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COMPUTER AIDED STRUCTURAL AND GEOMETRIC DESIGN OF POWER LINES

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Abstract - This paper describes an integrated computer environment for the structural design of new power lines, the evaluation of existing lines, and their long term management. The detailed content of the data files that need to be accessed is presented. Implementation of commonly used design and archiving functions on a workstation should help design optimization, reduce design mistakes and result in considerable gains in engineering productivity.

INTRODUCTION

The structural design of electric power lines involves gathering, manipulating and storing a very large amount of information that is traditionally kept on paper in miscellaneous locations: plan and profiles, design specifications, insulator data, cable data, structure drawings, structural calculations, etc. Improved engineering productivity requires that all that information be accessible interactively on a computer workstation. The workstation operator should be able to: 1) access any relevant information about a line, 2) check any element of the line for strength and clearances, and 3) change any design parameter of the line (such as adding, modifying or removing a structure or a conductor) and observe immediately the consequences of the change.

This paper describes the contents of the various data bases that are needed to describe an entire line. It proposes a new way of verifying the strength of transmission and distribution structures which is considerably more versatile than relying on allowable wind and weight spans as currently done with manual or computer spotting methods [2].

Finally, the paper illustrates how some of the engineering functions normally associated with line design can be performed interactively.

DATA BASES

All information needed to describe a line is contained in the files which are described below. The Terrain and Line Installation files are specific to a particular line: the other files can be shared across several line projects. In the interactive environment, the files are treated as objects, callable by name. Files should have ASCII format for ease of transportation between existing or future systems.

3-D Terrain Files (X-Y-Z-Attribute-Height)

The terrain through wich a line passes is traditionally represented by 3-D maps representing ground geometry, salient features, as well as soil characteristics. In its computerized description, the terrain should be represented in a single file by a vast collection of points, each with: 1) its global coordinates X, Y and Z (Z = altitude), 2) an attribute, and 3) a height above ground (if the point represents the base of an obstacle, say a structure, tree or a crossing line). The attribute is simply a numerical code that defines the nature of the point: road, river, fence, tree, etc. In the terrain file, it is only necessary to include points that are within a short distance from the centerline of the line. The terrain file can be prepared by digitizing existing maps or directly using automated survey data acquisition systems.

2-D Terrain Files (Station-Offset-Z-Attr.-Height)

By specifying the origin of the line and points at the ends of the straight line segments that define the exact line route on the 3-D terrain, the 3-D information can automatically be transformed into points that represent the ground profile at the centerline of the line together with a collection of features and obstacles which may have offsets from that centerline. A transformed point is now described by: 1) its distance from the beginning of the line (station), 2) its offset (perpendicular distance from the centerline), 3) its altitude Z, 4) its attribute, and 5) its projecting height above ground. We refer to the file of transformed points as the 2-Dimensional terrain file because, normally, most of the points that it contains have zero offsets. In the transformation from 3-D to 2-D, a special record is made of the points where there is a line angle, and the points are arranged in increasing order of station values. If the terrain slope in the direction perpendicular to the line is significant, there should be some terrain points with offsets equal to those of the outer phases. There should only be limited editing capability of a 2-D terrain file if it has been obtained by transformation of a 3-D file: the data at the line angles should not be accessible. However, direct preparation of the 2-D file from digitizing an existing plan-and-profile or using a text editor should be permitted. Interactive screen display of the content of the 2-D file should be available (see for example Figs. 6 to 9).

Loads Files

Any combination of wind, ice, temperature and load factor, which is used in connection with an engineering check of the line should be described as a separate load case in a Loads file. The information should allow traditional descriptions of loads (such as those of the National Electrical Safety Code, NESC), as well as those from new emerging reliability-based methods [1]. A typical file may include loads in the following categories: 1) three load cases for checking support strengths (NESC district, extreme wind, ice and wind), 2) one bare wire load case to describe the assumption

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for long term creep, 3) two bare wire load cases under which the initial and final cable tensions are checked against aeolian vibration damage avoidance limits, 4) one high temperature bare wire case to check ground clearances, 5) one cold temperature bare wire case to check uplifts, and 6) one or more load cases for checking insulator swings, clearances to obstacles or interphase clearances.

Allowable Clearances Files

Allowable clearances from phases to objects on the ground (defined previously by their attributes in the Terrain file) and clearances between cables are included in an Allowable Clearances file. Allowable insulator swings are defined in the Support file as described below.

