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Title: Interface Control Document for the EMPACT Module that Estimates Electric Power Transmission System Response to EMP-Caused Damage

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Interface Control Document for the EMPACT Module that Estimates Electric Power Transmission System Response to EMP-Caused Damage

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1. Problem Description

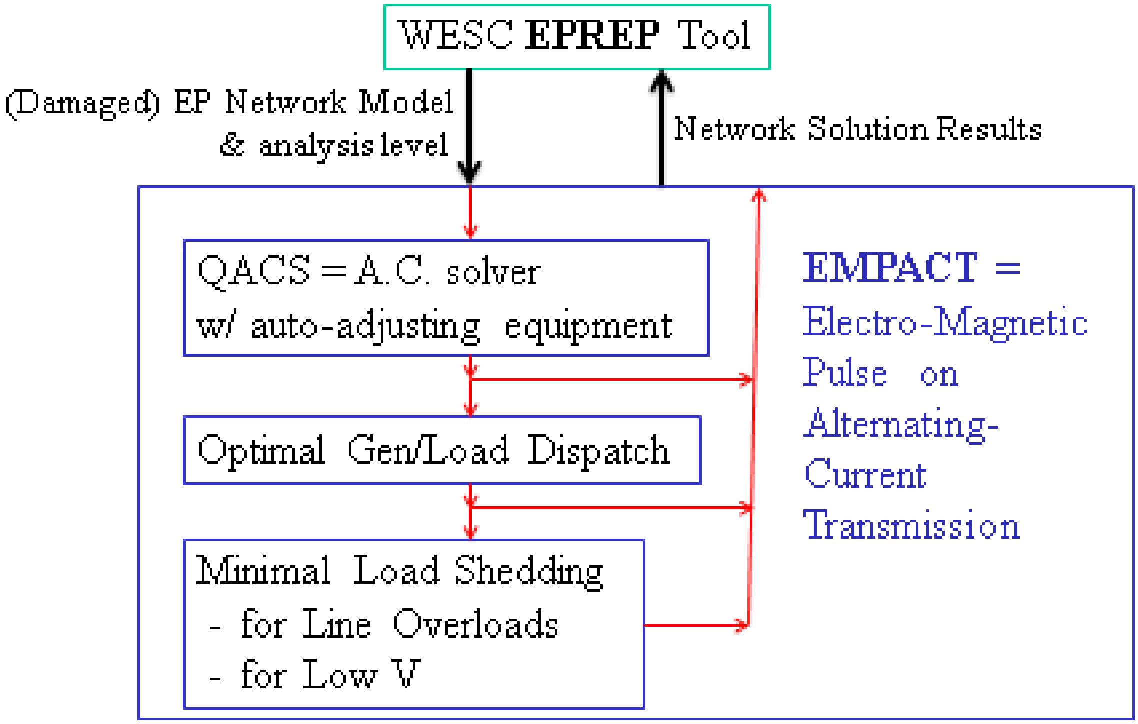
The EPREP code is designed to evaluate the effects of an Electro-Magnetic Pulse (EMP) on the electric power transmission system. The EPREP code embodies an umbrella framework that allows a user to set up analysis conditions and to examine analysis results. The code links to three major physics/engineering modules. The first module describes the EM wave in space and time. The second module evaluates the damage caused by the wave on specific electric power (EP) transmission system components. The third module evaluates the consequence of the damaged network on its (reduced) ability to provide electric power to meet demand. This third module is the focus of the present paper.

The EMPACT code serves as the third module. The EMPACT name denotes **EMP** effects on **A**lternating **C**urrent **T**ransmission systems. The EMPACT algorithms compute electric power transmission network flow solutions under severely damaged network conditions. Initial solutions are often characterized by unacceptible network conditions including line overloads and bad voltages. The EMPACT code contains algorithms to adjust optimally network parameters to eliminate network problems while minimizing outages. System adjustments include automatically adjusting control equipment (generator V control, variable transformers, and variable shunts), as well as non-automatic control of generator power settings and minimal load shedding. The goal is to evaluate the minimal loss of customer load under equilibrium (steady-state) conditions during peak demand.

