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Project Summary

A Simple Transmission Network Planning Method: Wisconsin Power Plant Impact Study

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This report describes a new model for planning the expansion or modification of transmission networks. The model is different from traditional models which employ mathematical optimization techniques, in that it closely parallels the logical steps followed in practice by planning engineers. No claim is made for the optimality of plans produced, but they will be similar to those developed by planning engineers on the basis of their working experience with the system.

The first step in analyzing a power network is to formulate a model that describes the components in the system and how they are interconnected. A classical network reduction algorithm models the system by simple equivalents, focusing attention on parts of the system that are of interest. Reliability criteria for the network are translated into a series of contingency studies which the algorithm treats as pass-fail tests. Sensitivity matrices simulate the experience of planning engineers. An overload logic then ranks the branches of the network according to their expected effect on the system, and performs a series of contingency studies to find the least costly changes that will alleviate line overloads in the network. When no overloads remain, the voltage correction logic checks for deviations of the voltage from specified limits and adjusts the bus reactive power injections where necessary. The program then advances to the next planning period and repeats the entire process. A line removal subroutine checks the usefulness of lines after passage of a number of planning periods and removes unnecessary lines.

Sample planning studies indicate that this method is applicable to practical problems in large networks, and that it will significantly shorten and simplify the planning process.

This Project Summary was developed by EPA's Environmental Research Laboratory, Duluth, MN, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Background

One of the most important areas to be considered in the planning of new or expanded sites for generating electricity is the accompanying modification of the transmission network. The network must be designed to carry electricity effectively and economically, with a specified degree of reliability, from the generating site to the load centers. Constraints on the network may limit or preclude development of certain sites. Therefore, modification of the transmission network must be considered in evaluating alternative plans for expansion.

This report describes a new model, unlike earlier models employing optimization techniques, for planning the expansion or modification of transmission networks. It closely parallels the logical steps followed in practice by planning engineers. The report contains the following major parts:

1. Review of the basic concepts in power systems.

2. Review of load-flow studies and methods.
3. Review of methods for network reduction.
4. Review of methods for network planning and expansion.
5. Description of the proposed method and examples of systems studies based on it.
6. Appendices: mathematical derivations for models, computer outputs for sample studies, and listings of programs for an AC model and a DC model.

Planning expansion of the transmission network is one of the most difficult parts of an electrical network study. Most of the problems relate to four factors:

1. The large numbers of possible expansion alternatives.
2. The complexity of reliability criteria, which vary with the system and the utility company.
3. External cost variables, such as environmental costs, that are difficult to quantify.
4. Uncertainties in predicting future power demand.

Traditionally, plans for network expansion have been designed by the utilities' planning engineers on the basis of their work experience with the system. The system is expanded to satisfy specified reliability criteria. Outages are simulated on critical branches, and for a predicted load profile the network is expanded by a standard procedure.

Most attempts to develop automatic algorithms for planning network expansion have treated the problem as one of optimizing a performance index subject to a set of equality and inequality constraints. These techniques are difficult to evaluate because few of them have been developed beyond the experimental stage. Planning engineers are reluctant to use the automated algorithms. Not only do plans produced by automated methods not always match those developed by standard engineering procedures, but "optimal solutions" obtained from different models and with different techniques differ from each other. The method developed in this report has been tested in several sample cases and appears to be a practical tool for the complex and lengthy process of planning expansion of transmission networks.

Review of Planning Models

A typical power system is composed of generating stations connected to load centers by a transmission network. Transport of electricity can also take place or from other power systems. The transmission system generally has a multiple loop structure with several multiple-interconnected voltage levels (in contrast to the radial structure common to distribution systems). The loop structure permits flexibility in routing of energy on various links and offers multiple path combinations for contingencies.

The first step in analyzing a power network is to formulate a model which describes the characteristics of individual components in the system and how they are interconnected. For computer applications, network matrices provide an accurate and convenient way of representing network models.

Load-flow calculations are performed during planning, operation, and control phases of power system studies. Digital computers have replaced the earlier "network analyzers" in these studies. The load-flow problem is solved with a set of nonlinear equations that describe the steady state performance of the system. The principal information that such a solution yields is the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line. The report discusses several so-called Y-bus methods for solving load-flow problems.

