An Investigation of Ferroresonance on Transformer 13-kV Ungrounded Tertiaries using the Electromagnetic Transients Program

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Presented to
The 53rd Annual Georgia Tech
Protective Relaying Conference
May 5-7, 1999
Atlanta, Georgia

Introduction

Over the past three years, TVA has had three customers pick up load on 13-kV delta tertiary windings of 161-kV wye grounded/46-kV or 69-kV wye ground/13-kV delta power transformer banks. In each case, TVA used its standard three-element 13-kV metering package, which included three wye-connected potential transformers. When the bus section to which the potential transformers were connected was energized, irreparable damage occurred to the potential transformers and equipment connected to the PT secondaries. In one of the cases, two of three arresters connected to the bus section faulted to ground. Overvoltage due to ferroresonance was suspected, and the Electromagnetic Transients Program was used to study the arrangement, determine the exact cause, and recommend a mitigating solution.

Several solutions were considered, including secondary loading resistance, connecting grounding transformers to the same bus as the VTs, connecting phase-to-ground capacitors to the bus, and changing the VT connection from wye-wye to delta-wye. Each of these prospective solutions were studied and confirmed by EMTP to mitigate future VT failures.

Background

As previously noted, there were three instances of overvoltage due to suspected ferroresonance: White Pine, Morristown, and Arab. The White Pine and Morristown incidents will be described briefly, while Arab will be discussed in detail.

- *White Pine, September 1995*: The 13-kV winding of the 161-kV wye grounded/69-kV wye grounded/13-kV delta transformer bank had been loaded for several years. TVA had scheduled an outage to replace the existing metering package, including the existing 8400-120V oil-filled metering potential transformers with a set of 7620-120V butyl-molded VTs. See Figure 1 for arrangement. The 13-kV main bus was being reenergized (using the same procedure which had been used many times before) by closing each of the single-phase disconnects one at a time. By the time all three switches were closed, all three metering VTs had been destroyed (although two gapped lightning arresters showed no apparent damage). It should be noted that the three-phase switch for the grounding bank was open at the time.

  In this case, the switching procedure was changed to have the grounding bank connected. and no damage occurred to the VTs. The same potential for future occurrences exists.

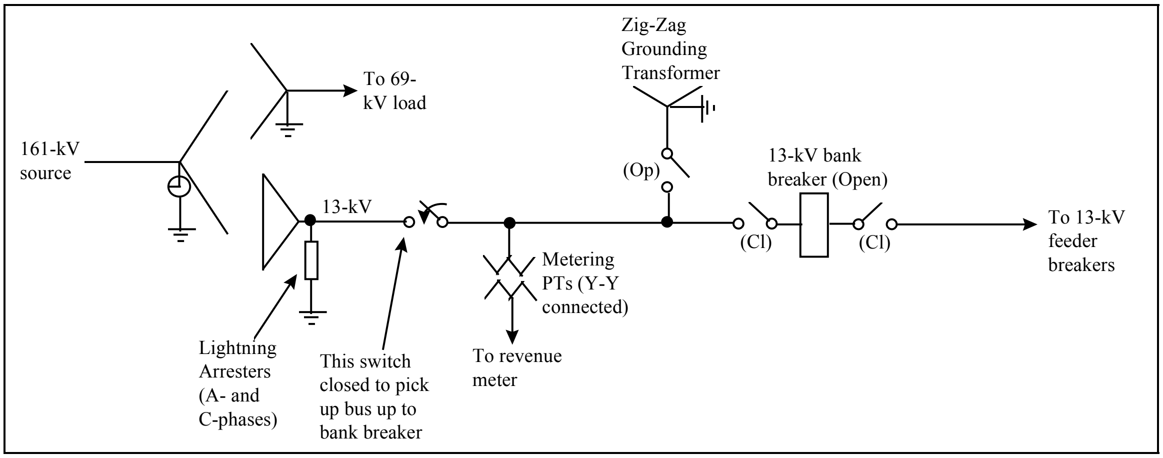

Figure 1. White Pine 13-kV switchyard

- *Morristown, circa September 1995*: The customer was building a 13-kV switchyard to load the previously unloaded 13-kV delta tertiary of the 161-kV wye grounded/69-kV wye grounded/13-kV delta transformer bank. The switchyard arrangement is similar to White Pine except for the series reactors for fault current limiting (see Figure 2). The metering package was identical to that for White Pine. With the 13-kV bank breaker open, the 13-kV three-phase disconnect switch was closed to energize the bus up to the open bank breaker, which included energizing the metering VTs. Before the bank breaker could be closed (less than five seconds, the revenue meter (connected to the metering VT secondaries) was destroyed (none of the three MOV lightning arresters showed any apparent damage).

  The solution chosen in this case was to move the metering VTs to the same bus as the grounding transformer. The same potential for overvoltage exists, however, if the grounding bank is for some reason left disconnected.

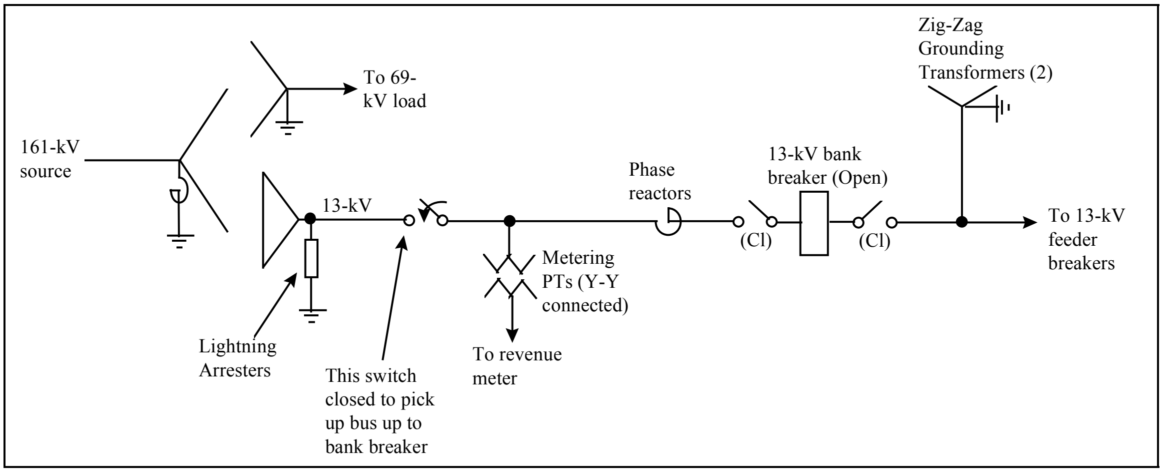

Figure 2. Morristown 13-kV switchyard

- *Arab, October 1997*: Similar to Morristown, the customer built a 13-kV switchyard to load the previously unloaded 13-kV delta tertiary of the 161-kV wye grounded/46-kV wye grounded/13-kV delta transformer bank (two banks in parallel). The same metering package was used as for Morristown, except that the metering VTs were 7200-120V. When switch 247 was closed to energize the portion of bus containing only Y-Y connected metering potential transformers (see Figure 3), 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.

