EMFWorkstation 2.5: Computer Software for Studying Magnetic Field Scenarios.

Presented at the
Missouri Valley Electric Association
1996 Engineering Conference

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***Abstract*-EMFWorkstation 2.5 is a collection of software modules that allows utility staff to estimate the ELF magnetic fields that result from transmission lines, primary and secondary distribution lines, service drops, grounding conductors, water pipes, and substation equipment such as buswork, power transformers, air-core reactors/wave traps, circuit breakers and capacitor banks. EMFWorkstation includes modules for estimating magnetic fields in residential environments (RESICALC) and in and around substations (SUBCALC). Modules for determining the electrical characteristics of one-, two- and three-phase circuits (Power Line Calculator) and estimating lateral profiles (ENVIRO) and two-dimensional exposure (EXPOCALC) for electric and magnetic fields are also included. A newly added expert system module (EMFX) provides information about field sources, field management and field measurement. When used separately or together, these modules enable utility staff to estimate field exposures and facilitate the development of field management plans.**

This software runs under Microsoft® Windows™ and features a full graphical user interface (GUI) that includes CAD-style entry of electrical system components. Output can be presented in a variety of formats (surface maps, contour maps, profile plots and statistical tables). A database of transmission, distribution and grounding conductors that can accept user-specified configurations facilitates the retrieval and use of electrical system components. Complete editing capabilities allows modification and storage of existing models.

I. INTRODUCTION

EMFWorkstation (EMFW) was developed for the Electric Power Research Institute (EPRI) by Enertech Consultants. This program runs under Microsoft® Windows™ version 3.1 or higher. EMFW consists of the following six software modules RESICALC 2.1, SUBCALC 2.0, EMFX 1.0, Power Line Calculator 1.12, ENVIRO 3.5 and EXPOCALC 3.5.

II. DESCRIPTION

A. RESICALC 2.1

i. *Overview*

RESICALC models the power-frequency magnetic fields from a user-specified array of transmission lines, primary and secondary distribution lines, and grounding system conductors. The resulting magnetic field environment can be presented in a variety of graphical formats including two-dimensional contour and three-dimensional surface maps.

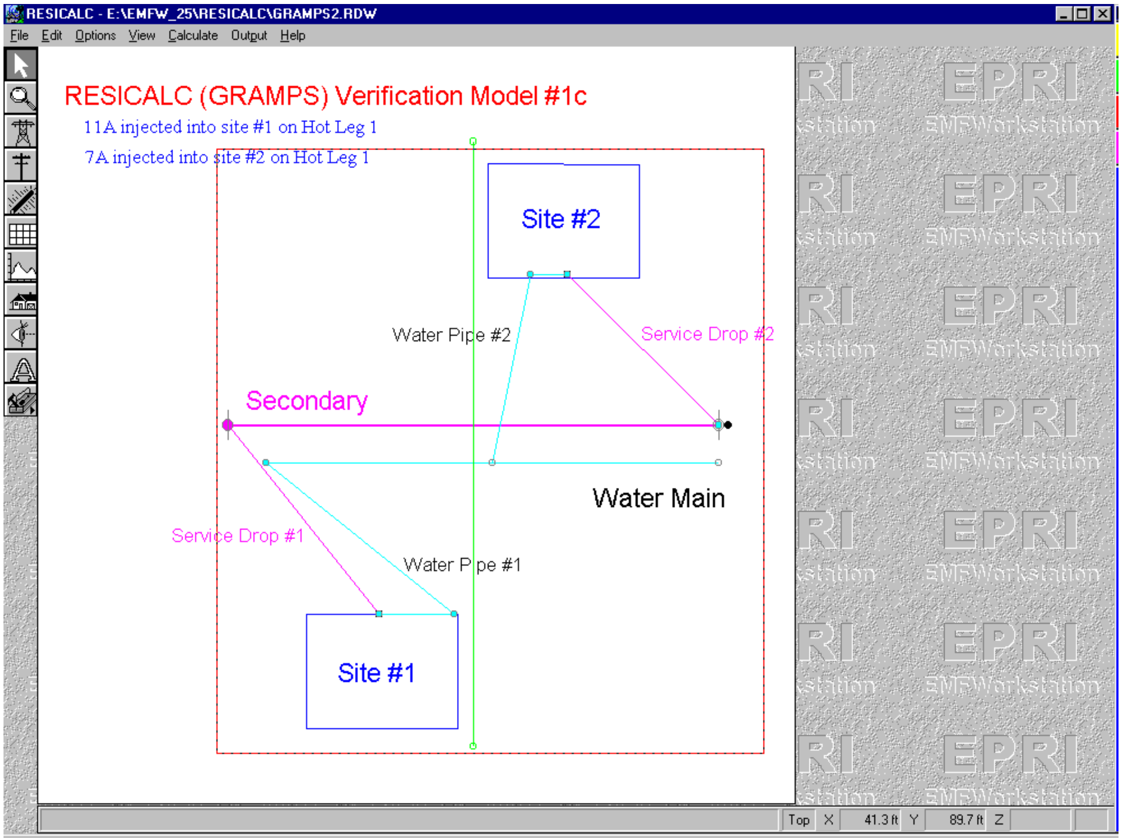

Fig. 1. RESICALC Main Screen

RESICALC's three-dimensional environment is easy-to-use, yet powerful and flexible. Using a mouse the user may enter conductors in the model taking advantage of RESICALC's CAD-style interface. Because RESICALC imposes no limit on the geometry of the conductors in the model, the configuration of power line conductors can change from pole to pole and individual lines can converge or diverge, just as they would in real situations. In addition any number of lines can be used in a right-of-way or model. Lines can make 90 degree turns or start above ground and then move underground. Line sag is approximated in the model and is visible to the user when using front or side views.