Support Files (Structure-Insulator-Foundation)

The support file concentrates in one place all the design information that pertains to a specific structure type and height. As discussed below, the structure file also contains insulator and foundation data. The various data blocks in the file are: 1) structure height and top geometry, 2) insulators configurations and allowable properties, and 3) strength data. Strength data can either be in the form of allowable wind and weight spans, or, better, be related to the strengths of critical axial or bending components as described later.

Structure height and top geometry. This block describes the locations of the attachment points of the ground wires or the insulators, relative to a local coordinate system x,y as shown in Fig. 1 for a double circuit tower. The local coordinate system is located in the transverse plane of the structure at a distance HT (structure height) above the center of the base. There is one set of attachment points (triangles, circles and squares in Fig. 1) for each potential set of cables. All cables in one set are assumed identical. Within one set, the attachment points are numbered consecutively in order that individual cables (or phases) can be identified. Switching phase numbers in otherwise identical structures will allow modeling of transposition. For V-type or stand-off insulators, there are two attachment points per phase.

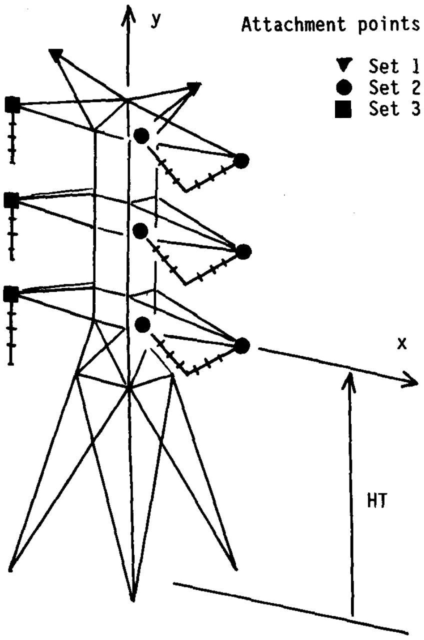


Fig. 1 Structure top geometry and insulators

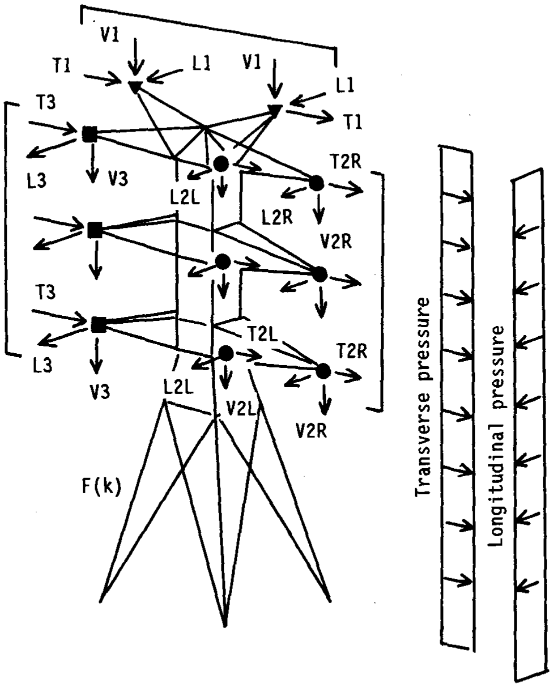


Fig. 2 Loads on tower of Fig. 1

Insulators. This block describes, attachment points set by attachment points set, the means by which corresponding cables are connected. The connections can be made with: 1) clamps, 2) strain insulators, 3) suspension links or insulators, 4) V-type insulators, or 5) stand-off insulators. Post insulators should be treated as extensions of the structure, i.e. the tips of the posts are structure attachment points which then belong to the first data block: the posts themselves are treated as bending components as described below. Insulators are characterized by their geometry, strength, as well as allowable swing angles. The inclusion of insulators in the structure file, rather than in a separate insulator file, is dictated by the fact that allowable swing angles are structure specific.

Strength data. One convenient way to describe the strength of a support is by its allowable wind and weight spans for given line angles. This is the method used in manual spotting of structures as well as in most automated spotting computer programs [2]. However, one should realize that allowable spans are not intrinsic properties of a support because they depend also on design loads, supported cables and their installation tensions: any change in load assumptions and use of cables invalidates the allowable spans. Therefore, alternates to the wind/weight span method should be available. Two alternate methods are described herein: 1) the component influence coefficients method, and 2) the full analysis method.

