RECENT ADVANCES IN SHORT CIRCUIT COMPUTATIONS

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I. INTRODUCTION

Significant breakthroughs in short circuit computations in the last five years resulted in a new generation of short circuit programs that are faster and more capable than traditional short circuit programs.

Most of the new capabilities resulted from improvement in the solution method. This paper will touch on four new short circuit algorithms published in years 1982 through 1985 (listed below in order of the papers' publication date):

- Method by Gross and Hong [1], in Pacific Gas and Electric Company's Short Circuit Program.
- Method by Han [2], in Bonneville Power Administration's Short Circuit Program.
- Method by Alvarado, Mong, and Enns [3], in the Electrocon Short Circuit Program.
- Method by Brandwajn and Tinney [4], in the ASPEN Short Circuit Program and the Systems Control Short Circuit Program.

The new solution methods brought about significant improvements in solution speed and scope of fault types, as well as the capability to handle very large networks. The new methods also led to other unrelated improvements, such as better component models and more realistic prefault voltage profiles.

This paper will explore these and other new program capabilities and their ramification on program usage by protection engineers. The paper begins with a definition of short circuit analysis in section 2. A review of the classical method for computing short circuits is given in Section 3. It is followed by a description of the new methods. The capabilities of the new short circuit programs are summarized in Section 4.

II. DEFINITION

A *short circuit analysis* is a steady-state simulation in which the power system is modeled as a linear network driven by constant excitation. The network is assumed to be a balanced 3-phase system, with the exception of small, localized changes in topology, which are referred to as *faults.*

III. THE CLASSICAL METHOD

The term "classical method" here refers to what was considered to be the standard technique for solving short circuits up to the late 1970s. Many production short circuit programs in use today are based on the classical method.

A review of the classical short circuit algorithm is given here with the aim of contrasting it with the new methods to be described in Section 4. Figure 1 illustrates the classical method, which has the following steps:

1. Build the system impedance matrix. (Note: The same basic method can also be implemented using the admittance matrix. In that case, steps 2 and 4 are identical to those of the new methods. See next section for details.)
2. Find a single-port Thevenin equivalent for each sequence at the faulted bus.
3. Compute the fault currents using the sequence equivalents.
4. Compute other network quantities of interest using the fault currents as compensating currents.

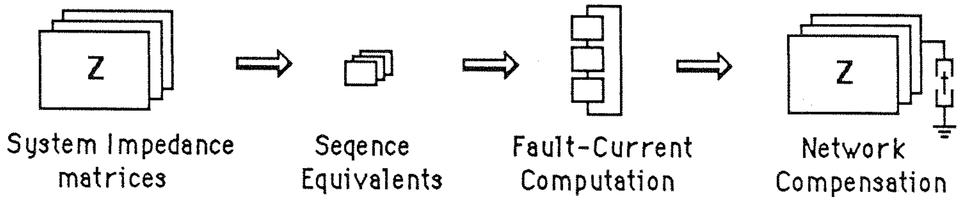


Figure 1: The four basic steps of the classical short circuit computation method.

The classical method models the network by means of the impedance matrix, **Z**. The impedance matrix is not sparse. Usually, for storage considerations, only a portion of **Z** is computed and stored in computer memory prior to the simulations.

The parameters of the single-port sequence equivalents in the second step are taken directly from the **Z** matrices. More specifically, the Thevenin impedances of the equivalents are the (k,k) diagonal terms in the respective **Z** matrix, where k is the index of the faulted bus (Figure 2).

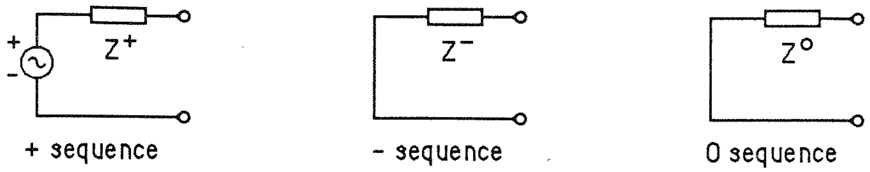


Figure 2: Single-port Thevenin equivalent used by classical methods. Z+, Z- and Z° are the Thevenin impedances.

The fault currents are computed by connecting the three sequence equivalents in series or in parallel. Figure 3 shows the well-known equivalent circuits for the common fault types [7].