RESICALC was primarily designed to model the magnetic field in and around a residence (though it can also model the magnetic field in and around a substation). RESICALC's features include:

- A full Graphical User Interface (GUI) featuring CAD-style data entry using an icon and menu driven interface.
- Calculation of magnetic fields from any arbitrary array of power lines. A broad selection of common transmission and distribution line configurations, grounding system conductors and simple substation conductor configurations are supported. Customized conductor configurations are also available.
- A database that allows easy retrieval and use of user-specified transmission line, distribution line, residential ground conductor and substation conductor configurations.
- Presentation quality profile, contour and surface maps of the calculated magnetic fields.
- Standard statistical analysis of the calculated magnetic fields.
- Full editing capabilities allowing the modification and storage of existing models.
- RESICALC uses Power Line Calculator (PLC), a Windows™ application that calculates the symmetric current components, power factor, apparent power and reactive power for arbitrary multi-phase power lines.

ii. *Magnetic Field Sources*

The following sources can be modeled in RESICALC, version 2.1: overhead transmission and distribution lines, secondary and grounding systems. The magnetic field calculations are performed using the well-known Biot-Savart method that has become standard throughout the industry.

a. *Overhead Transmission Lines*

RESICALC can model transmission line rights-of-way that include multiple circuits. The user "draws" the location of the transmission line towers using a mouse and specifies the phase and overhead shield wire currents. This program automatically places the conductors on the towers using attachment and load information defined by the user. Line sag is also modeled. Because currents on most transmission lines are well balanced, both in phase and magnitude, usually there is little or no error introduced by assuming a balanced condition. For very lightly loaded lines, radial lines, lines serving individual industrial customers, or other atypical situations, the user may specify different current magnitudes and phase angles in each conductor to provide more accurate inputs to the program.

b. *Overhead Distribution Lines*

The procedures used when modeling overhead transmission lines are also used when modeling overhead distribution lines. Frequently the magnetic field contribution of distribution lines is the dominant component of the magnetic fields near a residence or substation because these conductors are often close to the ground, their currents may be large, and net and ground currents may exist. Unlike transmission line currents, distribution line currents are often unbalanced in both magnitude and phase angle. Usually the vector sum of the phase currents and neutral current does not equal zero because some current flows on paths other than the electric neutral (e.g., on pipes, utility grounds, and in the earth). In order to correctly determine the magnetic field, all input values must be accurately measured or estimated. Users should exercise caution if balanced phase current magnitudes and angles are assumed because this may lead to large inaccuracies in the calculated magnetic field in areas near the distribution feeders.

c. *Secondary and Grounding System*

A unique feature of this program is its ability to model the complete secondary and grounding system in a residential neighborhood. Secondary wires, service drop, service cable, ground wires, water pipes and water mains play an important role in calculating ground currents. The user defines the geometry of the components, their impedances and applies a load to each residence. Once these data are provided, this program will automatically calculate all of the currents on the entire secondary and grounding system conductors.

iii. *Input Data Preview*

RESICALC makes it simple for a user to review input data. Because the program graphically displays the model as it is being entered, the user is able to visually verify the location and geometry of model elements. The model can be viewed from top, front and side views, or in a 3-D window (Fig. 2) that can be rotated and viewed from any perspective. In addition information such as load data (magnitude and phase angle), phase identifier (A, B, C, N, etc.), or reference direction for each conductor segment can be displayed. These data can also be saved to an ASCII file in report format that can then be viewed by the user.

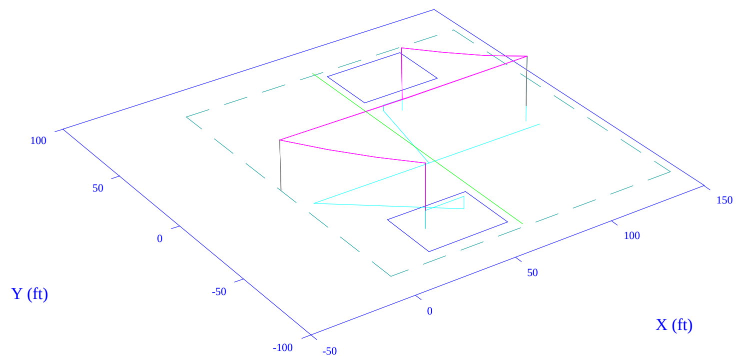

Fig. 2. A 3-Dimensional view of model

iv. *Output Generated by the Program*

Once the calculations have been performed over a user-defined area or profile, the results of the calculations can be displayed in a variety of formats. Each of the graphs can display the x, y and z directed magnetic field components, field resultant or major or minor axis of the field ellipse. All results, both graphical and tabular, can be printed producing presentation quality output. The user can add titles and subtitles, print in landscape or portrait orientation, and scale the output to achieve the desired appearance.

