6. Conducting an Investigation

Electric utility engineers may be confronted with harmonic problems on their own distribution feeders, or within customer facilities. Distribution feeder cases are the most difficult to deal with since a large harmonics source can pollute the voltage waveform for many miles, including adjacent feeders connected to the same substation transformer. Customer facility cases are the simplest to investigate because the distances are smaller and the offending load can usually be identified by turning candidates off-and-on while observing area voltage waveforms with an oscilloscope or spectrum analyzer.

The focus of this section is on investigating distribution feeder problems where the combination of harmonic current injection and resonant networks act together to create objectionable harmonic levels.

6.1 Field Measurements

In some cases, field measurements alone can be used to identify the source of a harmonics problem. To do this, consider the following:

1. It is important to remember that utility-side harmonics problems are almost always created by primary-metered customers, and the culprit is usually a 500kVA (or higher) ASD, rectifier, or induction furnace. Therefore, if the problem appears suddently, it is prudent to ask questions within your company to find out which large customers on the feeder (or adjacent feeders) may have added a large distorting load.

2. It is wise to make field measurements before contacting the customer. The basic tool needed is a portable spectrum analyzer that can monitor and record harmonic voltages and currents. Voltage measurements can be made at capacitor control circuits or at metering points. The frequencies of interest (e.g. 1500Hz and below) are low enough that standard metering, control, and service transformers accurately portray feeder voltage waveforms. Usually, the feeder voltage distortion is high near the harmonics source, but when there are many shunt capacitors, remote points may also have high voltage distortion. It is desirable, but perhaps impossible, to turn off all shunt capacitors when the measurements are made.

3. Next, it is prudent to monitor and record voltage and current harmonics at the customer's metering point for at least two days, and perhaps more. These data will help to correlate the customer's daily work shift patterns or nonlinear loads with distortion levels. THD_V, THD_I, the 5th and 7th harmonic magnitudes, and if possible, harmonic power, should be recorded. The main indicator is the customer's THD_I.

4. While there is debate on the subject, most power quality engineers believe that harmonic power is a good indicator of the source of harmonics. In fact, if a distribution feeder has one large distorting load, then that load is the source of all harmonic power on the feeder. Some spectrum analyzers compute harmonic power. If the customer is the source of harmonic power, then you can expect the net harmonic power (a few percent of

fundamental power) to flow out from the customer onto the feeder, further comfirming that the harmonics source is inside the customer's facility. The 5^{th} harmonic usually has the largest harmonic power.

If Steps 1 – 4 are inconclusive, then it is sometimes possible to "track down" a harmonics source by taking harmonic power measurements at convenient points along the feeder. For example, voltage measurements can be made at capacitor control boxes. Current measurements can be made with fiber optic-linked current transformers that connect directly to the feeder conductors. Using voltage and current, net harmonic power can be calculated. The expectation is that the net harmonic power flows away from the source.

A wire loop (i.e. "search coil") can be connected to the voltage input of a spectrum analyzer to monitor the current-induced $N\frac{d\varphi}{dt}$ signal that exists below an overhead feeder. The search coil has been used for decades by telephone companies to detect the presence of high harmonic currents. While the search coil gives no power or voltage information, it is useful because large harmonic currents exist on either or both sides of a resonating capacitor bank. Resonating capacitor banks are sometimes turned off, moved, or filtered in an attempt to relieve the harmonics problem.

6.2. Computer Simulations

Field measurements are useful when a harmonics problem already exists. However, computer simulations are needed to study potential problems in advance. For example, if a customer desires to add a 5000HP ASD, then an advance study is needed so that problems can be resolved before the ASD is installed. A harmonics study proceeds in much the same way as a loadflow, short circuit, or motor starting study.

Unless a distribution system is badly unbalanced, or there is a very large single-phase harmonics-producing load such as an electric train, harmonics analysis can usually be performed using the balanced assumption. The reasons are that

- Most problem-causing loads are large three-phase balanced loads such as ASDs.
- Distribution capacitors are usually applied in the form of three-phase banks, having a balancing effect on harmonics propagation.
- Phase identification of single-phase loads and load levels may not be available or easily obtained.
- The quality of harmonics data for the distorting loads may be poor, so that injection "rules of thumb" must be used.
- Systems are often studied in advance, so that not all of the actual data are available.

