Mathcad Analysis of Davidson Capacitor Bank Misoperation

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Abstract

This paper describes the analysis of a 161kV capacitor bank residual overcurrent scheme misoperation. Information available included local relay target indication, a digital fault recording from the local DFR, and system dispatcher logs. The dispatcher logs indicated that a 500kV intertie transformer bank one station away had been briefly energized with one phase on the wrong voltage tap. This occurred simultaneous with the 161kV capacitor bank misoperation. The Mathcad[1] (software by Mathsoft Inc.) environment was used to help determine why the zero sequence voltage supervised residual overcurrent (GE SFC) operated. The analysis and subsequent field-testing point out the vulnerability of this protection scheme to harmonic energy and therefore its misapplication to capacitor bank protection. Six months later this same scheme installed at five different substations (separated by hundreds of miles) operated on harmonic energy produced by a different mechanism, geomagnetically induced current. The MATHCAD files developed for this analysis are available at http://webspace.inet75.com/users/rwpatter/mathcad/ and are included in the appendix of this paper.

Abstract Correction

It was intended that a DFR shot of the Davidson capacitor bank misoperation be analyzed as part of this paper. Subsequent to the completion of this paper it was discovered that the shot in hand was not associated with this misoperation. In lieu of processing the actual shot the same methods (in Mathcad) will be demonstrated on another shot in hopes of being beneficial to some engineer in the future.

Biographical Sketch

Russell W. Patterson is a Project Specialist, System Protection for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. He is responsible for reviewing and making protective relaying recommendations on new construction and retrofit projects for the generation and transmission system. Russell also has responsibility for protective relaying and control settings and field support. Prior to his position as Project Specialist Russell was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances. Russell has performed transient simulations using EMTP for breaker Transient Recovery Voltage (TRV) studies including recommending mitigation techniques. Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991 and has completed all coursework toward the M.S.E.E. at Mississippi State University. Russell is a registered professional engineer in the state of Tennessee. Russell can be e-mailed at rwpatterson@tva.gov or russpatterson@inet75.com.

Background

On October 27, 1999 at 7:02AM (CST) TVA's Johnsonville Steam Plant 500kV to 161kV intertie transformer bank was energized with one phase on the wrong tap. Simultaneous with this energization the 161kV capacitor bank at the neighboring Davidson 500kV substation tripped by residual overcurrent relay (GE SFC). The residual overcurrent relay is supervised by a zero sequence voltage relay (Westinghouse SV).

The Johnsonville Steam Plant 500kV intertie bank is comprised of single-phase three-winding units rated 240/320/400 MVA connected Yn-yr-d. The Davidson 500kV substation is electrically connected to Johnsonville via a 57 mile 500kV transmission line. There are two 500kV to 161kV intertie banks at Davidson (single-phase units) connected Yn-yr-d. One rated 180/360/400 MVA, the second rated 268.8/358.4/448. Both Davidson banks and the Johnsonville bank have 4.5 ohm reactors in the 161kV neutrals. The Davidson 161kV capacitor bank is comprised of two 84 MVAR capacitor banks with seven series groups per phase. Each series group is made up of 20 – 13.2kV, 200kVAR capacitor units. Figure 1 below shows the simplified single line.

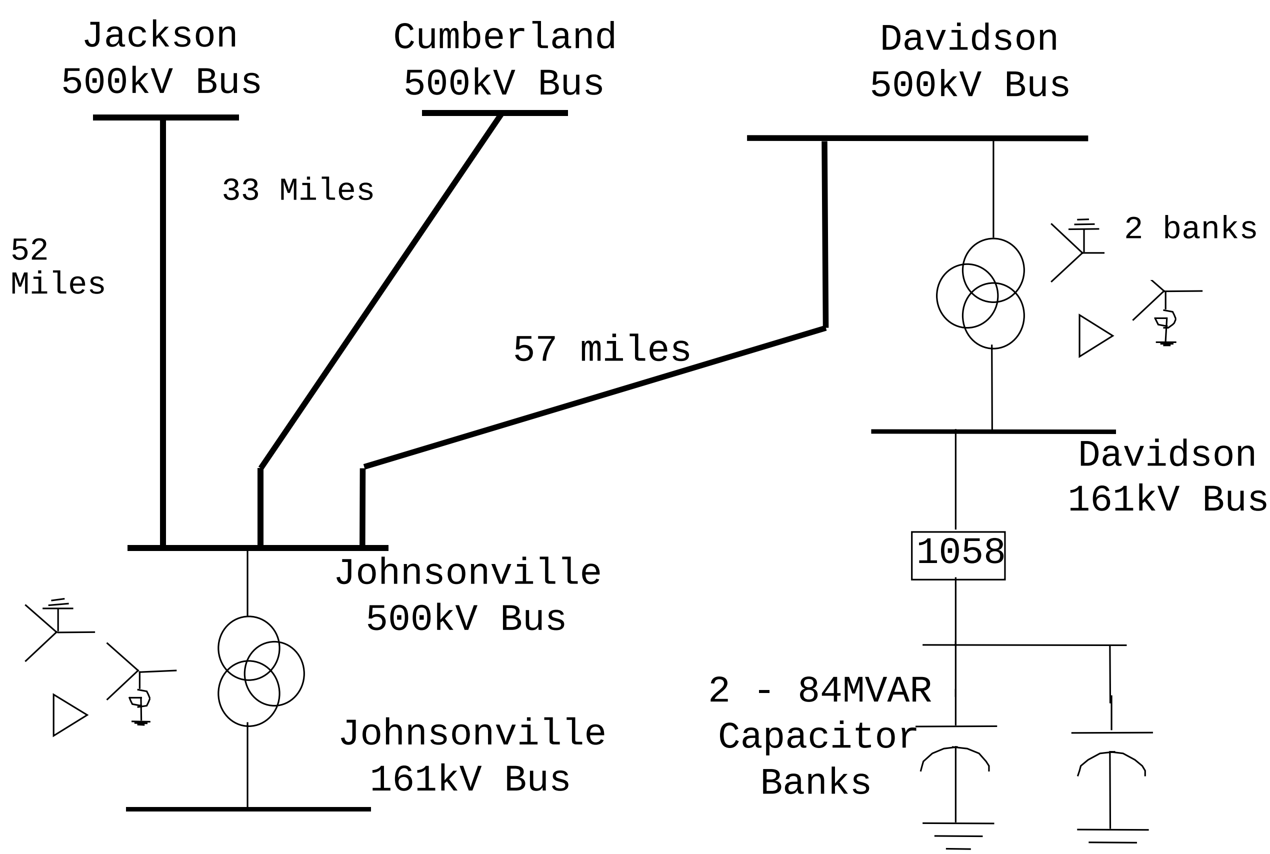


Figure 1. Single line of the network between Davidson and Johnsonville.

Part of the Davidson 161kV capacitor bank protection consists of the SFC (obsolete static type) overcurrent relay supervised by an SV (electromechanical plunger type) voltage relay. The SFC relay operates on the residual current from the capacitor bank breaker. This relay has a primary pickup of 38.4A with a time lever setting of 2 which results in the following characteristic curve:

% of pickup→	150%	200%	300%	500%	1000%
trip time →	90~	63~	43~	32~	25~

The SV relay operates on zero sequence voltage from the broken delta connection of the 161kV bus PTs. Its pickup is 7,200V primary 3V0 at 60Hz. Figure 2 shows this relaying in single line form.