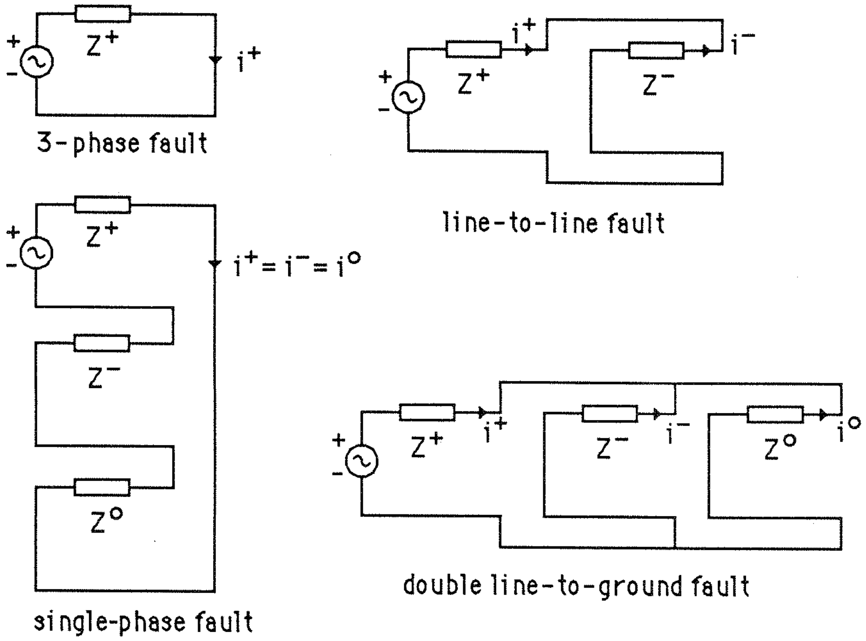


Figure 3: Fault currents in the classical method are computed from connecting the three sequence networks. The fault currents are denoted by i+, i- and i°.

In the final step, the change in bus voltages is computed by injecting the fault currents into the system. The change in voltage is equal to **Zi**, where **Z** is the unmodified impedance matrix of the system and **i** is the fault current. The theory behind this step is called network compensation. Network compensation is a powerful concept because it allows one to model the changes in network topology by injecting appropriate compensating currents into the unmodified network.

IV. NEW SOLUTION METHODS

From a very broad perspective, the new short circuit algorithms follow a method of attack that is quite similar to that of the classical method. The major steps of the new methods are these (Figure 4):

1. Build and factor the system admittance matrix.
2. Build a small sequence equivalent around the faulted buses.
3. Compute the post-fault solution of the equivalent network.
4. Compute the compensation currents and use them to compute other network quantities of interest.

These steps are described more fully in the following.

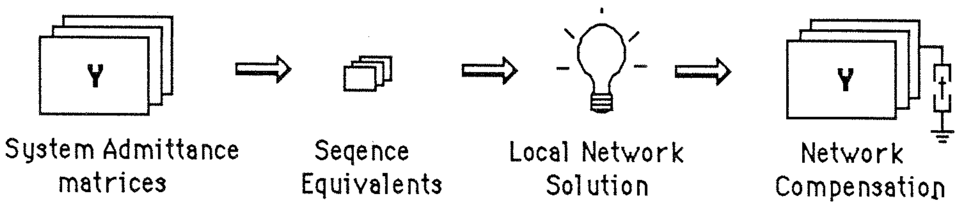


Figure 4: Four basic steps of the new short circuit computation method.

Admittance Matrix

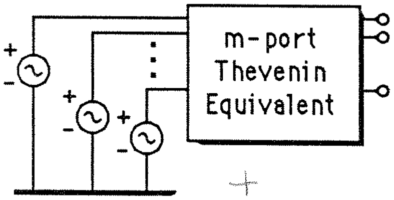
All the new short circuit methods employ the nodal-admittance-matrix formulation of the network. The admittance matrix **Y** has several important advantages over the impedance matrix that is used in the classical method:

- Sparsity — The admittance matrix is sparse. In most cases over 95% of the matrix elements are zeroes. The sparsity is preserved during factorization by sparsity-directed reordering. In contrast, the impedance matrix used by traditional short circuit methods is full. The use of admittance matrices in the new methods obviates the requirement of specifying a "study area" or a set of "retained buses" prior to a fault study. Users of the new programs can apply faults anywhere in the system.
- Ease in building and modification — The admittance matrix is much simpler to build and to modify than the impedance matrix. The zero-sequence mutual coupling can be incorporated directly, without approximation, into the admittance matrix. None of the new methods uses iterative schemes for handling mutually coupled groups.