In spite of these difficulties, experience has shown that distribution feeder harmonic simulations match "real world" measurements very well, and that simulation is a reliable tool for studying solutions such as passive filtering. The term "accurate" generally means that simulated voltage distortions match field measurements within a few percent (on a 100% base).

To obtain this accuracy, these eight rules must be obeyed:

1. When modeling a distribution feeder, include in your study all the feeders attached to the same substation transformer, and in equal detail. On the transmission side of the substation transformer, establish a simple Thevenin equivalent using the short circuit impedance. Transmission line capacitance can be added on the substation high-side, but it usually is not important to the study results.

2. Ten to twenty aggregated busses per feeder is usually adequate detail.

3. Load distributions along actual feeders are not known with great accuracy. However, total feeder kVA load and kVA ratings of individual transformers are known. Load distributions are typically estimated by assuming that the total feeder kVA load is distributed in proportion to individual load transformer ratings.

4. Harmonics models for conventional loads must be included. These can be simple shunt resistances, where the resistances are sized according to active power.

5. The worst-case for harmonics is usually when the harmonics-producing loads are at full power, and the conventional loads are at low power. Conventional loads add damping and reduce distortion levels, and their sinusoidal currents dilute the nonlinear load currents.

6. Capacitor banks are very important and must be included in the study. Usually this means a case with all capacitors on, and a case with only the fixed capacitors on. Other likely capacitor scenarios may also be needed.

7. If there are significant lengths of underground cables, cable capacitances may be important and should be lumped onto the trunk feeders in the form of shunt capacitors. "Important" is relative to the size of the other shunt capacitors. 100kVAr is a good rule for being "important." The capacitance of power cables can be estimated using Table 6.1.

Table 6.1. Capacitance and Charging of 12.47kV and 25kV Cables

Cable	Capacitance (12.47kV)	kVAr (12.47kV)	Capacitance (25kV)	kVAr (25kV)
1/0	0.163	9.56	0.124	29.2
4/0	0.222	13.02	0.162	38.2
350 kcmil	0.267	15.65	0.1914	45.1
500 kcmil	0.304	17.82	0.215	50.7
1000 kcmil	0.401	23.5	0.278	65.5

Capacitance: μF per km per phase
kVAr: (three-phase) per km

8. When the system has multiple sources operating at various power levels (i.e., 10 or more sources), then it is important to consider harmonics cancellation brought about by phase angle diversity. The simplest way to consider diversity is to multiply the harmonic injection currents for each load by the following:

    - 3rd harmonic, multiply by 1.0 (i.e., no diversity)
    - 5th and 7th harmonics, multiply by 0.9
    - 11th and 13th harmonics, multiply by 0.6
    - Higher harmonics, multiply by 0.2

There are two basic techniques for performing harmonics studies – time-domain and frequency-domain.

- Time-domain modeling is usually performed with full three-phase detail and precise models of nonlinear loads. Time-domain modeling is often used to study small networks where the focus of attention is inside specific equipment such as ASDs.

- Frequency-domain modeling is most often used for harmonics studies where the focus of attention is on the network. Approximate models are used for nonlinear loads. Each harmonic is studied individually, and the results are superimposed to produce time-domain waveforms.

Five-Bus Computer Simulation Example

An industrial customer will be served by constructing a three-mile 12.5kV overhead feeder from a dedicated 138/12.5kV substation transformer. The customer will have 5MW @ $dpf = 0.85$ of conventional load and a 2000HP, six-pulse adjustable-speed drive (ASD). The ASD is connected through a delta-delta transformer (i.e., no phase shift). The customer also has 1800kVAr of shunt power factor correction capacitors.

The 138kV substation bus has the following characteristics:

- $Z^{+} = 0.4 + j2.5\%$ (100MVA base)

- 50 miles of 138kV transmission lines are connected to it (line charging = 0.0808MVAr per km).

The dedicated substation transformer has the following characteristics:

- P_{base} = 15MVA
- 138kV delta / 12.5kV grounded-wye connection
- 0.95 per unit tap on the 138kV side
- Z^{+} = 0.5 + j10.5% (on 15MVA base).

The overhead feeder will be constructed with 477 ACSR arm-type construction that has the following characteristics:

- R^{+} = 0.1316 Ω per km
- X^{+} = 0.387 Ω per km (@ 60 Hz)
- C^{+} = 0.01106 μF per km.