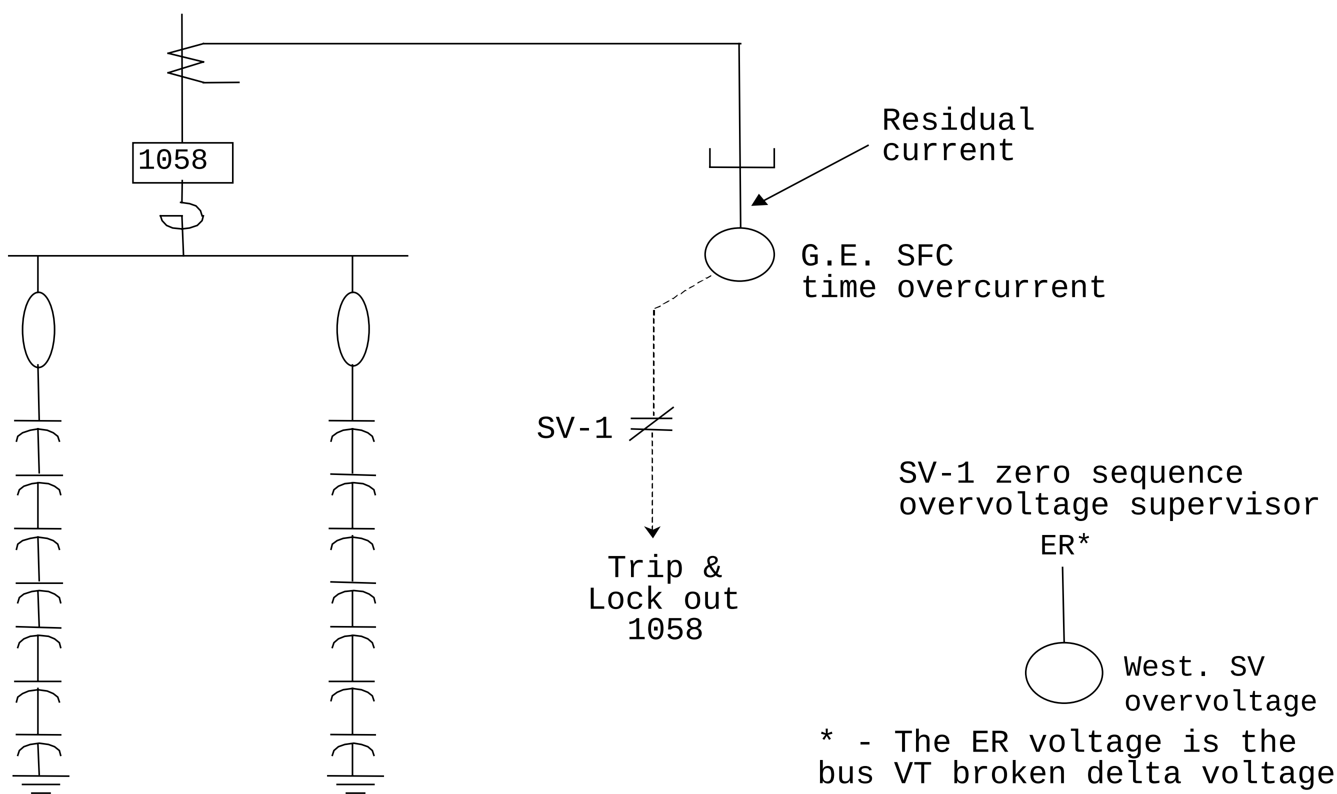


Figure 2. Single line of Davidson 161kV capacitor bank residual o.c. protection.

This scheme is designed to be a backup to capacitor unbalance protection and its overcurrent pickup is only marginally below the residual current that would flow due to the loss of one complete series group (seven groups parallel per phase, one group having 43A normal load current). The SFC is supervised by the SV zero sequence overvoltage relay to prevent its operation on normal zero sequence current from the capacitor bank that flows when 161kV system ground faults occur. The zero sequence voltage that is produced by system ground faults is significantly higher than the zero sequence voltage present due to capacitor bank unbalances, thus allowing discrimination between the two. The zero sequence voltage on the bus due to unbalance in the grounded wye capacitor bank can be simply calculated by taking the zero sequence current from the bank and multiplying times the zero sequence thevenin equivalent at the bus (e.g. If you have 10A in the capacitor bank neutral and the zero sequence thevenin at the bus is 9Ω the zero sequence voltage will be 10/3 x 9 = 30V). Alternatively, you can abuse yourself by solving a networks problem with the sequence equivalent of the unbalanced capacitor bank[2] which produces the same result.

The SV relays voltage pickup is typically set 150% below the lowest zero sequence voltage present for line end ground faults. In general this is significantly above the unbalance present for one complete phase open on the capacitor banks. This supervision allows a low residual overcurrent pickup setting while providing security against misoperation on 161kV ground faults. This scheme operated at Davidson when the Johnsonville Steam Plant 500kV intertie bank was energized with A-phase on the wrong voltage tap.

Analysis

The only clues to this misoperation where the dispatcher logs indicating that the Davidson 161kV capacitor bank tripped by SFC relay simultaneous with the energization of the Johnsonville Steam Plant 500kV intertie bank. Subsequent information from the field indicated that the A-phase transformer had been on 20.7:1 tap and the B and C phase transformers had been on 22.7:1. Since the 500kV and 161kV windings have taps these ratios are given with respect to the 13kV winding (it has no taps so can be a fixed reference). A 20.7:1 ratio indicates a tap of 20.7 x 13kV = 269.1kV. A 22.7 tap would be 295kV.

It is at this point that it was discovered (much to the authors dismay and with raucous laughter from his friends) that an unrelated DFR shot was being analyzed. The following several pages are still included, however, to show the method used in Mathcad for this analysis. The author hopes it will be of some benefit. The actual shot being analyzed occurred for a 161kV ground fault several buses away that was cleared by instantaneous ground relay.

The capacitor bank currents were not available so only the 161kV voltages were analyzed. The three phase-neutral voltages were converted to COMTRADE file format and imported into Mathcad for analysis.   Below, in Figure 3, is a plot of the three 161kV bus voltages. A noticeable dip in A-phase can be seen around the 2000 sample mark.

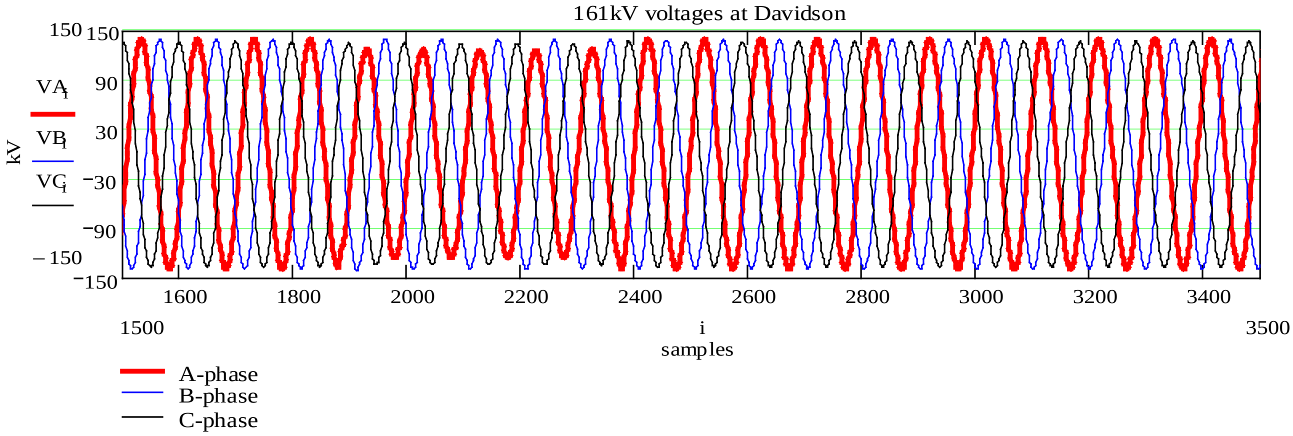


Figure 3. <u>A-phase voltage dips during ground fault event (heavy trace).</u>

The next figure shows the sum of the three phase-neutral voltages (VA+VB+VC = 3VO). The horizontal line is the 7200V line marking the RMS level of zero sequence voltage required to operate the SV voltage relay at 60Hz. The trace that travels just below this 7200V threshold during the event is the RMS value of the fundamental component of the 3V0 voltage.

