Harmonic Impacts Due to Induction Furnaces on a Distribution System

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Customer PQ Concerns
Harmonic
Harmonic Filter
Harmonic Resonance
Induction Furnace
Steel

Section 1.1: Introduction

An industrial customer, customer #1, has been experiencing a number of problems with the power converters used in their induction furnace loads. Harmonic distortion levels were measured on this system and found to be very high throughout the distribution system. The harmonics are being caused by the induction furnaces at the plant and at other industrial customers (including other induction furnace loads) on the same distribution system. There are also a number of capacitor banks located on the primary distribution systems which are aggravating the harmonic problem by causing resonance conditions. A one-line diagram of the system is illustrated in Figure 1.1.

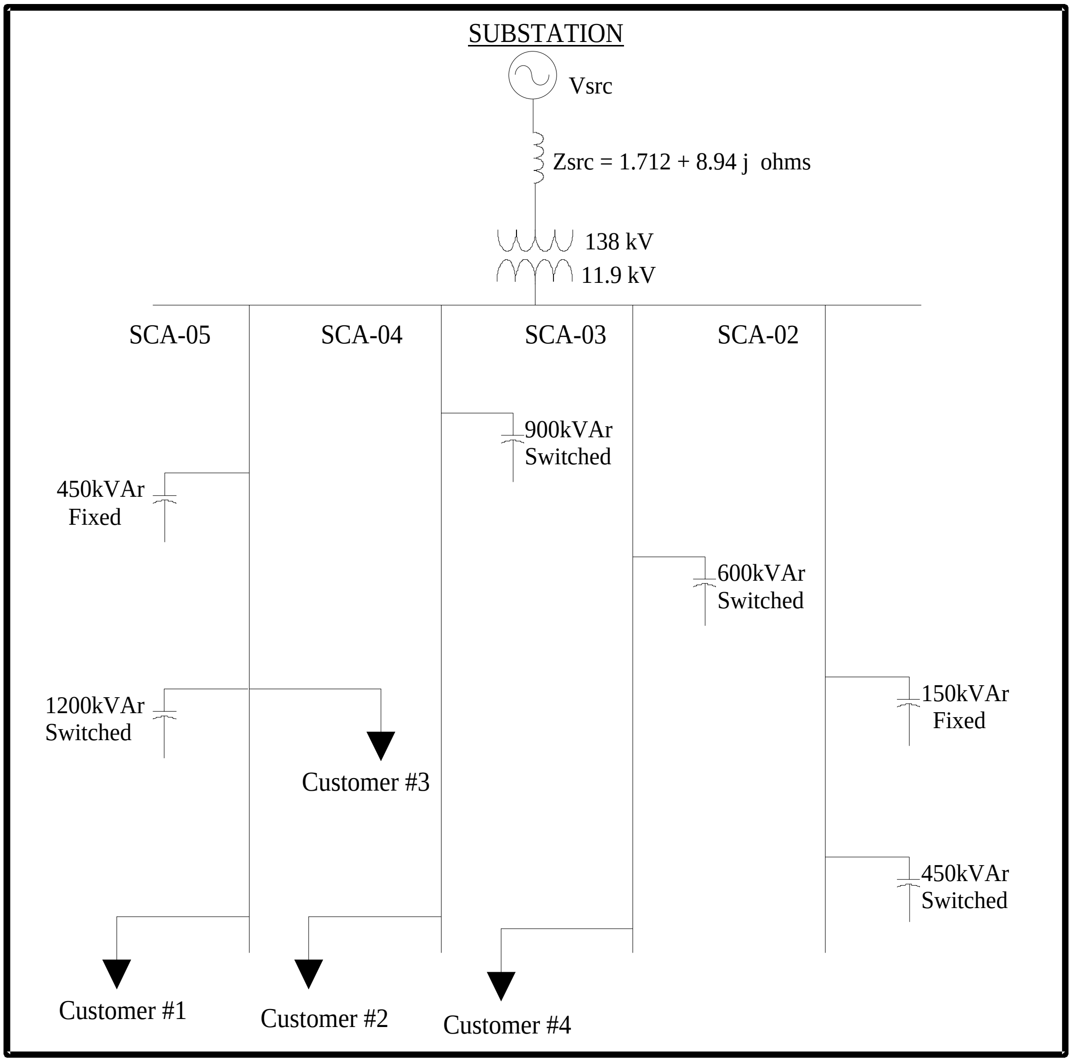

Figure 1.1: One-Line Diagram of System

In the interests of correcting the harmonic distortion levels throughout the system, harmonic filters have been proposed for the primary distribution system at customer #1 and customer #2 and low voltage filters have been proposed for two smaller industrial customers. This report presents the results of a harmonic investigation to verify the design of these filters and evaluate the effectiveness that can be expected when they are placed in service. The study also evaluates the proposed ratings for the filter components, including the effects of tolerances in the filter parameters.

A model of the power system was developed and simulations were run using a harmonic analysis program. These simulations studied the harmonic impact of different contingencies on the installed filters to verify the filter design.

The following report summarizes the results of the simulations and provides recommendations to improve overall system performance. Section 2 describes the system model and Section 3 outlines the process used to select the nonlinear harmonic source. In Section 4 the measured results are compared with the results obtained from the base case simulation. The proposed filter design is then investigated in Section 5 followed by the conclusions and recommendations in Section 6.

Section 2.1: One-Line Diagram

The power system investigated is shown in Figure 2.1. There are four customers which have a high percentage of nonlinear loads; customer #1, #2, #3 and #4. The substation transformer is a 15 MVA delta-wye connected transformer with an impedance of 8%. The capacitor banks in the one-line diagram are all ungrounded wye connected and the branches shown in the diagram were modeled with pi equivalents.

