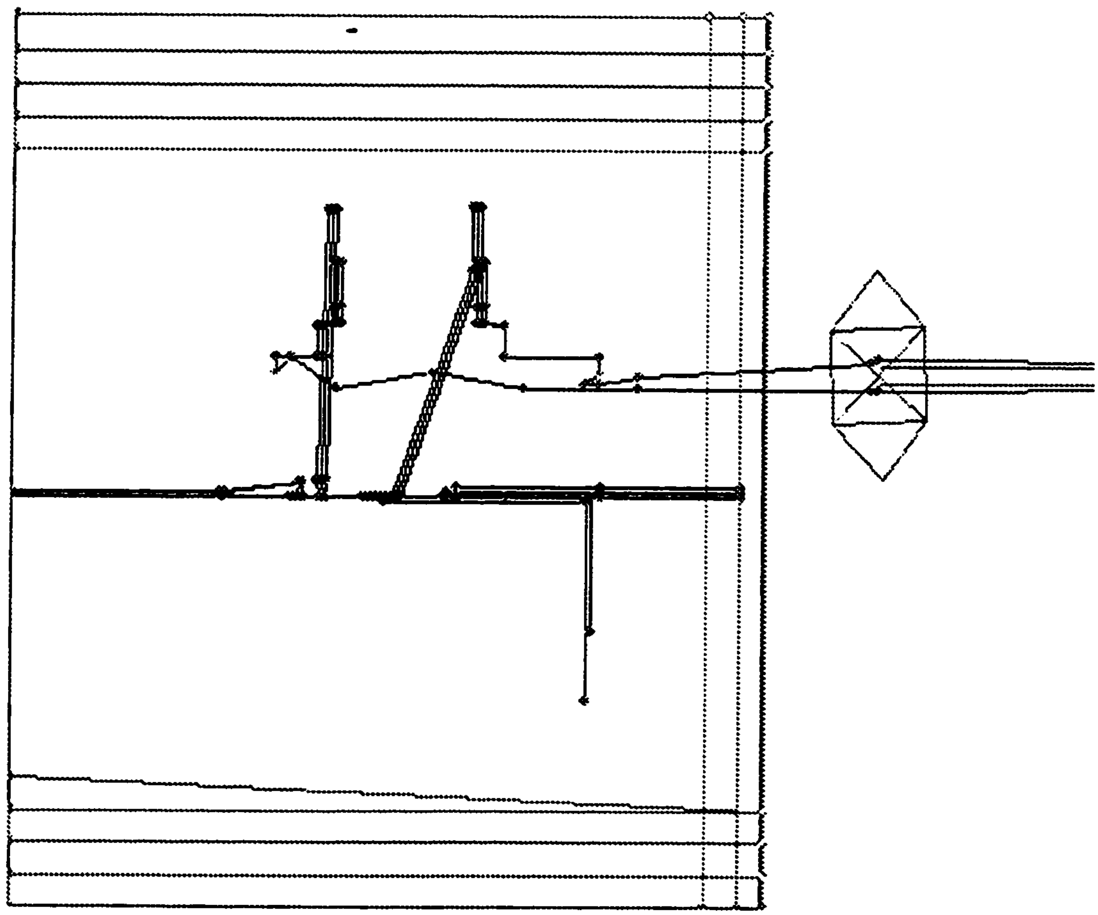

Figure 5-3: Case I-Top view of substation model with profile lines.

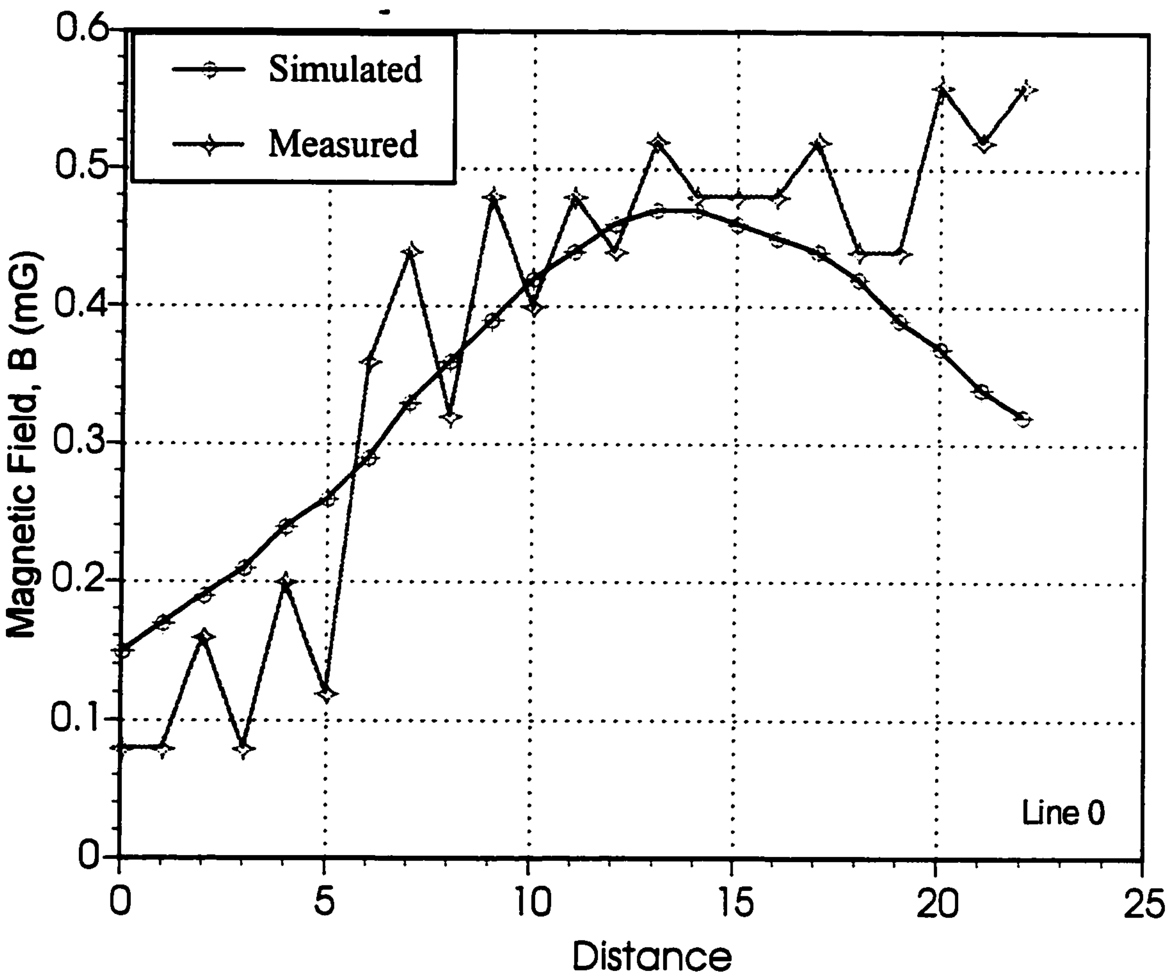

Figure 5-4: Case I-Magnetic Field profiles.

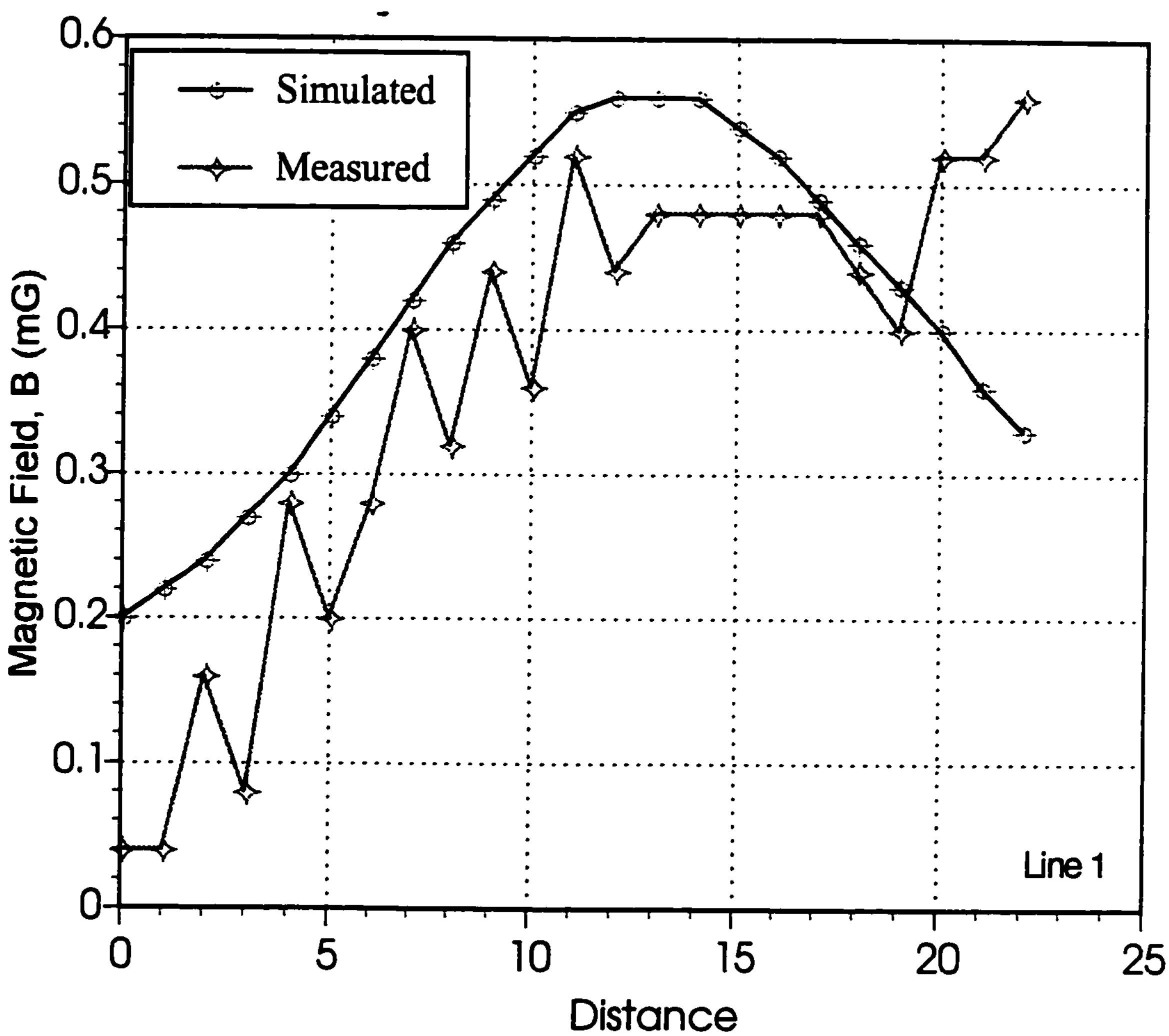

Figure 5-5: Case I-Magnetic Field profiles.

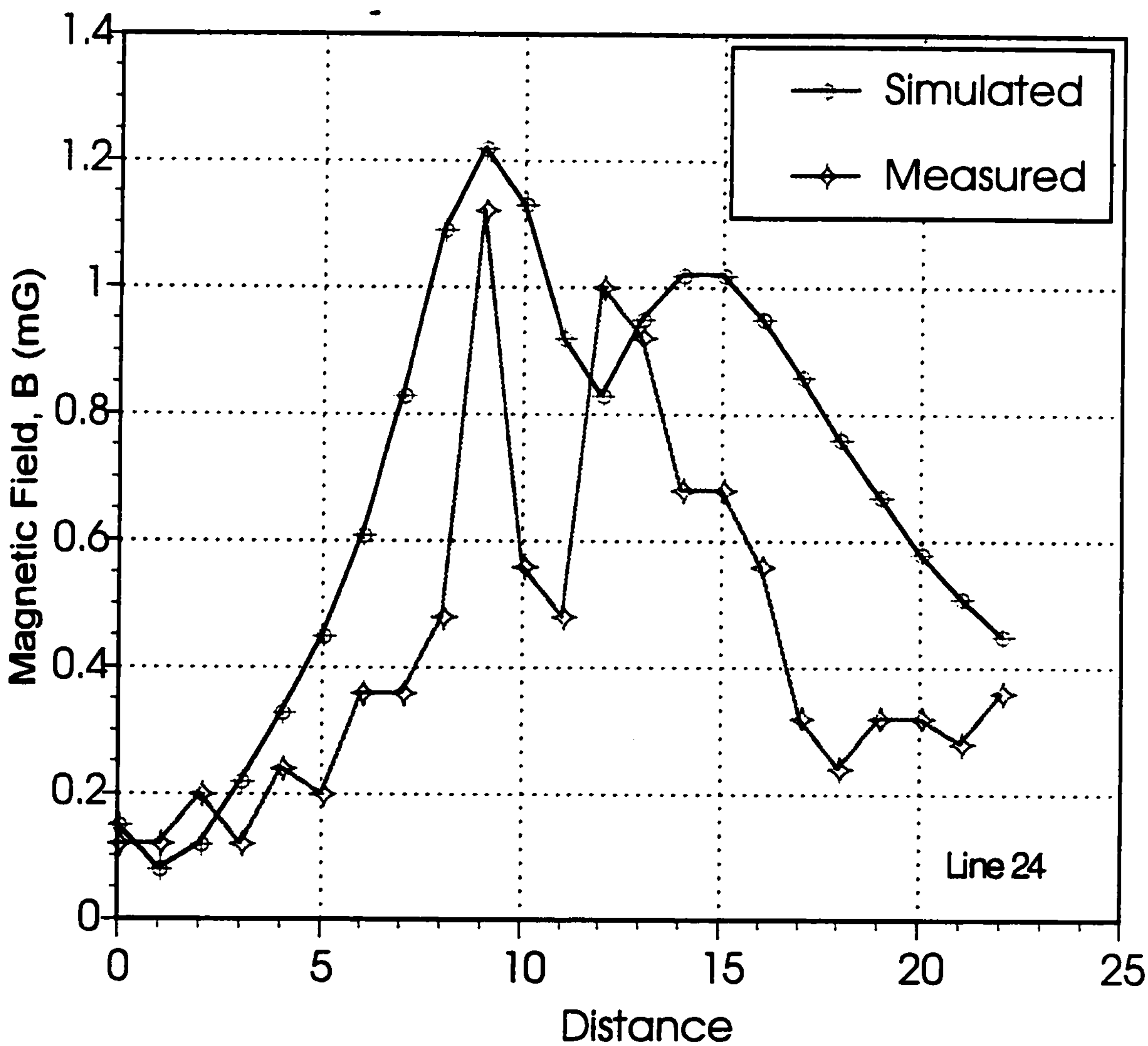

Figure 5-6: Case I-Magnetic Field profiles.

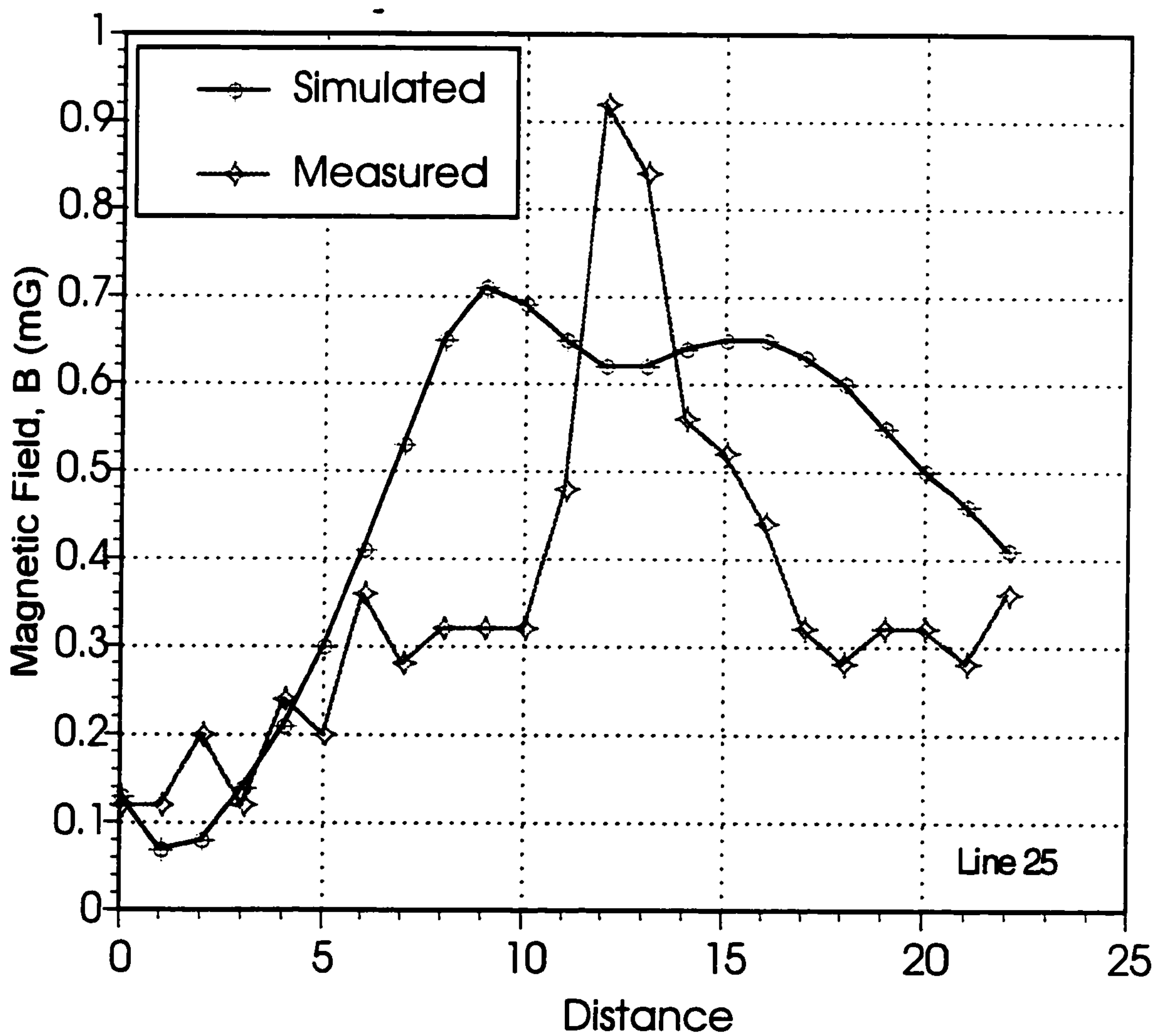

Figure 5-7: Case I-Magnetic Field profiles.

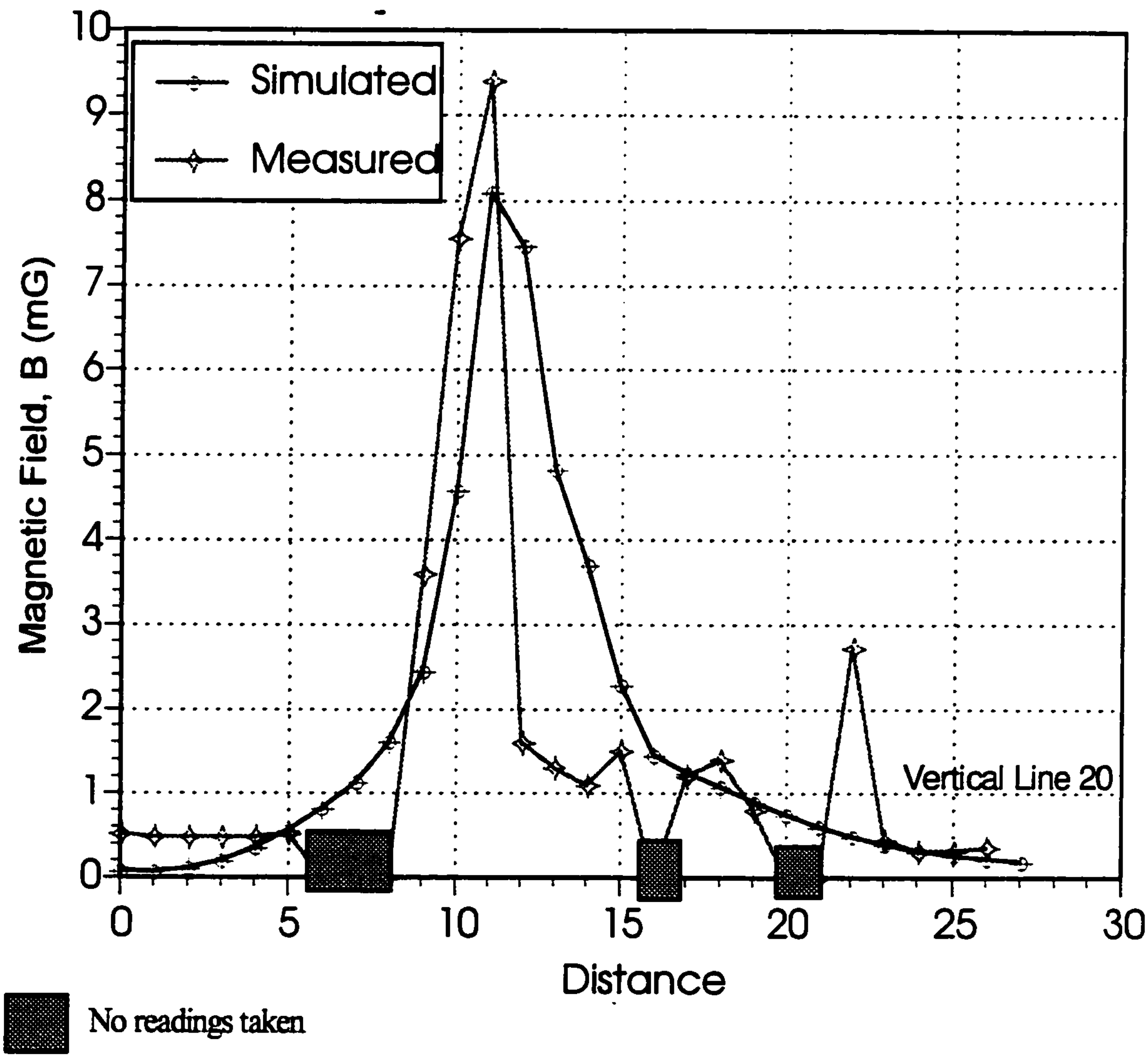

Figure 5-8: Case I-Magnetic Field profiles.

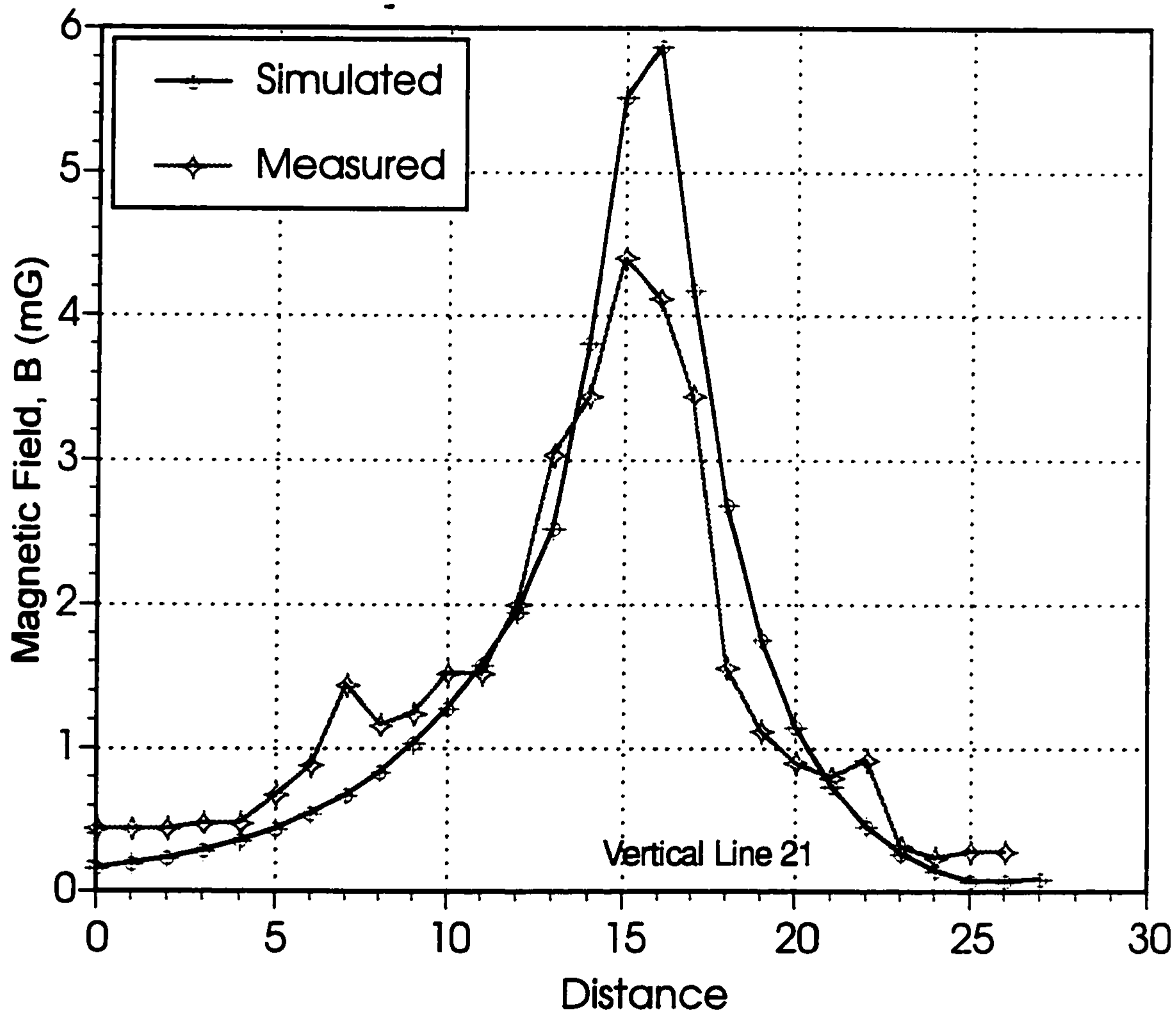

Figure 5-9: Case I-Magnetic Field profiles.

5.3.4 Simulation with rated currents

Using the rated current (250/1250 A), the substation is modeled using SUBCALC. The magnetic field descriptive statistics are shown in Table 5-2.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.04	3872.03	50.50	261.12	3872.03
Y Component	0.02	822.31	23.93	80.44	791.80
Z Component	0.02	2511.08	43.27	198.64	416.48
Resultant	0.22	3953.02	85.82	334.27	3953.02
Major Axis	0.22	3891.95	85.41	331.26	3891.95
Minor Axis	0.01	692.17	6.95	18.20	692.17

Table 5-2: Case I-Magnetic Field Descriptive Statistics (rated current).

5.3.5 Simulation with rated currents and elevated buswork

The substation is modeled in SUBCALC using the rated current with buswork elevated by 2 ft.,. The magnetic field descriptive statistics are shown in Table 5-3. The magnetic field profiles are shown in Figure 5-10 to Figure 5-15.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.09	2777.37	65.75	268.31	2777.37
Y Component	0.16	955.39	30.40	85.59	792.95
Z Component	0.18	2767.74	67.61	250.90	1153.00
Resultant	1.29	2941.16	115.63	372.43	2941.16
Major Axis	1.18	2900.78	111.93	364.99	2900.78
Minor Axis	0.26	683.15	25.87	19.10	683.15

Table 5-3: Case I-Magnetic Field Descriptive Statistics (rated current with elevated bus).

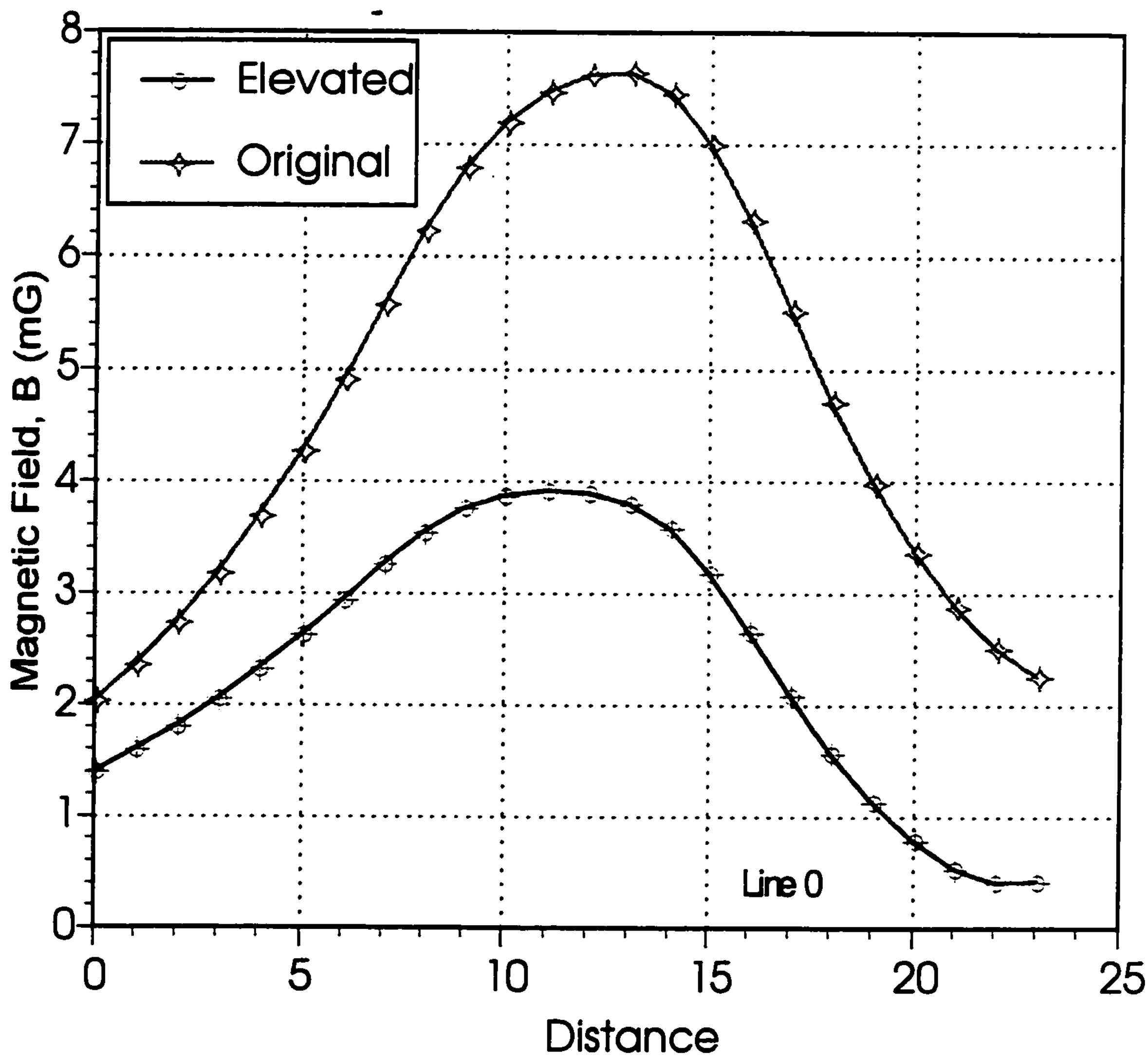

Figure 5-10: Original and Elevated Magnetic Field profiles.

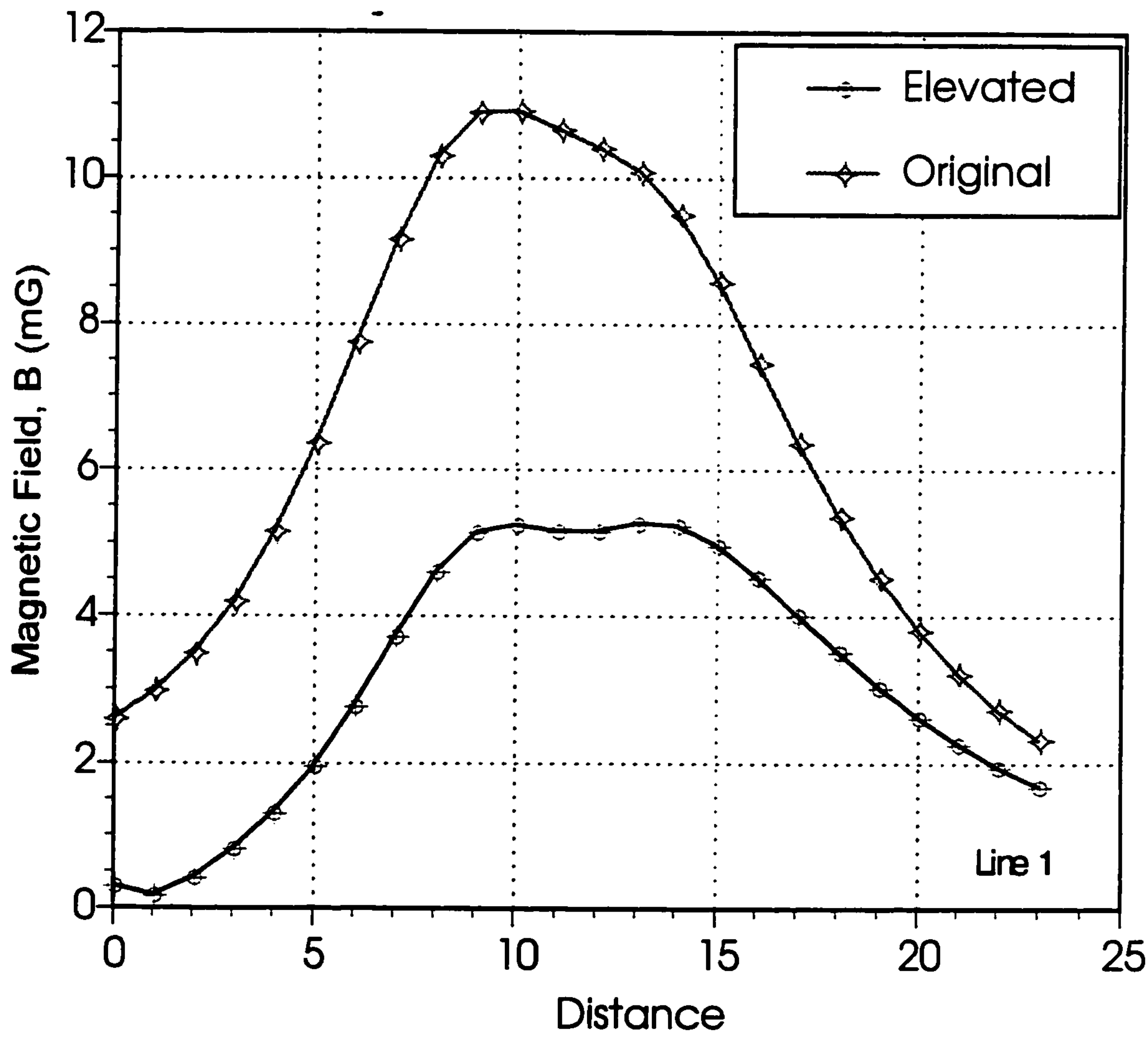

Figure 5-11: Original and Elevated Magnetic Field profiles.

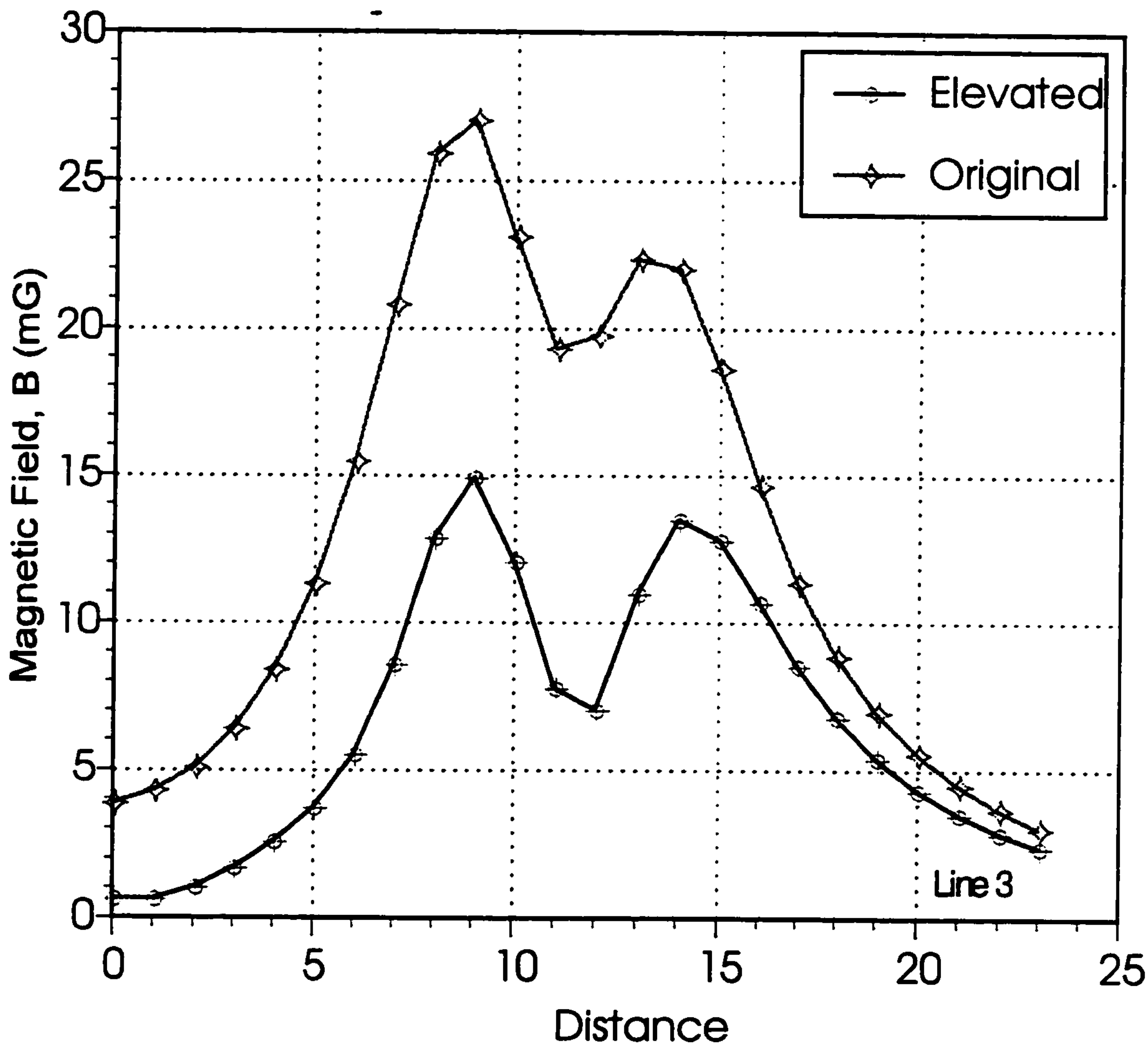

Figure 5-12: Original and Elevated Magnetic Field profiles.

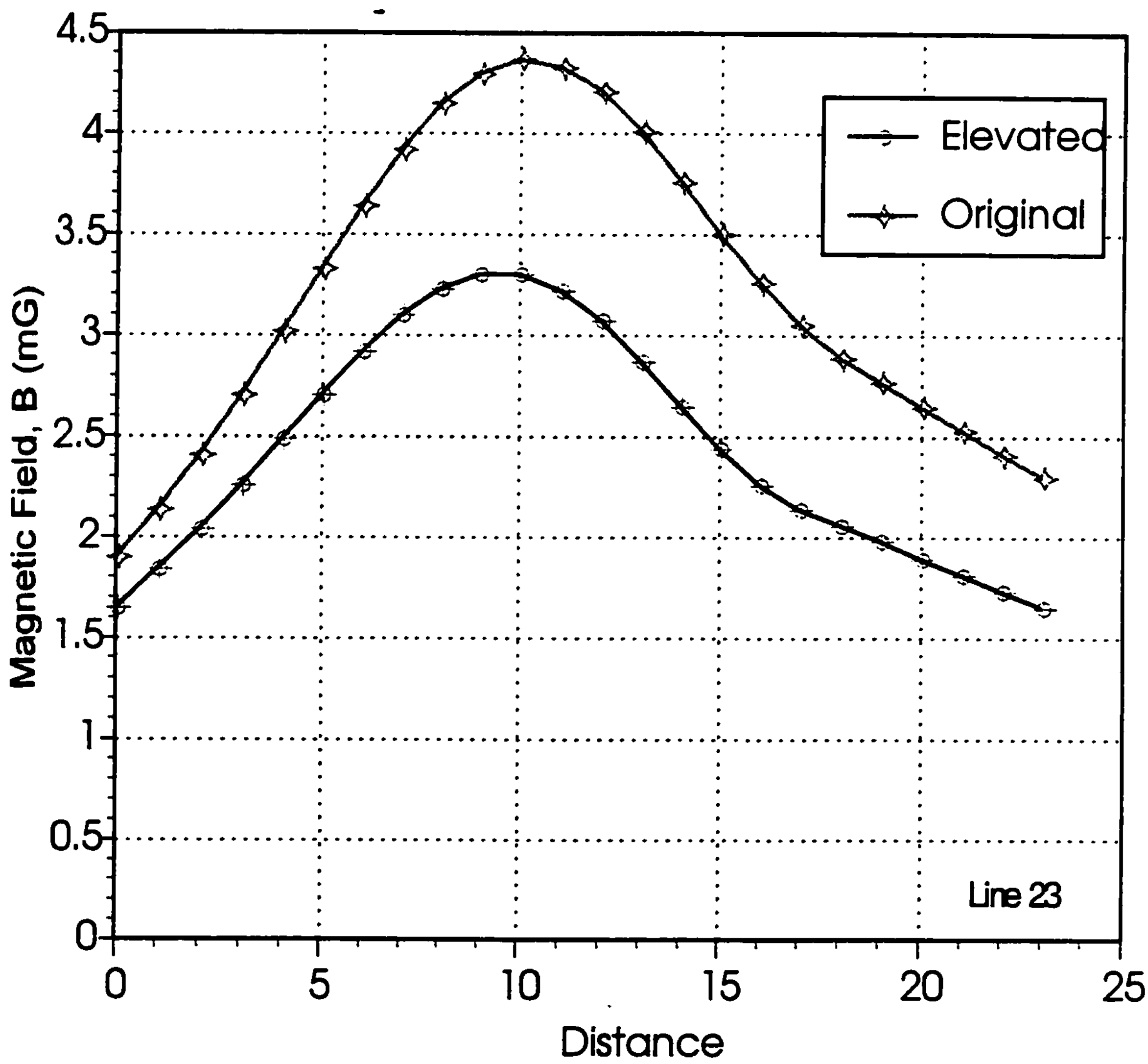

Figure 5-13: Original and Elevated Magnetic Field profiles.

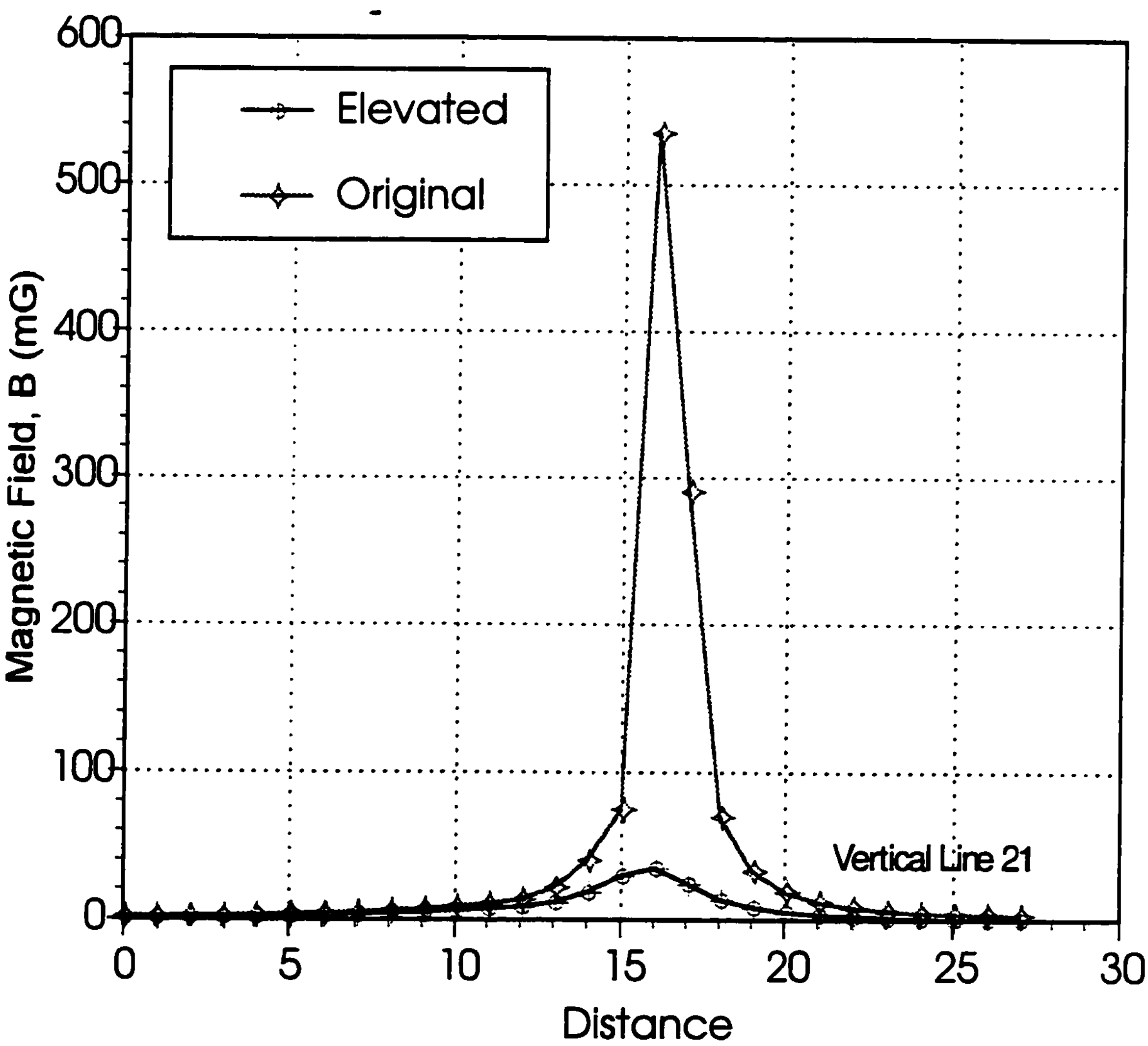

Figure 5-14: Original and Elevated Magnetic Field profiles.

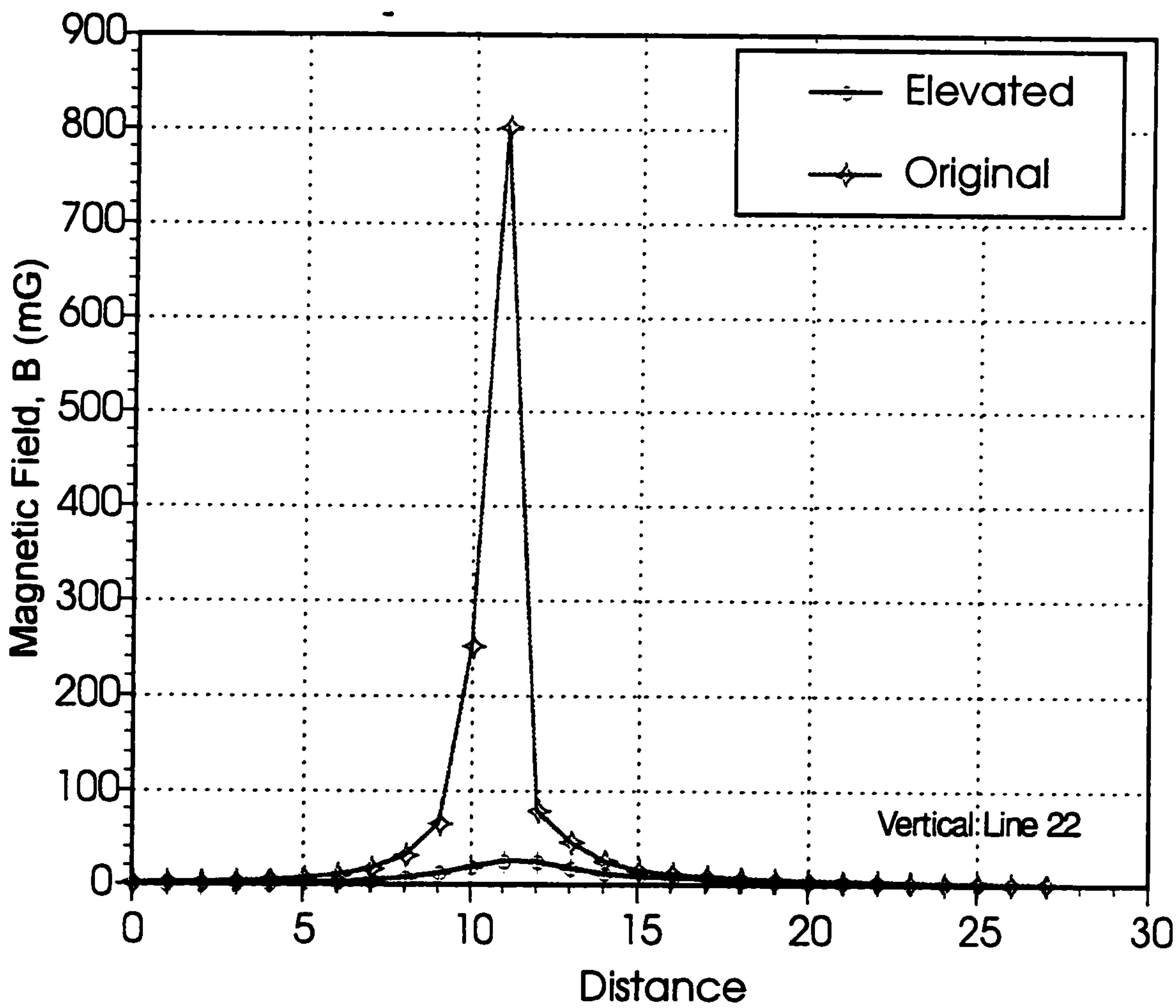

Figure 5-15: Original and Elevated Magnetic Field profiles.

5.3.6 Comments on Simulation Results

Following are the analysis results of the comparison between measurement and simulation:

- As can be seen, the contour maps show a high field concentration on the secondary side of the power transformers and the 13.8 kV bus. This is quite justifiable, because magnetic fields are proportional to current flowing in a conductor. Some discrepancies were noticed because of the previous assumptions such as modeling of power cables as bared buses, ignorance of transformer shielding, and neglecting field distortion due to existence of steel structures.
- The simulated max. resultant magnetic field is 790.7 mG.
- Along most of the profiles, the simulated field is following the measured field values. Discrepancies are due to the measurement and modeling assumptions.
- At some locations, measurements cannot be taken due to the presence of buildings or equipment. These regions are marked by patterned box.

Following are the comparative results of simulated magnetic field for rated currents and for rated currents with buswork elevated by 2 ft. :

- The max. resultant magnetic field is 3953 mG as compared to 2941.16 mG when buswork is elevated. The overall reduction is more than 25%.
- Magnetic field profiles show significant reduction in field because it is simulated for full rated currents.
- The reduction effect is more dominant near the magnetic field sources.
- At some locations (under incoming transmission lines), field reduction is around 5 to 7 times.

5.4 Case II: Outdoor Substation

5.4.1 Substation Description

The single line diagram of the substation is shown in Figure 5-16. This substation has two (115 / 13.8 kV), 30 / 40 MVA transformers connected to operate in parallel. The circuit breakers are arranged in π-configuration. The substation under consideration has two incoming and sixteen outgoing feeders. The incoming 115 kV over head lines are installed on double circuit wooden pole structure. However, the outgoing feeders are all 13.8 kV , 3-C underground feeders are two of which feed the station service transformers.