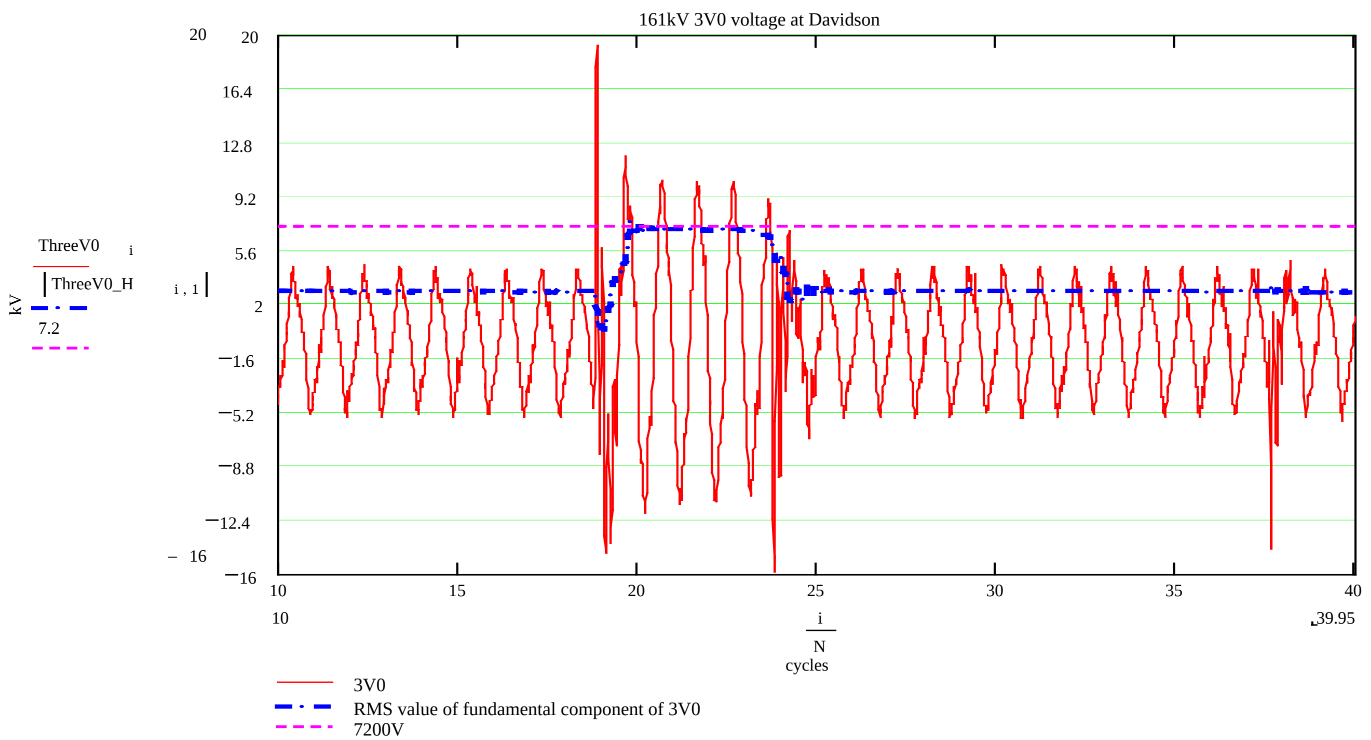


Figure 4. <u>Graph of 161kV 3V0, RMS of fundamental component, and SV pickup.</u>

The instruction book for the SV relay indicates that this relays pickup is proportional to frequency. In other words, if the frequency goes up by a factor of 1.25 the pickup voltage increases by that same factor. So, if the relay is set to pickup at 7200V at 60Hz it will pickup at 14,400V at 120Hz. In Figure 5 a plot of the first 15 harmonics of the 3V0 voltage are shown. Figure 6 shows the harmonics that are most significant in magnitude during the 5 cycles of the event.

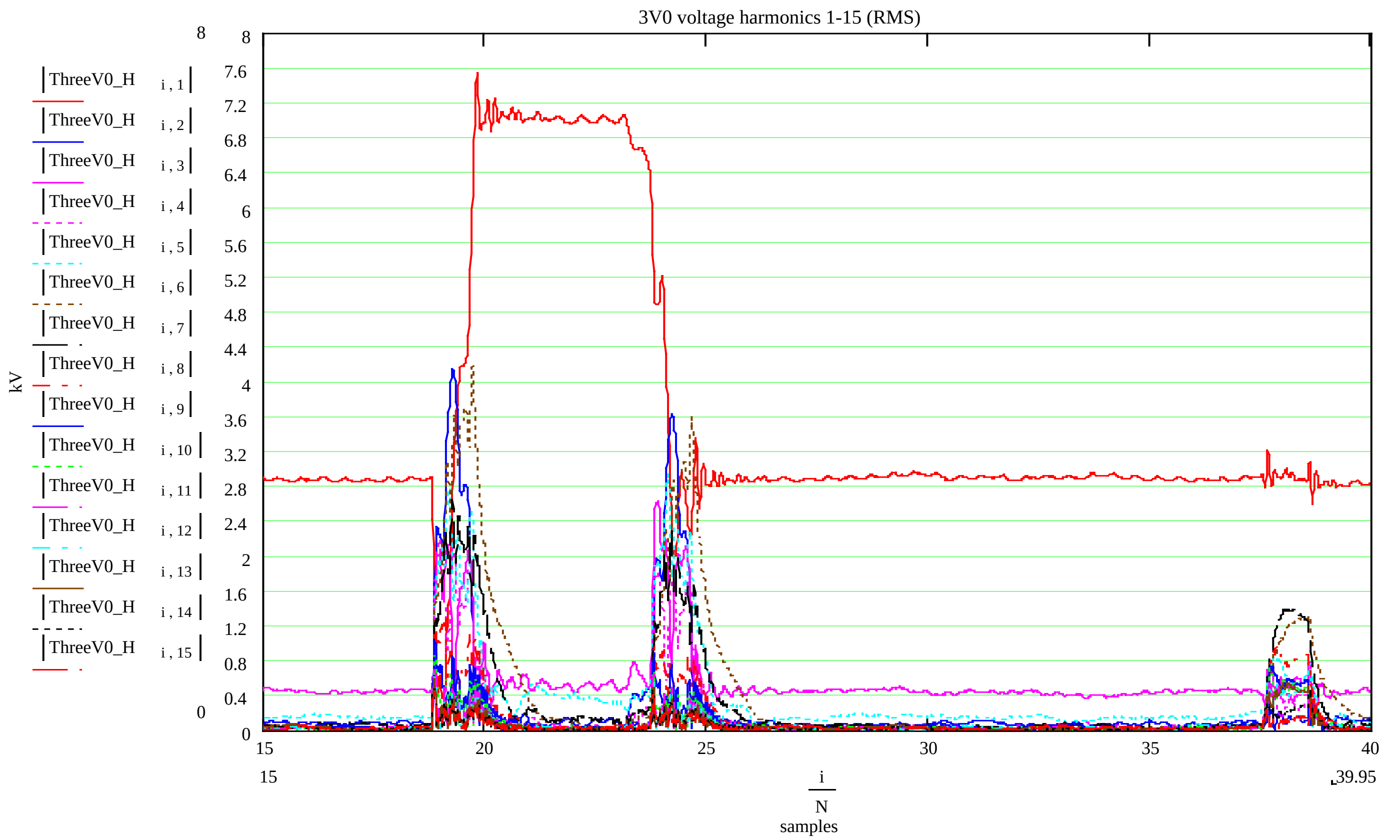


Figure 5. Harmonics 1 through 15 of the 3V0 voltage (RMS values).

