Analysis of Underfrequency Load Shedding and Reclosing into a Motor Load on a TVA 161 kV Transmission Line

Meyer Kao
Tennessee Valley Authority

Presented to the

Georgia Tech
Fault and Disturbance Analysis Conference
May 1-2, 2006

Abstract

On August 6th, 2005, there was a momentary operation on TVA's Johnsonville Fossil Plant - Monsanto No. 1 161 kV line. The line was successfully reclosed and placed back in service within 6 seconds. What appeared to be a normal momentary interruption to the transmission line and its 2 tapped substations resulted in an underfrequency load shedding event at one of the tapped substation, and a reclosing into a motor load at the other tapped substation.

This paper discusses the result of the investigation to the erroneous underfrequency load shedding event. As the subsequent of this investigation, it was discovered that the reclosing setup on this transmission line resulted in a reclosing into a motor load at the industrial customer's substation.

As result of the erroneous underfrequency load shedding event, the placement of underfrequency load shedding relay in substation tapped on a transmission line was reviewed. Also the reclosing setup of this transmission line was discussed with the industrial customer tapped on this line.

Introduction and Background

Tennessee Valley Authority (TVA) is the nation's largest public power company. TVA has 33,000 megawatts of generating capacity, providing electrical power to the Tennessee Valley service area spanning over portion of seven states. TVA owns over 17,000 miles of transmission line covering over 80,000 square miles. All of the generation, interchange of power, and system dispatching are coordinated and controlled from Chattanooga, TN. The operation and maintenance of TVA's transmission system are divided into 15 geographical offices.

TVA initially began installing underfrequency relays on industrial loads in 1949. In 1970, TVA expended the underfrequency load shedding program to include cooperative and municipal loads. The objective of the underfrequency shedding program is to shed up to 50% of the load in the event of a severe disturbance that result in a catastrophic sectionalizing of the transmission system in to one or more islands.

If part of the system is islanded, there may be excessive load and not enough generation to supply the demand. This excessive loading demand will result in a sagging of frequency in the islanded system. Operating in an off nominal frequency condition for a prolong amount of time may result in severe generator turbine damage. TVA's underfrequency load shedding program was setup to alleviate this unbalance loading condition and to prevent generator turbine damage.

TVA considers unacceptable loss of frequency starts at 59.5 Hz. A deviation of more then 0.5 Hz from nominal frequency indicates a severe abnormal condition of excessive load and out of synchronism at some part of system. TVA's underfrequency load shedding program for cooperative and municipal loads consists of five frequency steps with different time delays. Those frequency steps and trip time delays are listed below in Table 1:

Frequency Setting	Time Delay in cycles
59.5	10 ~
59.3	15 ~
59.1	20 ~
58.9	25 ~
58.7	30 ~

Table 1: TVA Underfrequency Load Shedding Steps

In most cooperative's and municipal's substation, customers are asked to shed up to 50% of the substation load where underfrequency relay is installed. It is up to cooperative's and municipal's own discretion as to which of the non critical load to shed. In an attempt to equally distributing the impact of load shedding interruption, TVA relay engineer will set the underfrequency relay on one of the 5 steps to equally distribute the amount of load shed at each frequency step among all customers.

The Momentary Event

The basic setup of this transmission line is shown below in Figure 1:

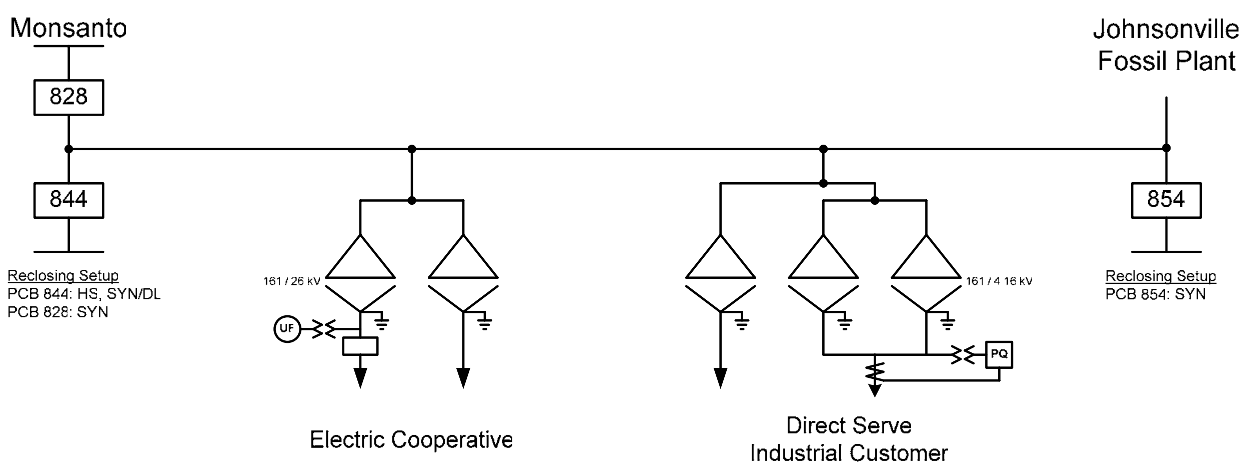

Figure 1: Johnsonville FP - Monsanto No. 1 161kV Line

Initially, only the direct serve industrial customer, a paper plant, was tapped on this 161 kV line. A new cooperative substation was built and tapped on this line in June, 2004. As part of TVA's underfrequency load shedding program, an underfrequency load shed relay was installed on one of its bank in the substation. This relay was set on the first step of the underfrequency load shedding program. As with all underfrequency relay, there is an undervoltage inhibit setting to prevent the relay from tripping due to sagging of voltage as result of a fault. Table 2 below lists the underfrequency relay setting at this particular cooperative substation:

Frequency Setting	Time Delay in cycles	Undervoltage Inhibit
59.5 Hz	10 ~	72 V (62% of nominal)

Table 2: Underfrequency Relay Setting

On August 6th, 2005 at 16:30:20.686, a C phase to ground fault 35 miles from Monsanto 161 kV substation occurred. At Johnsonville Fossil Plant, PCB 854 tripped in 6 cycles. At Monsanto, PCB 844 and 828 tripped in 10 cycles. Seventeen cycles after the Monsanto terminal breakers had initially tripped, PCB 844 high speed reclosed back into the fault and re-tripped in 4.5 cycles. Figure 2a shows the DFR shot from Monsanto 161 kV substation. Figure 2b shows the DFR shot from Johnsonville Fossil Plant.