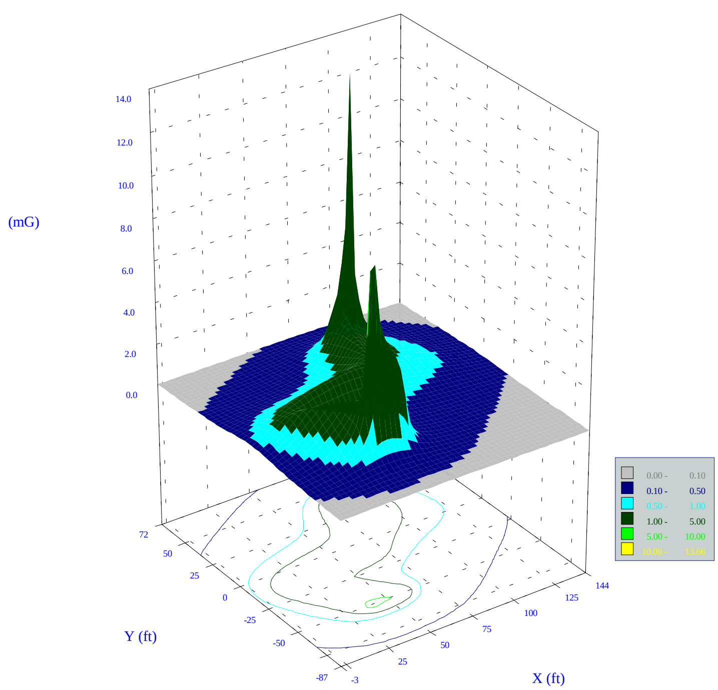

Fig. 3. 3-D magnetic field map

a. *3-D Magnetic Field Plots*

Area calculations can be displayed as 3-D wire frame or solid model graphics (Fig. 3). With this type of graph the viewer can immediately identify areas of high and low fields by looking at the peaks and valleys that are visible in the plot. The 3-D plot can be rotated and viewed from almost any perspective or manually scaled in the z (magnetic field intensity) direction.

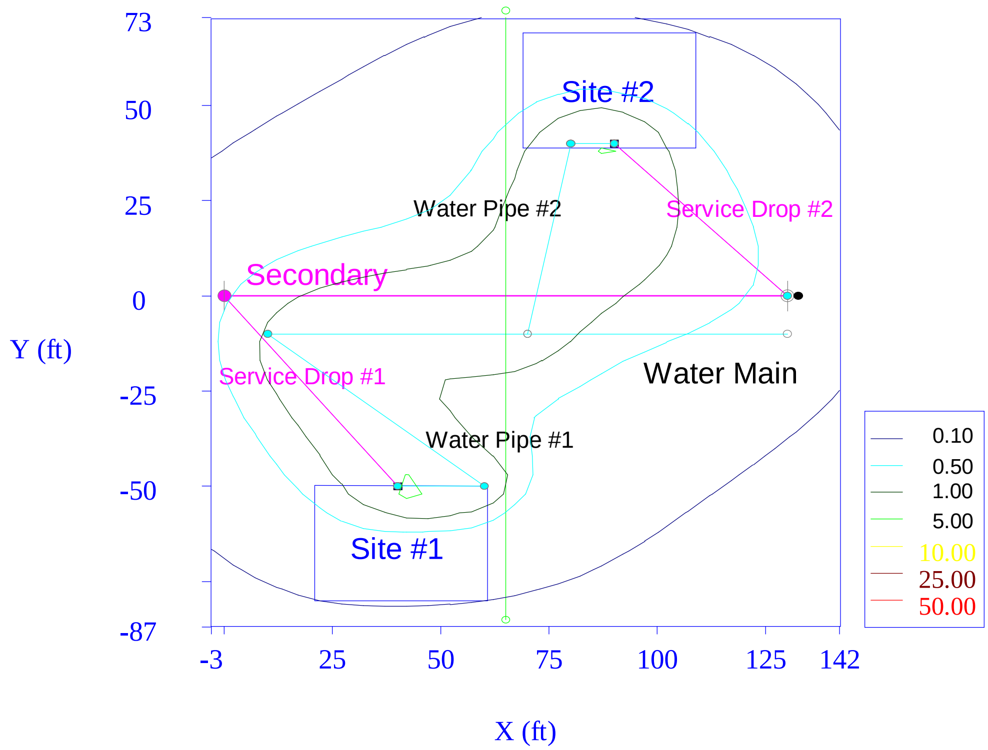

Fig. 4. Contour map with overlaid residences

b. *Equi-Field Contour Plots*

Area calculations can also be displayed as equi-field or contour plots (Fig. 4). These plots are similar to the elevation contour maps that are created by surveyors except in this case the contour lines represent magnetic field intensity rather than elevation. Users can change the values assigned to the contour lines allowing each graph to be customized. The objects in the model can be overlaid on the contour map, if desired, making it easy to identify which of these objects are major field sources. The user can enlarge (zoom in on) any area of the contour plot by drawing a rectangle around the area in question.

c. *Profile Plots*

A profile is a straight line or set of linked straight line segments along which the magnetic field is calculated at a user-defined interval. Unlike the 3-D and contour calculations, the profile need not be level. It can follow the contour of uneven terrain by changing the heights of the individual vertices. The results of these calculations are displayed in a standard x-y graph. As the user moves the mouse cursor along the profile plot, relevant information is displayed in the status bar located at the bottom of the plotting window (Fig. 5). The x, y and z coordinates, distance from the beginning of the profile, magnitude and phase angle of the field are updated in real-time according to the current position of the mouse cursor on the profile plot. The user may zoom in on the x-axis and manually scale the y-axis.