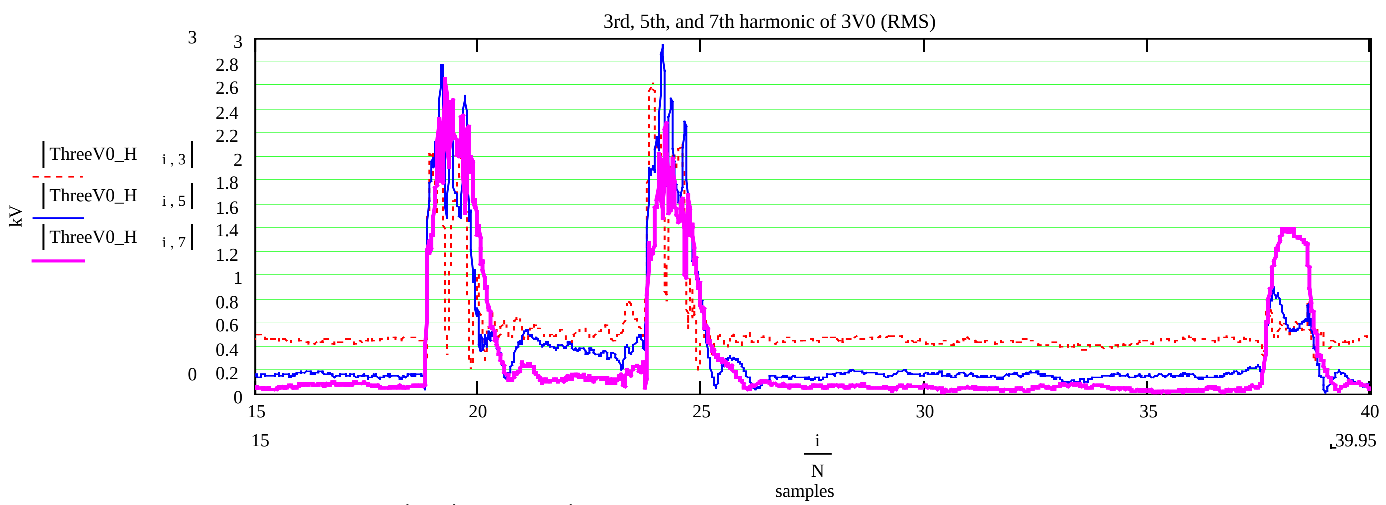


Figure 6. 3rd, 5th, and 7th harmonics of the 3V0 voltage (RMS).

If this had been the correct shot, a way to estimate the neutral current in the capacitor banks would have been to take the 3V0 voltage at each harmonic and divide by the harmonic impedance of the banks (assuming 150Ω impedance at 60Hz). At the higher harmonics the outrush suppression reactance would have to have been considered (1600uH phase reactors).

$$I_1 = 7200V / 150\Omega = 48A \quad \text{(60Hz current)}$$

$$I_3 = 600V / 50\Omega = 12A \quad \text{(180Hz current)}$$

$$I_5 = 400V / 30\Omega = 13\tfrac{1}{2}A \quad \text{(300Hz current)}$$

$$I_7 = 200V / 21\Omega = 9\tfrac{1}{2}\ A \quad \text{(420Hz current)}$$

Since the RMS values from different frequencies in the same signal add according to squares we get:

$$I_{RMS} = \sqrt{(48^2 + 12^2 + 13.5^2 + 9.5^2}\ A$$

$$I_{RMS} = 52.2A$$

Had this been the correct DFR shot this is the current seen by the relay (just under 140% of pickup) between the large perturbations or between the 20 and 25 cycle mark shown in Figure 6. Had the correct DFR shot been analyzed, it would have shown the 60Hz component of the 3V0 voltage below the 7200V pickup of the SV relay and enough harmonic current possible to have operated the SFC relay. Reports indicate that a large neutral current was noticed after energizing the Johnsonville bank, and they were quickly de-energized.

Testing

TVA field test personnel (see Appendix A for actual test report) bench tested the SFC relay to ascertain its frequency performance. The relay was tested up to the 14^{th} harmonic and was shown to have a flat frequency response. (i.e., The relay operates the same when it sees 5A at 480Hz as it does for 5A at 60Hz).

Additional Ramifications

The above analysis of the unrelated DFR shot at Davidson did result in a test of the relay that shows us its frequency characteristic. This was useful information when analyzing the simultaneous operation of SFC relays all over the TVA region on July 15 during a geomagnetic event.

The following table summarizes the tripping of capacitor banks across the TVA region on Saturday, July 15, 2000. Appendix C shows one page of a report from 1991 identifying this same problem during the previous solar cycle. Predictive "early warning" services are now available to predict these GIC events[3].

Trip Time (CST)	Location	Tripping relay
0939:01	Madison, AL 161kV	GE SFC
0939:01	New Albany, MS 161kV	GE SFC
1203:34	Philadelphia, MS	GE SFC
1328:00	"	"
1500:24	"	"
1633:00	"	"
1652:37	"	"
1656:00	"	"
1749:06	"	"
1757:00	"	"
1541:00	Davidson, TN 161kV	GE SFC
1203:35	Freeport, TN 161kV	S&C UP
1329:00	"	"
1545:00	"	"
1633:00	"	"
1541:00	Jackson, TN 161kV	GE SFC and S&C GPS

Table 1. List of July 15th capacitor bank operation times from dispatching logs.

It can be seen that several of these capacitor bank trips at different locations occurred simultaneously. These locations are separated by hundreds of miles (see Figure 7) as calculated from longitude and latitude[4].

