Ferroresonance on Transformer 13-kV Ungrounded Tertiary at Arab

Gary L. Kobet, P.E.
Tennessee Valley Authority

In October 1997, at TVA's Arab AL 161kV Substation, a distributor built a 13kV switchyard to load the previously unloaded (except for single-phase station service) 13kV delta tertiary of the 161kV wye grounded/46kV wye grounded/13kV delta transformer bank (two banks in parallel). A three-phase three-element metering package was used, using 7200-120V metering VTs.

When switch 247 (three-phase gang-operated) was closed to energize the portion of bus containing only Y-Y connected metering potential transformers (see Figure 1), two gapped lightning arresters on the 13-kV transformer bank faulted, tripping both banks by bank differential. The cause of the lightning arrester failure was suspected to be overvoltage due to ferroresonance. EMTP simulation supported this theory. No actual waveforms were available (all relaying electromechanical, no station DFR at this location).

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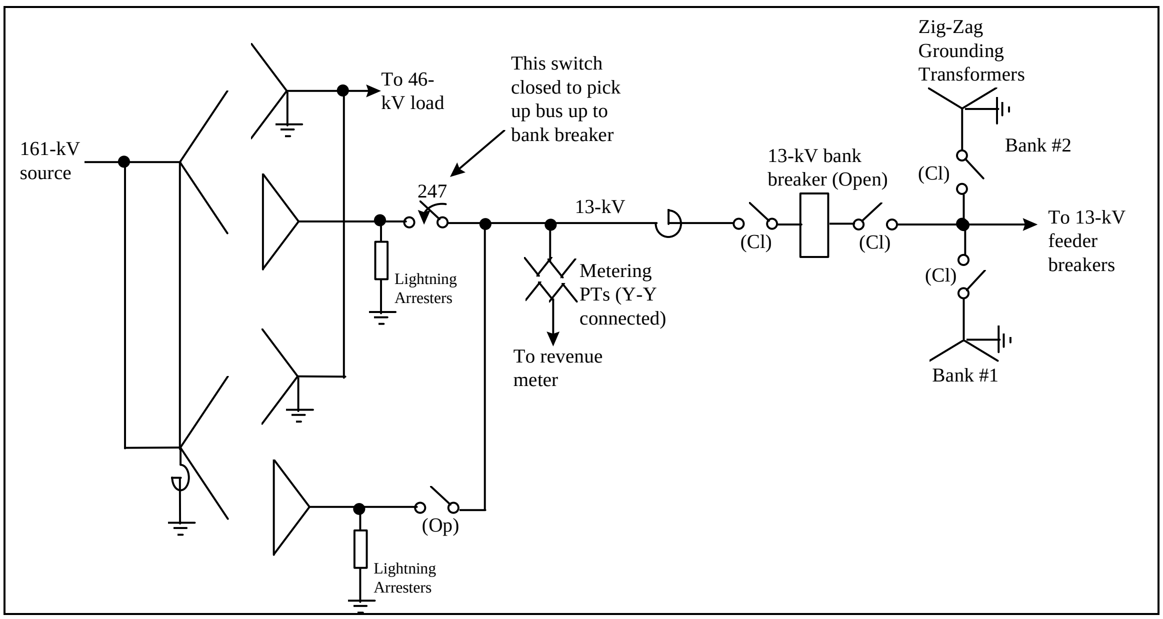

Figure 1. Arab 13-kV switchyard

Reasons Ferroresonance Occurred

Ferroresonance is an effect which can occur on ungrounded systems with Y-Y connected potential transformers. Actually there are no "ungrounded" systems; there is always some stray distributed capacitance of the bus runs, insulators, switches, transformer bushings and windings, etc. It is this small (hundreds of picofarads) capacitance which interacts with the nonlinear magnetizing inductance of the potential transformer which can cause resonance. The resonant circuit causes the magnetizing branch of the potential transformer to draw higher-than-normal magnitudes of excitation current. This current, across the VT magnetizing impedance, produces the overvoltage.

Note that the Arab 13kV buswork up to the open 13kV bank breaker is an “ungrounded” system, due to the delta-connected 13kV power transformer windings. Closing switch 247 energized only the 13kV Y-Y connected metering VTs and buswork up to the open 13kV bank breaker.