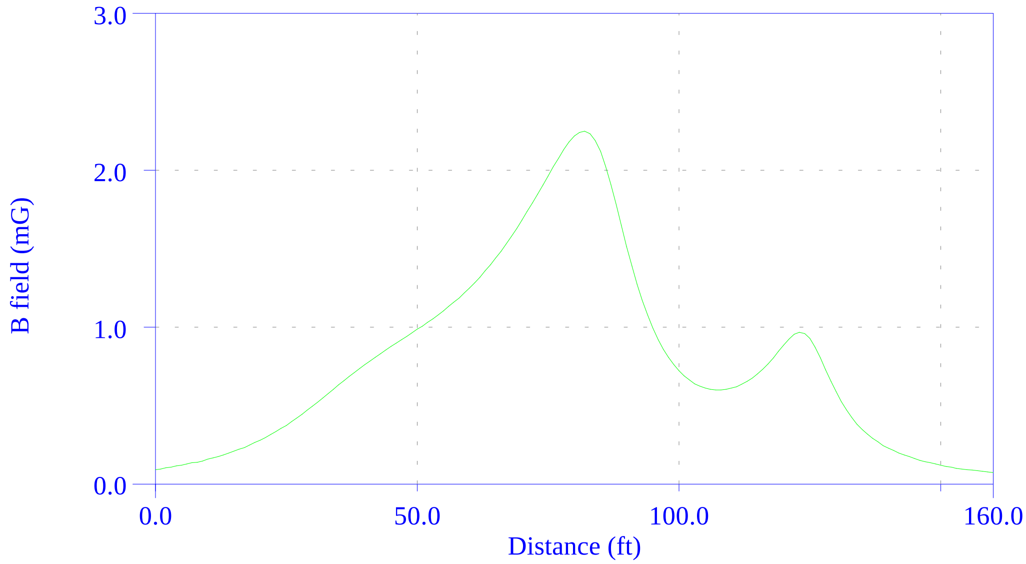

Fig. 5. Profile of neighborhood

d. *Tabular Results*

In addition to magnetic field calculations, several types of standard statistics are computed. Minimum, maximum, mean, median, standard deviation, and selected percentiles are computed for either area or profile data. Both the statistical results and calculation results can be written to ASCII text files in report form or in comma delimited form allowing their import into other analysis programs such as spreadsheets.

v. *Uses of the Program*

Several EPRI member utilities are using the RESICALC to help address a variety of problems. This program is being used for evaluating new transmission and distribution configurations and substation designs, studying substation bus layout to reduce fields outside the fence and thus exposure of the public, evaluating field management options and responding to questions from the public or regulatory agencies. Although our examples emphasized outdoor situations, RESICALC can also be used to model indoor substations, transformer vaults and raceways in office buildings and schools.

vi. *Program Verification and Accuracy*

RESICALC has been verified in several ways. Field measurement data from existing transmission and distribution lines and substations have been collected and were compared to the results of the RESICALC model. Measurements from actual test models built at EPRI's Power Delivery Center at Lenox compared very favorably with the calculated output of RESICALC models. The calculated values from the RESICALC model were within 3% of measured values.

B. SUBCALC 2.0

i. *Overview*

SUBCALC models the power-frequency magnetic fields from a user-specified array of transmission lines, primary distribution lines, substation conductors and substation equipment. The resulting magnetic field environment can be presented in a variety of graphical formats including 2-D contour and 3-D surface maps.

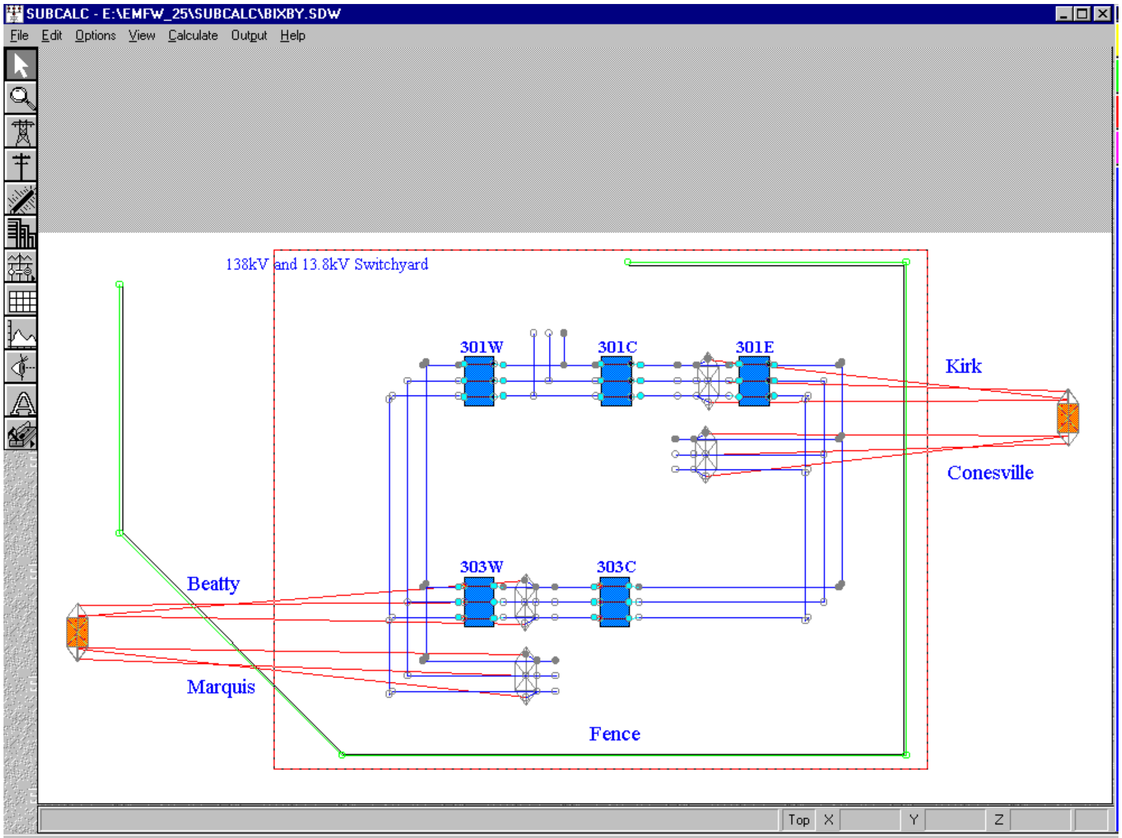

Fig. 6. SUBCALC main screen and drawing area

SUBCALC 2.0 is a substantial upgrade from the previous 1.X release and draws some of its features from RESICALC 2.1. Whereas, RESICALC's primary purpose is to model the magnetic field in and around a residence, SUBCALC's purpose is to model the magnetic field in and around a substation. Both programs can model the magnetic field from overhead transmission and distribution lines. SUBCALC's features include:

- A Graphical User Interface (GUI) featuring CAD-style data entry using an icon and menu driven interface.
- Calculation of magnetic fields from any arbitrary array of power lines and substation conductors. A broad selection of common transmission and distribution line configurations and substation conductor configurations are supported. Customized conductor configurations are also available.
- A database that allows easy retrieval and use of user-specified transmission line, distribution line, residential ground conductor and substation conductor configurations.
- High quality profile, contour and surface maps representing the calculated magnetic fields.
- Models for substation equipment such as circuit breakers, transformers, air-core reactors/wave traps and capacitor banks.
- Full editing capabilities allowing the modification and storage of existing models.
- SUBCALC uses the Power Line Calculator (PLC), a Windows™ application that calculates the symmetric current components, power factor, apparent power and reactive power for arbitrary multi-phase power lines.

ii. *Magnetic Field Sources*

The following sources can be modeled in SUBCALC version 2.0: substation buses, overhead transmission and distribution lines, circuit breakers, capacitor banks, air-core reactors/wave traps, power transformers and underground cables. These sources can be significant contributors to the magnetic field in areas both inside and outside the substation fence. Future versions of SUBCALC may include models of additional field sources that are currently being developed by other EPRI research projects. The magnetic field calculations are performed using the well-known Biot-Savart method that has become standard throughout the industry.

a. *Substation Buses*

SUBCALC can model all or most current carrying elements within the substation including horizontal, vertical, and skewed buses or conductors. Any current carrying element, such as a pipe, jumper, or single phase bus can be modeled using custom conductors.

b. *Overhead Transmission and Distribution Lines*

Transmission and distribution lines are modeled using the same procedures as in RESICALC. Because these same default assumptions are used in SUBCALC similar care must be exercised by the user when unbalanced line conditions exist.

c: *Circuit Breakers*

Live-tank circuit breakers can be modeled. When this type of circuit breaker is used, SUBCALC models the path of the current carrying elements in the breaker. The shielding effect of the tank is not presently modeled. Unlike other source elements, which operate correctly when disconnected, the breaker terminals of circuit breakers need to be connected to a bus to ensure valid calculations. Other types of circuit breakers can be approximated by positioning a conductor along the path the current will take as it passes through the breaker, the bushing and the connecting leads. Dead-tank breaker models may be added at a later date.

d. *Capacitor Banks*

Capacitor banks are modeled as single or multiple capacitor blocks. When multiple blocks are used these blocks may be connected in series, parallel or series and parallel combinations. Both live rack dead rack capacitor blocks are available. These capacitor blocks can either be fused or unfused. Once created from their component capacitor blocks, capacitor banks can be attached to a line or bus in either delta or wye configurations.

e. *Air-core Reactors/Wave Traps*

Air-core reactors are attached to lines or conductors individually or in groups. When more than one reactor is attached to a line or conductor, these reactors may be connected in parallel so that the current is divided between the reactors or in a twin configuration where the current is split between two reactors wound in opposite directions. In addition another type of reactor, called an inrush current-limiting reactor, which precedes a capacitor block, can be modeled using SUBCALC.

f. *Transformers*

Transformers can now be included in SUBCALC models. Both step-up, step-down, 3-phase, and single-phase banked transformers are available. Six different winding configurations are available: single-phase, delta-delta, wye-wye, wye-delta, delta-wye and wye-zip-zag. At present, this software does not determine the magnetic field shielding that results from the transformer tank which is expected to be small compared to other effects.

g: *Underground Lines*

Underground transmission and distribution cables can be approximated using the distribution line feature of the program. Because sheath currents and currents on a concentric neutral usually are not known, pipe-type and solid dielectric cables cannot be accurately modeled. If, however, the user knows the location of the cables, magnitude and angle of phase currents and neutral currents, and the split of the return current between the neutral and the other (earth) return paths, underground circuits can be successfully modeled.

An improved method that will require less user input may be added in the future. Like overhead distribution lines, the current imbalance in these cables may be substantial and simple assumptions for input values may introduce large errors near the underground circuit. If, however, these cables are closely spaced, the region where inaccurate results are produced will be smaller than the same region for overhead circuits.

iii. *Input Data Preview*

SUBCALC makes it simple for a user to review input data. Because the program graphically displays the model as it is being entered, the user is able to visually verify the location and geometry of model elements. This model can be viewed from top, front and side views, or in a 3-D window (Fig. 7) that can be rotated and viewed from any perspective. In addition information such as load data (magnitude and phase angle), phase identifier (A, B, C, N, etc.), or reference direction for each conductor segment can be displayed. These data can also be saved to an ASCII file in report format that can then be viewed by the user.

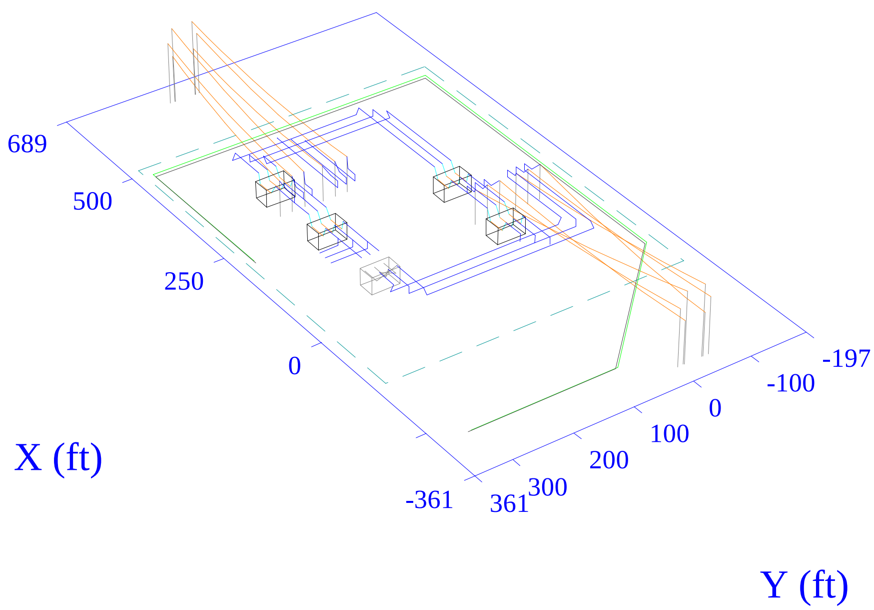

Fig. 7. 3-D View of Substation

iv. *Output Generated by the Program*

Once the calculations have been performed over a user-defined area or profile, these results can be displayed in a variety of formats. Each of the graphs can display the x, y and z directed magnetic field components, field resultant or major or minor axis of the field ellipse. All of the results, both graphical and tabular, can be printed producing presentation quality output. The user can add titles and subtitles, print in landscape or portrait orientation, and scale the output to achieve the desired appearance.

