DPQ Event: Back-to-Back Capacitor Switching

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Transient

Back-to-Back Capacitor Switching
A capacitor switching in general produces a high frequency voltage transient and inrush current. When an isolated capacitor bank is energized, there are typically high frequency, high magnitude inrush currents limited by the surge impedance of the capacitor bank and the system inductance. The maximum voltage transient in this situation is two per unit. However, when a capacitor is energized in close proximity to a bank that is already charged, there is an added factor. In addition to the inrush from the system source, there is a flow of energy from the already charged capacitor to the bank being switched in. The current in this situation is limited by the smaller inductance between the banks, resulting in higher inrush currents with a higher frequency than when energizing an isolated bank. This phenomenon is known as back-to-back capacitor switching.

On August 2, a high frequency, high magnitude transient was measured by instrument 4095 (Figure 1). The feeder (Figure 2) is a 3-phase system and is connected to another substation. It is fed from a 46.7 MVA, 15kV / 23kV transformer and has three important capacitive loads of 1800 kVAr each. It is also composed of overhead as well as underground systems. This event suggested a back-to-back capacitor switching event involving either banks 1 and 2 or banks 1 and 3. Although the actual switching schedule was not available at the time of this report's printing, an exchange of energy between banks 1 and 3 seemed a likely explanation according to the following preliminary calculations.