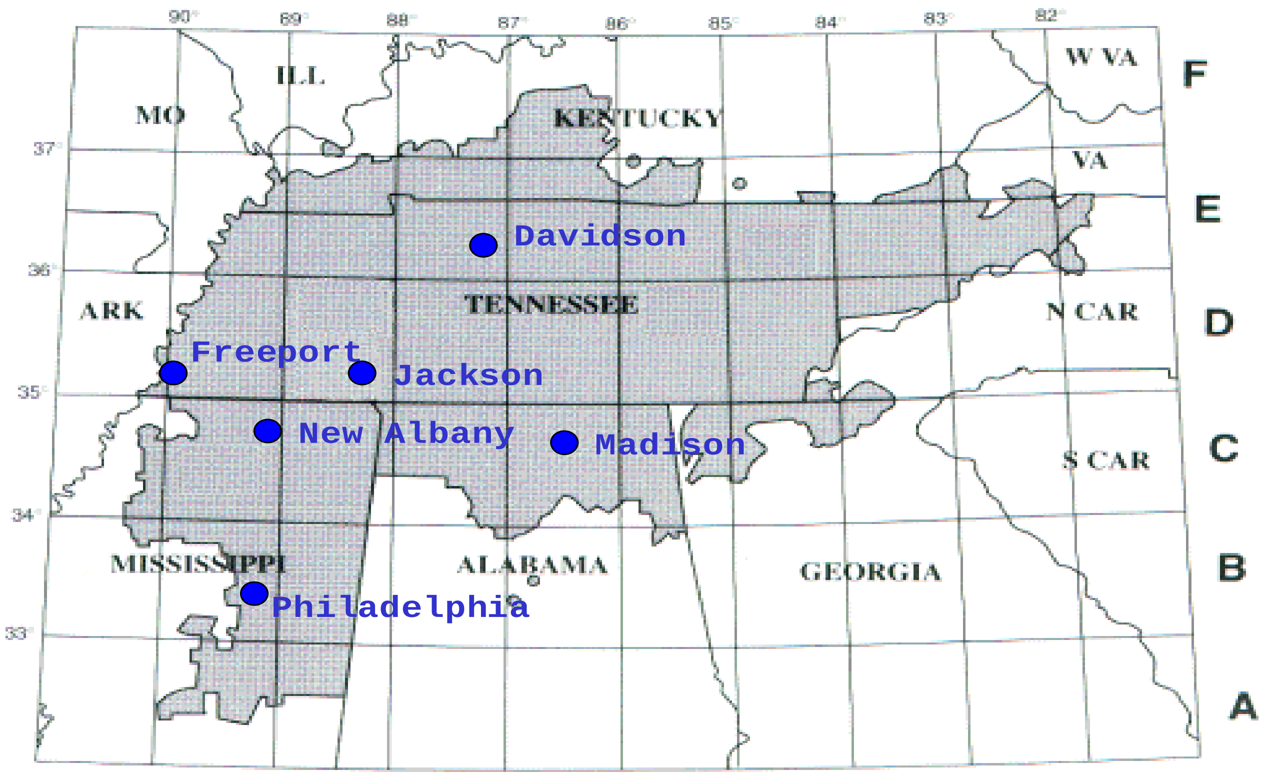


Figure 7. Geographic dispersal of simultaneous capacitor bank trips by SFC relay.

A quick look at the NASA space weather website[5] showed that one of the largest solar storms in a decade had occurred prior to this event and was the most likely candidate for the subsequent geomagnetic activity. During a geomagnetic event quasi-DC currents are induced in the earth. These currents find a path up the neutrals and over the transmission lines of our transmission systems. When these DC currents flow in transformers they can produce varying degrees of half-wave saturation. The saturation produces harmonics that find a convenient path to ground through the capacitor banks. This is a problem for the capacitor banks because they are absorbing harmonic energy. The following is an excerpt from a working group draft of IEEE 1036 (as of July 2000):

The effect of the harmonic components on the capacitor bank is to cause additional heating and higher dielectric stress. IEEE Std 18 gives limitations on voltage, current, and reactive power for capacitor banks, which can be used to determine the maximum allowable harmonic levels. IEEE Std 18 indicates that the capacitor can be applied continuously within the following limitations, including harmonic components:

- **a) 110% of rated rms voltage**
- **b) 120% of rated peak voltage**
- **c) 135% of nominal rms current, based on rated kvar and rated voltage.**
- **d) 135% of rated reactive power**

The point is that, even though the SFC relays misoperated, it *may* have been beneficial from the capacitor bank's perspective. This point was brought up during internal TVA discussions pertaining to the replacement of the SFC relays. It is this author's position that the SFC should be replaced because its function is for 60Hz protection of the capacitor bank. The SFC is not well suited to protecting the capacitors from harmonic energy because it only sees those harmonics that add in the neutral. It does not see positive or negative sequence harmonics (see Appendix D).

Conclusion

Analyzing every unexplained relay operation (even when the cause seems apparent) builds a knowledge base and insight into the operation of the protective schemes that can pay off in the future. The SFC relay was shown to be a poor choice for 60Hz protection of a capacitor bank due to its flat harmonic response. Similarly, it is not well suited to protecting the capacitor banks from harmonic energy since it only sees triplen (zero sequence harmonics e.g. 3, 6, 9, 12, etc.) and asymmetrical (see Appendix D) harmonic current. A more significant consideration is the susceptibility of this scheme to the harmonic energy that occurs during power transformer half-wave saturation during geomagnetic events. On Saturday, July 15, 2000 TVA experienced the loss of over 800MVAR of capacitor banks. This loss during peak hours on a weekday would have likely been catastrophic not excluding the possibility of grid collapse.

Appendix A - Field test report on GE SFC relay frequency response.

The relay settings show a critical pickup at 500% (5 times pickup) of 32 cycles. This was the test point used with only the frequency being varied between tests.

Test: TIMEI PASS CRITICAL PU CHECK PICKUP @ CRITICAL

Source	Amplitude	Phase	Freq
I1	ACTION	0	VARIOUS

ProTesT v.1.61 Test Results 02/03/00

Location 1: DAVIDSON 500 KV SUB. Terminal 24: CAPACITOR BANK RELAYS

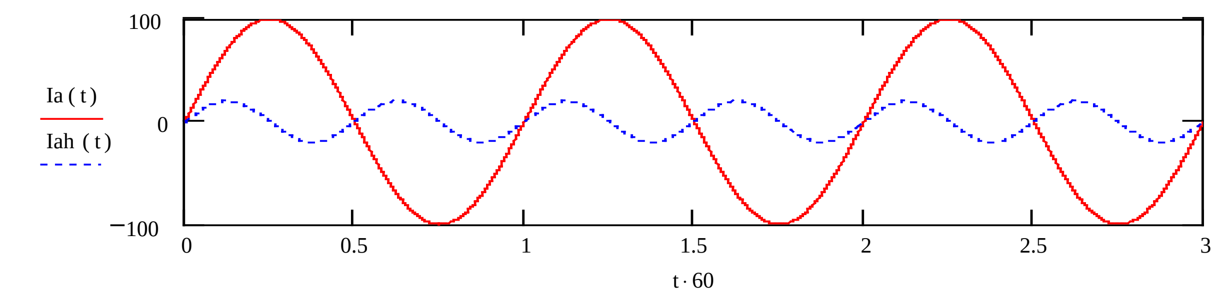
Relay 4: 12SFC151D1A S/N: 8837 Fct: RESIDUAL GROUND

