The first issue of PTI's "Newsletter" was published in June of 1975. While its purpose then and now is to convey technical information, this issue marks a change both in format and name. We think our readers will agree that the title "Power Technology" is more apt than "Newsletter".

LOAD FLOW: CONVERGENCE AND ACCURACY LIMITATIONS
T. E. Kostyniak — Senior Engineer
T. F. Laskowski — Senior Engineer
J. M. Undrill — Principal Engineer

Although load flow solutions for systems of 8000 buses and more are now routine, the computer time and resources they demand can be considerable. It is important when handling large load flow cases to avoid unproductive extra iterations and to stop unsatisfactory computer runs promptly. This requires a clear understanding of the convergence characteristics and precision limits of load flow calculations. These aspects of load flow solution work are examined in this article.

Three important aspects of the load flow solution process are:
- its inherent convergence characteristic given voltage estimates that are reasonably close to a solution
- the limit on its accuracy resulting from the numerical precision limitation of the digital computer
- its ability to adjust an initial voltage estimate, which may not be "close" to a solution, in a useful manner.

The majority of load flow programs use some form of Newton-Raphson solution technique. There are many variations of the technique, some recognizing the coupling of real and reactive power effects, and others using approximations in which the effects are assumed to be decoupled. The principles outlined here apply, in general, to all such load flow solutions.

The Newton-Raphson load flow solution methods proceed on three steps:
(a) Calculation of the mismatch at each bus on the basis of estimated bus voltages.
(b) Construction of a Jacobian matrix expressing mismatch in terms of a voltage correction vector.
(c) Solution of the large set of simultaneous linear equations involving the Jacobian for a vector of corrections to the voltage estimates.

This process normally converges towards a solution in which both the mismatches and the voltage correction vector are zero. Convergence is normally rapid but a variety of situations, such as a poor initial voltage estimate or unfavorable system loading, can cause the process to converge slowly or to diverge.

CONVERGENCE VERSUS ACCURACY

The convergence of the solution process is a function of the mathematical solution technique and the problem to which it is applied, but not of the computer in which the solution is executed. The accuracy that can be achieved is a function of the system being simulated and of the computer, but can be essentially independent of the mathematical solution technique.

In normal convergent cases the solution process reduces the mismatches in successive iterations until the precision with which the computer stores real numbers becomes the limiting

(Continued on page 2)

ANALYTIC METHODS IN STRATEGIC PLANNING
H. M. Merrill, Senior Engineer

Strategic planning is different from traditional planning. It addresses broader issues and looks for different kinds of answers. Strategic planning asks, "Where should we be going? What kind of an enterprise should we be?" Traditional planning is concerned with meeting objectives. Strategic planning is concerned with deciding what the objectives should be.

One of the most uncomfortable things a Chief Executive Officer has to do is weigh the conflicting interests of his constituencies. What is good for the rate payers is often bad for the shareholders. He also knows that uncontrollable events can tip the scales in favor of one plan or another, and he has had recent experiences where corporate directions that once looked good have turned sour. A Chief Executive Officer has access to vast amounts of data — and his organization can generate more data faster than it can be assimilated. The problem is not to create more data — it is to make sense out of what is available. And this "making sense" has to work with data that is inconsistent, not equally trustworthy, and never quite satisfying in terms of the questions being asked. Planners can help, but they have to change their methods. What is needed is not larger, more complicated, computer models. The real need is quite the opposite — it is for a simple way of structuring and attacking these problems.

How this is done will vary from organization to organization and from person to person. PTI has had considerable success in developing and applying methods built on three simple constructs: attributes, options, and uncertainties.

Attributes are measures of health of an organization, from the perspectives of various constituencies. For utilities, attributes might include measures of reliability, revenue requirements, capital needs, environmental impact, etc. These attributes frequently conflict: reducing environmental impact, for example, usually costs somebody money.

Options are potential decisions an organization might make.