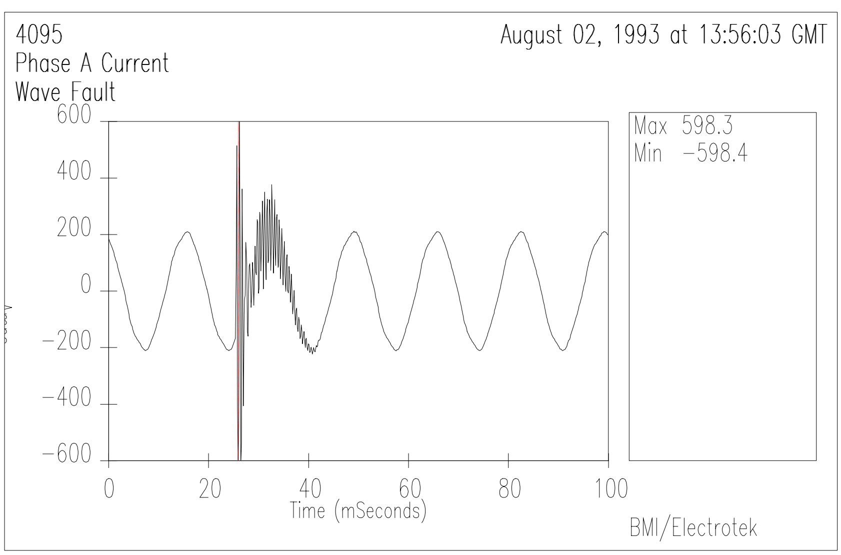

Figure 1: Typical Inrush Current Waveform for Back-to-Back Capacitor Switching

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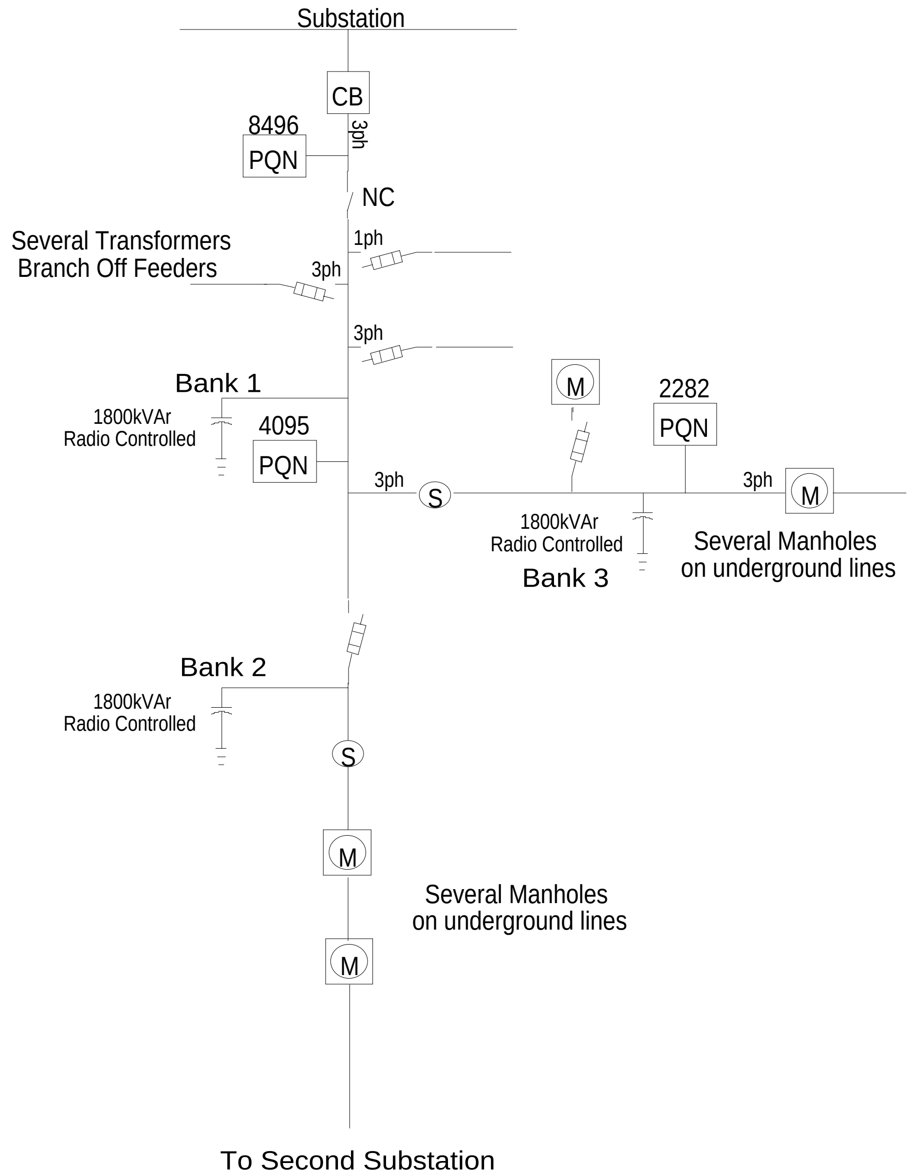
DPQ ONE-LINE
NODES:
8496, 4095, & 2282



XFMR MVA = 46.7
HKV = 115
LKV = 23

From	To	Distance (ft)
Bank 1	Bank 2	2870
Bank 2	Bank 3	4200
Bank 1	Bank 3	3300

SHORT DUTY = 228.31
% Z =
PRI. CONN. =
SEC. CONN. = M GND WYE

Figure 2: Feeder on Which Back-to-Back Switching Event Occurred

Figure 3 shows the equivalent circuit for this event. As a first order approximation, the capacitors' intrinsic inductance and the system resistance were ignored. Instrument 4095 measured the current flowing through this circuit. Given that the banks were separated by 4200 feet of 3-336 aluminum tree wire, we can calculate the lumped line inductance to be 1.38 mH. (See Figure Eq.1)