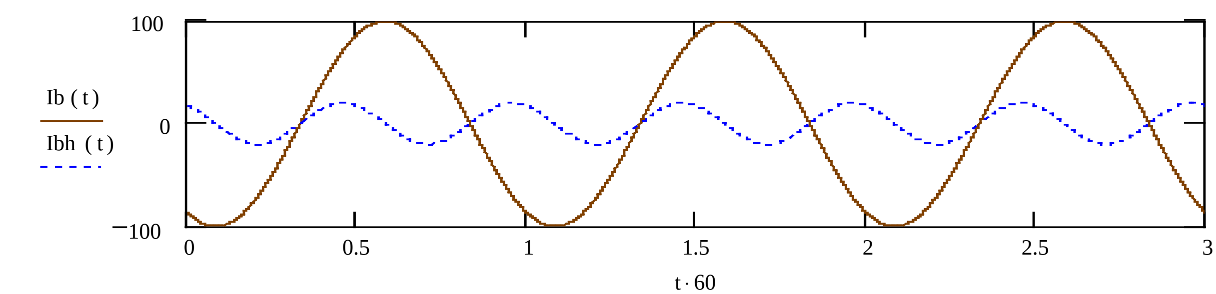
FREQ	Actual CYCLE	Expect	Error	P/F	Date	Time	Operator
840	31.243	32.000	-2.4	P	02/03/00	12:00:09	JDS
780	31.262	32.000	-2.3	P	02/03/00	11:59:36	JDS
720	31.283	32.000	-2.2	P	02/03/00	11:59:14	JDS
660	31.302	32.000	-2.2	P	02/03/00	11:58:53	JDS
600	31.323	32.000	-2.1	P	02/03/00	11:58:36	JDS
540	31.354	32.000	-2.0	P	02/03/00	11:58:18	JDS
480	31.381	32.000	-1.9	P	02/03/00	11:57:53	JDS
420	31.413	32.000	-1.8	P	02/03/00	11:57:38	JDS
360	31.459	32.000	-1.7	P	02/03/00	11:57:15	JDS
300	31.507	32.000	-1.5	P	02/03/00	11:57:00	JDS
240	31.560	32.000	-1.4	P	02/03/00	11:56:38	JDS
180	31.569	32.000	-1.3	P	02/03/00	11:56:09	JDS
120	31.654	32.000	-1.1	P	02/03/00	11:55:39	JDS
60	31.836	32.000	-0.5	P	02/03/00	11:55:07	JDS

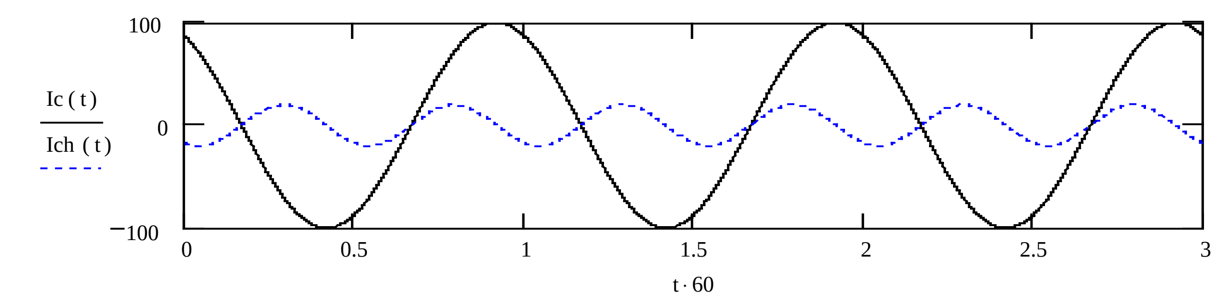
This important test was done courtesy Kirk Woodard and Jimmy Scarborough and others.

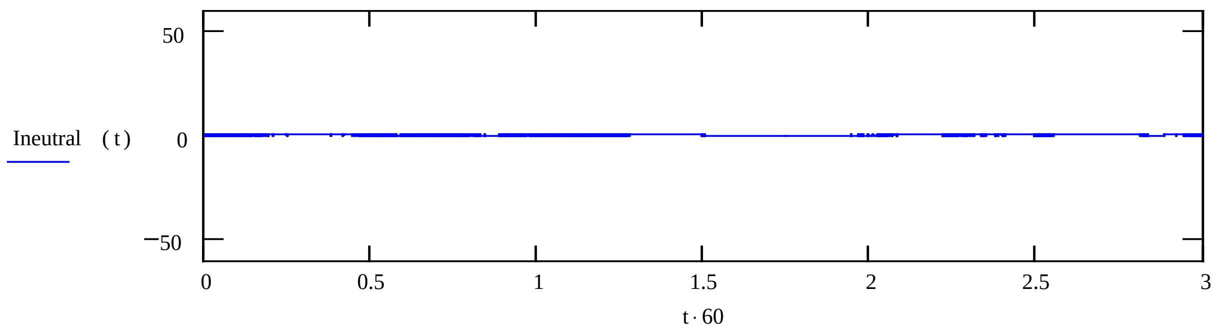
Appendix B – Positive, negative, and zero sequence harmonics.

The harmonics of 60Hz that behave as positive sequence are 1, 4, 7, 10, 13, etc. Those that behave as negative sequence are 2, 5, 8, 11, 14 etc. Those that behave as zero sequence (sum in the neutral) are 3, 6, 9, 12, 15 etc. and are also referred to as "triplen" harmonics[6]. This behavior depends on the harmonics being generated symmetrically across the three phases (magnitude and relative phase angle). Below are 3 cycle plots of A, B, and C 60Hz phase currents along with a 20% 2^{nd} harmonic that might be superimposed on these currents. The 2^{nd} harmonic is a negative sequence harmonic so the three components in each phase sum to zero at the neutral. Note that the harmonic energy is symmetrical across the phases because they have the same magnitude and phase angle relative to each 60Hz phase current.