2. Design Details

The EMPACT code is written in C++ and is provided to EPREP as a dynamic link library (.dll). The linkage between EPREP and the EMPACT module is illustrated in Fig. 1. The EMPACT code takes as input an EP nework flow model (either damaged or undamaged) and a specificication of the desired level of analysis. These input data and the function call are described in Section 3. The (corrected) flow solution is returned as the result. Result fields and formats are described in Section 4.

Figure 1. Diagram of the interface of EPREP with EMPACT Module.



3. Calling EMPACT

a. Analysis Options

The EMPACT code may be compiled as a C++ .exe. The EMPACT code requires a network model as input, provided as an *ascii* file in .pfw format. Additionally, the EMPACT code input requires specification of the analysis level. Analysis level options are listed in Table I. There are two primary options envisioned to be used by EPREP applications, they are highlighted in red. Option 1 is for solving the Basecase model and for checking the magnitude of the problems created in the "Damaged" models (without any dispatching or shedding). Primary Option 9 applies optimized correction to eliminate network problems.

Analysis Level option terminology used in Table I is described here. A "DC" solve means a "real power" solution only, reactive power and Bus voltages are ignored. A "QACS" solve implies a **Q**uasi-linear **A**.**C**. **S**olver covering real and reactive power, and the method is described in Ref. [1]. The QACS approach permits robust solutions in severely damaged networks. Generation and/or Load dispatching refers to optimal adjusting of the real-power sources and sinks in order to eliminate line overloads (if possible). Optimal load shedding to eliminate either line overloads or low voltages are addition analysis options. See Ref. [2-4] for descriptions of these techniques.

A sample command-line call of an executable EMPACT.exe is given by:

empact.exe c:\empact\utildata\   jepo.pfw 1

where the three input parameters include (1) the directory where the .pfw model resides, (2) the .pfw mdel file name, and (3) the desired analysis level (in this example a level "1" QACS solve is desired).

Table I. Analysis Level Options for EMPACT

Analysis_Level

0 = dc solve only
1 = qacs solve
2 = qacs solve & optimal dispatch Gen/IT for overloaded Lines
3 = qacs solve, dispatch Gen & Load for overloaded Lines
4 = qacs solve, dispatch Gen&Ld, and shed Load for overloaded Lines
7 = qacs solve & shed load for low V
9 = Step 4 folowed by Step 7

For application in EPREP, the EMPACT code is compiled as a C++ .dll. Example C++ code that links to the EMPACT .dll and performs and analysis is given in Table II. The same three input parameters are required for the .dll (as for the .exe example), and they are passed in within variable “argv”.

Table II. Sample C++ Progam Call of the EMPACT.dll

```
// ***************************************************************
// EMPACT4dll.cpp * Sample Program to call EMPACT.dll routines
//    kaw 5/17/2016
// ***************************************************************
#include <windows.h>
#include <stdio.h>;
typedef int (CALLBACK* lpEMPACTmain)(int,char**);

int main(int argc, char *argv[])
{ FILE *in;

  // List proper format, if needed
  if(argc<4)
  { printf("\nempact.exe = EMP on Alternating Current Transmission\n\n");
    printf("ERROR: empact.exe requires 3 arguments, e.g.\n");
    printf("empact4dll c:\\empact\\utildata\\ jepo.psa  1\n");
    printf("        path_to_model     .psa_model analysis_level\n\n");
    return 0;
  }

  // Load the .dll library
  HINSTANCE hEmpact;
  hEmpact=LoadLibrary("c:\\empactdll\\empact.dll");

  // Point to the main function
  lpEMPACTmain lpEmpact;
  lpEmpact=(lpEMPACTmain)GetProcAddress(hEmpact,"mainEMPACT");

  // Run the EPMACT tool
  lpEmpact(argc,argv);

  printf("All Done!");
  return 1;
}
```

3.b. Network Model Format

Along with the Analysis Level, the EMPACT routines require an EP network transmission model. Presumably a basecase (undamaged) A.C. model was developed and tested on the required solvers and was incorporated into the EPREP database.