The saturation voltage of the potential transformer is an important factor in determining the probability of ferroresonance occurring. As the normal operating voltage of the system approaches the VT saturation voltage, it becomes easier for ferroresonance to occur and more difficult to prevent it from persisting.[1]

It was discovered that these metering VTs were being operated well above their saturation point.

A combination of these factors (switching Y-Y connected VTs on an ungrounded bus, and operating the VTs above the saturation point) resulted in ferroresonance.

EMTP Simulation

The Arab 13kV switchyard was modeled in EMTP in an attempt to simulate the event. Notes concerning the EMTP modeling of the Arab 13-kV switchyard are as follows:

- A system equivalent was calculated at the Arab 161-kV bus.
- Both power transformer banks were modeled as two banks of three single-phase transformers. Leakage impedances were calculated from nameplate values. The 161-kV neutral reactor was included. Winding-to-ground and winding-to-winding capacitances were calculated from Doble test results.
- 13-kV bus capacitance was modeled at 10 pF/ft per C37-011 table 4.
- The zig-zag grounding transformers were modeled as two banks of three single-phase transformers. Leakage impedances were calculated from nameplate values.
- Load was connected to the 46-kV windings typical of the load at the time of the disturbance.
- The potential transformers (7200-120V, 1500VA thermal rating) were modeled using the EMTP saturable transformer model. Leakage impedances were obtained from the manufacturer’s test report, and winding-to-ground capacitances derived from Doble test results. The excitation curve (exciting volts vs. exciting amps) was obtained from the manufacturer and was fed into the auxiliary magnetic saturation routine, which provided the required peak current vs. flux data. This table was placed into the EMTP data file. The excitation curve is shown in Figure 2. As

[1] p. 609, “Ferroresonance of Grounded Potential Transformers on Ungrounded Power Systems,” 1959 AIEE Transactions on Power Apparatus and Systems.

previously stated, note that the normal operating voltage is located well above the knee of the saturation curve. Simple examination of this curve showed that there was a potential problem.

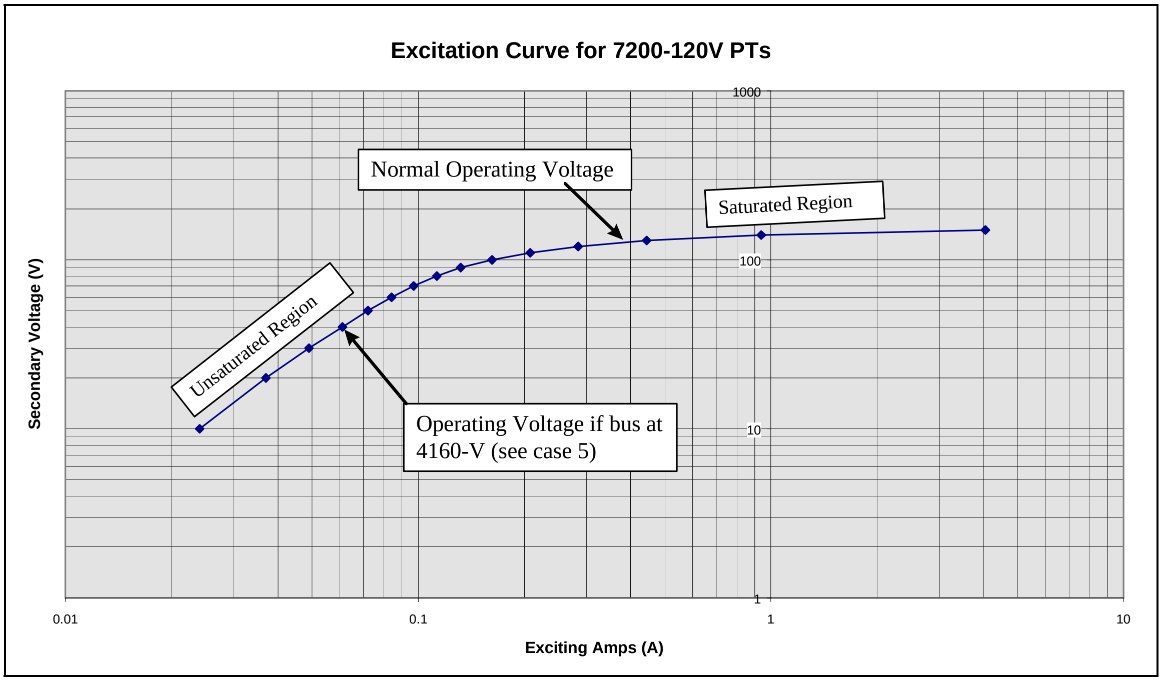

Figure 2. 7200-120 VT saturation curve

The EMTP data file is listed in Appendix A. The VT excitation data file is listed in Appendix B.