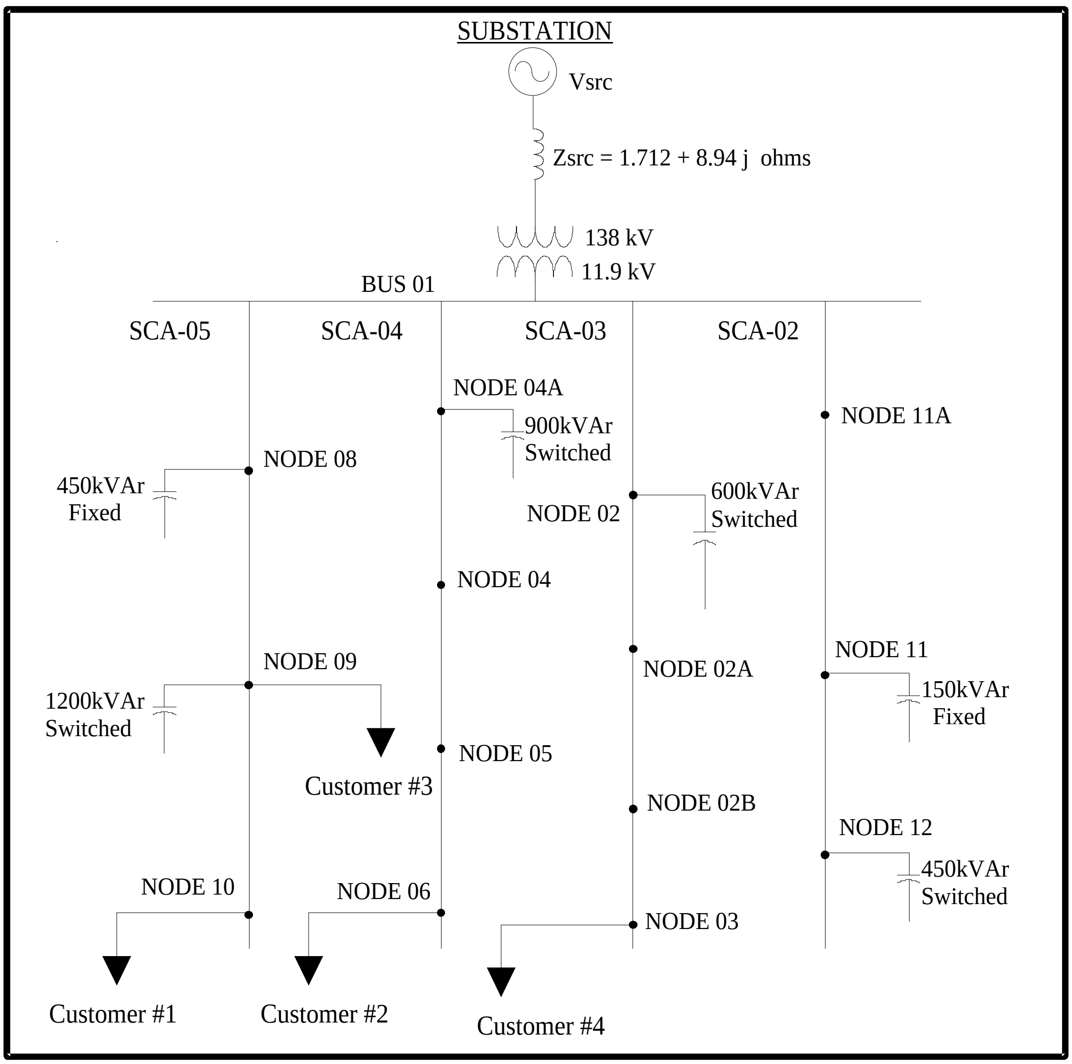

Figure 2.1: One-Line Diagram

Section 2.2: System Loads
The nonlinear loads modeled at each customer are tabulated in Table 2.1. The assumption made for the harmonic current content injection for these nonlinear loads is discussed in the following section. Linear loads were modeled at customer #4 and at node 11 according to Table 2.2. Once these system loads were incorporated in the model, the necessary base case simulations were performed and are discussed in Section 4.

Customer	Load	Transformer	Impedance	Load	Low Side
	No.	kVA	Z%	kW	Voltage
#1	1	1500	5.49	1250	480
	2	1250	5.56	1000	575
	3	1250	5.54	1000	575
	4	3000	4.85	2500	575
#2	1	750	6.31	400	480
	2	750	3.5	400	715
	3	530	4.33	400	750
	4	150	5.04	125	440
	5	150	5.04	100	460
	6	225	5.04	125	280
#4	1	500	5.04	350	480
#3	1	300	5.04	175	480

Table 2.1: Customer Nonlinear Loads

Customer	Load	Transformer	Impedance	Load	Low Side	Displacement
	No.	kVA	Z%	kVA	Voltage	Factor
#4	1	1500	5.49	1250	480	0.9
Node 11	1	1250	5.56	1000	575	0.9
	2	1250	5.54	1000	575	0.9

Table 2.2: Linear Loads

Section 3.1: Six-Pulse Rectifier Characteristics