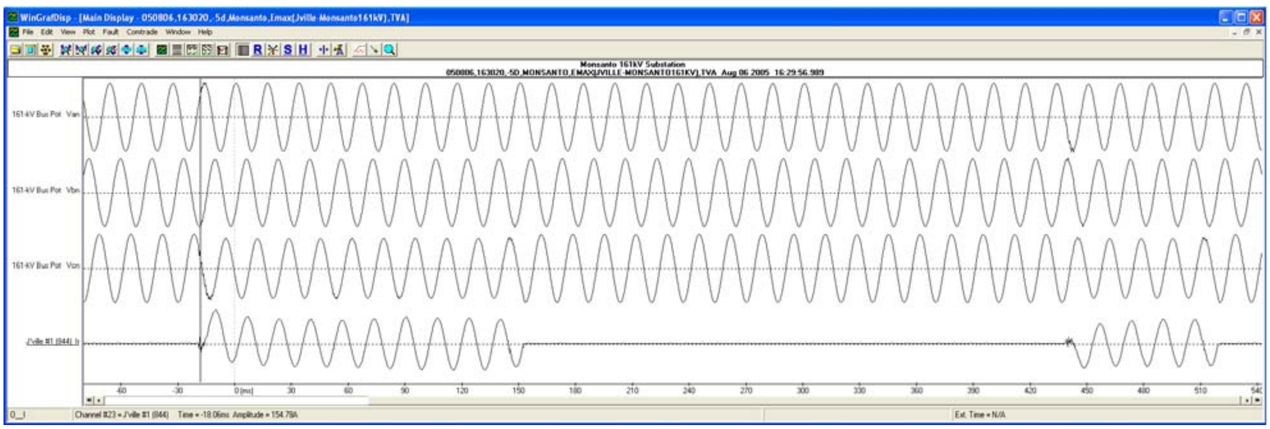

Figure 2a: DFR Shot from Monsanto 161 kV Substation

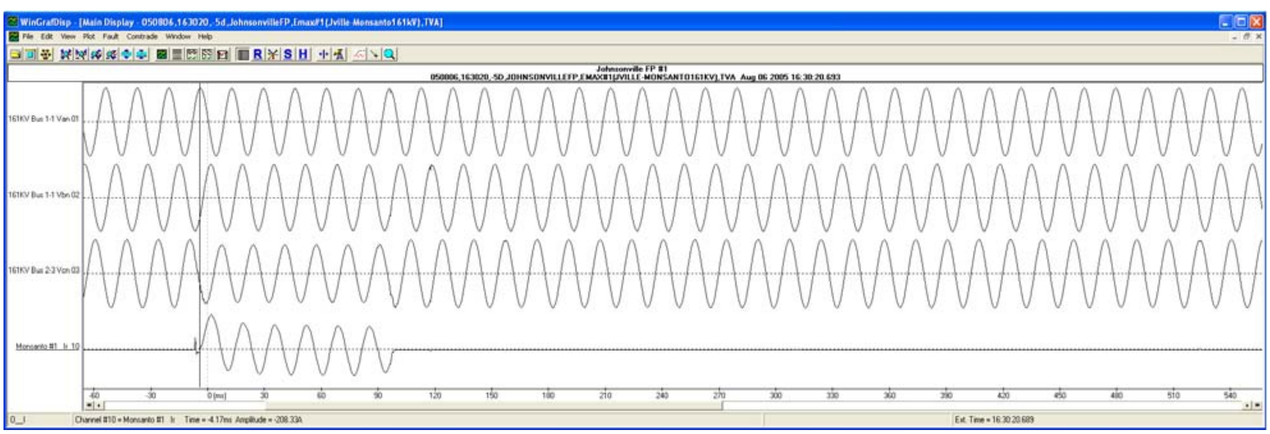

Figure 2b: DFR Shot from Johnsonville Fossil Plant

After the initial unsuccessful high speed reclose attempt at Monsanto, PCB 844 successfully reclosed 5 seconds later via dead line and re-energize the line. Subsequently, Monsanto PCB 828 and Johnsonville FP PCB 854 reclosed via synch check, tying the transmission line back in to service. All appeared to be a normal momentary interruption. It was just a simple interruption with an unsuccessful first high speed reclose, but a successful second dead line reclose.

Analysis of Underfrequency Load Shedding Event

TVA's System Protection and Analysis was notified that the electric cooperative's substation tapped on this line had an underfrequency load shedding operation associated with this momentary interruption. The underfrequency relay installed is a microprocessor relay, and the relay triggered an event record for this trip. This relay's event record is shown in Figure 3:

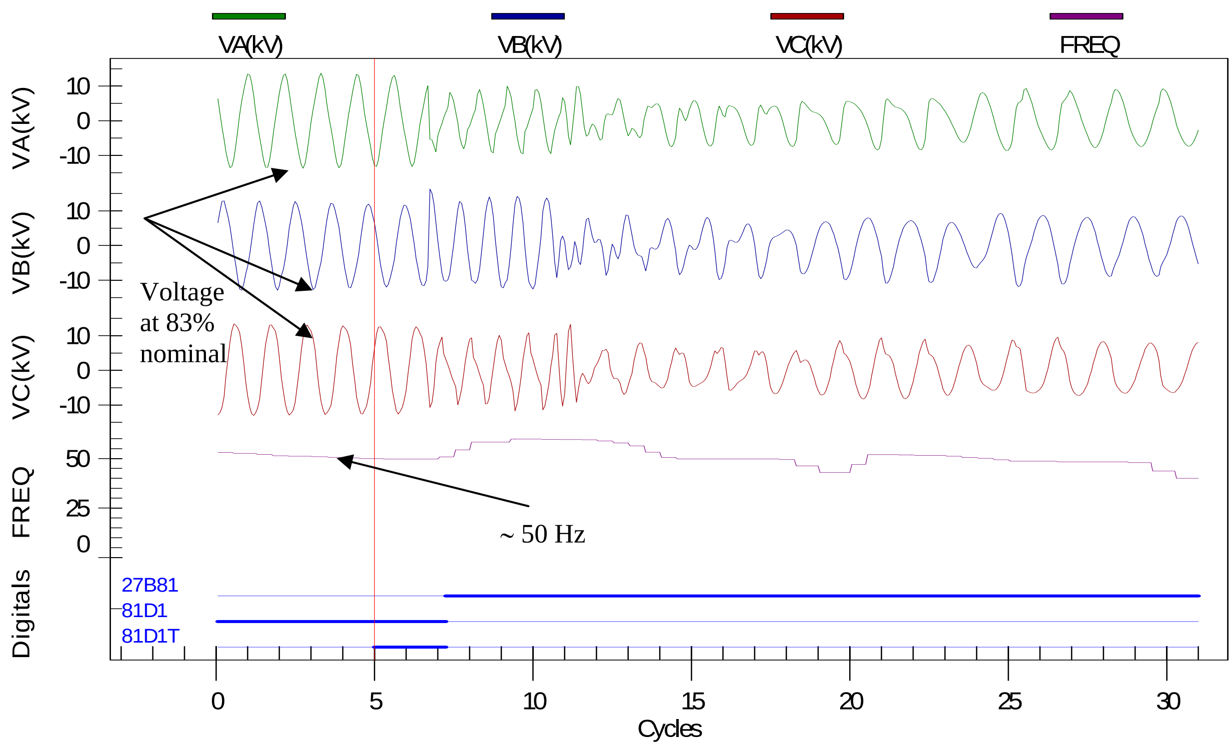

Figure 3: Underfrequency Relay Event Record

The underfrequency load shedding relay uses the metering VTs as its potential inputs. The metering VTs of ratio 14,400/120 are placed on the low side of the 161/26 kV delta-wye transformer.

From Figure 3, it is obvious the relay operated as intended. The 3 phase bus voltages were at 83% of nominal and they were above the undervoltage inhibit setting. The frequency was around 50 Hz right before the relay timed out and tripped.

From the above figure, couple of questions was raised:

1. Why the low side bus voltage stayed around 80% of nominal at 50 Hz, and did not decayed to zero after the 161 kV line terminal breakers had opened?

2. What caused the distorted waveforms few cycles after the underfrequency load shedding relay had operated?

With the 161 kV terminal breakers tripped, thus removing the 161 kV source, it was suspected that some motoring loads had held up the voltage. The source of the bus voltage can not come from the low side of the transformer, for this cooperative substation serves mostly residential load. The source of this voltage has to come from the high side of the transformer, or from the 161 kV line.

From Figure 1, the other tapped substation is a direct served industrial customer. Inside this paper plant, there are 32 motors with 12 motors of 1000 HP or more, for an accumulative of 24,350 HP. With the size of these motors, it is likely that the motors are induction motors. "A point to be watched in connection with induction motors is that voltage is generated for a short time after the removal of the supply..."[1] So it is obvious the voltage was being held up by the motors at this industrial customer when the 161 kV source was removed when the 161 kV breakers had tripped.

Reclosing into a Motor Load

There are 3 -161/4.16 kV delta-wye transformers at this direct serve industrial customer substation, with 2 of the transformers connected in parallel. A power quality monitor is installed on the 4160 V bus of the paralleled banks. Figure 4 shows the RMS voltages at the industrial customer's 4160 V bus for the 6 seconds duration of the Johnsonville Fossil Plant - Monsanto No. 1 161 kV line momentary interruption on August 6, 2005.