With the component influence coefficient method, the structure is described by a collection of axial and bending components. The total number of individual components need not be the number of physical elements, but a smaller number of critical ones, as will become clear later. Consider the double circuit tower in

Fig. 2. Once its terrain location and those of its neighbors are known, and the various cables are installed, the vertical, transverse and longitudinal components of the forces at all attachment points can be computed in a fraction of a second. A traditional computer structural analysis of the entire structure (which is the basis of the full analysis method and which would take a few seconds on current generation microcomputers) could then be performed to verify its strength capability. However, this may not be desirable for two reasons. First, a few seconds may seem too long a time in an interactive environment where, after pointing with a mouse to a structure, one would expect an almost immediate message as to the adequacy of that structure. Second, one may object to the amount of data kept in the support file. The solution to the requirement of speed and reduced data is to compute the forces, F(k), through simple multiplication of force influence coefficients by a few components of wire loads and pressures (shown in Fig. 2). Note that each component of wire load may appear twice or three times, and therefore only needs to be accounted for once. A force influence coefficient for component "k" is the force in that component caused by either: 1) a group of unit loads applied in the vertical, transverse or longitudinal direction at a set of structure attachment points (see Fig. 3.a for the effect of the vertical loads at the right attachment points in cable set 2), 2) a unit transverse or longitudinal pressure (see Fig. 3.b or c), or 3) the weight of the tower. Component "k" in Fig. 2 has a total of 15 influence coefficients. Storing a matrix of 15x500 force coefficients and a matrix of 2x500 component tension and compression capacities, allows the verification of the adequacy of 500 axial components to be made in a fraction of a second. The two matrices of force coefficients and component capacities can automatically be generated by the tower analysis and design program that was used for the initial design of the tower.

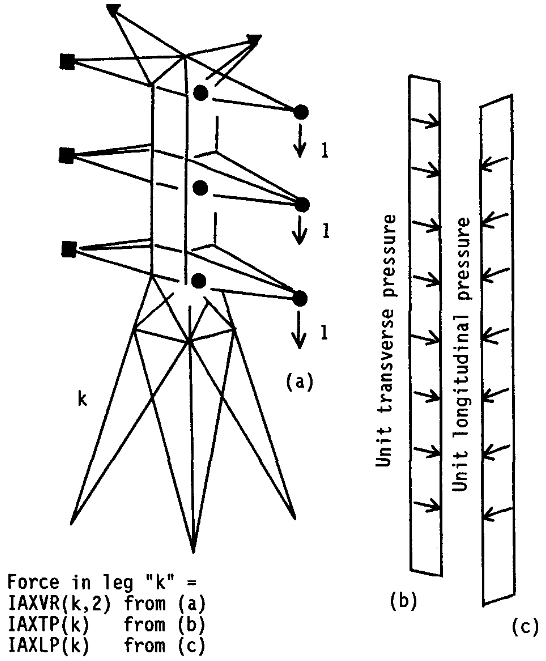


Fig. 3 Components force influence coefficients

The above discussion was restricted to structures with axial-type components (self-supporting or guyed latticed towers). However, the concept of representing a structure by a collection of components is equally applicable to structures with bending-type elements, such as poles and frames. Consider the single circuit wood pole in Fig. 4. It may be decided that the strength of that pole and its arms need only be checked at the base of one arm (Section A-A) and at the base of the pole (Section B-B). In that case, the support is modeled with only two bending-type components. This is certainly satisfactory in many applications where it can be ascertained beforehand that the weak sections are those selected as components. In components such as those in Fig. 4, the axial force F(k) and the bending moments about the two principal axes, MX(k) and MY(k), can also be computed rapidly from a matrix of force and moments influence coefficients. Then, these components can be checked by any specified interaction equation relating forces and moments to corresponding capacities or allowable stresses.

The strength verification by the component influence coefficients method assumes linear structural behavior under load. Significant P-Delta effect can be handled by multiplying moments by a factor such as:

$$\text{Moment amplification factor} = \frac{1}{1 - P/P_{CR}}$$

where P and P_{CR} are total vertical and buckling loads, respectively. However, when substantial deflections are expected, it is recommended that the full analysis method be used.

With the full analysis method, all data needed for a detailed structural analysis of a support are included in the support file. Performing a structure check can then be as simple as pointing to a structure on a plan/profile, and waiting a few seconds for the software to automatically: 1) calculate loads, 2) transfer control and appropriate files to a structural analysis program, and 3) return with conclusions in a window of the plan/profile environment. The authors believe that with the advent of more powerful workstations, the full analysis method will become the method of choice for checking existing lines or upgrades. It also allows viewing of the detailed geometry of the structure.