Uncertainties are beyond the control of the organization — but some of them might have major impacts, as measured by the attributes.

Figure 1 illustrates the relationship between attributes, uncertainties, and options.

EXOGENOUS (RANDOM) VARIABLES

ENTREPRISE

DECISION VARIABLES

ATTRIBUTE VARIABLES

(Continued on page 4)
LOAD FLOW CONVERGENCE (cont'd. from page 1)

factor. This generally occurs in step (c) where the voltage correction vector is calculated by solving a large set of simultaneous linear equations. The magnitude of the numerical errors in the solution of the simultaneous equations in a given load flow case is substantially constant, while the true solution tends towards voltage corrections of zero. Because of this, the voltage correction vector will eventually become dominated by numerical errors arising in the simultaneous equation solution. Hence, if the iterative process is convergent it will eventually reach the point where successive iterations produce no further systematic reduction in mismatch. The level of mismatch at which this occurs depends upon both the precision of the digital computer and the admittances of the network. In general the limiting level of mismatch that is achieved will be higher for systems having buses at which the connected branches have a wide range of impedances.

The relationship between the two stages of the load flow solution process is illustrated by figure 1 which shows the behavior of a Newton-Raphson solution of a typical system of about 1650 buses. The graph plots the magnitude of the largest reactive power mismatch against iteration number.

Curve B of figure 1 shows the behavior of the same calculation when executed on an IBM computer, and curve C shows the behavior as obtained in a Prime computer. The behavior in the initial iterations is identical in the three computers, but the limiting mismatches reflect the differences in the precision with which the three machines store floating point numbers. All three machines use 32 bits to store a floating point number; but, because of differences in hardware design, they store numbers with differing precision, as summarized in Table I. It is apparent that the ratios between limiting mismatches shown by figure 1 are generally consistent with the ratios between the precision and truncation error levels of the computers.

The following remarks may be made about the two aspects of the load flow solution process, based on observation of the operation of our load flow programs on a very wide variety of power system problems:

(i) The inherent convergence of Newton-Raphson solution processes is not directly dependent on the number of buses in the power system model; that is, the largest mismatch can be reduced by essentially the same factor from iteration-to-iteration in an 8000 bus problem as in a 40 bus problem.

(ii) The causes of poor inherent convergence in large problems are the same as those in small cases; notably inadequate reactive power capacity, severe overloading of transformers or transmission lines, large ratios between the highest and lowest impedances of branches connected at a bus, and poor initial voltage estimates.

(iii) The limiting value to which the largest mismatch can be reduced does increase with increasing problem size because it is associated with numerical imperfection in the solution of simultaneous linear equations and this imperfection increases with increasing problem order.

Point (i) is illustrated by figure 2 which shows the convergence behavior of several representative and typically behaved load flow problems involving from 20 to 3950 buses. It is quite noticeable that the solution process is generally able to reduce the largest mismatch by a factor of approximately 10 in each iteration, until numerical errors overwhelm this inherent characteristic. One can certainly find problems that converge more slowly than those covered by figure 2, but the important point is that problem size, itself, is not a cause of poor convergence.

Figures 3 and 4 further illustrate the effect of computer precision. Figure 3 shows the behavior or real and reactive power mismatch in the solution (on a VAX computer) of a 2316 bus model of a large urban system with a particularly unfavorable mix of branch impedances. The limiting mismatches in this case are approximately 0.2 MW and 0.6 MVAR, and they are reached decisively after very good initial convergence. In this case the worst mismatch is a quite good indication of the overall quality of the solution in the urban part of the network; the several largest mismatches are as follows:

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<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>.02</td>
</tr>
<tr>
<td>3</td>
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<tr>
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<td>.00</td>
</tr>
<tr>
<td>10</td>
<td>.03</td>
</tr>
</tbody>
</table>