a. *3-D Magnetic Field Plots*

Area calculations can be displayed as 3-D wire frame or solid model graphics. With this type of graph the viewer can immediately identify areas of high and low fields by looking at the peaks and valleys that are evident in the plot. The 3-D plot can be rotated and viewed from almost any perspective or manually scaled in the z (magnetic field intensity) direction.

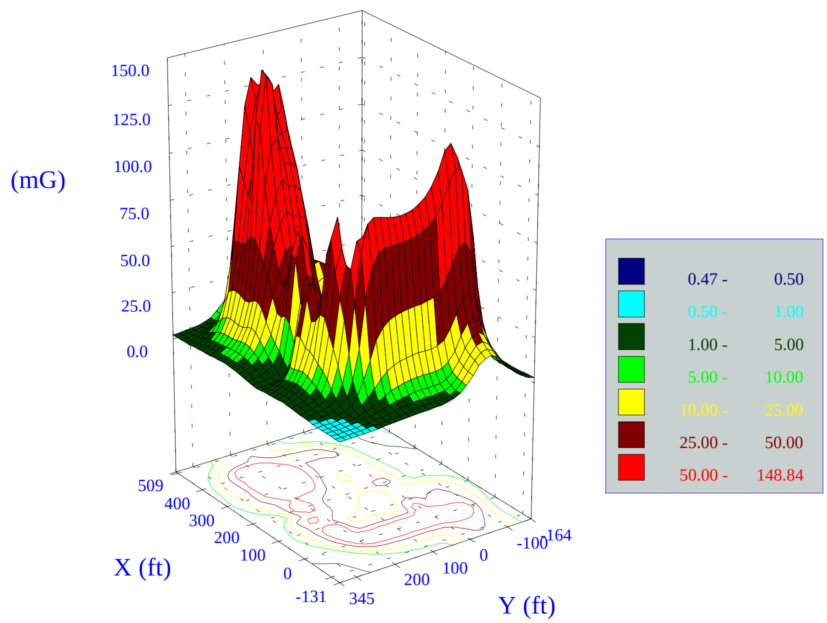

Fig. 8. 3-D Magnetic Field Map

b. *Equi-Field Contour Plots*

Area calculations can also be displayed as equi-field or contour plots (Fig. 9). These plots are similar to the elevation contour maps that are created by surveyors except in this case the contour lines represent magnetic field intensity rather than elevation. Users can change the values assigned to the contour lines allowing each graph to be customized. The objects in the model can be overlaid on the contour map, if desired, making it easy to identify which of these objects are major field sources. The user can enlarge any area of the contour plot by drawing a rectangle around the area in question.