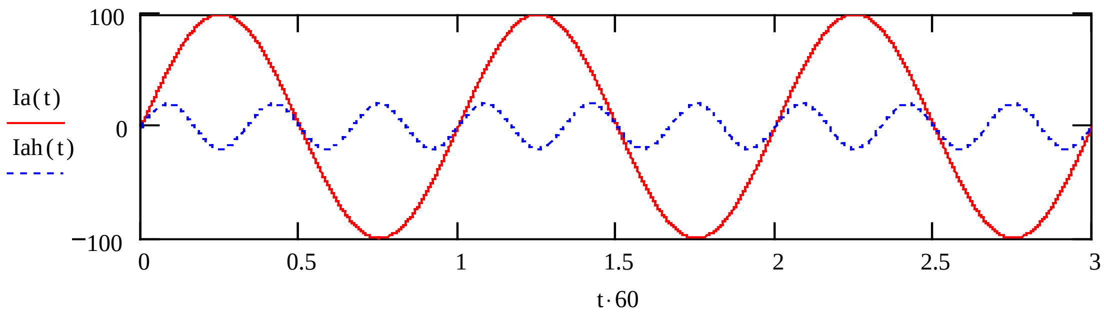


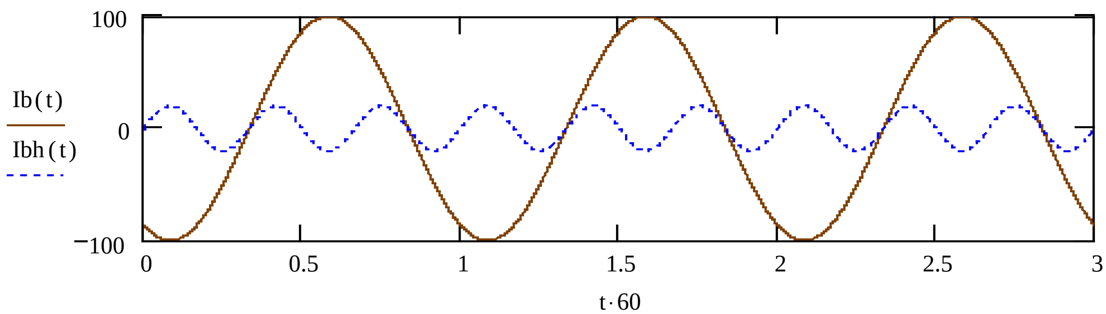


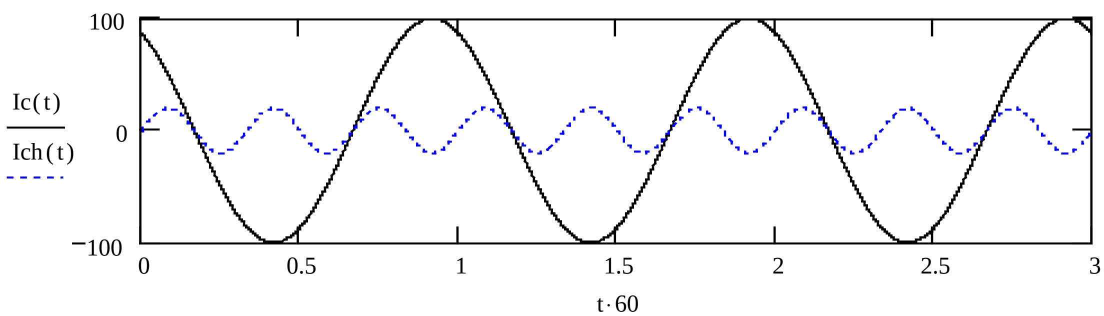


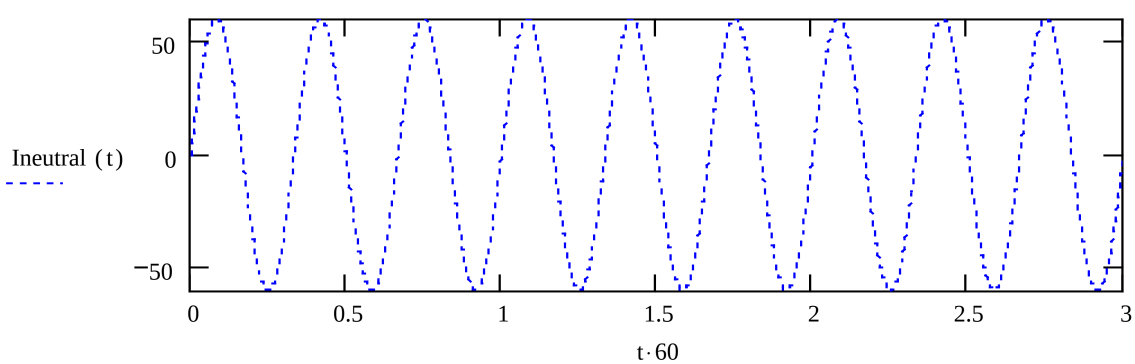


Below are 3 cycle plots of A, B, and C 60Hz phase currents along with a 20% 3rd harmonic that might be superimposed on these waveforms. The 3rd harmonic is a zero sequence (triplen) harmonic so the components in each of the three phases sum to three times in the neutral.









Appendix C - Excerpt from system event review report in November, 1991.

J05 On October 28, a solar magnetic disturbance (SMD) of K-9 intensity resulted in three reported unusual events on the TVA system. A 161-kV capacitor bank tripped by backup ground relay operation at West Point 500-kV Substation. A low voltage alarm came into the Nashville ADCC from the Maury 500-kV Substation. The Wilson 500-kV Substation experienced a noticeable increase in the audible noise generated by the 500/161/13-kV transformer bank and the oscillograph recorded detectible harmonics in the 500-kV voltage for more than 20 seconds. All three events happened simultaneously. There were no interruptions or known equipment damage as a result of these incidents. The K-9 level SMD was reported to TOD two days later.

1. What method is used to quickly inform the ADCC offices that a potentially significant SMD is underway so that appropriate actions/responses can be made? Is there any quicker source of information? JJB/JBG

2. Was there a correlation between the reported SMD, the above events, and the magnetic and GIC monitoring stations maintain by Energy Research? Could alarms or SMD status indicators be conveniently developed from these installations to more quickly inform us of impending SMD events? JBG

3. Can the ground relay characteristic or setting on the 161-kV capacitor bank at West Point be changed to make it less sensitive to the harmonic currents associated with SMDs? BWS/DMA

4. Has the Wilson 500-kV bank been tested after this reported incident? Should it be? JWC/MBG

This agenda was prepared by Gary Bullock, Customer Group (6002-C)
Hms GCB
HMS:GCB
11/4/91
0049D

Appendix D - Mathcad 2001 Professional data files.

Note: The methods used can be implemented in older versions of Mathcad as well. The first file below calculates the RMS values of the harmonics of the 3V0 voltage from fundamental to 15th harmonic.

$\text{Input} := \text{READPRN}(\text{"e:\\davidson\\data1011.dat"})$ <-- input data from COMTRADE data file.

$VA := (0.145064 \cdot \text{Input})^{\langle 2 \rangle}$ $VB := (0.145064 \cdot \text{Input})^{\langle 3 \rangle}$ $VC := (0.145064 \cdot \text{Input})^{\langle 4 \rangle}$ <-- Scale the 3rd, 4th and 5th data columns as per C37.111-1991 (a newer COMTRADE standard is now out.)

$N := 100$ samples/cycle $nmax := \text{rows}(\text{Input})$ $nmax = 4096$ $h := 1..15$

$n := 0, 1..nmax - 1$ $i := 0..(nmax - N - 1)$ $k := N..nmax - 1$

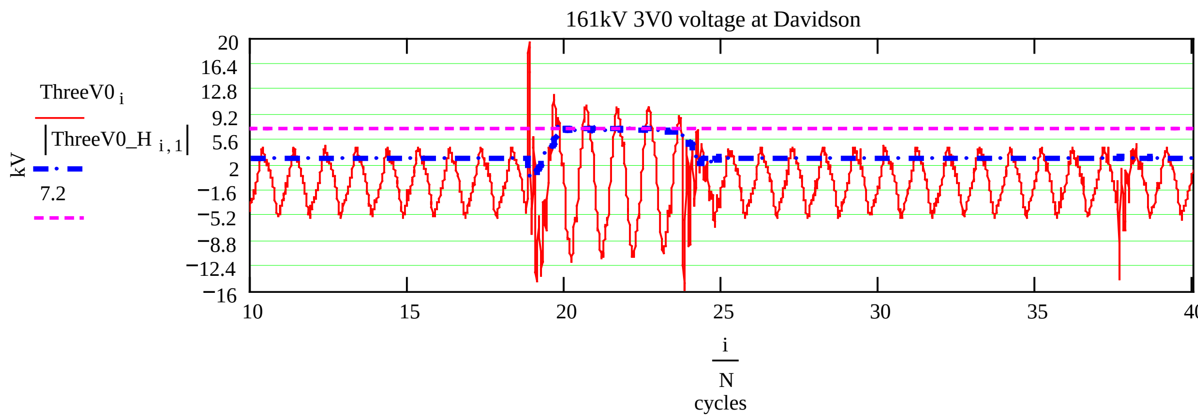
<-- The EMAX recorder that took the shot samples at 100 samples/cycle. The variable nmax is the number of data points in the event. The variable h is the number of harmonics to analyze.

$ThreeV0_n := VA_n + VB_n + VC_n$ <-- the ThreeV0 vector is just the sum of the phase voltages.

Harmonic analysis

$$ThreeV0\_H_{k,h} := \frac{2}{N} \cdot \sum_{n=k-N+1}^{k} ThreeV0_n \cdot e^{-j \cdot n \cdot \frac{h \cdot 2 \cdot \pi}{N}} \qquad ThreeV0\_H_{k,h} := \frac{ThreeV0\_H_{k,h}}{\sqrt{2}}$$

<-- The equation with the summation symbol is where the work is being done. This formula performs the discrete Fourier transform using a "sliding" window of 100 data points. This is done for fundamental through the "h" harmonic. Since the results of this are in peak magnitudes the RMS values are obtained by dividing by root 2.



Note: Importing ASCII COMTRADE data is as easy as reading comma separated data. There are several methods of reading data into Mathcad. The path chosen in this data file (see VA:= input equation at top) references the first column of data as column 0. The A-phase voltage is at column 3 so it is referenced as 2. The data is scaled as per C37.111 by the "a" constant of "0.145064" from the associated CFG file. This satisfies the equation ax+b with b = 0 in the CFG file.