The report also reviews four techniques for network reduction. These techniques simplify non-essential parts of the network so that the planner may focus on those parts of the network that are of interest.

Planning studies for expansion of power systems can be divided into four steps: forecasting loads, planning generation capacity, planning transmission networks, and planning distribution networks. Planning has traditionally been treated as a problem in mathematical optimization. The techniques employed include heuristic methods, linear programming, nonlinear programming, dynamic programming, and integer programming. The report describes the major features of these methods. All of them require a mathematical model of the system and a statement of the problem in terms of mathematical optimization of a performance index or cost function. The major differences among present automatic network planning techniques are in their methods of optimization.

None of the earlier methods has so far led to a practical solution. This failure may be caused by the large number of variables that are difficult to quantify and predict, such as costs and environmental, political, geographical, social, and technical constraints. The various methods are nearly impossible to evaluate and compare because few of them have been developed beyond experimental stages and the demonstrations that have appeared represent systems of very limited size.

The Proposed Model

The algorithm developed in this report divides the problem into three parts: modeling the network, contingency analysis, and expansion logic. In modeling the network, a classical network reduction algorithm is used to model the external system by simple equivalents and to let the planner focus on the areas of interest. Two different modeling techniques are utilized: DC modeling and AC modeling. In the DC model, the network is represented by a DC power flow method whereas in the AC model the network is modeled by a decoupled AC power flow model. For contingency analysis an automatic contingency selection method using network sensitivity matrices is developed. This technique selects only the contingencies that are critical and avoids having to simulate all possible contingencies. The expansion logic is composed of an overload logic and a voltage correction logic. The overload logic uses the sensitivity matrices to identify the most economical set of branch reinforcements and the voltage correction logics determines that reactive power adjustments at buses to correct voltage level violations. The voltage correction logic is used in conjunction with the AC model only.

Before a planning study for the transmission network begins, the sites, sizes, and dates of future additions of generating capacity will be tentatively planned. The following data are needed:

1. Descriptions of the existing transmission system.
2. Forecasted load profiles for the entire planning period.
3. A list of potential rights-of-way, specifying their lengths, constraints, and the particular transmission facilities they can accommodate.
4. Impedances, shunt capacitances, and capacities of available new transmission facilities, together with data on their cost.
5. Operating constraints for the system, which are strongly influenced by limitations in transmission.
6. Legal, environmental, and political constraints.
7. Reliability criteria.

Sensitivity matrix

The sensitivity matrix J is an r x r full matrix, where r is the number of branches.

Each element $J_{i,j}$ is the ratio of the branch phase angle difference $\Delta\Psi$, to the branch capacity Δyj.

Contingency analysis

The expanded network must satisfy prescribed reliability criteria. In planning studies, these criteria are translated into a series of contingency studies and are treated as pass-fail tests. The network is to be designed to withstand any single line outage with no cascading overloads for the given load and generation profile. Multiple contingency tests are made by removing lines or generators one by one and proceeding as with the single contingency test.

An automatic contingency selection method has been implemented to select critical branches and thus reduce the number of contingency cases studied.

For every branch, a number is calculated showing the relative effect that removal of Y_{max} units of susceptance from that branch will have on the system.

The Effect Indices are then used to rank branches according to their expected effect on the system. The magnitudes of the Effect Indices indicate the expected effect that the removal of the largest capacity line from the branch may have on the system. For contingency studies, the branch with the largest Effect Index is outaged first. The results of the load flow are checked for overloads. Then, the branch with the next largest Effect Index is outaged. This process is repeated until no overloads are observed over several successive contingency cases. Different stopping criteria may be used. Tests on the IEEE 14 Bus Test System and the Wisconsin Upper Michigan System's reduced network show that with the stopping criterion of "no overloads over four successive outages" the results are identical to those obtained using an exhaustive contingency checking approach.

Cost vector

The total cost of adding capacity on a branch is a function of capital cost, operating cost, and environmental cost. Because many environmental (including social and political) costs cannot be quantified, the environmental cost is usually treated as a "go" or "no go" type of factor. It can be assigned an arbitrarily large value for a particular right-of-way in order to exclude that right-of-way from consideration by the automatic expansion algorithm. Methods are needed for assigning realistic dollar values to environmental costs so that the model can treat these costs as it does conventional capital and operating costs.