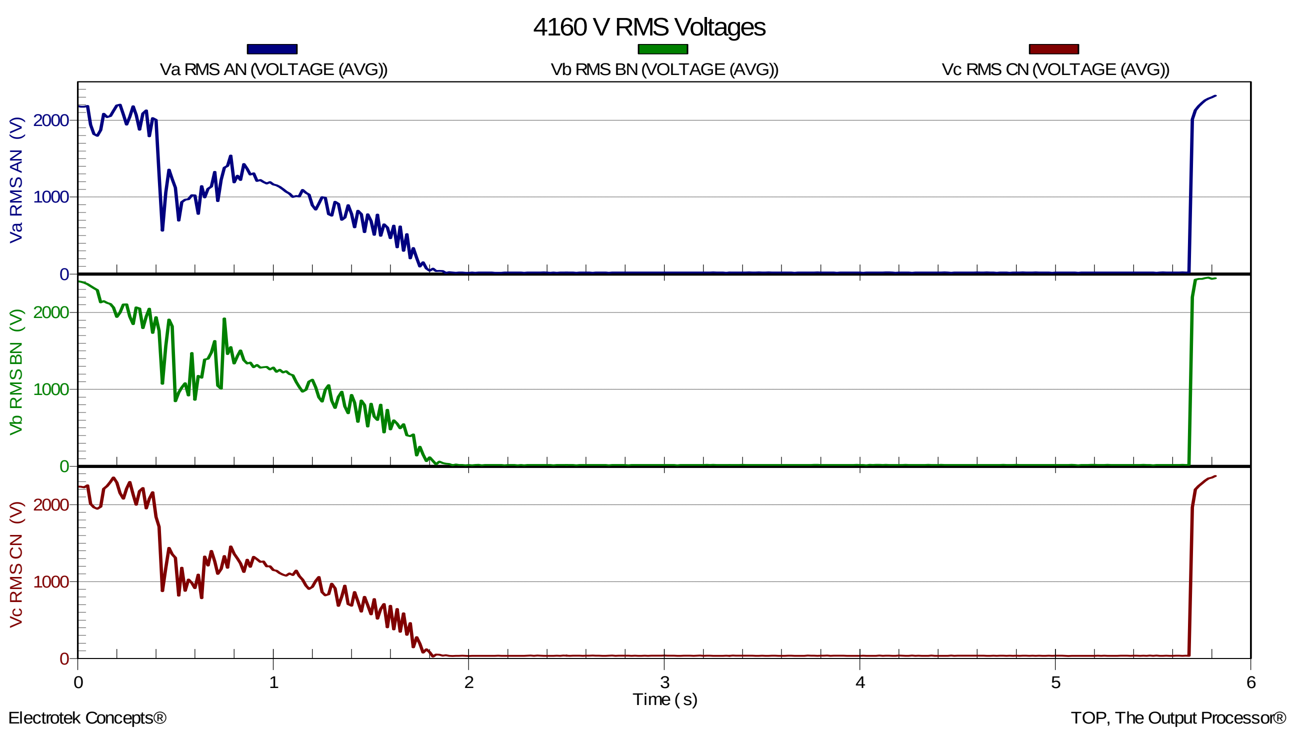

Figure 4: RMS Voltage at the Industrial Customer's 4160V Bus

Figure 5a, 5b, and 5c show the A phase, B phase and C phase RMS voltage waveforms respectively at the 4160 V bus for the first 40 cycles of this 161 kV line interruption.

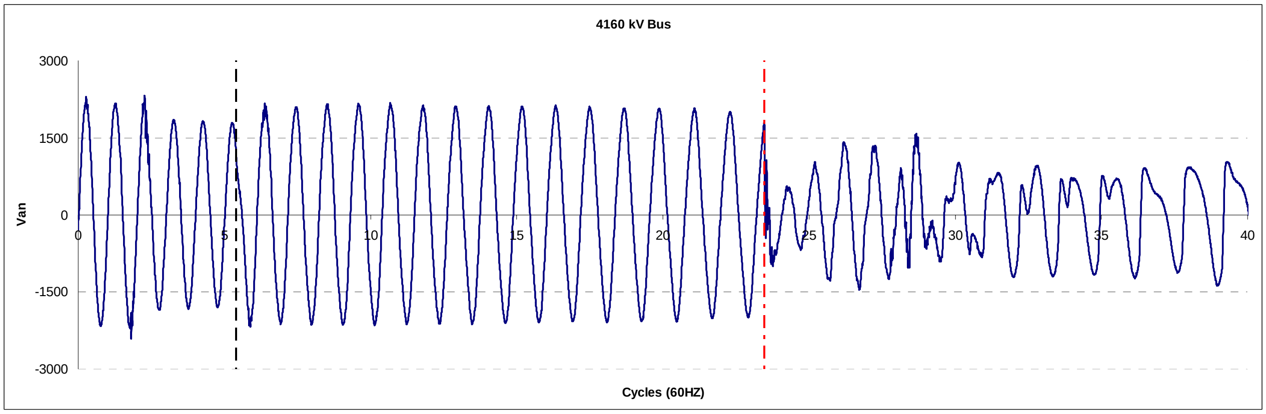

Figure 5a: 4160V Bus Van, 1st 40 Cycles

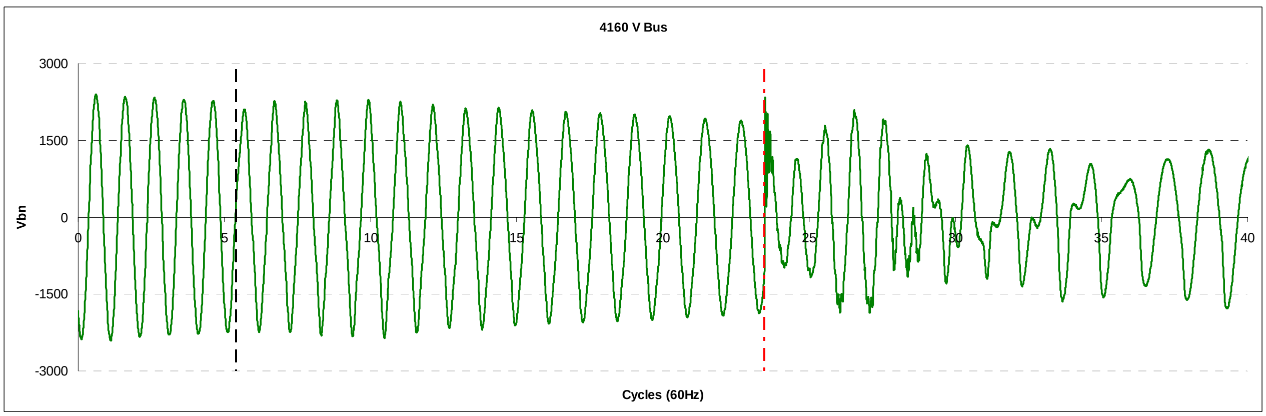

Figure 5b: 4160V Bus Vbn, 1st 40 Cycles

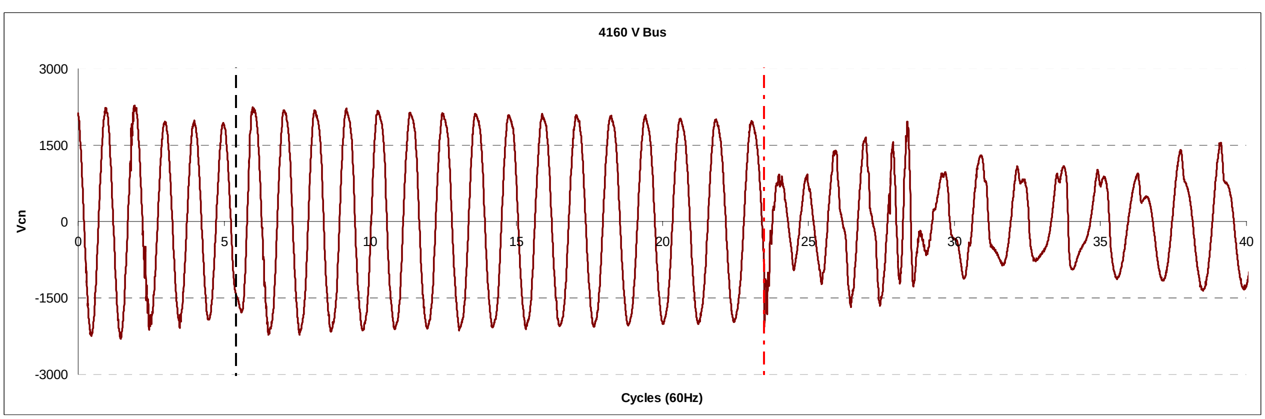

Figure 5c: 4160V Bus Vcn, 1st 40 Cycles

Note the dip in A and C phase voltages at the beginning. A C phase to ground fault on the 161 kV line will collapses both A and C phase voltages on the low side of the transformer due to the delta-wye phase shift.