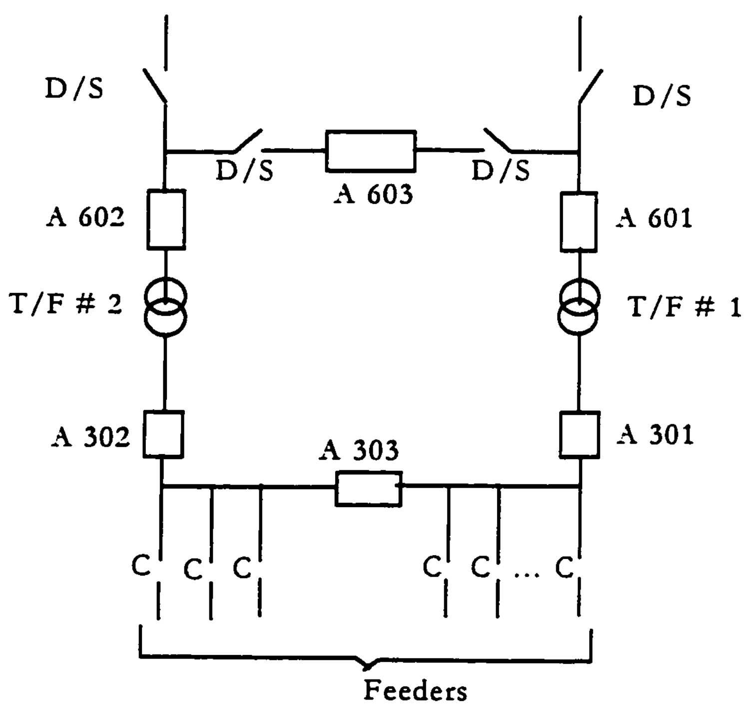

Figure 5-16: One-line diagram (Case II).

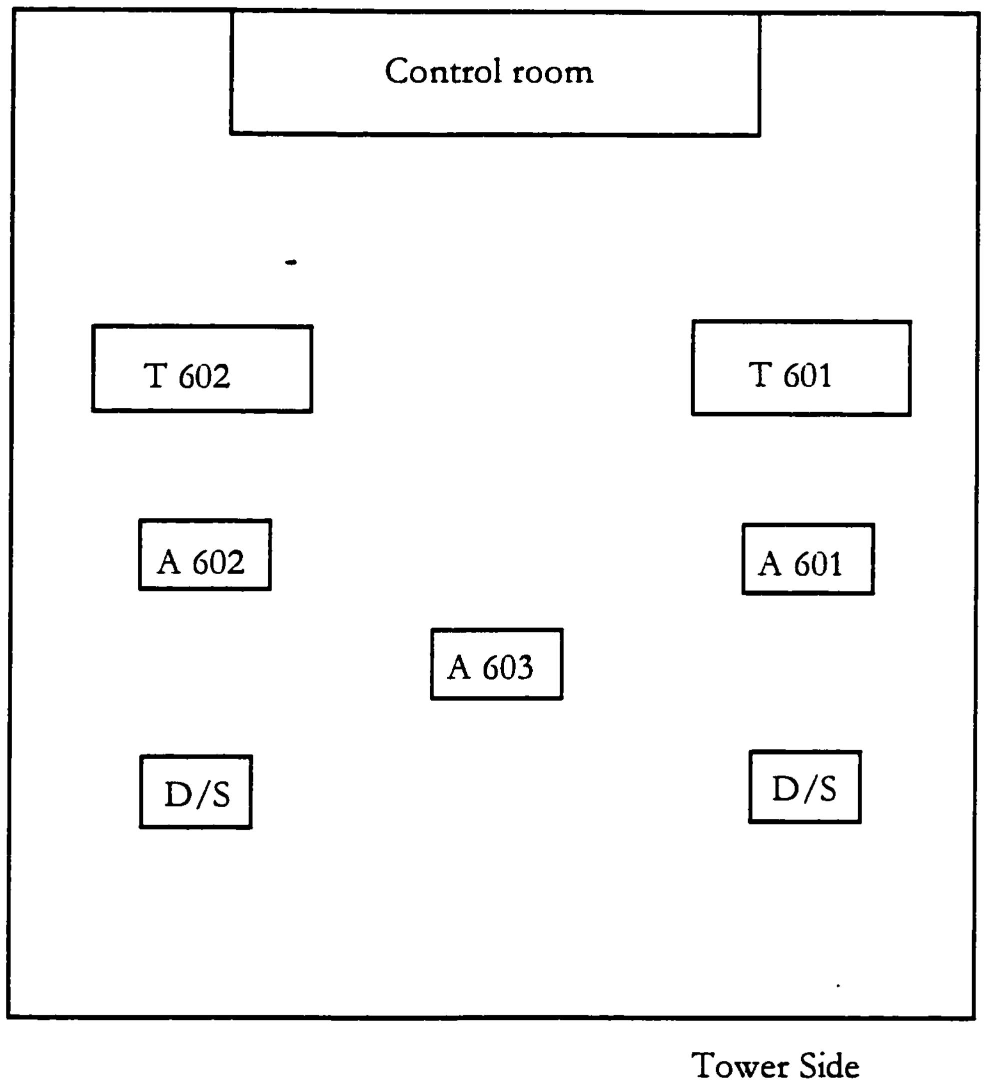

Figure 5-17: Substation Layout (Case II).

5.4.2 Measurement Results

The layout of this substation is shown in Figure 5-17. Following the measurement methodology described earlier, the measurement results are shown in both contour and 3-D maps in Appendix C. A title on each figure helps in understanding these graphs.

It is clear from the substation data that the maximum measured magnetic field is 288 mG. This occurs only at areas close to the power transformers. At other places of the substation yard, the magnetic field is generally of a small value (0.36 to 18.4 mG). This is also very clear from the substation yard contour and 3-D plots.

The cable trench measurements show some high values of magnetic fields (36.8 mG to 272 mG). This is natural because the low voltage (LV) cables carry high currents as compared to some other equipment. The higher values of magnetic fields occur at the side of the cable trench that is adjacent to the transformer LV side.

For the power transformers, the measurements show that the maximum magnetic field values are measured beside the LV cables. Values of 2000 mG and more are measured very close to the LV cables.

5.4.3 Simulation with Buswork Phasing ABC-ABC

The substation is modeled with the aid of SUBCALC. Simulation results are shown in Appendix D with directive headings. The magnetic field descriptive statistics are shown in Table 5-4.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.03	611.69	7.64	43.18	455.21
Y Component	0.03	928.33	9.80	59.21	928.33
Z Component	0.66	597.83	20.72	67.42	576.54
Resultant	0.87	1052.01	27.80	98.62	1052.01
Major Axis	0.76	1049.83	27.30	97.47	1049.83
Minor Axis	0.03	193.89	4.28	9.87	89.03

Table 5-4: Case II-Magnetic Field Descriptive Statistics(phasing ABC-ABC).

5.4.4 Simulation with Buswork Phasing ABC-CBA

The substation is modeled again with buswork phasing ABC-CBA. The magnetic field descriptive statistics are shown in Table 5-5.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.00	611.00	7.27	41.81	455.38
Y Component	0.00	928.29	9.15	59.05	928.29
Z Component	0.36	598.60	20.09	67.60	577.27
Resultant	0.75	1052.24	26.55	98.18	1052.24
Major Axis	0.69	1050.08	26.05	97.05	1050.08
Minor Axis	0.04	193.75	4.22	9.85	88.81

Table 5-5: Case II-Magnetic Field Descriptive Statistics (phasing ABC-CBA).

To test the validity and the accuracy of the model, profile lines selected as shown in Figure 5-18. Measured and simulated (ABC-ABC and ABC-CBA phasing) magnetic field values were plotted along these profiles as shown in Figure 5-19 to Figure 5-24.

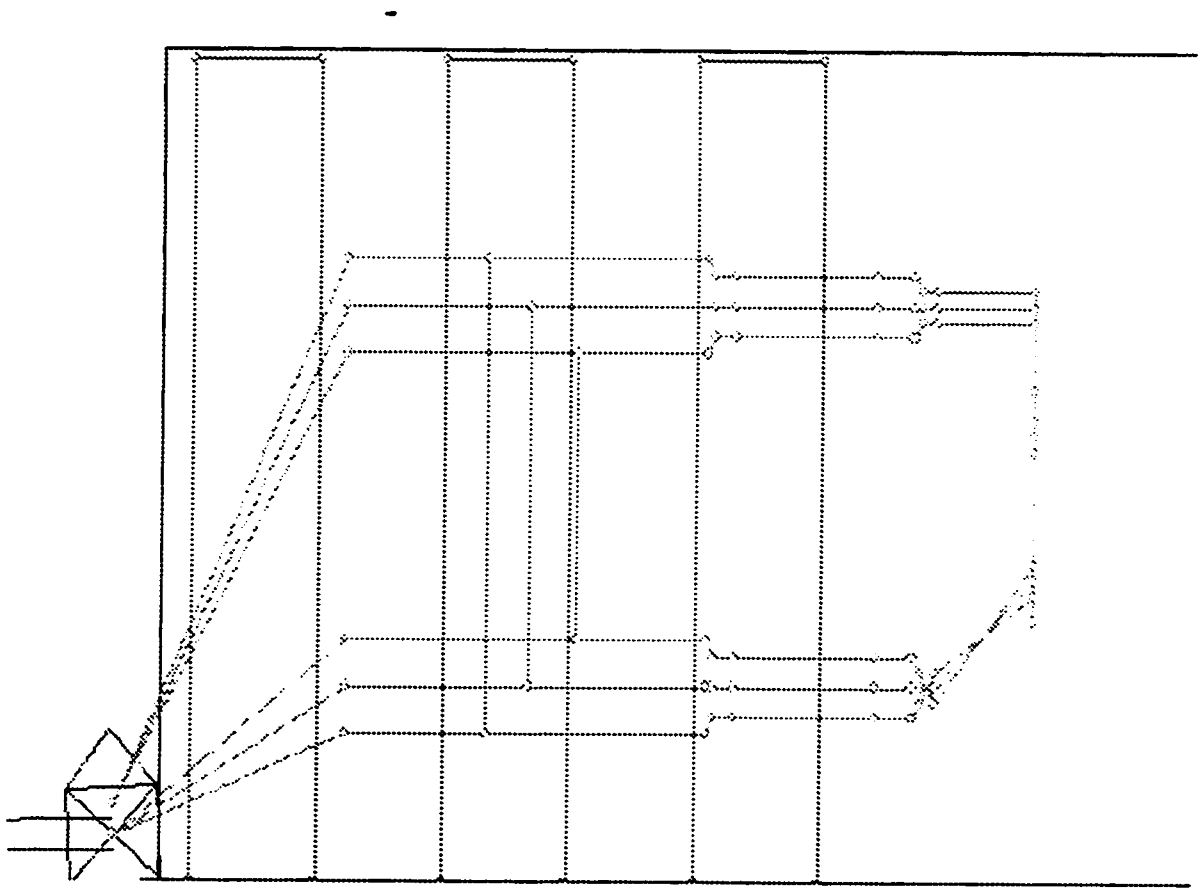

Figure 5-18: Case II-Top view of substation model with profile lines.

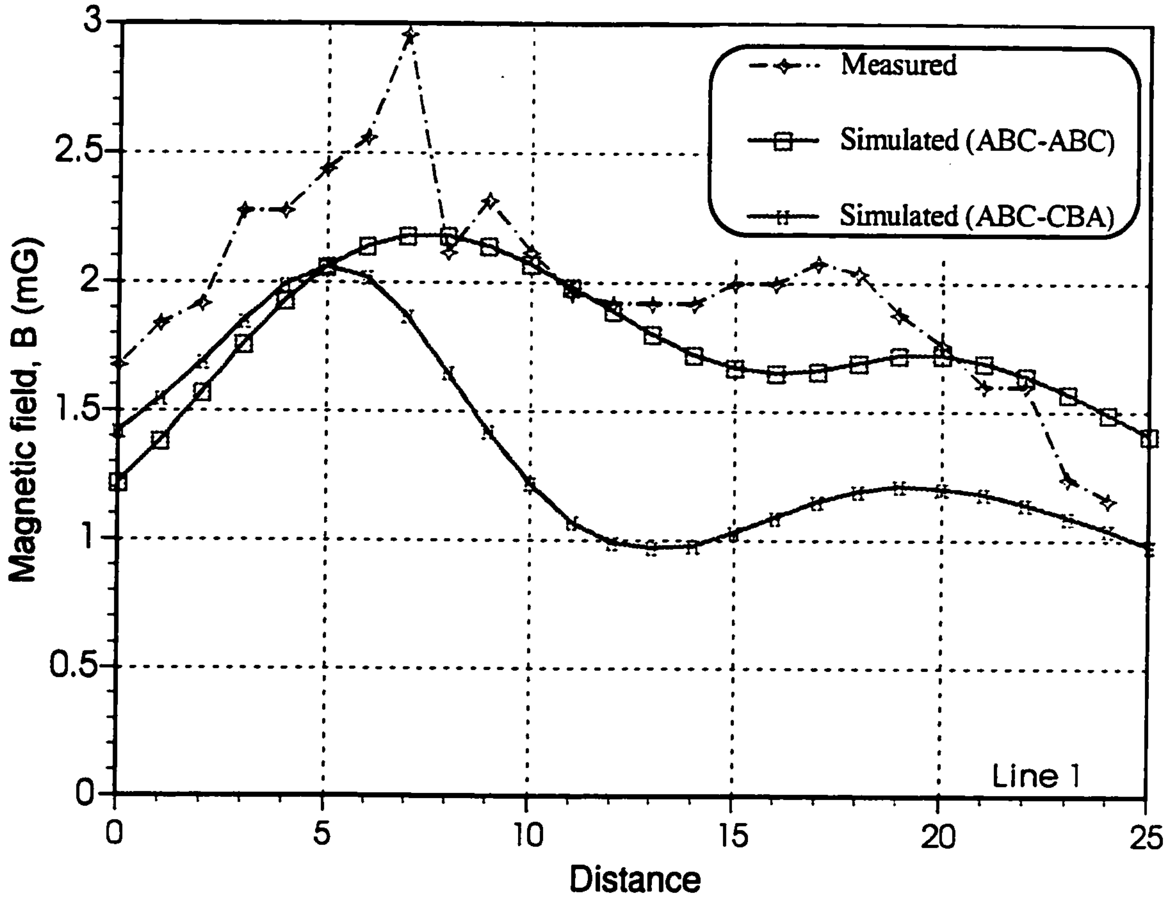

Figure 5-19: Case II-Magnetic Field profiles.

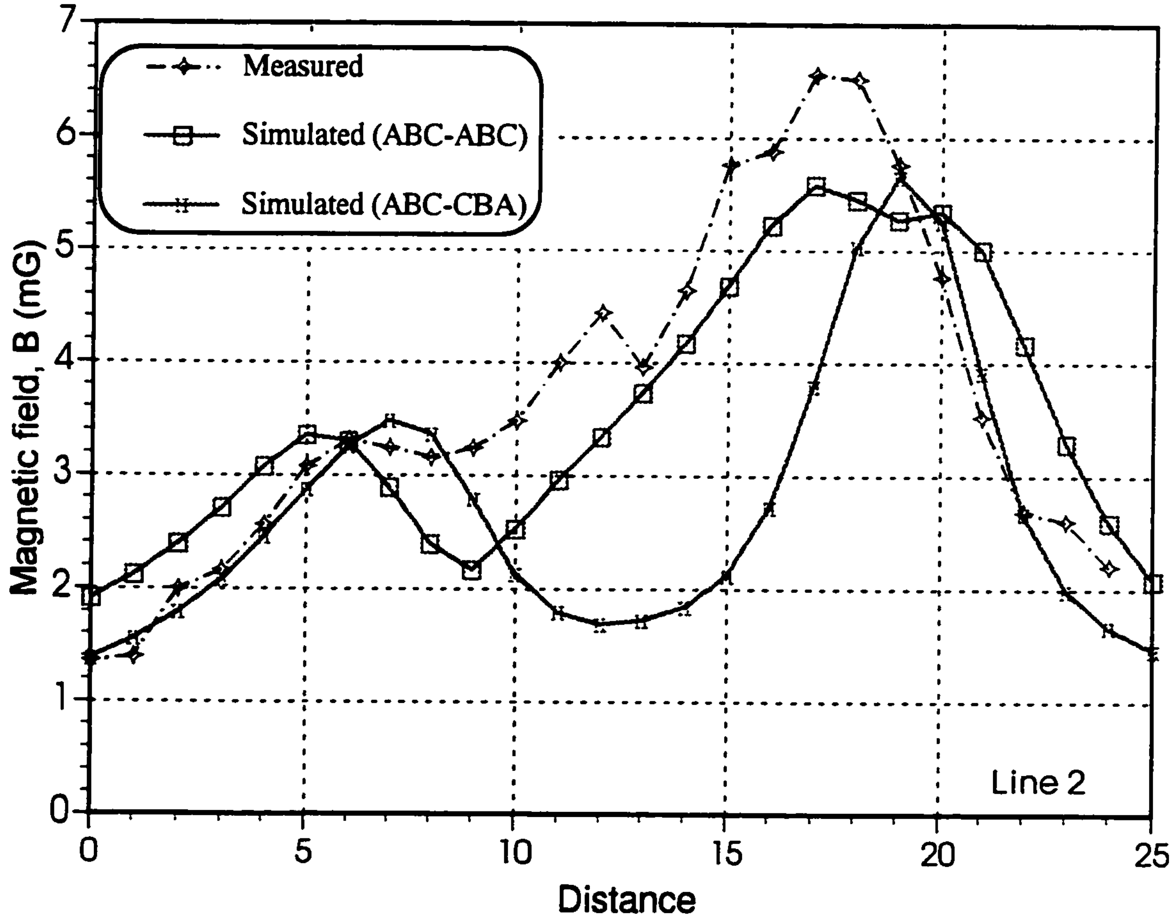

Figure 5-20: Case II-Magnetic Field profiles.

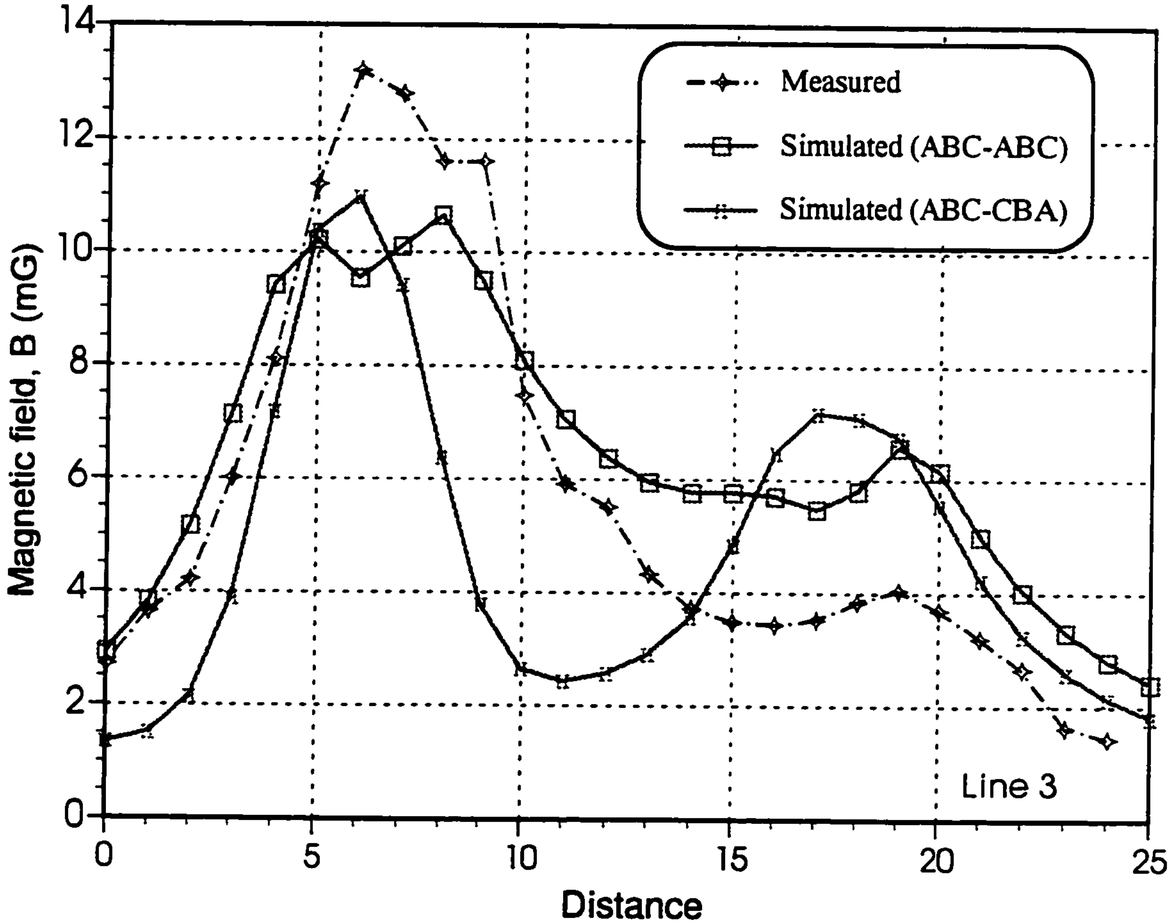

Figure 5-21: Case II-Magnetic Field profiles.

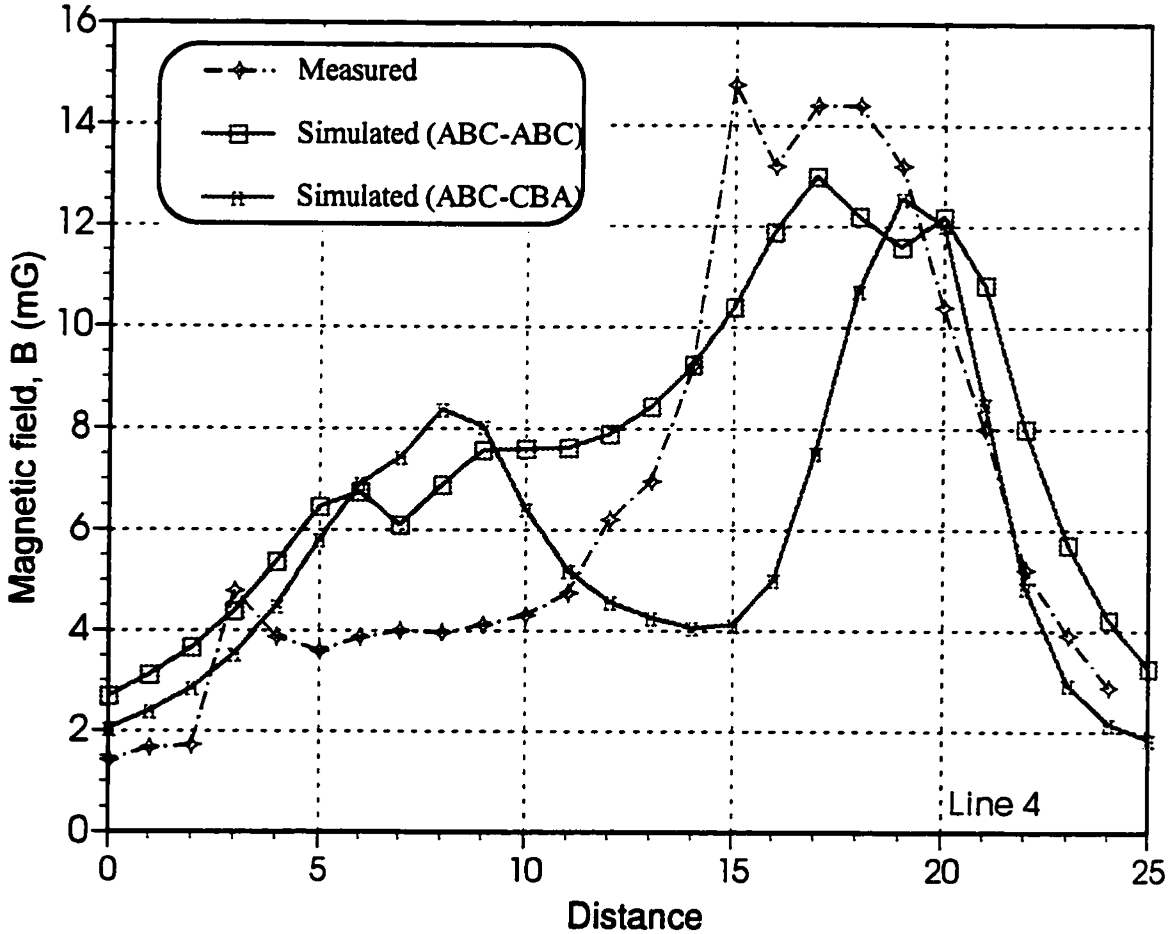

Figure 5-22: Case II-Magnetic Field profiles.

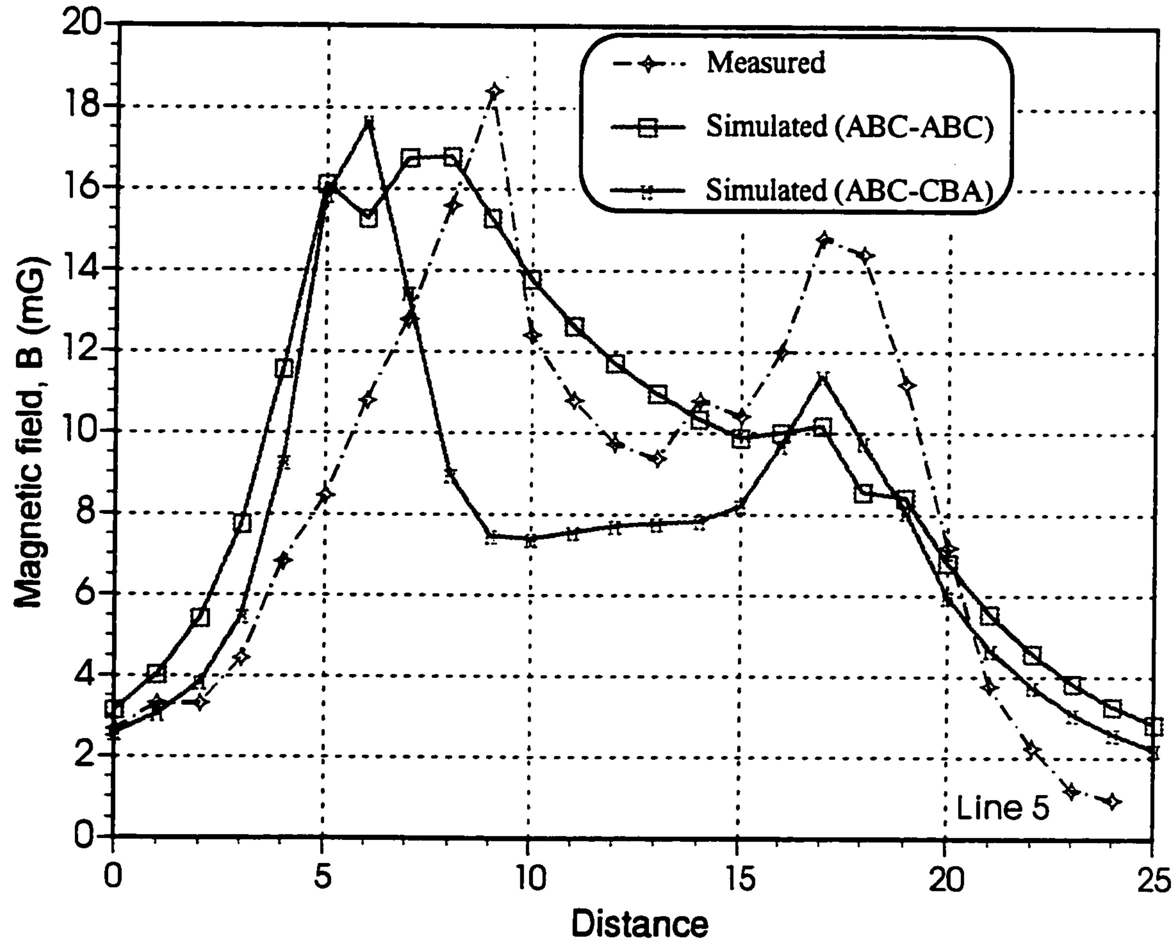

Figure 5-23: Case II-Magnetic Field profiles.

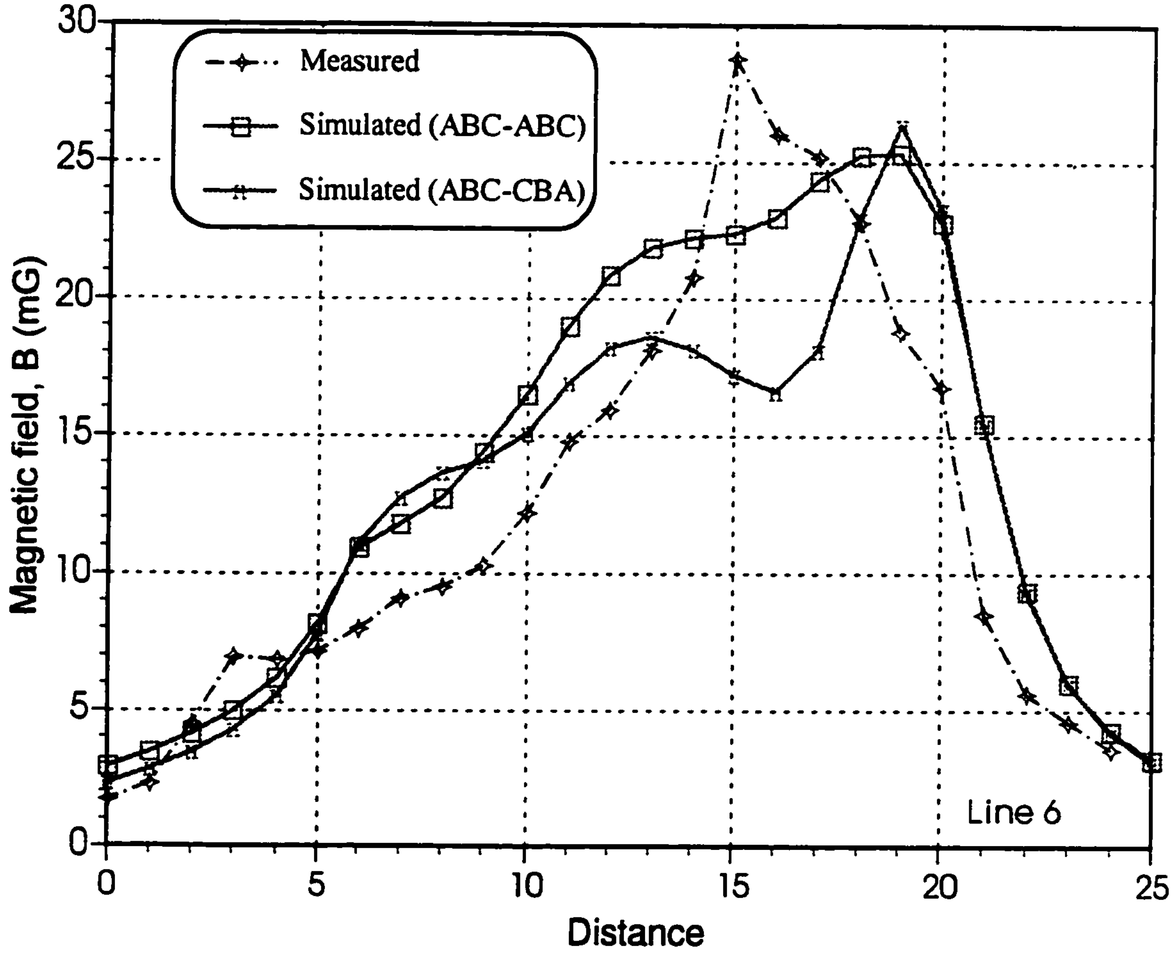

Figure 5-24: Case II-Magnetic Field profiles.

5.4.5 Simulation with Increased Elevation of Conductors

As a first design option, conductors are raised by one and half feet for case II. The magnetic field statistics are shown in Table 5-6. The layout diagrams and magnetic field plots are shown in Appendix-E.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.03	645.72	9.12	45.43	341.53
Y Component	0.02	897.82	9.37	56.60	897.82
Z Component	0.33	444.01	17.27	51.88	424.54
Resultant	0.75	994.48	24.90	88.36	994.48
Major Axis	0.69	989.05	24.36	86.98	989.05
Minor Axis	0.07	197.43	4.26	9.33	103.75

Table 5-6: Case II-Magnetic Field Descriptive Statistics (conductors raised by 1½ ft.).

5.4.6 Simulation with Buswork Compaction by 1 feet

Case II is simulated with compacted buswork to study the effect on magnetic field reduction. The magnetic field statistics are shown in Table 5-7. The layout diagrams and magnetic field plots are shown in Appendix-E.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.00	826.69	7.88	56.38	826.69
Y Component	0.02	782.37	6.55	39.04	782.37
Z Component	0.24	597.56	18.94	64.86	576.32
Resultant	0.62	964.99	25.08	93.51	964.99
Major Axis	0.53	961.70	24.70	92.63	961.70
Minor Axis	0.04	150.06	3.59	9.62	79.67

Table 5-7: Case II-Magnetic Field Descriptive Statistics (compaction by 1 ft.).

5.4.7 Simulation with Buswork Compaction by 2 feet

Conductors are compacted by two feet for case II. The magnetic field statistics are shown in Table 5-8. The magnetic field plots are shown in Appendix-E.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.03	776.95	6.53	45.27	456.64
Y Component	0.02	503.98	5.91	29.72	503.98
Z Component	0.35	597.57	18.11	63.62	575.29
Resultant	0.59	892.00	23.08	82.78	683.22
Major Axis	0.46	876.03	22.71	81.73	679.11
Minor Axis	0.01	168.05	3.49	9.04	74.78

Table 5-8: Case II-Magnetic Field Descriptive Statistics (compaction by 2 ft.).

5.4.8 Simulation with Buswork in Delta configuration (original spacing)

Conductors are reconfigured to Delta with original phase spacing (10 ft.) for case II. The magnetic field statistics are shown in Table 5-9. The layout diagrams and magnetic field plots are shown in Appendix-E.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.00	664.58	7.11	40.50	432.14
Y Component	0.06	818.61	7.47	41.47	818.61
Z Component	0.45	598.74	18.62	63.95	577.68
Resultant	0.92	961.09	24.17	85.55	961.09
Major Axis	0.87	957.11	23.48	84.07	957.11
Minor Axis	0.03	195.33	4.66	9.17	87.33

Table 5-9: Case II-Magnetic Field Descriptive Statistics (Delta configuration).

5.4.9 Simulation with Buswork in Delta configuration (compaction by 2 ft.)

Conductors are reconfigured to Delta with compacted phase spacing (8 ft.) for case II. The magnetic field statistics are shown in Table 5-10. The magnetic field plots are shown in Appendix-E.

B (mG)	Min.	Max.	Mean	Std. Dev.	Median
X Component	0.01	736.23	6.85	41.21	308.88
Y Component	0.07	429.11	6.55	28.07	429.11
Z Component	0.42	598.84	18.15	63.27	577.95
Resultant	0.91	810.81	23.16	79.82	588.37
Major Axis	0.87	789.18	22.52	78.23	583.03
Minor Axis	0.03	195.23	4.47	8.85	79.14

Table 5-10: Case II-Magnetic Field Descriptive Statistics (compacted Delta configuration).

5.4.10 Discussion and Comparison

- It is clear that the concentration of magnetic fields is basically around the power transformers and the 13.8 kV bus in the control room. Relatively, low magnetic field values were computed else where. This was expected as magnetic field is heavily dependent on the value of the current in the conductors.
- The maximum resultant magnetic field is 1052 mG for both phasing schemes.
- The overall field is less for ABC-CBA phasing in comparison with ABC-ABC.
- The field values obtained from the ABC-ABC phasing is more close to measured field along all of the profiles.

The comparative results of different management techniques are summarized in Table 5-11 and the magnetic field profiles of different techniques are shown in Figure 5-25 to Figure 5-30.

- The simulation didn't show significant field reduction because all techniques were applied only on high voltage side buswork and conductors which, off course, carrying lesser current than low voltage side cables and the magnetic field produced by these LV cables dominate the overall field.
- The field reduction is not significant also due to the reason that the substation is lightly loaded and magnetic field values are not very high.
- Delta configuration results in lowest field along almost all of the profiles.
- The overall field is also reduced for other configuration. However, there are some locations where the field levels are higher than the original field. This is because of the complex nature of the magnetic fields generated in the substations and field cancellation effects.

Max. Field (mGauss)	Original	Elevated by 1½ feet.	Compacted by one feet.	Compacted by two feet.	Delta Configure (original spacing)	Delta Configure (compacted by 2 feet)
X-component	611.7	645.7	826.7	776.95	664.58	736.23
Y-component	928.3	897.8	782.4	504	818.6	429.11
Z-component	597.8	444	597.56	597.57	598.74	598.84
Resultant	1052	994.5	965	892	961.1	810.8
Resultant Mean	27.8	24.9	25.08	23.08	24.17	23.16
Resultant Stand. Dev.	98.62	88.4	93.51	82.78	85.55	79.82

Table 5-11: Comparison of different reduction techniques.

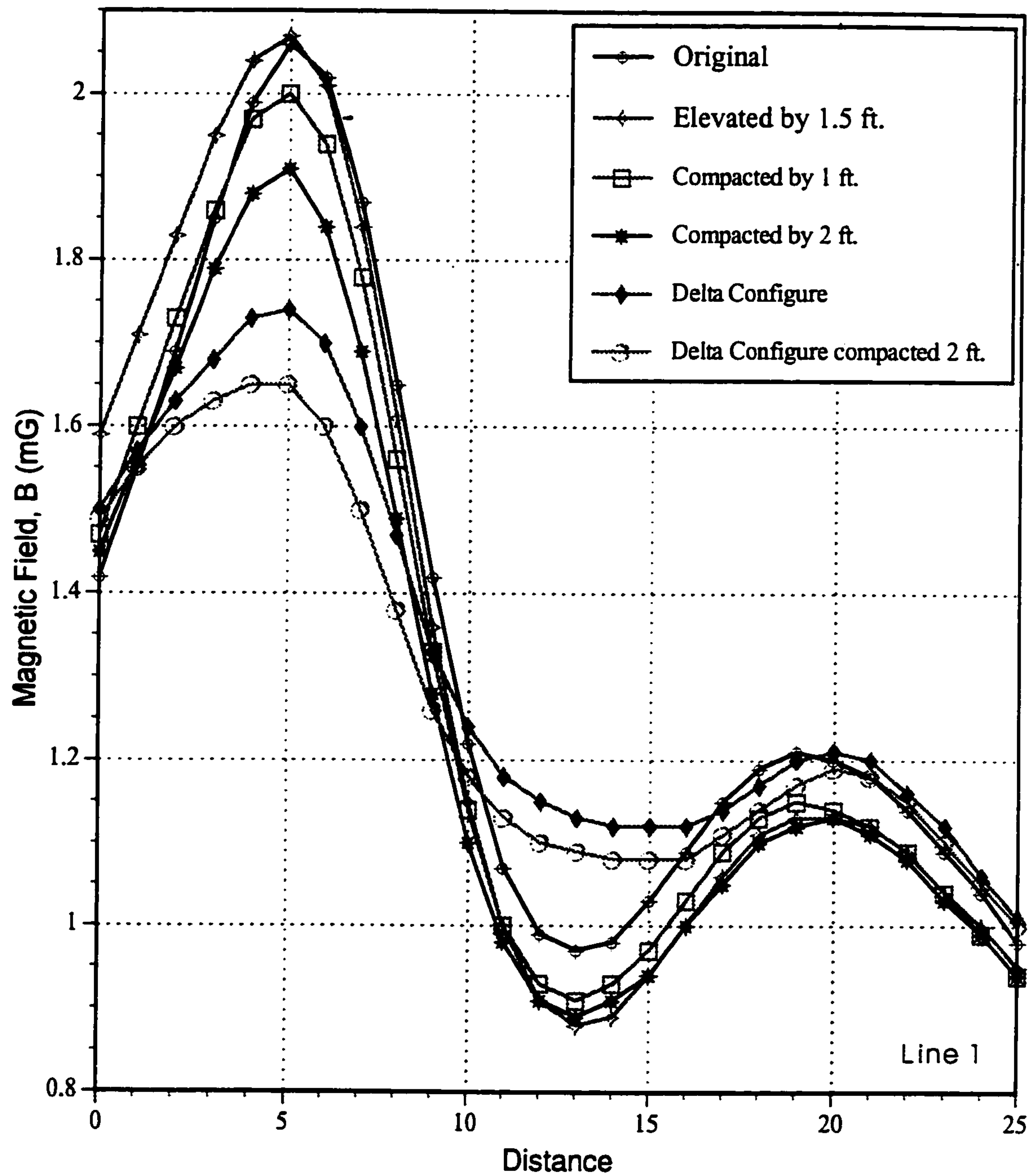

Figure 5-25: Comparison of profiles of different management techniques.

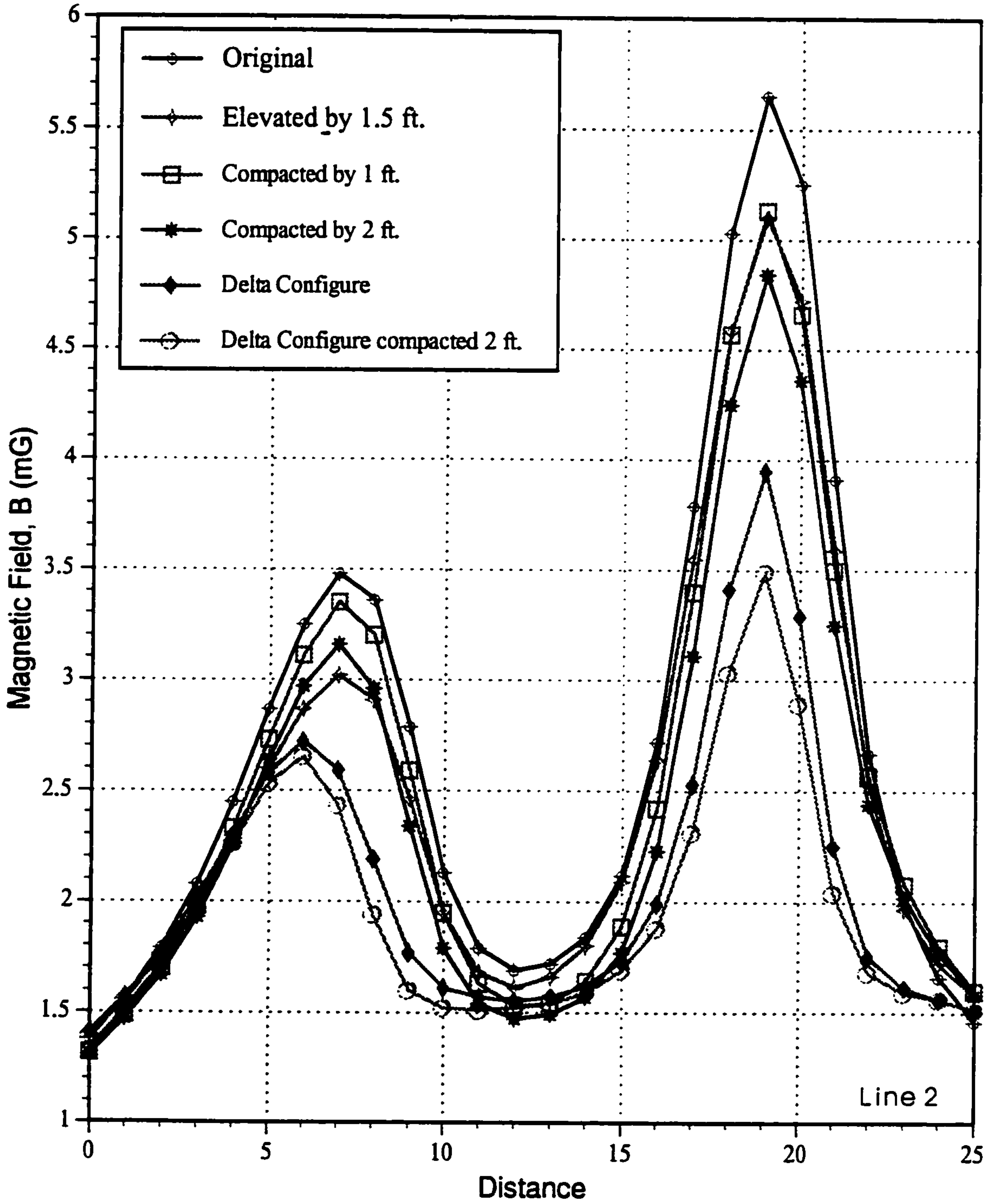

Figure 5-26: Comparison of profiles of different management techniques.

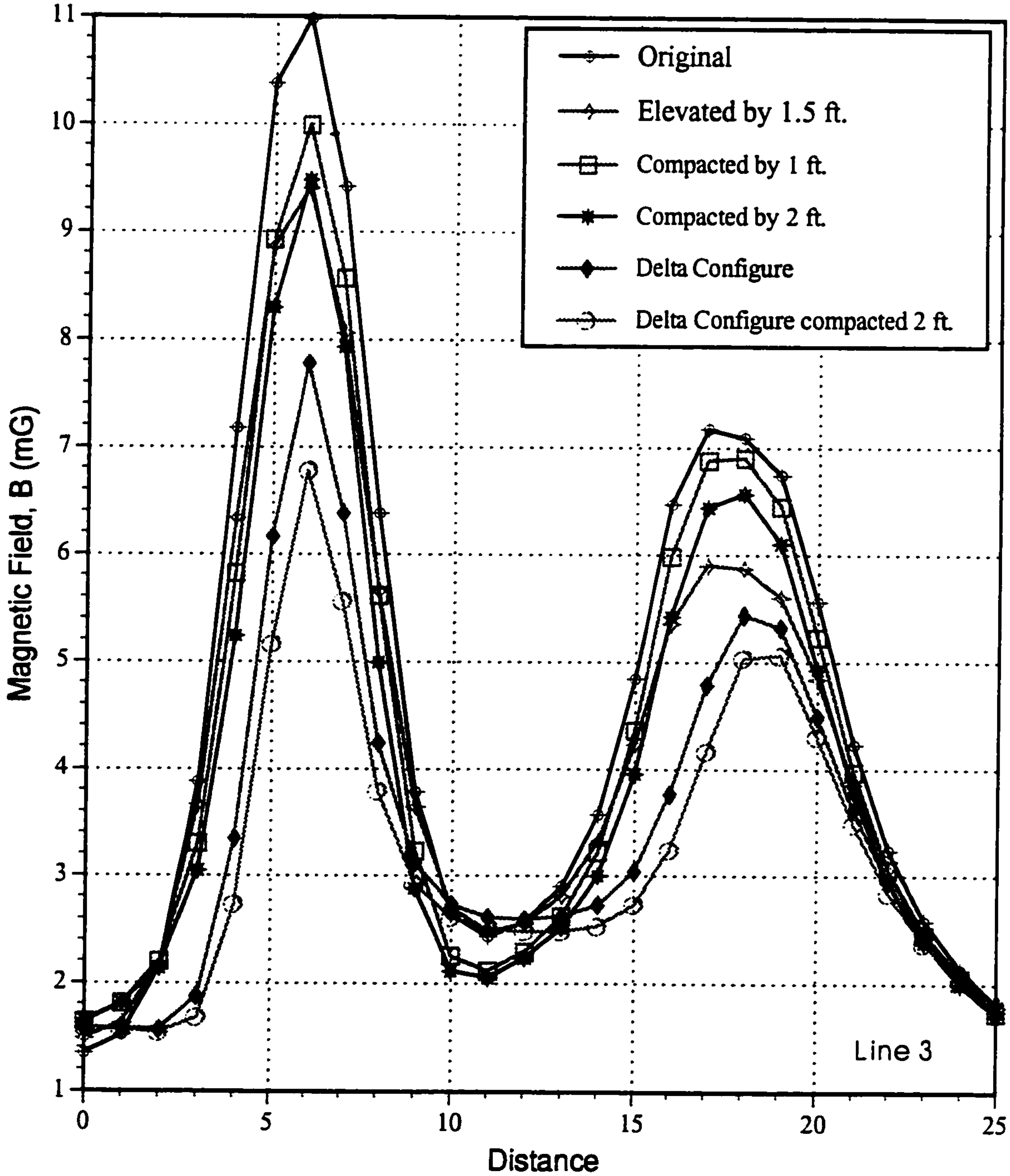

Figure 5-27: Comparison of profiles of different management techniques.

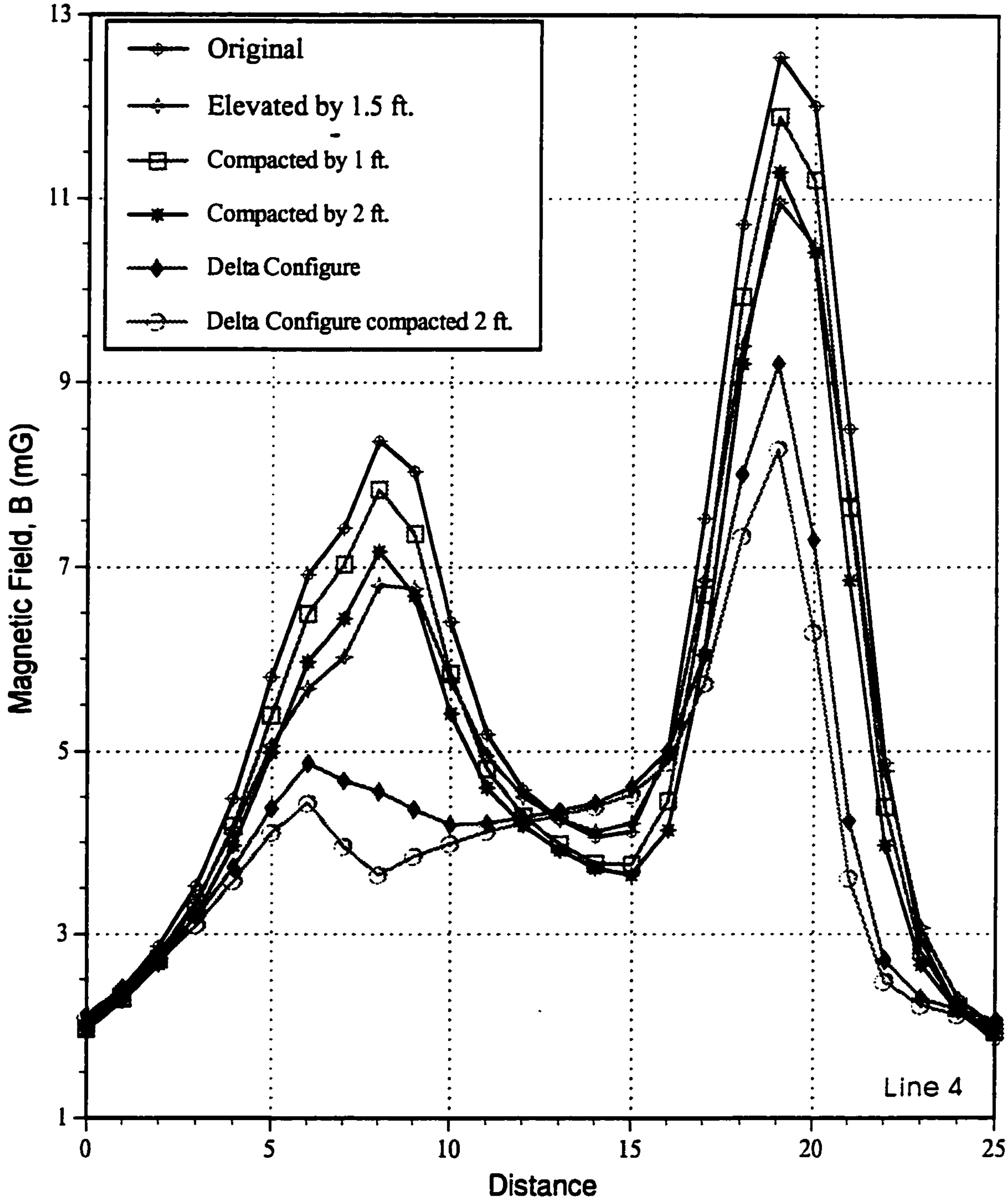

Figure 5-28: Comparison of profiles of different management techniques.