The expansion logic

The planning logic is divided into two parts:

1) The Overload Logic
2) The Voltage Correction Logic

The overload logic utilizes the sensitivity matrices to find the least costly network changes to alleviate line overloads. This is a simple approach and can be classified as a heuristic method that treats the problem as a sequence of unconstrained minimization problems.

There are two assumptions made:

1) Transmission capacity of a branch can be increased by adding lines only.
2) Only specific type of lines or voltage levels that are provided to the program can be used in expanding the system.

In the absence of an input table containing types of lines to be chosen from, the line types already existing on rights-of-way are used during the line selection process.

The voltage correction logic

The voltage correction logic is initiated after all line overloads are alleviated. The steps are as follows:

1) The contingency tests are carried out and a vector is formed that shows the largest voltage magnitude deviations from the specified limits for every bus during the contingency tests.
2) From the reactive power flow equation, the adjustments to the bus reactive powers needed to bring the voltage magnitudes within the specified limits are calculated.

Line removals

As the network is developed through successive planning periods, lines added in earlier periods may become unnecessary. Therefore, a subroutine was developed to test the possibility of removing lines from the system. A line removal program checks the usefulness of lines after passage of a number of planning periods and removes unnecessary lines. This algorithm may be viewed as the reverse of contingency analysis, in that it tests the results of removing branches having the least effect on the system.

Planning studies

Several sample planning studies were carried out using network data for a model of the Pacific Northwest System, the IEEE 14-Bus Test System, and a 26-bus model of part of the Wisconsin Upper Michigan System. These are presented in the Appendices of the full report. Where real data were unavailable, arbitrary values were assumed. In practice, the planning engineer would have access to the necessary data and would be able to use the computer programs developed here to solve real, practical problems.

Conclusions and Recommendations

1. A simple automated method for network expansion has been developed. It is especially suited for studies of alternative schedules for expanding the generation and transmission of electricity.
2. The steps in the algorithm follow the logical steps carried out in practice by planning engineers.
3. No claim is made for the optimality of the plans produced by this method, but they will be similar to those obtained by planning engineers and the automated method will shorten and simplify the planning process.
4. The method has three new features:
   a. A network expansion technique which uses sensitivity matrices to obtain economical plans.
   b. Use of the "B" matrix from the fast-decoupled load-flow algorithm in an iterative procedure for adjusting bus reactive power to bring voltage within specified limits.
   c. An automatic contingency selection procedure that ranks branches according to their expected effect on the system, thus reducing the number of contingency studies required.
5. Of the two models developed, the non-iterative DC model is simpler and faster and convergency difficulties do not occur with certain ill-behaved networks. The AC model is more realistic and more flexible. It uses a more accurate network model and it provides information on voltage magnitudes as well as on load flows.
6. Interaction between the planner and the program is not only possible but necessary:
   a. New, updated information should be fed into the program regularly. The program cannot be expected to give satisfactory results over many planning periods unless it "knows" everything the planning engineers know.

b. A variety of generation and load schedules should be considered for the network under study.
c. Various ratings of network components should be considered: for example, emergency ratings, normal summer, normal winter, etc. Ratings on other components such as breakers or line traps may also limit the flow in a branch.
d. The reliability criterion incorporated in the program is a single contingency criterion. The user might want to examine other contingency cases. Generator outages and multiple line contingencies can also be simulated.
e. The program cannot introduce either new nodes or new rights-of-way into the system. The planner can represent potential but initially unused rights-of-way as lines of high impedance, and potential but initially unused nodes as nodes connected to the network by potential rights-of-way.
f. If abnormal plans result, the planner should consider alternatives such as lines of higher voltage, changes in transformer taps, or additional lines for voltage support.

7. Several avenues for future research are apparent:
   a. Further work on the load-flow algorithm should include transformer tap changing under load.
   b. Combining network reduction and network planning into one program would overcome the need for multiple editing programs and relax restrictions on the system size.
   c. The program should be modified to include other techniques for network reduction.
   d. Research is needed to implement sparse matrix techniques in the planning programs.
   e. Continued efforts are needed to quantify the broad range of environmental and social costs of transmission networks.

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The complete report, entitled "A Simple Transmission Network Planning Method: Wisconsin Power Plant Impact Study," (Order No. PB 84-199 553; Cost: $16.00, subject to change) will be available only from:
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