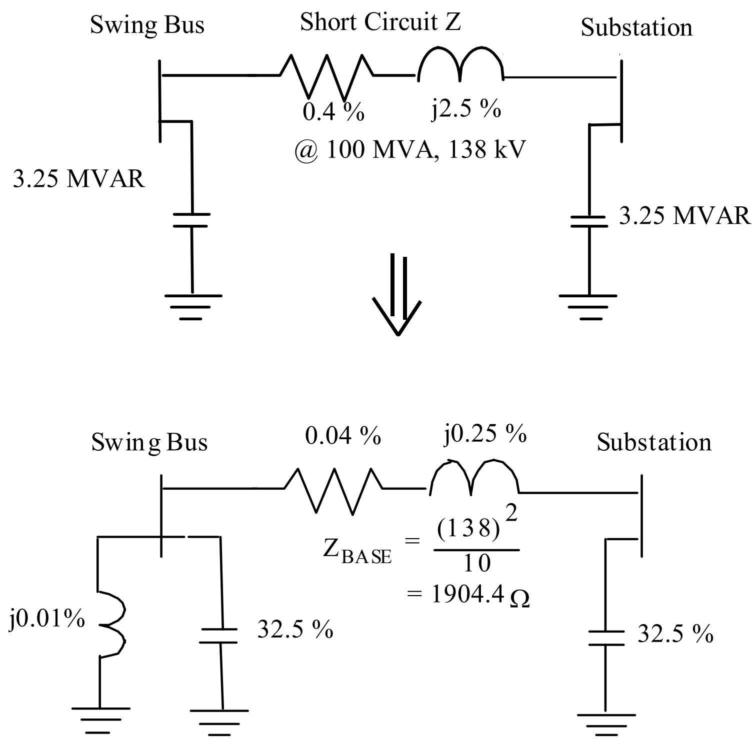
The conventional load transformer is rated at 7.5MVA and has Z^{+} = 0.50 + j5.0% (on 7.5MVA base).

Once the data have been gathered, the next step is to draw a one-line diagram with all impedances and loads expressed on a common base. The base values are selected as 10MVA throughout, and 12.5kV on the feeder section. The voltage base varies throughout the circuit according to nominal transformer turns ratios.

The swing bus is effectively grounded for harmonics with a j0.01% "harmonics-only subtransient impedance." The purpose of this grounding impedance is to model the ability of the "far-distant" system to absorb harmonic currents without incurring appreciable voltage distortion.

Calculations for the above steps are shown below.

For the transmission system,



For the distribution feeder,

$R^{+} = 0.1316\ \Omega$ per km • 1.609 km/mile • 3 miles = 0.635Ω

$X^{+} = 0.387\ \Omega$ per km • 1.609 km/mile • 3 miles = 1.868Ω

$C^{+} = 0.01106\ \mu F$ per km • 1.609 km/mile • 3 miles = $0.0534\mu F$

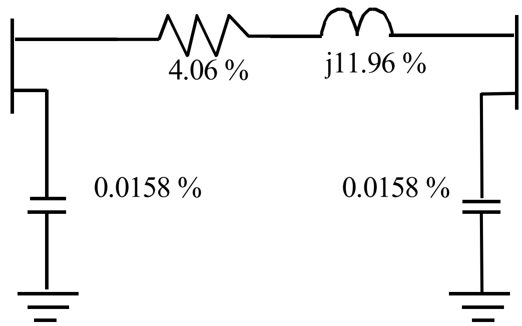
$Z_{BASE} = (12.5)^2 / (10) = 15.625\Omega$

$$\text{Line Charging} \quad = 3\left(\frac{12500}{\sqrt{3}}\right)\left(\frac{12500}{\sqrt{3}}\right)(2\pi)(60)(0.0534 \bullet 10^{-6})\ \text{VAr}$$