Usually two admittance matrices are built for the entire network: one for the positive sequence and one for the zero sequence. The transpose of the positive-sequence admittance matrix also serves as the admittance matrix of the negative sequence. It is also possible to use a separate admittance matrix for each sequence.

Sequence Equivalent

The sequence equivalents in the new methods are m-port Thevenin equivalents around the faulted buses (Figure 5). The size, m, is a function of the number and type of the simultaneous faults being simulated, and it is usually very small (5 or less). The m-port equivalents is a direct extension of the single-port equivalents used by the classical method for standard bus faults (for which m=1).



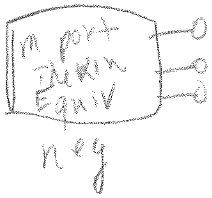


Figure 5: M-Port Thevenin equivalents used in the new methods. The voltage sources on the left- hand side represent the open-circuit voltages. The ports or terminals of the equivalents are shown on the right.

The Thevenin equivalents can be computed with sparse vector methods "on the fly" [5], or they can be precomputed in the form of a sparse inverse [6]. Both methods are extremely efficient.

Local Fault Solution

The network solution for the faulted buses is computed based on the sequence equivalents and the characteristics of the faults. The end results of this step are the post-fault voltages in the immediate vicinity of the faults and compensating currents which can be used to compute other desired output quantities. The four new short circuit methods differ substantially in this step.

Han's Method

Han's method [2] for simultaneous faults is an extension of the idea of generalized fault diagrams [7]. In Han's method, each of the faults is characterized by boundary conditions on the voltage and currents on the respective terminals of the sequence equivalents. An example of the boundary conditions is that for a single-line-to-ground fault, two of the phase currents are zero, and the voltage of the faulted phase is equal to the voltage drop across the fault impedance. The voltage and current of the faulted buses are computed from a simultaneous solution of the boundary conditions and the network equations of the sequence equivalent.

Gross's Method

Gross's method [1] requires the separation of the simultaneous faults into balanced modifications and unbalanced modifications. Conceptually, these two classes of faults are treated in two steps. The differentiation between balanced and unbalanced modifications is a good idea because it separates the balanced modifications, which can be accounted for by working separately with each of the sequences, from unbalanced modifications, which create coupling between the sequence networks. This ideas was taken up in the two later papers [3,4].

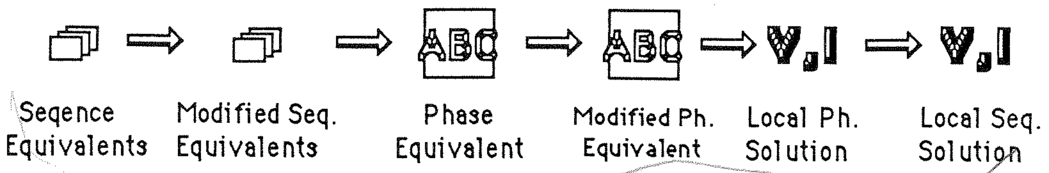
The effects of each of the unbalanced modifications in Gross's method are represented by compensating current injections into the three sequences. These compensating currents are functions of the fault type. For example, the compensating current for a single-line-to-ground fault is the same in all three sequences, and its value is a function of the prefault voltages, the fault impedance and Thevenin impedances. Gross's method combines these currents for the set of simultaneous faults with the effects of balanced modifications to produce a single set of compensating currents.

A limitation common to the methods by Gross [1] and Han [2] is that the fault types that a program can handle are restricted to a limited set for which the effects on the sequences have been precomputed (usually in the form of formulas) and stored in program memory. In Gross's method, the effects of each fault type on the sequence equivalent must be precomputed in the form of compensation currents; in Han's method, the effects of each fault type must be precomputed in the form of boundary conditions. Moreover, these two methods have great difficulties in handling faults that span between different ports of the equivalent — for example, a short circuit between the phases of two or more buses.