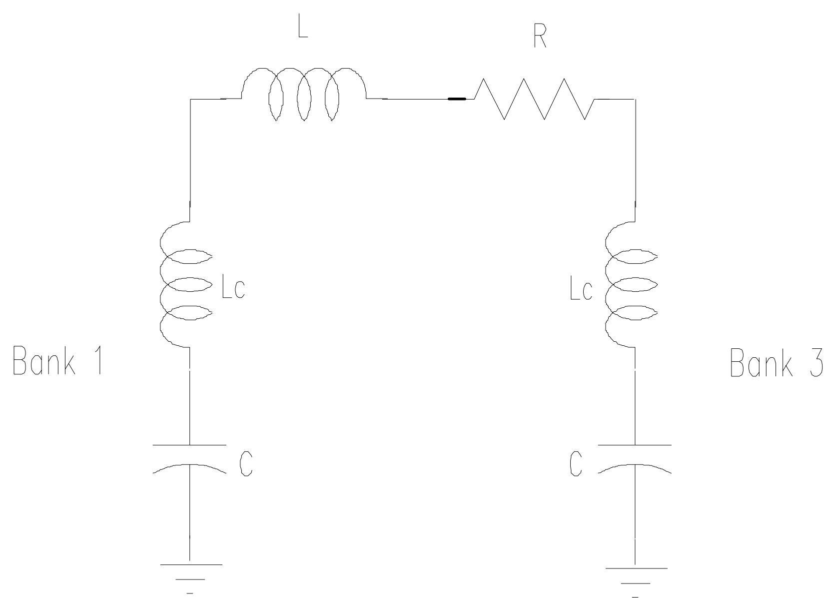


Figure 3: Equivalent Circuit for a Back-to-Back Switching Involving Banks 1 and 3

$$X_L = \frac{0.124\ \Omega}{1000\ \text{ft}} 4200\ \text{ft} = 0.494\ \Omega$$
$$L = \frac{X}{\omega} = \frac{0.494\ \Omega}{120\pi} = 1.38\ \text{mH}$$

Figure Eq. 1: Equation 1

Using the system and the capacitor ratings, we can calculate the lumped capacitance of both banks, which is the same since they are both rated at 1800 kVAr. (See Figure Eq.2)

$$X_C = \frac{(kV)^2}{MVAr} = \frac{(23)^2}{1.8} = 293.9\ \Omega$$
$$C = \frac{1}{wX_C} = 9.03\ \mu\text{F}$$

Figure Eq. 2: Equation 2

The capacitor banks are in series, so the equivalent capacitance of the two would be 4.51. The LC combination would have a natural frequency of 2036 Hz. (See Figure Eq.3)

$$f = \frac{1}{2\pi\sqrt{LC_{eq}}} = 2063 \text{ Hz}$$

Figure Eq. 3: Equation 3

The surge impedance of the LC circuit can be used to calculate the peak current for this back-to-back capacitor switching. (See Figure Eq.4)

$$Z_0 = \sqrt{\frac{L}{C_{eq}}} = 18.4\ \Omega$$

$$I_{peak} = \frac{\sqrt{2}/\sqrt{3}\ V_{system}}{Z_0} = 1019\ \text{A}$$

Figure Eq. 4: Equation 4

The calculated value would be lower if the system resistance and the inductance of the capacitors were taken into consideration.

These calculations can be used in analyzing the switching event that occurred on August 2. Figure 4 shows the current waveform for phase A. The waveform was recorded by the mid feeder node 4095. Note the high frequency, high magnitude inrush current. The maximum value of current is 600 A, which is probably explained by saturation of the node's CT. However, the measured current does fit the magnitude predicted by the calculations for a back-to-back switching involving banks 1 and 3.