The EMTP graphs are as follows:

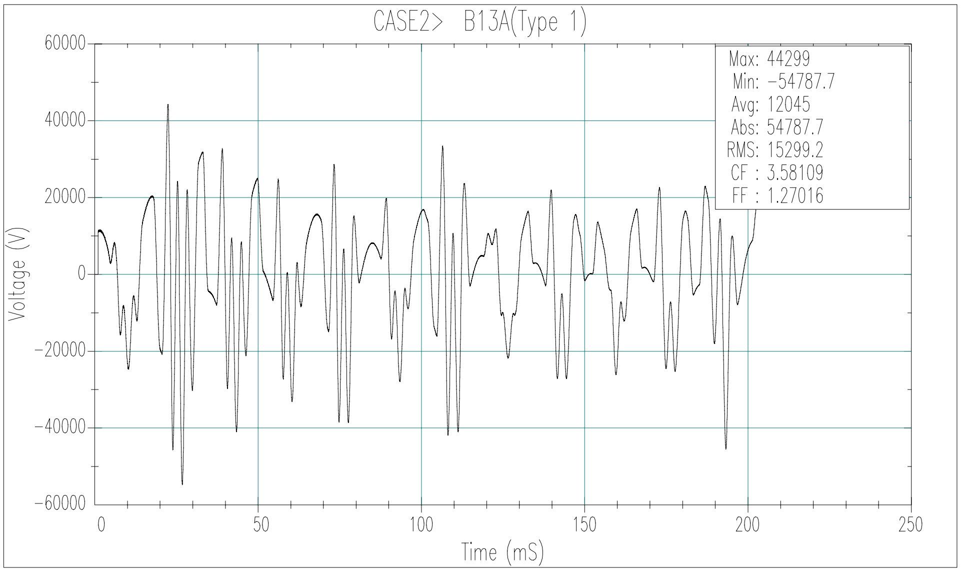

Figure 3a. 7200-120 VTs connected Y-Y. Voltage waveform.

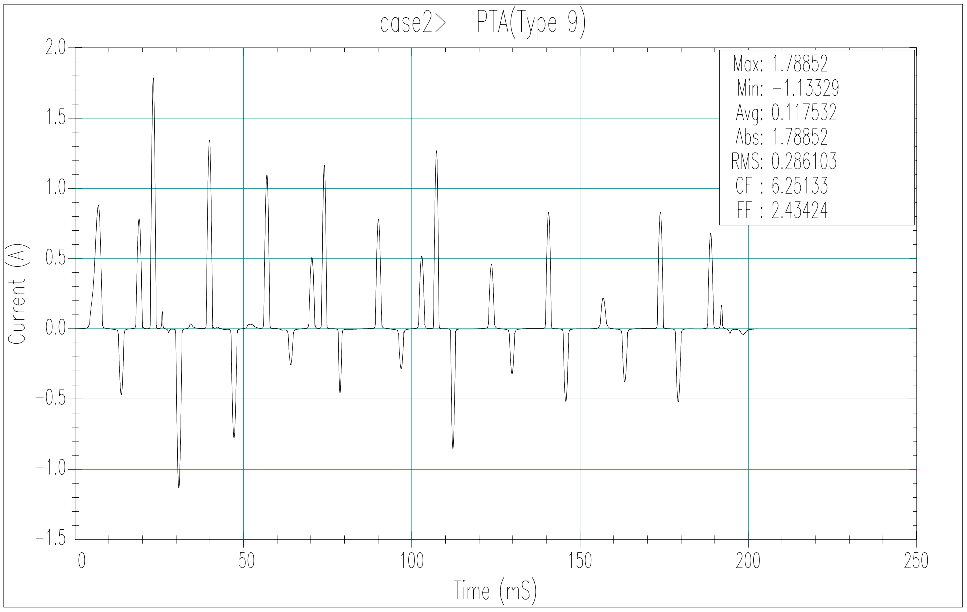

Figure 3b. 7200-120 VTs connected Y-Y. Waveform for current drawn by VT magnetizing branch (saturated).