First consider curve A which applies to execution of the calculation on a VAX computer. The mismatch is reduced by a factor of about 10 in each of the first four iterations, and is 0.002 p.u. after the application of four voltage corrections. This initial convergence involves voltage corrections of the order of 0.1 p.u. in the first iteration, and of the order of 0.0001 p.u. in the fourth. In iterations after the fourth the successive voltage corrections do not produce clear reductions of mismatch; rather, the largest mismatch "dithers" in the region of about 0.002 p.u. The dithering of mismatch is associated with dithering of the voltage corrections in a band around 0.00007 p.u. This indicates that the numerical error introduced into the voltage corrections are of about this magnitude (0.00007 p.u.), and hence that true values of required voltage corrections smaller than this are swamped by the numerical error and rendered meaningless. Iterations 1 through 4, then, show that the solution converges nicely in this problem, while iterations 5 through 9 indicate that the precision with which the VAX computer stores floating point numbers limits the accuracy of the solution to a worst mismatch of about 0.002 per unit, or about 0.2 MVAR on a 100 MVA system base.
All of these mismatches are within an area containing branches with very low impedance in close proximity to branches of much higher impedance.

The above list of mismatches exhibits typical behavior in that the real power mismatches are generally significantly smaller than the reactive power mismatches.

Figure 4 illustrates a typical difficult case. Curve A of figure 4 shows the behavior of a solution of a 3952 bus problem. The solution is well behaved and readily reaches a precision limited largest mismatch of about 0.003 p.u. or 0.3 MVAR. Curve B in figure 4 shows the solution behavior when two previously disconnected generators, and three buses associated with them, are reconnected to the system. This addition creates a small ill-behaved subsystem and the inherent convergence of the solution becomes very slow at a mismatch level far above that associated with computing precision. In this case the largest mismatch is a poor indicator of the quality of the solution, as is illustrated by the following list of the 10 largest mismatches after the eighth iteration:

<table>
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<td>4.43</td>
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<td>10</td>
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</table>

The largest mismatches are very localized within the subsystem associated with the newly connected generators. The table indicates that the solution is quite acceptable, with the possible exception of the detailed results for two or three buses.
This situation where a very few buses have significant mismatch, while the great majority are solved to a very acceptable mismatch is quite common. Hence it is important for the engineer to examine the magnitude of the largest few mismatches, their location, and the magnitudes of the mismatches in key parts of the system. In many, if not most cases, it would not be worthwhile to continue iterating the solution simply to force the largest mismatch down to some stated tolerance value such as 0.1 MVA.

GETTING STARTED

While Newton-Raphson methods are quite reliable and predictable when launched from reasonably good initial voltage estimates, they are unpredictable and prone to divergence when given arbitrary voltage estimates such as a uniform \((1 + j0)\) voltage at each bus. Since such "flat-start" initial voltage estimates are necessary in handling new problem setups and in recovering from previously diverged solution attempts, it is important to have a way around the starting problem.

The usual way to overcome a starting problem with a Newton-Raphson solution is to use a few iterations of an alternative solution method to give a rough initial adjustment of the voltages which, presumably, will get them into the region from which the preferred solution method is able to start on a convergent path. A few iterations of the Gauss-Seidel method is often a good starting technique but, unfortunately, it cannot be used in systems having negative branch reactances.

Another good starting method is to use several iteration of a decoupled Newton-Raphson method such as the "fast-decoupled" method which separates real and reactive power effects and uses a series of simplifying approximations in building its Jacobian matrices. This iterative scheme, while it is a Newton-Raphson method, has a generally softer inherent convergence characteristic than the fully coupled methods, and is often able to converge from a flat start where the fully coupled method would diverge.