Foundations data should also be part of the strength block. The foundations can be treated just like any other component.

Other blocks. Other blocks of text of numerical data can be added to the support file.

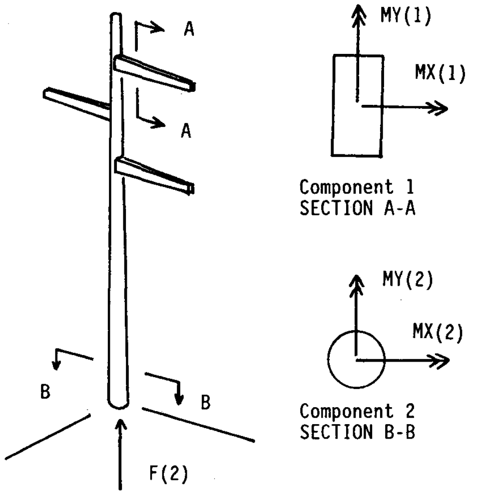


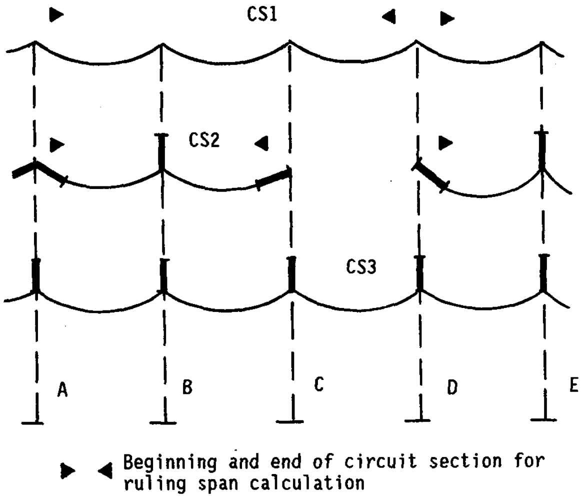
Fig. 4 2-Components wood pole model

Cable Files

Ground wires and conductor properties are kept in a library of cable files. For each cable, there is a file that includes: description, cross section area, outside diameter, unit weight, ultimate tension, thermal expansion coefficient and whatever set of parameters is necessary to describe nonlinear stress-strain relationships and creep behavior [3,5]. It is appropriate to name the file after the cable code name (for example KIWI or 3#6AW).

Line Installation File

This file includes information on structures spotting and cables installation conditions for a particular line. Wherever a structure is located on the terrain, its location and type (defined by reference to a support file), is kept. The installation conditions for the cables require that, for each set of cables, and for each section of that set, a cable type and its reference tension be known. A section corresponds to one or more spans over which the horizontal component of cable tension is assumed constant. It is the length of line over which a ruling span is calculated and is usually the length of line between strain attachments. In Fig. 5, the ground wire is part of cable set CS1. Assuming that structures A and D are relatively rigid at the ground wire attachment points and that structures B and C are somewhat flexible, a ground wire section is defined between structures A and D. Cable set CS2 has one section between structures A and C. It is interrupted between structures C and D, and it starts again after structure D. The ends of the section for cable set 3 are beyond the limits of the figure. One should be able to install any cable set at any tension in any section. The section limits, which by default are at locations of clamps or strain insulators, can be specified. They are kept in the line installation file. It should be possible to specify the installation of any section by specifying one of the following conditions: 1) specify limits of tensions for several load cases and let the computer find the tightest installation that does not violate any of the limits (option at design stage), 2) specify a tension under a given load case, or 3) specify a sag in a given span for a given load case.



▶ ◀ Beginning and end of circuit section for ruling span calculation

Fig. 5 Various cable sets installation conditions

All the files described above, except the "Line Installation File", can be created and modified individually by other programs or through the use of interactive input screens. However, the content of the Line Installation File is the result of actually building or modifying the line computer model interactively. The building and modifying functions should be as simple and direct as possible, preferably through the use of a mouse and pull-down menus. The following section describes some of the basic functions that should be available to describe a line, check its compliance with codes, produce permanent records such as construction plan and profile drawings, etc.