Some explanation is in order for the "sliding DFT" being used. The digital Fourier transform is meaningful when you have enough samples to create one complete cycle of the fundamental waveform. In this case we require 100 samples to make one waveform since the fundamental is 60Hz. The "sliding" comes in because this routine takes the first 100 data points and spits out the harmonic content, then it drops off the first data point and adds in the 101st data point. In this manner it "slides" down the waveform spitting out harmonic content values with a 100 data point wide window. This next Mathcad file creates the harmonic plots to demonstraight the positive, negative, and zero sequence behavior of symmetrical harmonics. A is the magnitude of the fundamental used, H is the magnitude of the harmonic used, and h is the harmonic number (3rd harmonic in this particular case).

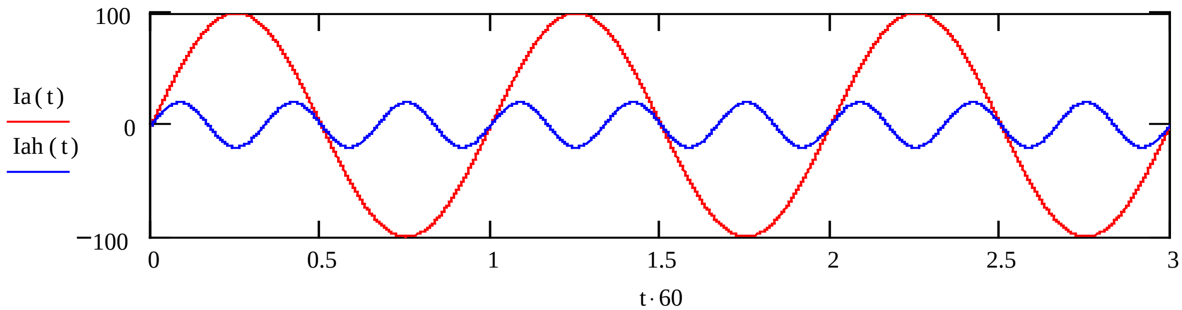
$A := 100 \qquad t := 0, .00001 .. .05 \qquad H := 20 \qquad h := 3$

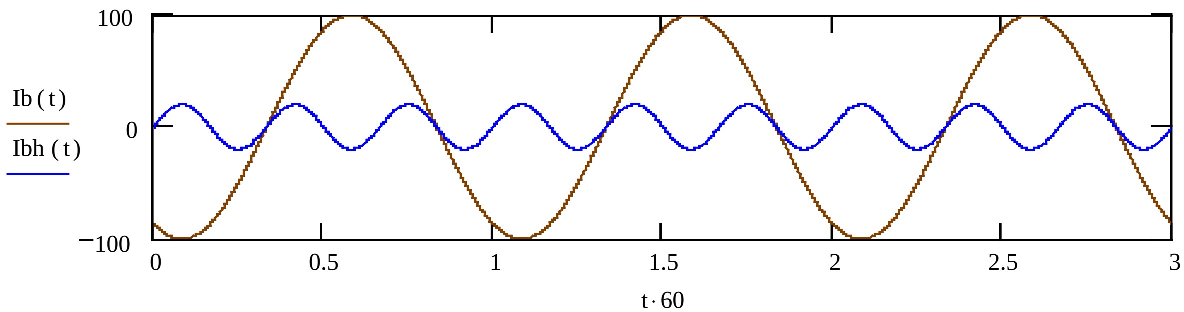
$Ia(t) := A \cdot \sin(2 \cdot \pi 60 \cdot t) \qquad Ib(t) := A \cdot \sin\left(2 \cdot \pi 60 \cdot t - 2\frac{\pi}{3}\right) \qquad Ic(t) := A \cdot \sin\left(2 \cdot \pi 60 \cdot t + \frac{2\pi}{3}\right)$

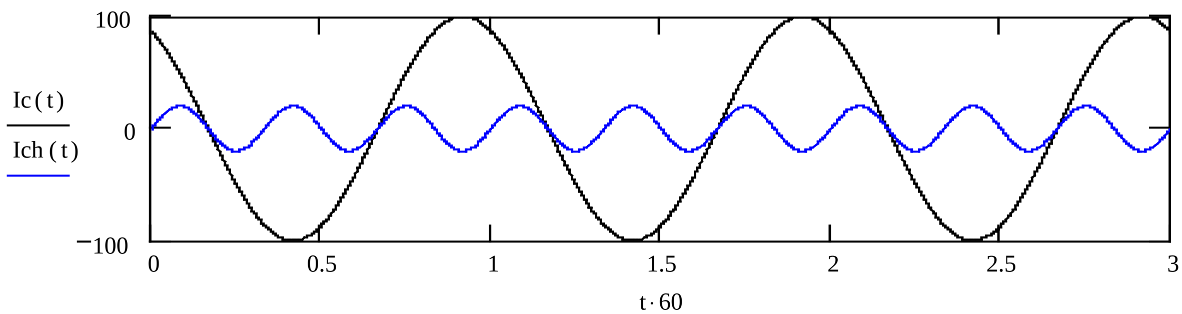
$Iah(t) := H \cdot \sin(2 \cdot h \cdot \pi \cdot 60 \cdot t) \qquad Ibh(t) := H \cdot \sin\left(2 \cdot h \cdot \pi \cdot 60 \cdot t - \frac{2 \cdot h \pi}{3}\right) \qquad Ich(t) := H \cdot \sin\left(2 \cdot h \cdot \pi \cdot 60 \cdot t + \frac{2h \cdot \pi}{3}\right)$

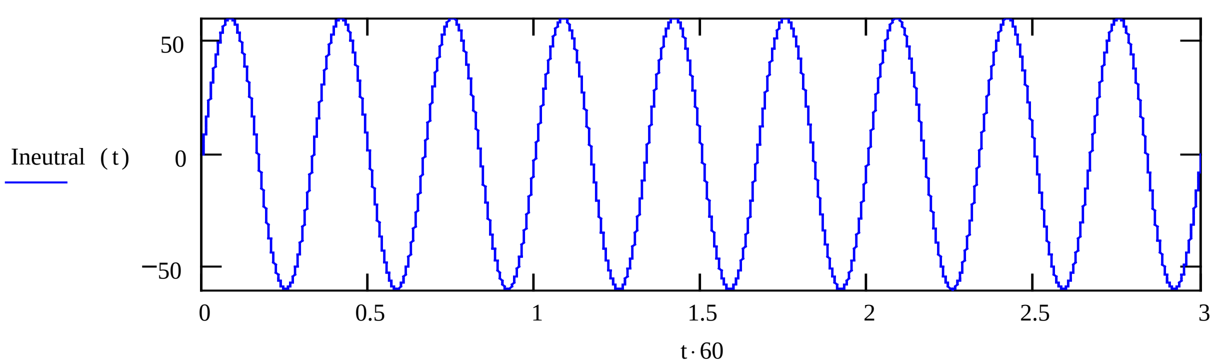
$Iasum(t) := Ia(t) + Iah(t) \qquad Ibsum(t) := Ib(t) + Ibh(t) \qquad Icsum(t) := Ic(t) + Ich(t)$

$Ineutral(t) := Iasum(t) + Ibsum(t) + Icsum(t)$









References

[1] Mathcad by Mathsoft, Inc. http://www.mathcad.com/
[2] Applied Protective Relaying, ABB, 1994, Note L, Figure 2-33.
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