In examining the graphs, it should be noted that normal phase-to-ground voltage is 7.5-kV rms, and normal peak voltage (maximum *and* minimum) should be 10.6-kV (see case 1). The voltages examined in the EMTP output graphs are phase-to-ground voltages, since this is the voltage which stresses the system insulation, cause lightning arresters to sparkover, and can damage equipment connected to the VT secondary.

Note that peak voltage spikes of 60-kV (six times normal) were predicted. This would have been enough to cause lightning arrester failure.

Mitigating Solution

Several solutions were considered, including replacing VTs with models having a saturation voltage well above the expecting operating voltage, rearranging the switchyard so that the VTs were on the same bus as the grounding transformers, adding secondary loading resistance to the VTs, and installing additional phase-to-ground capacitance to the 13kV bus.

The solution chosen in this case was to replace the three Y-Y connected VTs with two 14400-120V VTs connected delta-wye. The bus section between the transformer bank and the open bank breaker was energized successfully on December 16, 1997.

Conclusions

It is very important to recognize the potential for ferroresonance. Equipment characteristics and connections must be thoroughly reviewed to avoid creating an operating arrangement which could result in equipment damage or, more importantly, safety hazards to operating personnel or the public.

In the case of Arab, the 247 switch was being closed manually by a human operator. The lightning arresters that failed were within 10 to 20 feet of the switchplate on which the operator was standing. Had the arresters blown apart, the operator could have been severely injured.

The results of the EMTP studies also revealed that two classical solutions for mitigating ferroresonance were not effective in this particular case. Specifically, the addition of VT secondary loading resistance would not have prevented ferroresonance without significantly degrading the metering VT accuracy, due to the additional burden. Additionally, this case also demonstrates that three-phase switching will not always prevent ferroresonance. This was proven both by EMTP study and in actual practice, since switch 247 was a three-phase gang-operated switch.