For EMP damaged systems, EPREP must incorporate the damage into the network flow model by linking damaged equipment to Network flow model components and marking the Lines or Buses as out of service by using the "status" variable. Next the model data is written to an *ascii* file in .pfw format.

3.b.1 . pfw Format

The EP network flow model data are passed to EMPACT in a .pfw formatted file. The .pfw format is defined by Commonwealth Associates, Inc for use by their PFLOW code. The details of the variable definitions are described in Appendix E of Ref. [5] and are not repeated here. An example of the .pfw format is listed in Appenix A. The format of each variable is given within the .pfw file section headers. The .pfw file begins with alot of control information that must be present, but that are not used by the EMPACT module. Actual model data begins after the "HEADER BUS" line that contains parameter names and format specification. This HEADER is folowed by two sample lines of Bus data. Model data of the standard .pfw format definition proceed through the HEADERS of GENERATION, LOAD, SHUNT, SWITCHED_SHUNT, LINE, TRANSFORMER, and ZONE sections. This is followed by an "END OF DATA" line that signifies the official end of a standard .pfw file.

3.b.2 Additional Input Data

The EMPACT code requires some additional data beyond that contained with the standard .pfw format. This extra data has been added to Table II and tested that it does not interfere with the operation of the PFLOW code. The first extra data are added to the BUS section. Bus location latitude and longitude values are added to the end of each line of Bus data.

All other additional data follow the an "END OF DATA" line. First, an HEADER ITERTIE section is added. Interties are boundary conditions in a network model that represent the effect of connections to external (omitted) networks. Each Intertie is described by eight fields, including a Bus ID number, the real and reactive power injection, the maximum real and reactive power injection limit, the minimum real and reactive power injection limit, and , finally, whether the real power of the Intertie may be dispatched (adjusted). The Intertie section is ended with an an "END2 OF DATA" line.

Two single parameters of additional data follow. These specify the "reference_bus" ID and the "joulossfctr". The reference bus specifies a Generator or Intertie that has a "0" phase angle and where power injection is adjusted (within capacity) to provide global power balance (i.e., total sources = total sinks) across the model. The Joule loss factor parameter is used to approximately spread real power line losses into load Buses, while conserving the total real power loss of the model. This parameter is estimated for each model by performing a full A.C solution and computing:
joulossfctr = 1.0 + total_real-power_line_losses / total_real_load .

The final section of extra data lists the geometry (polyline) of each arc (lines and transformers). This starts with listing the number of POLYLINES. This example has 133 lines and transformers. Then, each polyline is identified with an arc ID that equals 1 for the first line, 2 for the second line, ... 133 for the final transformer done consequetively in the same order as listed in the LINE and TRANSFORMER sections above. The arc ID is folowed by from (*fr*} and to (*to*) ID's of the two endpoints, and then the total number of polyline points (*npts*). This is followed with a list of *npts* latitude/longitude pairs of location along the polyline. That completes the additional input data attached to the .pfw-formatted network model file.

4. Returned Results

The results of the EMPACT analysis that includes solving, dispatching, and shedding are the final solution parameters. If the analysis started from a basecase model, one need simply report parameters that change. However, since the EMAPCT analysis is envisioned to start from a damaged model, it is necessary to report all potentially changed parameters. Thus, it will be up to EPREP to compare results againts the basecase to determine significant changes. Potentially changed parameters include all flow parameters that are computed (the line flows, the phase angles, and the per unit voltages) along with any control equipment parameters that may have been adjusted (e.g., loads, generation, shunt capacitance, and variable transformer settings). The results output file is named *"forEPREP.out"*. A sample of file "*forEPREP.out*" is listed in Appendix B. The results output file begins with a one line repeat of the command line that was used to generate the results. This is followed by Bus results. For each Bus, the identifying number read in from the .pfw input is listed. This is followed by the real and reactive load generation and intertie solution values. This is followed by the compensation, the per unit voltage, the phase angle (in degrees), and, finally, the Bus name. A second line of information begins with "b:" lists similar load, generation, intertie power, and compensation field values that existed at the time the model was read in. An optional third line of data is written when the Bus contains either a generating station, an intertie, or a compensator. The third line of data begins with "mx:" and lists the maximum capability of the generating station, intertie, and compensator. An optional third line of data is written when the Bus contains either a generating station or intertie. The third line of data begins with "mn:" and lists the minimum capability of the generating station and intertie.