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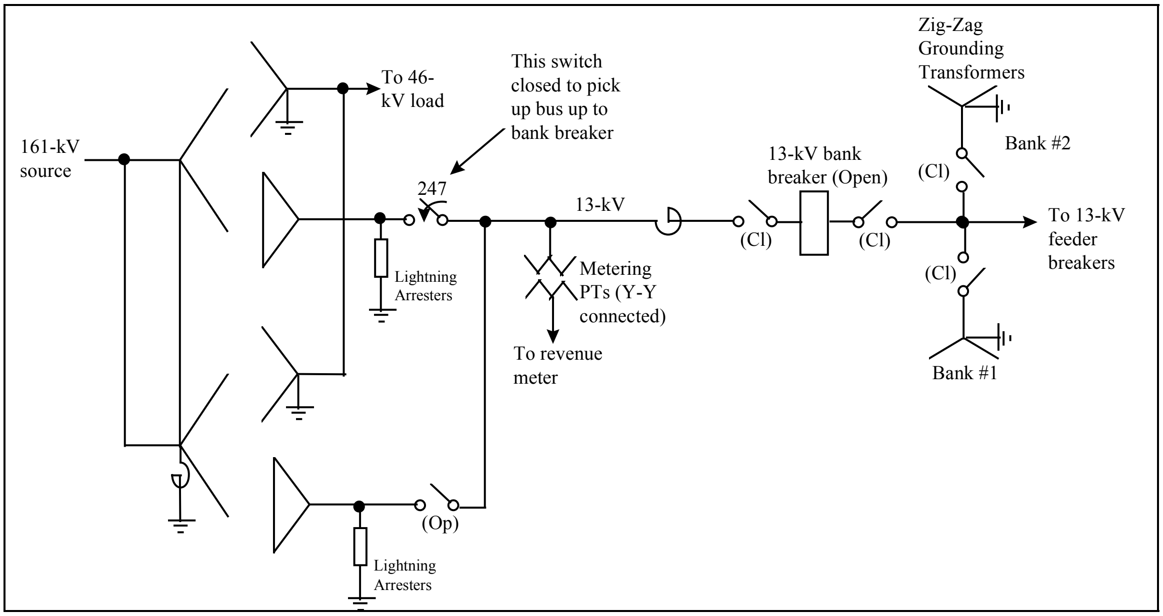

Figure 3. Arab 13-kV switchyard

The remainder of the paper discusses ferroresonance and how EMTP was used to study its effect in the Arab 13-kV switchyard. The EMTP allowed solutions to be tested by computer prior to reenergizing the Arab 13-kV equipment.

Discussion - Ferroresonance

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.

The saturation voltage of the potential transformer is an important factor in determining the chances for ferroresonance to occur. 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]

One of the most widely accepted methods of preventing ferroresonance involves resistance loading of the VT secondary to around 30 percent of thermal rating. The resistance effectively damps out the transient overvoltage due to ferroresonance.

Modeling of the Arab 13-kV Switchyard

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, 1500-VA 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 4. 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.

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

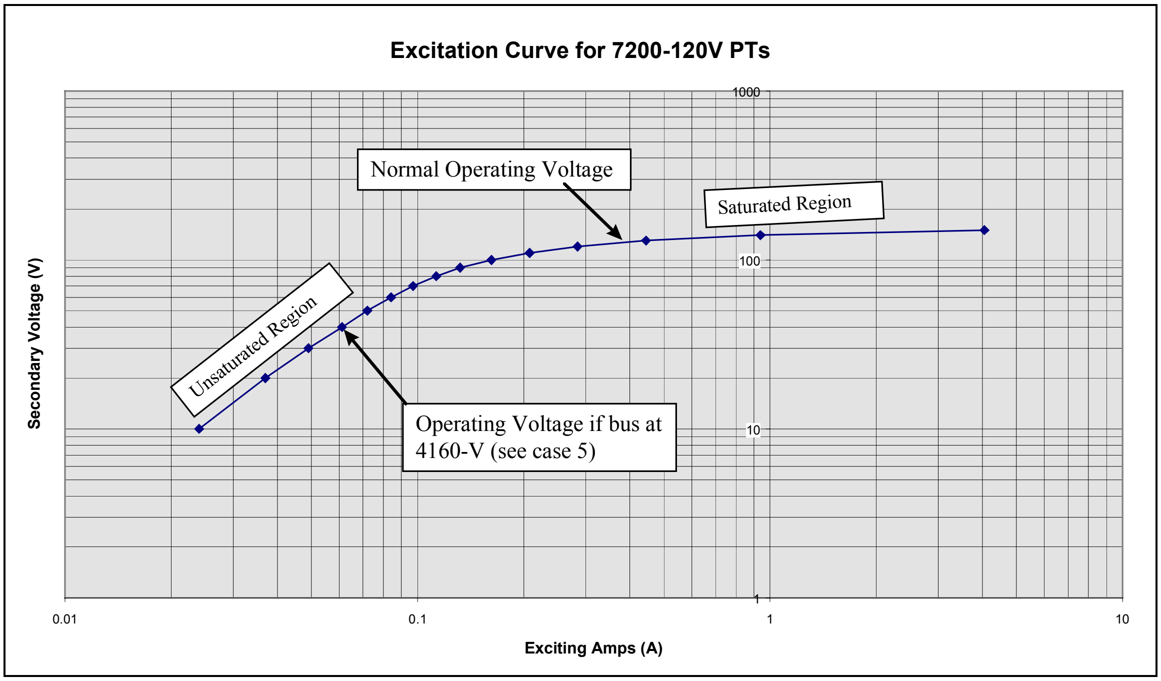


Figure 4. 7200-120 VT saturation curve

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

EMTP Cases Studied/Analysis of Results

Table 1 lists the cases which were performed using the above model. A discussion of each case follows the table. EMTP output graphs are included in Appendix C. 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.

