PQSoft Case Study

General Reference
Modeling for Voltage Variation Analysis

Document ID:	PQS0307	Date:	February 4, 2003
Customer:	N/A	Status:	Completed
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Keywords:

Power Quality Category	Voltage Variations		
Solution	Reduce Utility Faults	Power Conditioning	Custom Power Devices
Problem Cause	Voltage Sags	Interruptions	Outages
Load Type	Adjustable-Speed Drives	Power Electronics	
Customer Type	Utility	Industrial	Commercial
Miscellaneous1	Simulations	Measurements	Voltage Sags
Miscellaneous2	Fault	Undervoltage	Interruption
References			

Abstract:

Voltage variations, such as voltage sags and momentary interruptions are two of the most important power quality concerns for customers. Voltage variations and interruptions are inevitable on the power system. The most important of these variations occur during fault conditions on the power system. Since it is impossible to completely eliminate the occurrence of faults, there will always by voltage variations to contend with.

The document provides an overview of system modeling for voltage variation studies.

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GLOSSARY AND ACRONYMS

ASD	Adjustable-Speed Drive
CT	Current Transformer
EMTP	Electromagnetic Transients Program
HVAC	High-Voltage Air Conditioning
MOV	Metal Oxide Varistor
PF	Power Factor
PWM	Pulse Width Modulation
TVSS	Transient Voltage Surge Suppressors

INTRODUCTION

Voltage variations, such as voltage sags and momentary interruptions are two of the most important power quality concerns for customers. Customers understand that interruptions cannot be completely prevented on the power system. However, they are less tolerant when their equipment misoperates due to momentary disturbances that can be much more frequent than complete outages. These conditions are characterized by short duration changes in the rms voltage magnitude supplied to the customer. The impact to the customer depends on the voltage magnitude during the disturbance, the duration of the disturbance, and the sensitivity of the customer equipment.

Voltage variations and interruptions are inevitable on the power system. The most important of these variations occur during fault conditions on the power system. Since it is impossible to completely eliminate the occurrence of faults, there will always by voltage variations to contend with. This chapter describes some of the concerns associated with short duration voltage sags and interruptions. Voltage swells can also be associated with fault conditions but these short duration overvoltages are usually not severe and problems are uncommon.

Power quality complaints occur either when the customer has equipment that is very sensitive to these voltage sags and is critical to the overall process or when the frequency of occurrence of the interruptions or sags is interpreted as being unacceptable.

On the utility system, protective systems are designed to limit damage caused by unusual events like faults or lightning strikes, and to localize the impact of such events to the smallest number of customers. This is accomplished with overcurrent protection devices, such as reclosers, sectionalizers, and fuses.

MODELING FOR VOLTAGE VARIATION ANALYSIS

Analysis Methods

Load Flow Programs - Load flow is the terminology used to describe the analysis of the flow of power from one or more sources to loads consuming energy. When the system is radial, power flows directly to the load. However, most systems today are more complex and contain a network of parallel and series paths over which power can flow.

Computer programs used to solve load flows are divided into two types - static and dynamic (real time). Most load flow studies for system analysis are based on static network conditions. Real time load flows are primarily used for optimization of generation, VAr control, dispatch, losses, and tie line control.
A load flow solution gives the power flow in all branches for a given set of operating conditions. It represents a steady state in which the influential parameters are in balance and a solution has been found. A load flow study is a collection of such solutions made when certain equipment parameters are set at different values.

A variety of system conditions can be evaluated, including contingency conditions, such as the loss of a transmission line, generator, transformer, or load. This type of analysis will often identify conditions that may cause equipment problems. In addition, analysis of this type is very useful for determining the optimum size and location of transmission and distribution capacitor banks. Digital computer programs are used extensively in load flow studies due to the complexity of the calculations involved.