The Bus Results are followed by a Line Results section that lists results for all arcs (lines and transformers). Each Line result lists eight fields, including an arc ID, the from and to endpoint Bus IDs, the present real and reactive power flow, the percent loading of the line, and, finally the line status at both when the model was read in and the present status.

5. Summary

This document describes the procedure for calling the EMPACT routines located with a C++ .dll . Input data requirements include the model in a ammended .pfw formatted file along with an analysis_level parameter. The (corrected) model solution results are written to a forEPREP.out file. Descriptions and examples of the input and output files are presented. It remainds the user's (EPREP) responsibility to compare the damaged-model results to basecase solutions to extract and display significant results.

6. References

[1] K.A. Werley, "**A Fast Quasi-Linear Real and Reactive Power Flow Solver for Electric Power Transmission Networks**",
Los Alamos National Laboratory Energy Infrastructure Simulation Project (EISim) report
LA-UR-03-8267, November 14, 2001, pp 1-19.

[2] K.A. Werley, "**Automatic Electric Power Transmission Network Linear "DC" Flow Solver, Generator and Intertie Dispatcher, Load and Generation Shedder, Constrained Cellular Colonization (C^3) Service and Outage Area Estimation, and Identification of EP-Dependent Other Infrastructure Components Losing Service -- SDSC^3 --**",
Los Alamos National Laboratory Energy Infrastructure Interdependence Simulation Project (EISim) report
LA-UR-02-7776, December 5, 2002, pp 1-21.

[3] K.A. Werley, "**Using Unphysical AC Solutions to Fix (Dispatch) Severely Damaged Electric Power Transmissions Systems**",
Los Alamos National Laboratory Energy report
LA-UR-04-4603, June 24, 2004, pp 1-14.

[4] K.A. Werley, M. Anghel, and M. Salazar, **"Combined Source and Sink Optimized Dispatching for Eliminating Line Overloads in Electric Power Transmission Networks"**,

Los Alamos National Laboratory report
LA-UR-06-4609, May 6, 2006, pp 1-17.

[5] **"Transmission 2000 Prower Flow Program User's Reference Manual"**, Commonwealth Associates, Inc., Jackson, Michigan, (April 2008).