The determination of the nonlinear load harmonic spectrum was based upon previous observations of six pulse rectifiers found in drives, traction power converters, induction furnaces, and other applications requiring ac/dc power conversion. These rectifiers generate harmonic currents at the following characteristic harmonics:

$Ih = 6n \pm 1$, $n = 1, 2, 3...$

In the ideal case of an infinite bus supplying the rectifier and an infinite choke on the dc side, the harmonic currents are:

$Ih = (1/h) \times I1$, $I1$ = fundamental frequency current

The resulting current spectrum from can be found in Table 3.1.

Harmonic	Magnitude
1	100%
5	20%
7	14%
11	9%
13	8%

Table 3.1: Six-Pulse Rectifier Current Spectrum

Section 3.2: Harmonic Source Modeled

In the actual case, the commutation reactance associated with the supplying transformer and system somewhat reduces the harmonic currents as compared to those given in Table 3.1. The modeling of multiple six-pulse rectifiers instead of a single rectifier further reduces the current spectrum based on the fact that multiple rectifiers operating at different firing angles result in harmonic cancellation. The current harmonic spectrum utilized in the simulation model based on these previous observations can be found in Table 3.2. This spectrum was injected at each customer bus based on the loading information given in Table 2.1. These assumptions result in a fairly conservative analysis.