Table 1. EMTP Cases Performed on Arab 13-kV Switchyard

Case	*Tertiary Voltage/Connection*	*VT rating/connection*	*Switching*	*Comments*
1	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	No VTs connected
2	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	Recreation of October disturbance
3	13.2 Δ	7200/120 Y-Y	13-kV switch (A-phase only)	Single-phase switching
4	13.2 Y-grounded	7200/120 Y-Y	13-kV switch (Three-phase	No ferroresonance

5	4.16 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	No ferroresonance
6	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	Grounding bank connected - no ferroresonance
7	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	VT 30 percent thermal loading
8	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	VT 100 percent thermal loading
9	13.2 Δ	7200/120 Y-Y	161-kV switch (Three-phase)	High-side energization
10	13.2 Δ	7200/120 Y-Y	13-kV switch (Three-phase)	50-kVAR capacitances connected phase-ground
11	13.2 Δ	14400/120 D-Y	13-kV switch (Three-phase)	No ferroresonance

- *Case 1*: This case was run with the yard set up as it was when the overvoltage disturbance occurred (base case), but with no potential transformers connected. This is to show what the normal bus voltage waveform should look like.

- *Case 2*: This case is identical to case 1 except with the VTs connected. Note that peak voltage spikes of 60-kV (six times normal) were predicted. This would have been enough to cause lightning arrester failure.

- *Case 3*: Same as case 2 except single-phase switching (A-phase only).

- *Case 4*: This case was run to show that ferroresonance would not occur on a Y-grounded system.

- *Case 5*: Note that the tertiary voltage was reduced to 4.16-kV. This was done to show that operating the VT in the unsaturated region of its excitation curve would also prevent ferroresonance.

- *Case 6*: Same as case 2, but with grounding bank connected. This case was run to show that ferroresonance would not occur on a delta ungrounded system with a zig-zag grounding bank connected.

- *Case 7*: Resistance loading of the VT secondary was attempted. At the 1500-VA rating, the equivalent minimum loading resistance is 9.6-W. This case uses 30 percent of thermal rating (450-VA), or 32-W. Note that the overvoltage problem still exists.

- *Case 8*: This case uses 100 percent thermal rating. Waveforms are still distorted, although peaks are still up to 1.6 times normal. Loading the VT at this value may prevent ferroresonance, but metering accuracy would be unacceptable.

- *Case 9*: This case was run at the request of personnel who suggested that energizing the same bus section through the power transformer, rather than by closing the 13-kV switch with the bank energized, might prevent ferroresonance. The EMTP output indicated that would not be the case.

- *Case 10*: This is the same as Case 2, but with 50-kVAR (0.75-mF) capacitors connected between each phase and ground. Note that this appears to be a valid solution to prevent ferroresonance.

- *Case 11*: In this case, the VTs were reconnected delta, as they would be connected in a standard two-element metering package. Only two VTs are needed for this arrangement rather than three. The VTs in this case were rated 14400-120V, 2000-VA thermal. Leakage impedances, capacitances, and excitation/saturation data were all determined as described above for the 7200-120V VTs. Note that no ferroresonance is predicted.

Conclusions

The EMTP results prove that ferroresonance was the cause of the overvoltage. The cases studied demonstrate that there are several means of mitigating the problem. The following comments summarize the results of the studies:

- Connect the 13-kV winding of the power transformer in a Y-grounded setup. This was impractical in this case, and may not be practical in many other cases where three-winding power transformers are located.

- Make sure the maximum operating voltage the potential transformers will experience will be well below the knee of the saturation curve. From the description of the White Pine incident in the background information above, it appears that the original oil-filled potential transformers operated in the unsaturated region. It is not known if modern VT designs are available with this characteristic.

- Connect the potential transformers to the same bus as the grounding transformers. This may be feasible for future designs, but there is still the danger that the disconnect switch for the grounding transformer will be left open by accident. In addition, since the grounding banks are on the load side of the bank breaker, tripping the bank breaker would also leave the VTs on an “ungrounded” bus section.

- Use secondary loading resistance in the potential transformer. Not only did output waveforms show that this would not prevent ferroresonance in this case, but loading the secondary at 30 percent thermal rating actually would exceed the ANSI metering accuracy of the typical 13-kV VT. This is yet another reason why this solution was unacceptable.

- Energizing an ungrounded delta bus through a power transformer will not prevent ferroresonance.

- Connect additional phase-to-ground capacitance to the VT bus. According to the output waveforms, this would be a feasible option. The additional capacitance evidently detunes the resonant circuit between the nonlinear magnetizing inductance of the VTs and the stray capacitance on the 13-kV buswork. In this case, 50-kVAR units were large enough to prevent resonance.

  Some possible disadvantages to this option would be:
    - This adds an additional element in the circuit subject to failure;
    - If one of these capacitors failed to ground, station load would be tripped;
    - If one failed open, ferroresonance protection would be lost. This failure mode may or may not be noticed visually.
    - The current waveform for the VT magnetizing branch appears to show that the VT is still saturated.

- Connecting the metering VT delta/wye will prevent ferroresonance. This option proved to be the best in the Arab switchyard, and has several advantages:
    - This eliminates the need to require the grounding banks to be connected to the bus at all times;
    - Only two VTs are needed instead of three;
    - VT accuracy is not affected by secondary loading resistance;
    - Complete operating flexibility is maintained for the switchyard.

  The tradeoff in this case is the difference between two-element and three-element metering. TVA has many two-element metering installations already in service, and is evidently satisfied with the balanced-load assumption.

Field Experience

The three Y-Y connected potential transformers were replaced as described above 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. A power disturbance analyzer was connected to the metering potential to record any transient events. The results are shown in Appendix D.