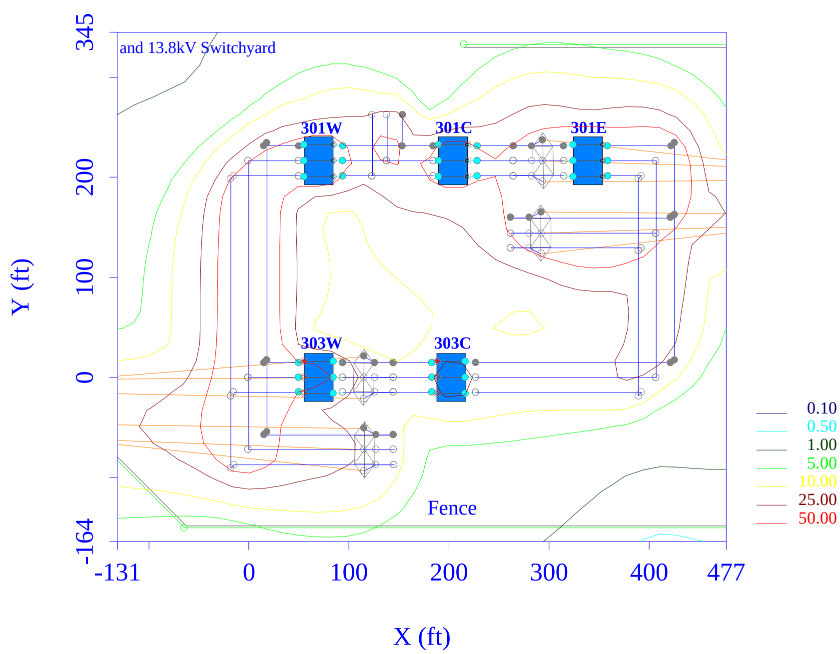

Fig. 9. Equi-field Contour Plot

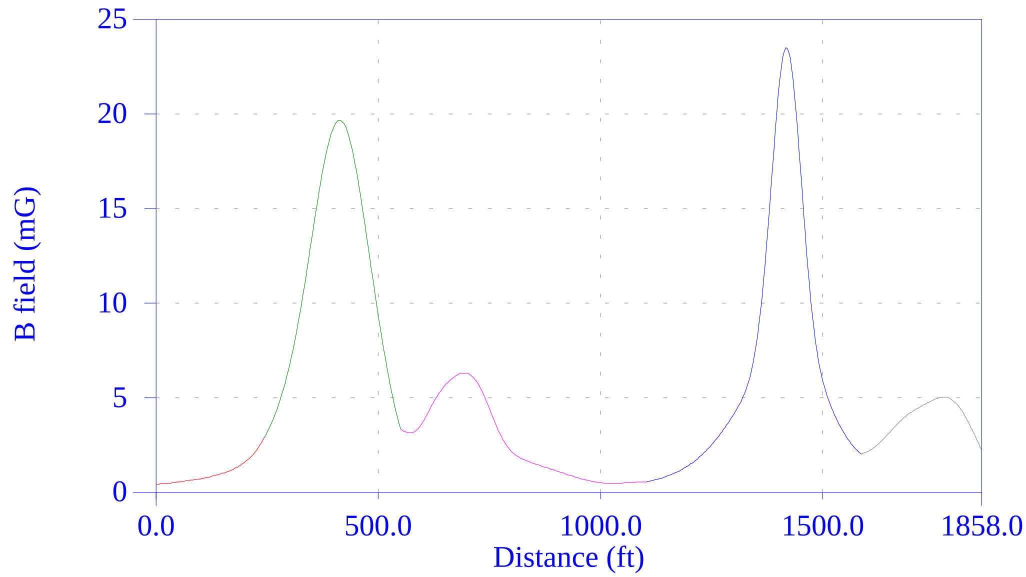

Fig. 10. Profile Plot of Magnetic Field

c. *Profile Plots*

A profile is a straight line or set of linked straight lines segments along which the magnetic field is calculated at a user-defined interval. The results of these calculations are displayed in a standard x-y graph. As the user moves the mouse cursor along the profile plot, relevant information is displayed in the status bar located at the bottom of the plotting window. The x, y and z coordinates, distance from the beginning of the profile, the magnitude and phase angle of the field are updated in real-time corresponding to the current position of the mouse cursor on the profile plot. The user may zoom in on the X axis and manually scale the Y axis.

d. *Tabular Results*

In addition to magnetic field calculations, several types of standard statistics are computed. Minimum, maximum, mean, median, standard deviation, and selected percentiles are computed for either area or profile data. Both the statistical results and calculation results can be written to ASCII text files in report form or in comma delimited form allowing their import into other analysis programs such as spreadsheets.

v. *Uses of the Program*

Several EPRI member utilities are using the SUBCALC to help address a variety of problems. The program is being used for evaluating new substation designs, studying the placement of equipment and bus layout to reduce exposure of workers, reviewing fields outside the fence for their impact on the public, evaluating field management options and responding questions from the public or regulatory agencies. In addition to its ability to model outdoor facilities, SUBCALC can model indoor substations as well as transformer vaults in office buildings.

vi. *Program Verification and Accuracy*

The SUBCALC program has been verified in several ways. Field measurement data from existing substations collected by Ohio State University compared favorably with the results derived from the SUBCALC model. Comparisons to a scale model substation developed by Ohio State University and to hand calculations for conductor configurations with well-known solutions were also used to validate this program. In each case, the magnitude and angle of the individual field vector components were checked for accuracy. The results from the straight line conductor segments (transmission and distribution lines, and buswork) are within 10%. Preliminary tests of substation equipment models are accurate to within 5% and 20% depending on the type of equipment and relative distance from the source.

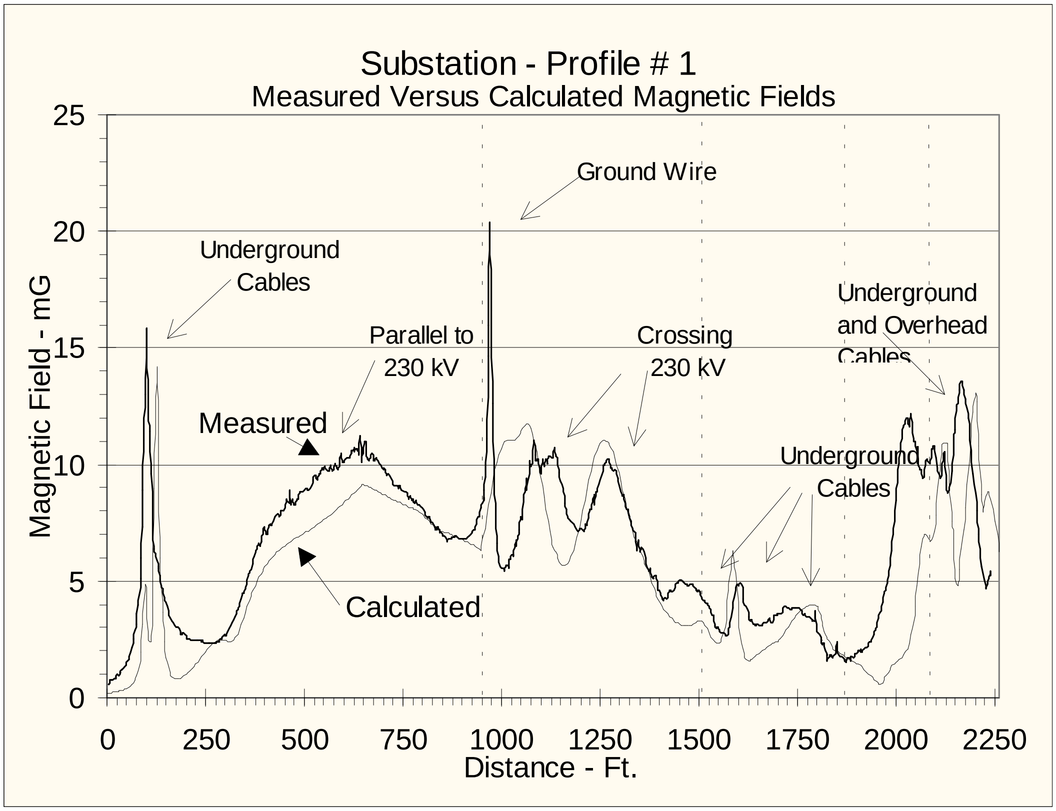

Fig. 11. Calculated vs. measured field

C. EMFX 1.0

i. *Overview*

EMFX is an EMF expert system that acts as a tutorial and glossary on magnetic field theory, technology and terminology. Three tutorials (electric and magnetic field fundamentals, transmission line magnetic field primer, and distribution line magnetic field primer), a glossary of terms related to EMF and a unit conversion utility are incorporated in EMFX. Because of increasing public awareness to magnetic fields, EMFX describes protocols, techniques for magnetic field measurements, and a survey of available magnetic field meters. Preliminary information on magnetic shielding is also provided. In addition to its tutorial, glossary and reference functions, EMFX can also be used to launch other EMFWorkstation 2.5 modules.