Harmonic	Magnitude
1	100%
5	15%
7	8%
11	3%
13	2%

Table 3.2: Nonlinear Load Current Spectrum

Section 4.1: Simulation Results

The system described in Section 2 was simulated using a harmonic analysis program. Figure 4.1 shows the frequency scan of the base case simulation at customer #1. This case modeled the system before the installation of the filters but with all distribution capacitor banks in. It is evident in this figure that there exists a potential resonance problem due to the capacitor banks located throughout the power system. The figure shows that the impedances at characteristic harmonic frequencies (5th and 7th) are high which results in a high level of voltage distortion. The actual system resonance is between the sixth and seventh harmonic.

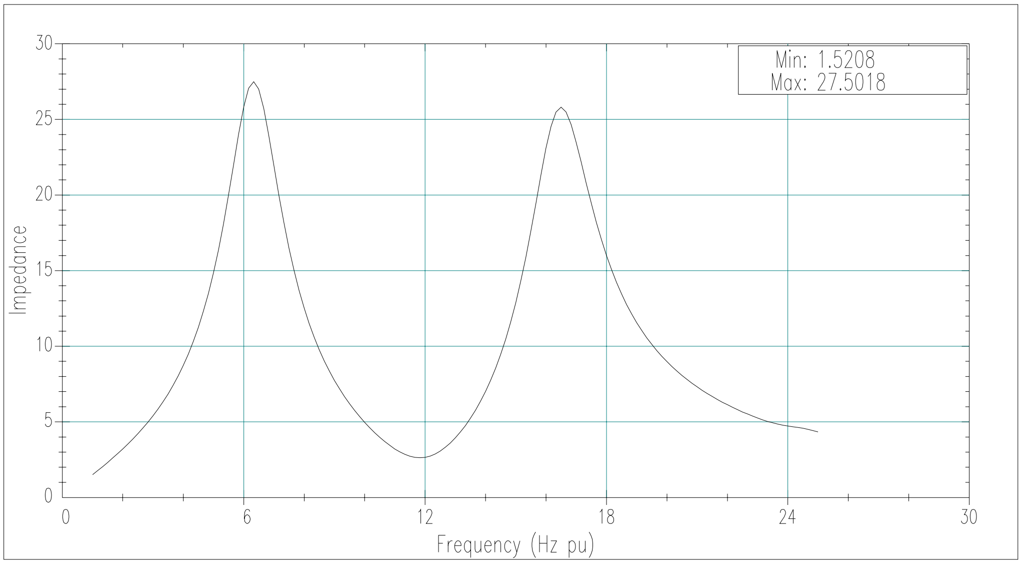

Figure 4.1: Frequency Scan at Customer #1

Table 4.1 shows the voltage total harmonic distortion (THD) values at the high side of the transformer for customer #1 and customer #2 based on the harmonic current generation assumptions described previously.

	Customer #1	Customer #2	Feeder Sub
Vthd	14.55%	11.70%	10.55%

Table 4.1: Simulated Results

The harmonic voltage spectrum can be seen in Figure 4.2 at customer #1. The distortion is particularly evident at the 5th and 7th harmonics, contributing to a total harmonic distortion of 14.55% on the high side of the transformer.

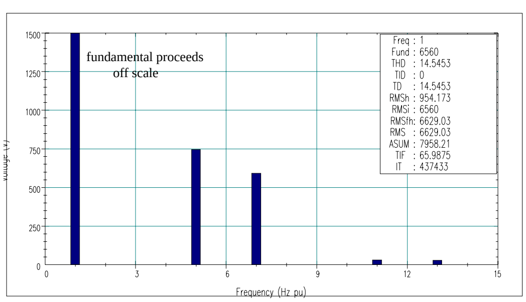

Figure 4.2: Harmonic Voltage Spectrum at Customer #1 (High Side)

Section 4.2: Measurement Results

Measurements of the voltage harmonic content were obtained for each customer in the system as well as at the substation. In order to verify an effective model the measured values obtained were compared with the simulated values. The current harmonic spectrum used for each customer's nonlinear load can be seen in Table 4.2. These current spectrums represent the worst case that was measured at each location. Note that these agree quite well with the harmonic current generation assumptions described in the previous section.