Figure 5 shows the behavior of the standard fully coupled Newton-Raphson method and the fast-decoupled Newton-Raphson method on a representative problem of about 1800 buses, which diverges when started with the standard method. Curve A shows the largest reactive power mismatch after each half-iteration of the fast-decoupled method. Convergence is good initially and remains good, though somewhat slow, as the initial large mismatch is brought below about 0.3 p.u. Curve B shows the largest mismatch as produced by starting with the fast-decoupled method and switching to the standard fully coupled method after two iterations, when the largest mismatch has been reduced from 40 p.u. to 3 p.u. The standard method shows the characteristic behavior indicated in figures 1 through 4, reducing the mismatch by a factor of about ten in each iteration.

We have found this relative behavior of fully coupled and decoupled Newton-Raphson load flow methods to be consistent over a broad spectrum of load flow problems.

USERS CHOICE

Experience with many widely varied load flow problems and many variations on the mathematical solution themes has shown that there is no one ideal load flow solution method, and no one proper way to address the difficulties that arise in load flow work. The proper approach is to try out the various available solution methods on the problem at hand, to properly recognize which of the factors described above is critical in each instance, and then to be prepared to change from one method to another as circumstances require. This is a very natural process with a modern computer and interactive program where the user has hands-on control.

ANALYTIC METHODS (cont'd from page 1)

An important step in strategic planning is to identify the interested constituencies and to define attributes that represent their concerns. Options are identified — and we have never seen a case where an organization, no matter how buffeted by fate, had nothing it could do. Key uncertainties must also be recognized.

This step represents major progress — having accomplished it, the problem has been identified! What follows can take a variety of forms, from back-of-the-envelope calculations to detailed computer studies. An example of the latter is described in a companion article in this issue.

Another example is not a typical utility problem. Suppose that an international agency has certain funds which can be invested in public works projects. The number of candidate projects far exceeds available funds. Which projects should be funded?

The first question that must be addressed is "That kind of things does the agency want to accomplish?" Attributes measure these, and might include:

- effect on local employment during construction
- new long-term employment opportunities created
- short and long term effect on other industries
- balance of payments effects
- likelihood of recovering investment

Options at first glance might be obvious — projects generally clamor for available funds. But the best options might be created by the agency. For example, building a cogeneration facility with joint funding from a local industry might be far more desirable than the small power plant that was originally proposed for agency financing.

Uncertainties measure such imponderables as government stability, local inflation rates, quality of project cost estimates and schedules, availability of other resources needed, etc.

Having formulated the problem in this way, a wide variety of tools can be employed to analyze it. Econometric models of economies and corporate models of potential entities could be employed in the same role as the production cost models used in the study reported elsewhere in this issue. Delphi methods, simple graphical techniques, variants of a celebrated 3 x 3 matrix, and other tools can be employed where they are appropriate.

PTI staff have had extensive involvement in strategic planning, and can provide:

- training seminars,
- software, and
- consulting services, as needed to solve a particular problem.
TRANSFER CAPABILITY OBJECTIVES: A STRATEGIC APPROACH

H. M. Merrill, Senior Engineer

Transfer capability, the ability to transmit power from one area to another, is a measure of the strength of a network. Determining transfer capability objectives is a strategic planning problem which requires trading off multiple, conflicting objectives.

A new methodology for finding this trade-off considers attributes, options, and uncertainties. See a companion article in this issue.

Description of the Methodology

The approach consists of the following steps:

• simulation of a relatively small number of plans used existing software.
• modeling and regression to compute attribute values for hundreds of thousands of plans.
• trade-off evaluations to select the plan which seems to offer the most desirable set of trade-offs among the various attributes.
• sensitivity studies to evaluate robustness.

Application and Illustration

The methodology described above has been applied to a large three-area interconnected system.

Figure 1 is a scatter plot of 1166 plans, consisting of permutations of available transmission options and in-service dates, in terms of two of the attributes. Each letter on the plot identifies one of the 1166 plans (since there are only 26 letters, each is used more than once). Several plans might be so close together, in terms of these attributes, as to occupy the same print position. When this occurs, a number identifies the number of such plans. The symbol "x" means more than 9.