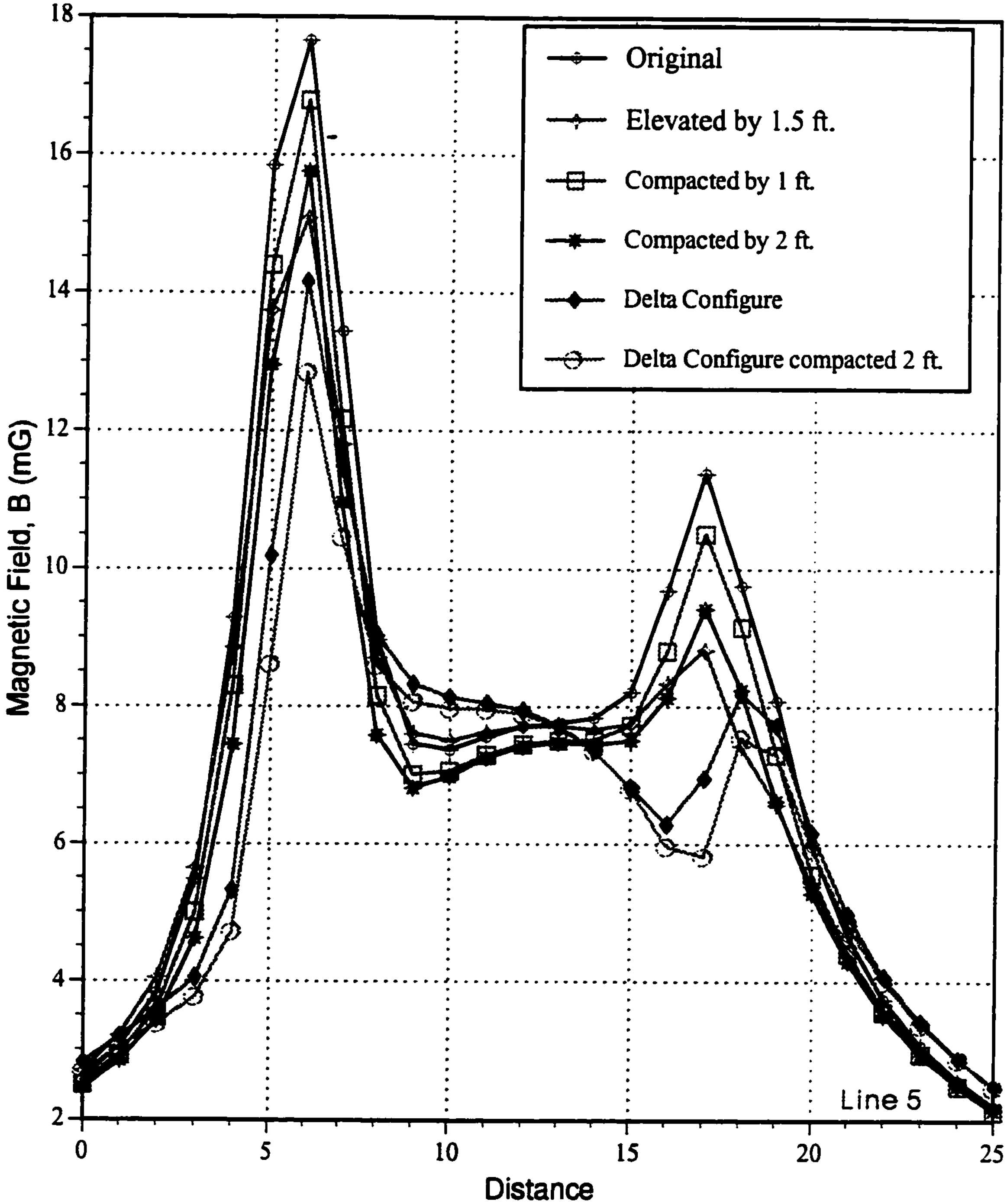

Figure 5-29: Comparison of profiles of different management techniques.

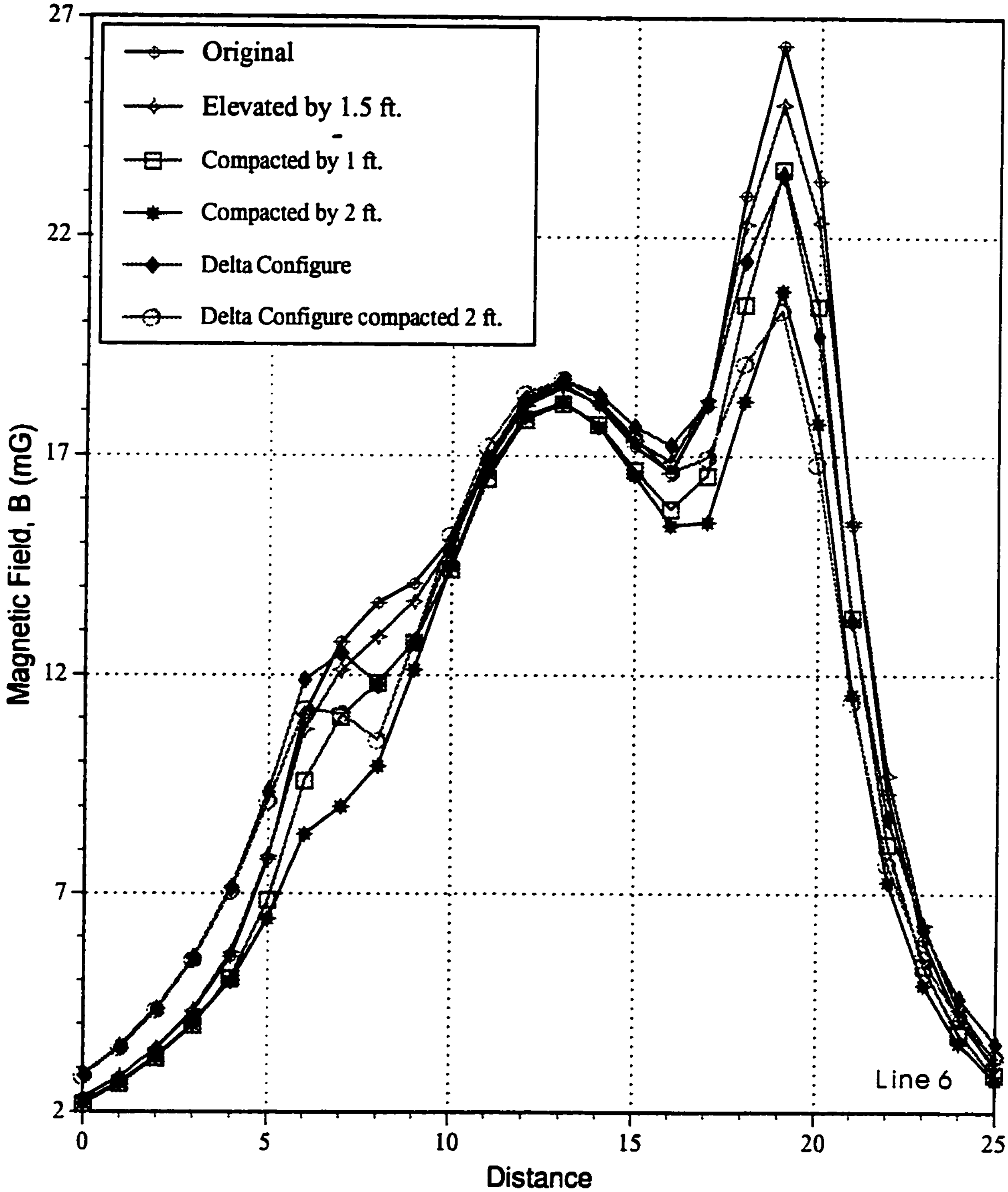

Figure 5-30: Comparison of profiles of different management techniques.

5.5 Case III: Small Substation with Shielding

Magnetic field measurements are done at a small substation supplying power to a mosque, with and without shielding. The shielding used was a magnetic material sheet of one by one meter. The material used was 3% silicon steel, primarily used for transformer core. This sheet was placed just adjacent to transformer and readings are taken. The comparative values at each location are shown in Table 5-12. The contour and 3D profile of magnetic field levels are shown in Figure 5-31 to Figure 5-34, while the comparative profiles are shown in Figure 5-35 to Figure 5-39.

- The maximum field level without shielding was 40.8 mG and with shielding was 21.2 mG.
- Closer to transformer (source), the shielding effect is more dominant because of the finite size of the shielding sheet.
- On the average, field reduction is about 50%.
- At some locations, the shielded magnetic field values are greater than without shielding. This is due to presence of another source which is not shielded.
- At some locations, the measurements cannot be taken due to presence of equipment (transformer, control panel or switchgear). These locations are marked by patterned box in the plots while in Table 5-12, these locations are represented by an asterisk (*).

Magnetic field levels (no shielding / with shielding)

x\y	0		1		2		3		4		5		6		7		8		9		10	
6	*	*	*	*	*	*	*	*	7.64	4.2	10.4	5.28	11.2	5.56	12.8	7.6	8.48	4.92	4.9	2.84	*	*
5	*	*	*	*	*	*	14.8	10.4	12.4	7.4	25.6	13.2	30.4	14.1	31.6	21.2	21.2	12.4	7.8	3.88	*	*
4	*	*	3.56	3.56	12	3.68	40.8	16.8	30	15.6	*	*	*	*	*	*	*	*	34.4	21.2	8.8	6.12
3	1.6	1.48	1.84	1.4	4.96	3.68	9.56	6.08	33.2	14	*	*	*	*	*	*	*	*	21.2	19.6	7.24	4.48
2	1.96	2.3	1.48	1.56	*	*	*	*	*	*	*	*	*	*	*	*	*	*	4.88	3.48	3.76	2.88
1	*	*	1.36	0.72	0.56	0.48	0.64	0.52	0.88	0.48	0.8	0.36	1.08	0.68	1.6	0.96	1.52	0.92	2.76	1.34	*	*
0	*	*	0.92	0.76	0.84	0.84	1	0.88	1.28	0.92	1.12	0.76	0.84	0.64	0.88	0.8	1.08	0.88	1.16	1.08	*	*

Table 5-12: Comparative values of magnetic field with and without shielding.

* represents those locations where measurements are not taken.

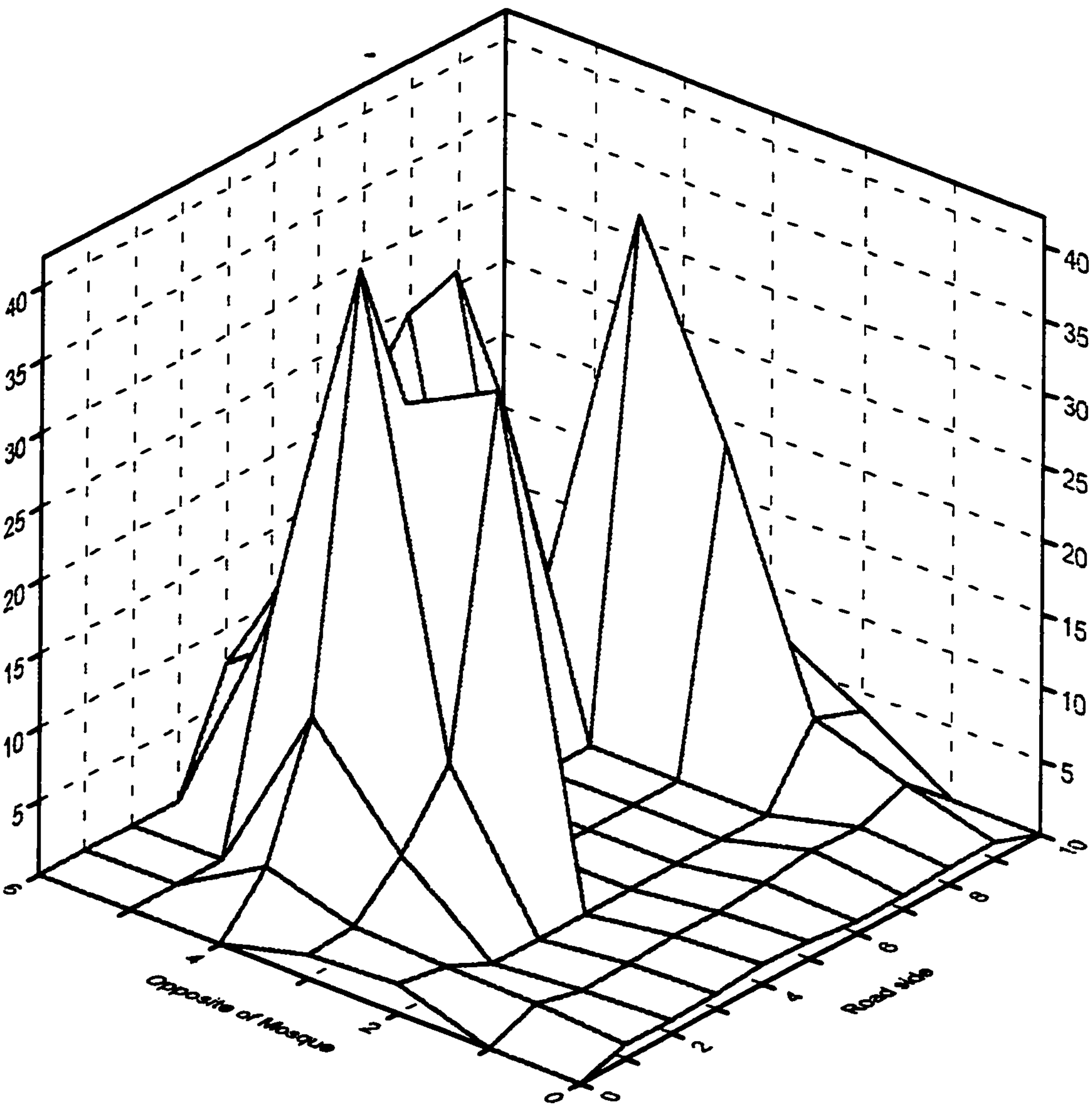

Figure 5-31: 3D Magnetic field map of mosque SS without shielding.

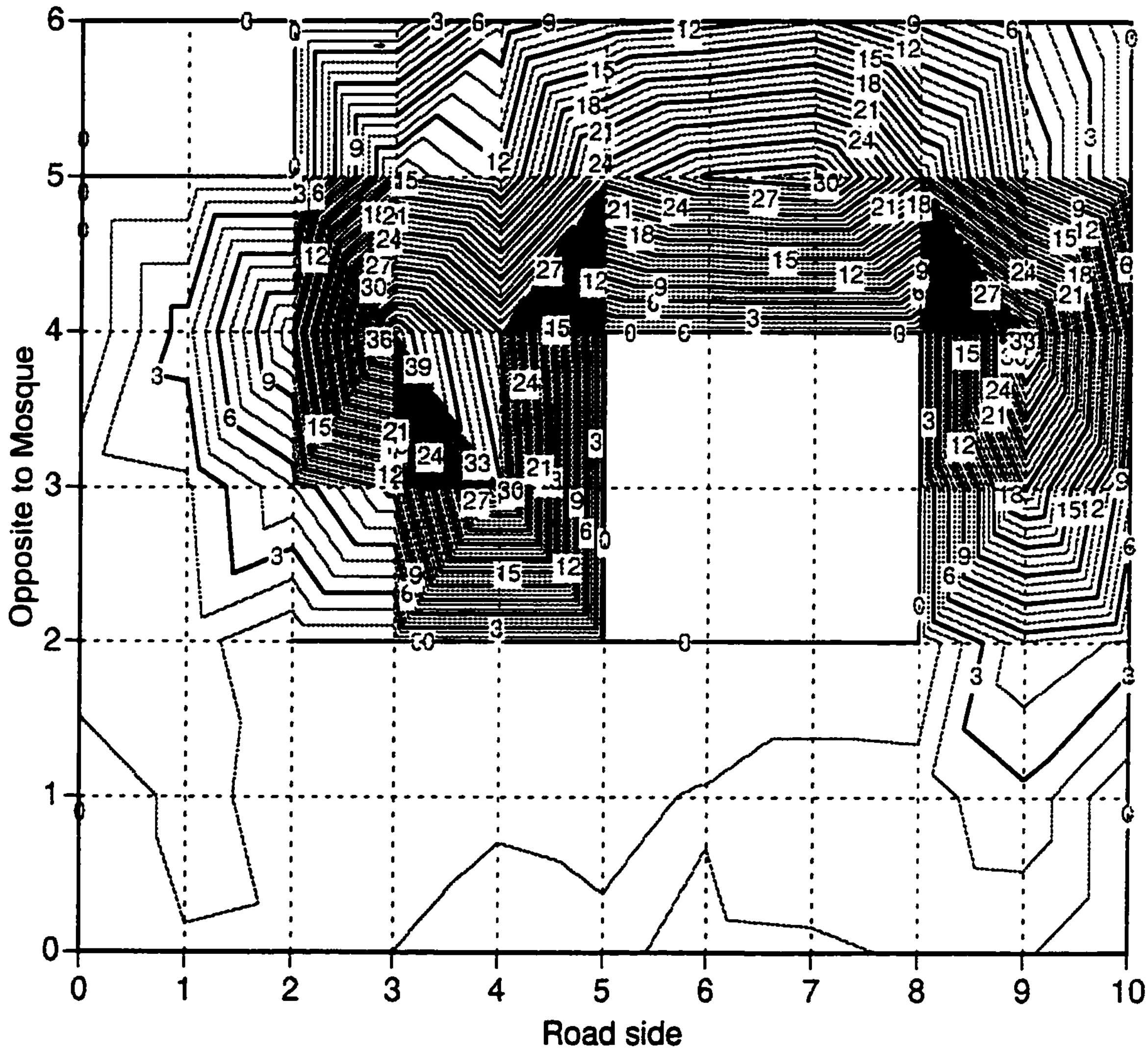

Figure 5-32: Magnetic field contour map of mosque SS without shielding.

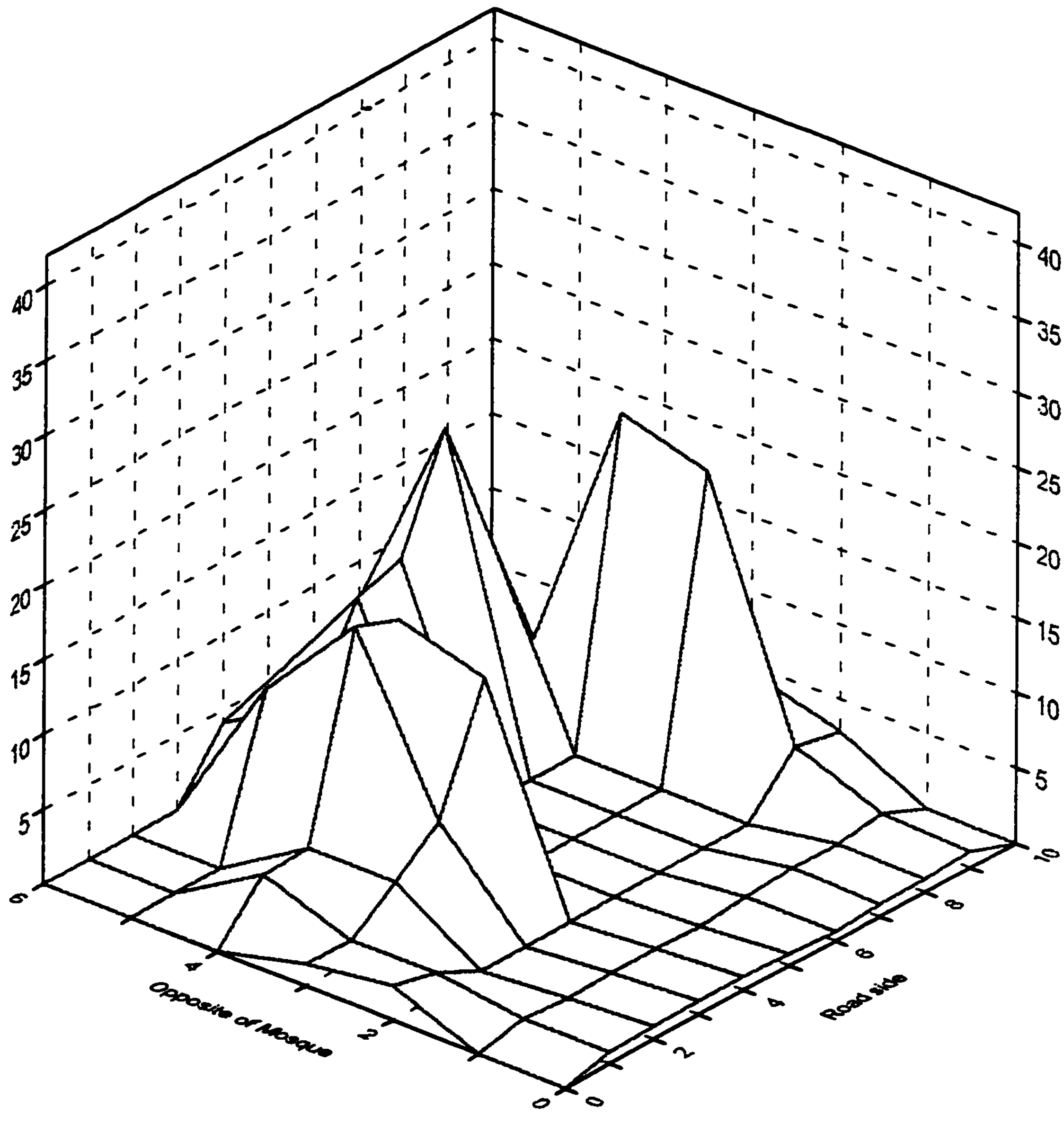

Figure 5-33: 3D Magnetic field map of mosque SS with shielding.

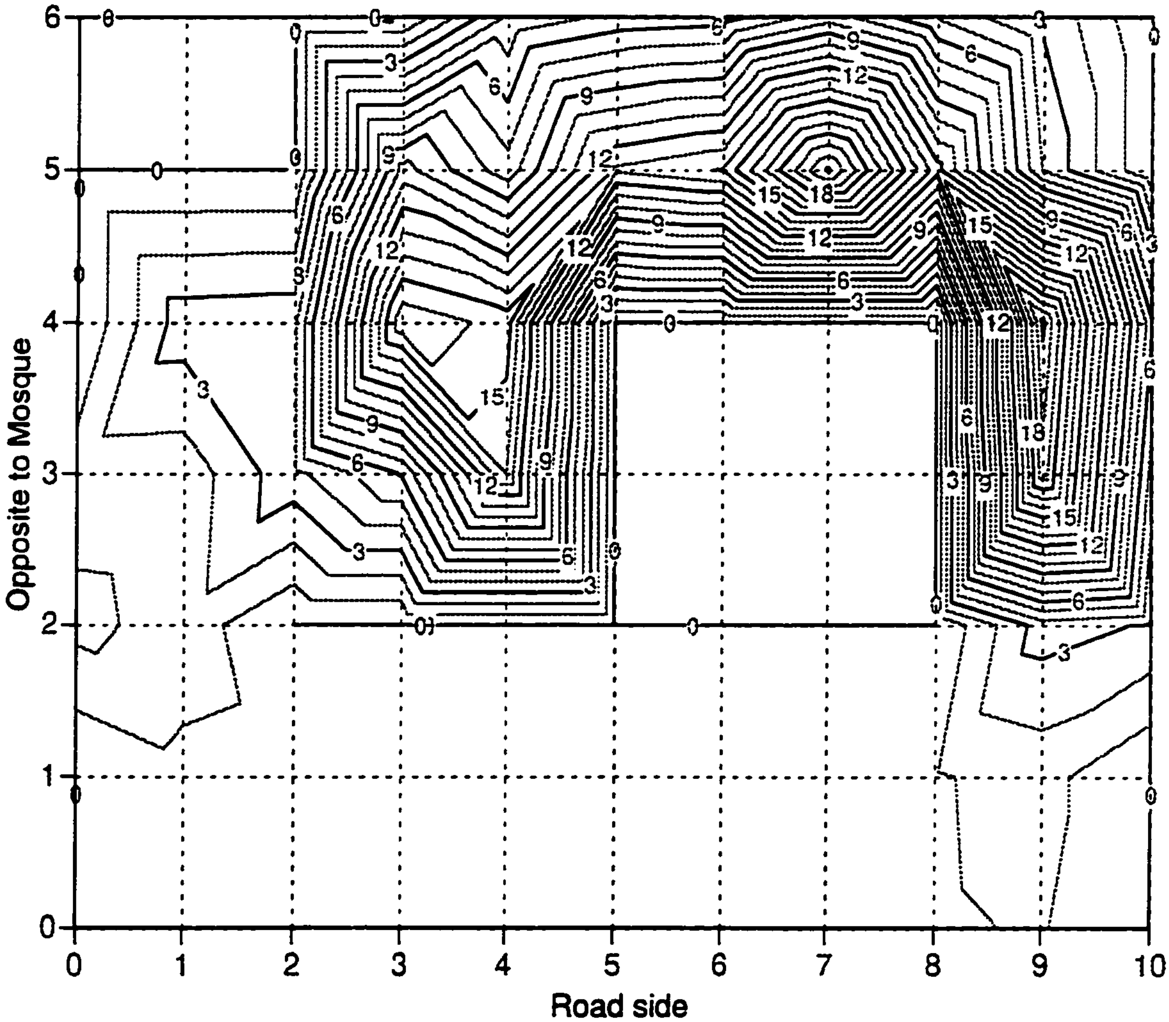

Figure 5-34: Magnetic field contour map of mosque SS with shielding.

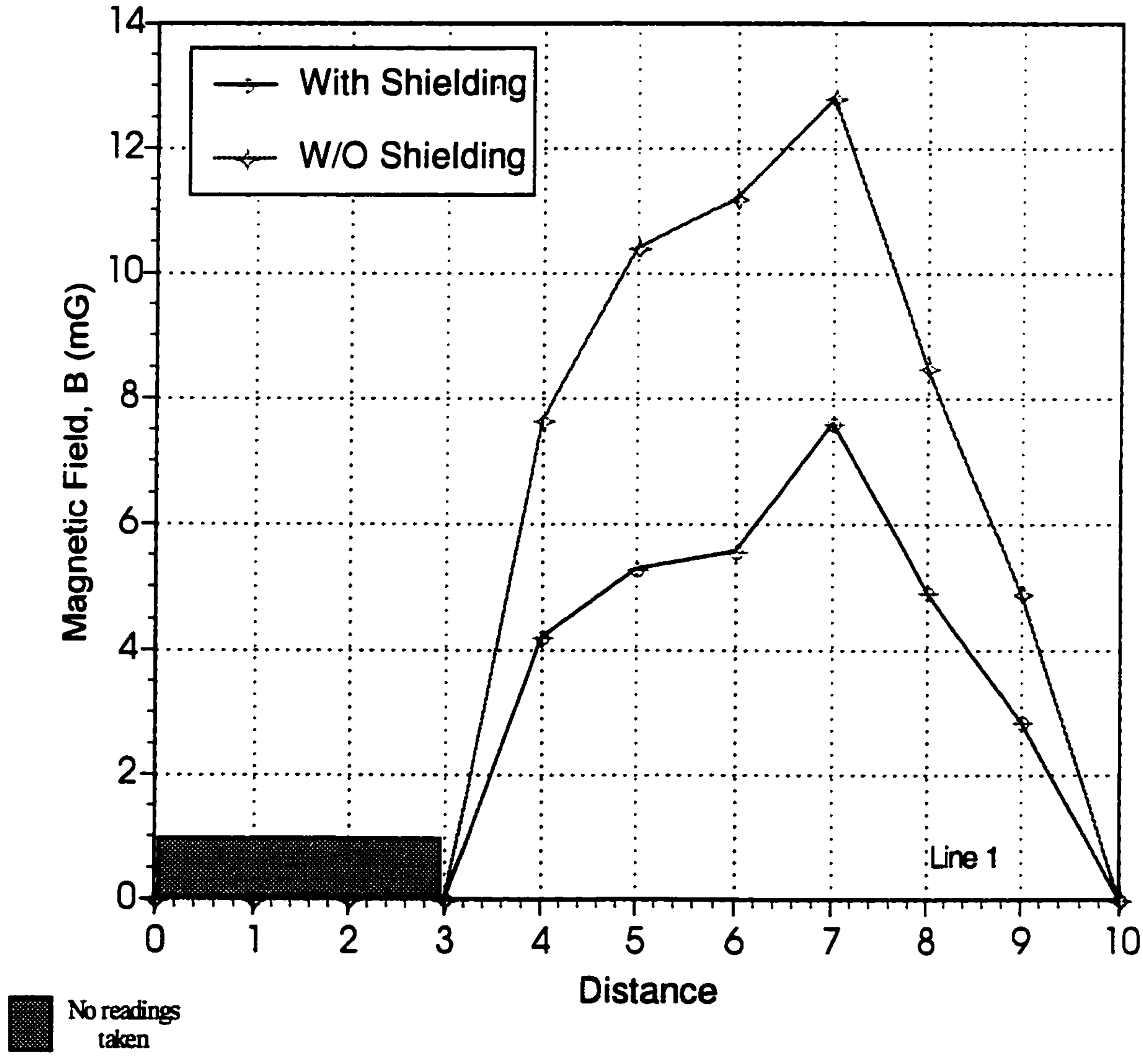

Figure 5-35: Comparative Magnetic Field profiles.

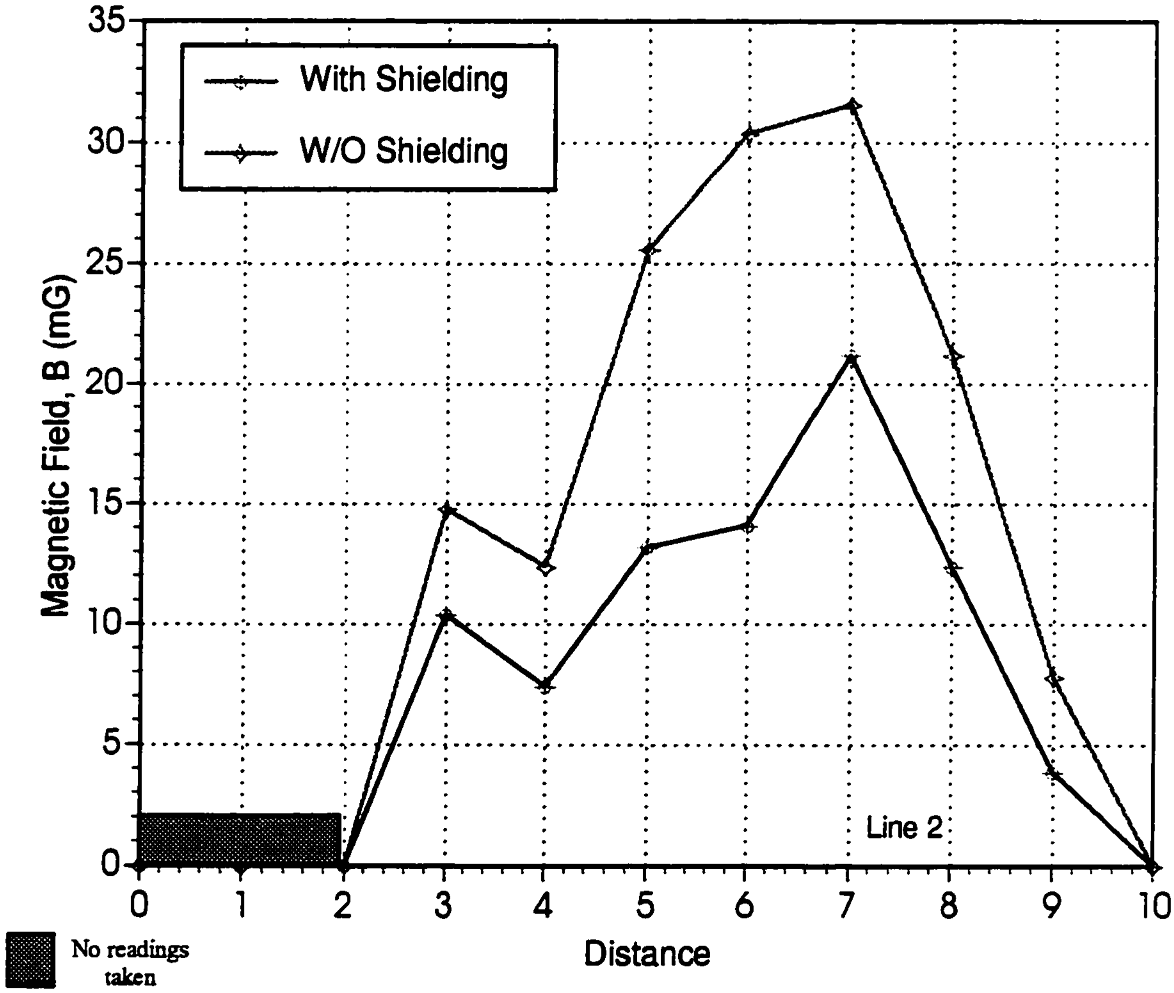

Figure 5-36: Comparative Magnetic Field profiles.

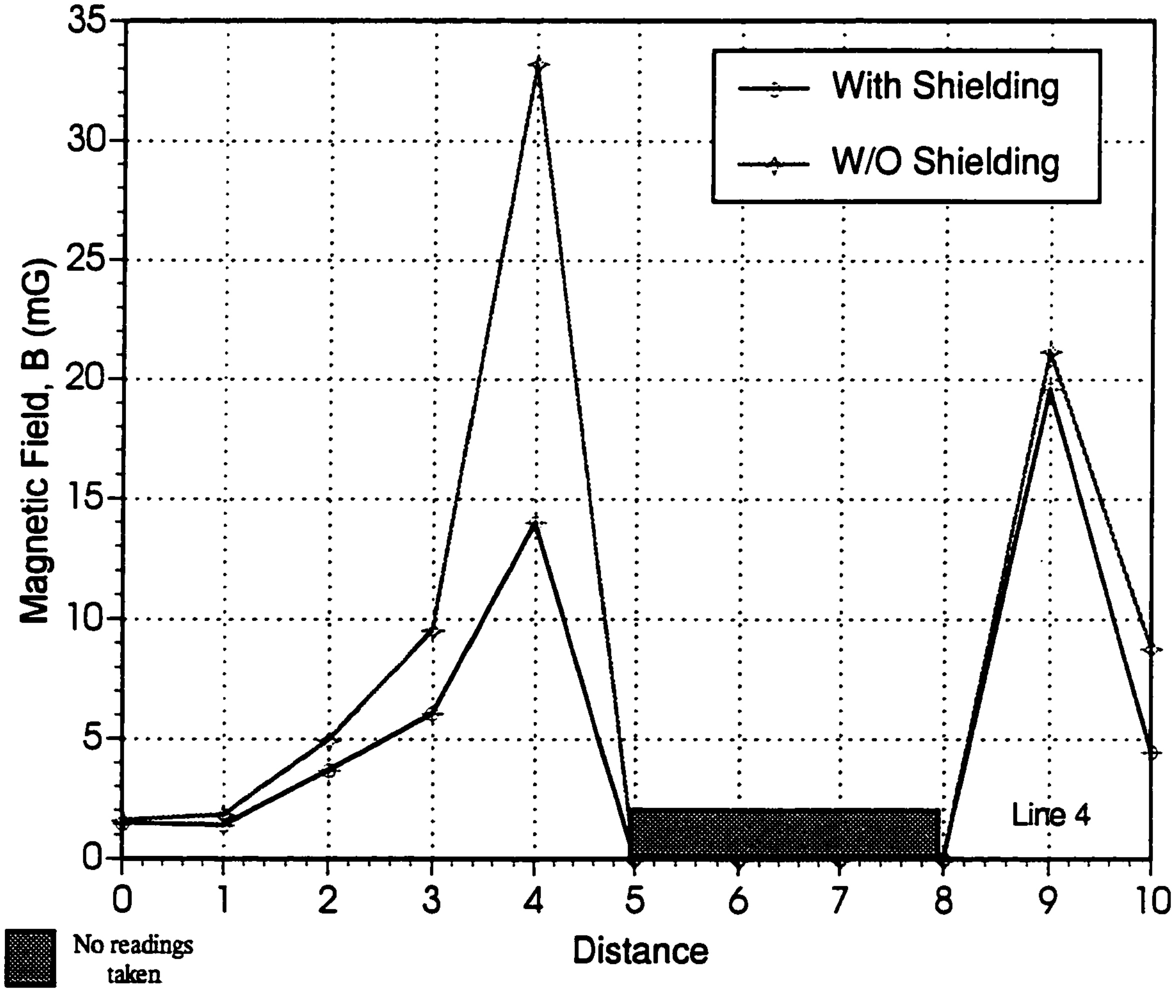

Figure 5-37: Comparative Magnetic Field profiles.

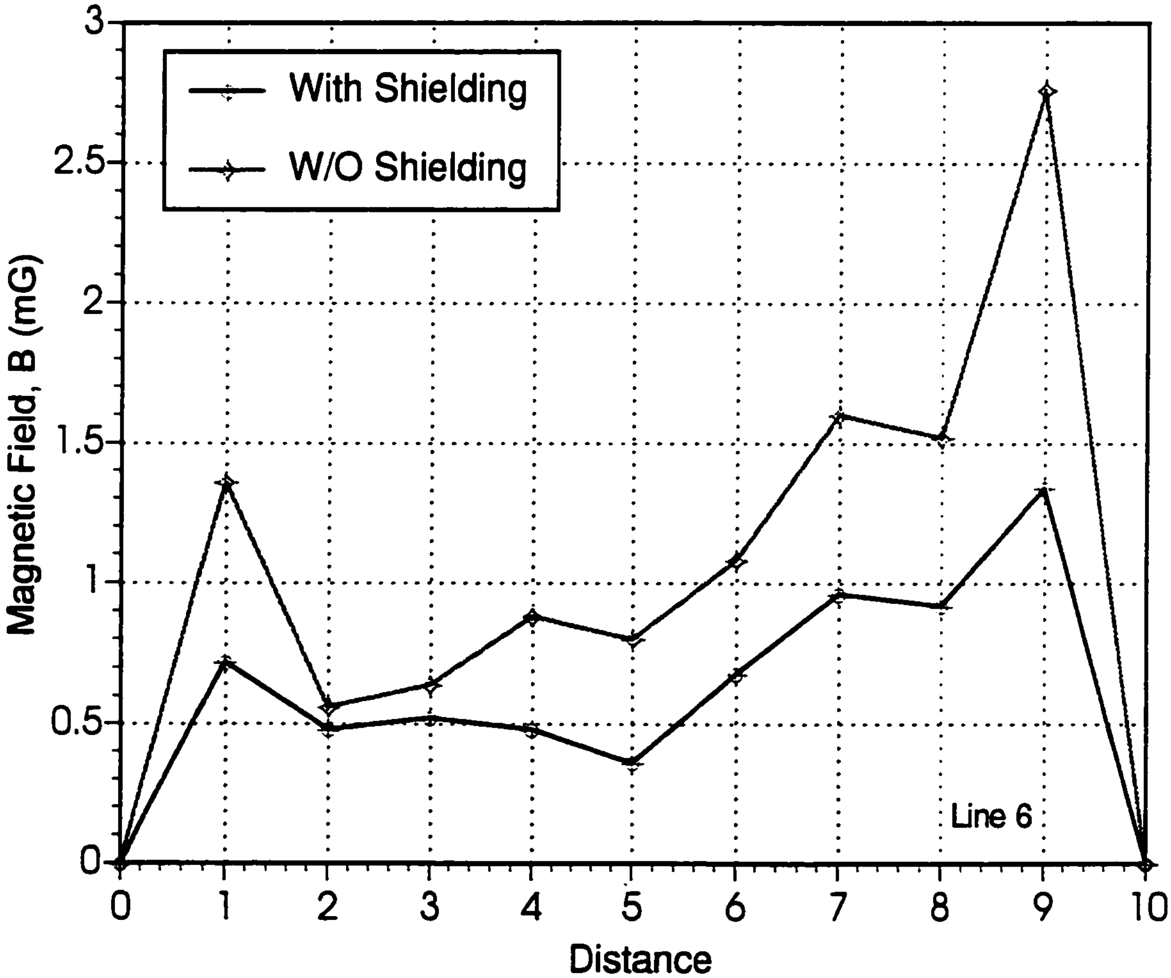

Figure 5-38: Comparative Magnetic Field profiles.

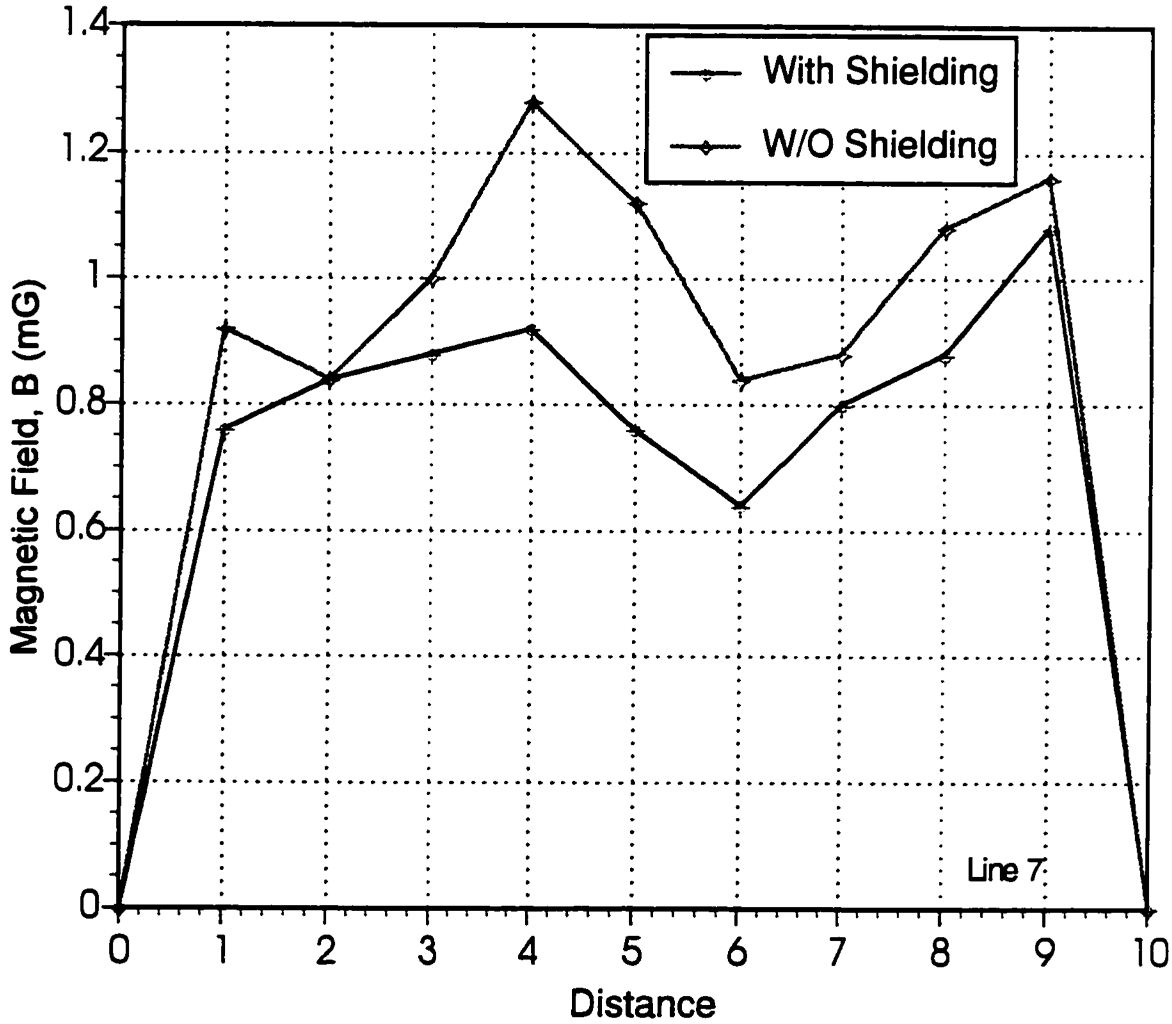

Figure 5-39: Comparative Magnetic Field profiles.

CHAPTER 6

CONTRIBUTION, CONCLUSION AND RECOMMENDATIONS

6.1 Contribution

- Identification and verification of major magnetic field sources in substations.
- Implementation and analysis of magnetic field measurement in substation using latest magnetic field meters.
- Application of modern state-of-the-art magnetic field simulation packages for modeling and magnetic field calculation in substation.
- Simulation, analysis and comparison of different magnetic field management techniques.
- Application of shielding techniques in substation.
- This work will help Engineers, Scientists and utility people of this region to better understand magnetic field characteristics in substation and try to utilize feasible field reduction methods in existing and future electrical facilities.

6.2 Conclusion

This study describes and compares various engineering techniques and practices available for managing magnetic field strength levels in and around substations implementing the no-cost and low-cost field management measures.

Two typical cases are analyzed: one indoor type and other outdoor type substation. In order to investigate the effects of magnetic fields in and around substations efficiently, measurements of magnetic field are done using standard magnetic field meters. These measurements are plotted (contours, 3D and profile plots) using available graphical packages.

These substations are modeled in SUBCALC from given geometrical and electrical data of the conductors in the substation. The software produces contour maps, 3D maps and profile plots of magnetic field levels. Case I is simulated for actual (on the day of measurements) and rated currents, while case II is simulated for actual currents with ABC-ABC and ABC-CBA phasing for HV buswork.

The comparative results of measurement and simulation are acceptable. However, there are some discrepancies, as expected. The reasons for these discrepancies can be summarized as below:

- Assumptions made during modeling.
- Current may not be fixed during measurement.
- There may be some hidden sources that are not modeled.
- In simulation, buildings and metallic structures can not be modeled which change the field patterns.
- Substation as built design differ from the paper (planned) design, which is used for

modeling of substation.

These measurements and simulations help in identifying the major magnetic field sources in substations. These sources are transformer, LV and HV side conductors/cables entering or leaving the substation, transformer buswork, circuit breakers and pot heads.

Magnetic field management (reduction) techniques were simulated. The comparison of different techniques is also discussed. For case I, management techniques are applied at rated values of current. It is important to note that the field reduction is not significant for lightly loaded systems as compared to the fully loaded (rated) systems. The reduction is dominant near the magnetic field sources when compared with the reduction away from the sources (near substation's fence). The field reduction is within 20% for case II because it can be simulated only for high voltage side as low voltage side cables are placed so closed that they cannot be reconfigured.

A shielding sheet is designed to compare magnetic field levels with and without shielding around a small substation. The result shows, on the average, reduction up to 50%.

6.3 Recommendations

Although there is no definite answer about how magnetic fields are dangerous to humans, it is in the interest of the public, utilities and government agencies to consider it as a possible health hazard.

- For substation's accurate magnetic field measurement, complete information about the substation should be available. This include layout/electrical drawings, rating of each equipment, any modification during construction, etc.

- Preferably, one engineer of the utility (who know every aspect of the substation very well) should accompany the measuring team.
- Better measurement and simulation methodology should be developed for more accurate results, including continuous load current measurements.
- Improved software should be used for modeling and simulation. User friendly software could be developed, if possible.
- Different shielding materials should be applied and analyzed for field minimization. Multi-sheets shielding with different inter-sheet space should also be considered.
- Universities, research institutes and utilities should encourage research for better understanding of low frequency magnetic field characteristics and its management.

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[15] A. S. Farag, A. M. Al-Shehri, T. C. Cheng, Y. Du, et. al., "Magnetic Field Management of Substations in High-Rise Buildings," Paper presented at the *Stockholm Power Tech. Conference*, Stockholm, June 1995.

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[19] EPRI, "EMDEX II - Electric and Magnetic Field Digital Exposure system Version 1.02," *Technical Reference Manual*, June 1991.

APPENDICES

Appendix-A: Measurement Results of Case I

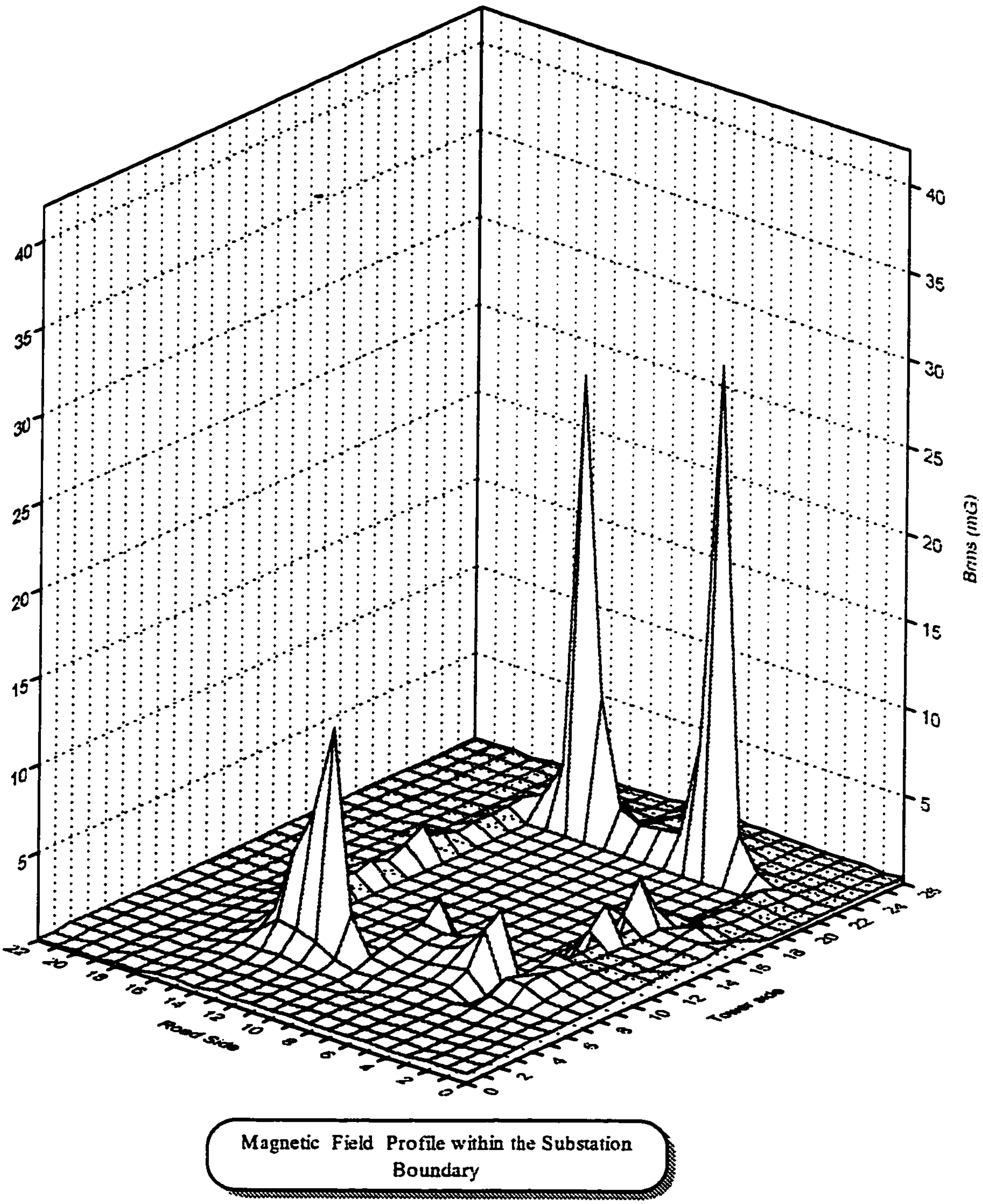


Figure A-1: 3D magnetic field map of complete substation.