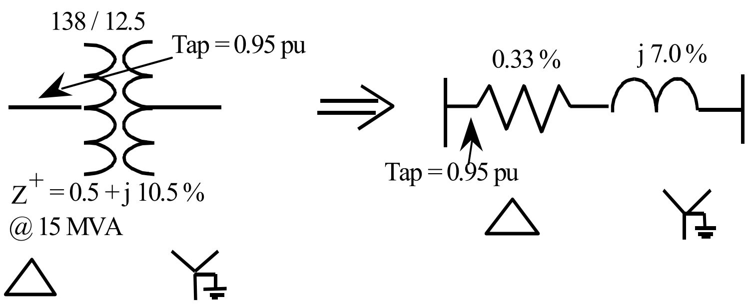
$$= 3.15\text{kVAr} = 0.0315\ \%\ @\ 10\text{MVA}$$

$$R_{pu} = \frac{0.635}{15.625} \bullet 100\% = 4.06\%$$

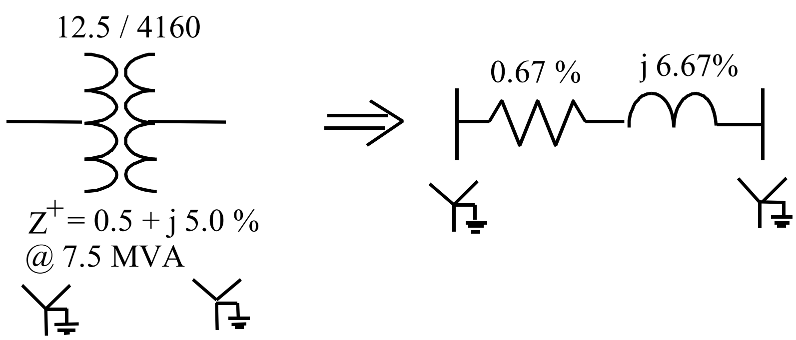
$$X_{pu} = \frac{1.868}{15.625} \bullet 100\% = 11.96\%$$



For the substation transformer,



For the conventional load transformer



The 1800kVAr of shunt power factor correction capacitors becomes 18% on a 10MVA base.

The final one-line diagram is shown in Figure 6.1.

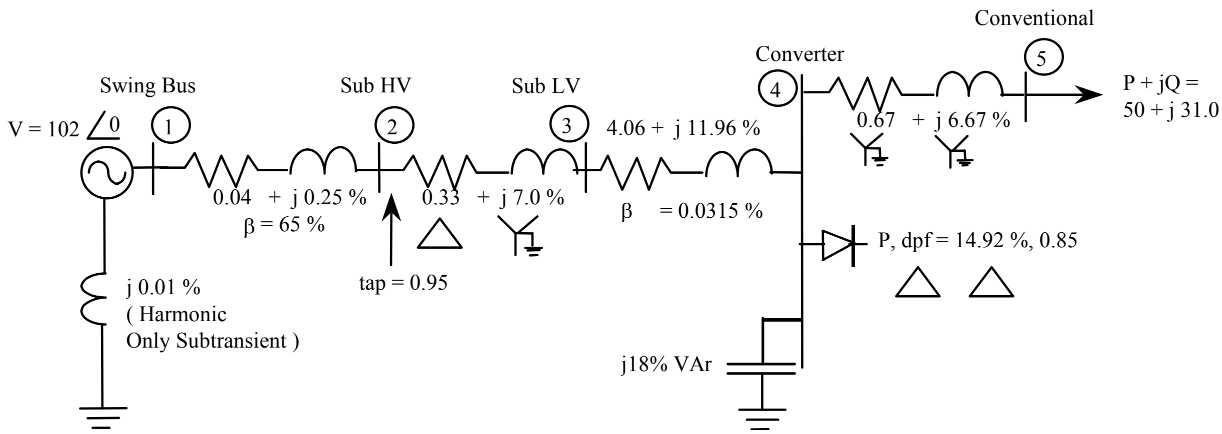


Figure 6.1. System One-Line Diagram for Five-Bus Example

6.3. Passive Filters

Filters accomplish two objectives – power factor correction of nonlinear loads, and shunting one or more harmonic currents to ground. A series tuned filter can be constructed in each phase to ground by placing a choke in series with a shunt capacitor, and then tuning the choke so that the inductive and capacitive reactances are equal but opposite at the desired harmonic. Tuning a filter slightly below the desired harmonic, for example at the 4.7^{th} instead of the 5^{th} harmonic, helps to reduce capacitor voltage without significantly degrading filter performance. Often the addition of a 4.7^{th} (i.e., 5^{th}) filter is adequate to solve harmonics problems.

Care must taken to dedicate enough kVAr to the filter. In most cases, the filter kVAr should be approximately the amount needed to power factor correct the nonlinear load. Filters with smaller kVAr will have sharp tuning curves and will be easily overloaded by stray harmonics that are present in the network.