On Figure 2a, the Monsanto DFR shows the 161 kV breaker reclosed in 17 cycles after it had initially tripped. From Figure 5a, 5b, and 5c, the waveforms became distorted about 16 cycles after the initial dip on A and C phase. It is suspected that the distorted waveforms were caused by the 161 kV source voltages being out of phase when the 161 kV breaker reclosed.

The power quality monitor that recorded this event has a sampling rate of 128 samples per cycle. Knowing that the 4160 V bus voltage was in synch with the transmission system before the 161 kV breakers had tripped, a nominal 60 Hz reference waveform can be superimposed on top of the recorded voltage waveform for each phase (see Appendix A on generating the reference 60 Hz waveform). This is shown on figure 6a, 6b, and 6c. Also shown with each figure is the frequency of the respective 4160V phase voltage. The frequency can be estimated by the number of samples between zero crossing (see Appendix B).

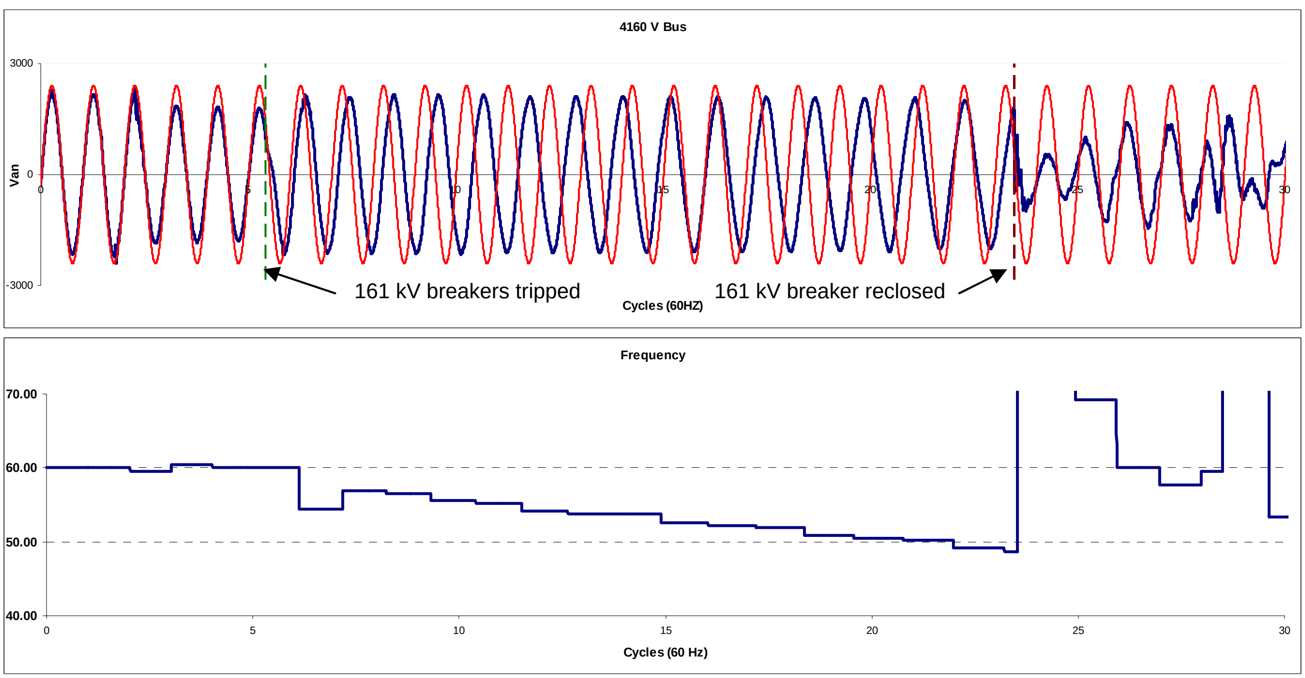

Figure: 6a: 4160V Van vs. 60 Hz Nominal Reference

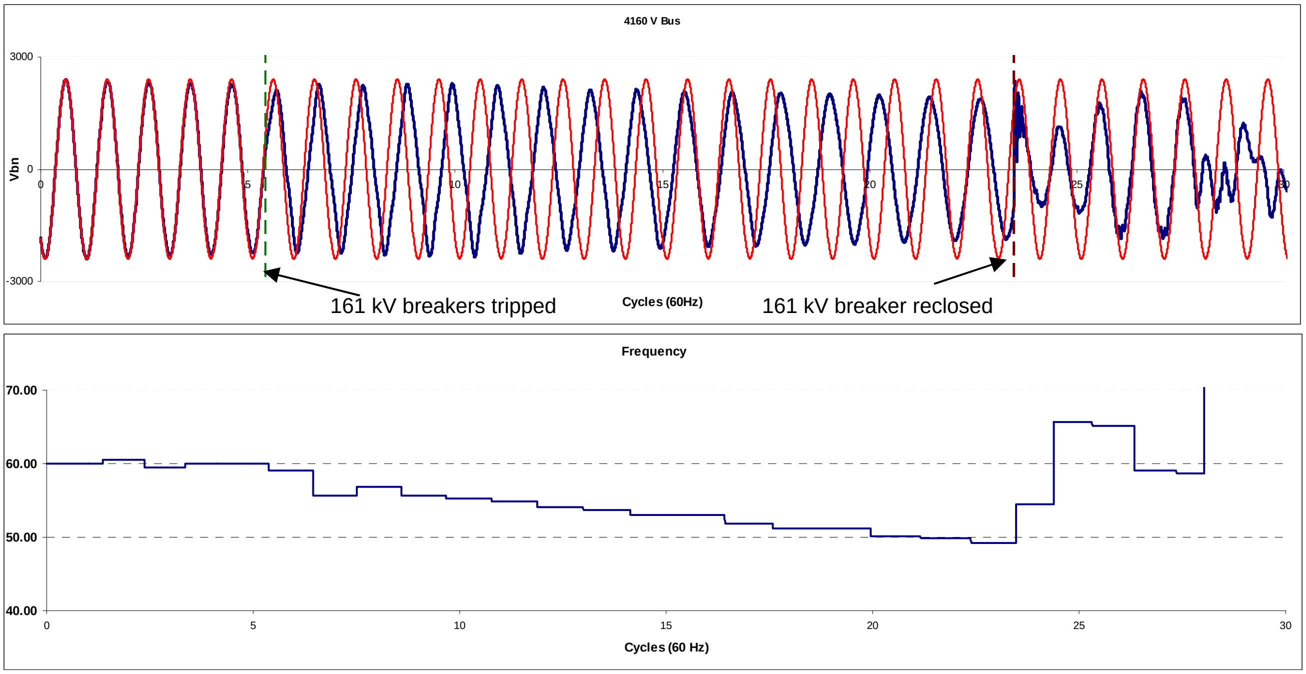

Figure: 6b: 4160V Vbn vs. 60 Hz Nominal Reference

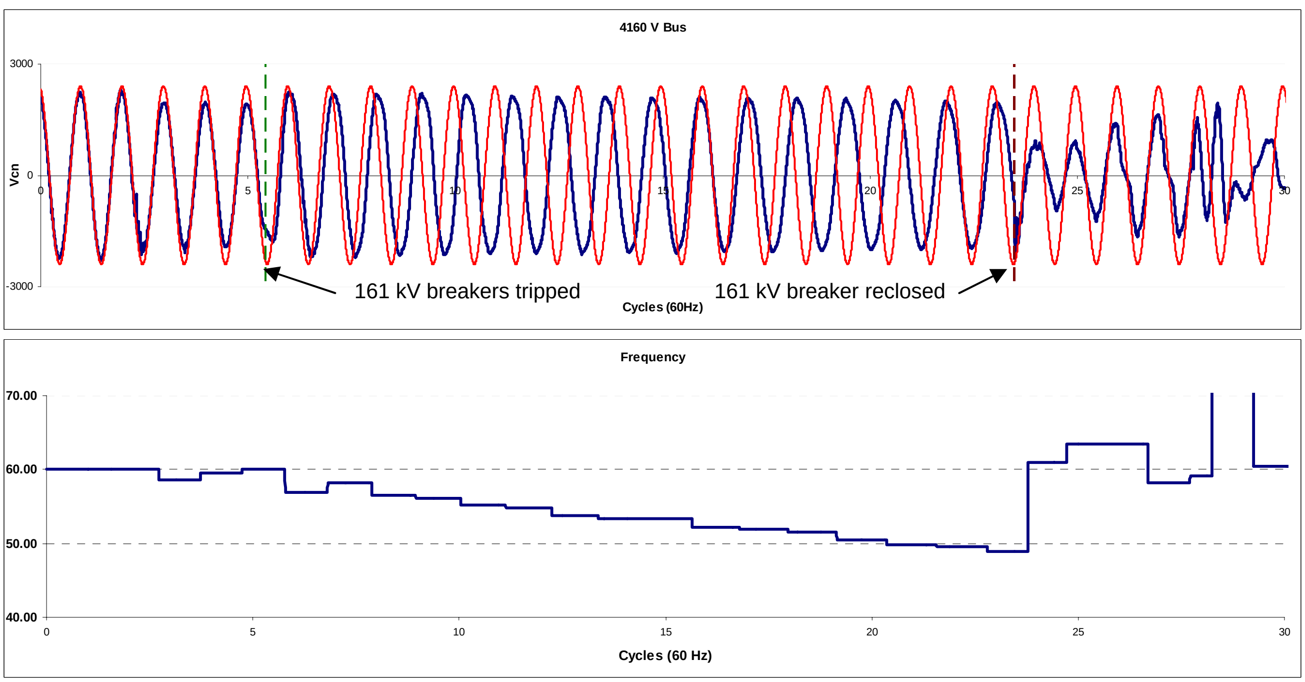

Figure: 6c: 4160V Vcn vs. 60 Hz Nominal Reference

From the above figures, we can make few observations:

1. 161 kV breakers tripped and removed the 161 kV source around 5.4 cycles on the time line (green dashed line).

2. It took about 6 cycles (on a 60 Hz base) for the 4160 V bus voltages to be 180 degrees out of phase with the 161 kV reference.
3. 161 kV breaker reclosed at 23.5 cycles on the time line (red dashed line).
4. 4160 V bus voltages were “snapped” back in phase with the 161 kV reference for about 4 cycles after the 161 kV breaker reclosed. From Figure 2a, the Monsanto 161 kV breaker reclosed high speed 17 cycles after the initial trip. It tripped back out in 4.5 cycles.
5. 4160 V bus voltage waveforms became severely distorted after the 161 kV high speed reclose.

Now we will take a closer look at the point where the 161 kV breaker recloses. These are shown in Figure 7a, 7b, and 7c below:

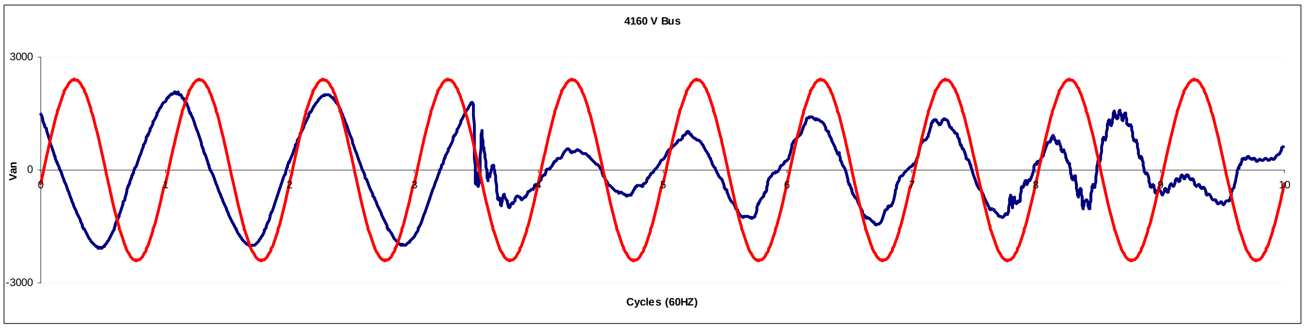

Figure 7a: Detailed View, Van at Point of Reclose

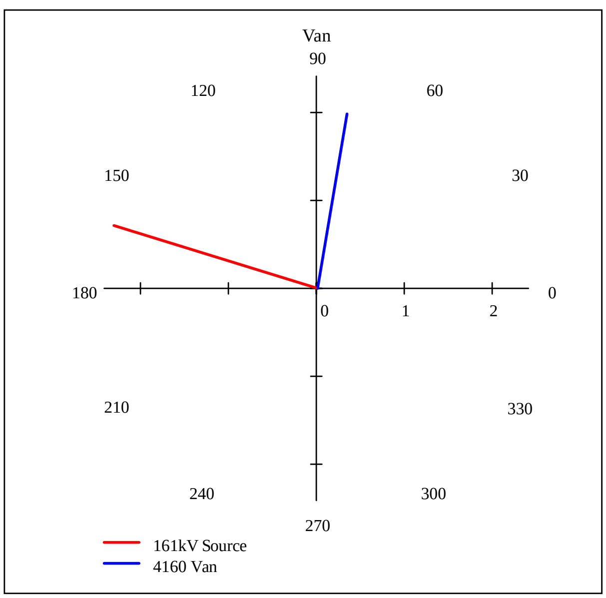

Figure 7b: Van Phase Angle at Point of Reclose

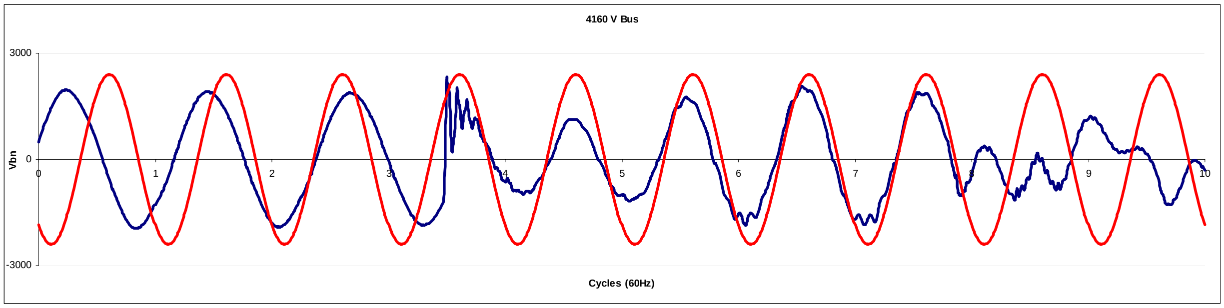

Figure 7c: Detailed View, Vbn at Point of Reclose

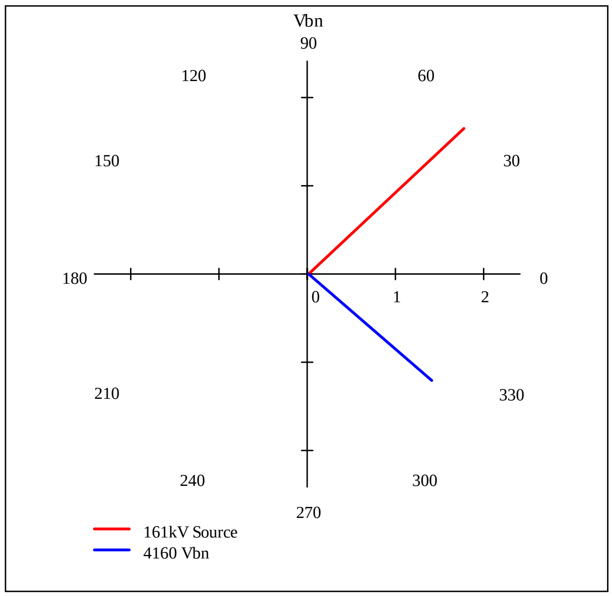

Figure 7d: Vbn Phase Angle at Point of Reclose

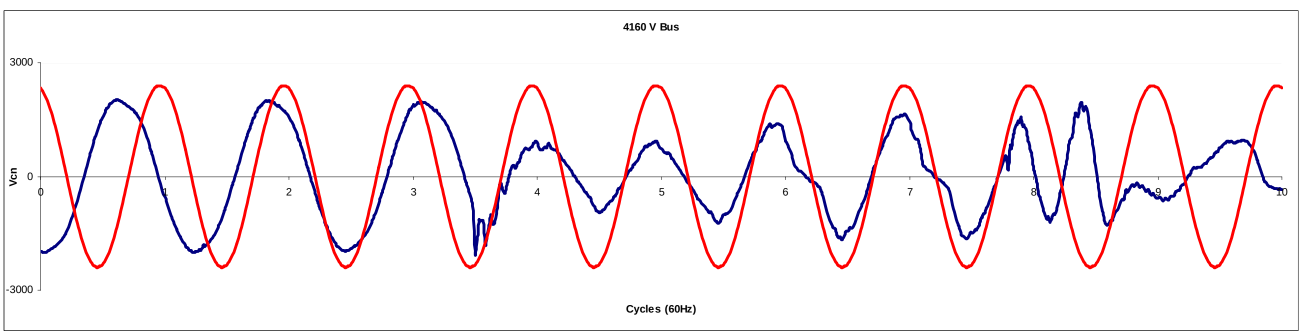

Figure 7e: Detailed View, Vcn at Point of Reclose

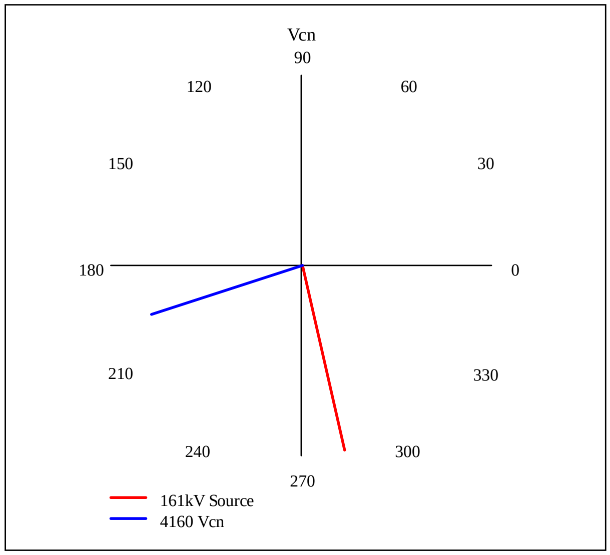

Figure 7f: Vcn Phase Angle at Point of Reclose

Inrush Current and Sustaining the 161 kV line fault

At the point of 161 kV reclose, the angular difference between the 161 kV source and the 4160 V bus voltage was estimated to be around 83° (see Appendix C). With this angular difference between the voltage sources, there will be an inrush current between the 161 kV system and the motor load at the point of 161 kV breaker reclose.

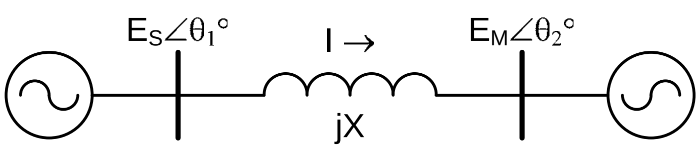

Figure 8: Equivalent Circuit

Figure 8 shows the equivalent circuit just after the point of reclose. The inrush current is calculated to be:

$$I = \frac{E_S\angle\theta_1° - E_M\angle\theta_2°}{jX}$$

where $E_S\angle\theta_1°$ is the 161 kV source voltage, $E_M\angle\theta_2°$ is the motor terminal voltage, and jX is the equivalent impedance of the circuit. The estimated inrush current based on the formula above is shown in Appendix D.

These actual inrush currents and respective phase voltages are shown in the figures below:

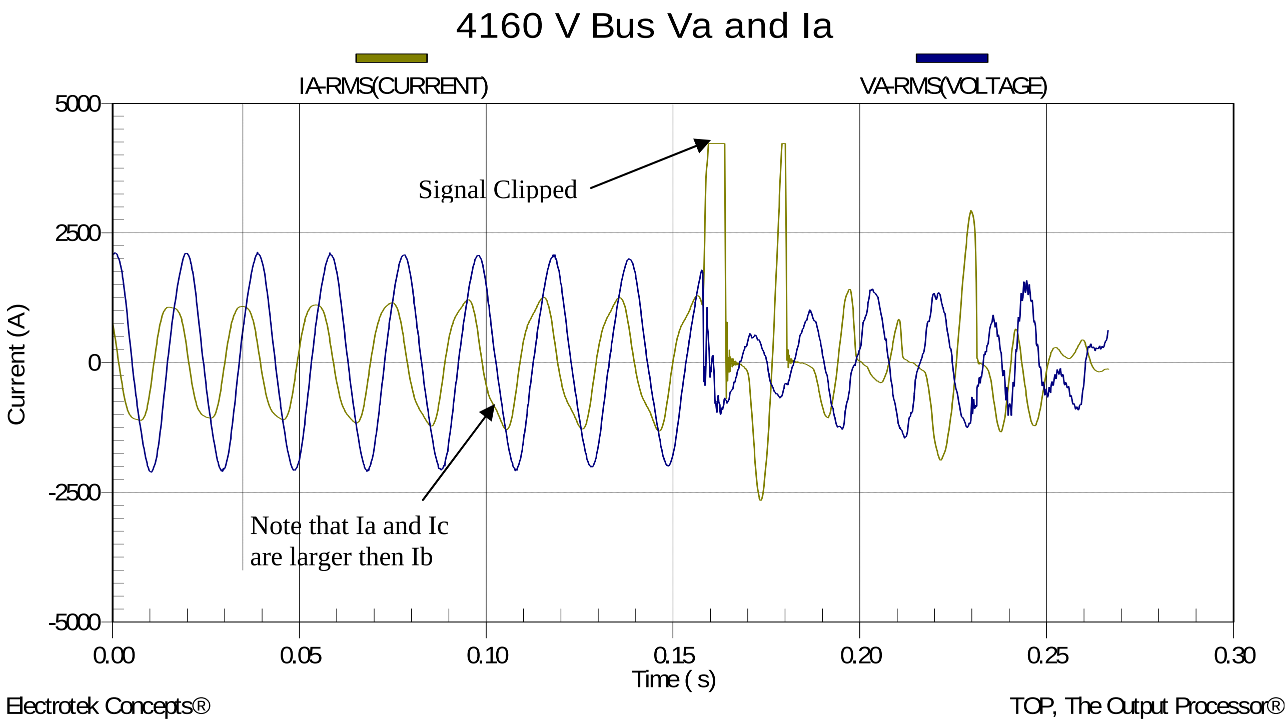

Figure 9a: 4160 V Bus Van and Ia

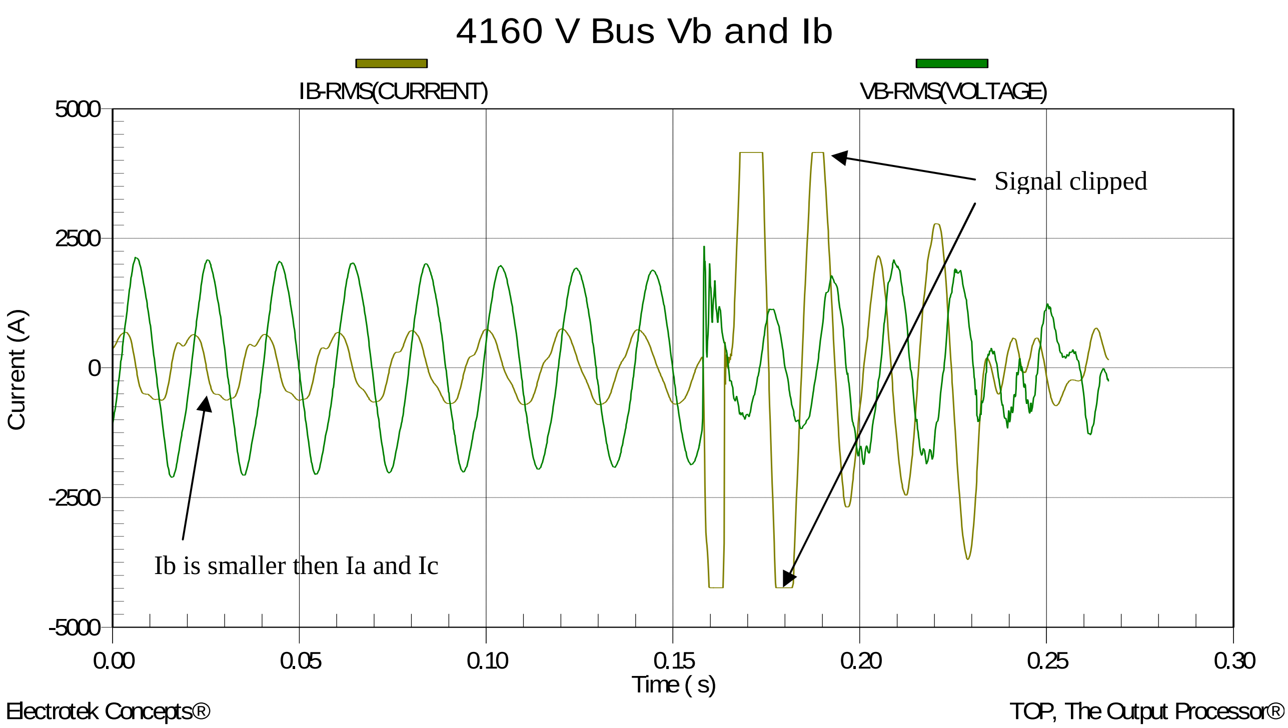

Figure 9b: 4160 V Bus Vbn and Ib

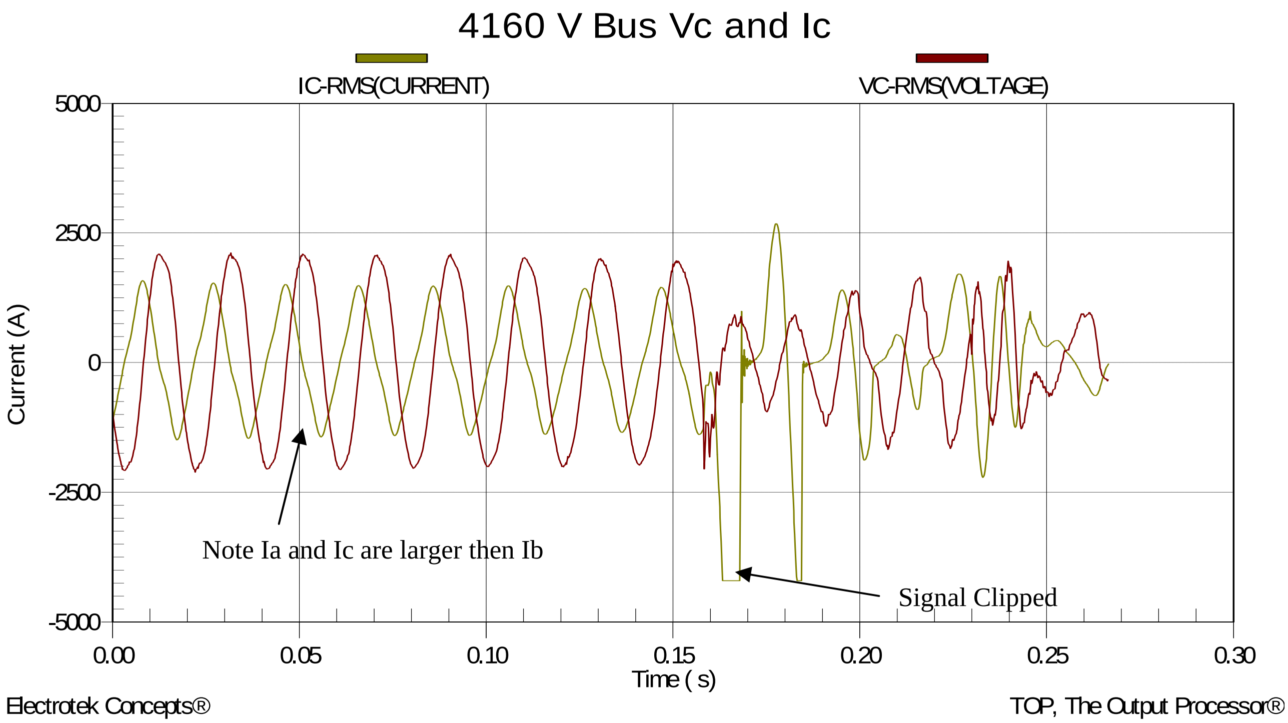

Figure 9c: 4160 V Bus Vcn and Ic

From Figure 9a, 9b, and 9c, the inrush currents were significant so that they were beyond the recording range of the PQ monitor. Note that before the point of reclose, the currents are leading the voltages by approximately 90°, indicating that the motor load was supplying the capacitive charging current for the 161 kV line. Another interesting fact is that the capacitive currents are of higher magnitude on both A and C phase. This would indicate that the higher currents on A and C phase are continuing sustaining the arc on the 161 kV line from the initial C phase to ground fault.

Summary and Conclusion

Due to the August 14th, 2003 northeast blackout, emphases have been placed for the municipals and cooperatives to participate in the underfrequency load shedding program. As result of this operation, future consideration for the placement of underfrequency relay should be carefully considered. Whenever a new tap station is being added to a transmission line, type of load begin served must be careful examined. For line with multiple tapped loads, special care must be made so that tapped substation with large motor load does not co-exist with substation that has underfrequency load shedding relay.

On substation with motor load, reclosing option must be carefully considered. "When motors, either induction or synchronous, are reenergized before they have stopped rotating, high transient torques can result, with possible damage or destruction… "As the utility is anxious to restore service promptly to its customer, they frequently use high-speed reclosing (about 0.20-0.60 s), and thus reenergize the motors, with possible damage… "…the best policy is either to delay a reclosure or reenergize induction motors, or to ensure that the motors are quickly disconnected from the system. For induction motors, reenergization should not occur until the motor voltages have dropped to 33% or less of nominal."[2]

An option to be considered is to block auto reclosing if voltages exist on the line.[3] However, TVA's 161 kV high speed reclosing is a blind auto reclose without any supervision. Another reason to avoid high speed reclosing is the arc on the faulted line can be sustained beyond the high speed reclose time due to the sustained voltage cause by the motor loads and the intra-capacitance between the phase conductors of the transmission line.[3, 4] Therefore TVA's System Protection and Analysis has recommended that the high speed reclosing be removed from this line. Five seconds dead line reclose should be adequate. This voltage would have decayed to a minimum level within the dead line reclose time interval.