DESIGN AND EVALUATION FUNCTIONS

The screen-based line installation and evaluation program will be referred to herein as CALD, for Computer-Aided Line Design. Some of the desirable functions (Commands) that should be available in a CALD-type program are described below. These functions are all accessed from pull-down menus arranged under the following major headings which are initially present at the top of the computer screen:

Files Views Supports Sections Infos Calculations

Functions availables under each major heading are:

Files

About : print name of project being viewed
Open : load a project file - transfer to a submenu requesting (or verifying) names of:
1) 2-D terrain file
2) loads file
3) allowable clearance file
Save : save project file
Plot : prepare DXF or equivalent file for permanent plotting on CAD system
DOS-Shell : access DOS temporarily and return to CALD where left off
Quit : leave CALD

Views

Different functions for manipulating picture of entire line: colors, text, zooming, panning, scaling, setting parameters for plotter, etc. For example, with a few keystrokes and mouse moves, one can go from the global 31-span view of in Fig. 6 to the detailed view near structure 26 (with ground clearance line, structure numbers and span lengths visible) as shown in Fig. 7.

Supports

The selection of a support and its location in connection with the commands below is done by pointing with the mouse.

Add : add a support at location of pointer - support name to be provided
Remove : remove support at location of pointer
Replace : replace support by another one
Move : grab support and move it
Move on : grab support and move it to closest point defined on profile
Store : store info. about support at pointer
Copy : add support currently Stored at pointer
Info. : show information about support: Name, height, insulators, back and ahead spans, etc.

Sections

The commands are used to describe the various cables and their installation conditions. As described previously, a separate section needs to be used every time a different combination of cable type and horizontal component of tension may occur. The ends of a section are automatically determined by information in the support file.

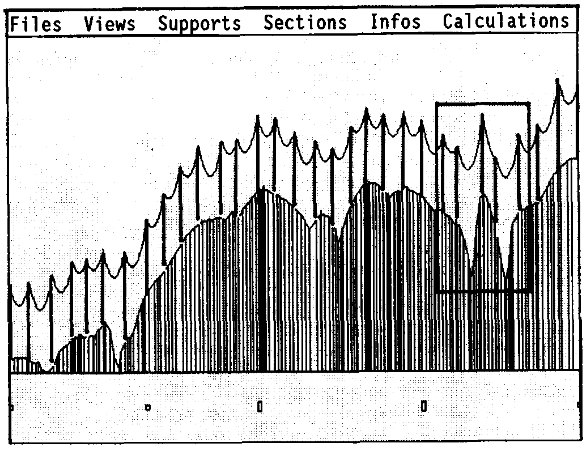


Fig. 6 Overview of 31-span line segment

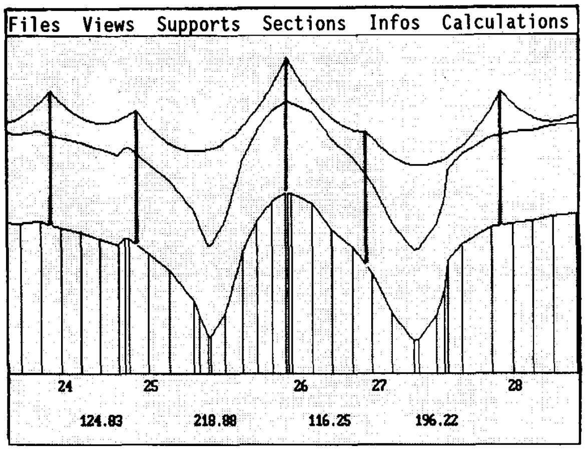


Fig. 7 View inside window shown in Fig. 6

String : 1) point to support at origin of span and give number of attachment set (see Fig. 1)
2) point to support at end of span and give number of attachment set
3) provide name of cables in set
Sag : provide information for tensioning a specific section
Modify : change any of the above information
Remove : remove a section - identified by number
Info. : show information about all sections traversing the vertical plane at the location of the pointer (mouse)

Infos

Terrain : give coordinates and description of item pointed to
Vert.dist.: give vertical distance between two indicated points
Dist. : give actual distance between 2 points

Calculations

For each one of the calculation types described below, the number of one or more corresponding load case is requested. If not identified, the applicable load cases are those defined as defaults in the loads file. Results of the calculations appear in windows that temporarily overlap the current line view.
Loads : show components of loads on support pointed to
Support : verify strength of support pointed to for load cases indicated
Section : compute tension in section pointed to for load case indicated
Ins. clea.: check insulator clearances at indicated support
Clear. : check clearances between point on terrain and nearest phase or nearest section
Cab.clear.: check clearances between pairs of specified cables
Line : check entire line for strength and clearances: print a summary of all deficiencies - this function may take a substantial amount of time and is therefore not "interactive"