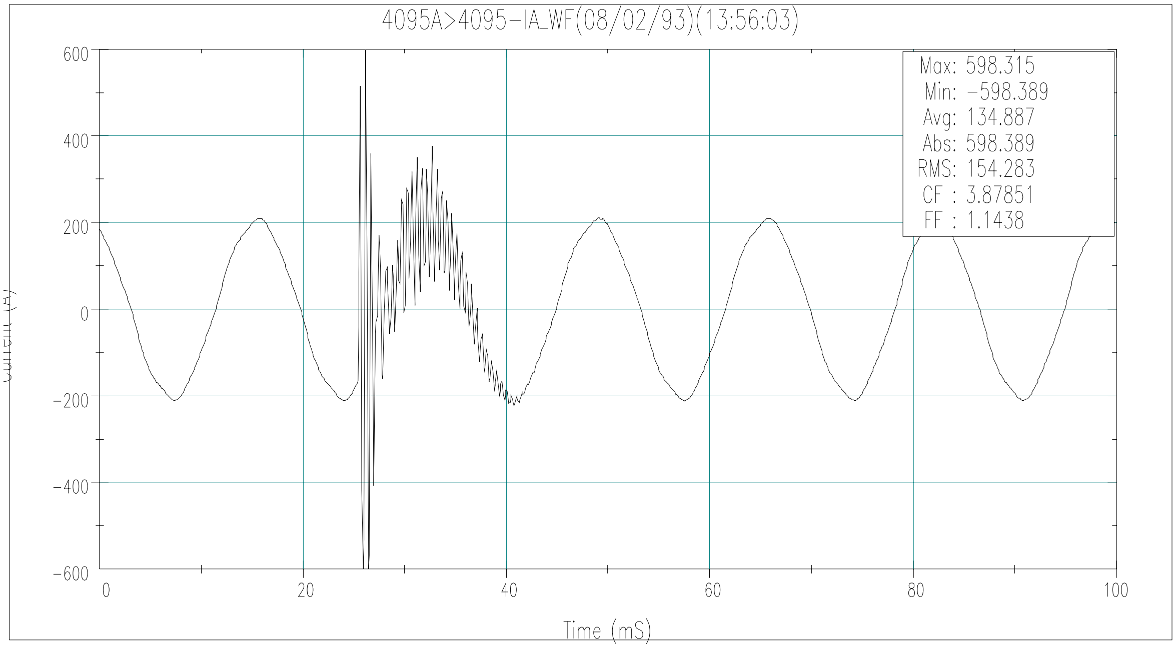


Figure 4: Phase A Current Measured at Node 4095

Figure 5 shows the same current waveform, but with the scale expanded during the transient. Its frequency could be estimated from this time domain plot, but it would helpful to filter out the fundamental frequency and then perform an FFT on the derived waveform. Figure 6 shows what is left after the 60 Hz component is removed, and Figure 7 shows its FFT.

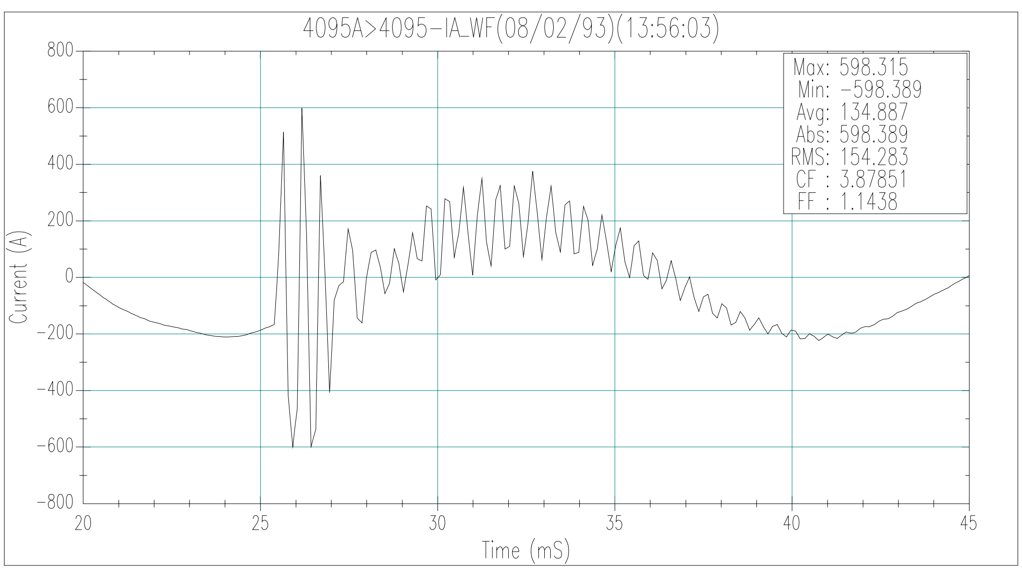


Figure 5: Phase A Current Measured at Node 4095, Scale Expanded to Show Only Transient