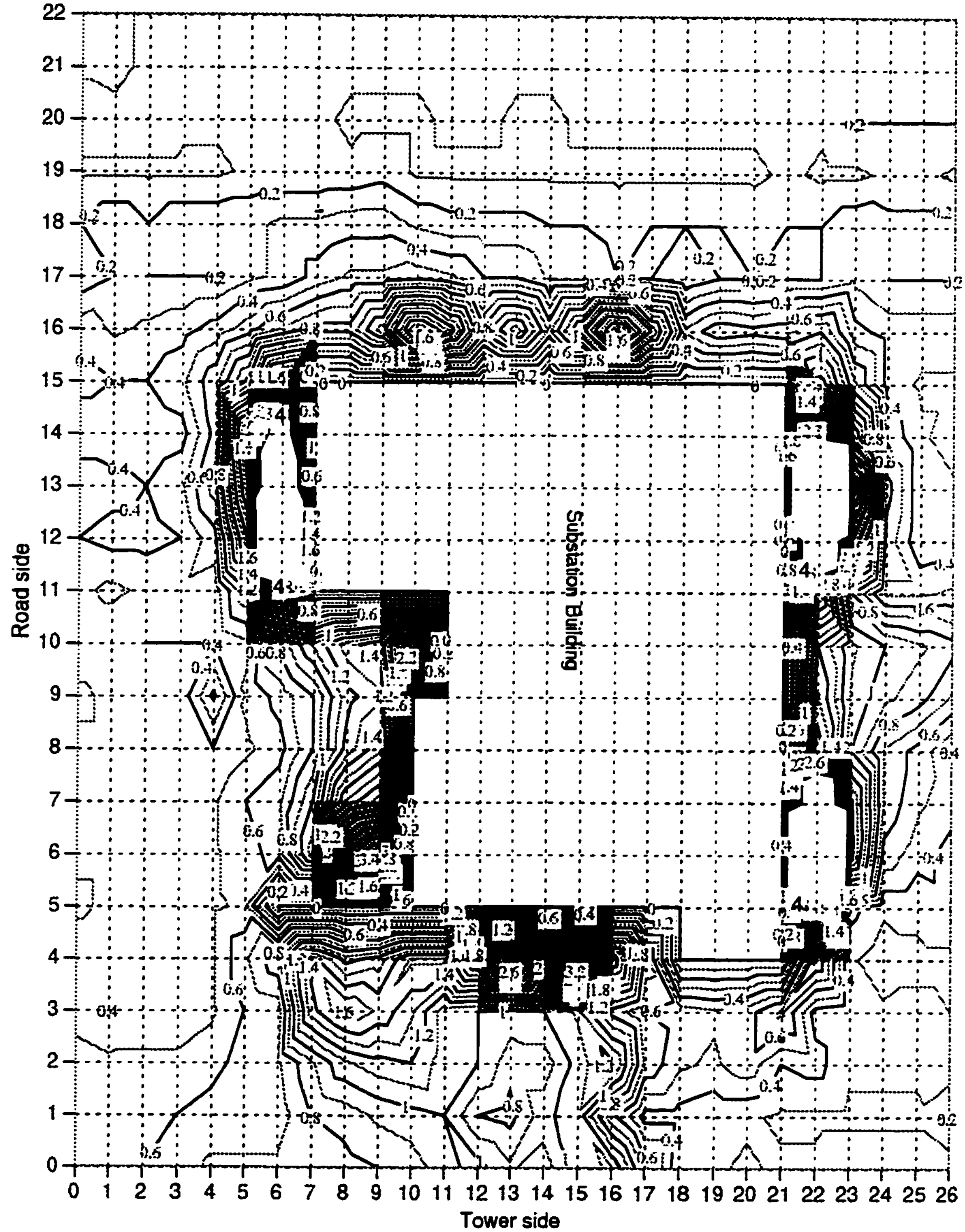


Figure A-2: Magnetic field contour plot of complete substation.

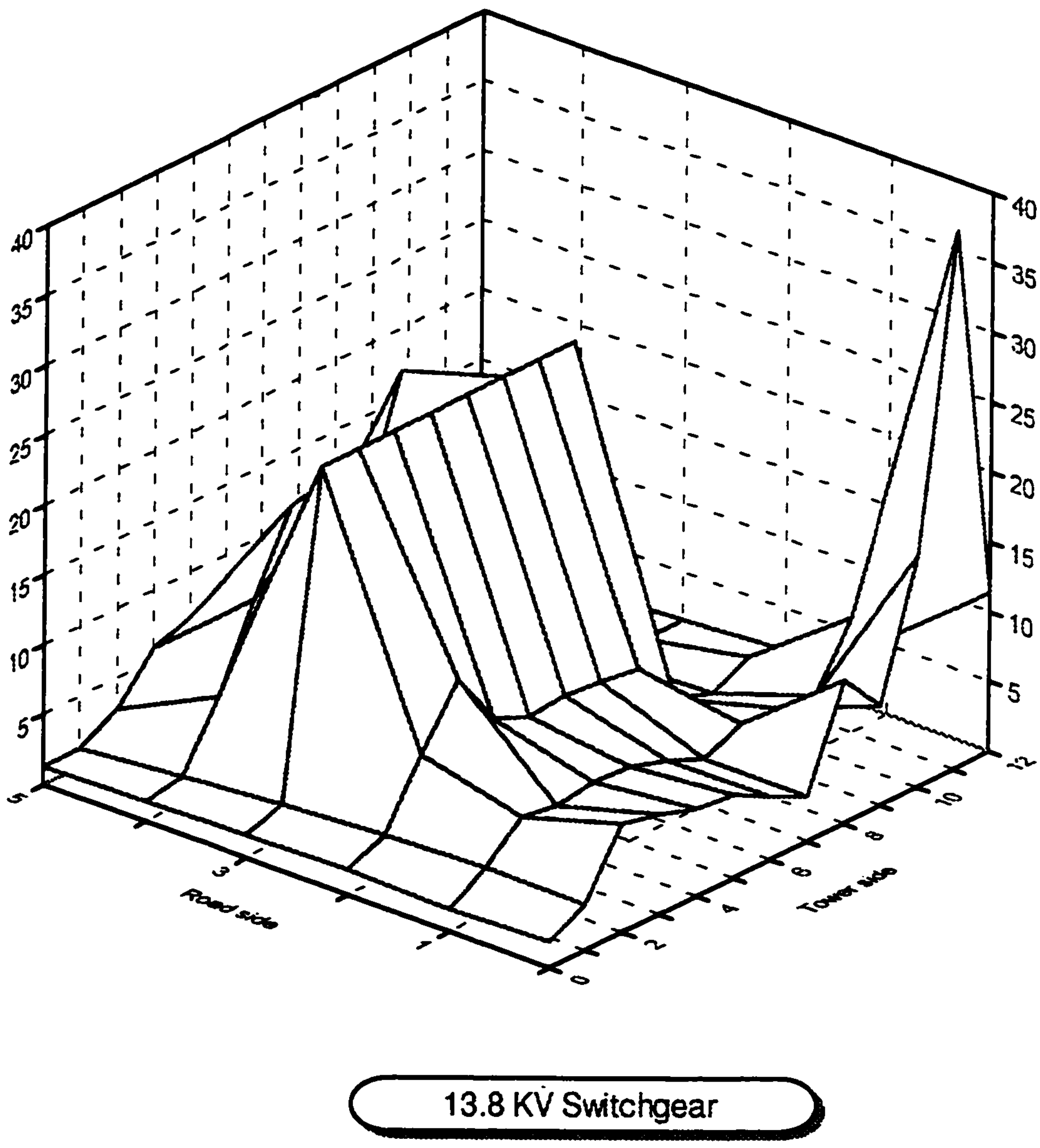


Figure A-3: 3D magnetic field map in 13.8 kV switchgear room.

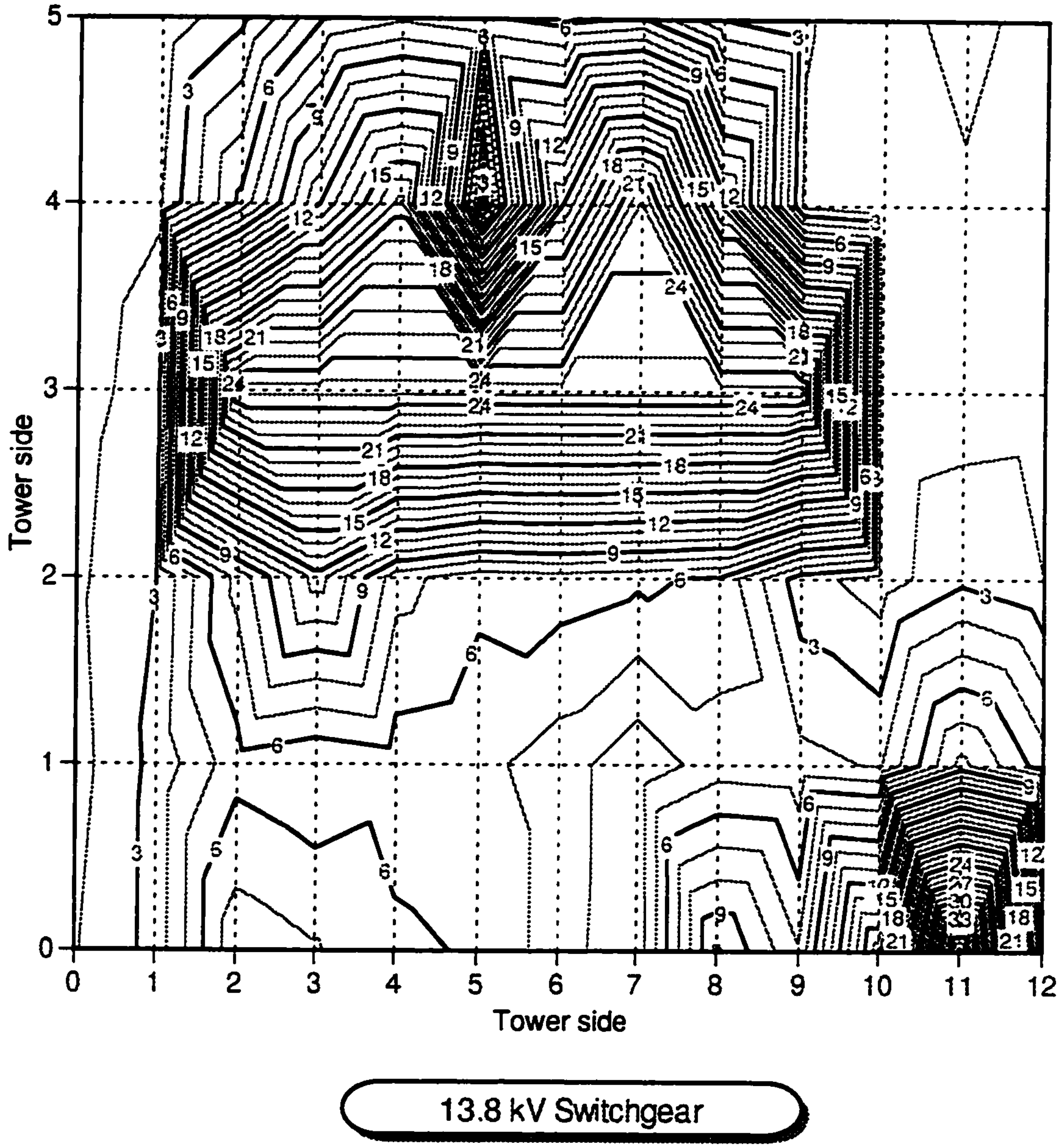


Figure A-4: Magnetic field contour plot in 13.8 kV switchgear room.

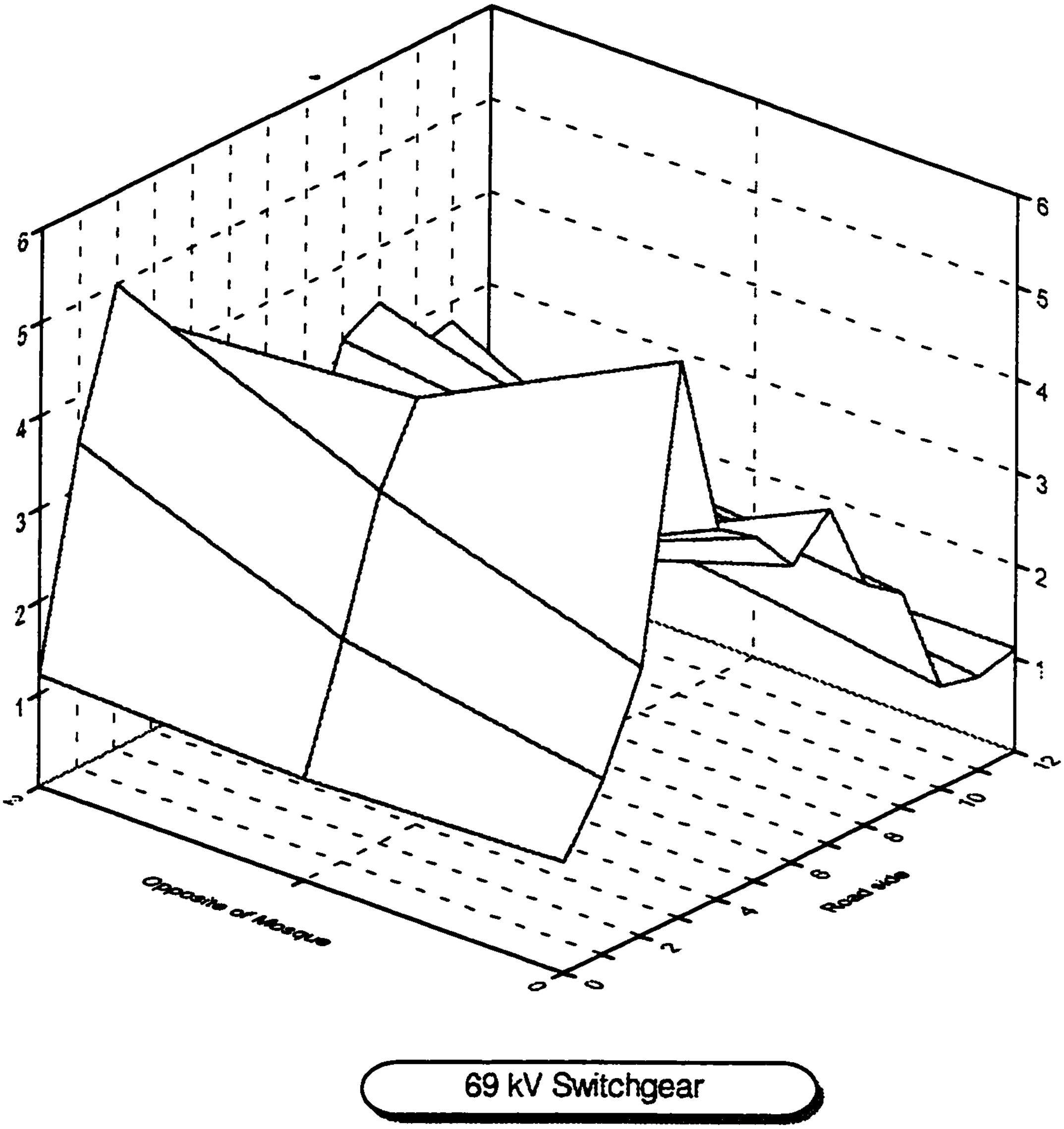


Figure A-5: 3D magnetic field map in 69 kV switchgear room.

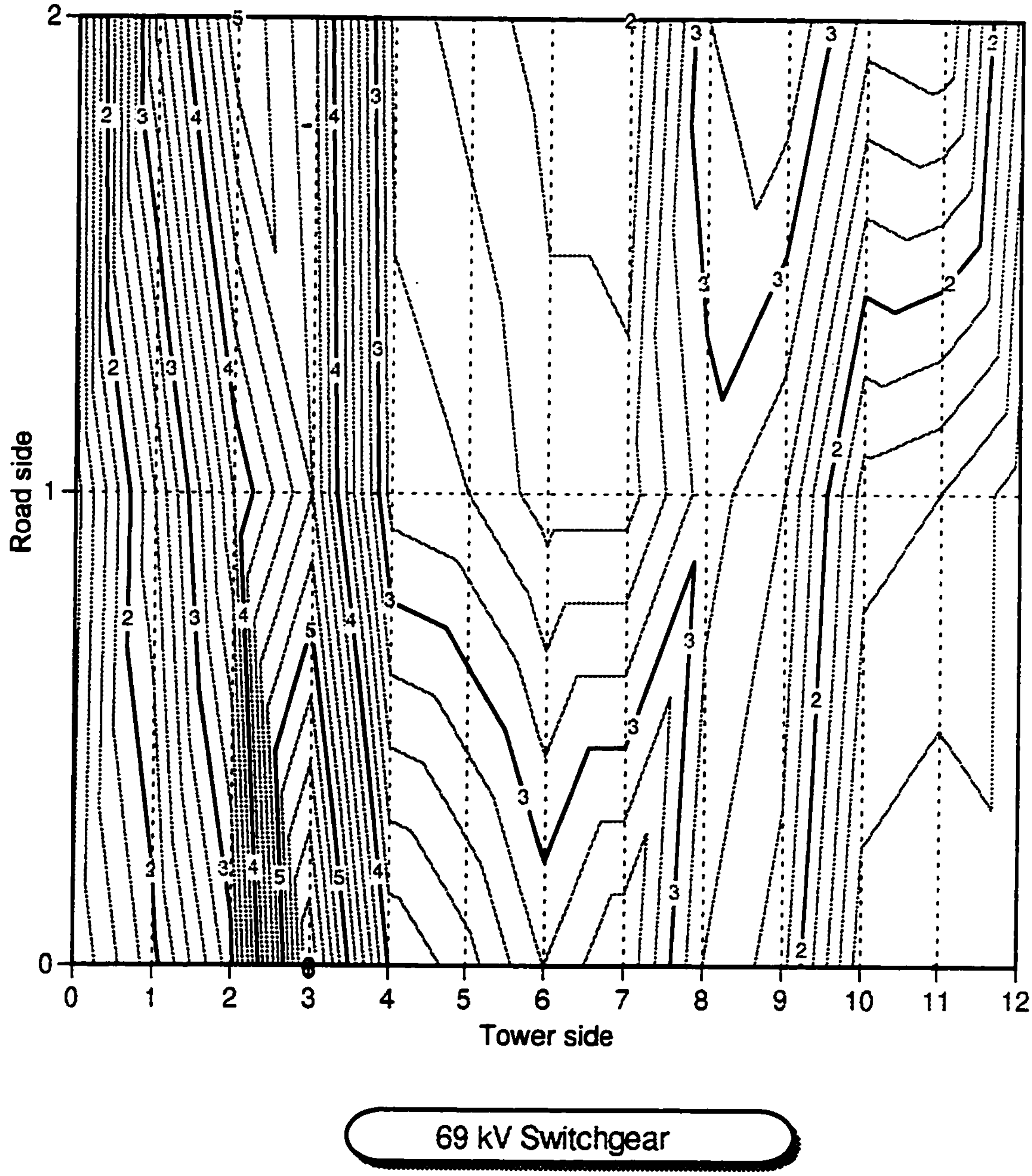
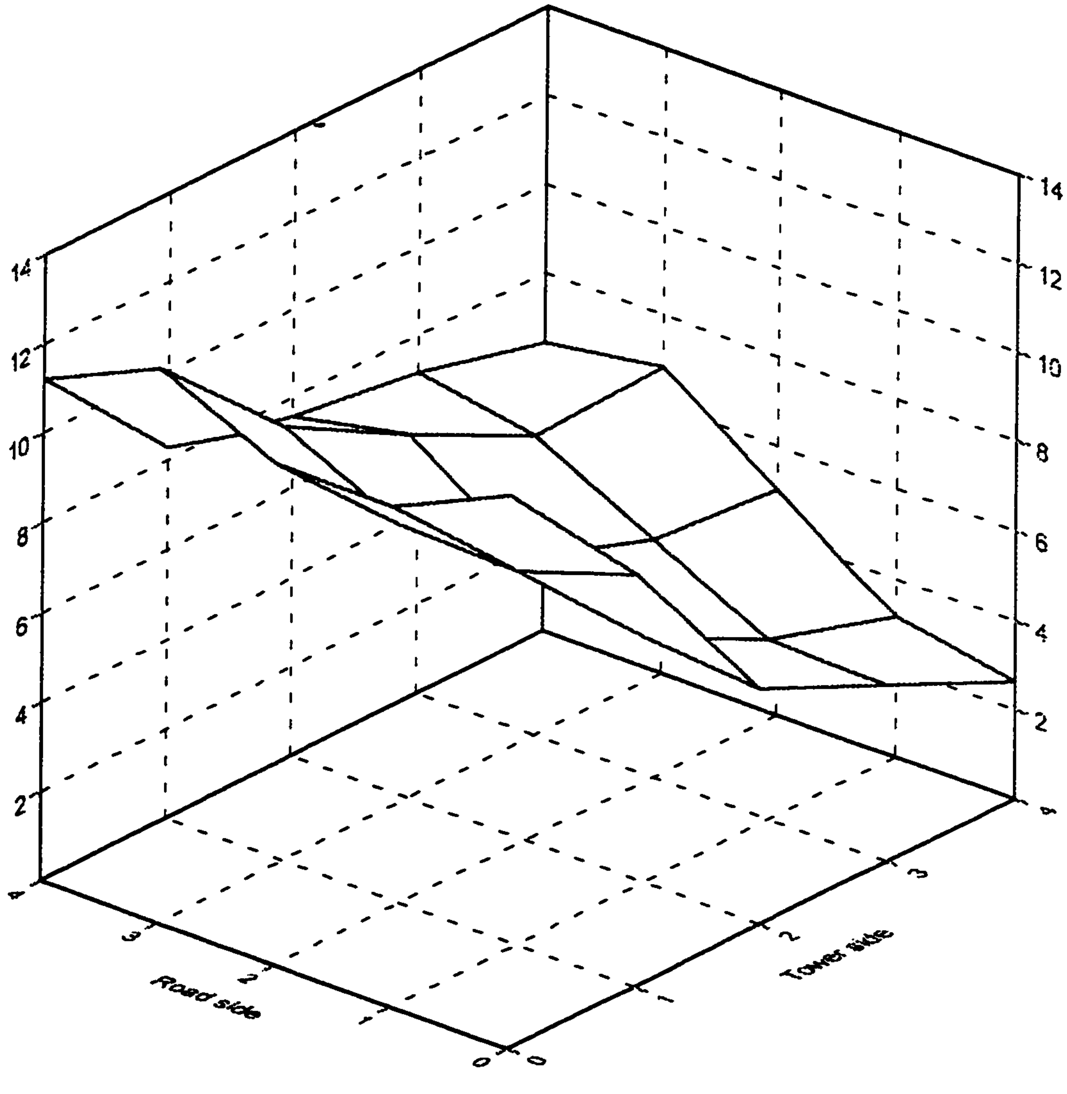


Figure A-6: Magnetic field contour plot in 69 kV switchgear room.



Battery Room

Figure A-7: 3D magnetic field map in battery room.

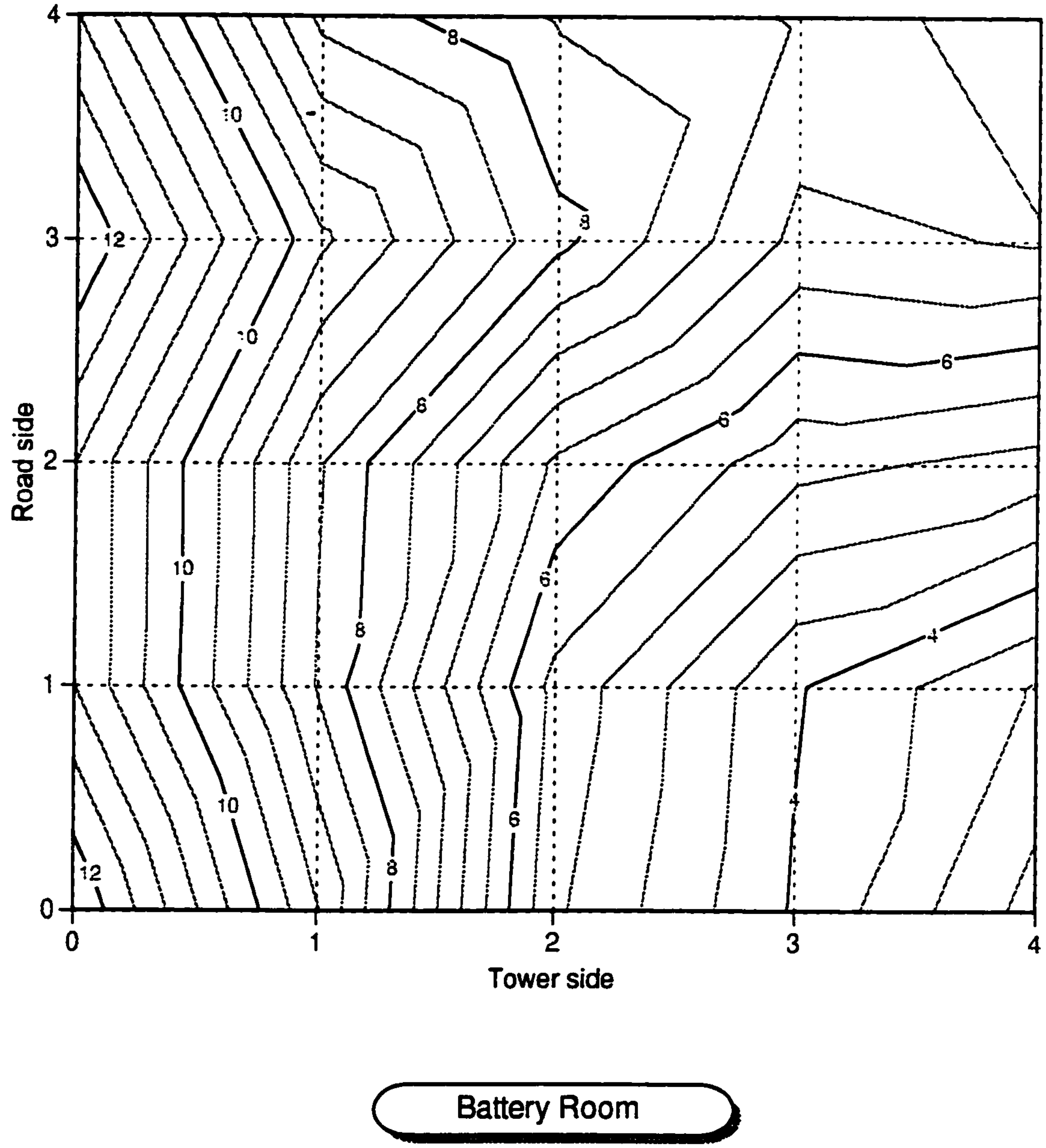


Figure A-8: Magnetic field contour plot in battery room.

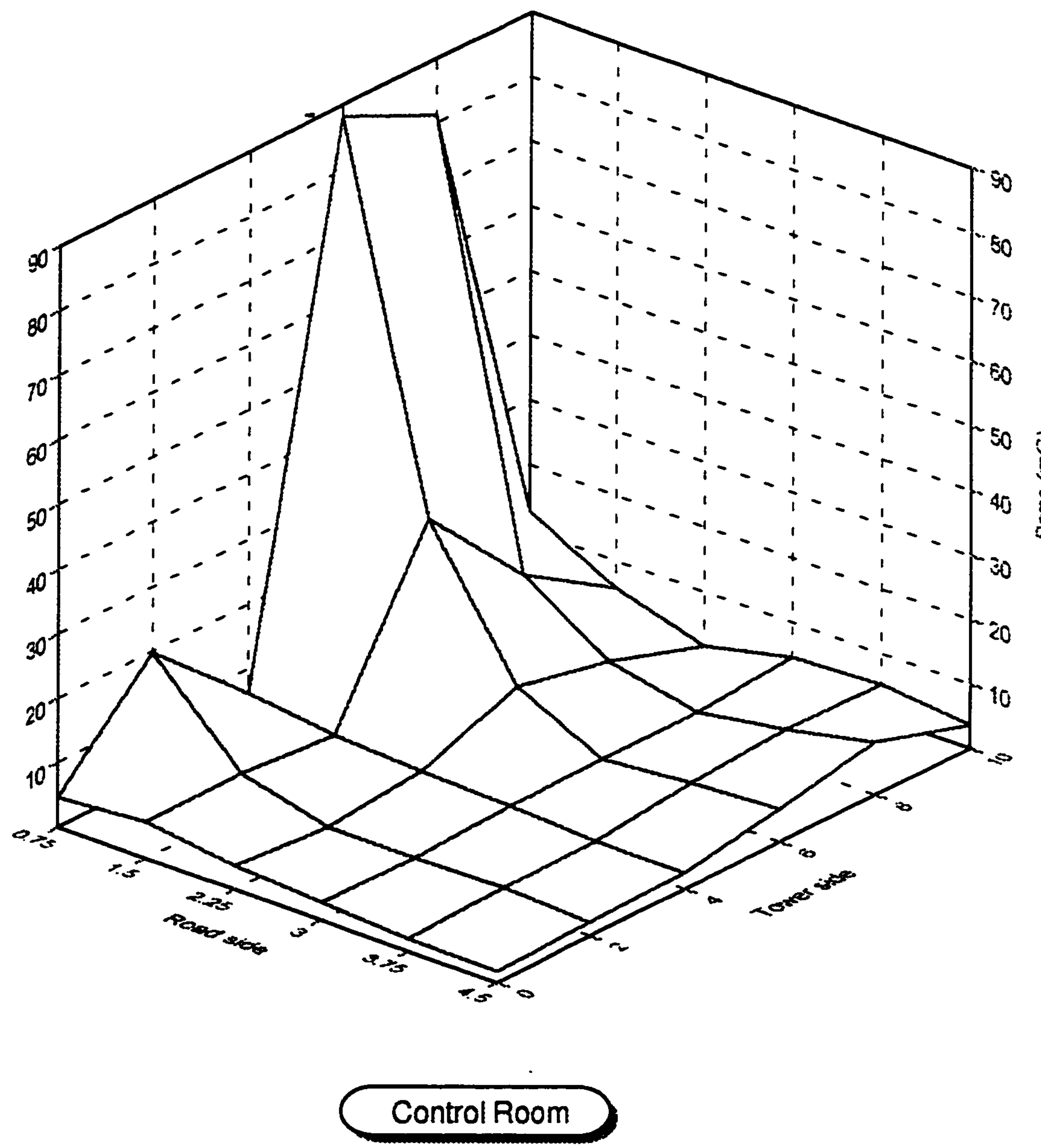


Figure A-9: 3D magnetic field map in control room.

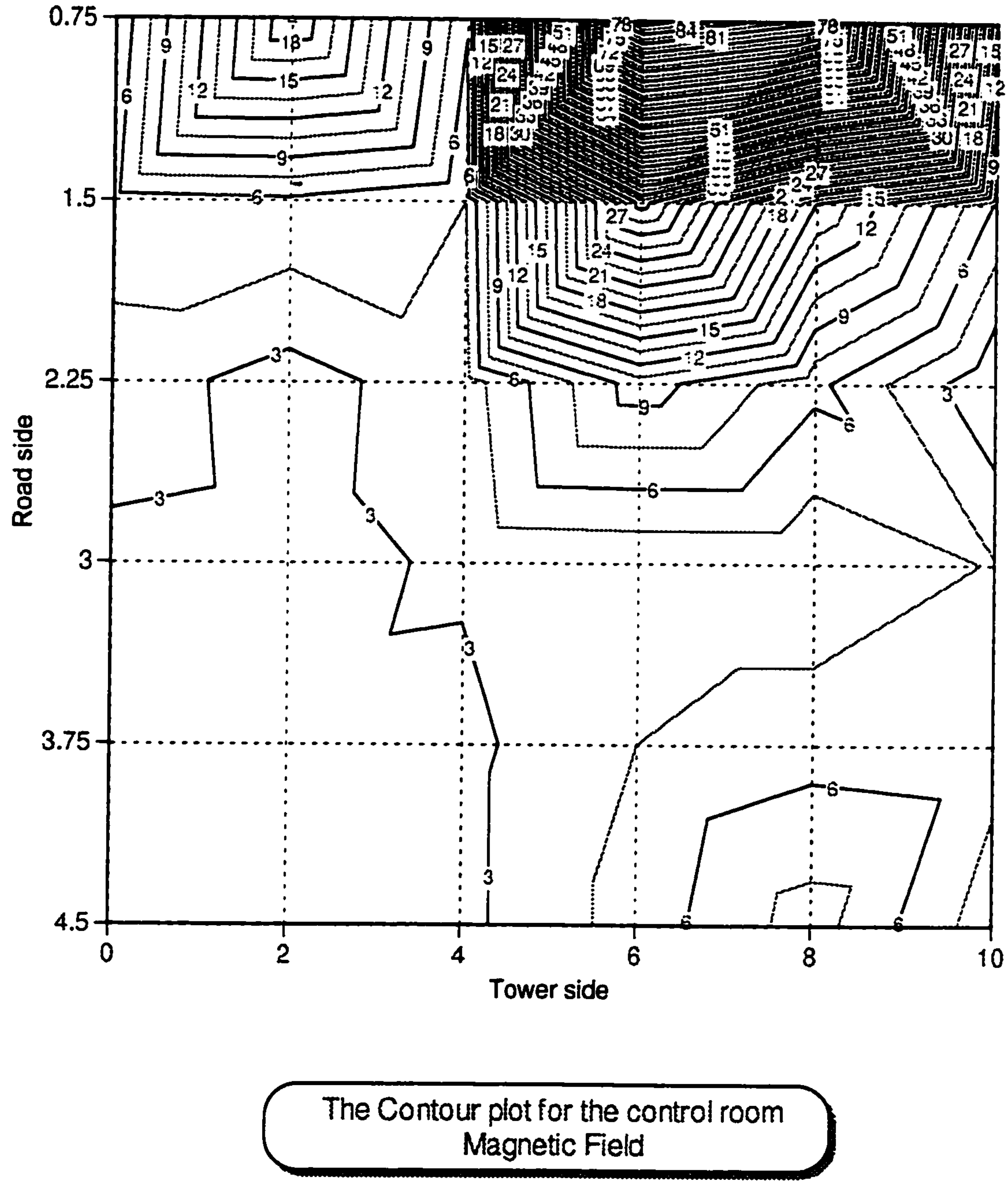


Figure A-10: Magnetic field contour plot in control room.

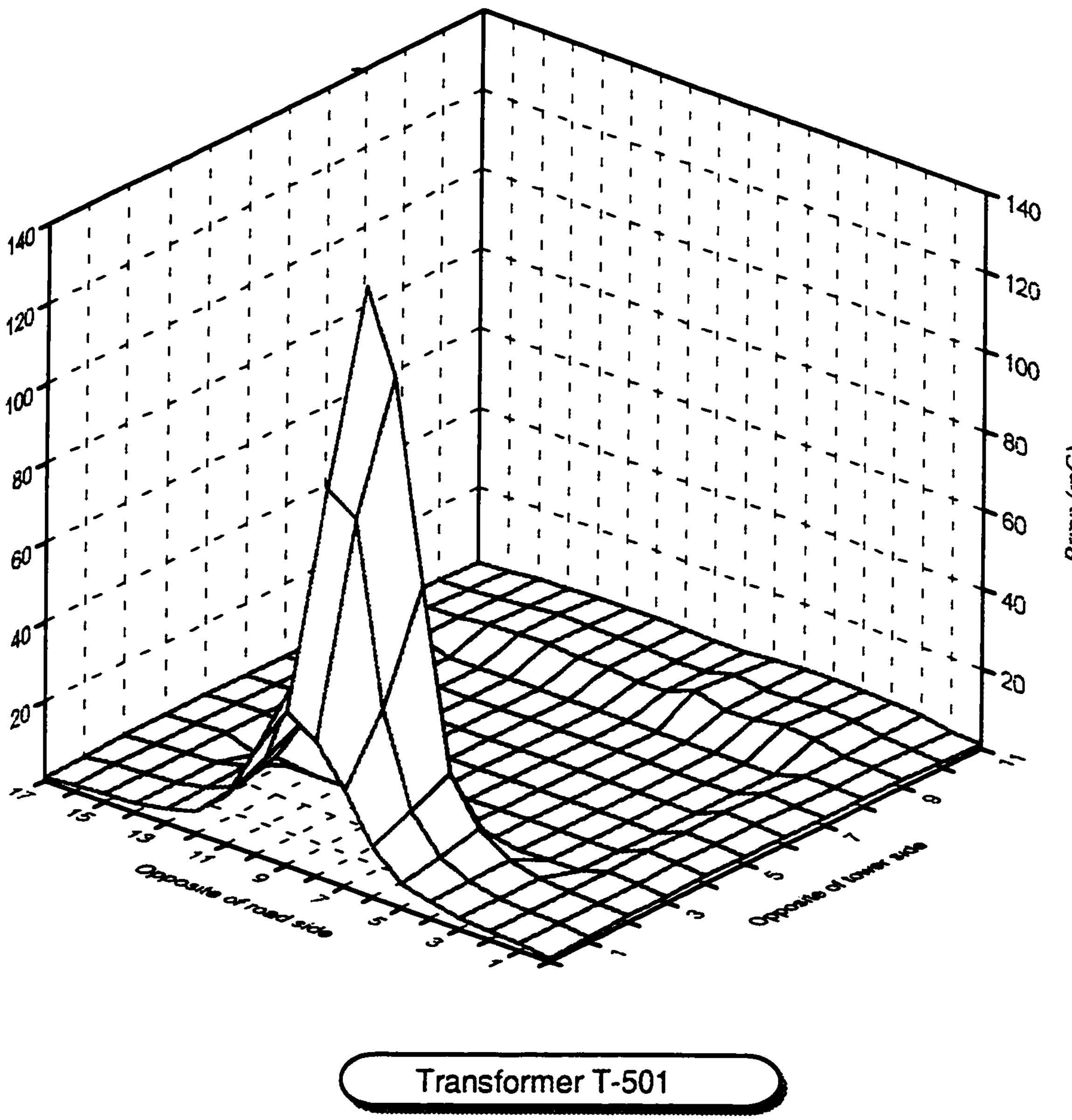


Figure A-11: 3D magnetic field map around main transformer T-501.

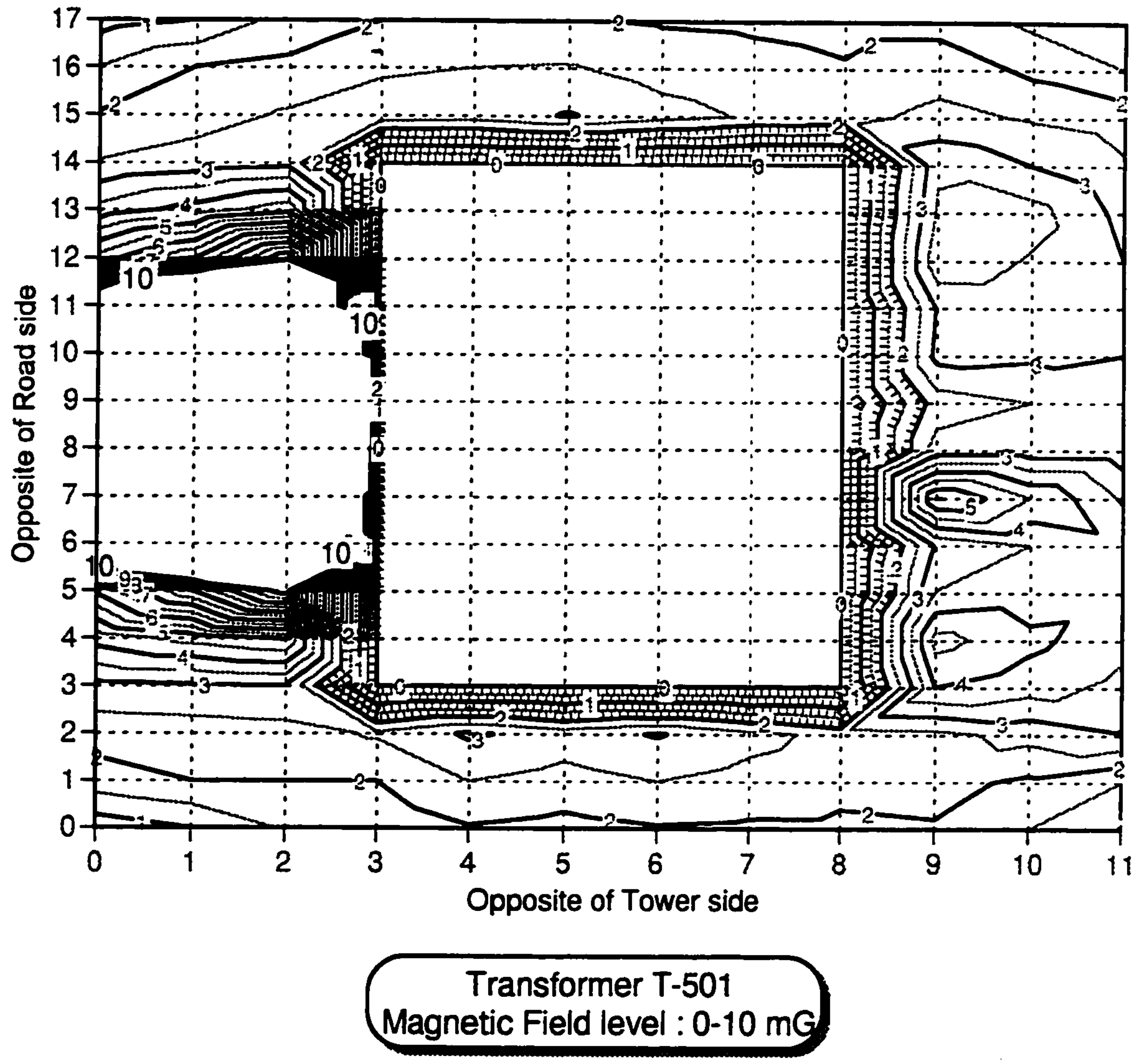


Figure A-12: Contour plot around main transformer T-501 (0-10 mG).

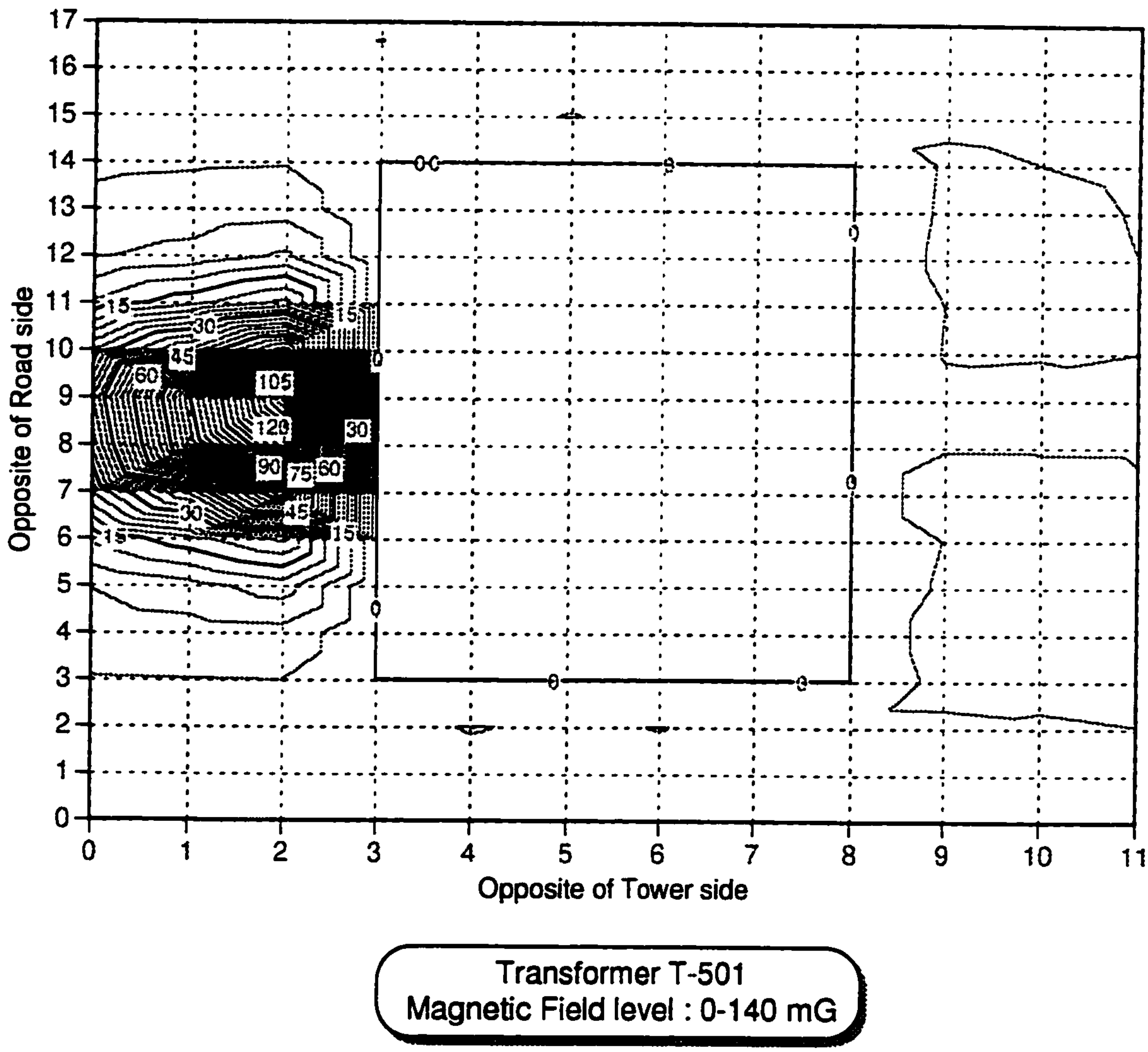


Figure A-13: Contour plot around main transformer T-501 (0-140 mG)

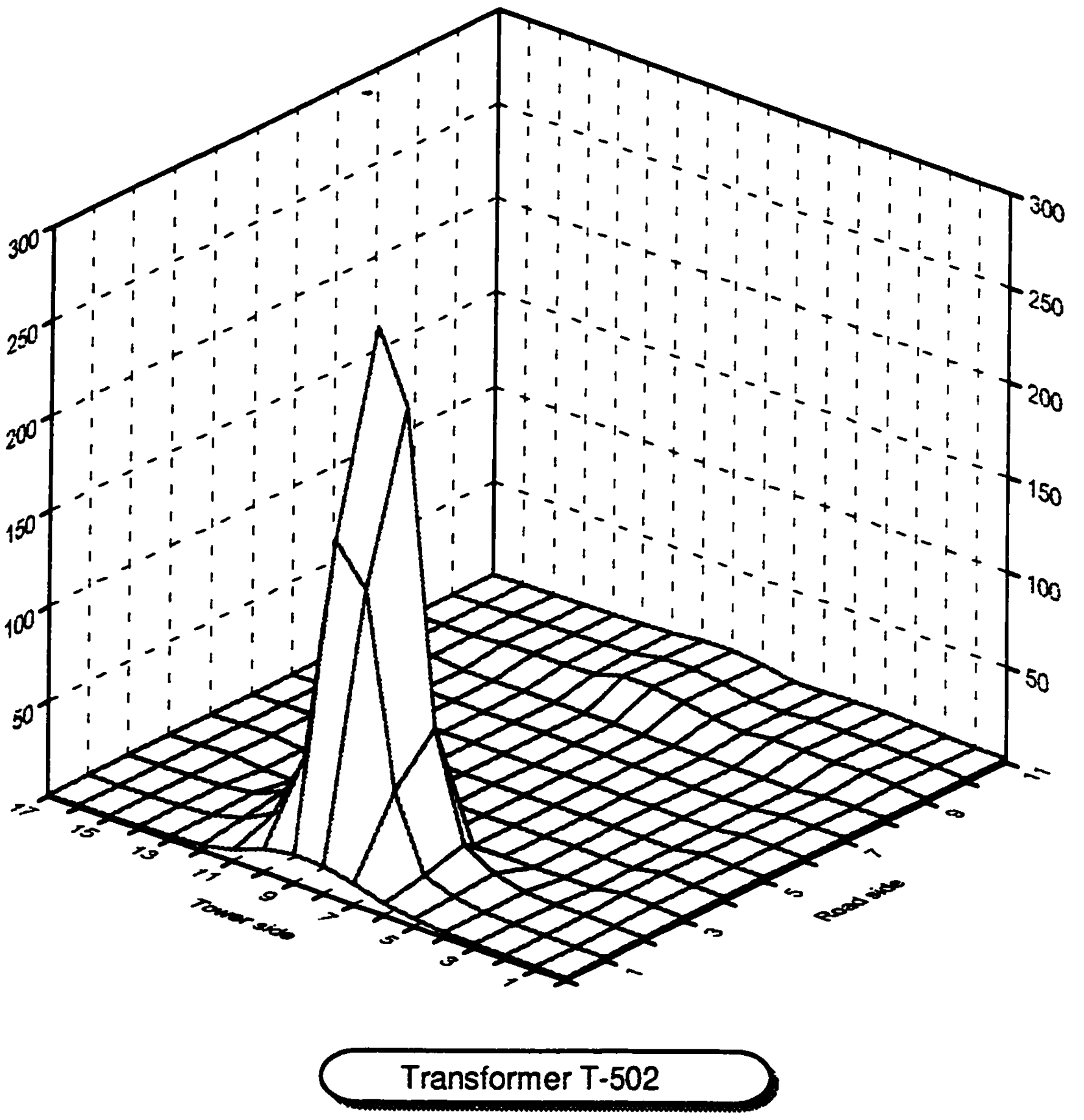


Figure A-14: 3D magnetic field map around main transformer T-502.

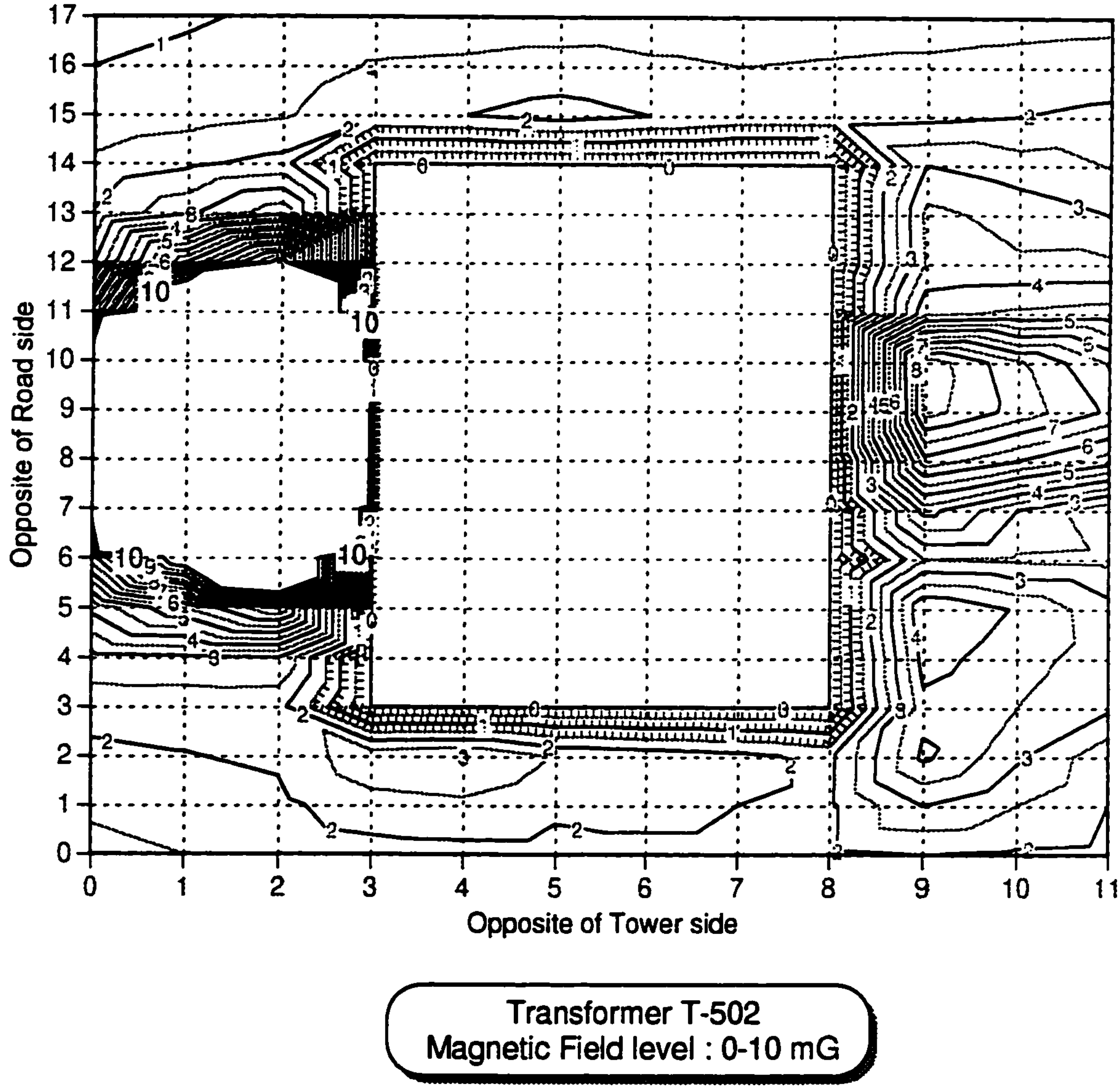


Figure A-15: Contour plot around main transformer T-502 (0-10 mG).