APPENDIX A. Sample .pfw Model Data Format

(Note: Wrapped continuation lines are denoted by starting with " ~ ".)

```
PSAD 6.01
HEADER CASE_IDENTIFICATION, TITLE1:255:T, TITLE2:255:T, TITLE3:255:T, TITLE4:255:T,
 ~ TITLE5:255:T, VERSION:5:T
" from PSA ",
" 2014 test mdl ",
" ",
"",
"",
6.00
HEADER PARAMS_R, NAME:20:T, VALUE:8:R
"PTOL                ", 0.10000
"QTOL                ", 0.10000
"VMAXPU              ", 1.10000
"VMINPU              ", 0.90000
"FTOL                ", 1.00000
"VTOL                ", 0.00500
"BASEMVA             ", 100.000
"LZTHRES             ", 0.00010
"INFTOL              ", 1000000
"MVATOL              ", 0.01000
HEADER PARAMS_I, NAME:20:T, VALUE:8:I
"DCTAP               ",       1
"GCD                 ",       1
"MAXITER             ",     200
"SVD                 ",       1
HEADER PARAMS_B, NAME:20:T, VALUE:1:T
"FLATSTART           ",F
"AREACON             ",T
"VARCON              ",T
"RMTCON              ",T
"XFCON               ",T
"XVCON               ",T
HEADER T2KPF_PARAMS_R, NAME:20:T, VALUE:8:R
"QDAMP               ", 0.80000
"PCTLTOL             ", 10.0000
"QCTLTOL             ", 10.0000
"BADXR               ", 0.50000
"RMTTOL              ", 0.00500
"RATE_FACTOR         ", 1.00000
"MAXACHANGE          ", 1.00000
"MAXVCHANGE          ", 0.50000
"AMP_FACTOR          ", 1.00000
"BQB0_FACTOR         ", 1.00000
"VCHANGEPU           ", 0.05000
"OLIMIT              ", 1.00000
HEADER T2KPF_PARAMS_I, NAME:20:T, VALUE:8:I
"CTRLITER            ",     100
"PAGESIZE            ",      60
"SCREENSIZE          ",      24
"PAGENO              ",       0
"OL_OPTION           ",       0
"TAPITER             ",       5
"GENITER             ",       5
"RATENUMBER          ",       0
"RMTITER             ",     100
```

```
HEADER T2KPF_PARAMS_B, NAME:20:T, VALUE:1:T
"SOLVEDEBUG         ",F
"AREADEBUG          ",F
"VARDEBUG           ",F
"RMTDEBUG           ",F
"XFDEBUG            ",F
"XVDEBUG            ",F
"SMOOTHSTEP         ",F
"OUTINCLUDE         ",F
"XFSKIP             ",F
"PRINTLOSS          ",T
"PRINTRATE          ",T
"ECHO               ",T
"SHOWMVA            ",T
"PRINTMAG           ",T
"PRINTTAP           ",F
"PRINTRX            ",F
"BYNAME             ",T
"DATA_ERROR         ",F
"BX_OPTION          ",F
"SHOWTITLES         ",F
"LOCALREMOTES       ",F
"BYREACTIVEPOWER    ",F
"BYREALPOWER        ",T
"BYFLOWS            ",T
"BYNOORDER          ",F
"BYRATING           ",F
"BYPERCENT          ",F
HEADER MISC_PARAMS_I, NAME:20:T, VALUE:8:I
"SELECTED_SET       ",       0
HEADER MISC_PARAMS_B, NAME:20:T, VALUE:1:T
"SOLVED             ",T
"BY_DSOLVE          ",F
"SHORTCUTS          ",F
"USEDIALOGS         ",F
"SCHEDULE_REMOTES   ",F
"OLD_FLATSTART      ",F
"SWITCHEDSHUNTSSMOOTH",F
"SS_DEBUG           ",F
HEADER SET_DEFINITIONS, DEFINITION:255:T
HEADER BUS, I:8:I, NAME:12:T, AREA:4:I, ZONE:4:I, VM:8:R, VA:8:R, BASKV:8:R, VS:8:R,
 ~ STATUS:1:I, LAT:10:R, LON:11:R
       1,"Calh-Tap-(FP",   1,   1, 0.00000,   0.000,  115.00,  1.0134,1, 30.278290,
 ~ -81.953178
       2,"Baymeadows-1",   1,   1, 0.00000,   0.000,  138.00,  0.0000,1, 30.236441,
 ~ -81.542747
HEADER GENERATOR, I:8:I, NAME:12:T, AREA:4:I, ZONE:4:I, TYPE:1:T, PG:10:R, QG:10:R,
 ~ VS:8:R, QT:8:R, QB:8:R, IREG:8:I, STAT:1:I, PMAX:8:R, PMIN:8:R, VT:8:R, VB:8:R
       7,"Eastport-138",   1,   1,2,  250.0000,   46.3000,  1.0330,  82.000,  -82.00,
 ~         7,1,  250.00,    0.00, 1.50000, 0.50000
      28,"Northside-13",   1,   1,2,  318.3000,  111.9700,  1.0400, 260.000, -120.00,