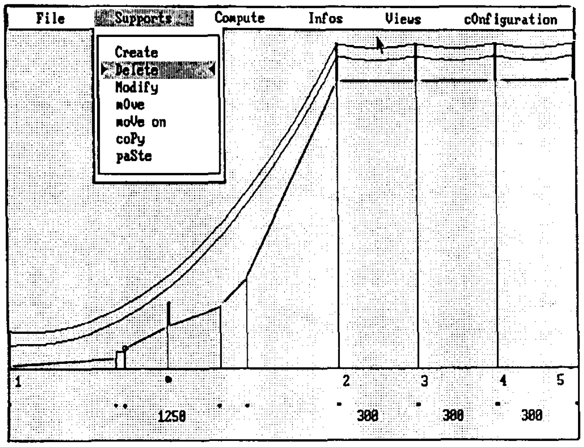


Fig. 8 Four-span line section described in Ref. 5

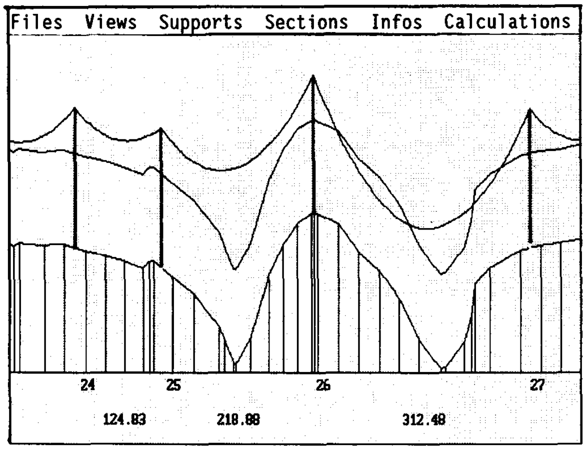


Fig. 9 Line after removing support 27 in Fig. 7

While the CALD program has the potential to perform a very large number of line engineering tasks, it may also be used to solve problems of smaller scope. For example, the problem of determining design wire loads at a take-off substation structure (support 1 in Fig.

8) in a four-span line section has been described in Ref. 5. These loads can quickly be calculated and displayed by CALD. The structures in the line need only be described by very short files that include the locations of two cable attachment points (one for one ground wire cable and the other for one conductor). No strength information is needed.

Response to any function call from CALD should be almost instantaneous. This can be achieved on current generation 386/486 microcomputers (operating at 20 MHz or faster). For example, pointing to support 27 in Fig. 7 while being in the **Support Remove** mode results in the almost instantaneous redrawing of the picture as shown in Fig. 9. With instant feedback, the CALD user is able to quickly evaluate design alternatives towards an optimum solution.

Once a design has been verified within the CALD environment, data can be transmitted to any commercial drafting system (Autocad(R), Versacad(R), MicroStation(R), etc.), where paper copies of plans and profiles can be produced.

The files and the CALD integration discussed above did not include costs information and manipulations: however, such items could easily be added.

APPLICATIONS AND CONCLUSIONS

There has been considerable interest recently in the use of computers to optimize line designs. One useful contribution to approaching the global optimization of a line has been the ability to obtain the optimum spotting of a family of available structures [2]. However, the multitude of constraints that a line designer encounters in developed terrains often do not leave much room for a practical mathematical optimization. When the constraints are many, the authors and others [6] believe that line optimization has a better chance of being succesful if the design is controlled by an experienced engineer, especially if he/she operates in an interactive environment such as described in this paper.

It should be emphasized that the usefulness of operating in the CALD environment goes much beyond the opportunity provided for optimizing new line designs. The integrating and inventoring of information on existing lines can greatly facilitate their future management and evaluation. For example, new clearance checks of an existing line may become necessary because of changes in regulations or unexpected permanent conductor elongation due to creep or accidental overloading. The task of performing the clearance check is trivial in the CALD environment. However, it is monumental if the line information is dispersed in various paper documents. Within the CALD environment, the potential for upgrading an existing line can easily be established. This is only practical if support strength is described by influence coefficients or by a full analysis model. Allowable wind and weight spans are not useful quantities when cable types, cable tensions or load assumptions are varied. Upgrading itself and archiving of the upgraded line is a straightforward task with CALD.

In addition to being a productivity improvement tool, CALD has great potential for reducing human errors, thus helping with ever-increasing quality control requirements.

Finally, the potential for economic savings through standardization of procedures and products will become more apparent with widespread CALD use. CALD can become a tool with which a utility, or a group of utilities, can control the application of their standards.

Experience with some CALD concepts applied to single circuit distribution lines supported by standardized poles has already been proved immensely successful [4].

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