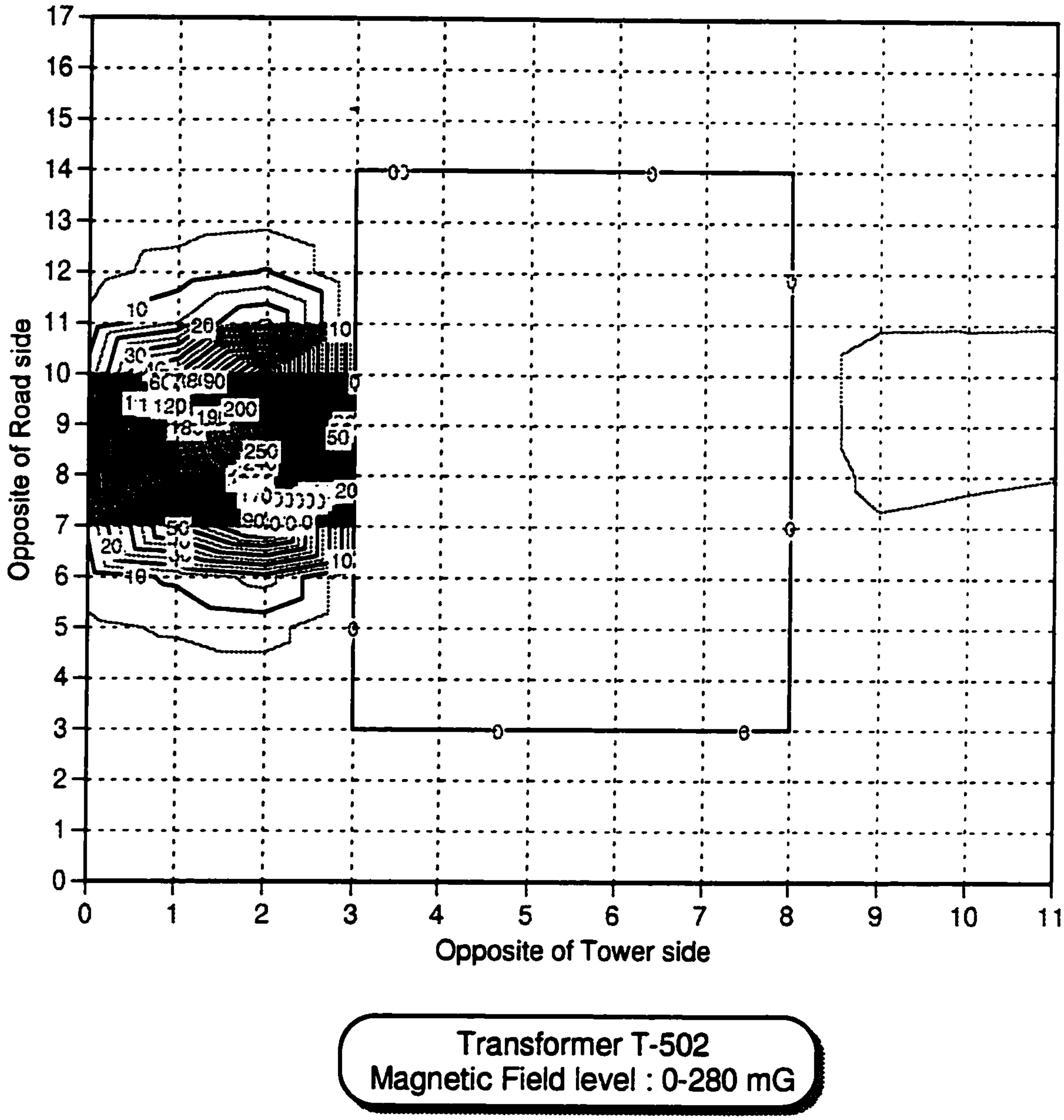


Figure A-16: Contour plot around main transformer T-502 (0-280 mG).

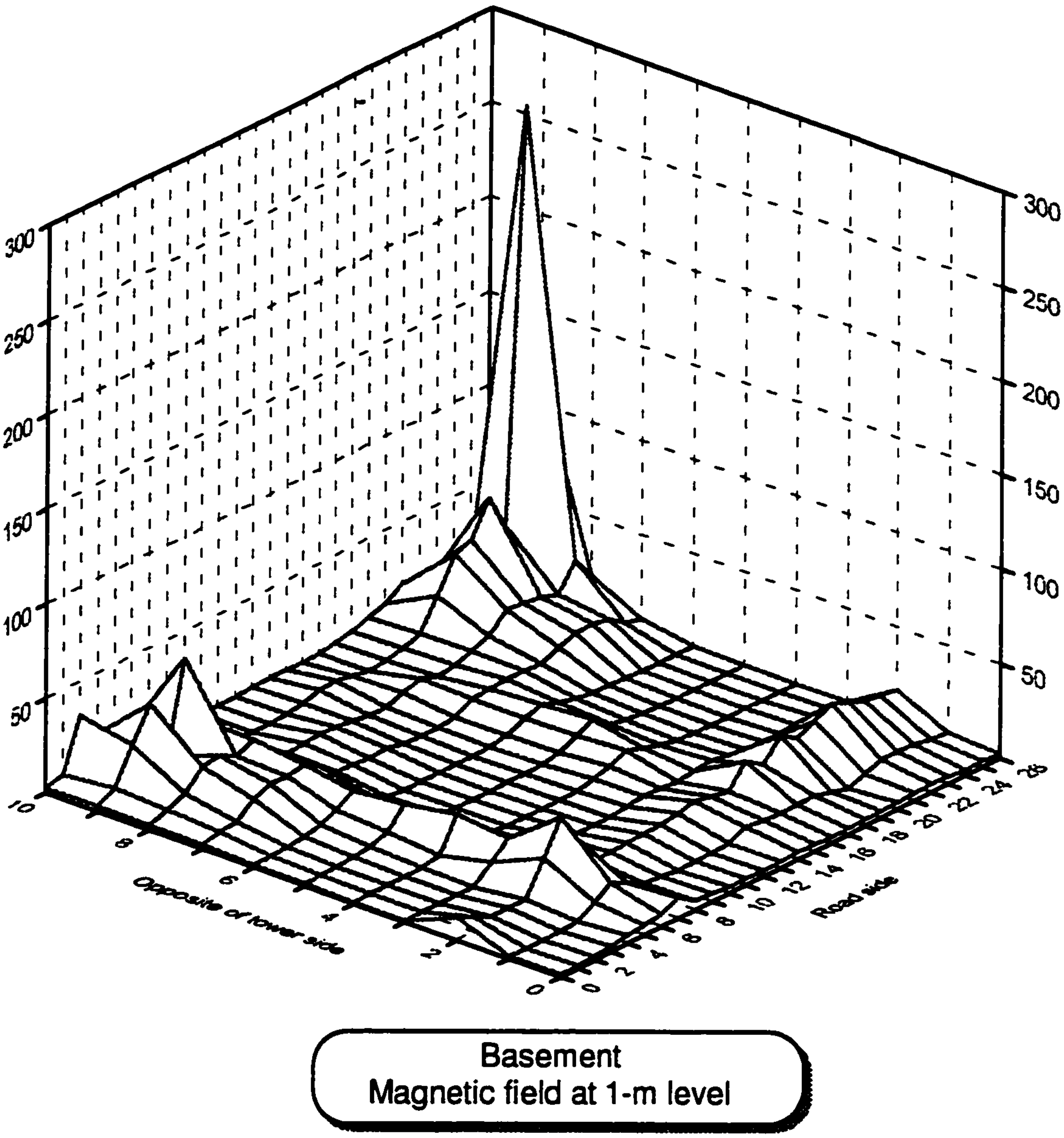


Figure A-17: 3D magnetic field map in basement.

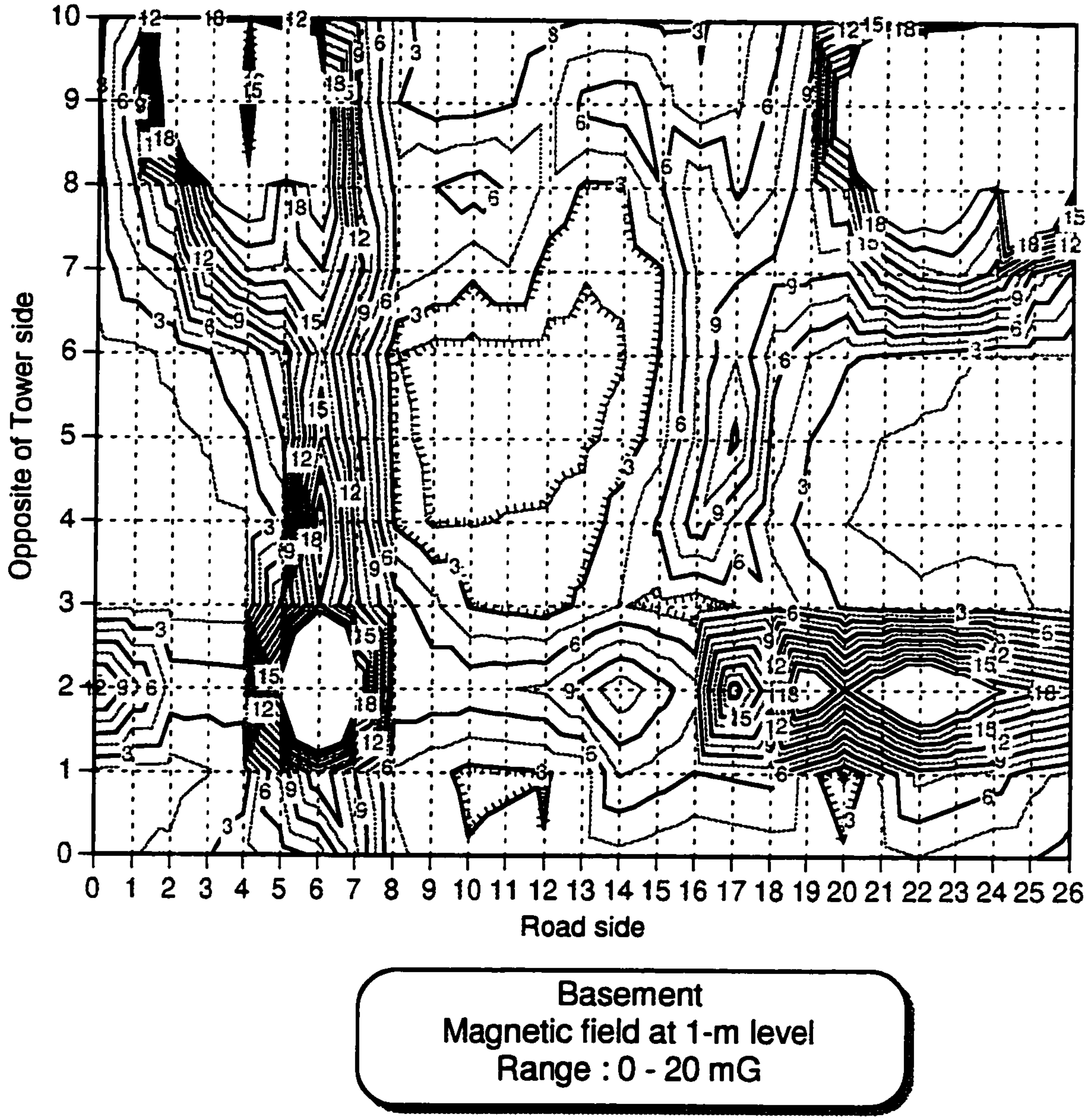


Figure A-18: Magnetic field contour plot in basement (0-20 mG).

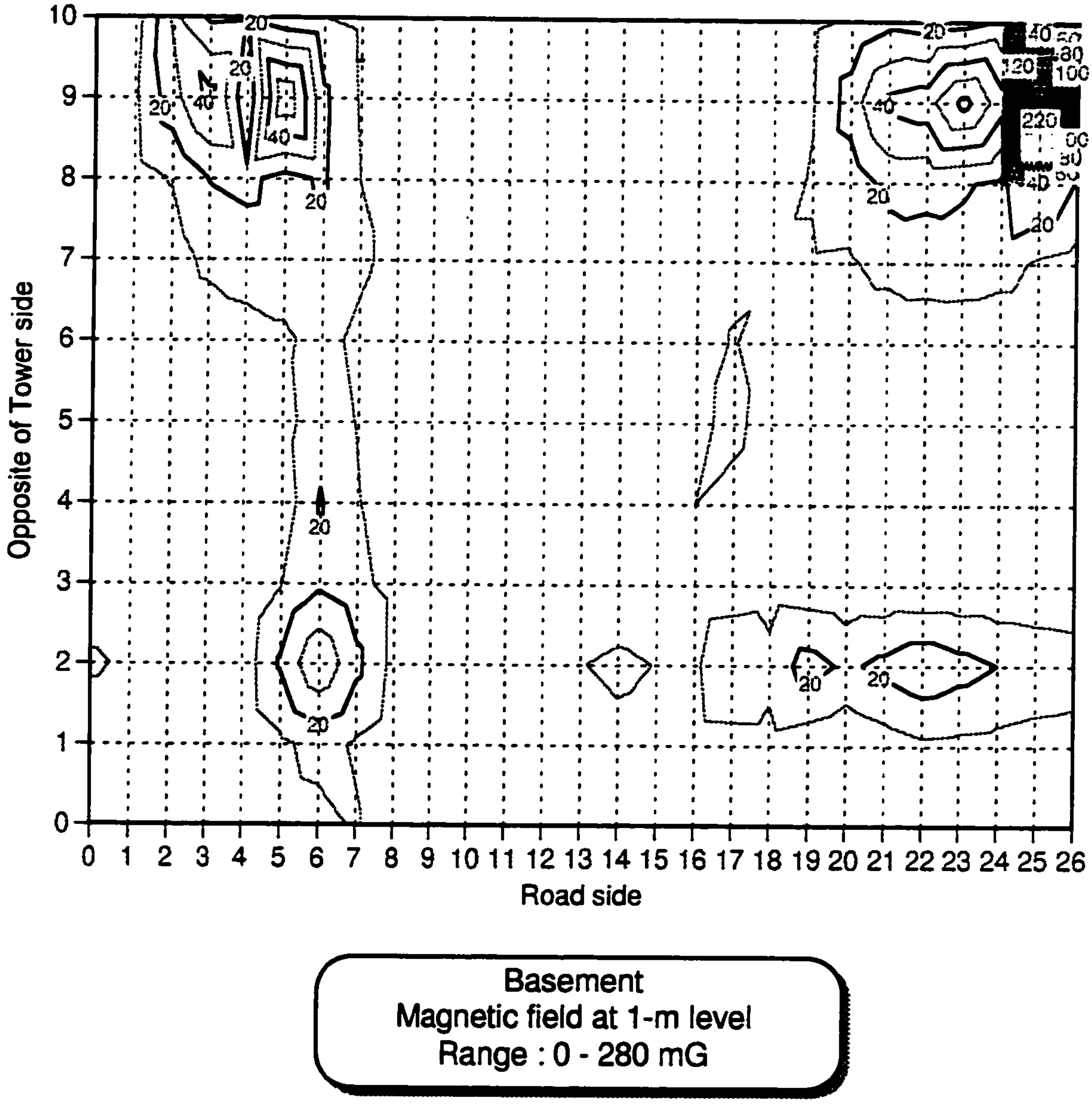


Figure A-19: Magnetic field contour plot in basement (0-280 mG).

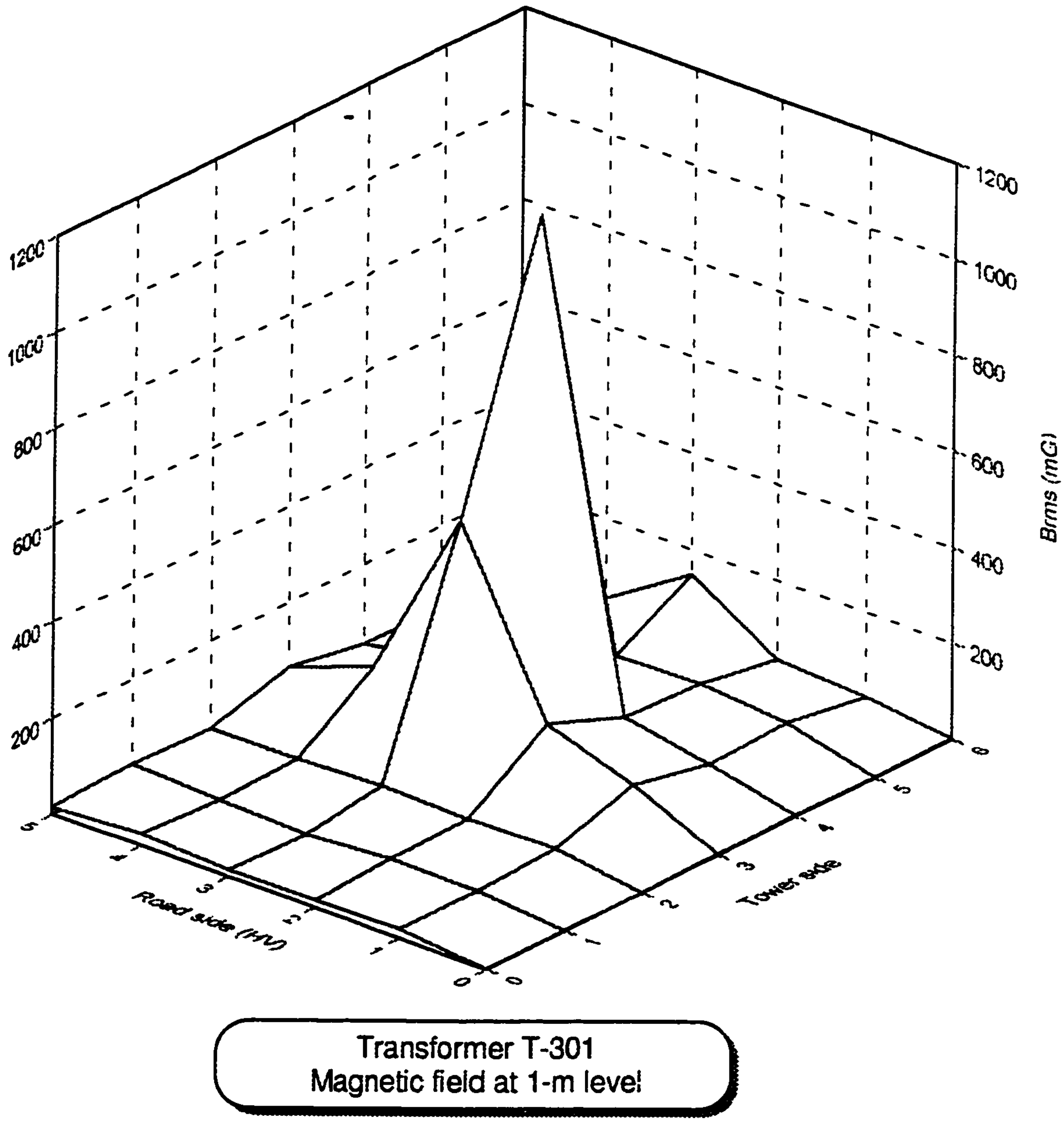


Figure A-20: 3D magnetic field map around transformer T-301 (1-m level).

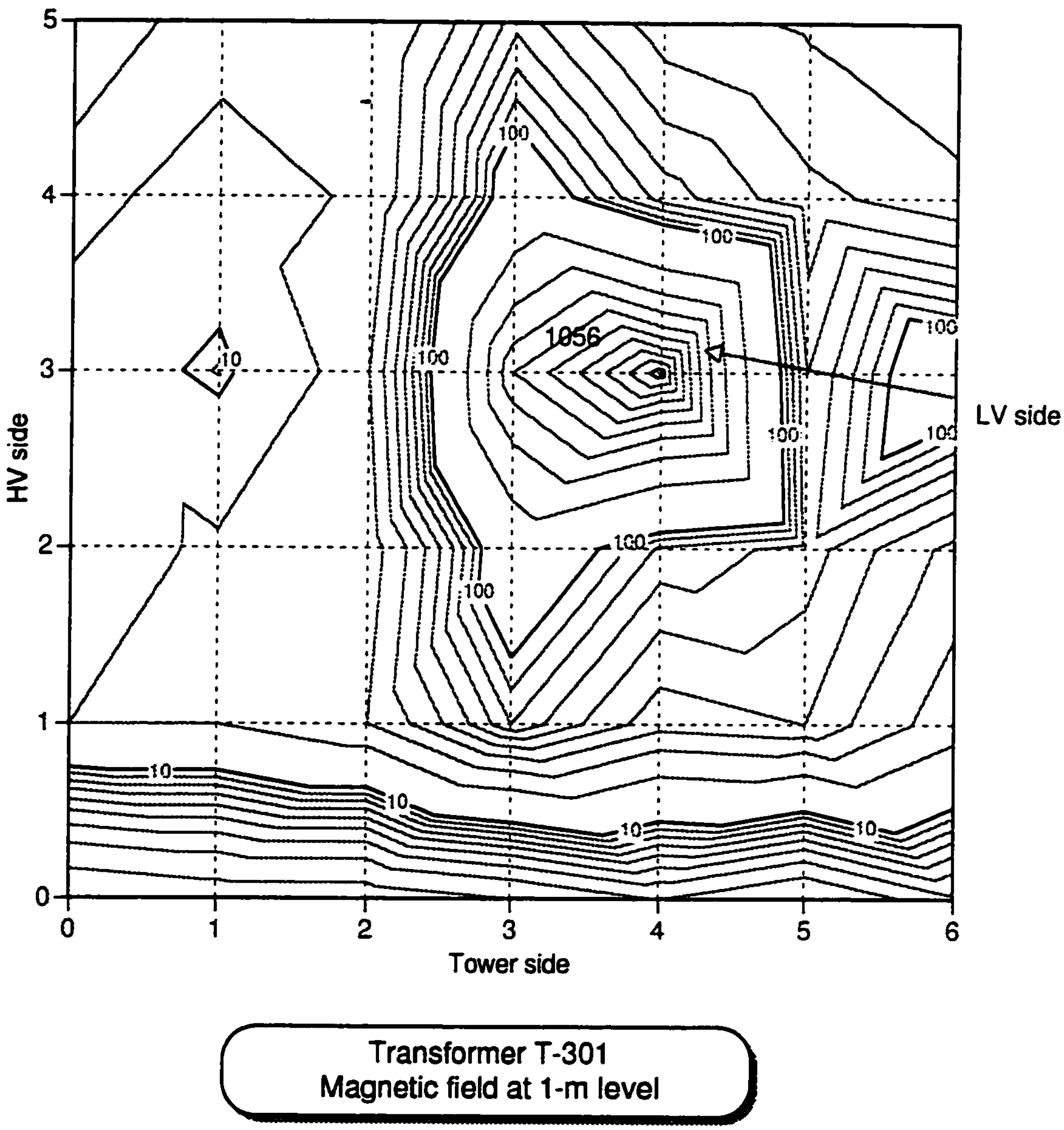


Figure A-21: Magnetic field contour plot around transformer T-301 (1-m level).

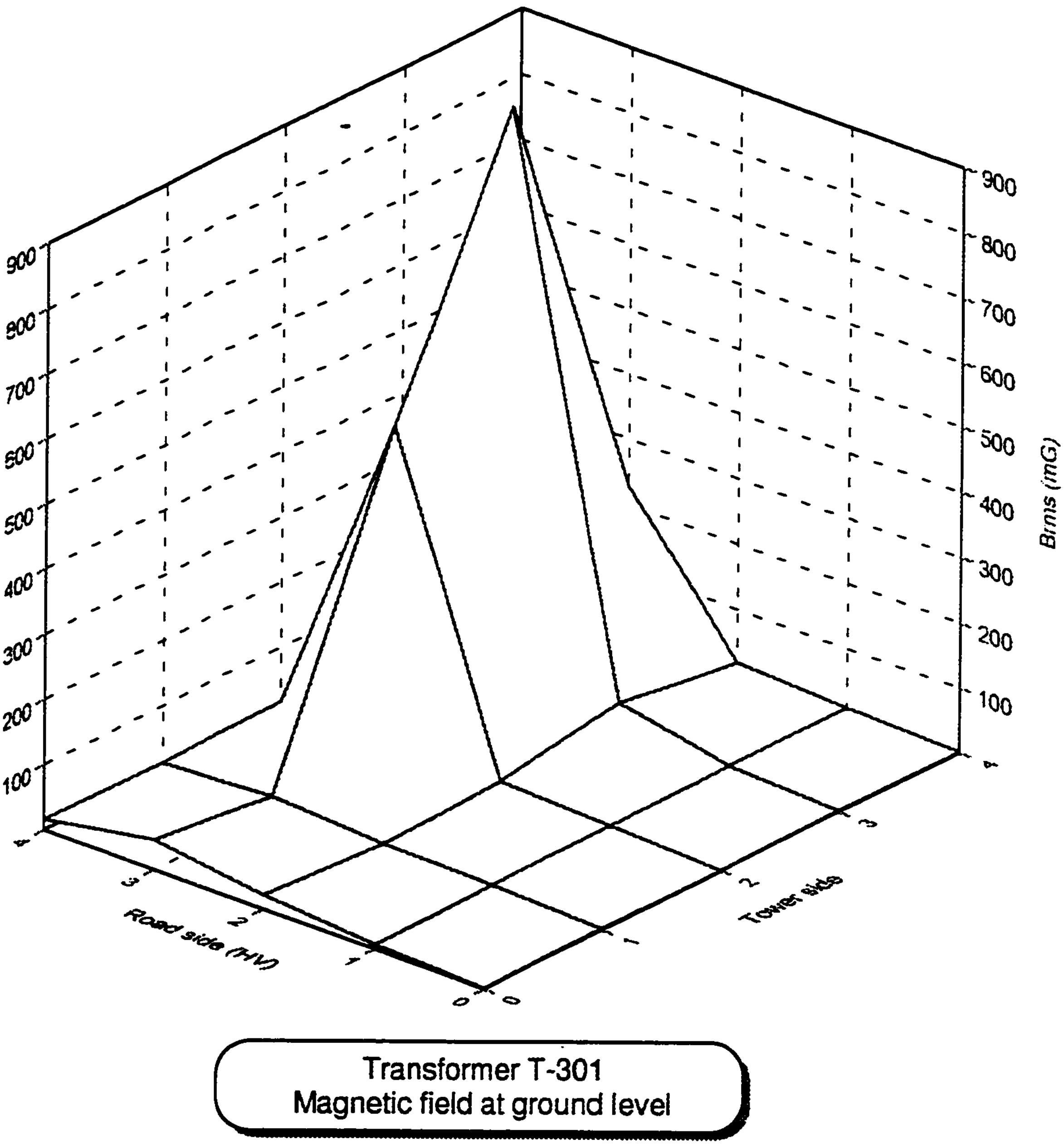


Figure A-22: 3D magnetic field map around transformer T-301 (ground level).

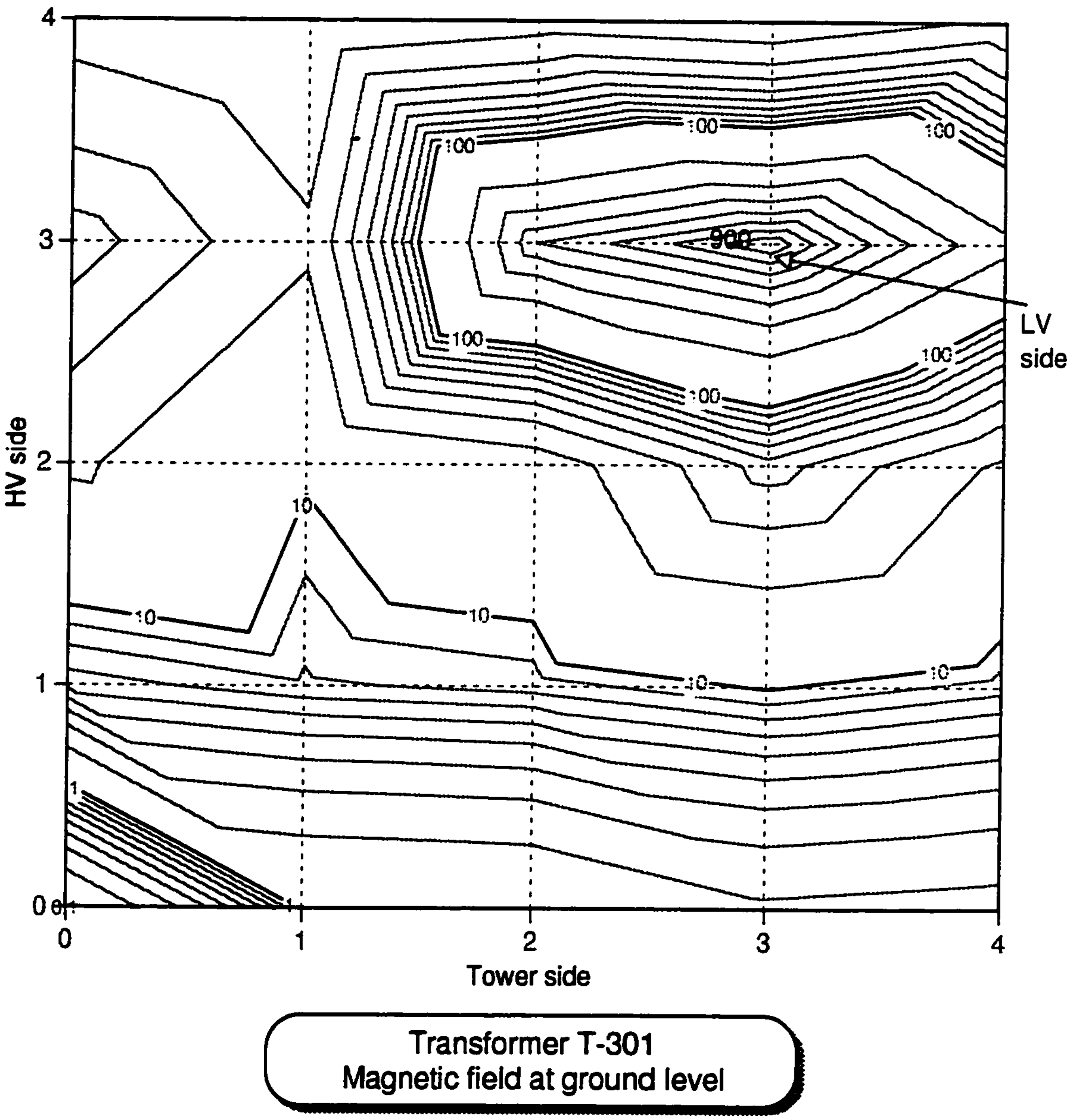


Figure A-23: Magnetic field contour plot around transformer T-301 (ground level).

Appendix-B: Simulation Results of Case I

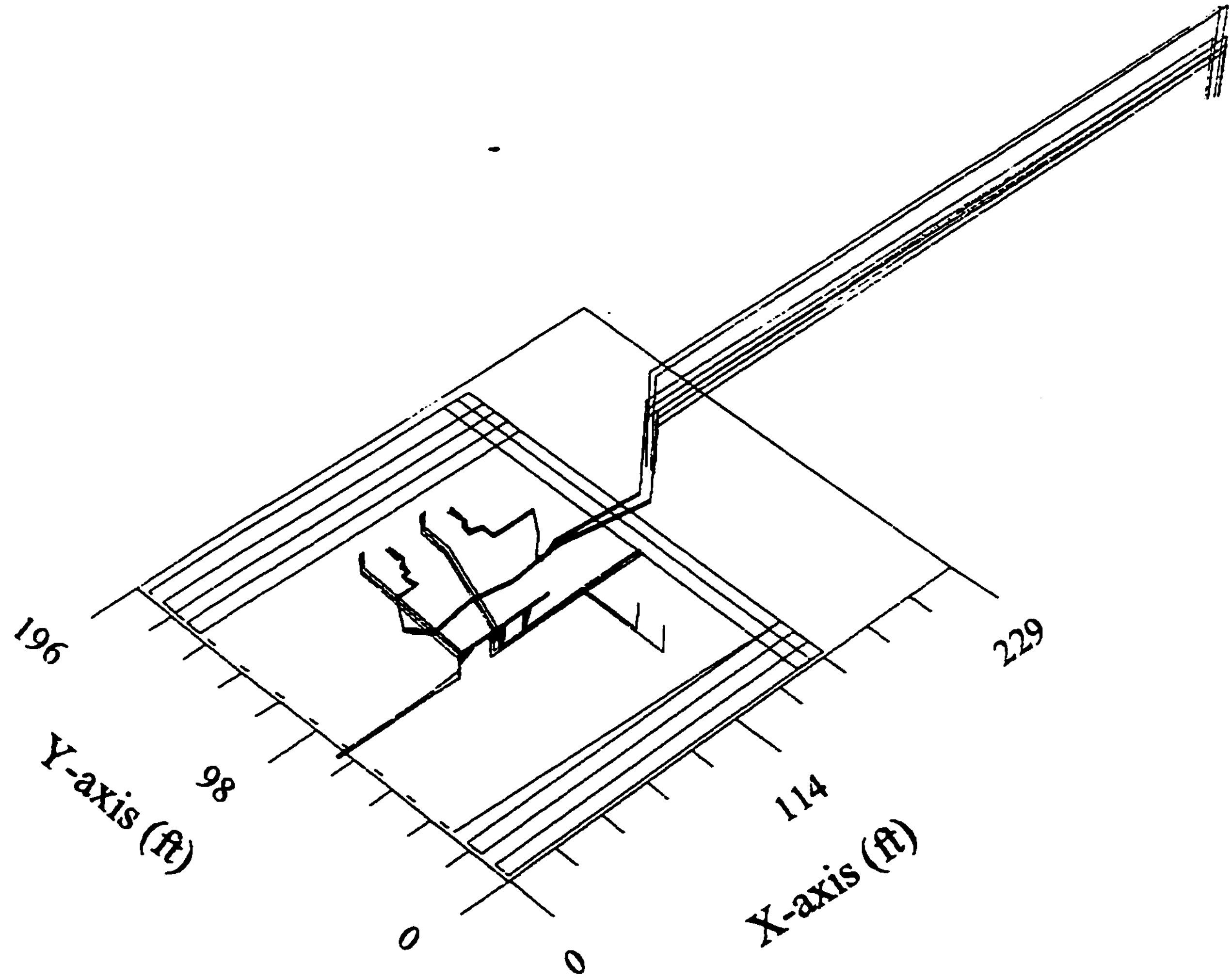


Figure B-1: 3D view of conductors in substation (Case I).

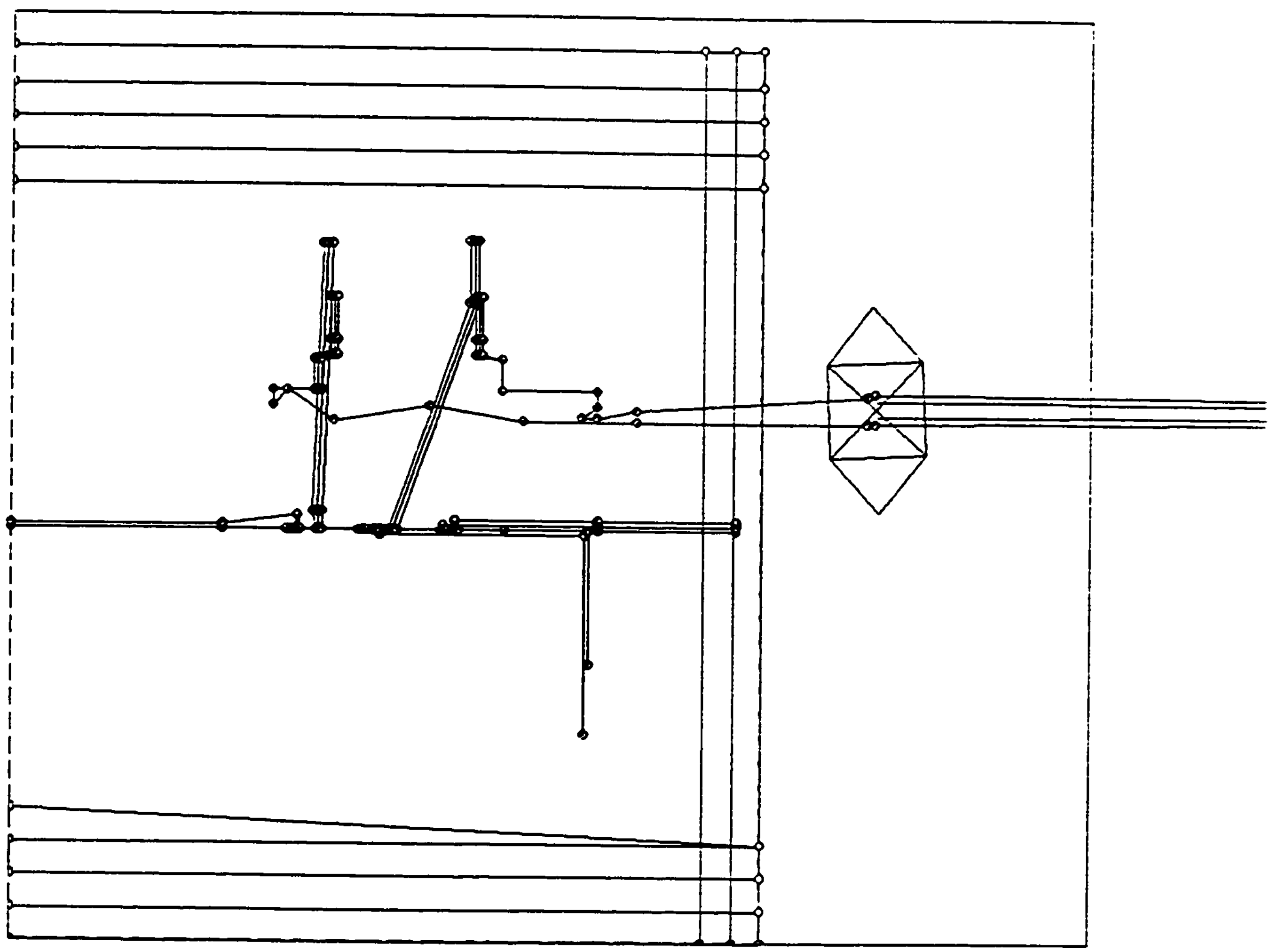


Figure B-2: Top view of conductors in substation (Case I).

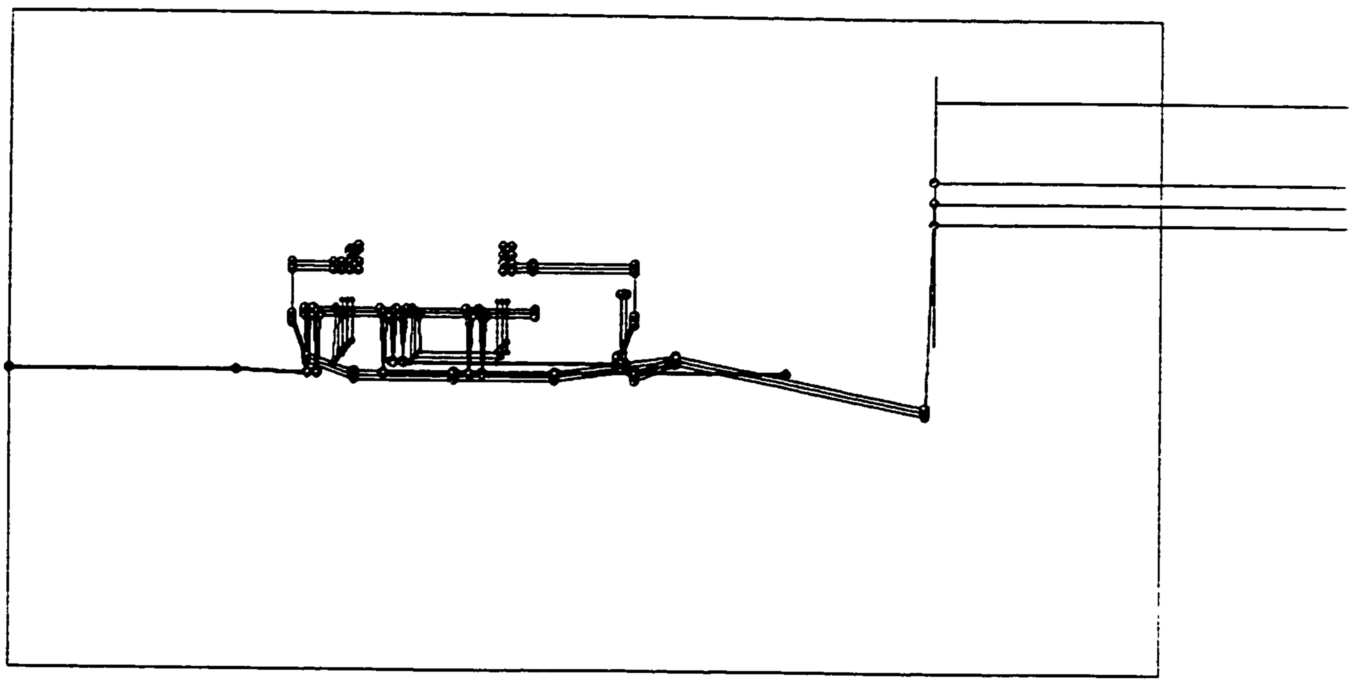


Figure B-3: Front view of conductors in substation (Case I).

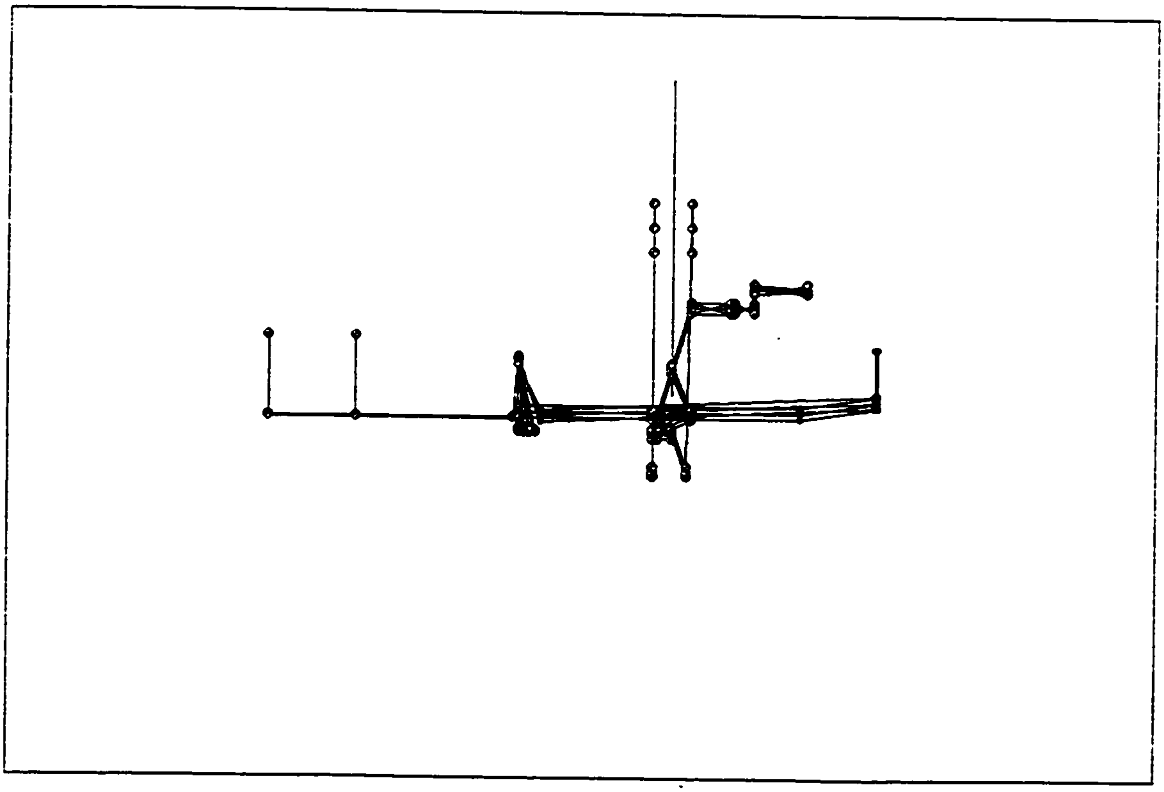


Figure B-4: Side view of conductors in substation (Case I).

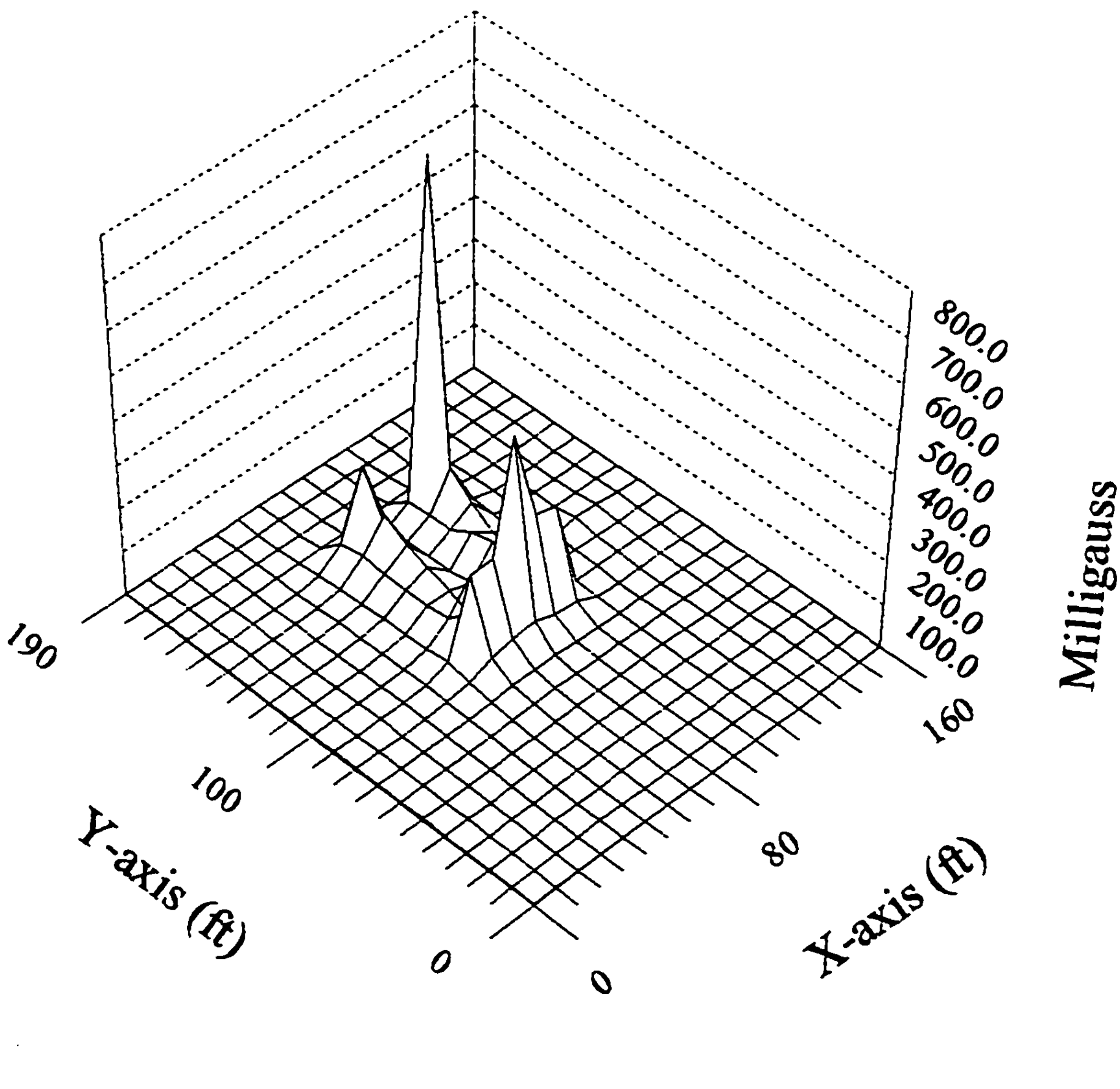


Figure B-5: 3D map of resultant magnetic field (Case I).

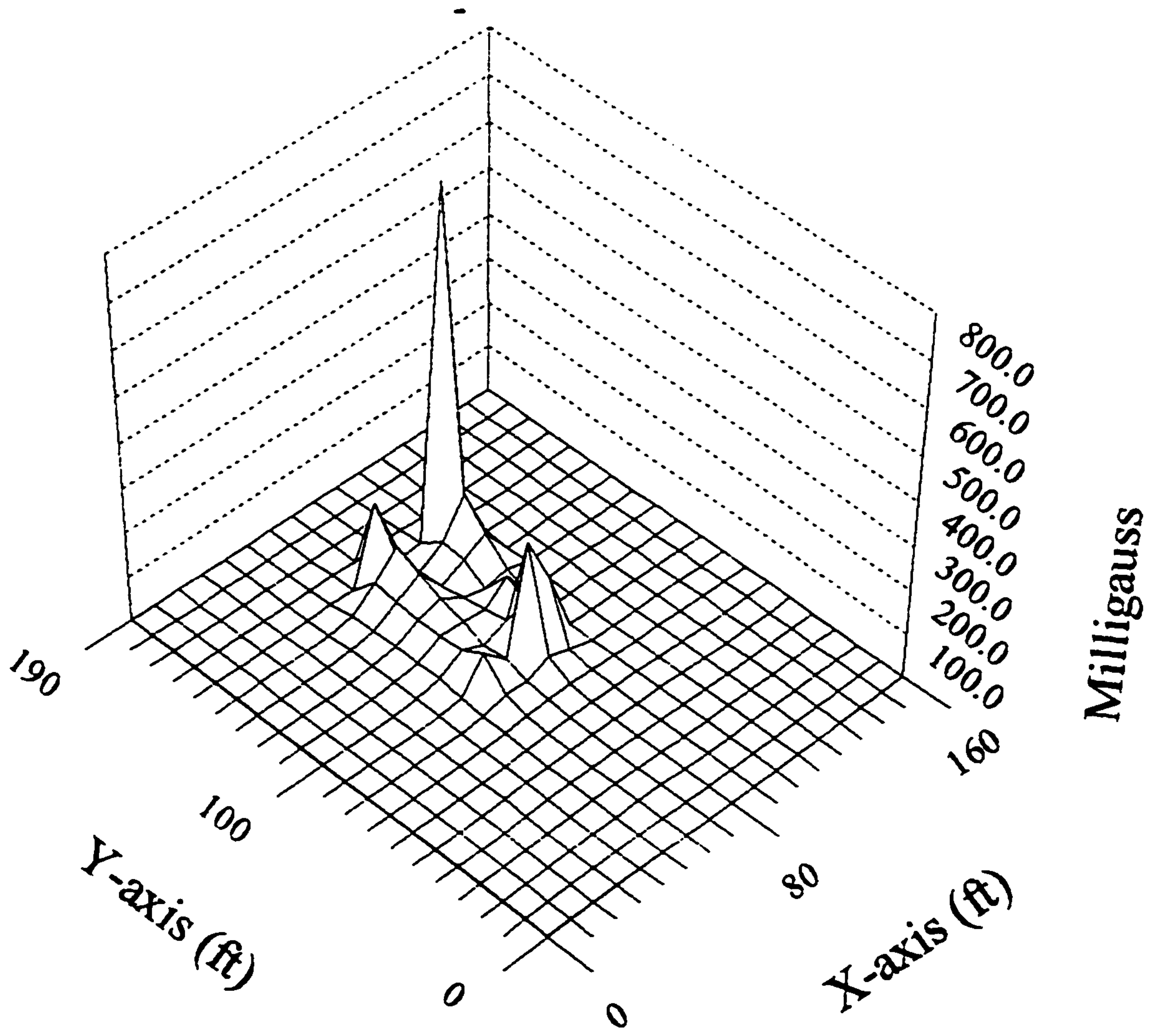


Figure B-6: 3D map of x-axis magnetic field (Case I).