Appendix A
EMTP Data File

```
C Arab, AL, 161-kV Substation Study Case
C Gary L. Kobet
C October 1997
C
C This case uses a system equivalent at the Arab 161-kV bus.
C
BEGIN NEW DATA CASE
C
C Floating-point miscellaneous data (See Section 5.2.1)
C ----dt<---Tmax<---Xopt<---Copt<-Epsiln<-Tolmat<-Tstart
   25E-6     1.0
C .....^.......^.......^.......^.......^.......^.......^
C
C Integer miscellaneous data (See Section 5.2.2)
C -Iprnt<--Iplot<-Idoubl<-Kssout<-Maxout<---Ipun<-Memsav<---Icat<-Nenerg<-Iprsup
    1001       1       1       1       1       0       0       2
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C
C Source impedance data (looking into TVA system at 161-kV bus)
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
    SRCA B16SA             1.751  26.7
    SRCB B16SB             1.751  26.7
    SRCC B16SC             1.751  26.7
C
C Power transformer model
C Bank 1 A-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER                  .1 9999.BANK1A1.58E5
          9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161A B161N              1.13 176.1  88.9
02  B46A                   0.052   0.1  26.6
03 B131A B131B             0.0231.6878  13.2
C Bank 1 B-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER BANK1A                  BANK1B
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161B B161N
02  B46B
03 B131B B131C
C Bank 1 C-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER BANK1A                  BANK1C
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161C B161N
02  B46C
03 B131C B131A
C Bank 2 A-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER BANK1A                  BANK2A
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161A B161N
02  B46A
03 B132A B132B
C
C Bank 2 B-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER BANK1A                  BANK2B
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161B B161N
02  B46B
03 B132B B132C
C
C Bank 2 C-phase
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER BANK1A                  BANK2C
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<-------------------------------IMAG
01 B161C B161N
02  B46C
03 B132C B132A
```

```
C
C Wye grounding impedance
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                  V
  B161N                           26.5
C
C Bank 1 capacitances
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                  V
  B131A                               0.0042
  B131B                               0.0042
  B131C                               0.0042
  B161A                               0.0011
  B161B                               0.0011
  B161C                               0.0011
   B46A                               0.0009
   B46B                               0.0009
   B46C                               0.0009
   B46A B131A                         0.0035
   B46B B131B                         0.0035
   B46C B131C                         0.0035
  B161A  B46A                         0.0024
  B161B  B46B                         0.0024
  B161C  B46C                         0.0024
C
C Bank 2 capacitances
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                  V
  B132A                               0.0042
  B132B                               0.0042
  B132C                               0.0042
  B161A                               0.0011
  B161B                               0.0011
  B161C                               0.0011
   B46A                               0.0009
   B46B                               0.0009
   B46C                               0.0009
   B46A B132A                         0.0035
   B46B B132B                         0.0035
   B46C B132C                         0.0035
  B161A  B46A                         0.0024
  B161B  B46B                         0.0024
  B161C  B46C                         0.0024
C
C Station service transformer on bank #1 13-kV bus (single phase connected A-B)
  B131A                               0.0002
  B131B                               0.0002
C
C Station service transformer on bank #1 13-kV bus (single phase connected A-B)
  B132A                               0.0002
  B132B                               0.0002
C
C 14400-120V Instrument transformers
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
C  TRANSFORMER             0.004954.452   PTA1.75E6                            3
C <---Current---<----------Flux
C  0.61282588E-03  0.71845242E+01
C  0.85340258E-03  0.12856517E+02
C  0.10037076E-02  0.16097656E+02
C  0.12661239E-02  0.22039743E+02
C  0.15167492E-02  0.27441641E+02
C  0.19281731E-02  0.34842241E+02
C  0.23213816E-02  0.39271798E+02
C  0.31695871E-02  0.45970151E+02
C  0.48836398E-02  0.52452429E+02
C  0.15215124E-01  0.64768756E+02
C  0.39100056E-01  0.69252331E+02
C  0.86113602E-01  0.72817584E+02
C  0.13466451E+00  0.74978343E+02
C  0.16349163E+00  0.76436855E+02
C  0.21548177E+00  0.78489576E+02
C            9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<------------------------------IMAG
C 01  B13A  B13B             942.0        14.4                                  1
C 02  SECA                   0.057 0.507  0.12
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
C  TRANSFORMER    PTA                     PTC                                  3
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<------------------------------IMAG
```

```
C 01  B13C  B13B
C 02  SECC
C
C 7200-120v Instrument transformers
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER            0.008827.009   PTA2.88E6                              3
C <---Current---<-----------Flux
  0.56568542E-03  0.22417876E+01
  0.79173890E-03  0.45105847E+01
  0.10896106E-02  0.67523724E+01
  0.13681169E-02  0.89941600E+01
  0.16026080E-02  0.11262957E+02
  0.19218959E-02  0.13504745E+02
  0.22513641E-02  0.15746532E+02
  0.27214398E-02  0.18015329E+02
  0.32708947E-02  0.20257117E+02
  0.43632949E-02  0.22498905E+02
  0.59547641E-02  0.24767702E+02
  0.87782054E-02  0.27009489E+02
  0.15240792E-01  0.29251277E+02
  0.36669038E-01  0.31520074E+02
  0.17977154E+00  0.33761862E+02
          9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<------------------------------IMAG
01  B13A                  417.3        7.2                                     1
02  SECA                  0.085 0.498  0.12
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER    PTA                    PTB                                    3
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<------------------------------IMAG
01  B13B
02  SECB
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER    PTA                    PTC                                    3
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt<------------------------------IMAG
01  B13C
02  SECC
C
C Damping resistance
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
C    SECA                    32.
C    SECB                    32.
C    SECC                    32.
C
C VT Capacitance to ground
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
    B13A                             1.1E-4
    B13B                             1.1E-4
    B13C                             1.1E-4
C
C 13kV bus capacitances (all aluminum bus @10 pF/ft per C37-011 Table 4)
C 13-kV bus from switches to phase reactors (94.5 feet)
    B13A                             9.5E-4
    B13B                             9.5E-4
    B13C                             9.5E-4
C
C Phase reactors between 13-kV transformer bus and bank breaker
    B13A                             0.0002
    B13B                             0.0002
    B13C                             0.0002
C
C Load on 46-kV bus (30+j5) MVA
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<----------------------------Output
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
    B46A                  68.8  30.2
    B46B                  68.8  30.2
    B46C                  68.8  30.2
C
C Load on 13-kV bus (15+j5) MVA
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<----------------------------Output
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
C    B13A                  10.1  8.97                                           3
C    B13B                  10.1  8.97                                           3
C    B13C                  10.1  8.97                                           3
C
C Zig-zag grounding transformers on load side of bank breaker
```

```
C TRANSFORMER <--Ref<---->< --Iss<--Phi<-Name<-Rmag<----------------------IOUTMAG
  TRANSFORMER              0.001 0.031   ZZA  1.E6
            9999
C <-Bus1<-Bus2<---------->< ---Rk<---Lk<-Volt<-------------------------------IMAG
01ZIGAGAB13ZZA             0.044 0.623   1.0                                    1
02ZIGAGC                   0.044 0.623   1.0                                    1
  TRANSFORMER    ZZA                     ZZB
01ZIGAGBB13ZZB                                                                  1
02ZIGAGA                                                                  1
  TRANSFORMER    ZZA                     ZZC
01ZIGAGCB13ZZC                                                                  1
02ZIGAGB                                                                  1
C
C Additional capacitance on 13-kV bus (attempt to detune ferroresonance)
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   V
C    B13A                                0.75                                    3
C    B13B                                0.75                                    3
C    B13C                                0.75                                    3
C
BLANK end of circuit data
C
C 13-kV switch to connect bank #1 to 13-kV transformer bus
C <-Bus1<-Bus2<---Tclose<----Topen<-------Ie<----Flash<--Request<-----Target<--O
   B131A  B13A     1.E-3      999.
   B131B  B13B     1.E-3      999.
   B131C  B13C     1.E-3      999.
C 161-kV switch to check energization from high-side of power bank
   B16SA B161A    -1.E-3      999.
   B16SB B161B    -1.E-3      999.
   B16SC B161C    -1.E-3      999.
C 13-kV switch to connect grounding bank to 13-kV main bus
C  B13ZZA  B13A    -1.E-3      999.
C  B13ZZB  B13B    -1.E-3      999.
C  B13ZZC  B13C    -1.E-3      999.
C
BLANK end of breaker data
C
C Source voltage data (1.03 pu)
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14  SRCA 1  135399.6      60.0       0.0                          -1.0      9999
14  SRCB 1  135399.6      60.0    -120.0                          -1.0      9999
14  SRCC 1  135399.6      60.0     120.0                          -1.0      9999
C
BLANK end of source data
C
C Output request
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
    SRCA  B13A  SECA  SRCB  B13B  SECB  SRCC  B13C  SECC B161A B161B B161C
C  B13ZZAB13ZZBB13ZZC BZZAB BZZBC BZZCA
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C
BLANK END OF OUTPUT REQUEST
BLANK CARD ENDING PLOT CARDS
BLANK END OF DATA CASE
BEGIN NEW DATA CASE
BLANK END OF ALL CASES
```