Typical load flow program input and output data is provided in the following example.

```
                     FIVE BUS SAMPLE SYSTEM
Reference Stagg and El-Abiad "Computer Methods in Power System Analysis"
McGraw-Hill 1968; pages 283-292
          .0001                                                        1.4
2   1North       1.06
    2South                20.0  10.0  40.0  30.0
    3Lake                 45.0  15.0
    4Main                 40.0   5.0
    5Elm                  60.0  10.0
 9999
              1        2 0.02  0.06  6.0
              1        3 0.08  0.24  5.0
              2        3 0.06  0.18  4.0
              2        4 0.06  0.18  4.0
              2        5 0.04  0.12  3.0
              3        4 0.01  0.03  2.0
              4        5 0.08  0.24  5.0
           9999


                     FIVE BUS SAMPLE SYSTEM
 Reference Stagg and El-Abiad "Computer Methods in Power System Analysis"
 McGraw-Hill 1968; pages 283-292
                         POWER FLOW SUMMARY

   ------ FROM ------    -------- TO ------
    BUS      BUS          BUS      BUS            P          Q         S    %
     #      NAME           #      NAME          (MW)       (MVAR)     (MVA) RATNG
      1  North              2  South            88.858     -8.583   89.272    .0
      1  North              3  Lake             40.721      1.157   40.738    .0
      2  South              1  North           -87.448      6.152   87.664    .0
      2  South              3  Lake             24.694      3.545   24.947    .0
      2  South              4  Main             27.936      2.961   28.093    .0
      2  South              5  Elm              54.824      7.343   55.313    .0
      3  Lake               1  North           -39.529     -3.012   39.644    .0
      3  Lake               2  South           -24.342     -6.783   25.270    .0
      3  Lake               4  Main             18.877     -5.198   19.580    .0
      4  Main               2  South           -27.495     -5.927   28.126    .0
      4  Main               3  Lake            -18.842      3.208   19.113    .0
      4  Main               5  Elm               6.333     -2.284    6.733    .0
      5  Elm                2  South           -53.698     -7.167   54.174    .0
      5  Elm                4  Main             -6.303     -2.833    6.910    .0

                                      GENERATION SUMMARY


    BUS         BUS     Pgen      Qgen      Qmin      Qmax     Vmag    Vsch
    NAME         #      (MW)     (MVAR)    (MVAR)    (MVAR)     (pu)    (pu)

 North            1   129.580    -7.427      .000      .000    1.06    1.06 S
 South            2    40.000    30.000      .000      .000    1.05     .00

 System MVA base =     100.00
 Maximum # of itterations =  1000   Itterations Used =    14
 Mismatch Tolerance (pu) =    .000100
 Acceleration Factor = 1.40
 # of Buses               5
 # of Branches            7
 # of Unique Branches     7
                                     MW       MVAR
               TOTAL POWER INPUT   169.58     22.57
                     TOTAL  LOAD   165.00     40.00
             TOTAL LINE CHARGING              31.18
                      TOTAL LOSS     4.59     13.76
              ALGEBRAIC MISMATCH     -.01      -.00

          SWING GEN (inc in tot)   129.58     -7.43  (Bus #    1)
       SHNT LD (inc in tot,+cap)      .00       .00
            MAXMIMUM MW MISMATCH      .01       .01  (Bus #    3)
          MAXMIMUM MVAR MISMATCH      .01       .01  (Bus #    3)
```

Short Circuit Programs - A power system short circuit analysis can be performed to determine any of the following:

- Calculation of system fault current duties (first cycle ratings, withstand ratings)
- Selection and setting of protective devices
- Evaluation of current flows for various system faults
- Determination of bus voltages for various system faults

In general, short circuit programs use symmetrical component analysis techniques, thereby allowing the investigation of unsymmetrical faults and mutual coupling. Digital computer programs using symmetrical components are especially useful for simulating large complex networked systems.