Since a filter capacitor usually experiences 1.2 to 1.3 pu rms voltage, plus significant harmonics, care must be taken that the capacitor voltage rating is adequate. The fact that kVArs decrease by the square of voltage must also be taken into consideration.

To illustrate filter design, the five-bus system is modified by converting the 1800kVAr capacitor bank into a 4.7^{th} harmonic filter. First, a new bus (#6) is created, and the 1800kVAr capacitor bank is moved from Bus 4 to Bus 6. In reality, the 1800kVAr bank would be replaced with a higher-voltage rated bank, with sufficient kVArs so that it produces 1800kVAr at system voltage. Then, Bus 4 is connected to Bus 6 with a series choke that has the appropriate reactance. The tuning formulas for harmonic k are

Let $\dfrac{-X_C(pu@60Hz)}{k} = kX_L(pu@60Hz)$, so that

$$X_L(pu@60Hz) = \frac{-X_C(pu@60Hz)}{k^2}.$$

In this example,

$$X_C(pu@60Hz) = \frac{1}{-0.18pu} = -5.55pu \text{, so that}$$

$$X_L(pu@60Hz) = \frac{5.55pu}{4.7^2} = 0.251pu \text{, or } 25.1\%.$$

On a 12.5kV, 10MVA base, the choke inductance (each phase of wye connection) is

$$L = X_L \bullet Z_{BASE} \bullet \frac{1}{2\pi f} = \frac{0.251 \bullet 15.625}{2\pi \bullet 60} = 10.4mH \text{ .}$$

Assuming

$$\frac{X_L(pu@60Hz)}{R} = 50$$

for the choke, the choke resistance is estimated to be $R = \frac{25.1\%}{50} = 0.502\%$, or 0.0784Ω. The modified system diagram is shown below in Figure 6.2.

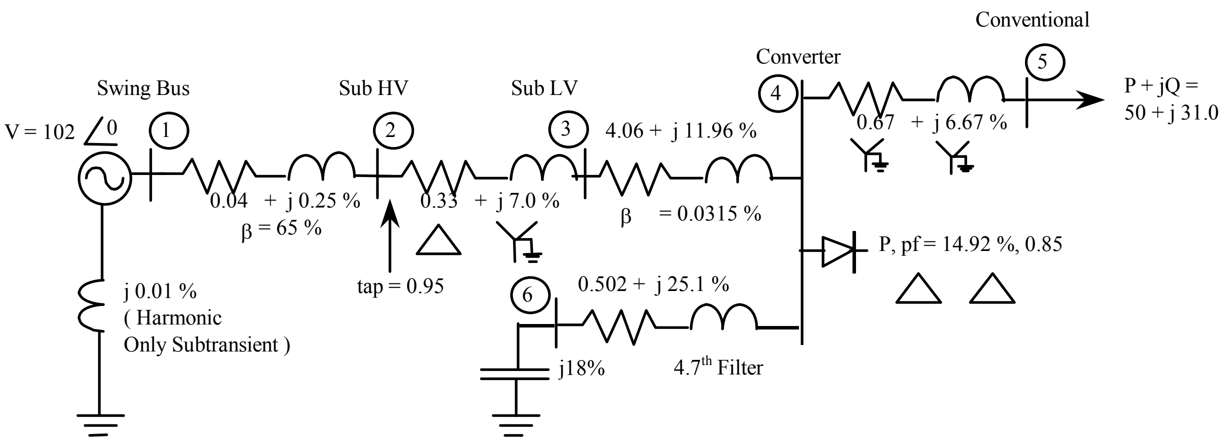


Figure 6.2. System One-Line Diagram for Five-Bus Example with Filter

Filter performance is checked using three steps.

1. Impedance scans are performed, without and with the filter. The filter notch should be at the design harmonic.

2. The converter bus voltage waveform, without and with the filter, is examined. 5th harmonic filtering is usually adequate. However, if the voltage distortion is still more than 4 or 5%, it may be necessary to add a larger 5th filter, or possibly 7th, 11th, and 13th filters, in that order. Usually, the higher the harmonic, the fewer kVArs committed to a filter. A good rule for dedicating kVAr when multiple filters are needed is to stairstep the kVAr as follows: if Q kVArs are used for the 5th harmonic, then Q/2 should be used for the 7th, Q/4 for the 11th, and Q/4 for the 13th. Of course, actual sizes must match standard sizes. The total kVAr should power factor correct the nonlinear load. For best performance, a filter should have at least 300 kVAr.