 ~        28,1,  524.20,   25.00, 1.50000, 0.50000
HEADER LOAD, I:8:I, NAME:12:T, AREA:4:I, ZONE:4:I, PL:10:R, QL:10:R, IP:10:R, IQ:10:R,
 ~ YP:10:R, YQ:10:R, ID:2:T
       2,"Baymeadows-1",   1,   1,   59.5000,   28.0300,       0.0,       0.0,
 ~       0.0,       0.0,"RC"
       3,"Blount-Islan",   1,   1,    5.8000,    4.4000,       0.0,       0.0,
 ~       0.0,       0.0,"RC"
HEADER SHUNT, I:8:I, NAME:12:T, AREA:4:I, ZONE:4:I, GS:8:R, BS:8:R
      13,"Greenland-23",   1,   1,     0.0, 0.42000
      25,"Normandy-230",   1,   1,     0.0, 0.84000
HEADER SWITCHED_SHUNT, I:8:I, MODSW:1:I, VSWHI:8:R, VSWLO:8:R, DV:8:R, REMOTEDV:8:R, SWREM:8:I,
```

```
 ~ BINIT:8:R, SUSCEPT:8:R, AREA:4:I, ZONE:4:I, ST:1:I, NST:1:I, N1:4:I, B1:8:R,
 ~ N2:4:I, B2:8:R, N3:4:I, B3:8:R, N4:4:I, B4:8:R, N5:4:I, B5:8:R, N6:4:I, B6:8:R,
 ~ N7:4:I, B7:8:R, N8:4:I, B8:8:R, N9:4:I, B9:8:R, N10:4:I, B10:8:R
    1951,0, 1.06620, 1.00620, 1.03620, 1.03620,    1951, 110.400, 110.400,    1,    4,1,1,
~    3, 36.8000,    ,        ,    ,        ,    ,        ,    ,        ,    ,        ,
 ~    ,        ,    ,        ,    ,        ,    ,
    1957,0, 1.50000, 0.50000, 1.00000, 1.00000,    1957, 165.600, 165.600,    1,    4,1,1,
 ~    1, 36.8000,    1, 36.8000,    1, 36.8000,    1, 36.8000,    1, 36.8000,    1, 36.8000,
 ~    ,        ,    ,        ,    ,        ,    ,
HEADER LINE, I:8:I, J:8:I, CKT:2:T, AREA:4:I, ZONE:4:I, R:10:R, X:10:R, B:10:R,
 ~ RATEA:5:R, RATEB:5:R, RATEC:5:R, ST:1:T, RATE_UNIT:1:T
       5,      17," 1",   1,   1,   0.00130,   0.00700,   0.13411,  259,  259,  259,1,M,
 ~ 0
       7,      28," 1",   1,   1,   0.00350,   0.02180,   0.00760,  346,  346,  346,1,M,
 ~ 0
HEADER TRANSFORMER, I:8:I, J:8:I, CKT:2:T, AREA:4:I, ZONE:4:I, R:10:R, X:10:R, B:10:R,
 ~ RATEA:5:R, RATEB:5:R, RATEC:5:R, ST:1:T, RATECHAR:1:T, TYPE:2:T, RATIO:8:R,
 ~ ANGLE:8:R, MINTAPANG:8:R, MAXTAPANG:8:R, STEP:8:R, VMIN:8:R, VMAX:8:R, ICONT:8:I,
 ~  SIDE:2:T
      10,      11," 1",   1,   1,   0.00120,   0.05380,   0.00000,  200,  200,  200,1,M,
 ~ 1,  0.9938,     0.0, 0.90000, 1.10000, 0.00625, 1.00000, 1.00000,       0, 0
      13,      14," 1",   1,   1,   0.00140,   0.04320,   0.00000,  200,  200,  200,1,M,
 ~ 1,  0.9875,     0.0, 0.90000, 1.10000, 0.00625, 1.00000, 1.00000,       0, 0
     202,     203," 1",  11,   4,   0.01719,   0.21583,       0.0,   40,   40,   40,1,M,
 ~ 2,  1.0156,     0.0, 0.94058, 1.14058, 0.00625, 1.02000, 1.03000,     202, 0
    8183,   89450," 1",   8,   7,   0.00107,   0.03318,       0.0,  181,  222,  222,1,M,
 ~ 4,  1.0000,   -1.70,-30.0000, 30.0000, 1.93548, 80.0000, 85.0000,    8183, 0
HEADER ZONE, I:4:I, ZONAM:12:T
   1,"jax         "
END OF DATA
HEADER INTERTIE Ibus:8 P:8 Q:8 Pmx:8 Qmx:8 Pmn:8 Qmn:8 ok_to_dsptch:2
       0   -28.33     0.00   129.60   129.60  -129.60  -129.60  1
       5  -110.20     0.00  1528.80  1528.80 -1528.80 -1528.80  1
      22   -47.04     0.00   108.00   108.00  -346.80  -346.80  1
      29  -294.70     0.00   602.40   602.40  -602.40  -602.40  1
      91   -88.56     0.00   801.60   801.60  -801.60  -801.60  1
END2 OFDATA
reference_bus 6
joulossfctr 1.0130
POLYLINES 133
ln fr to npts lat lon
 1 5 17 11
30.363079 -81.626938
30.364433 -81.628204
30.365183 -81.631622
30.367306 -81.636482
30.368797 -81.638832
30.378700 -81.641678
30.385792 -81.640808
30.389009 -81.648071
30.392111 -81.647499
30.405661 -81.650581
30.407509 -81.634720
 2 7 28 7
30.418951 -81.598228
30.417809 -81.597824
30.412378 -81.584999
30.412374 -81.557121
30.414164 -81.556984
30.415705 -81.555824
30.417147 -81.550591
```