Methods of Alvarado and Brandwajn

The latest methods by Alvarado [3] and Brandwajn [4] are completely general in that they are capable of solving practically any fault scenario. The power of these methods comes from their ability to solve the post-fault voltages and currents in phases rather than in sequences.

Figure 6 shows the details of the local fault solution used by Alvarado [3] and Brandwajn [4]. The methods begin by computing an m-port sequence equivalent for each sequence, as before. The methods then call for a modification of the sequence equivalents to take into account the balanced network modifications, followed by a transformation of the sequence equivalents into the phase domain. The resulting phase admittance matrix and current injections are further modified to reflect the unbalanced changes in network topology.



[illegible] with local network solution

Figure 6: Details of the local network solution used in [3] and [4], showing the intermediate step in which the faults are simulated in the phase domain.

Methods for manipulating the phase admittance matrix to simulate unbalanced network modifications are well known and have been used in the Electromagnetic Transients Program (EMTP) for over a decade. It is known, for example, that a direct short between two phases can be modeled simply by adding the two corresponding rows and columns of the admittance matrix, and the corresponding current injections on the right-hand side.

The phase voltages and currents are computed by solving the modified phase admittance matrix equation. The local network solutions in phases are converted back to sequences only at the end of this step. The solution of post-fault voltages in phases in an intermediate step was the major breakthrough that finally freed the short circuit program from any restrictions in the types of faults that it can simulate.

Network Compensation

All four new short circuit method use the compensation method [8] to compute the network quantities requested by the user. The compensation method used by the new methods is a direct extension of the compensation method used in the classical method.

In Gross's method, the compensating injections are given directly by the local network solution. In the other three methods, the compensating injections are computed in a simple way using the local post-fault voltage solution, the sequence equivalents, and the prefault current injections.

The compensation method in the new short circuit programs are extremely efficient because the sparse vector methods make it possible to selectively compute the voltages needed for the output and avoid the calculation of unwanted network quantities.

V. NEW CAPABILITIES

This section describes some of the new capabilities in short circuit programs. The purpose here is to convey a sense of the new directions in short circuit computations. The description is not specific to any one implementation.

Simultaneous Faults

The salient feature that sets the new methods apart from traditional methods is the ability to simulate simultaneous faults. Figure 7 shows a simple example of a simultaneous fault where a "stuck breaker" scenario is modeled by a phase-open fault and a line-end fault. Figure 8 shows a much more complicated scenario. These and other simultaneous faults can be handled easily by the new methods.

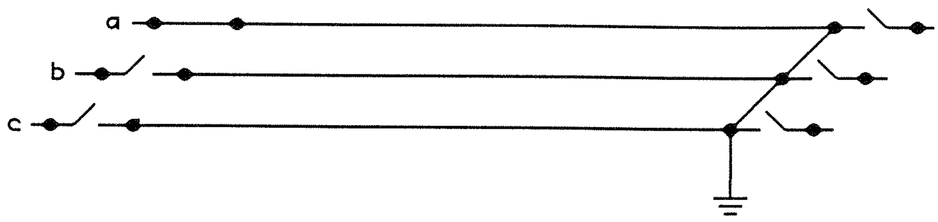


Figure 7: A "stuck breaker" scenario represented by the simultaneous application of a phase-open fault and a line-end fault.

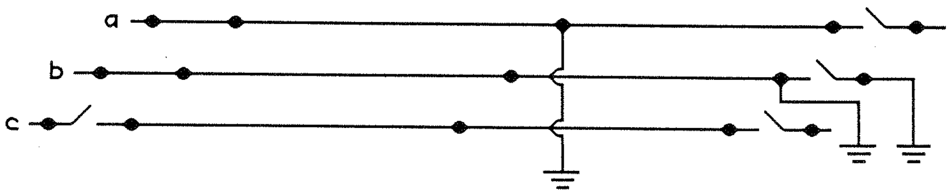


Figure 8: A complicated, but improbable, scenario involving the simultaneous occurrence of (from left to right) a single-phase-open fault, an intermediate single-phase-to-ground fault, a single-phase-to-ground line-end fault, and a single-phase-to-ground bus fault, along the length of a transmission line that is part of a mutually coupled group.