Typical short circuit program input and output data is provided in the following example.

```
?
  1
 04/01/93  EXAMPLE SHORT CIRCUIT STUDY
?
 37
   0     784       0.00  1.69  0.00  6.45
   0     665       0.00 13.75  0.00 15.85
   0     664       0.00  2.88  0.00  7.75
 784     225       1.34  3.46  1.34  3.46
 225     665       0.05  0.10  0.05  0.10
 225     324       0.59  1.32  0.59  1.32
 324     024       0.00  0.01  0.00  0.01
 024     361       5.20 52.00     X     X
   0     361          X     X  5.20 52.00
 023     361       5.20 52.00     X     X
   0     361          X     X  5.20 52.00
 323     023       0.64  1.44  0.64  1.44
 323     664       0.77  1.85  0.77  1.85
 361     101       1.55  5.29  1.55  5.29
 101     401       0.00 304.0     X     X
   0     401          X     X  0.00 304.0
 401     225          X     X     X     X
9999
 38
 784     EQUIV BUS #1
 225     TAP POINT #1
 324     FALSE BUS #1
 024     XFMR HIGH #1
 023     XFMR HIGH #2
 323     TAP POINT #2
 664     EQUIV BUS #2
 665     EQUIV BUS #3
 361     XFMR LOW  #1
 101     SUB #1 13.8
 401     SUB #1 480
9999
 40                          511
 023
 024
9999
 30
?
 30
?
```

```
1 04/01/93  EXAMPLE SHORT CIRCUIT STUDY
+                                                                                      BASE KV= 138.000 KV
-                                           X------B U S   F A U L T  (LINE OPEN)-----X  X-------L I N E   E N D   F A U L T-------X
                                            X--------10-G  FAULT--------X X-30  FAULT-X  X--------10-G  FAULT--------X X-30  FAULT-X
+                                                     /                      /                     /                      /
                                            Q BUS VOLTS  X--AMP  FLOWS--X Q BUS    AMP   Q BUS VOLTS  X--AMP  FLOWS--X Q BUS    AMP
                                             E1     E0    2I1+I0     I0   VOLTS    FLOW   E1     E0    2I1+I0     I0   VOLTS    FLOW
0         N O   L I N E S   O U T             +---23---X---+  X-------------10-G FAULT-------------X  30  FAULT
+                                                                            /                         /
                                              (XFMR HIGH #2)  TOTAL AMPS  E1    E0    Z1(PU)  Z0(PU)  TOTAL AMPS
 X-------C O N T R I B U T I O N S-------X    +------------+   5438.6     .741  .482   .0599   .1113   6988.97 MAGNITUDE
 X-----P BUS-----X  X-----Q BUS-----X CKT                      -80.01      .88  2.71   77.49   82.72    -77.49 ANGLES
  BUS     NAME       BUS     NAME     I.D.
                                                                                     Z1=  .0130+J  .0584              X1/R1=    4.51
                                                                                     Z0=  .0141+J  .1104  (2X1+X0)/(2R1/R0)=    5.68
   23 XFMR HIGH #2   361 XFMR LOW  #1        .864   .000   197.7      .0   .476   381.2
                                         1    .45    .00  -86.40     .00    .41  -83.88
   23 XFMR HIGH #2   323 TAP POINT #2        .804   .417  5242.1  1812.9   .249  6610.3
                                         1   -.27   5.40  -79.77  -80.01 -11.09  -77.13
0-----------------------------------------------------------------------------------------------------------------------
0         N O   L I N E S   O U T             +--401---X---+  X-------------10-G FAULT-------------X  30  FAULT
+                                                                            /                         /
                                              ( SUB #1 480 )  TOTAL AMPS  E1    E0    Z1(PU)  Z0(PU)  TOTAL AMPS
 X-------C O N T R I B U T I O N S-------X    +------------+    128.0     .655  .310  3.3815  3.0400    123.72 MAGNITUDE
 X-----P BUS-----X  X-----Q BUS-----X CKT                      -89.44      .13   .56   89.18   90.00    -89.18 ANGLES
  BUS     NAME       BUS     NAME     I.D.
                                                                                     Z1=  .0483+J 3.3811              X1/R1=   70.03
                                                                                     Z0=  .0000+J 3.0400  (2X1+X0)/(2R1/R0)=  101.52
  401 SUB #1 480     101 SUB #1 13.8         .965   .000    85.4      .0   .899   123.7
                                         1    .27    .00  -89.44     .00    .82  -89.18
  401 SUB #1 480       0 REFERENCEBUS       1.000   .000    42.7    42.7  1.000      .0
                                         1    .00    .00  -89.44  -89.44    .00     .00
  401 SUB #1 480     225 TAP POINT #1        .998   .000      .0      .0   .994      .0
                                         1    .02    .00     .00     .00    .06     .00
  401 SUB #1 480     784 EQUIV BUS #1        .999   .000      .0      .0   .998      .0
                                         1   -.00    .00     .00     .00   -.01     .00
  401 SUB #1 480     665 EQUIV BUS #3        .998   .000      .0      .0   .994      .0
                                         1    .02    .00     .00     .00    .05     .00
  401 SUB #1 480     323 TAP POINT #2        .998   .000      .0      .0   .993      .0
                                         1    .02    .00     .00     .00    .06     .00
  401 SUB #1 480     664 EQUIV BUS #2        .999   .000      .0      .0   .996      .0
                                         1    .00    .00     .00     .00   -.00     .00
    0 REFERENCEBUS   665 EQUIV BUS #3        .998   .000    12.0      .0   .994    17.4
                                         1    .02    .00   80.17     .00    .05   80.42
    0 REFERENCEBUS   664 EQUIV BUS #2        .999   .000    42.3      .0   .996    61.3
                                         1    .00    .00   90.56     .00   -.00   90.81
    0 REFERENCEBUS   784 EQUIV BUS #1        .999   .000    31.3      .0   .998    45.4
                                         1   -.00    .00   94.55     .00   -.01   94.80
  225 TAP POINT #1   665 EQUIV BUS #3        .998   .000    12.0      .0   .994    17.4
                                         1    .02    .00  -99.83     .00    .05  -99.58
  225 TAP POINT #1   784 EQUIV BUS #1        .999   .000    31.3      .0   .998    45.4
                                         1   -.00    .00  -85.45     .00   -.01  -85.20
  323 TAP POINT #2   664 EQUIV BUS #2        .999   .000    42.3      .0   .996    61.3
                                         1    .00    .00  -89.44     .00   -.00  -89.19
```