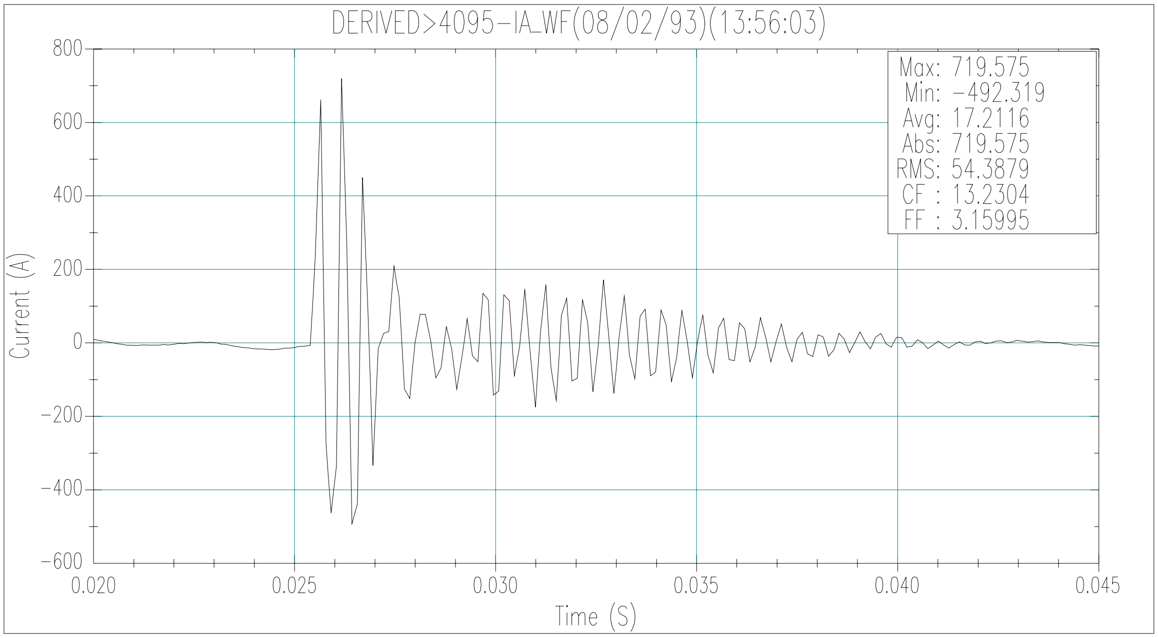


Figure 6: Current Waveform After Filtering Out 60 Hz

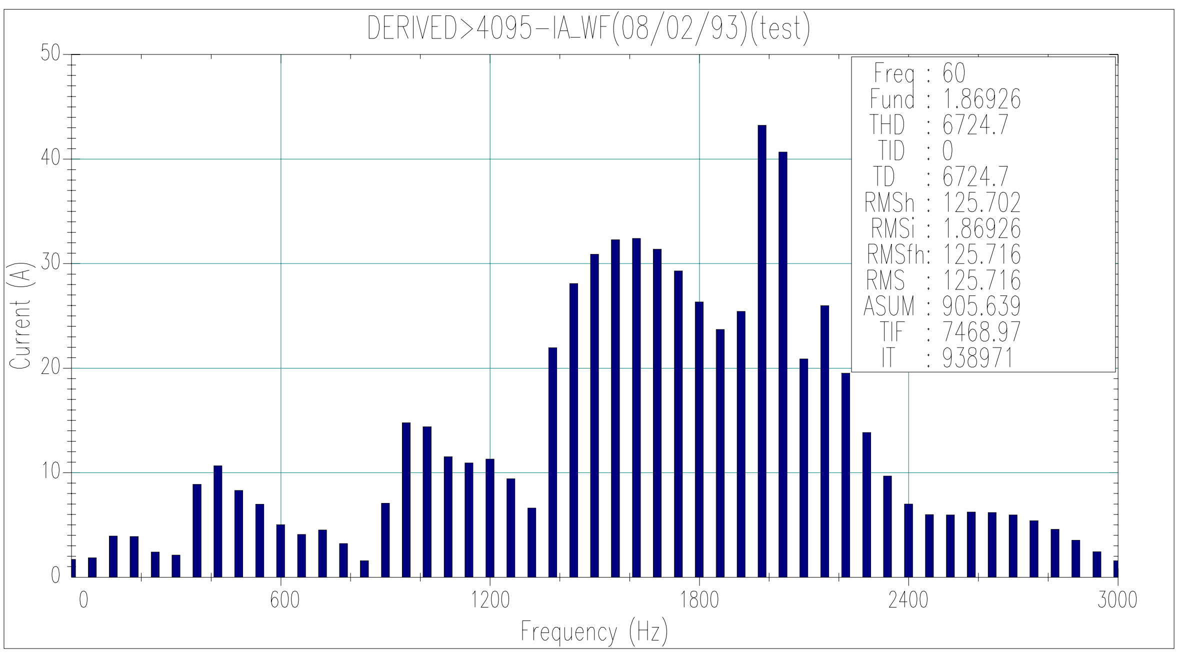


Figure 7: FFT of Filtered Current Waveform

Figure 7 shows that the dominant frequency of the transient is centered around 2000 Hz, which was predicted in the calculations for a back-to-back switching of banks 1 and 3. The disturbance summary for this event can be found in Figure 8.