The major benefit of the simultaneous-fault capability for protection engineers is the ability to duplicate many actual faults and field tests without resorting to more complicated programs such as the EMTP. Of course the short circuit program, even with the most advanced algorithm, is not a substitute for the EMTP. But for studies where the balanced 3-phase-network assumption is appropriate, the new short circuit programs do offer a viable alternative.

System Modeling

The improvements in the solution method were accompanied by equally impressive improvements in component modeling in short circuit programs. (It should be emphasized that the new solution methods were only the catalyst that brought about this improvement in modeling; the new methods could have been implemented without the new models.) The following is a representative list of new models:

- Two- and three-winding transformer models that take into account the magnetizing impedance and 30° phase shift between wye-delta windings. Ideally, the program accepts the voltage taps and short circuit impedances as input parameters and does not require the use of fictitious center nodes for 3-winding transformers.
- Two- and three-winding auto-transformer models that have the same capabilities as regular transformer models.
- Phase shifter models that take into account the actual phase shift and magnetizing impedance.
- shunt and load models.
- Generator models that have the capability to model winding resistance and neutral impedances.
- Mutually coupled line models that accept very large groups and take into account the capacitive coupling between lines.

The new models bring the modeling complexity in short circuit programs on par with that of power flow, transient stability and other utility programs.

The improved component models make the short circuit programs more accurate and easier to use. With the improved modeling it is now possible, for example, to give the user directly the circulating current in delta windings and neutral currents in auto-transformers, in amperes. This was not possible in traditional short circuit programs where the lines, transformers and phase shifters all shared the same branch model.

Prefault Voltage Profile

Most traditional short circuit programs assume that all the buses have a voltage magnitude of 1.0 per-unit and an angle of 0° before the faults are applied. Such a flat voltage profile is not physically possible in a system with loads and shunts. Those who have modeled loads and shunts in a traditional short circuit program may have noticed that the contributing branch currents do not sum to zero when a fault is applied to a bus that has a load or a shunt.

Other short circuit programs allow the users to input directly the prefault voltage magnitude and angle at each bus and calculate the post-fault solution based on these voltages. This scheme is an improvement over the flat-voltage assumption, but it also has problems satisfying Kirchhoff's current law when the user does not input a valid power flow solution as the initial condition.

One way a short circuit program can avoid this problem is to calculate its own prefault voltages using the values inputted by the user only as estimates for establishing the current injections for generators and the shunt admittance for loads. The prefault voltages calculated this way should agree with the voltages inputted by the user if they were taken from a power flow solution of the same network. Otherwise the two sets of voltages may differ substantially.

Most new short circuit programs employ one or more of the above schemes as options for the starting voltage profile. Increasingly, the flat-voltage assumption is being abandoned in favor the most realistic power-flow voltage profile. Some utilities have already implemented mechanisms for transferring the power flow solutions to the short circuit program. Figure 9 is an example of such an interface.

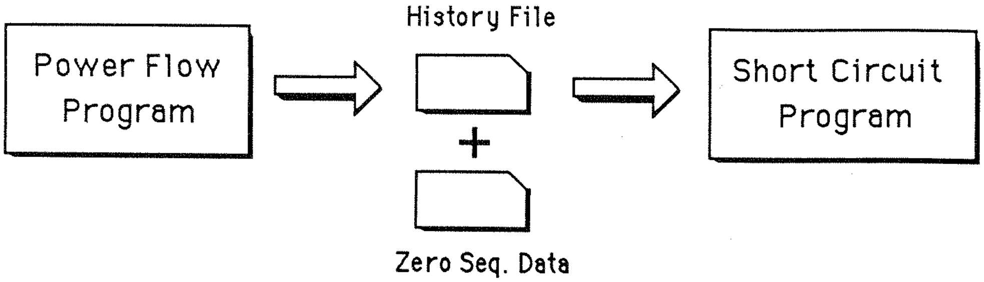


Figure 9: An automatic interface between a power flow program and a short circuit program. First the power flow program is run. The voltage solution of the power flow and the positive-sequence data are written out to a History File. A Data Preparation Program (not shown) then combines the information in the History File with additional zero-sequence data to produce an input file for the short circuit program.