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

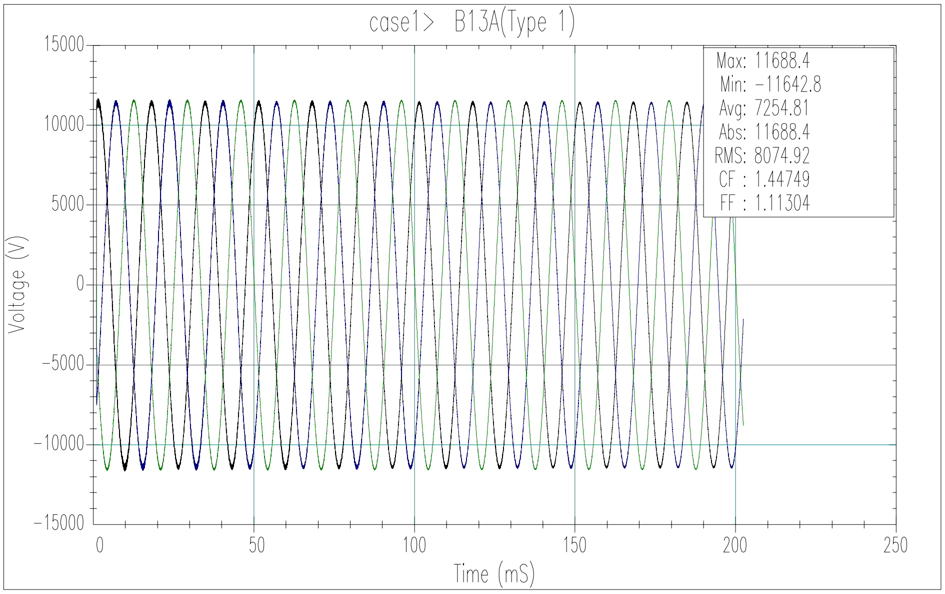
Magnetic Saturation Data file for 7200-120V VTs

```
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 34567890123456789012345678901234567890
     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
```

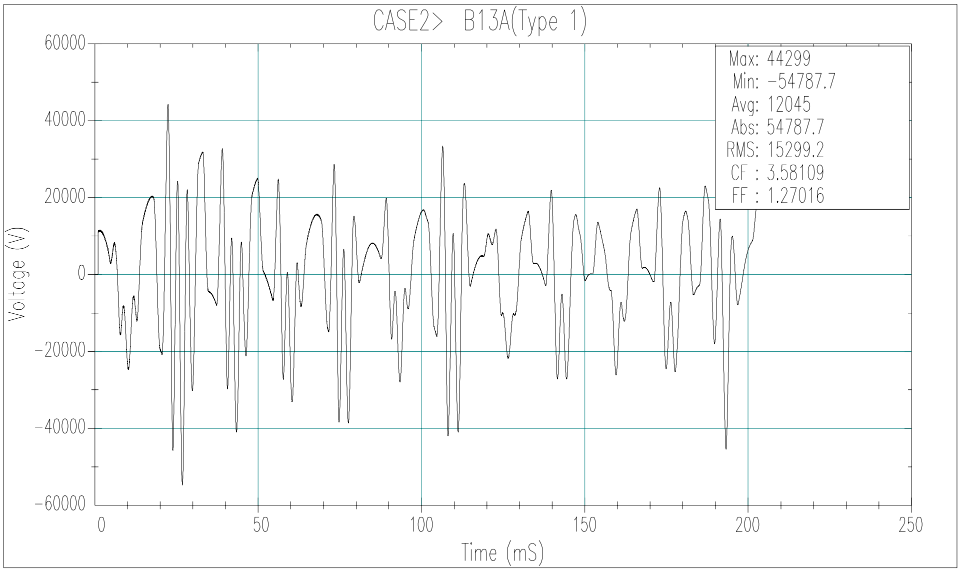
Magnetic Saturation Data file for 14400-120V VTs

```
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
```