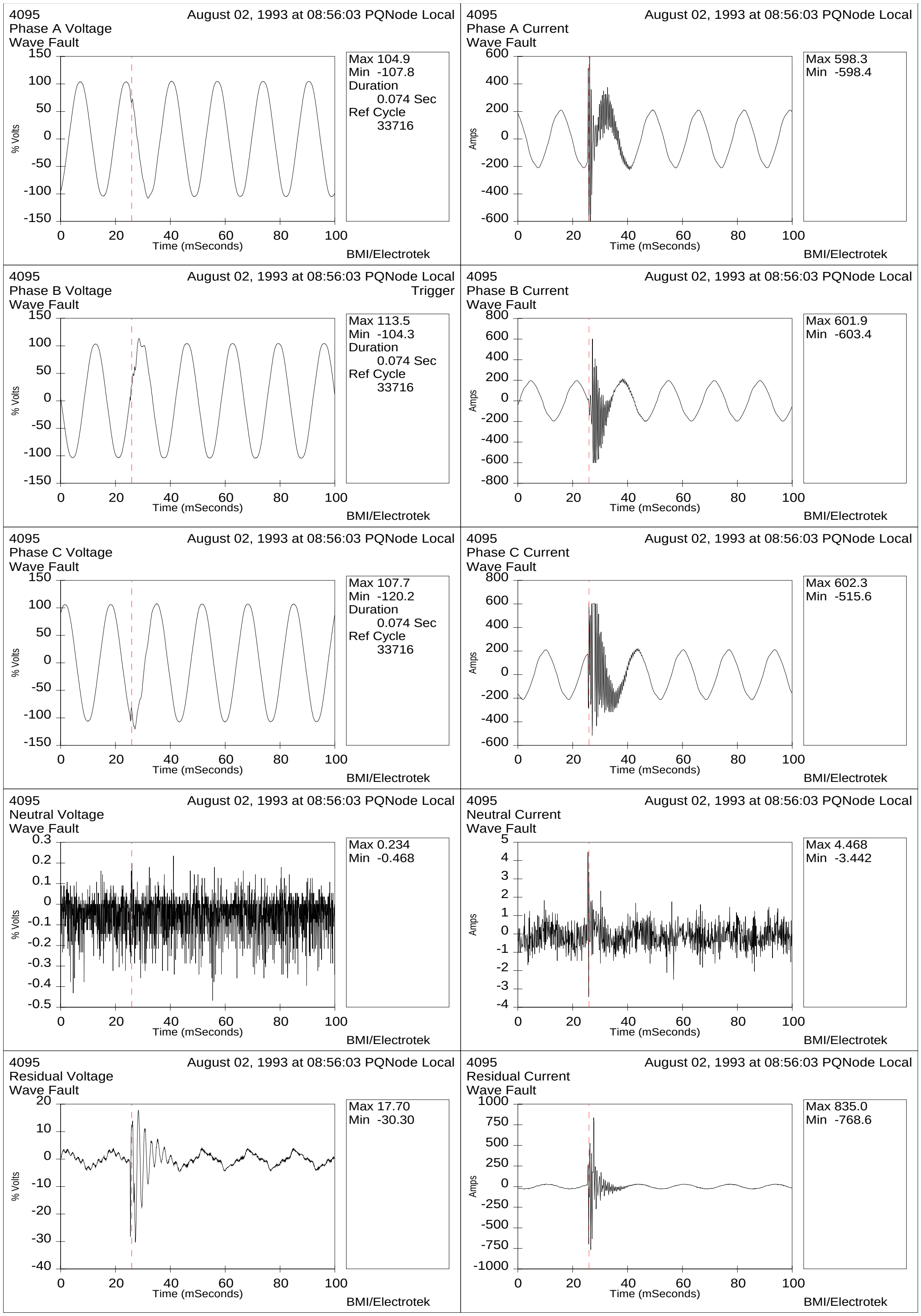


Figure 8: All Phases of Voltage and Current Showing Back-to-Back Switching Event

It is important to point out that the calculated value of Ipeak would be lower if the system resistance and inductance of the capacitors are taken into consideration.   The whole scenario of the preliminary calculation was then simulated using the EMTP. Its results are shown in Figure 9 which shows a strong correlation with the actual transients measured.