Study Procedure

The following is a suggested procedure for using a short circuit simulation program to perform fault studies:

- Identify Study Objectives. The objectives will dictate the modeling requirements and the variables to be investigated.
- Develop System Model. The extent of the system model depends on the objectives of the study. Very often, however, utilities maintain short circuit data files for the entire system.
- Draw Connection Diagram and Label Buses. The bus labels will be used in the data file for identification.
- Calculate Impedance of Component Models. Impedance for power system elements are determined and converted to a common base (i.e. % @ 100 MVA).
- Run Solution Cases. The type of fault to be investigated must be determined before completing this step. Often, three-phase and single-line-to-ground faults are selected for protective relay settings. However, it may be desirable to simulate a fault involving unbalanced conditions.
- Estimate Expected Results. This can be done from previous studies, from the literature, or from hand calculations. It is important to know what to expect from the simulation so that major problems can be identified quickly.
- Sensitivity Analysis for Important Variables. Important variables from the simulation should be evaluated to determine their impact on results. These could include source strength, transformer size, line length, operating conditions, etc.
- Solution Evaluation. Possible solutions include utility and customer options (power conditioning), as well as manufacturing design enhancements. Simulations and economic considerations are evaluated on a case-by-case basis to determine the option solution.

Computer Solution and Component Models

Variations in the fundamental frequency voltage can be evaluated with conventional analysis tools. Power flow programs provide system voltages as a function of load levels on the system. Fault programs (short circuit analysis) can calculate system voltage profiles during fault conditions for analysis of voltage sag concerns.