Harmonic Number	Magnitudes Customer #1	Magnitudes Customer #2
1	100%	100%
5	18%	19%
7	10%	11%
11	4%	7%
13	2%	4%

Table 4.2: Measured Harmonic Current Spectrums

Table 4.3 compares the measurement and simulation results at customer #1 and #2 locations. The measurements presented are considered to be typical levels after reviewing all the different measurement cases submitted. Since the status of existing capacitor banks was not indicated for the measurements, simulations were performed with and without the distribution system capacitor banks in service. Note that only the fixed capacitors were in service for the case with capacitors in. If all the capacitors are in service, the voltage distortion levels are even higher due to a resonance between the fifth and seventh harmonic.

Customer Name	P (W)	Q (Var)	DF	Measured Vthd (Low)	Simulated Vthd (Low) w/fixed cap	Simulated Vthd (Low) w/o caps
#1	540	525.2	0.717	11.46	10.18	8.77
#2	128	44.68	0.944	11.23	10.83	11.21

Table 4.3: Measured vs. Simulated Results

It can be seen in Table 4.3 that the simulated values compare favorably with the measurements at both locations. It is likely that at least the fixed capacitor banks were in service during the measurements. Figure 4.3 is an example of the harmonic spectrum at customer #1 for the case with the fixed capacitor banks in service.

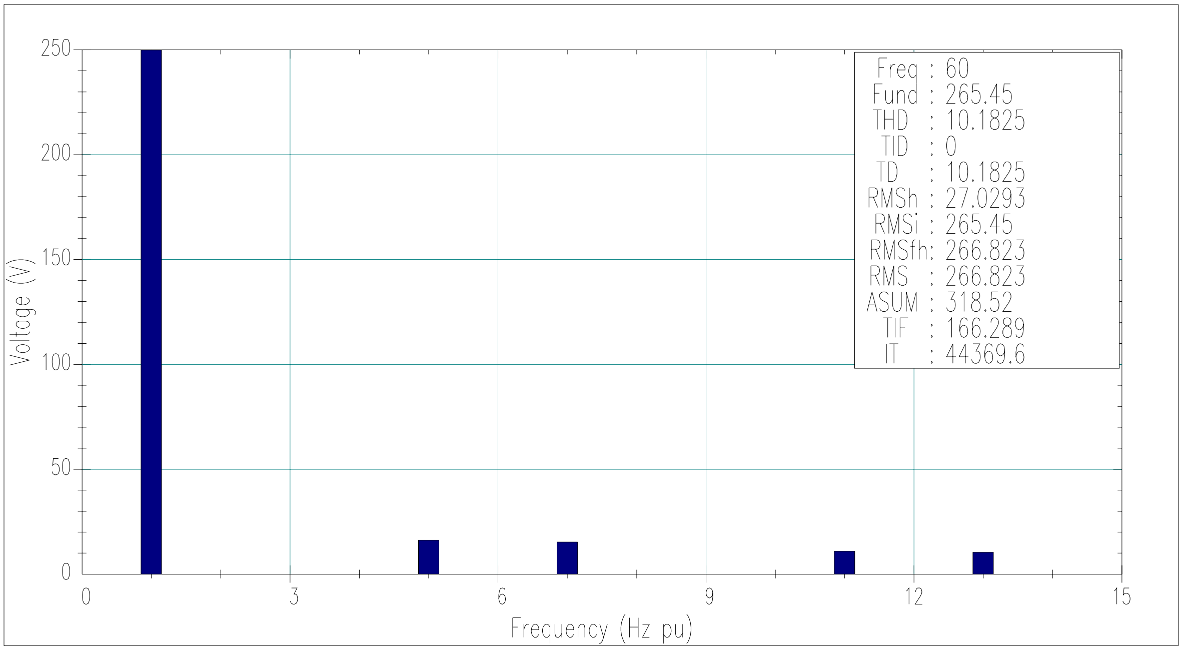

Figure 4.3: Simulated Harmonic Voltage Spectrum at Customer #1 (Low Side)