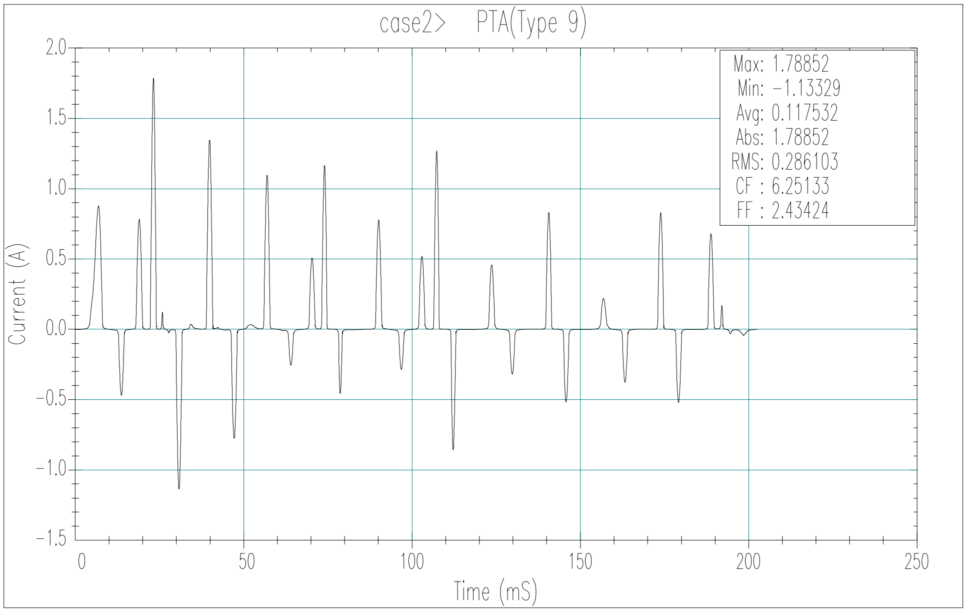
Appendix C
EMTP Output Graphs



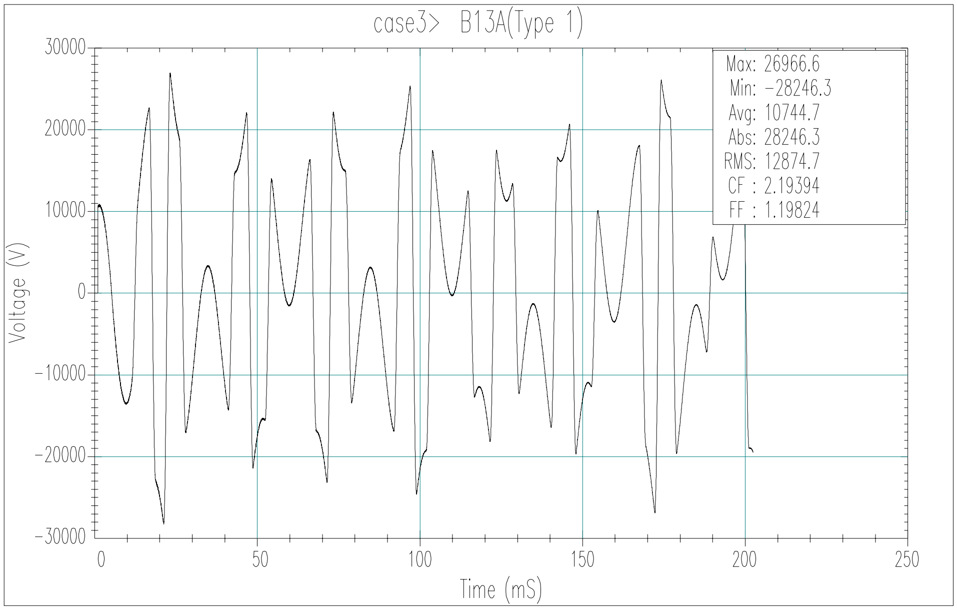
Case 1. Base Case, No VTs connected



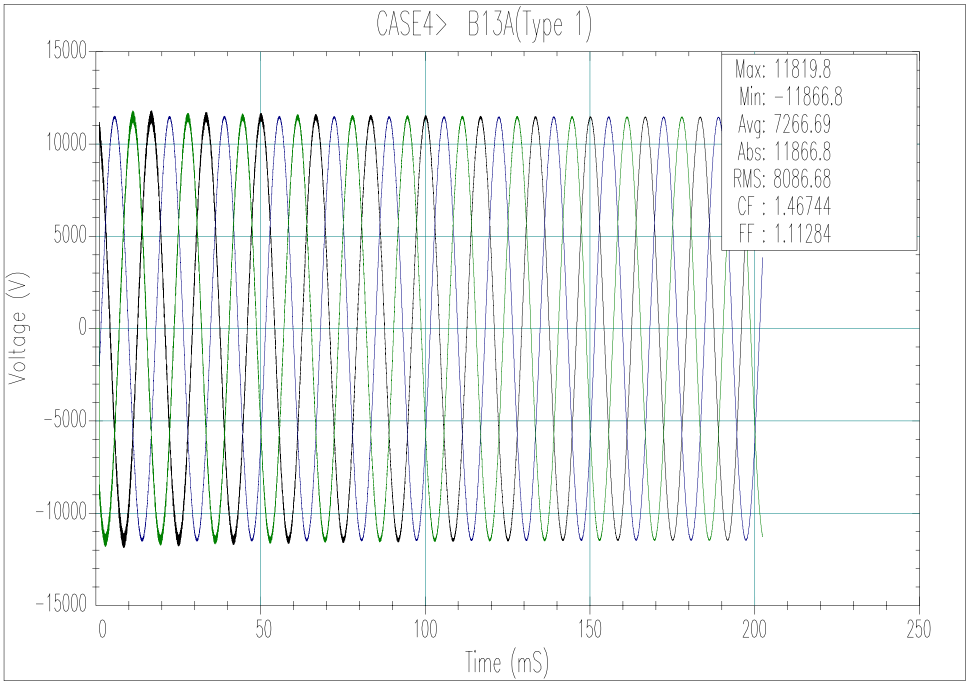
Case 2. 7200-120 VTs connected Y-Y. Voltage waveform.



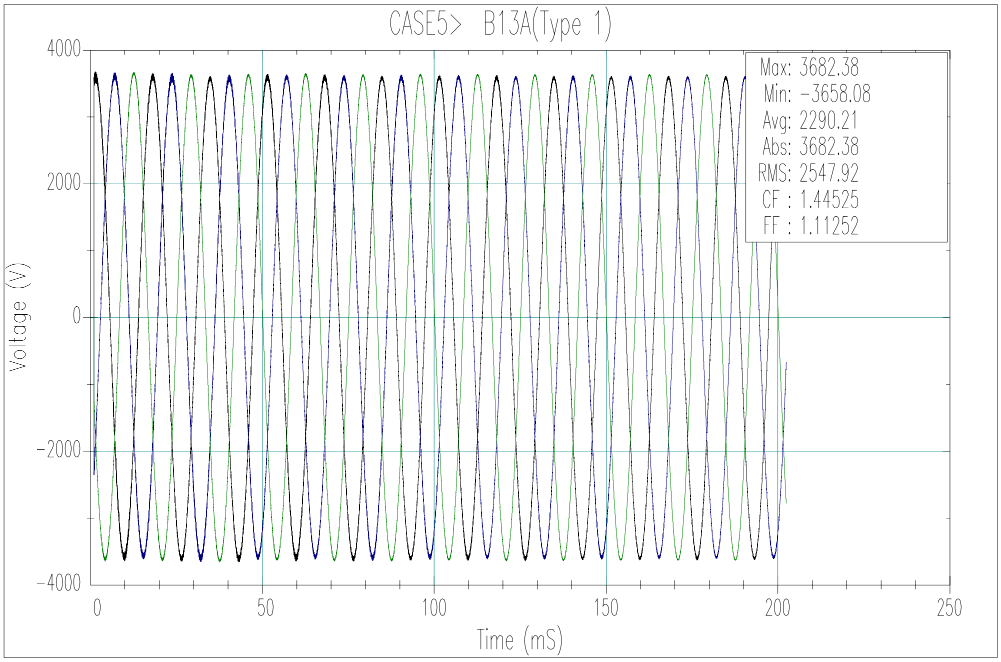
Case 2. 7200-120 VTs connected Y-Y. Waveform for current drawn by VT magnetizing branch (saturated).