3. The filter current waveform is checked to make sure that it is absorbing the appropriate harmonic and that the filter current is within rating.

Simulation results for the five-bus system, without and with the filter, are given in Figures 6.3 – 6.5.

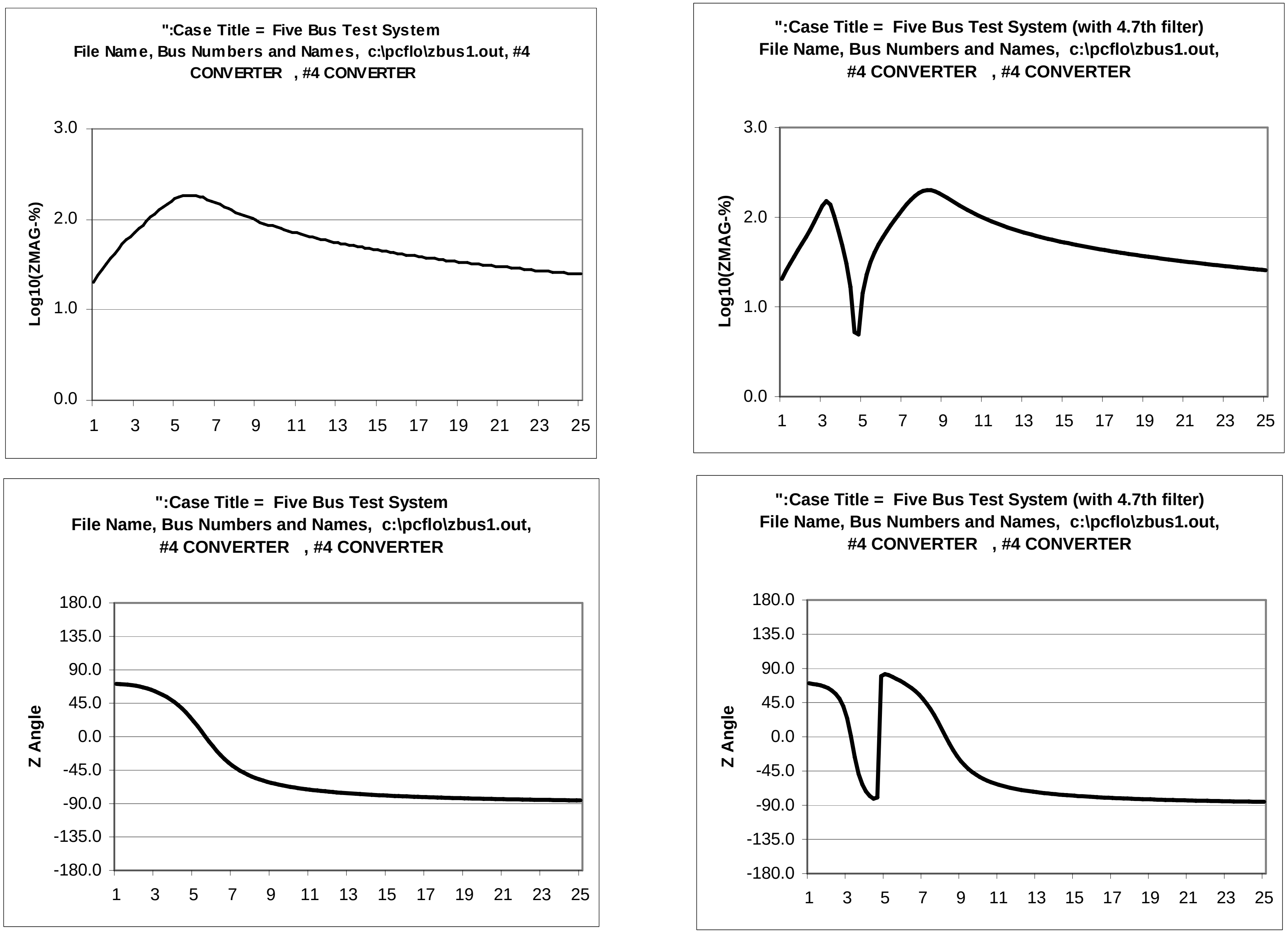


Figure 6.3. Impedance Scans at Converter Bus (Without Filter on Left, With Filter on Right),
(plots produced by program PCFLO_ZBUS_PLOT.XLS)