Section 4.3: 60 Hz Furnace Concerns

The 60 Hz furnaces are of concern because they can presently only be run at 60% of full power. Plant engineers at customer #1 would like to increase production with this furnace. The 60 Hz furnace was modeled using an equivalent parallel RLC circuit as shown in Figure 4.4. This furnace is very difficult to model because three different parameters can vary. These parameters include the tap changing autotransformer, furnace coil, and furnace power factor correction capacitors. The furnace parameters modeled in Figure 4.4 represent one estimated operating condition. This condition resulted in severe voltage distortion at the 600 V bus (about 27%). A series resonance draws harmonic currents down from the high voltage bus at customer #1 as shown in Figure 4.5. A parallel resonance causes magnified voltage distortion as shown in Figure 4.6. This bus is very important and should be monitored.

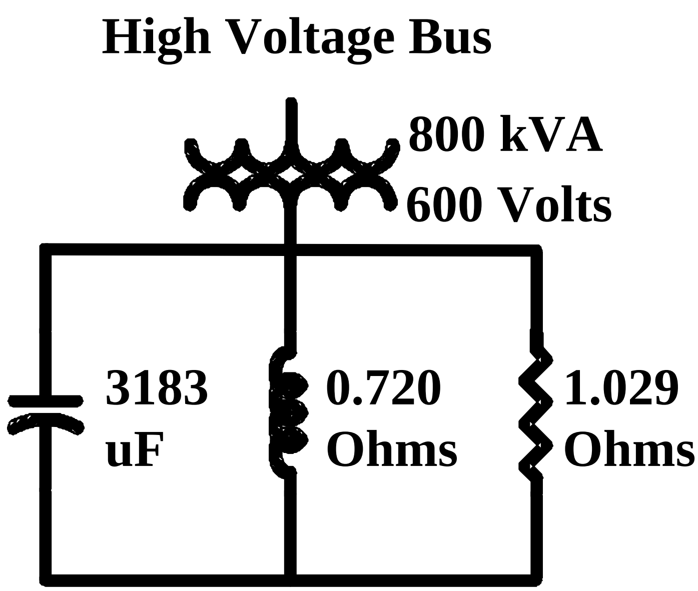

Figure 4.4: Equivalent Furnace Model

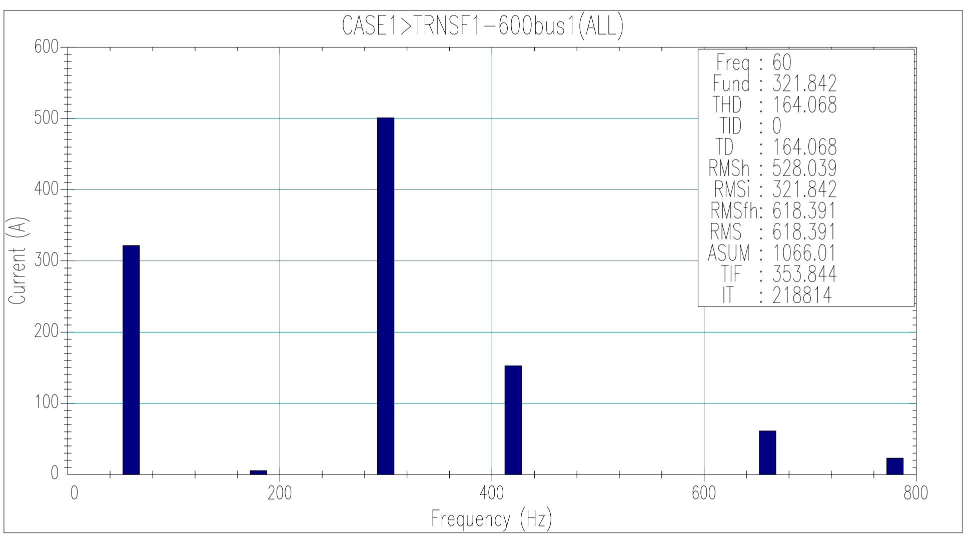

Figure 4.5: 60 Hz Furnace Current

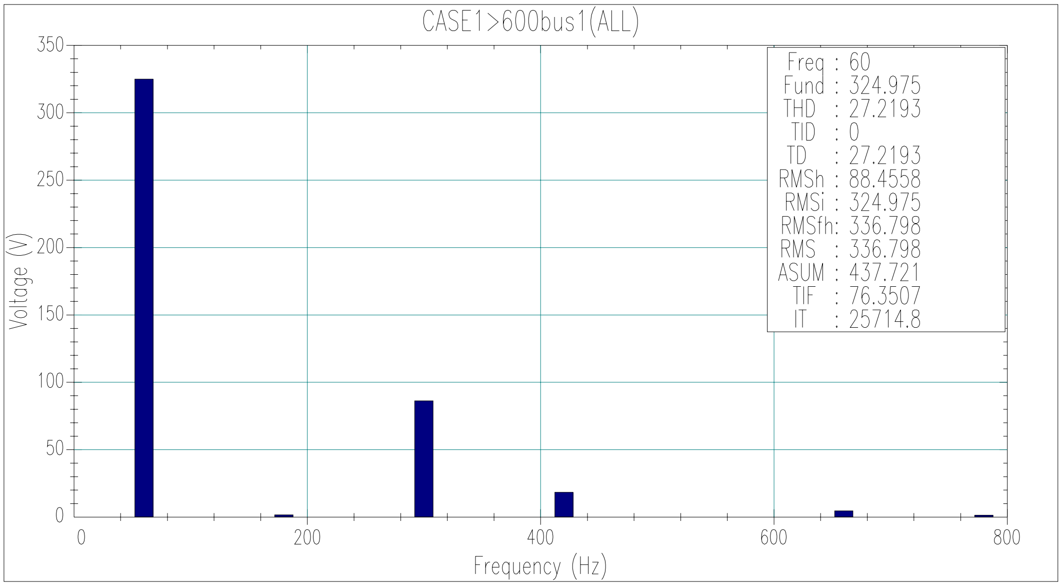

Figure 4.6: 60 Hz Furnace Low Side Voltage Distortion

Section 5.1: Primary Filters

The verification of the proposed filter designs commenced with simulations of the filters for the primary side at customer #1 and #2. The proposed filters were added to the system model. As was noted in Figure 4.1, the capacitors in the system contribute to the resonance conditions observed at higher harmonics, therefore, the other capacitor banks were removed from the system. Figure 5.1 compares the frequency scans at customer #1 with and without filters.