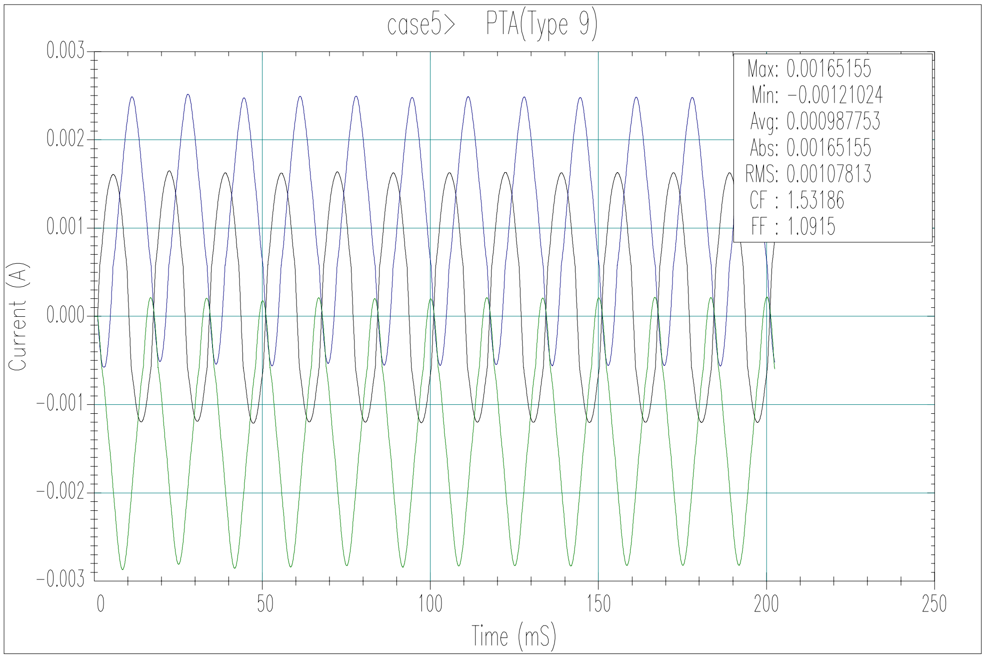
Case 3. Single-phase switching



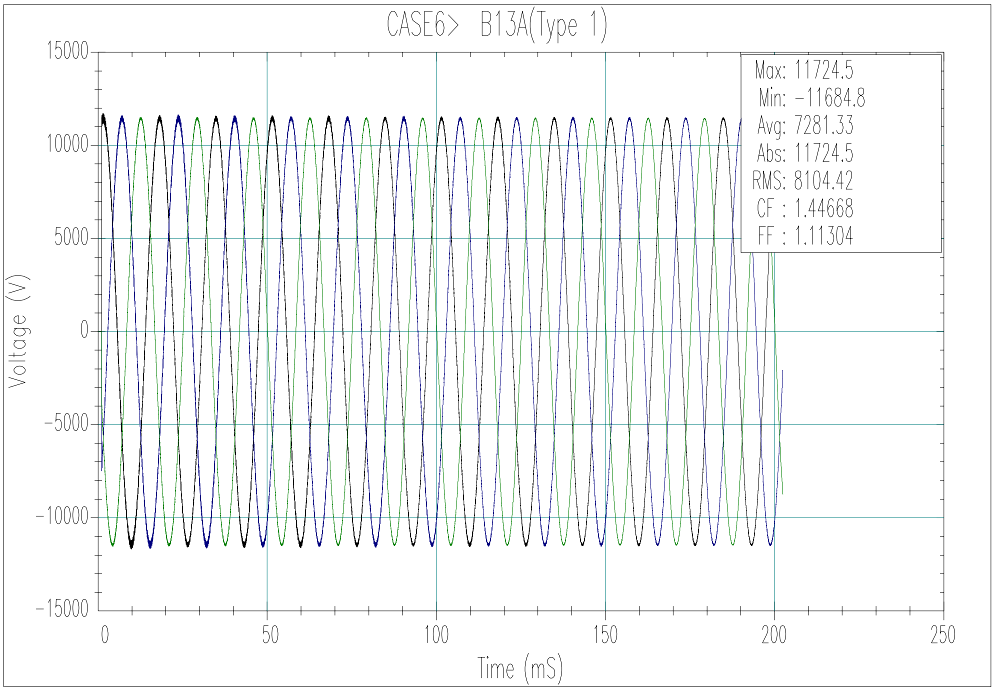
Case 4. 13-kV wye-grounded tertiary



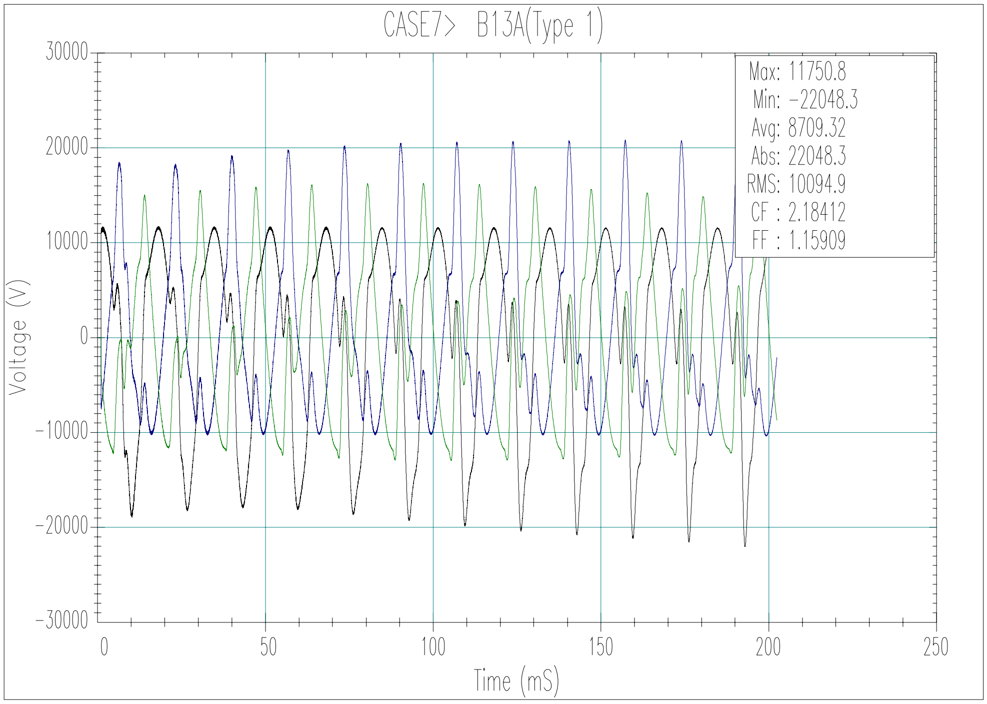
Case 5. 4.16-kV delta tertiary



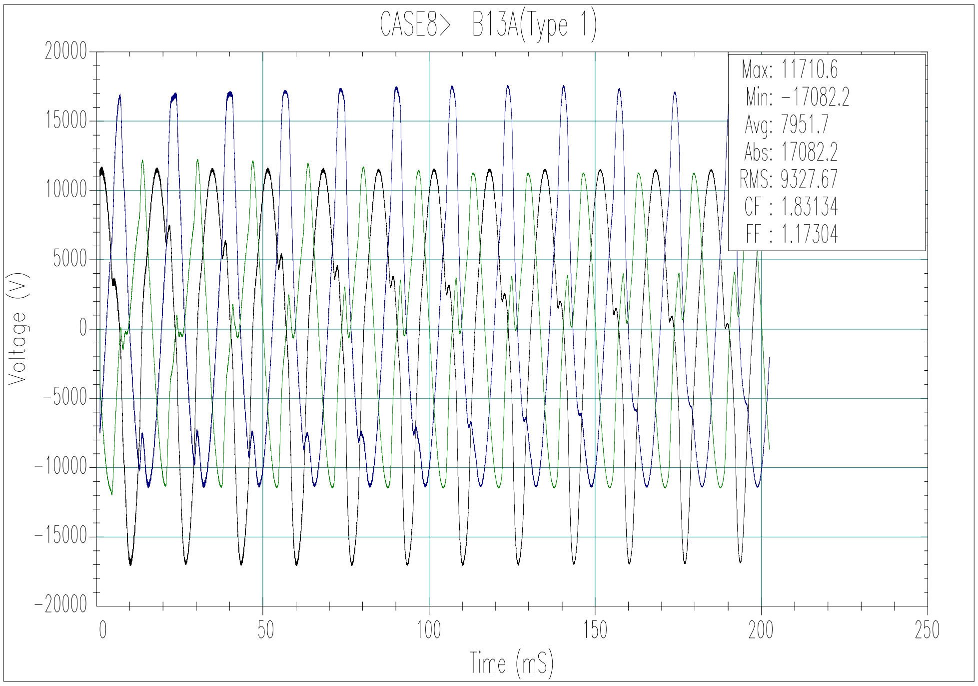
Case 5. 4.16-kV delta tertiary. Waveforms for current drawn by VT magnetizing branch. (unsaturated).