Appendix A: Displaying Voltage Waveforms

The power quality monitor installed at the industrial customer's substation is a Dranetz 7100 PQNode. It has sampling rate of 128 samples per cycle and the files generated are in the PQDIF format. TOP is used to read in the PQDIF files. The waveforms are of instantaneous values, so a $1/\sqrt{2}$ factor is multiplied to convert the waveform values to RMS. These RMS waveforms were then exported in COMTRADE format.

Microsoft Excel is used to graph the waveforms. COMTRADE data file was imported in Excel as common separated delimited values. A 60 Hz reference waveform is then graphed along with the imported data. This 60 Hz reference waveform can be generated by the following formula:

$$V_{60} = V * \sin(\omega t + \theta)$$

The nominal voltage at the 4160 V bus is V = 4160/$\sqrt{3}$ $\cong$ 2400. Since the sampling rate is 128 samples per cycle, on a 60 Hz base, each data point is recorded at 1/128 of cycle. This also means that each data point is recorded at every 360°/128 = 2.8125°, or $\omega = 360° / 128$. θ is the offset along the time line. This value needs to be determined, so that we can adjust the reference waveform to be in synchronism with the 4160 V bus voltage. In our example, the A phase voltage crosses 0 degree on the 5th sample into the record. In our example the reference 60 Hz waveform for A phase has this formula:

$$Van_{60} = 2400 * \sin\left(\frac{360°}{128} * (t - 5)\right)$$

Appendix B: Estimating the Frequency

Frequency can be estimated by counting the number of samples between zero crossings. This can be expressed as:

$$Freq = \frac{(S_{RATE} / 2)}{\#\_of\_Samples} \times 60 \text{ Hz}$$

where #_of_Samples is the number of data points where sign of the data changes from positive to negative, or vise versa, and S_{RATE} is the sampling rate. Signs of Data point changes every half cycle.

Looking at Figure 7a and from the PQ monitor A phase voltage, the number of samples for the last good 1/2 cycle (between zero crossings) before the 161 kV reclose is 79 samples. With PQ monitor sampling rate of 128 per cycle, the estimated frequency is then:

$$V_{an} Freq = \frac{(128 / 2)}{79} \times 60 = 48.6 \text{ Hz}$$

Appendix C: Calculating the Angular Difference between 2 Waveforms

To calculating the angle of the waveform on any data point, the number of samples per cycle of the waveform must be known. The angle can be expressed as:

$$\text{Angle} = 360° \times \frac{\text{Data\_Point}}{\text{Samples\_Per\_Cycle}}$$

Continuing use the example in Appendix B, it took another 35 samples from the last zero crossing, or 0 degree, to the point of 161 kV reclosing. Using the previous half cycle of 79 samples as the reference frequency, at the point of reclosing, the A phase 4160 V bus voltage has phase angle of:

$$V_{an}\text{Angle} = 360° \times \frac{35}{79 \times 2} = 80°$$

For our reference 60 Hz Van, it took 58 samples from 0 degree to the point of reclose. This equates to:

$$VREF_{an}\text{Angle} = 360° \times \frac{58}{128} = 163°$$

The angular difference between the 2 voltages is then 163° - 80° = 83°. The angular difference for the B and C phase voltages are calculated similarly.

Appendix D: Calculating the Inrush Current

From Figure 7a, it can be shown that the 4160 V bus voltage had decayed to 0.83 p.u at the point of the reclose. Know that the 2 voltages were at $1.0\angle 163°$ and $0.83\angle 80°$ per unit, the inrush current at the point of reclose can be estimated.

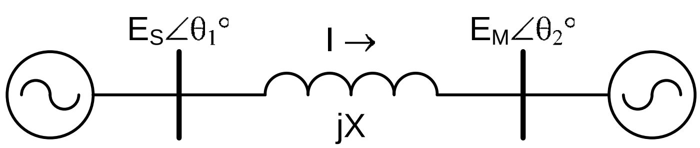

Figure 8: Equivalent Circuit

The inrush current is calculated to be:

$$I = \frac{E_S\angle\theta_1° - E_M\angle\theta_2°}{jX}$$

where $E_S\angle\theta_1°$ is the 161 kV source voltage, $E_M\angle\theta_2°$ is the motor terminal voltage, and jX is the equivalent impedance of the circuit.

For a induction motor, the typical positive sequence impedance from stalled condition to fully running condition changes from approximately 0.15 p.u.(Slip S = 1.0) to 0.9 or 1.0 p.u. (S = 0.01), where as the negative sequence impedance remains at approximately 0.15 per unit.[2] This is based on motor's kVA rating, which is roughly equal to the motor horsepower rating.

At this industrial plant, the accumulative horse power for all the motors is 24,350 HP. At the point of reclosing, the 4160V bus voltage was running at 48.6 Hz. The slip at this point is then approximately (60-48.6)/60 = 0.19. Interpolating between stalled motor impedance of 0.15 p.u. and running motor impedance of 0.9 p.u., the estimated motor impedance at this point is about 0.79. On the 100 MVA base, the motor equivalent impedance is then estimated to be:

$$X_{MOTOR} = 0.79 \times \frac{100MVA}{24.350MVA} = 3.24 \text{ p.u.}$$

Rest of the system impedances are listed below:

1. Source X_S = 0.025 p.u.
2. Line X_L = 0.11 p.u.
3. Transformer X_T = 0.3 p.u.

The total impedance is then X = 3.24 + 0.025 + 0.11 + 0.3 = 3.675 p.u. Now we can estimate the inrush current.

$$I = \frac{1.0\angle 163° - 0.83\angle 80°}{j3.675} = \frac{1.22\angle 155°}{j3.675} = 0.332\angle 116° \text{ p.u.}$$

Base amp at the 4160 V bus is $100 \times 10^6 / (4160 * \sqrt{3}) = 13{,}879$ amps. The inrush current is then estimated to be 13879x0.332 = 4608 amps. Note that if the two voltages are 180° apart, the maximum possible inrush current would have been 13879*2 / 3.675 = 7553 amps.

References

1. “GEC Protective Relays Application Guide”, section 14.5.1: Auto-Reclosing - Dead time

2. “Protective Relaying: Principles and Applications”, J. Lewis Blackburn, 2nd edition, Section 11.4, 11.14

3. C37.104-2002 IEEE Guide for Automatic Reclosing of Line Circuit Breakers for AC Distribution and Transmission Lines, sections 5.3.6(a), 6.1.1.5, 6.2.1

4. “Modern Power System Protection: Applications and Performance Analysis”, tutorial class sponsored by University of Wisconsin-Madison, John Boyle, Stan Horowitz, and Arun Phadke

Software

TOP – The Output Processor. TOP reads data from a variety of sources and transforms it into high quality graphics for inclusion in reports and documents. TOP was developed by Electrotek Concepts® to visualize data from a variety of simulation and measurement programs. It can be freely obtained at the following website: http://www.pqsoft.com/TOP/index.htm

Mathcad 11- Mathcad® is a comprehensive design environment that enables engineers from all industries to explore, calculate and document their mathematical formulas, methods and values during the design phase of a product. For more information, visit: http://www.mathcad.com/products/

Biographical Sketch

Meyer M. Kao is a Transmission System Engineer in System Protection & Analysis group for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. He is responsible for performing detailed technical analysis for unusual system events, including equipment failure and misoperation. He also had responsibility for protective relaying and control settings and field support. Prior to his position as Transmission System Engineer, Meyer was a field test engineer for the TVA’s Chattanooga Transmission Service Center. One of Meyer’s main responsibility as a field test engineer was new installation and retrofit of substation control and protection circuits. Meyer earned the B.E.E. degree from the Georgia Institute of Technology in 1990. He is a registered professional engineer in the state of Tennessee. Meyer can be emailed at mmkao@tva.gov