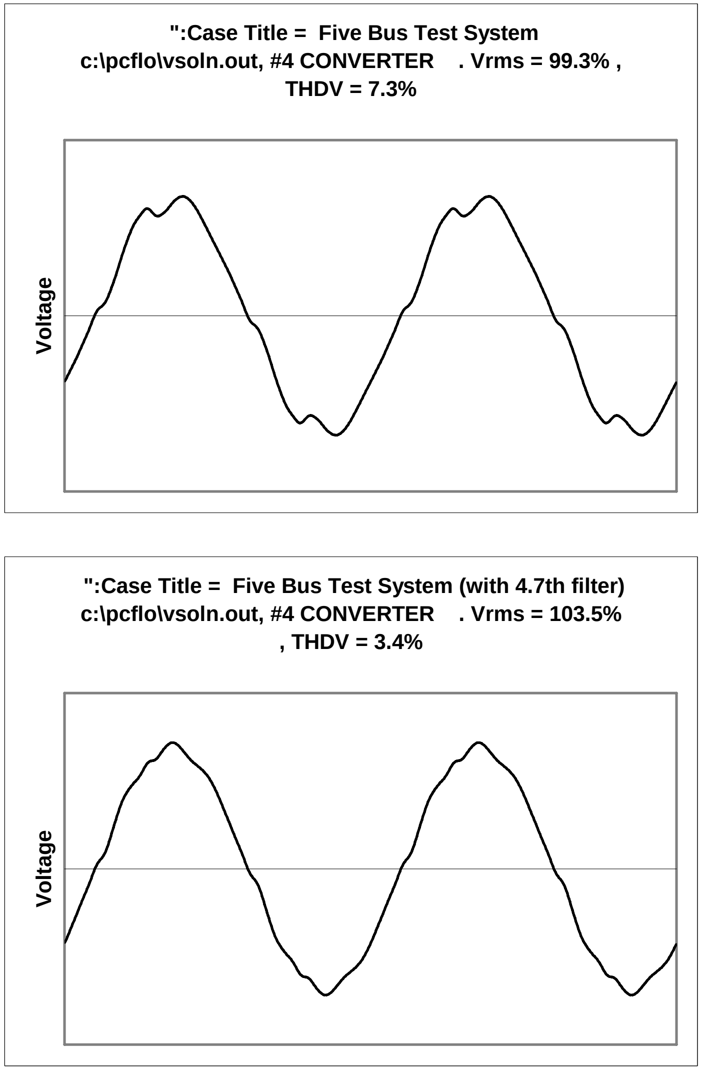


Figure 6.4. Converter Bus Voltage Waveforms Bus (Without Filter at Top, With Filter at Bottom), (plots produced by program PCFLO_VSOLN_PLOT.XLS)

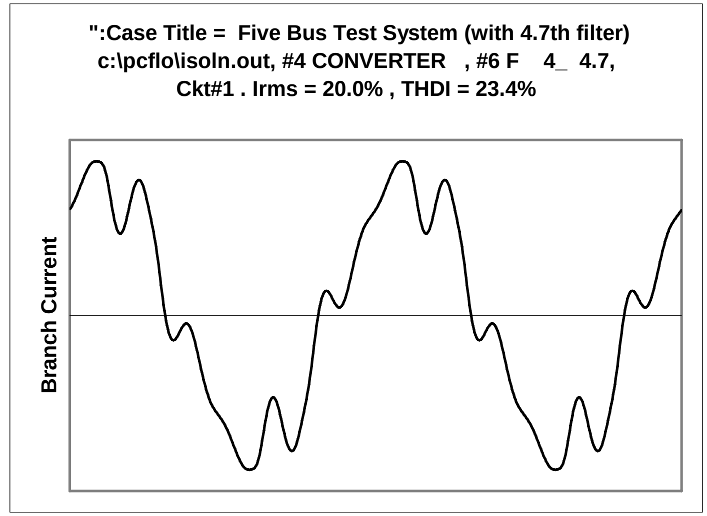


Figure 6.5. Filter Current Waveform) (plot produced by program PCFLO_ISOLN_PLOT.XLS)