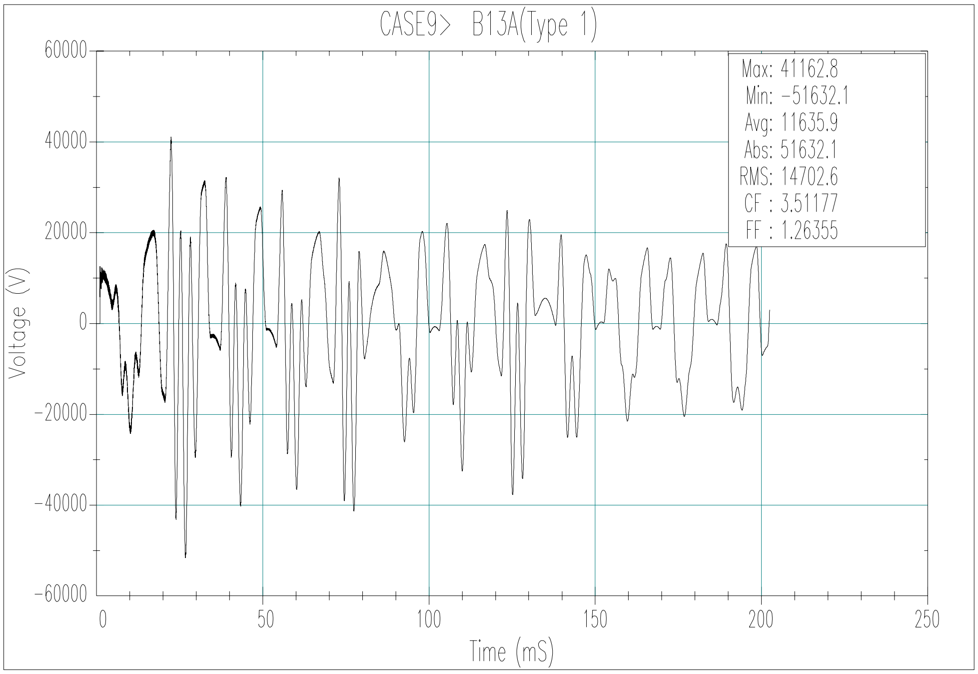
Case 6. Grounding bank connected



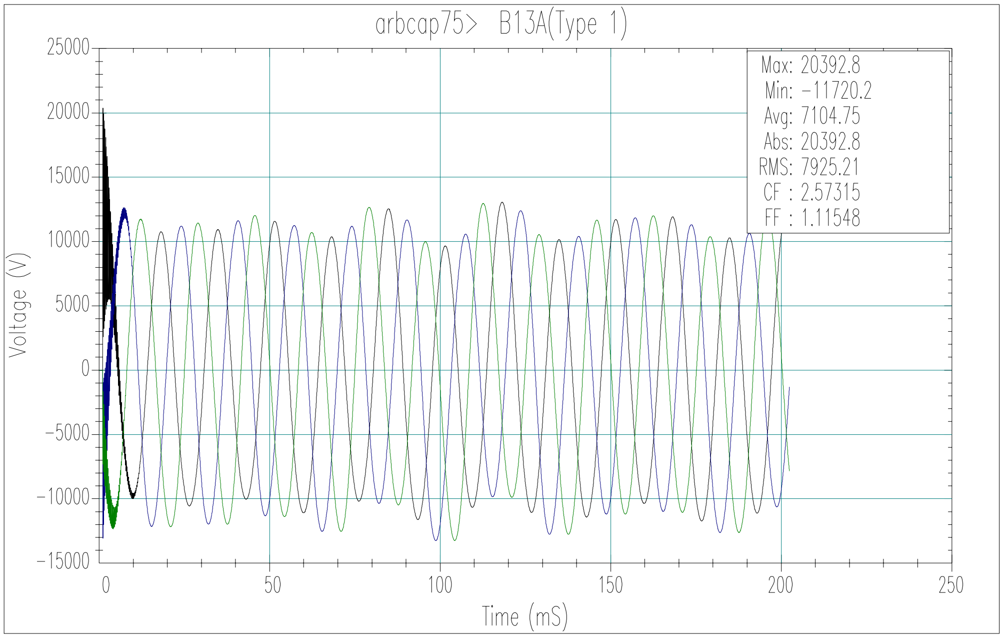
Case 7. VT 30 percent thermal loading



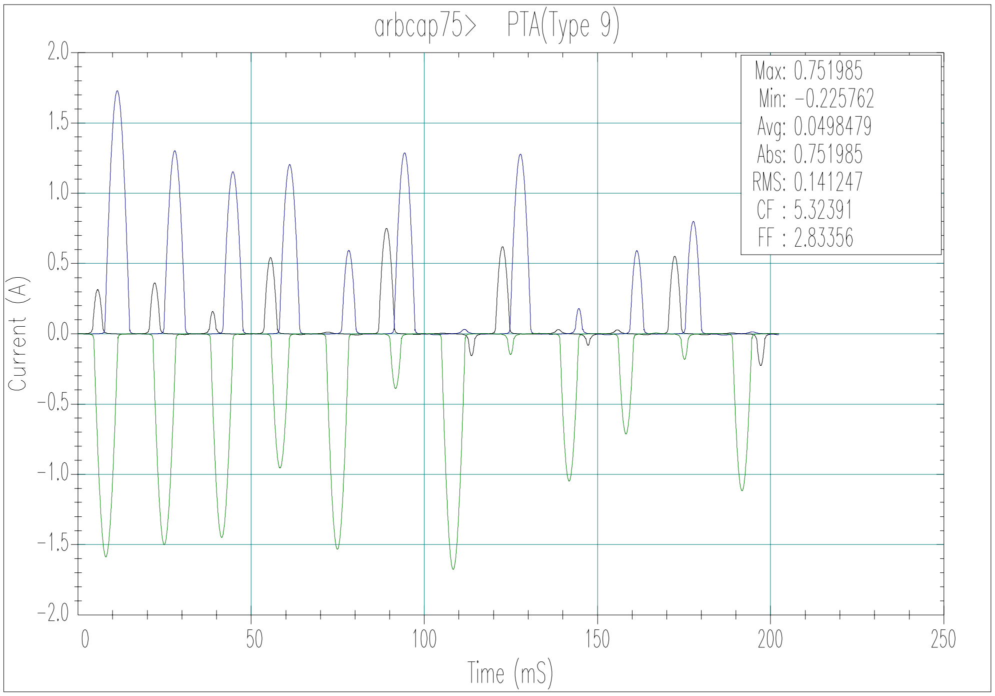
Case 8. VT 100 percent thermal loading



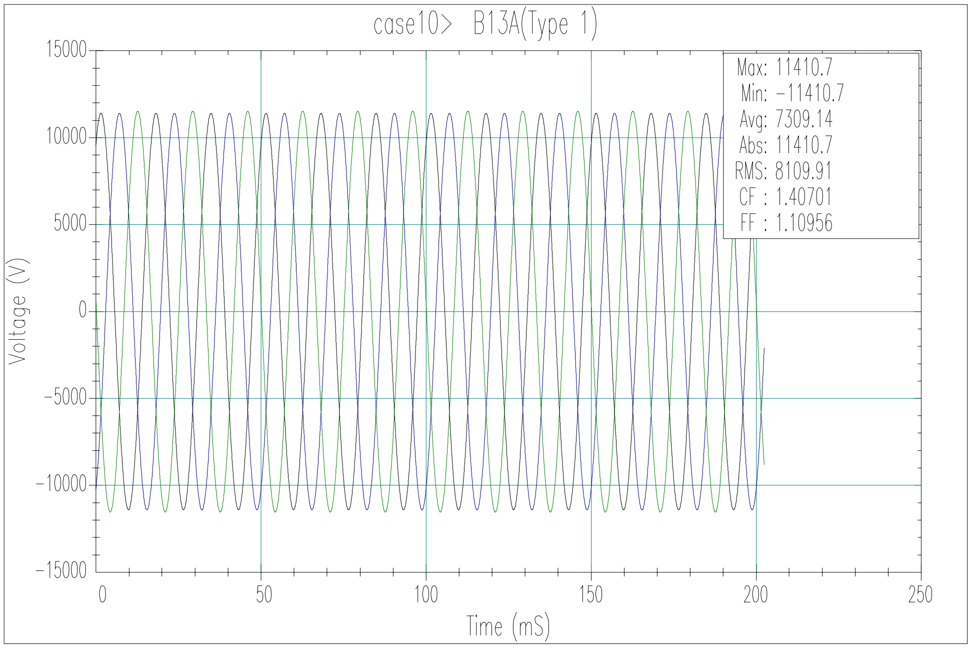
Case 9. High-side bank energization



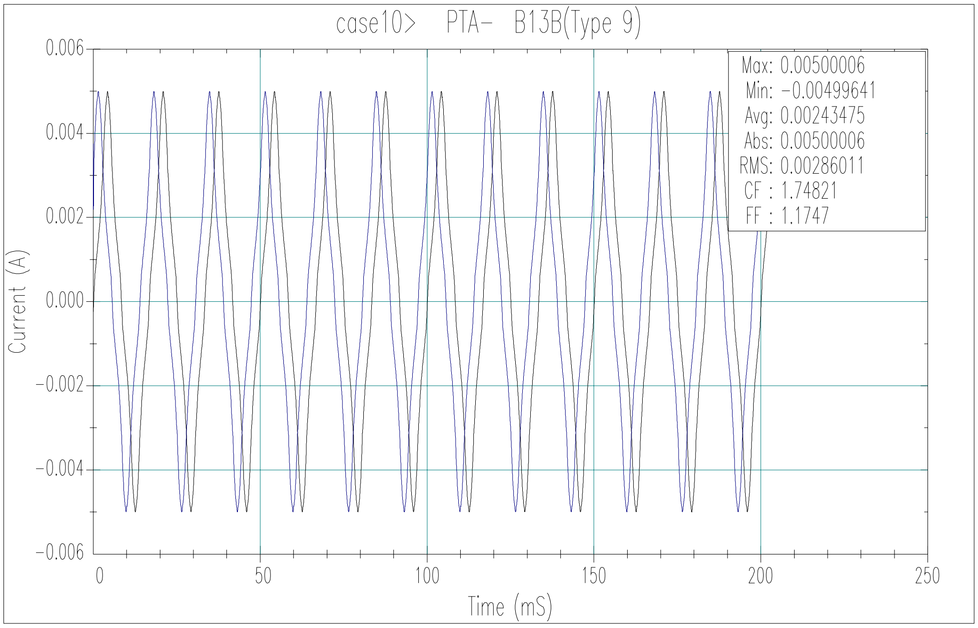
Case 10. With 50-kVAR capacitors connected to 13-kV bus. Voltage waveforms.



Case 10. With 50-kVAR capacitors connected to 13-kV bus. Waveform for current drawn by VT magnetizing branch (unsaturated).



Case 11. With 14400-120V Delta-Y connected VTs. Voltage waveforms.



Case 11. With 14400-120V Delta-Y connected VTs. Waveform for current drawn by VT magnetizing branch (unsaturated).

Appendix D
Disturbance Analyzer Output Graphs for Bus Energization with 14400-120V VTs

BIOGRAPHY

Gary Kobet is Transmission Power Quality Specialist for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. His responsibilities include developing and recommending TVA's transmission power quality program activities. He has performed transient studies using EMTP for breaker TRV studies and station service overvoltages due to switching surges. Previously he has worked as a field engineer and in the System Protection department. Mr. Kobet earned the B.S.E. (electrical) from the University of Alabama in Huntsville in 1989 and the M.S.E.E. from Mississippi State University in 1996. He is a member of Eta Kappa Nu, Tau Beta Pi, and is a registered professional engineer in the state of Alabama.