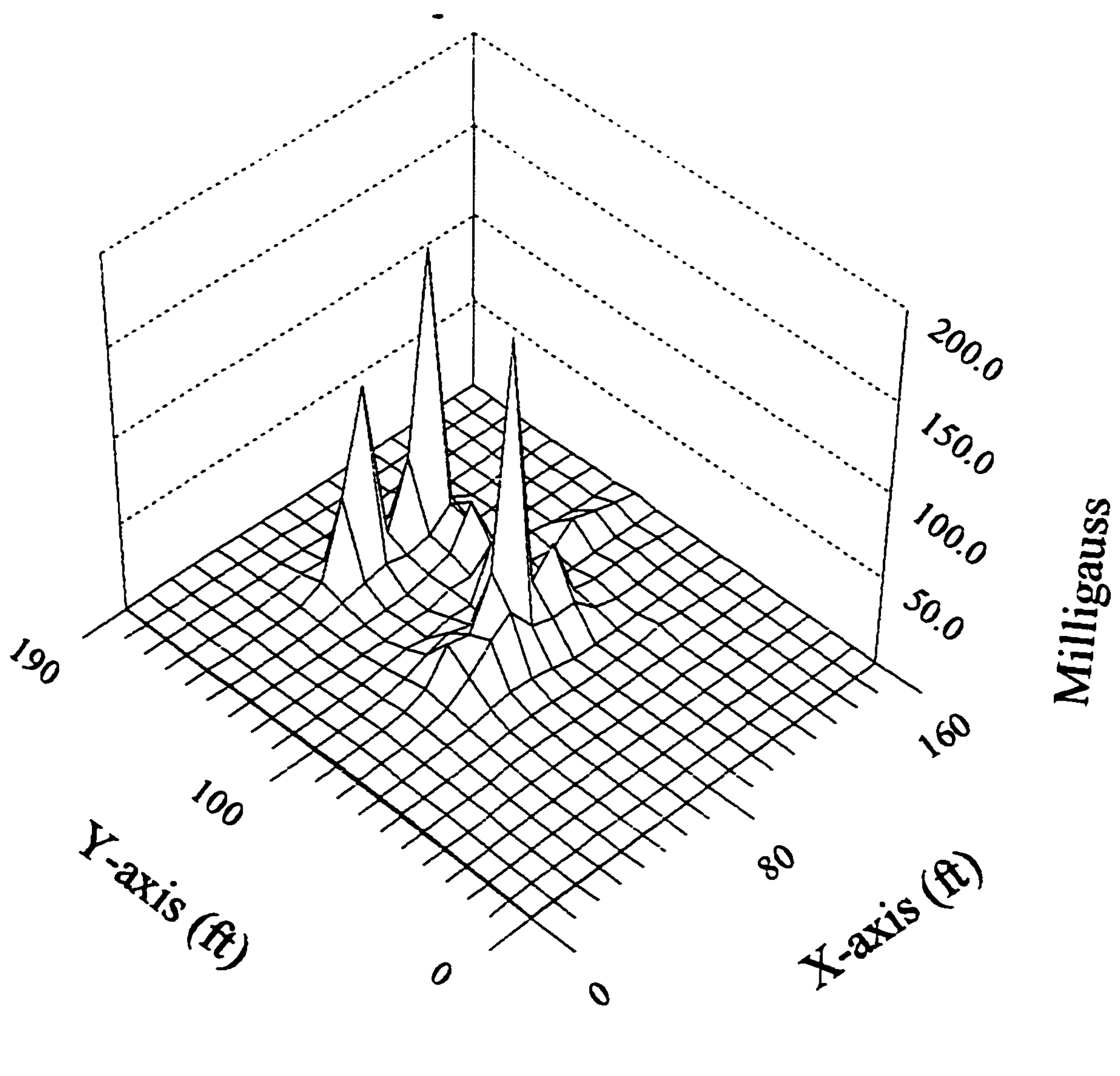


Figure B-7: 3D map of y-axis magnetic field (Case I).

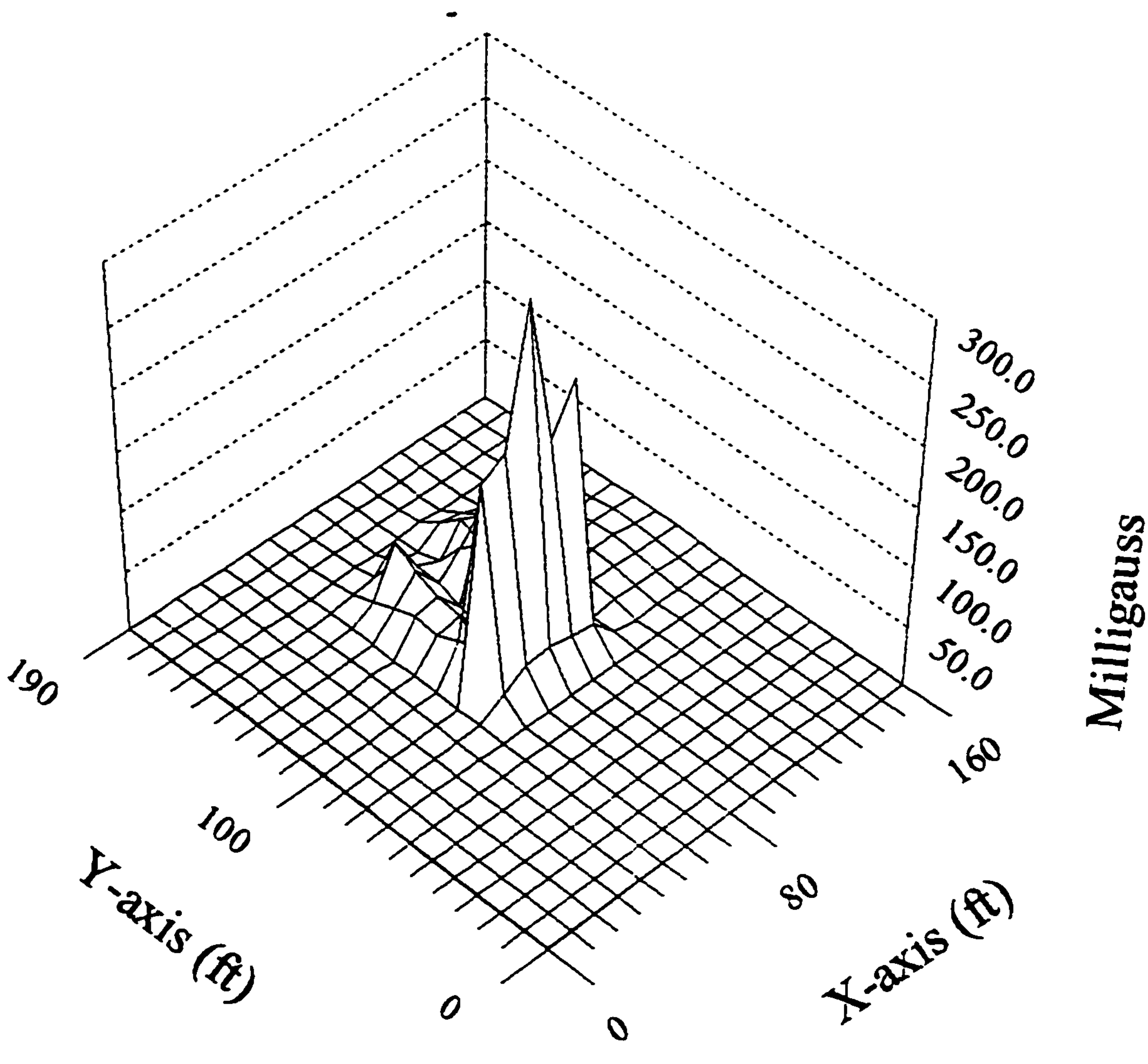


Figure B-8: 3D map of z-axis magnetic field (Case I).

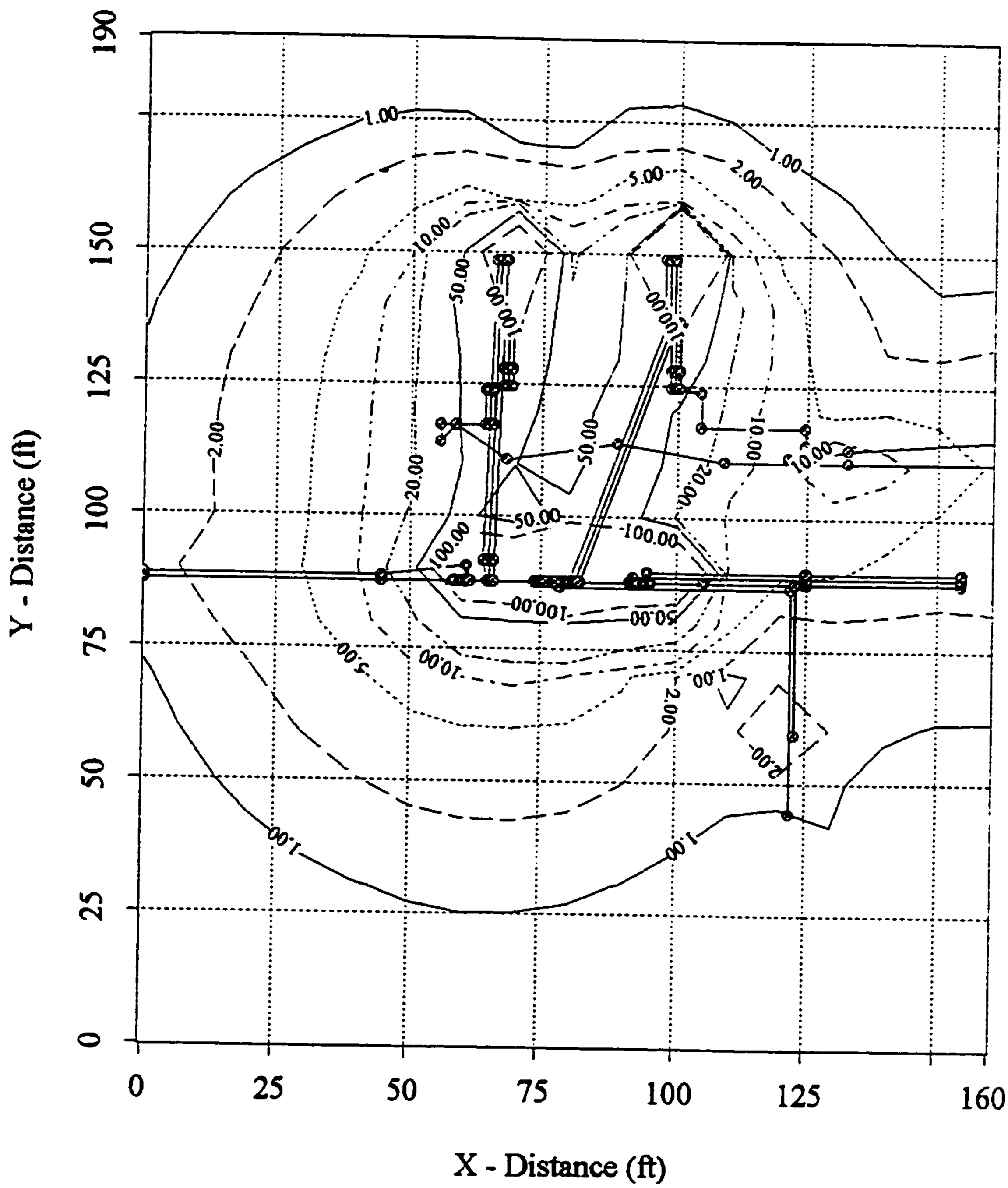


Figure B-9: Resultant contour from 0-100 mG(Case I).

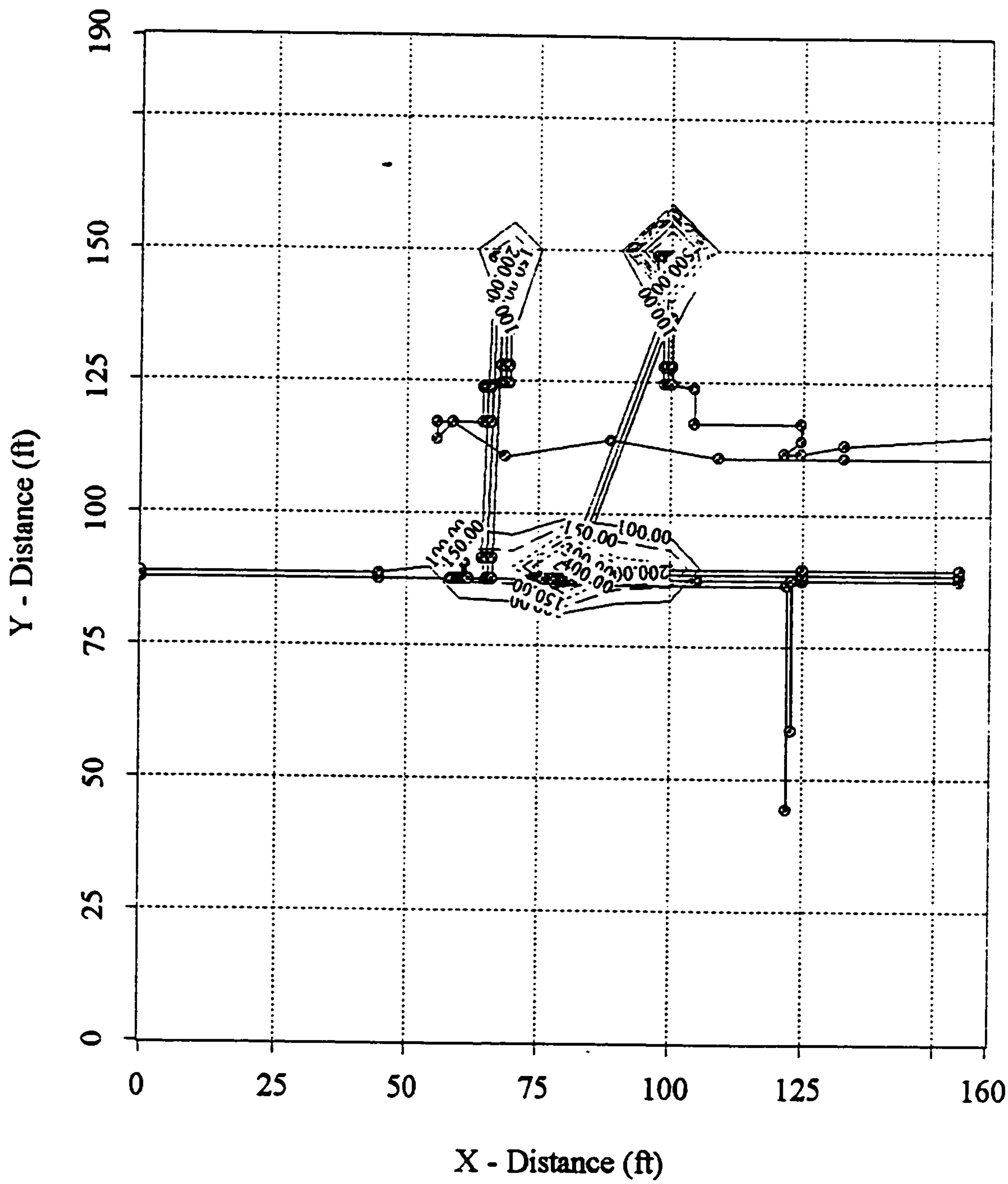


Figure B-10: Resultant contour from 100-500 mG (Case I).

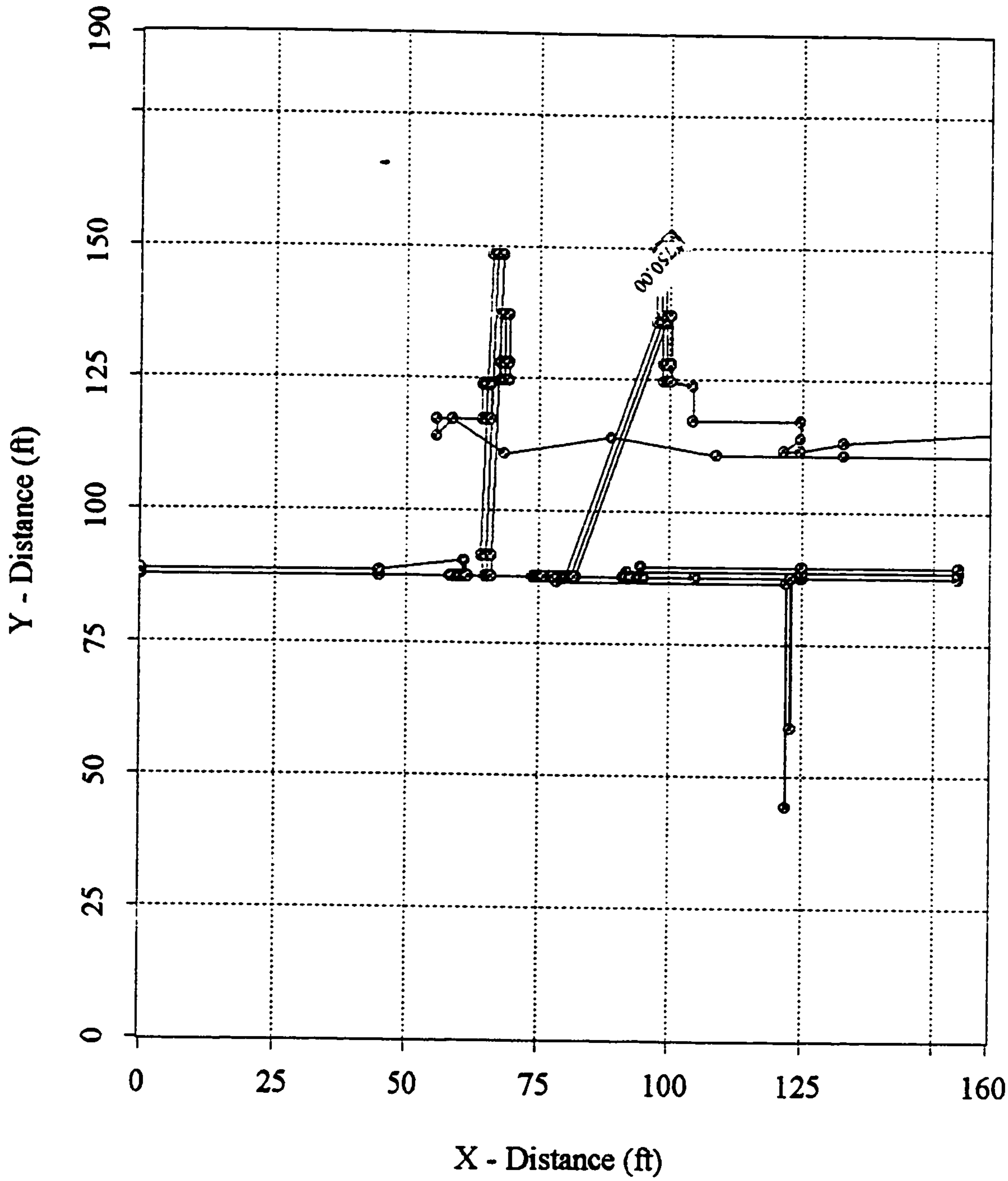


Figure B-11: Resultant contour from 500 mG to higher (Case I).

Appendix-C: Measurement results of Case II

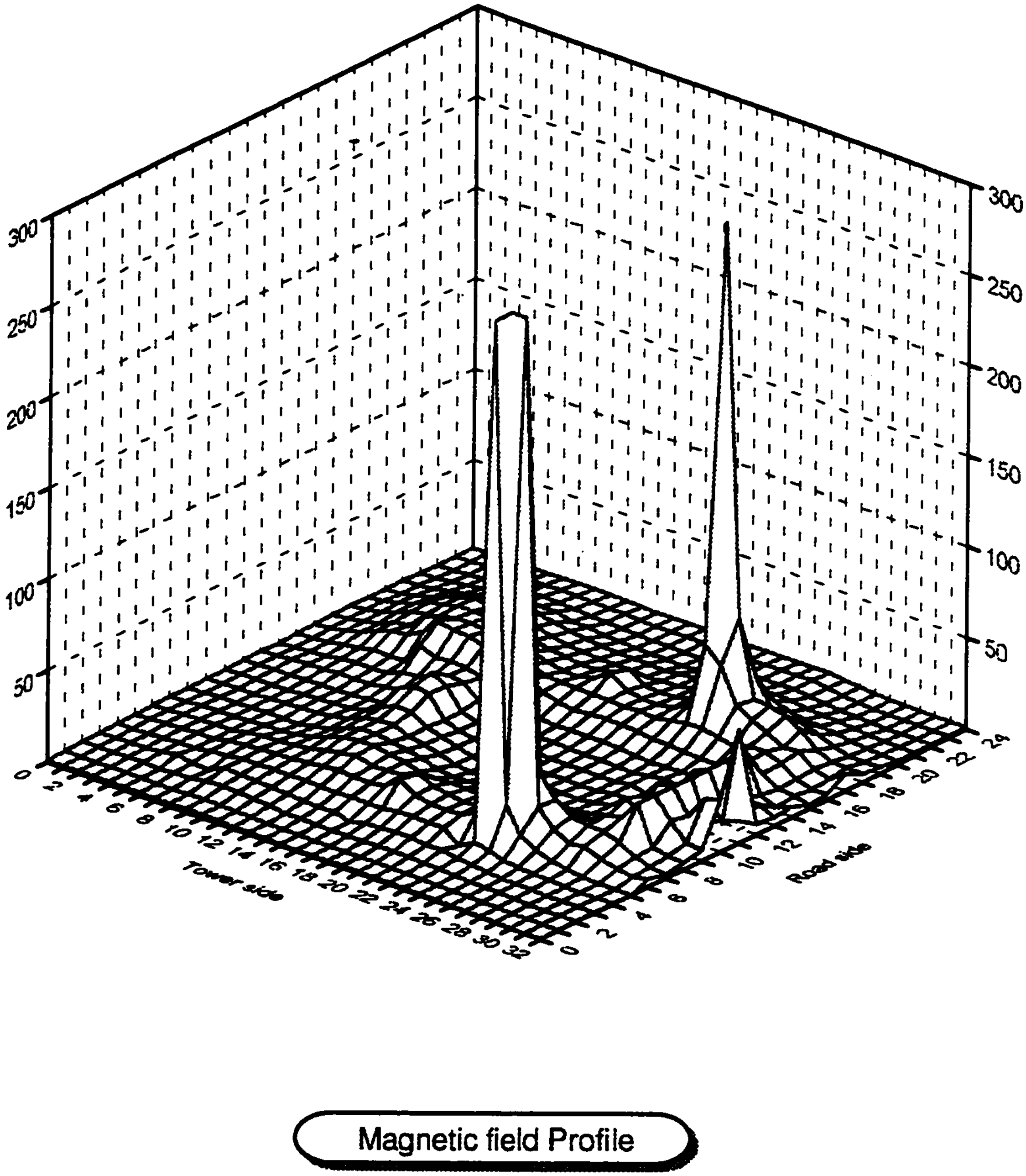


Figure C-1: 3D magnetic field map of complete substation.

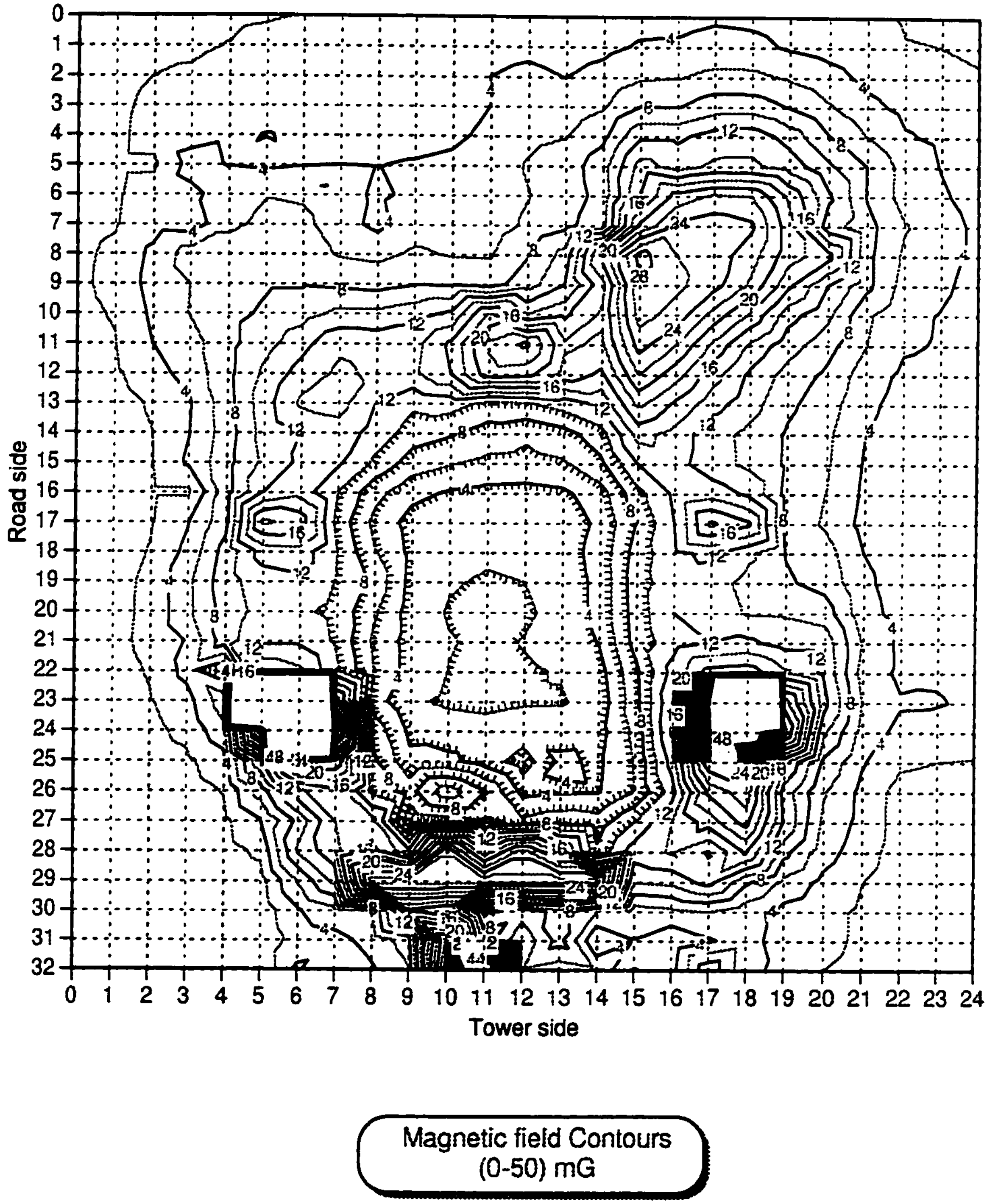


Figure C-2: Magnetic field contour map of complete substation.

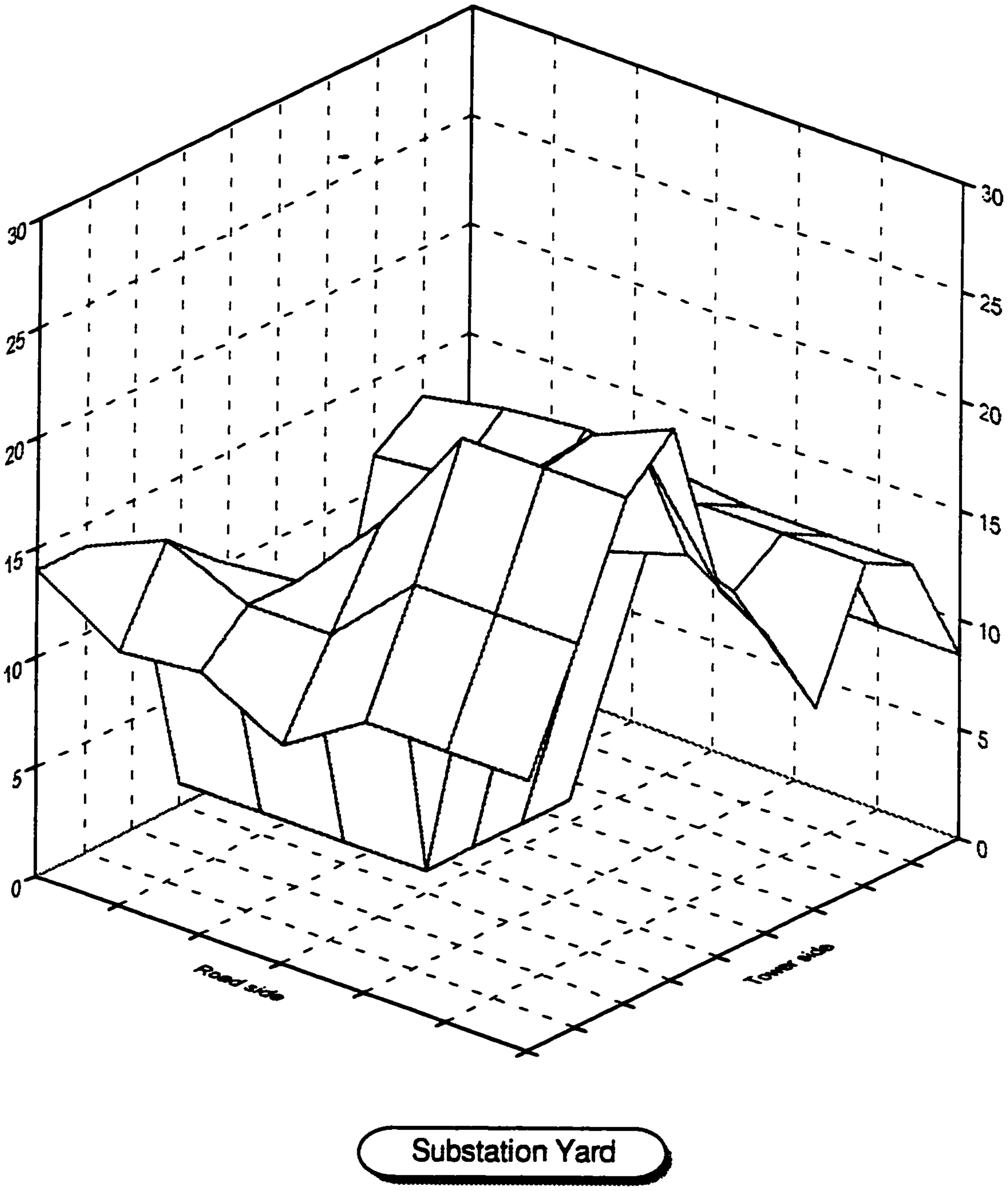


Figure C-3: 3D magnetic field map of substation yard.

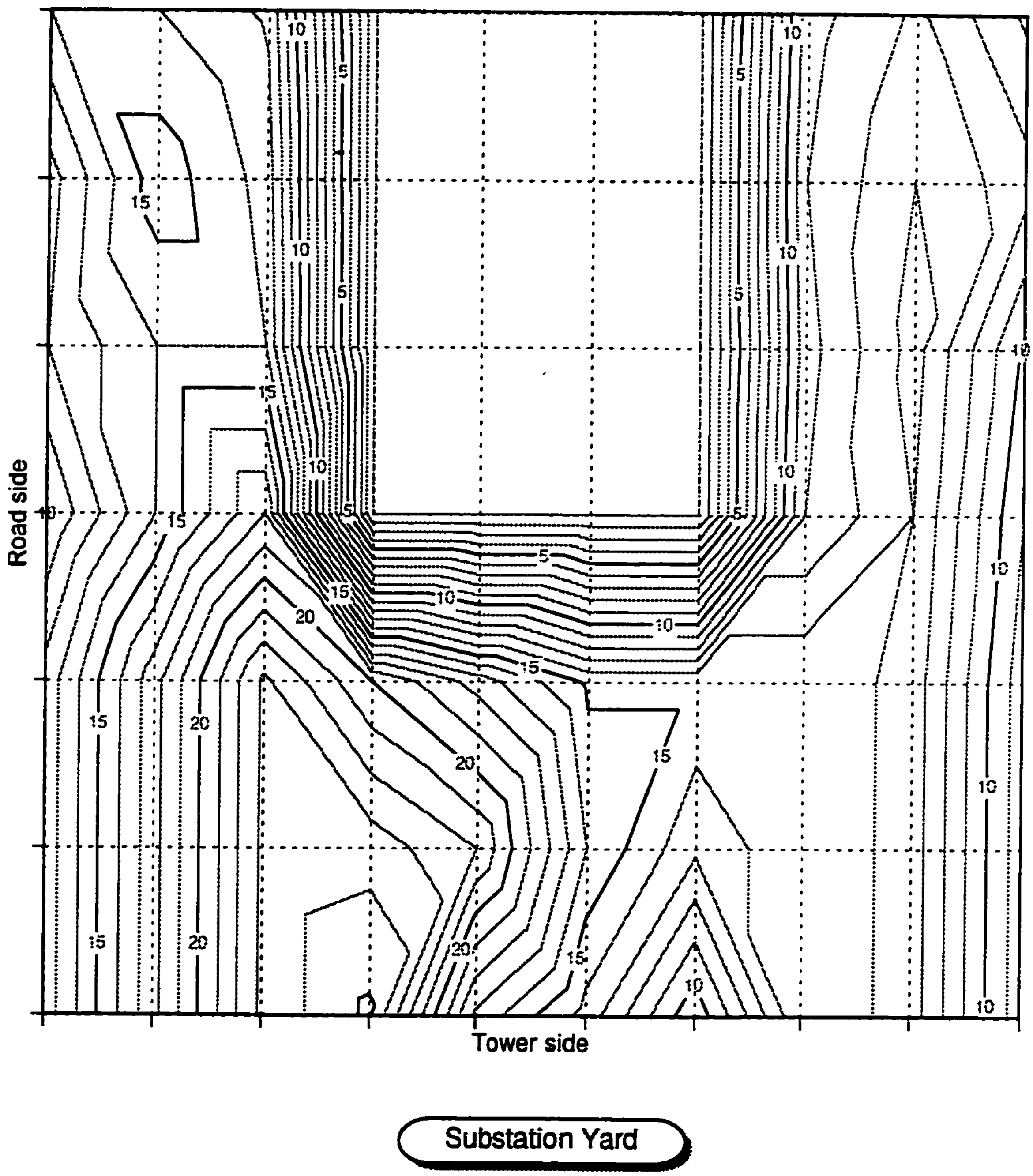


Figure C-4: Magnetic field contour map of substation yard.

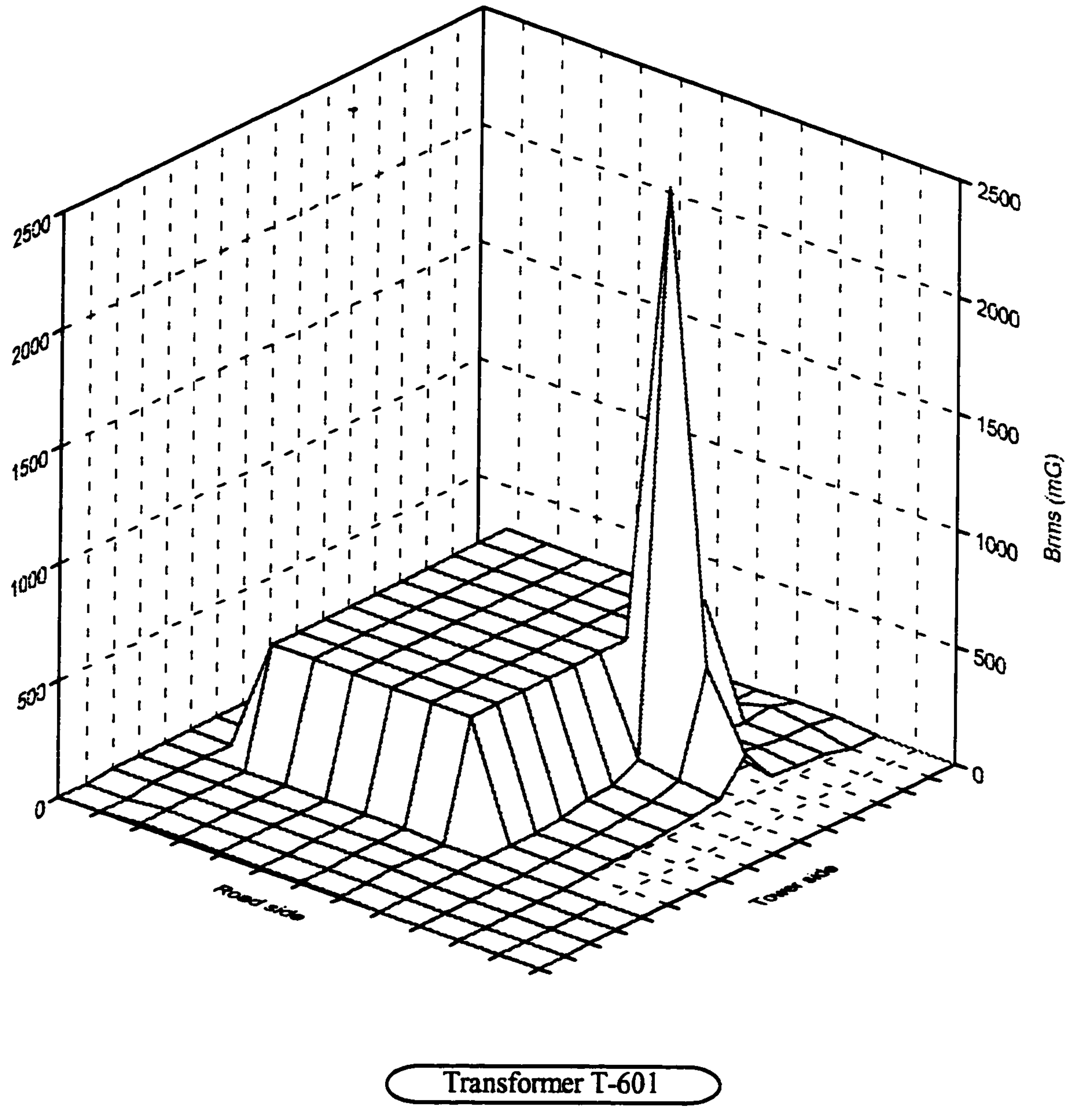


Figure C-5: 3D magnetic field map around transformer T-601.

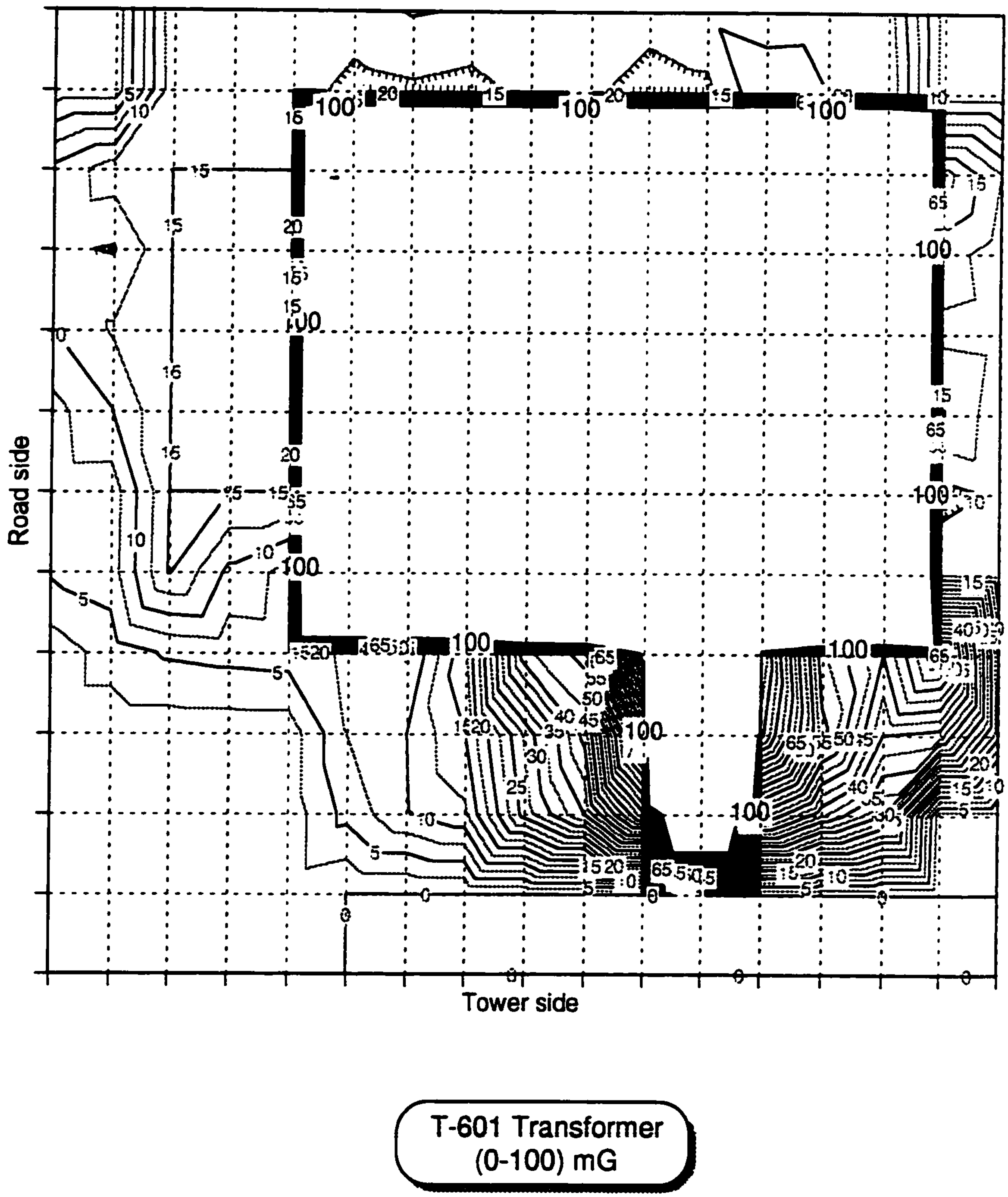


Figure C-6: Magnetic field contour map around transformer T-601 (0-100 mG).

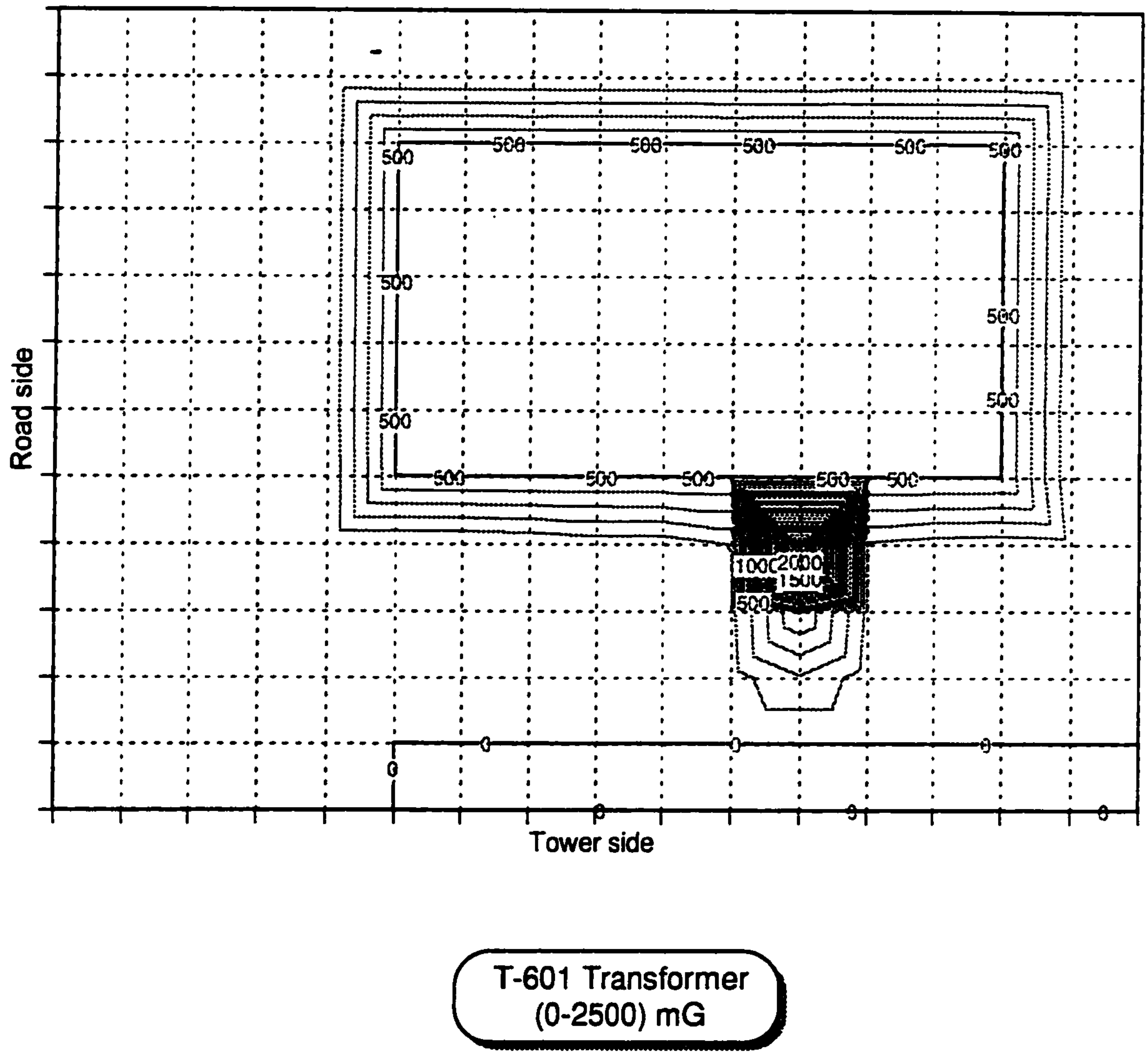


Figure C-7: Magnetic field contour map around transformer T-601 (0-2500 mG).

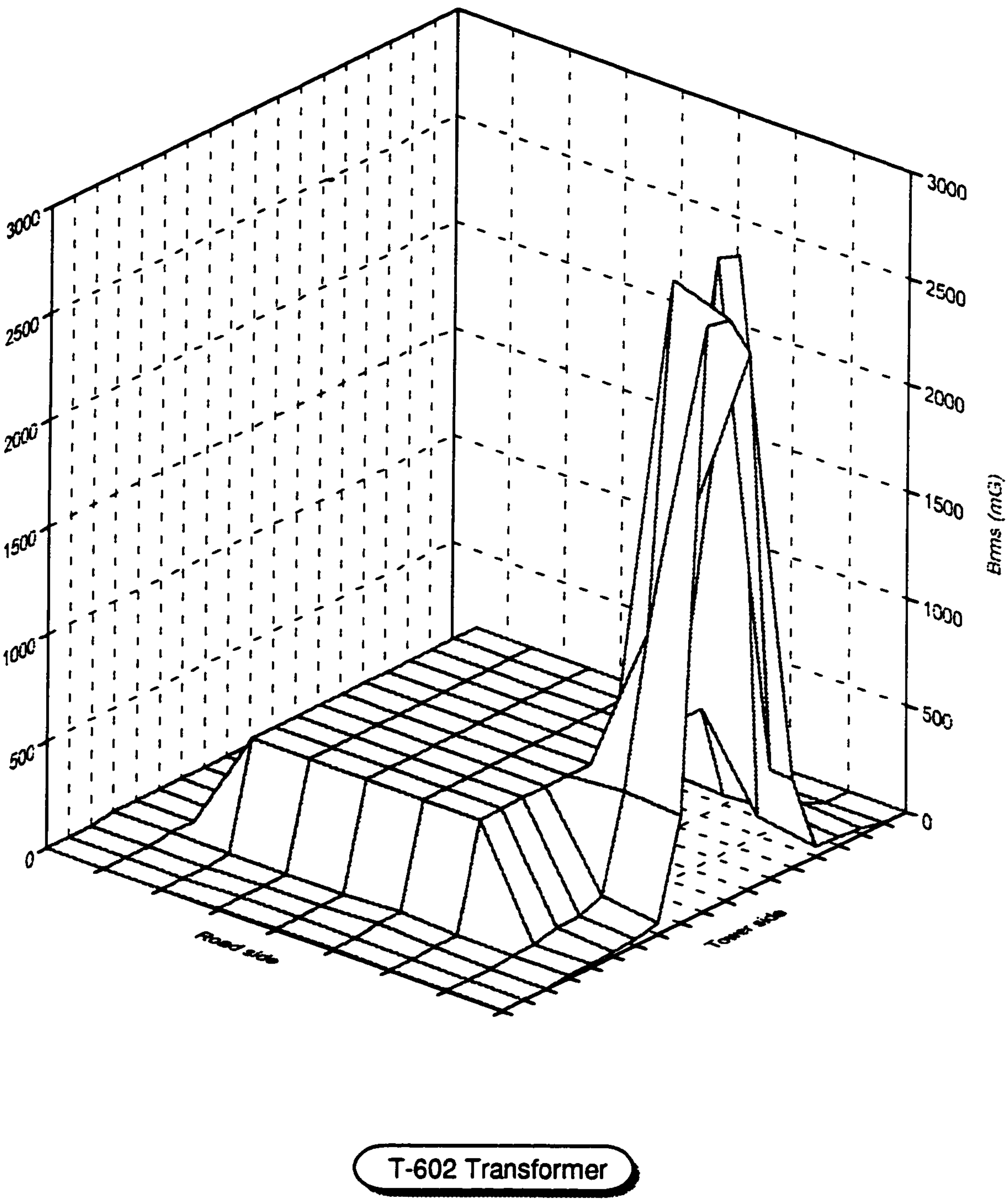


Figure C-8: 3D magnetic field map around transformer T-602.