EMFX is easy-to-use. Using a mouse to select subject topics and subtopics of interest, EMFX guides the user using hypertext links and questions to the appropriate subject material within its database. Utility engineers and technical communication staff will find EMFX a handy tool for learning or refreshing information related to magnetic fields.

D. Power Line Calculator 1.12

i. *Overview*

Power Line Calculator calculates various electrical characteristics of one-, two- and three-phase power lines. Using this program engineers can calculate symmetric components, power factor, apparent power, reactive power, magnitude and angles of phase-current, net phase-current, neutral-current and ground-current. Given up to six input parameters Power Line Calculator can determine the remaining system parameters.

While Power Line Calculator can be used as a stand-alone program for calculating power line parameters, its main benefit is that it can be used with RESICALC and SUBCALC to define the operating characteristics of power lines. When called from RESICALC or SUBCALC Power Line Calculator can determine the operating characteristics of power lines based on a small number of input variables. Once these characteristics are determined these and other parameters are transferred back to RESICALC or SUBCALC. This integration is important when power lines are used that are not operating at default (balanced) load conditions.

E. ENVIRO 3.5

i. *Overview*

ENVIRO calculates lateral profiles for magnetic and electric fields and audible noise from user defined conductor bundles that comprise power lines. A unique feature of this software is its ability to calculate induced current on shield wires. ENVIRO can incorporate certain effects of weather (fog, rain, snow) when calculating audible noise. Enhancements to ENVIRO include the ability to model up to 50 conductor bundles, usage of Windows™ common dialog boxes, an upgraded interface and the ability to read TLWorkstation input files.

Using this software a utility engineer can produce both tabular and graphical plots of magnetic and electric field profiles and audible noise profiles. Only tabular plots are available for conductor surface gradient electric fields.

While other software modules within EMFWorkstation can produce magnetic field profiles, ENVIRO allows a user to produce electric field profiles, audible noise profiles and conductor surface gradient electric fields. ENVIRO can supplement either RESICALC or SUBCALC by providing an estimate of induced shield wire current if shield wires are needed in a model.

F. EXPOCALC 3.5

i. *Overview*

EXPOCALC calculates electric and magnetic field values and exposure from user-defined power lines. A unique feature of EXPOCALC is its ability to calculate the effects of objects such as trees, transmission line towers, and buildings on electric fields. EXPOCALC can predict electric and magnetic field exposure using the Activity Systems Model that combines the time spent in a physical area with calculated fields for the same area. Enhancements to EXPOCALC include the ability to model up to 50 conductor bundles, usage of Windows™ common dialog boxes and an upgraded interface.

Using this software a utility engineer can produce both tabular and graphical plots. Graphical output is provided as 2-D equipotential (contour) maps and bar graphs of magnetic and electric fields. Tabular plots are available for magnetic and electric fields, magnetic and electric field exposure.

EXPOCALC enhances EMFWorkstation by providing an ability to calculate time-weighted exposure either in an area (distributed exposure) or along an arbitrary path composed of straight line segments (linear exposure).

III. FUTURE VERSIONS

Possible enhancements being considered for version 3.0 of EMFW include rewriting the software for Windows 95. This change would allow EMFW to use long file names, 32-bit code execution, and multi-threaded operation. Features from SUBCALC and RESICALC will be combined into a new version of RESICALC. This will eliminate the need of the user to select which program to use when developing a new model. Other enhancements may be added if warranted from user feedback and as resources permit.

IV. SUMMARY

EMFWorkstation links software and database modules into a comprehensive package that can be used to understand and resolve EMF-related issues. EMFWorkstation provide a powerful, yet flexible, set of tools that can be used by utility engineers or environmental scientists to analyze EMF levels near electric utility facilities. The newly added expert system module, EMFX, will help utility personnel find quick answers to commonly asked questions related to EMF.

V. REFERENCES

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VI. BIOGRAPHIES

Randall M. Takemoto-Hambleton is a manager of exposure assessment studies at the Electric Power Research Institute in Palo Alto, California. He received his Ph. D. degree in Electrical Engineering from Duke University in 1991. While at EPRI he has managed Electric and Magnetic Field Project for Utilities-The EMDEX Project, AC Field Exposure Study and EMF Database Project.

John R. Pappa (M’89) is the software manager at Enertech Consultants in Campbell, California. He received his B.S. degree in Computer Science and Math from the University of California at Davis in 1984. He has developed software at Lockheed Missiles and Space Company and Theta Corporation. At Enertech, he was responsible for the development of EMCALC, the analysis and communications software package used with the EMDEX II magnetic field meter as well as several of the programs included in the EPRI EMWorkstation. John is a member of IEEE and the Computer Society.

James G. Stewart is a software engineer at Enertech Consultants in Campbell, California. He received his B.S. in Computer Science and Math from the California State University at Chico in 1985. Before coming to Enertech he developed real-time software at CAE-Link Flight Simulation Division. After joining Enertech he has been involved in the development of the SUBCALC and RESICALC programs.