Appendix B
VT Excitation Data File

Magnetic Saturation Data file for 7200-120V VTs

```
BEGIN NEW DATA CASE
C Calculation of the current vs flux saturation curves from the knowledge
C of the RMS magnetization current of the transformer.
C
SATURATION
C --Freq<-KVbase<MVAbase<-Ipunch<-kthird
C 3456789012345678901234567890123456789O
     60.     7.2  0.0015       0       0
C <---------Irms<-----------Vrms
         0.00192           0.083
         0.00296           0.167
         0.00392           0.250
         0.00488           0.333
         0.00576           0.417
         0.00672           0.500
         0.00776           0.583
         0.00904           0.667
         0.01056           0.750
         0.01296           0.833
         0.01664           0.917
         0.02272           1.000
         0.03552           1.083
          0.0752           1.167
         0.32464           1.250
            9999
BLANK End of Saturation Cases
BEGIN NEW DATA CASE
BLANK End of Run
```

Magnetic Saturation Data file for 14400-120V VTs

```
BEGIN NEW DATA CASE
C Calculation of the current vs flux saturation curves from the knowledge
C of the RMS magnetization current of the transformer.
C
SATURATION
C --Freq<-KVbase<MVAbase<-Ipunch<-kthird
C 34567890123456789012345678901234567890
     60.    14.4   0.002       0       0
C <---------Irms<-----------Vrms
         0.00312           0.133
         0.00468           0.238
         0.00546           0.298
         0.00684           0.408
         0.00810           0.508
         0.01002           0.645
         0.01152           0.727
         0.01476           0.851
         0.02052           0.971
         0.05658           1.199
         0.11700           1.282
         0.24300           1.348
         0.37380           1.388
         0.47280           1.415
         0.63600           1.453
            9999
BLANK End of Saturation Cases
BEGIN NEW DATA CASE
BLANK End of Run
```