APPENDIX B. Sample Flow Results Data Format

(Note: Wrapped continuation lines are denoted by starting with " ~ ".)

```
CASE:  empact c:\psdata\utildata\ ercot2015h5.psa 1

Bus Results:
 ibus   ld_MW ld_MVAR  gen_MW genMVAR    itMW  itMVAR compMVAR   puV  ph_angl Name
    1    -4.0    -0.7     0.0     0.0     0.0     0.0     2.4   1.015     7.2
 ~ ROANSPRARE----(1)
b:       -4.0    -0.7     0.0     0.0     0.0     0.0     2.4   1.018
mx:                       0.0     0.0     0.0     0.0     2.4
    2     0.0     0.0     0.0     0.0     0.0     0.0     0.0   1.015     7.3
 ~ KEITHSW-----(2)
b:        0.0     0.0     0.0     0.0     0.0     0.0     0.0   1.018
    3     0.0     0.0     0.0     0.0     0.0     0.0     0.0   1.015     7.3
 ~ IOLA--------(4)
b:        0.0     0.0     0.0     0.0     0.0     0.0     0.0   1.018
 6585     0.0     0.0    14.0    -5.1     0.0     0.0     0.0   1.000    -5.4
 ~ SENDERO-WIND----(907640)
b:        0.0     0.0    14.0    -5.1     0.0     0.0     0.0   1.000
mx:                      14.0    50.0     0.0     0.0     0.0
mn:                       0.0   -50.0     0.0     0.0
 Tot outage load=-1.1/-77722.8 MW

Line Results:
  iln  from    to    MW     MVAR  Loading NormStat Status
    1     1   502   -11.5     1.0    0.07   1       1
    2     1     6    -2.3     0.7    0.01   1       1
    3     1     5     9.7     1.7    0.03   1       1
    4     2  4559     0.7     0.4    0.00   1       1
 8394  6606  2010     0.0     0.0    0.00   0       0

Variable Transformer Results:
  iln  from   to typ TapRat  baseTR TapAngl   AdjMx   AdjMn  TargMx  TargMn
   27    18    19 2    0.98    0.98   0.000    1.11    0.91    1.03    1.02
   86    63    64 2    0.97    0.97   0.000    1.06    0.88    1.03    1.02
  136    98    99 2    1.02    1.02   0.000    1.14    0.94    1.03    1.02
 4636  2971  2972 4    1.00    1.00   8.367   30.00  -30.00   50.00   45.00
 4688  3009  3034 4    1.00    1.00   8.130   30.00  -30.00  -10.00  -15.00
```