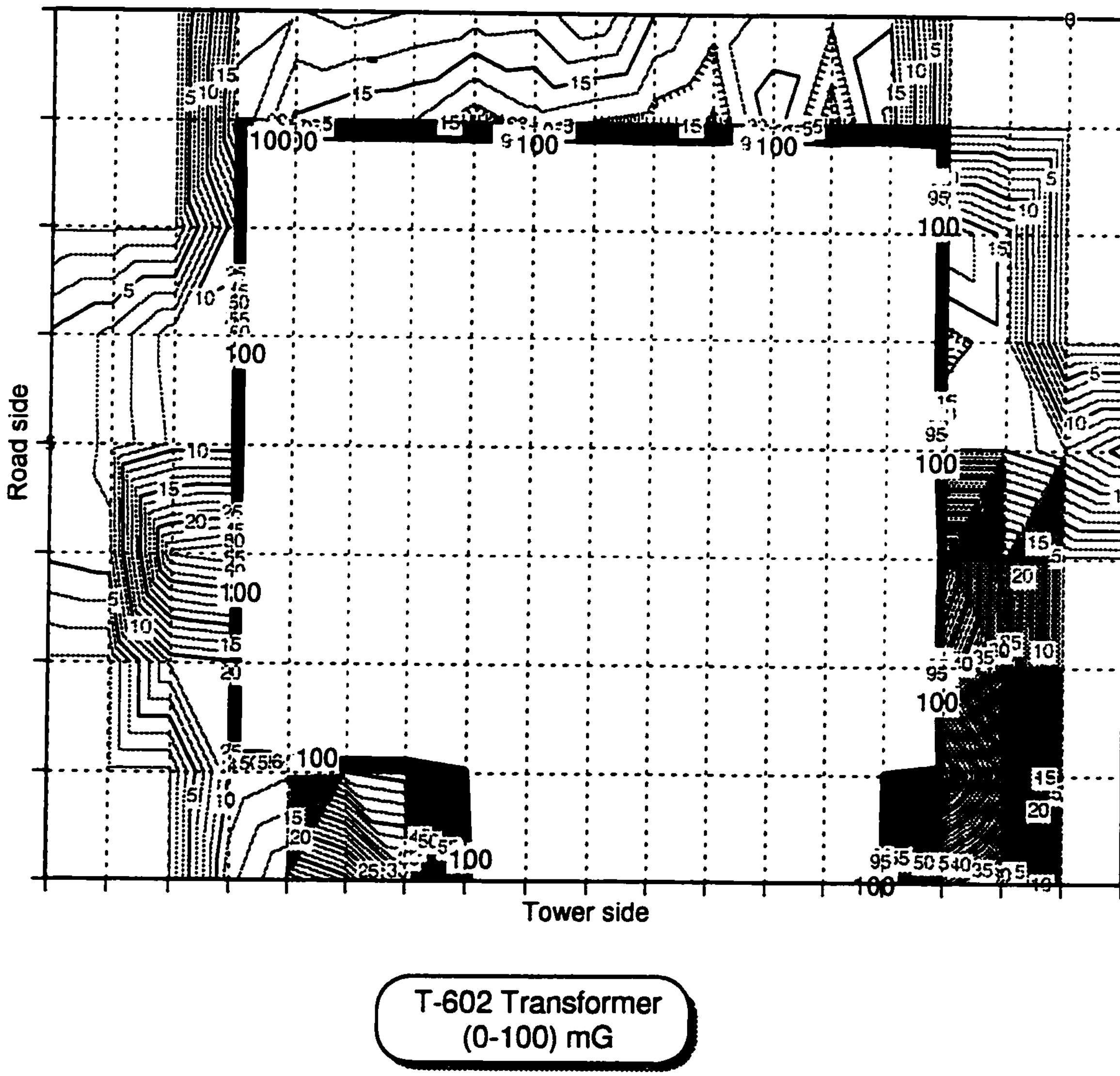


Figure C-9: Magnetic field contour map around transformer T-602 (0-100 mG).

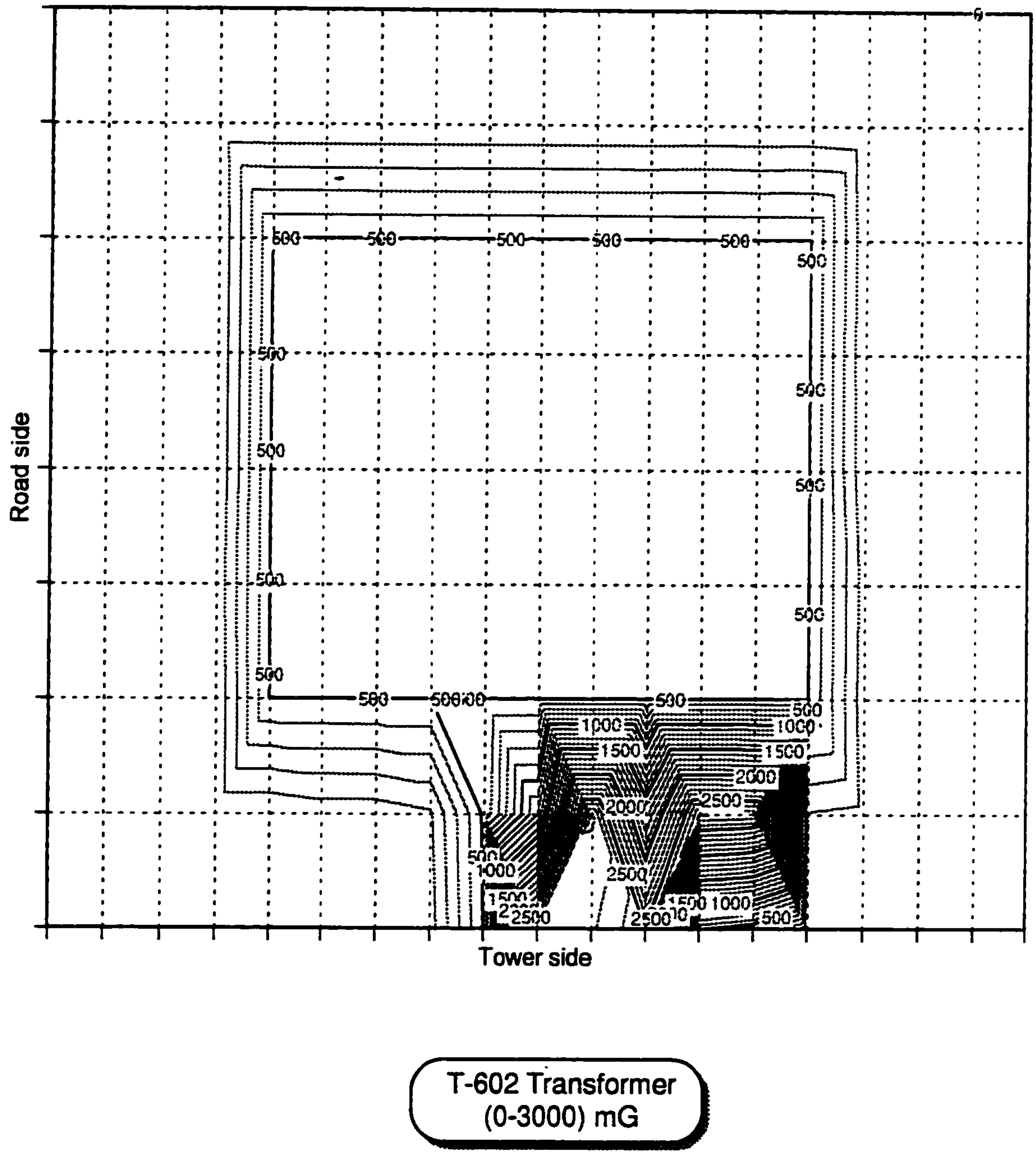


Figure C-10: Magnetic field contour map around transformer T-602 (0-3000 mG).

Appendix-D: Simulation Results of Case II

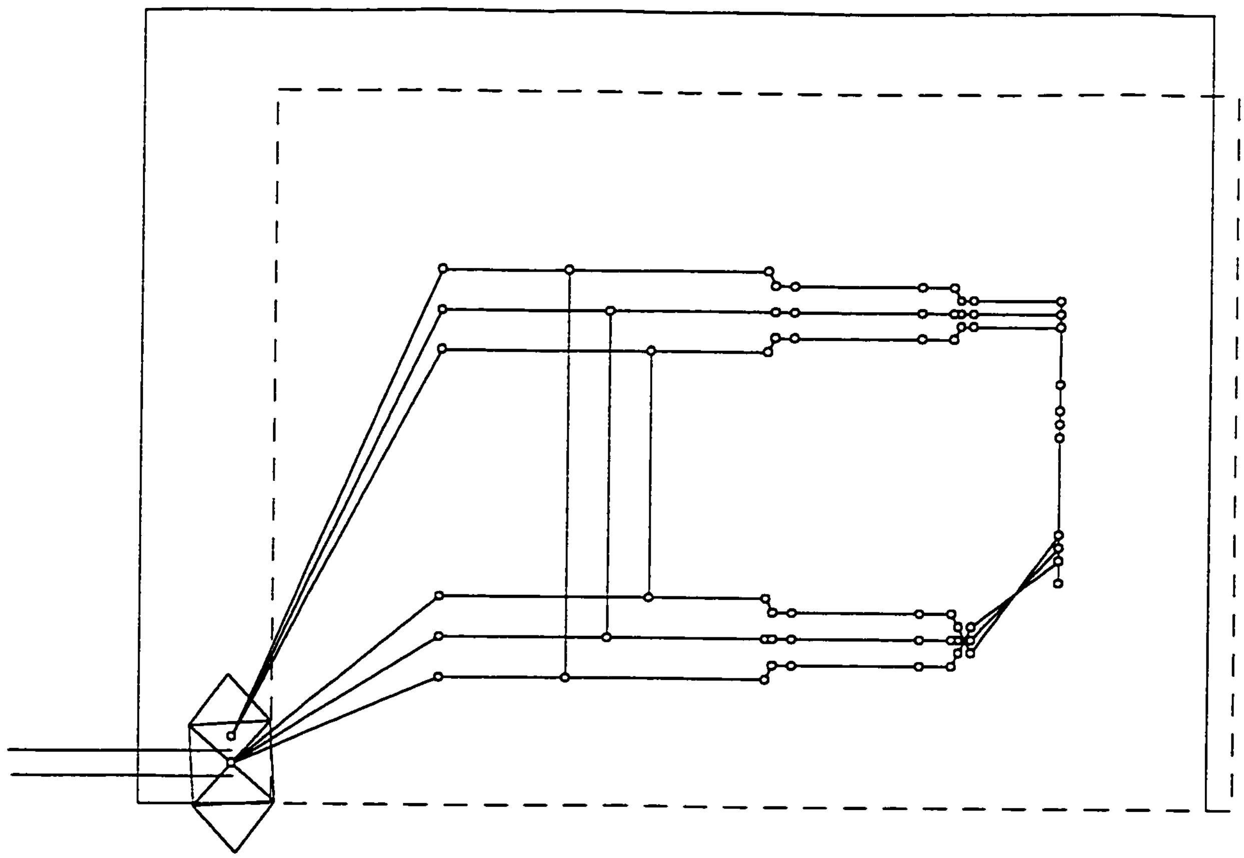


Figure D-1: 3D View of conductors in Substation (Case-II).

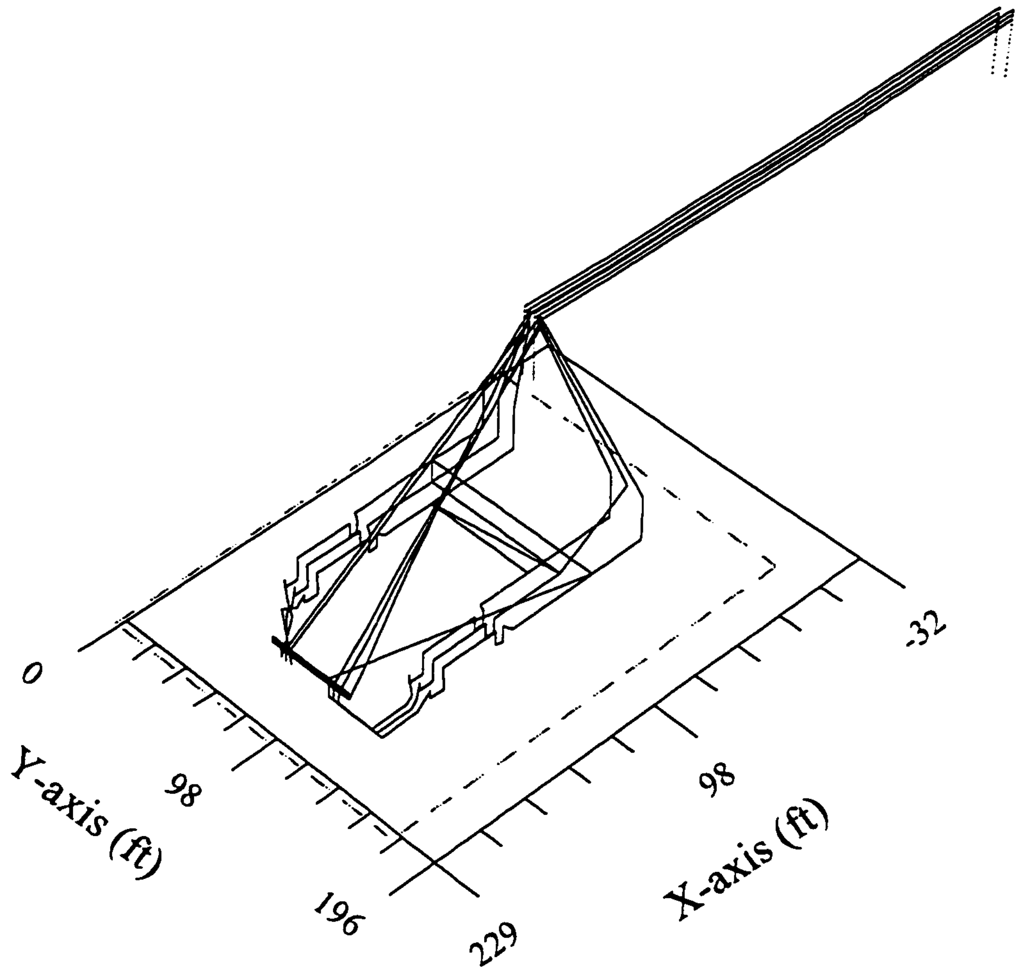


Figure D-2: Top View of conductors in Substation (Case-II).

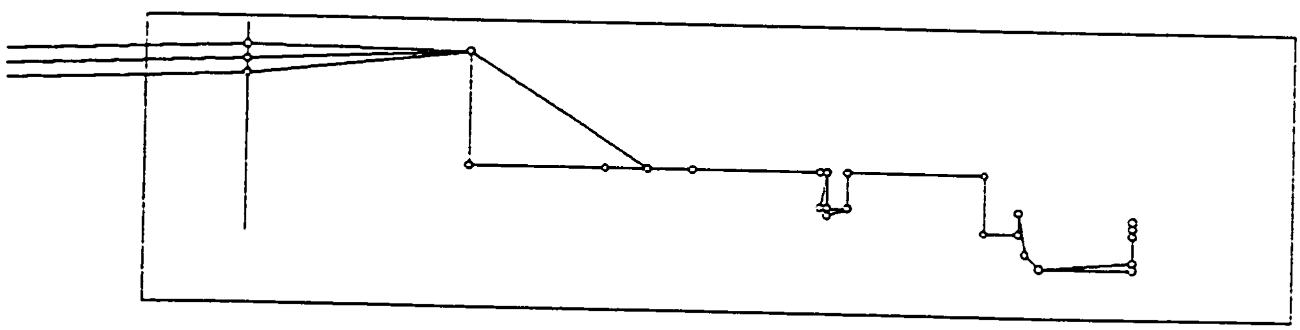


Figure D-3: Front view of conductors in substation (Case II).

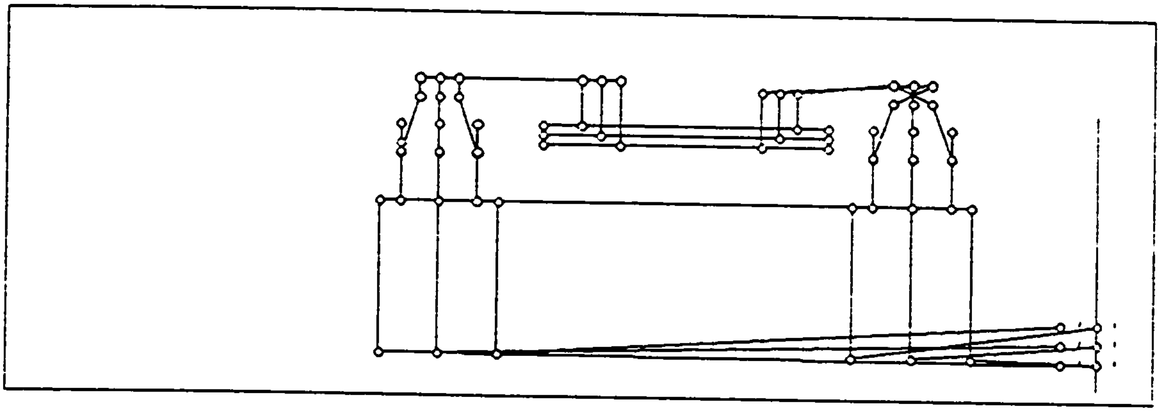


Figure D-4: Side view of conductors in substation (Case II).

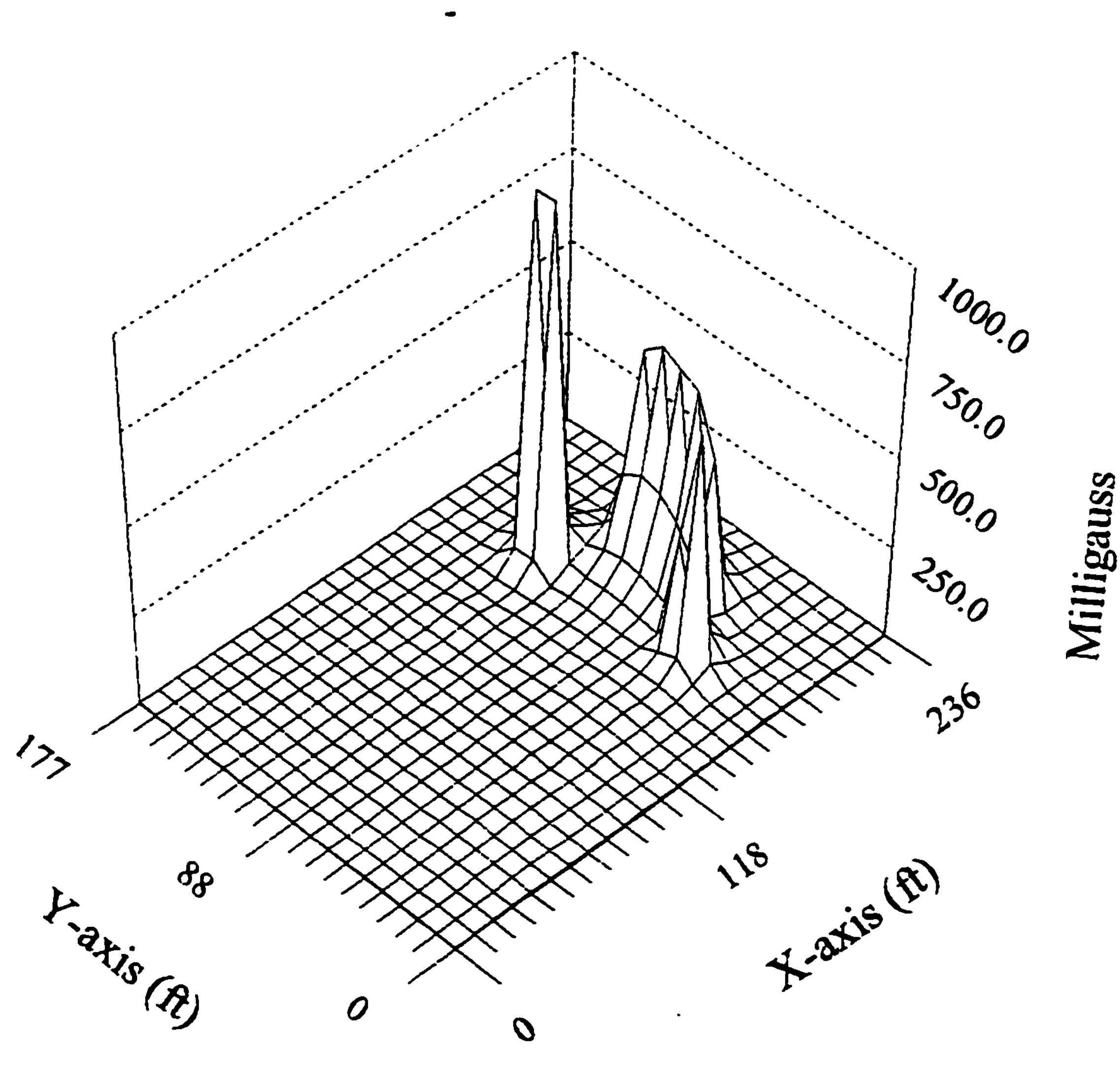


Figure D-5: 3D map of resultant magnetic field (Case II).

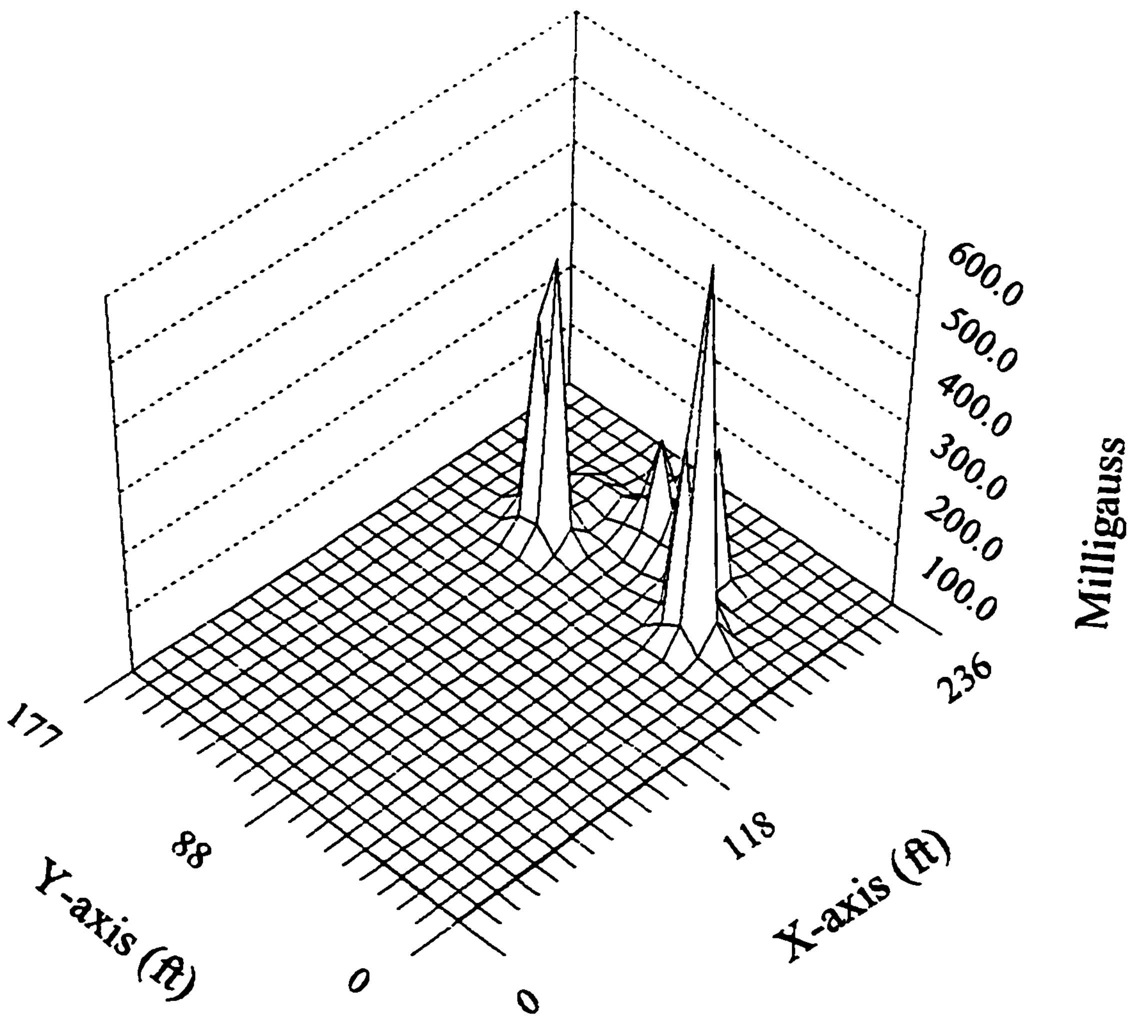


Figure D-6: 3D map of x-axis magnetic field (Case II).

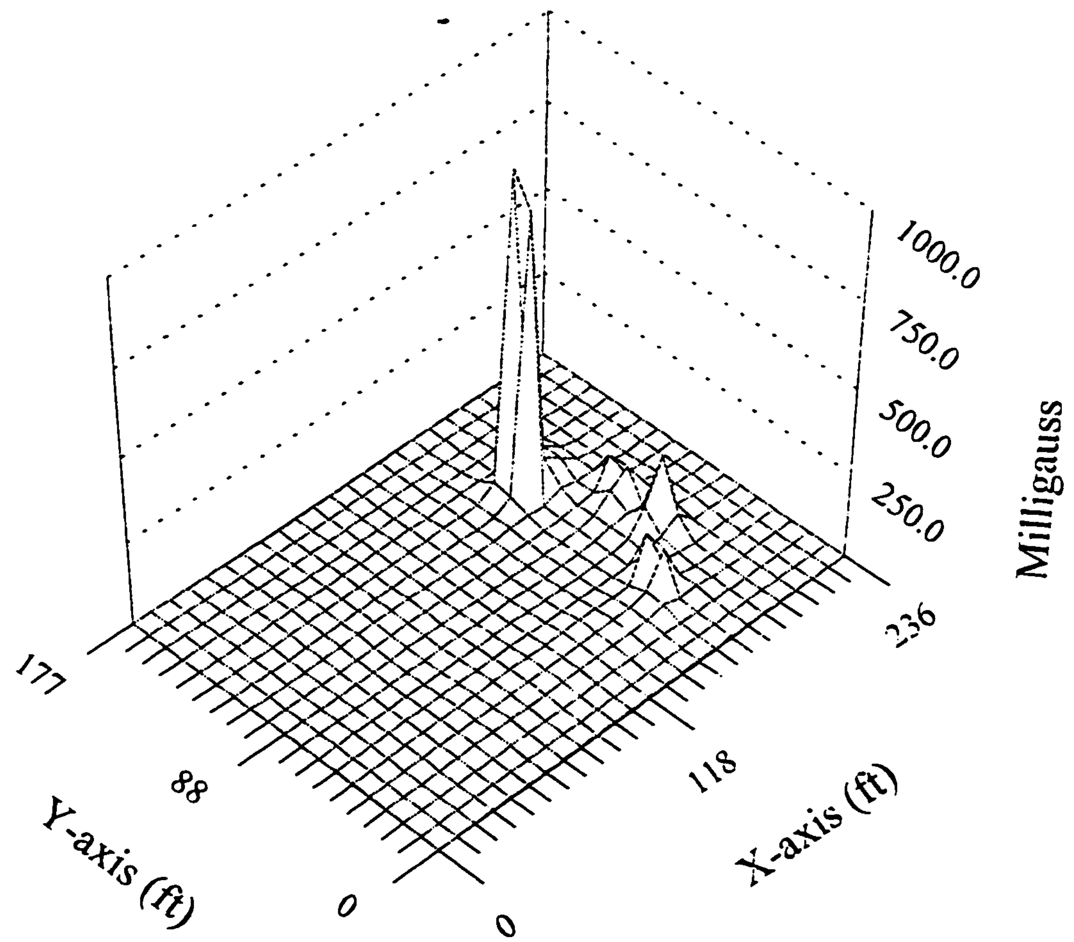


Figure D-7: 3D map of y-axis magnetic field (Case II).

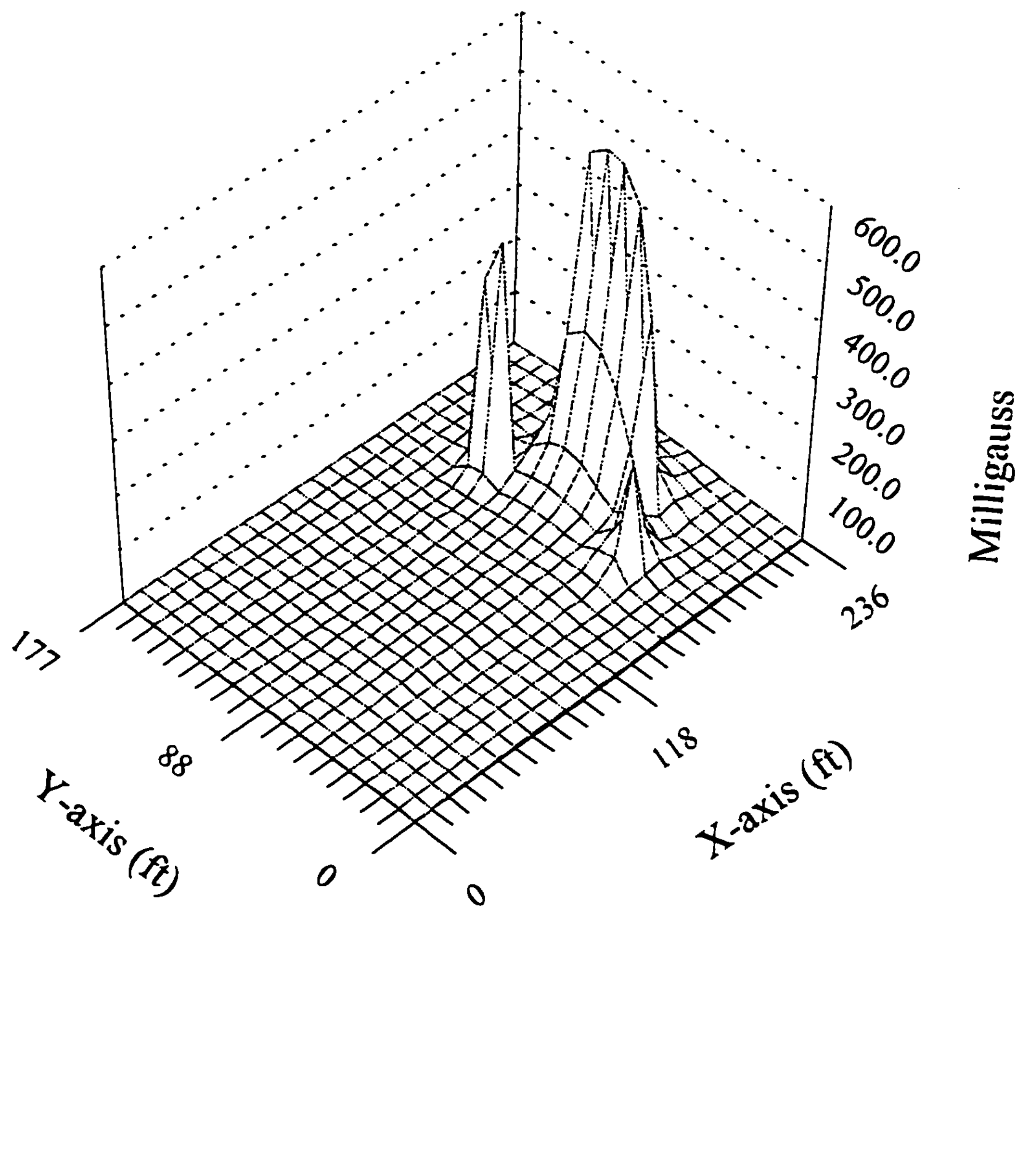


Figure D-8: 3D map of z-axis magnetic field (Case II).

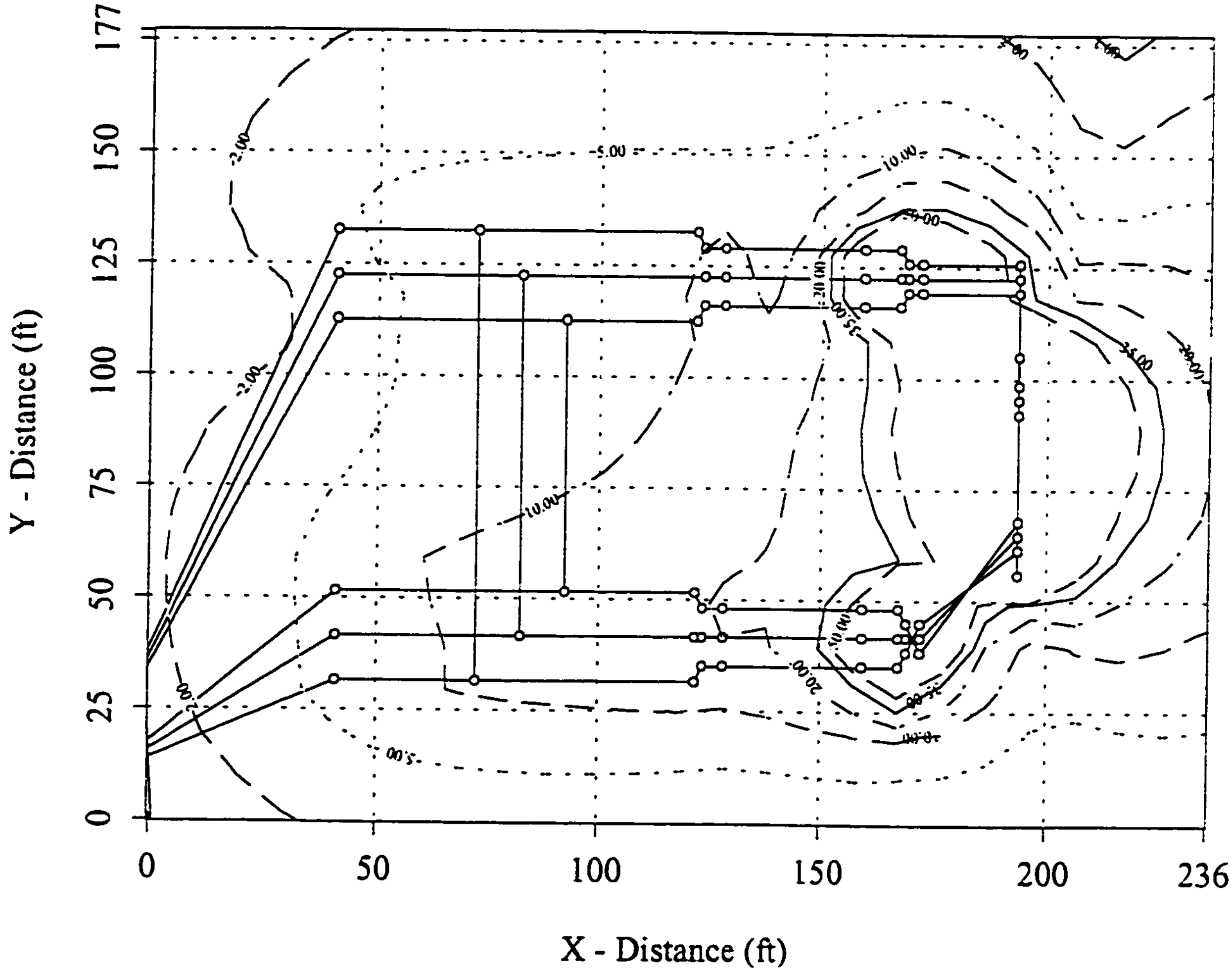


Figure D-9: Resultant contour from 0-50 mG (Case II).

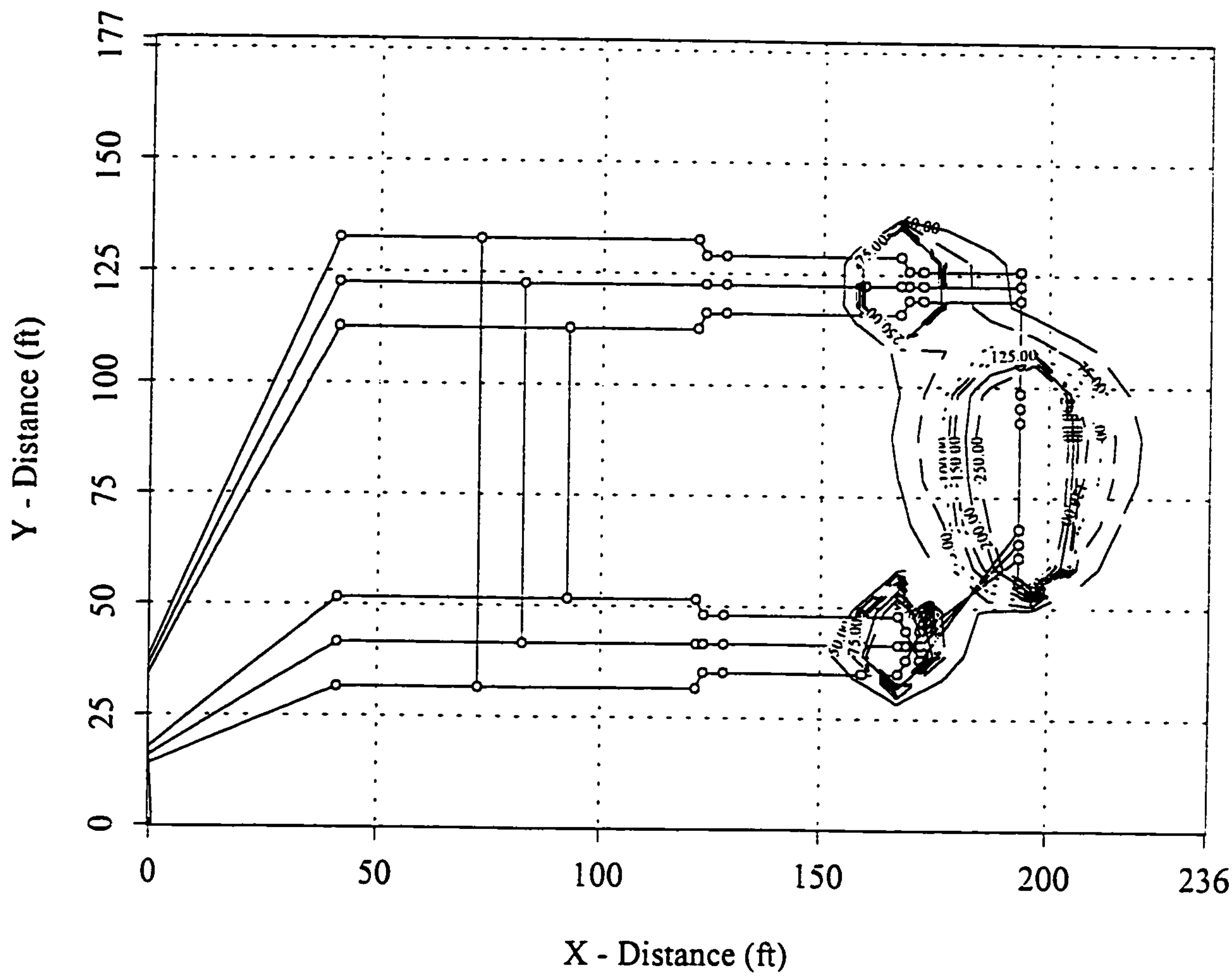


Figure D-10: Resultant contour from 50-250 mG (Case II).

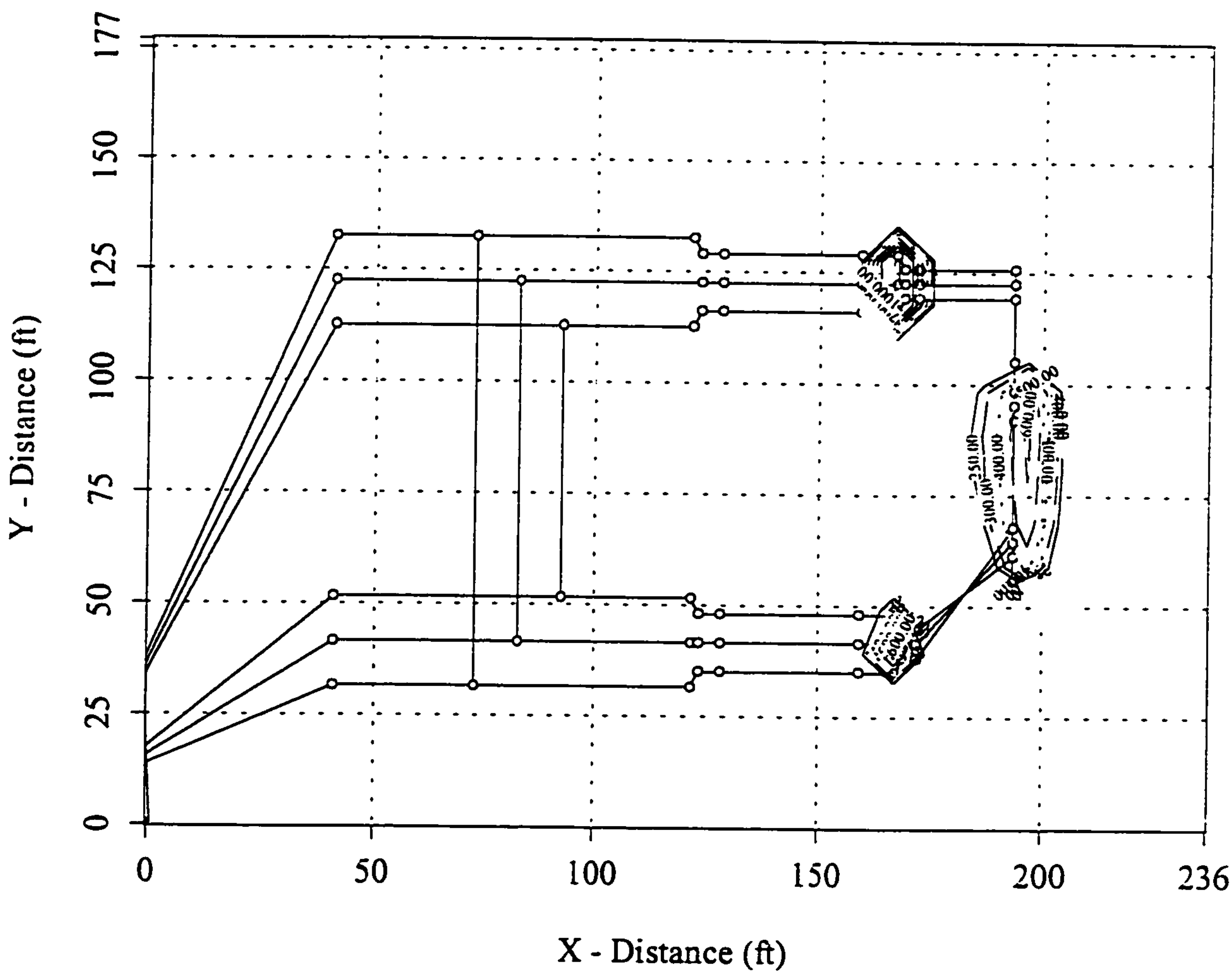


Figure D-11: Resultant contour from 250 mG or higher (Case II).

Appendix-E: Application of Management Techniques

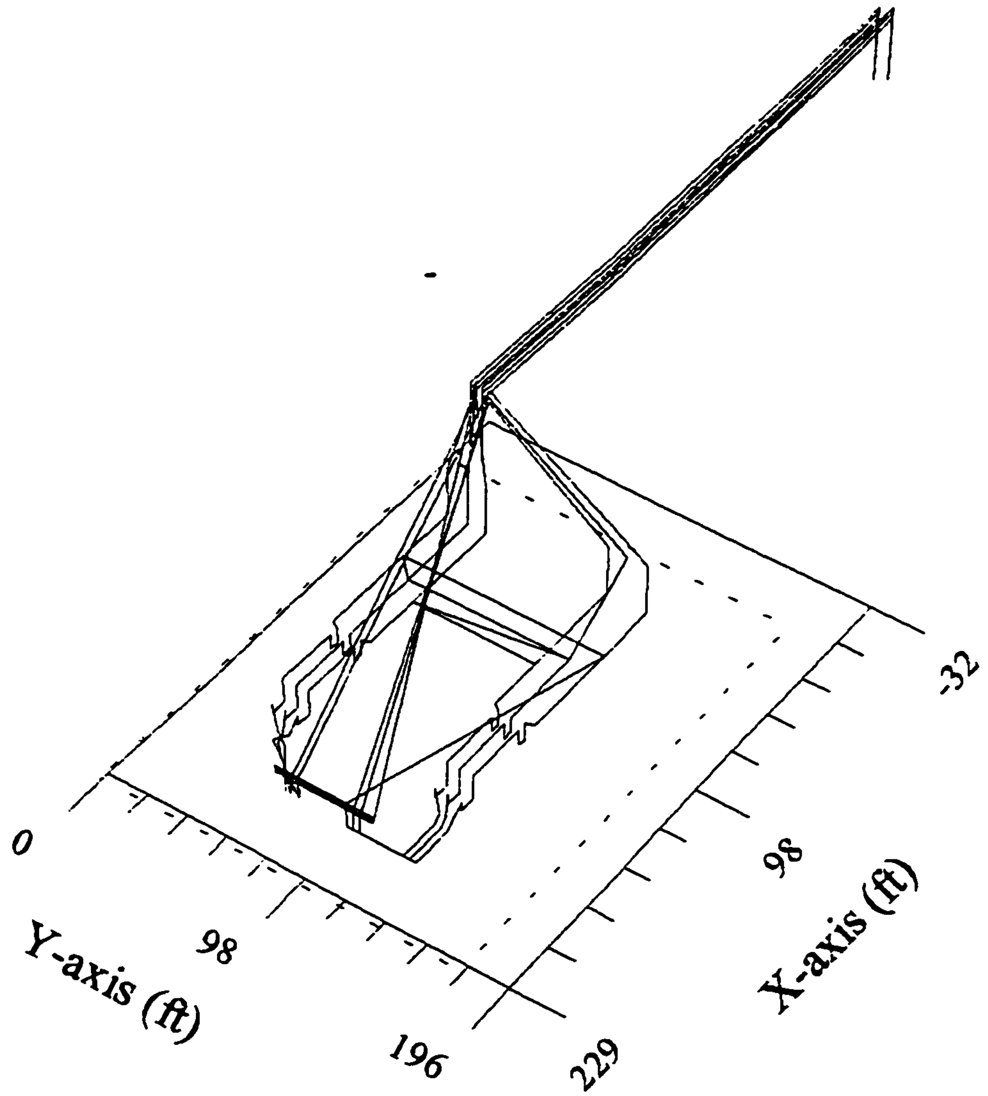


Figure E-1: 3D view of conductors in substation (elevated by 1½ ft.).

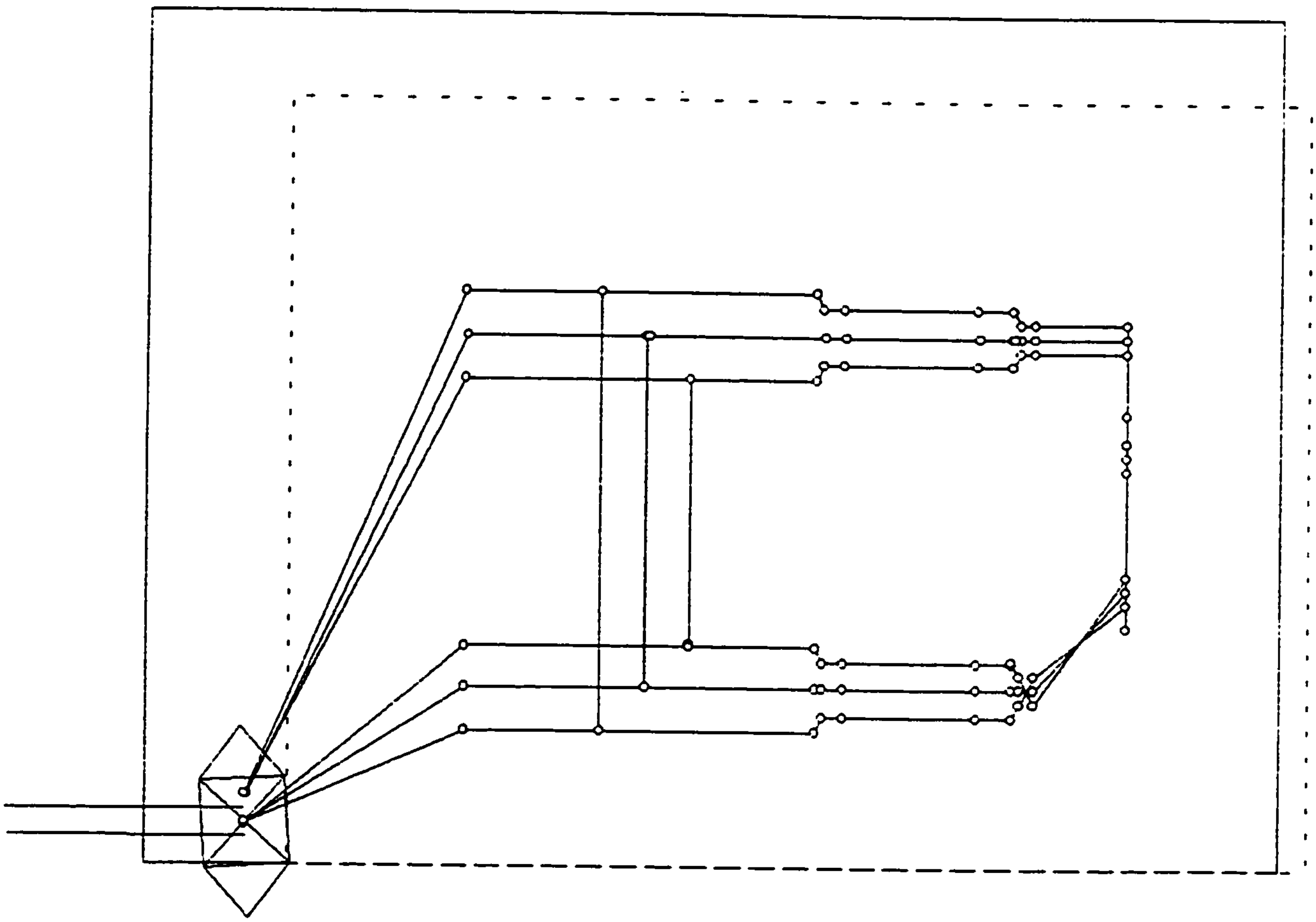


Figure E-2: Top view of conductors in substation (elevated by 1½ ft.).