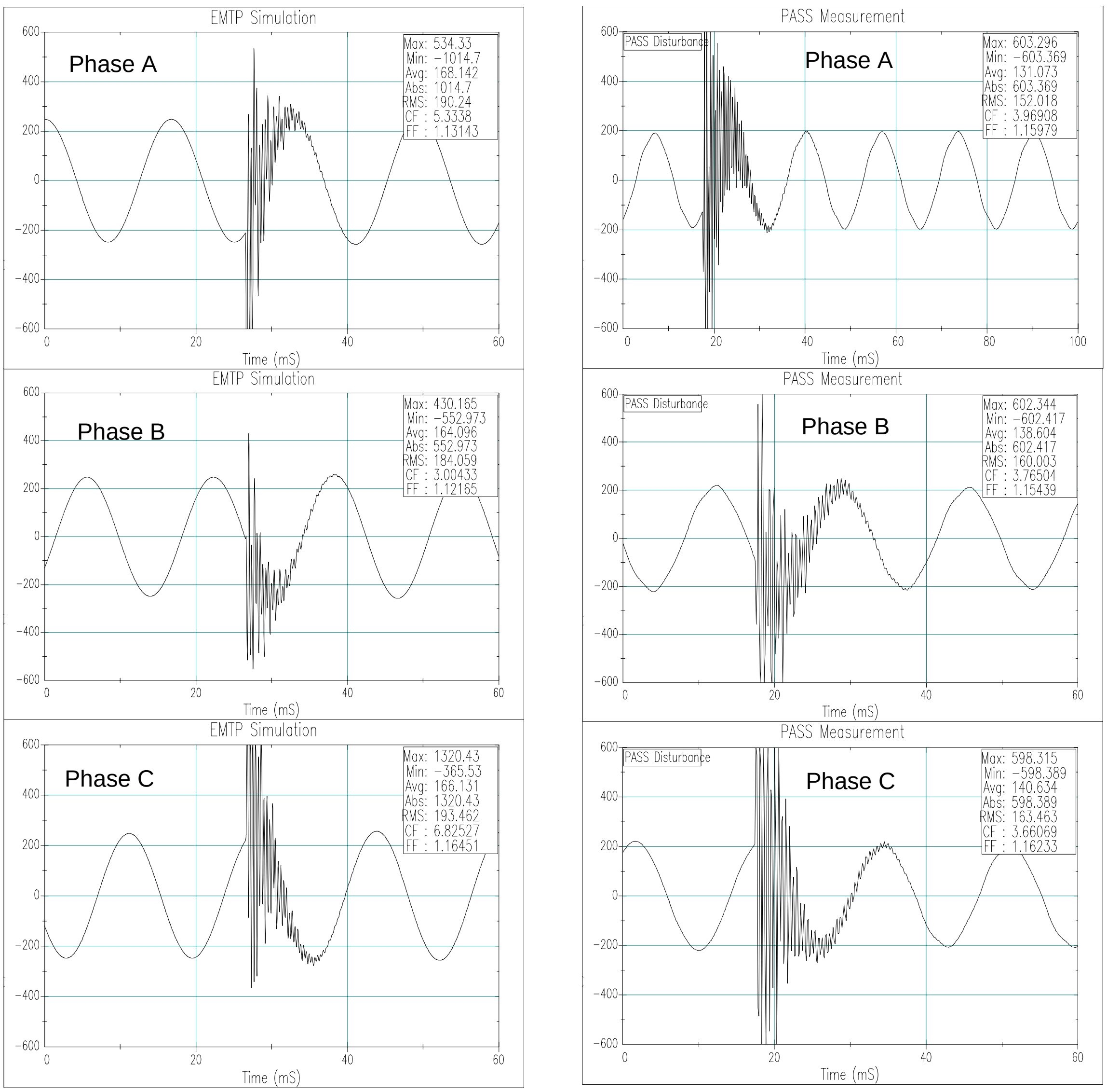


Figure 9: Simulated vs. Measured Waveforms

One of the challenging aspects of the model was in establishing the correct times to switch in each of the phases of bank 3 (which was assumed to be the energizing capacitor). For example, if the capacitors were to be switched in when the system voltage was at a peak, then the bank would try to instantaneously equalize with this

voltage but would give a transient voltage with a magnitude of twice nominal. In order to minimize the voltage transient associated with switching an uncharged bank to system voltage, it is ideal to close the contacts at a zero voltage. However, this is an impractical procedure to perform routinely at the distribution level. A simple gang switch is usually employed,
meaning that the contacts for all three phases are operated at the same time. In the actual waveforms measured by instrument 4095, it is evident that the switch was triggered to the zero crossing of phase B. Not all of the contacts came together at the same time. The switches are mechanical and may have slightly different operating times, or a prestrike may occur, meaning that current is established before the contacts actually are physically connected. In Figure 5, the scale at the initial moment of current inrush can be expanded to show that phase A inrush began 2.8 degrees before phases B and C.

At the distribution level this is not considered a significant problem, since there is enough inductance separating the capacitor banks to limit inrush current to acceptable levels. However, at a substation, where two banks may be within several yards of each other, the inductance between them will be on the order of microhenries instead of millihenries. This means that extremely high frequency, and high magnitude inrush currents will occur in a bank-to-bank event, possibly causing insulation failure and even system outages. Here the scheme of independent pole closing is more useful. This kind of capacitor switch employs logic to accurately close a phase contact within a few hundred microseconds of zero voltage. More frequently, though, this high inrush current is limited either through an insertion reactor or a pre-insertion resistor. The insertion reactor, an inductance inserted between the banks, serves to increase surge impedance and reduce current. The pre-insertion resistor dampens the oscillation during the transient, but must be removed after energizing to avoid steady-state power loss.