The principal benefit of starting from a power flow solutions is improved accuracy. Utility experience indicates that the difference in short circuit current between a flat start and a power-flow voltage profile can differ by as much as 10% in some cases. The 10% change is significant if the equipment is operating near its limit.

The ability of the short circuit program to accept power flow solutions raises a number of institutional and technical issues:

- Protection engineers may have to work closely with transmission planners to maintain a consistent company-wide database for power flow and short circuit programs.
- Protection engineers may have to consider several power flow solutions — such as heavy- and light-load cases — as initial conditions for the short circuit studies.

There is also a need for consistency in modeling between the power flow program and the short circuit program. The most glaring inconsistency between the two programs today is the power flow program's inability to model the 30° phase shift of wye-delta transformers. To remedy this problem will require the modification of the power flow program.

Solution Speed

The discovery of the new short circuit methods in the early 1980s coincided with the development of the sparse vector methods [5], which are very efficient algorithms for solving the sparse matrix equation $\mathbf{A}\,\mathbf{x} = \mathbf{b}$, when a) the right-hand-side vector $\mathbf{b}$ has a large number of zeroes, and/or b) only a small number of the unknowns in the vector $\mathbf{x}$ are wanted.

The sparse vector methods turned out to be almost tailor-made for two otherwise time-consuming operations in the new short circuit algorithms: the computation of the sequence equivalents, and the computation of the post-fault voltages. The combination of the sparse vector methods and the new short circuit algorithms resulted in new short circuit programs that are 5 to 10 times faster than traditional programs, notwithstanding the added complexity in component modeling and input/output processing in the new programs.

VI. CONCLUSION

Four new solution methods developed in the last five years have greatly expanded the capabilities of short circuit programs. The newest short circuit methods can handle one or more arbitrarily complex short circuits that occur simultaneously. The major challenge facing those implementing the new methods is how to facilitate this new capability without making the program too complex and difficult to use.

This paper described four new short circuit algorithms. Two of the new methods by Gross and Han handle the unbalanced network modifications in sequences. They are less flexible in comparison to the later methods by Alvarado and Brandwajn which handle the unbalanced network modifications in the phase domain. The recently-developed sparse vector methods were also shown to be crucial to the efficiency of the new short circuit programs.

The implementation of the new methods was accompanied by significant improvements in the starting-voltage assumption and in the modeling of loads, shunts, transformers and phase shifters. These new features make the new short circuit programs more accurate and much easier to use.

The capability, accuracy and speed of the new short circuit programs represent significant improvements over the traditional short circuit programs. In the near term, protection engineers will benefit from the improved models and input/output processing, as well as the ability to simulate simultaneous faults.

The short circuit program is also a major component of computed-aided relay coordination programs. The speed of the new short circuit methods will be crucial in making interactive relay coordination on a small computer workstation a reality in the near future.

REFERENCES

[1] G. Gross and H.W. Hong, "A Two-Step Compensation Method for Solving Short Circuit Problems," *IEEE Trans. on PAS*, pp. 1322-31, June 1982.
[2] Z.X. Han, "Generalized Method of Analysis of Simultaneous Faults in Electrical Power Systems," *IEEE Trans. on PAS*, pp. 3933-42, October 1982.
[3] F.L. Alvarado, S.K. Mong, and M.K. Enns, "A Fault Program with Macros, Monitors, and Direct Compensation," *IEEE Trans. on PAS*, pp. 1109-20, May 1985.
[4] V. Brandwajn and W.F. Tinney, "Generalized Method of Fault Analysis," *IEEE Trans. on PAS*, pp. 1301-06, June 1985.
[5] W.F. Tinney, V. Brandwajn and S.M. Chan, "Sparse Vector Methods," *IEEE Trans. on PAS*, pp. 295-301, February 1985.
[6] K. Takahashi, J. Fagan and M.S. Chen, "Formulation of a Sparse Bus Impedance Matrix and Its Applications to Short Circuit Study," *Proceedings of the PICA Conf.*, pp. 63-69, June 1973.
[7] P. Anderson, *Analysis of Faulted Power Systems*, Ames, Iowa: The Iowa State University Press, 1973.
[8] O. Alsaç, B. Stott and W.F. Tinney, "Sparsity Oriented Compensation Methods for Modified Network Solutions," *IEEE Trans. on PAS*, pp. 1050-1060, May 1983.