Analysis of large networks, such as those found in utility transmission and distribution systems, requires the use of computers and specialized programs. Hand calculations are suitable for estimating the characteristics of very simple circuits, but accurate calculation of voltage, power flows, or short-circuit currents throughout a utility system would be impractical without the use of a simulation program. Unlike power system transient analysis (using a program like the EMTP), options for fundamental frequency simulations are abundant. Many vendors provide short circuit and load flow programs and a number of utilities have even written their own simulation tools. In addition, due to the large number of system configurations and study types possible, no standards exist for specific models for all circumstances. One factor that may need to be addressed during a voltage variation study is model reduction (system simplification). All power system models will include some level of system reduction, such as equivalent impedance for a neighboring utility, however, no specific rules exist for an optimum method. Several factors that affect system reduction include:

- model development and simulation time (not a significant factor)
- limitations of the simulation program (i.e. number of busses)
- problem definition
- accuracy of system equivalents (it is the user’s responsibility to verify the model after each reduction)

Program documentation should be utilized for guidance on component modeling and simulation rules.

Voltage Sag Evaluations

The most general approach to voltage sag analysis (illustrated in Figure 1) would characterize the system voltage sag performance by analyzing the fault performance on both the transmission system and the distribution system. Computer calculations, using a short circuit analysis program, can be used to determine voltages around the system for any fault location. These calculations can be used to define an "area of vulnerability" for a particular customer. The likelihood of a fault can then be calculated from past fault records of the area, or from the fault performance of similar locations. Voltage sags and momentary interruptions are often the most costly power quality variations affecting industrial and commercial customers. Faults over a wide area of the power system can affect the operation of a facility that has sensitive equipment. Faults can occur on the transmission system or on the distribution system. For most facilities, both cases need to be evaluated to estimate the overall performance expected. For facilities that are supplied directly from the transmission level, only transmission faults usually need to be considered.

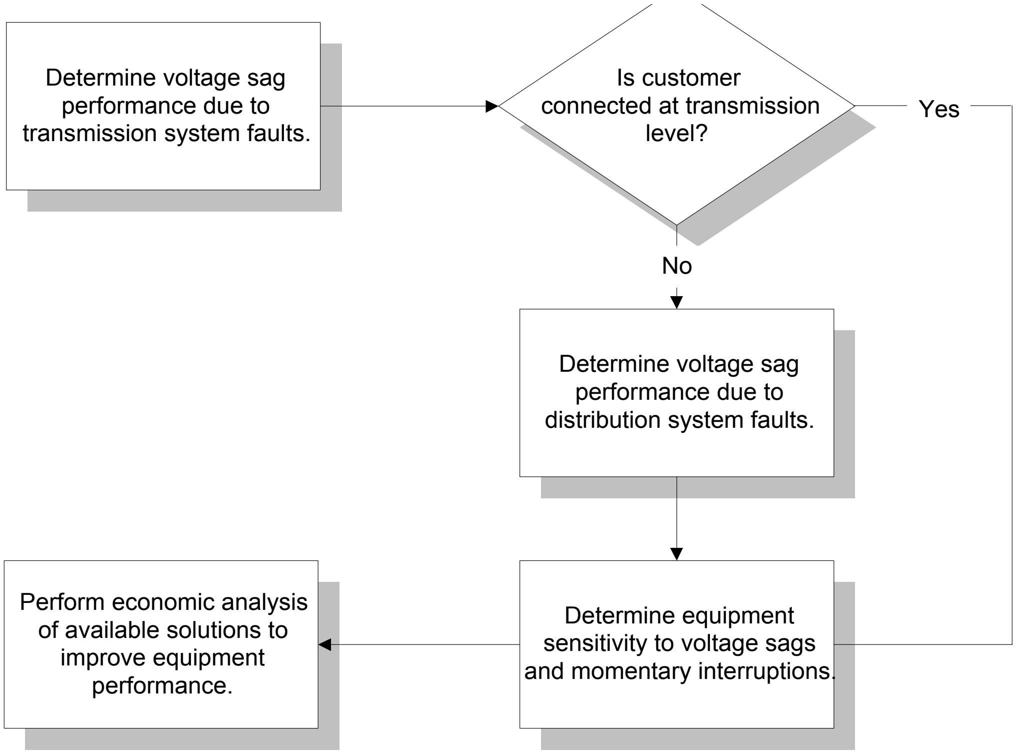

Figure 1 - Voltage Sag Evaluation Procedure

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