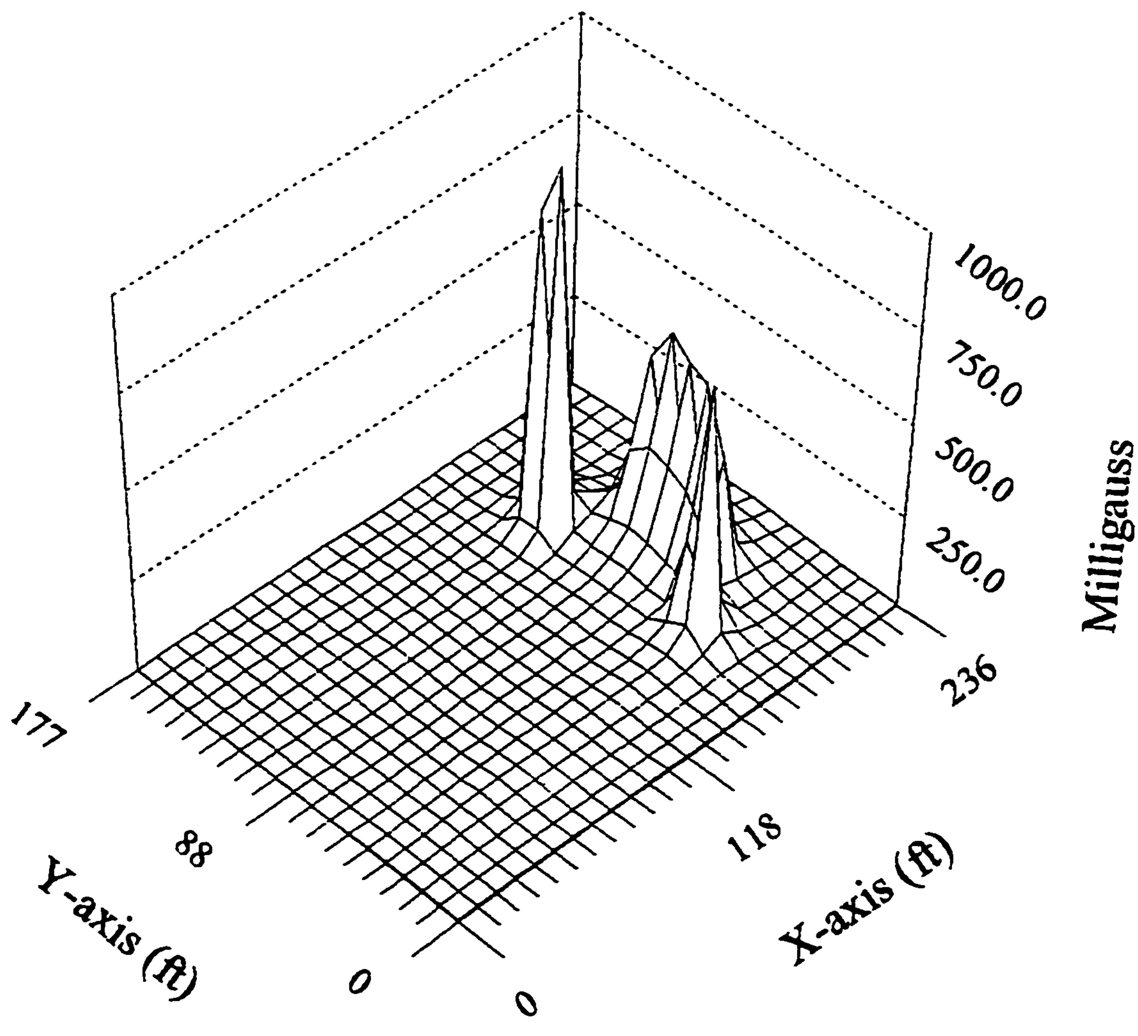


Figure E-3: 3D map of resultant magnetic field (elevated by 1½ ft.).

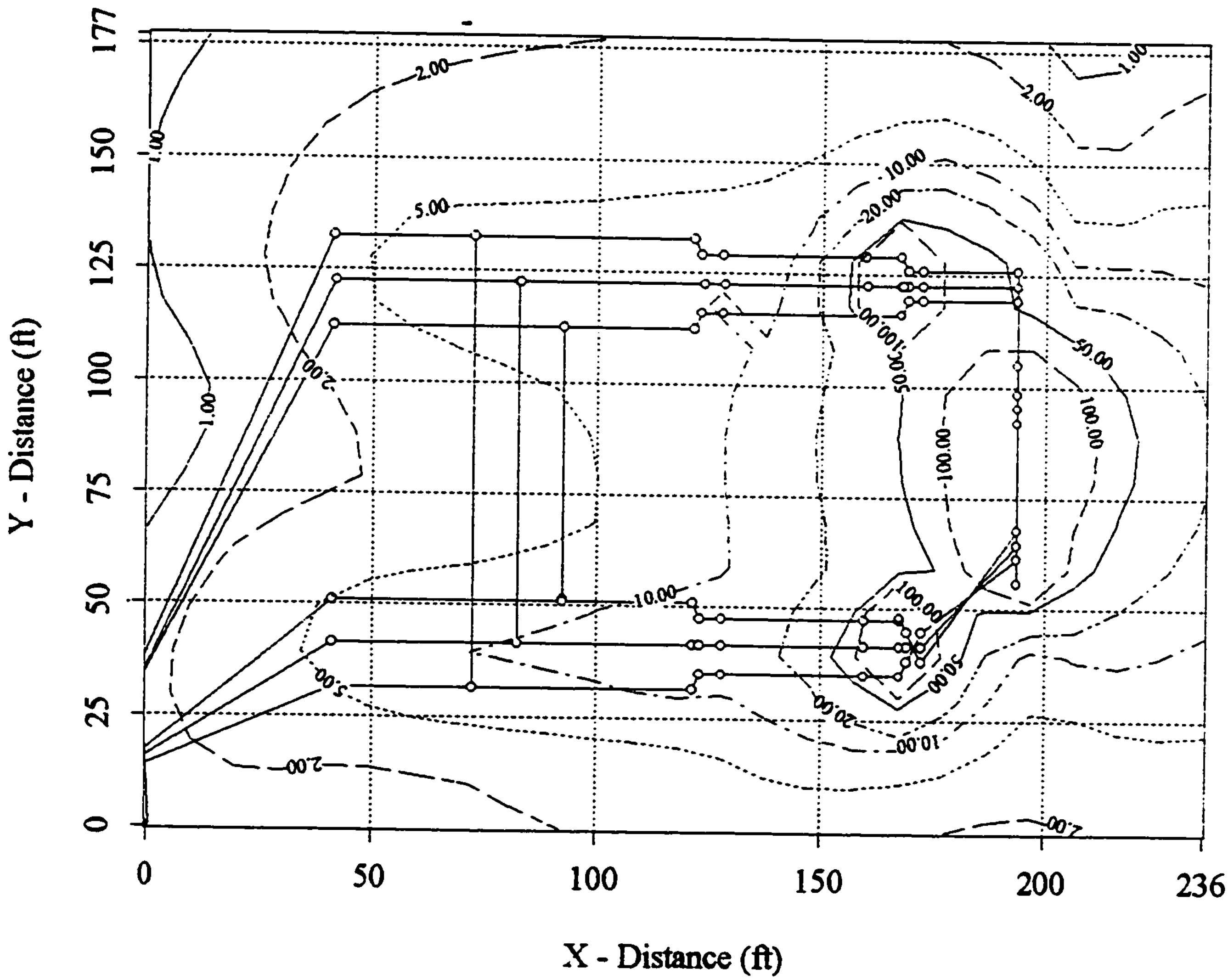


Figure E-4: Resultant contour of magnetic field (elevated by 1½ ft.).

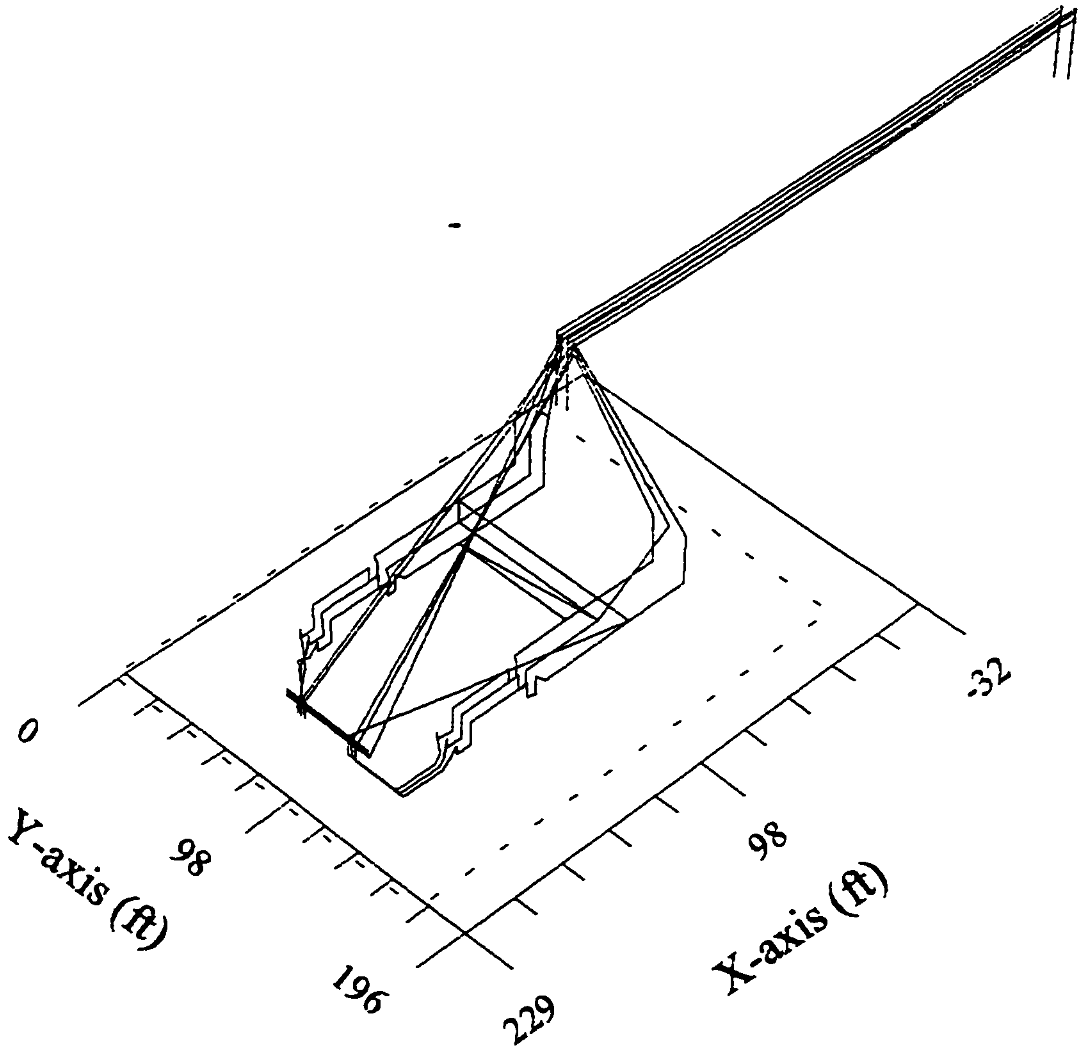


Figure E-5: 3D view of conductors in substation (compaction by 1 ft.).

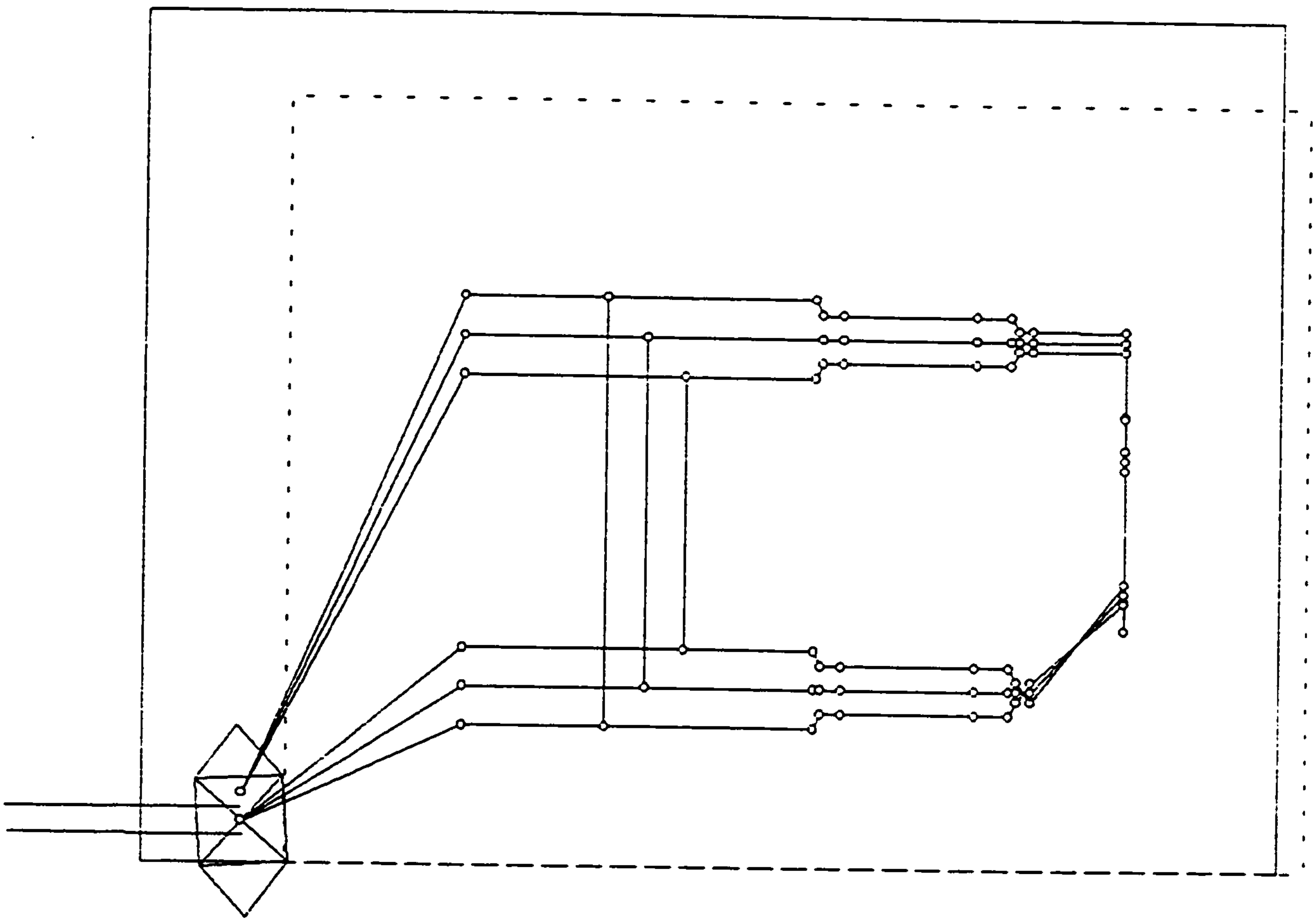


Figure E-6: Top view of conductors in substation (compaction by 1 ft.).

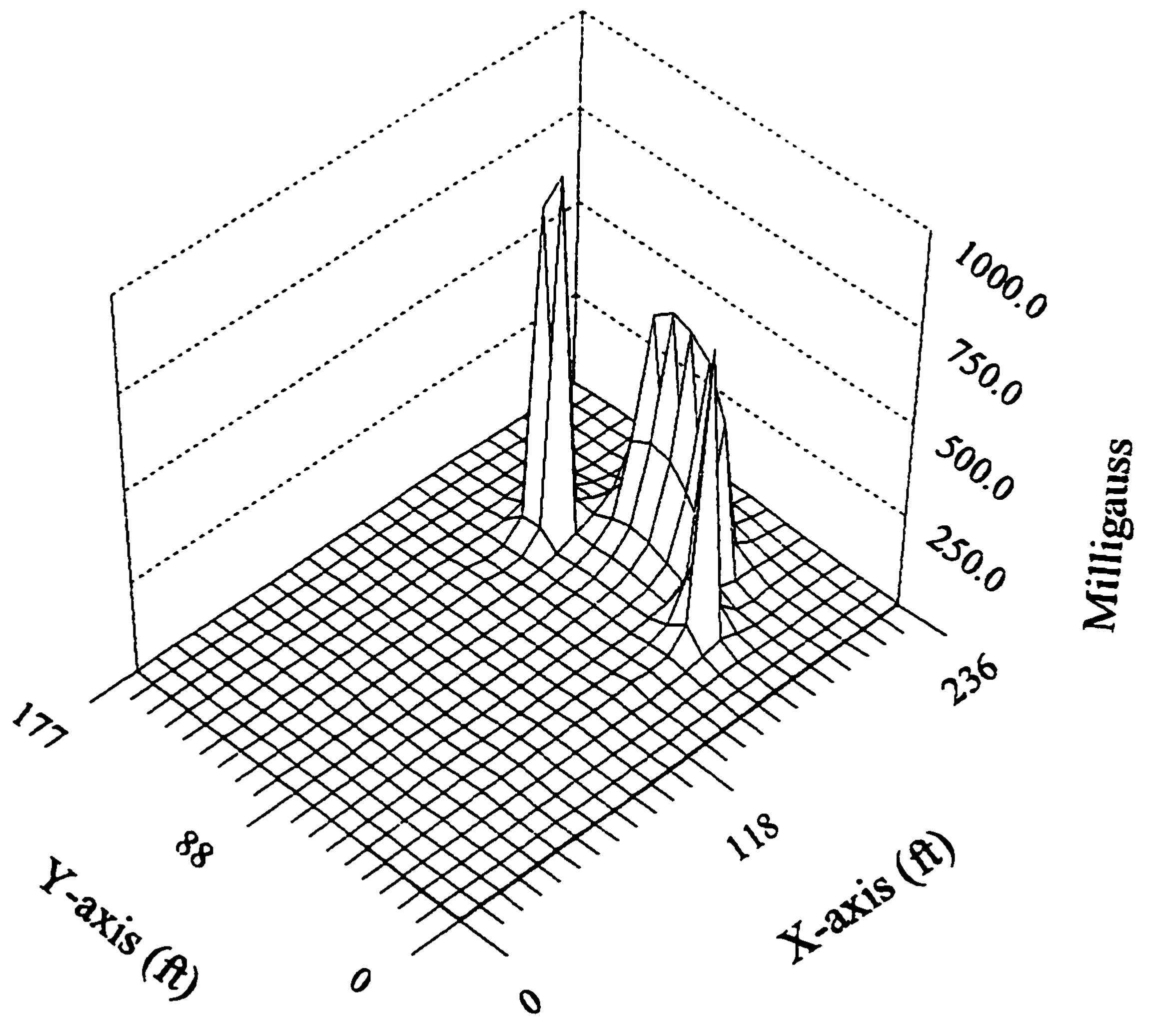


Figure E-7: 3D map of resultant magnetic field (compaction by 1 ft.).

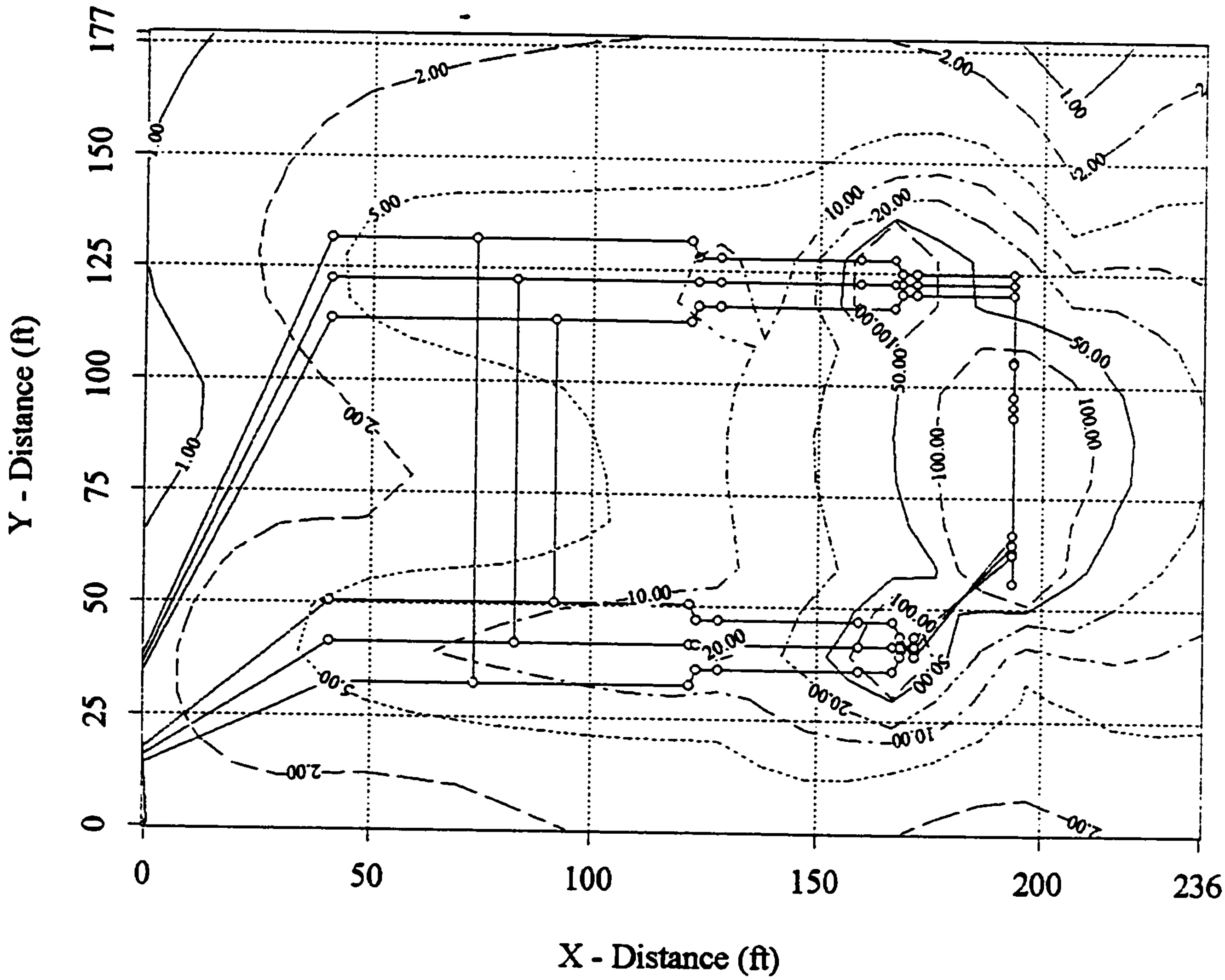


Figure E-8: Resultant contour of magnetic field (compaction by 1 ft.).

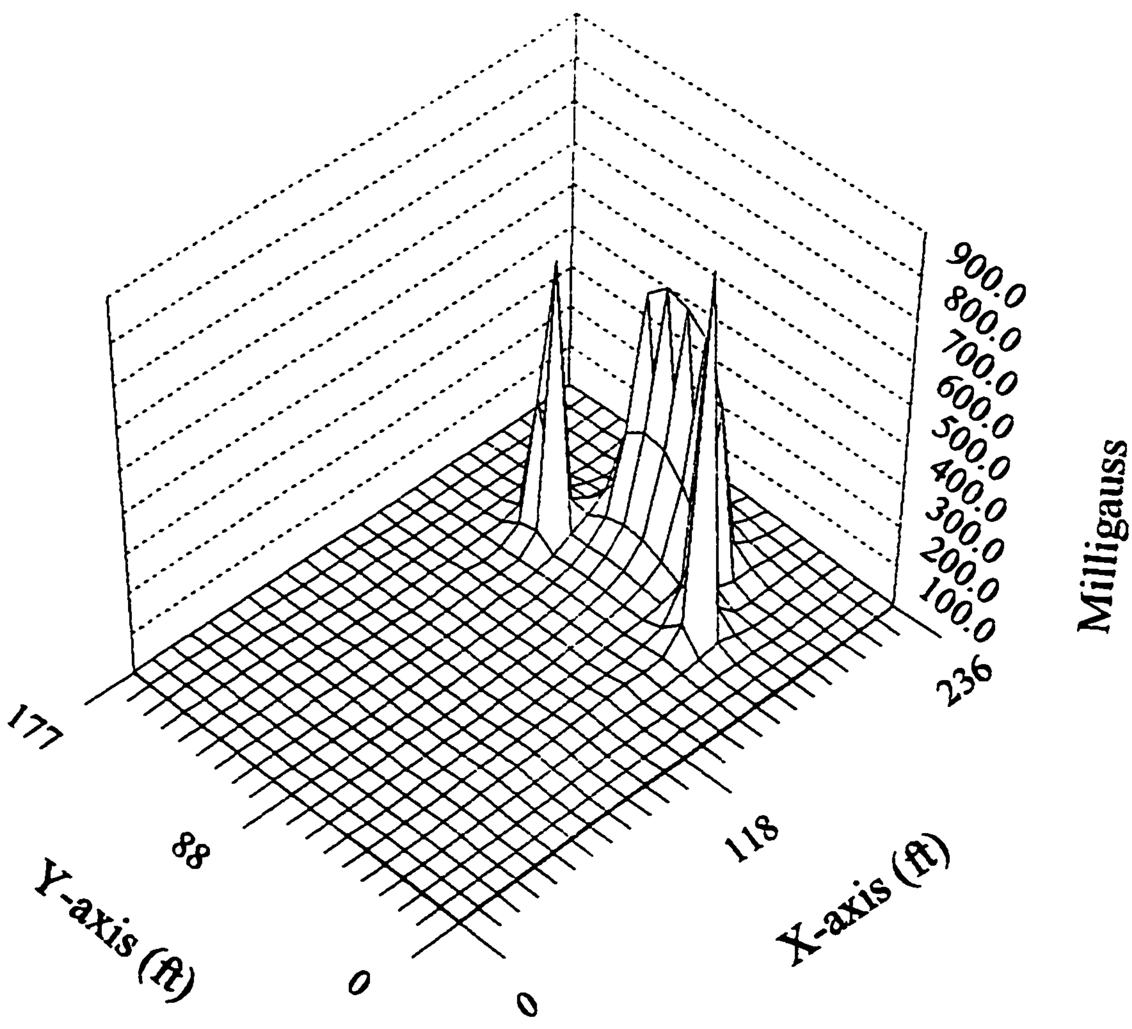


Figure E-9: 3D map of resultant magnetic field (compaction by 2 ft.).

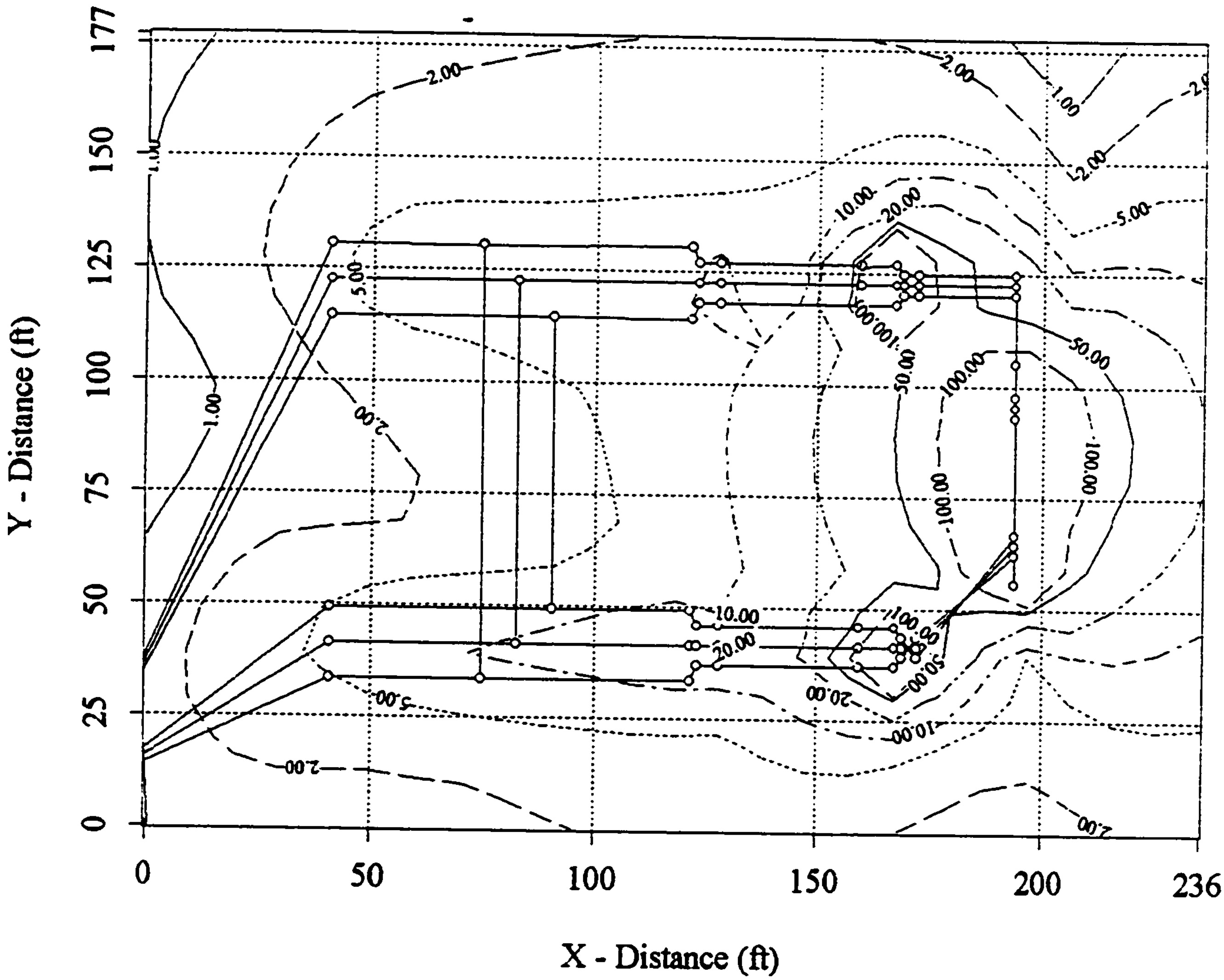


Figure E-10: Resultant contour of magnetic field (compaction by 2 ft.).

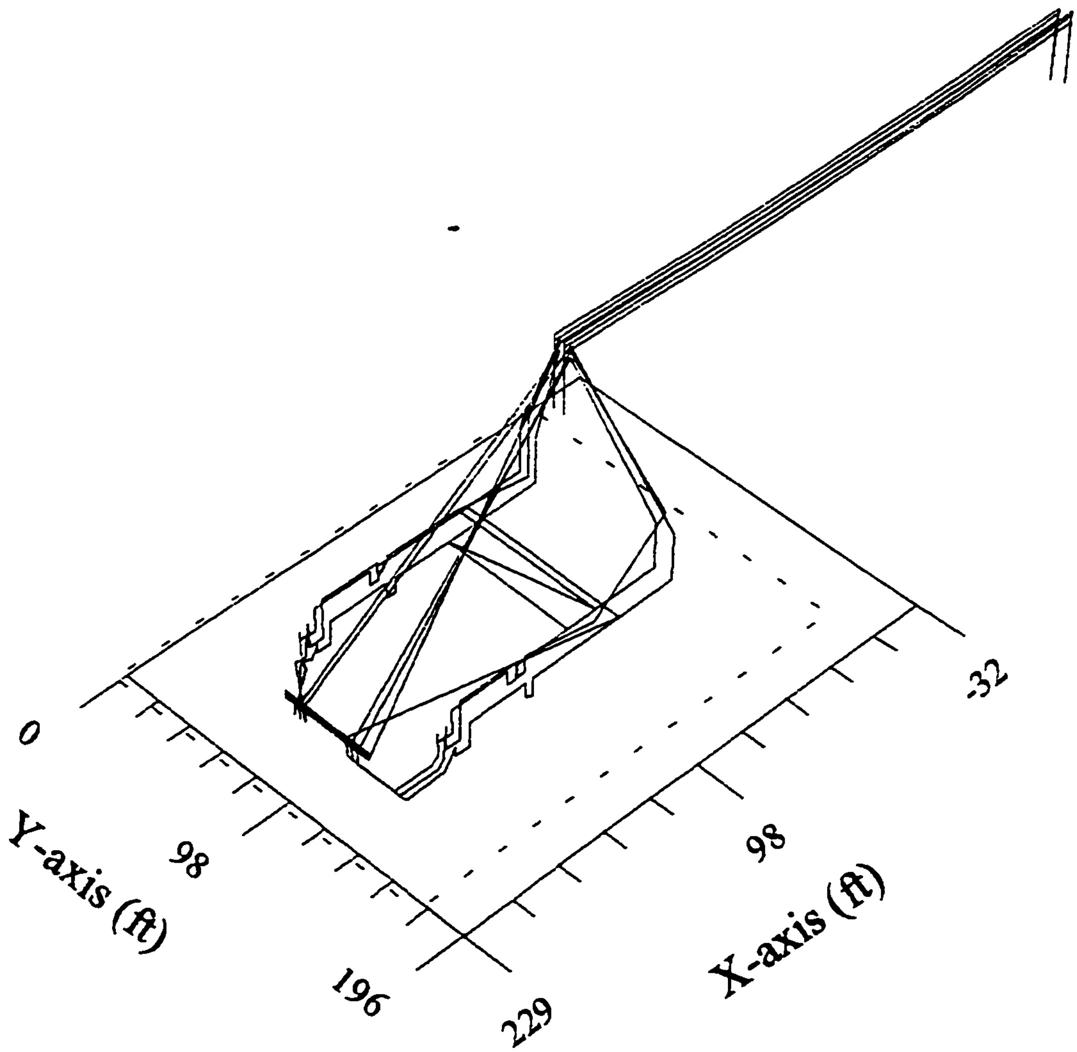


Figure E-11: 3D view of conductors in substation (Delta configuration).

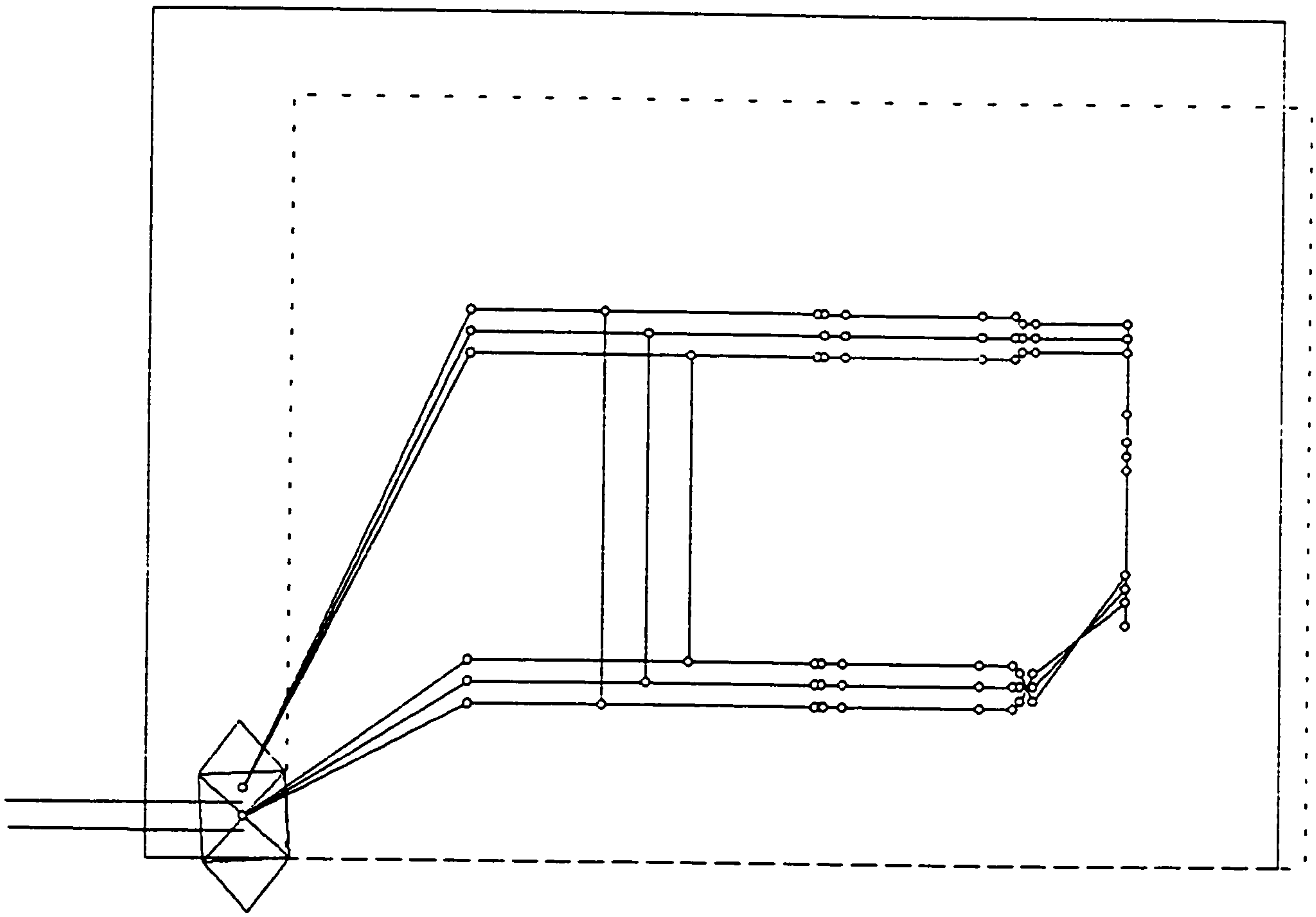


Figure E-12: Top view of conductors in substation (Delta configuration).

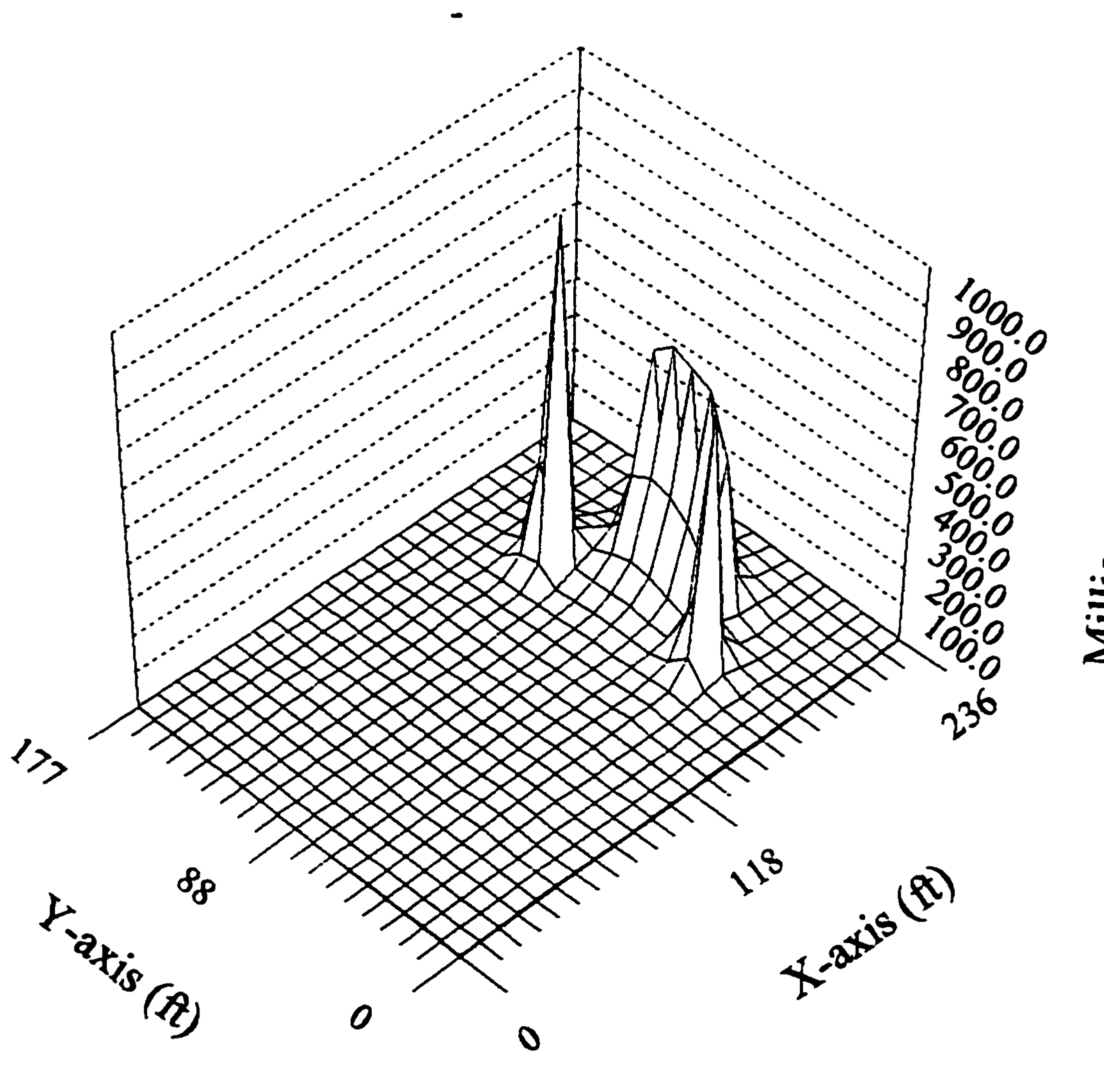


Figure E-13: 3D map of resultant magnetic field (Delta configuration).

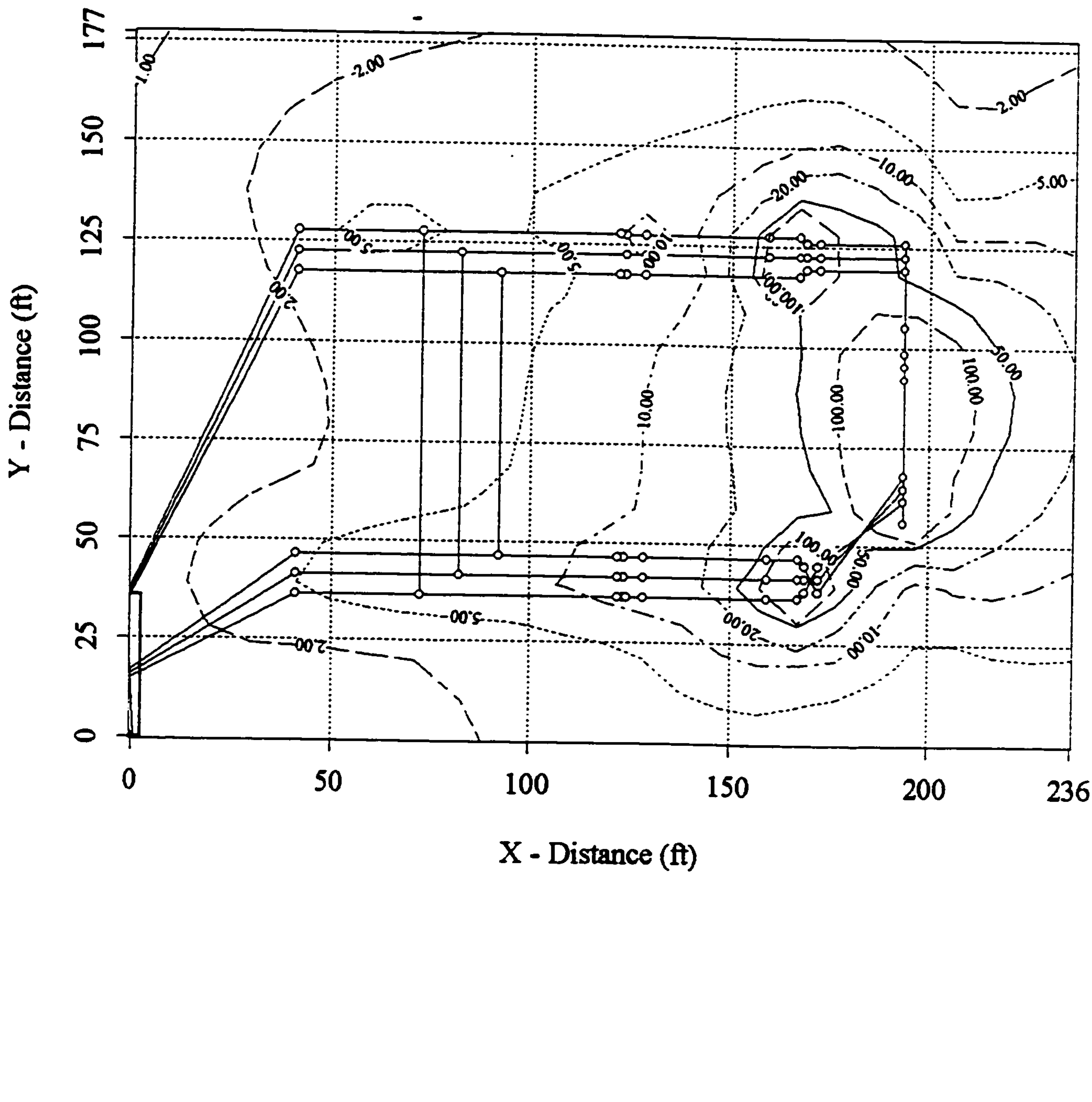


Figure E-14: Resultant contour of magnetic field (Delta configuration).

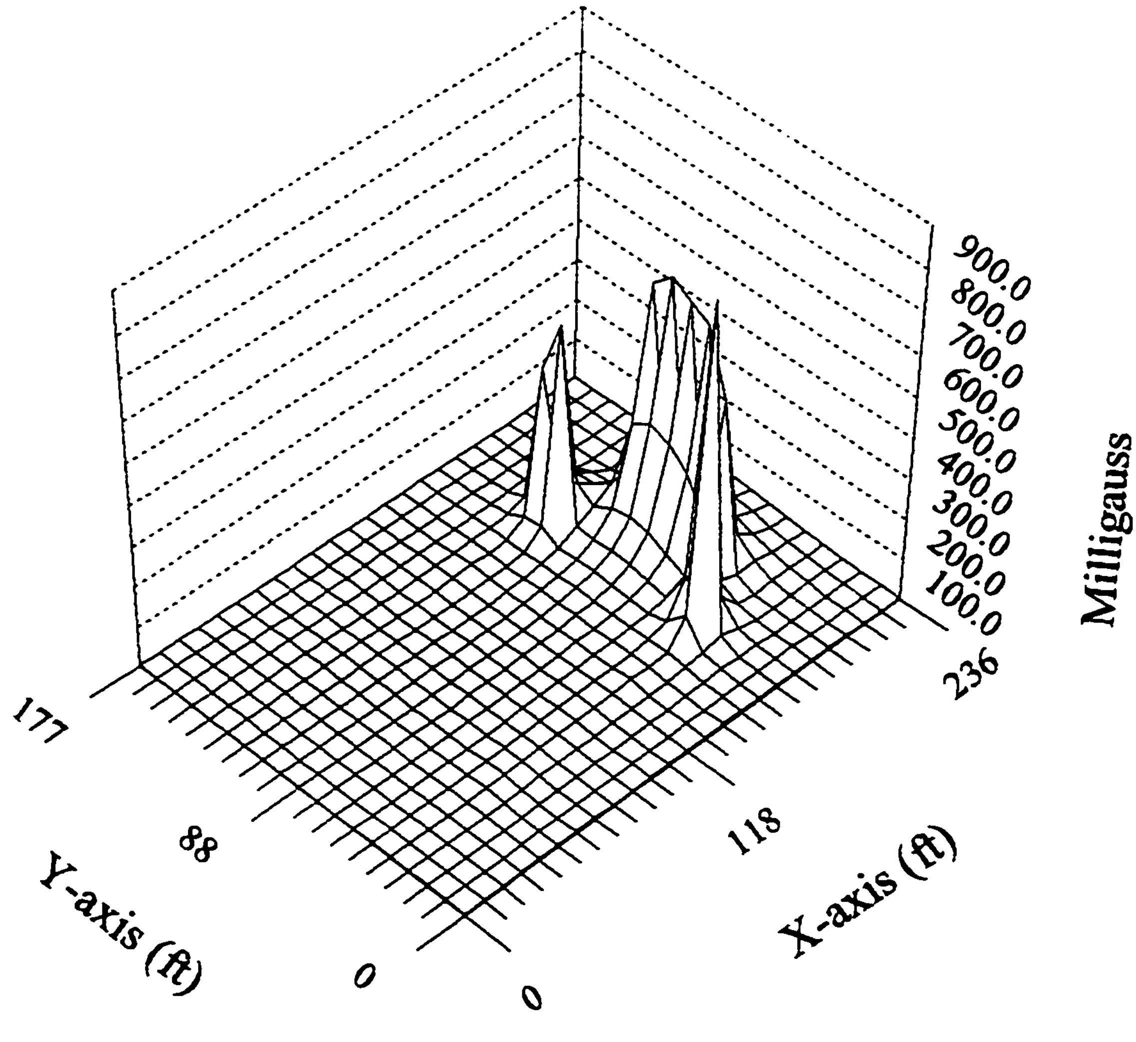


Figure E-15: 3D map of resultant field (Delta configure compacted by 2 ft.).

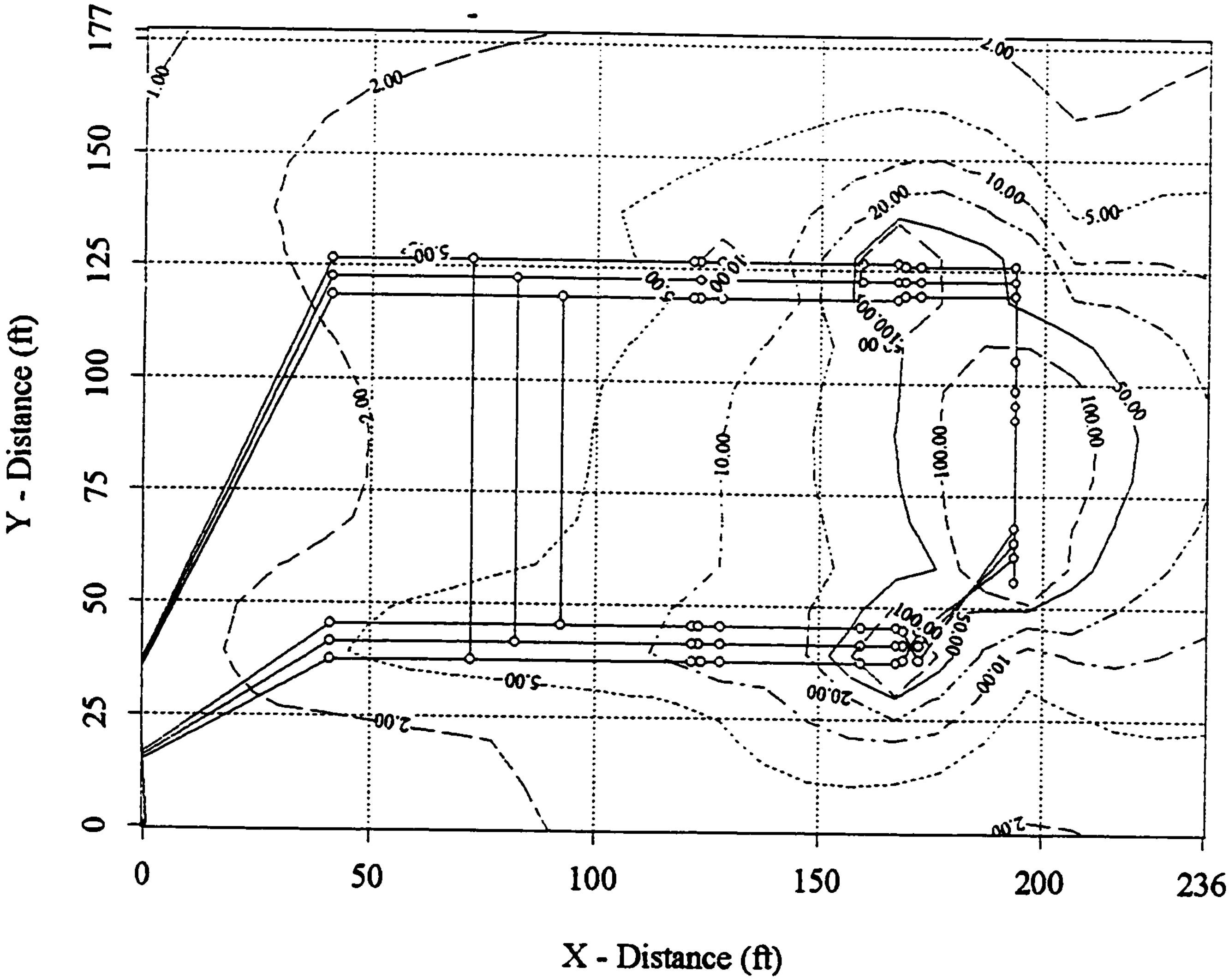


Figure E-16: Resultant contour (Delta configure compacted by 2 ft.).

BIOGRAPHY

Farrukh Shahzad was born in Karachi, Pakistan, on August 6, 1969. He did his BE(EE) from the NED University of Engineering & Technology, Karachi, Pakistan in 1992. He worked with Philips (Consumer Electronics), Karachi for one year. He joined King Fahd University of Petroleum & Minerals (KFUPM), Dhahran, Saudi Arabia in 1994 as research assistant and completed his MS (EE) from there in 1996. His areas of interest are power system electromagnetic fields and transient analysis, control systems and signal processing with emphasis on computer application, modeling and software development. He is US copyrigth holder of four Engineering Softwares.