The most interesting plans, in terms of these two attributes, are the ones with the lowest corridor impact and capital requirements (corridor impact is represented by an index where "less" is better). Plan "S", in the lower left, minimizes both of these attributes. This plan is the base case "do nothing" plan.

Figure 3 illustrates conflicts. No single plan simultaneously minimizes area A SO2 emissions and total capital requirements. The plans along the trade-off curve are the best in the sense that any plan remote from the curve can be improved upon, in terms of both attributes, by rejecting it in favor of a plan on the curve. The most interesting plans are those nearest the knee of this curve (roughly the region between plan "F" and plan "Z"). This is because plans remote from the knee in either direction are significantly worse than plans near the knee in terms of one attribute, and only slightly better in terms of the other. None of the plans near the knee correspond to the "do nothing" or "very high levels of transfer capability" plans which appear most attractive in Figures 1 and 2.

Figure 3 shows the same 1166 plans, plotted in terms of load probability (LOLP) and operating cost. The seven plans at the lower left of Figure 2 simultaneously minimize both of them. These seven plans involve very high levels of transfer capability. The conflict in objectives is apparent by comparing Figure 2 (which says "build very high levels of transfer capability") and Figure 1 (which says "do nothing").

A way was found to make simultaneous trade-offs involving more than the two attributes which can be shown on two-dimensional paper. It identified the two plans circled in Figures 1-3 as representing the best overall trade-off when six attributes were considered simultaneously. These plans could not have been selected by sequentially examining these figures, one by one.

The methodology described in this article is not a black box computer program which produces "the" answer. It isn't even a computer program. It is an organized approach to solving a very difficult problem.

Acknowledgements: Work described in this article was supported in part by EPRI under EP 1960-1.
NEW COURSE OFFERINGS

Three new short courses have been initiated this year by PTI. The Power Distribution Systems course was given in early June to a group of utility engineers in Schenectady and is scheduled again for November 26-30, 1984. Power System Scheduling and Operation is set for October 15-19 and the third new short course, Power System Planning Techniques, is to be given November 12-16, 1984.

The Power Distribution Systems course starts with a fundamental overview of the distribution system and continues to describe recent trends in system development. Topics covered in-depth include overcurrent and overvoltage protection, voltage control and metering, emergency conditions, distribution systems economics and automation and load management implementation and effects. This course, as well as the other two new offerings, is scheduled to last four-and-one-half days.

The Scheduling and Operation Course provides the participants with an understanding of current methods and techniques used in the scheduling of power generation systems for both economy and security. Fundamental areas such as economic dispatch are covered in the course, as are advanced topics like state estimation. Additional topics covered include practical implementations of the techniques in control center software and fuel scheduling. The text used is Power Generation, Operation and Control, by Wood and Wollenberg, John Wiley and Sons, Inc., 1984.

Power System Planning Techniques is a course which describes modern methods and techniques for addressing the current problems in utility bulk power planning. The topics covered include a general discussion planning, its objectives and the criteria used, an introduction to load forecasting methods, utility economic and financial analyses, reliability methods applied to generation and transmission systems and utility strategic planning concepts.

All three programs are also offered for "on-location" presentation at the offices of an electric utility. Further information may be obtained from Barbara Gnat, Administrative Assistant-Educational Programs.

FALL 1984 SHORT COURSE SCHEDULE
Courses to be presented at PTI offices in Schenectady, N.Y.

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<td>Power System Dynamics</td>
<td>Sept. 17-21, 1984</td>
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<td>Utility Economics &amp; Finance</td>
<td>Sept. 24-28, 1984</td>
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Special Presentations — 1985
Courses to be presented in Salt Lake City, Utah

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For further information and registration contact: Margaret R. Stambach, Manager, Educational Programs, Power Technologies, Inc., 1482 Erie Blvd., Schenectady, N.Y. 12301-1058, Telephone (518) 374-1220