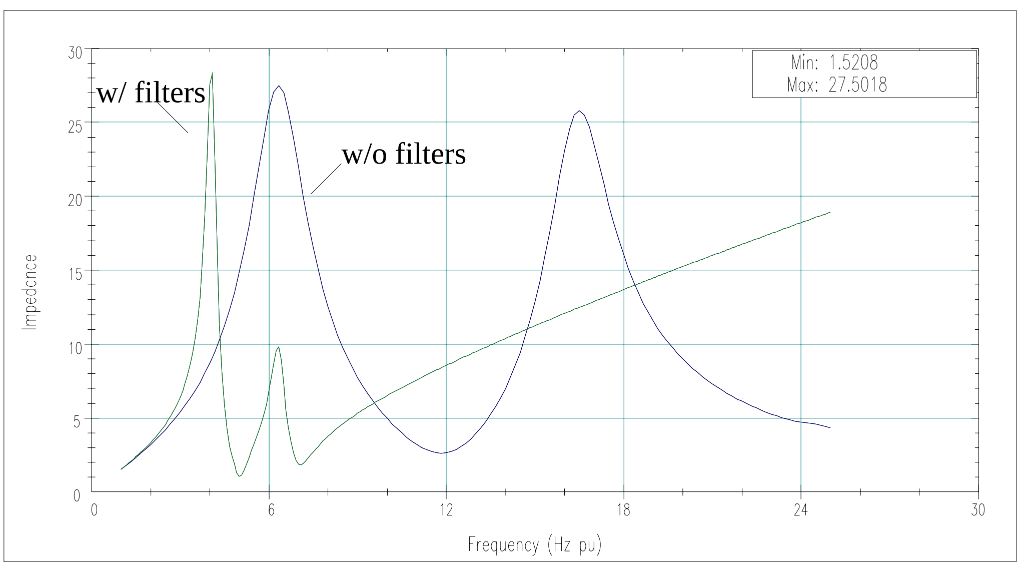

Figure 5.1: Frequency Scan at Customer #1

The frequency scan with filters shows an expected parallel resonance before a reduction in the impedance at characteristic harmonic frequencies. As desired, the fifth and seventh harmonic filters have effectively lowered the impedance at these frequencies. The effect of the filters on the voltage distortion levels can be observed in Figure 5.2. The addition of the filters reduced the total harmonic voltage distortion at customer #1 to 1.56%. Table 5.1 compares the voltage THD values at the other locations. These values are significantly less than the distortion evident before the installation of the filters.

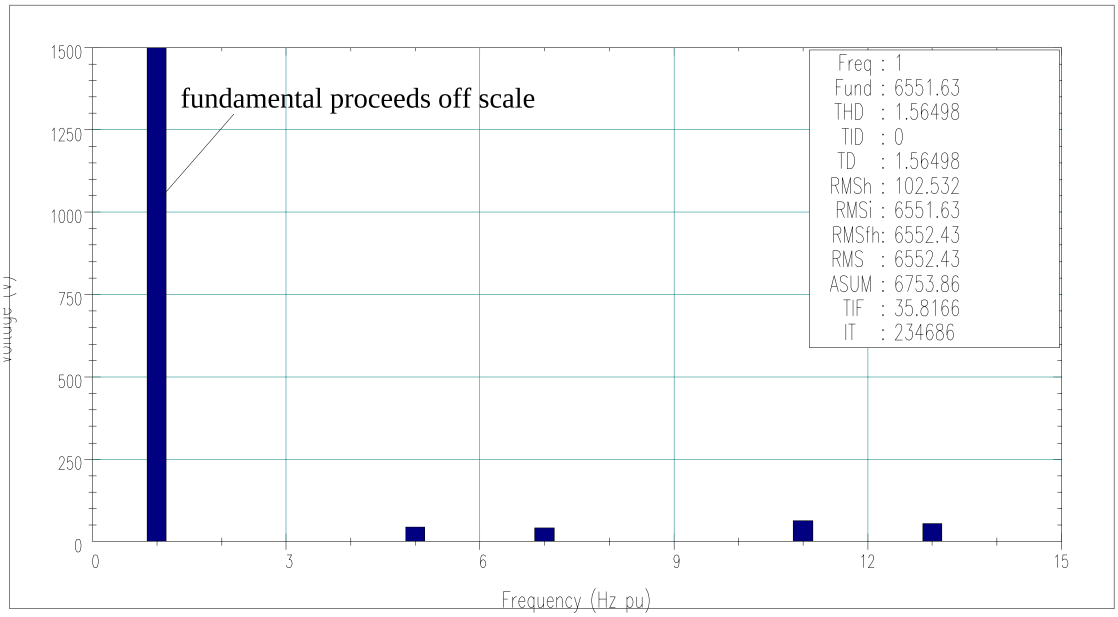

Figure 5.2: Harmonic Spectrum with Filters at Customer #1 (High Side)

	Customer #1	Customer #2	Feeder Sub
Vthd	1.56%	0.86%	0.75%

Table 5.1: Vthd Values With Primary Filters In

The initial peak observed in Figure 5.1 occurs at the fourth harmonic with an impedance of 28 ohms. The uncharacteristic injection of a third harmonic current of 1.5% was cause for some concern due to this high impedance. The addition of this non-characteristic harmonic showed a voltage distortion of only 30 V at the third harmonic. This satisfies the concern of high third harmonic voltage levels and verifies the primary filter design.

Section 5.2: Secondary Filters

In order to verify the secondary filters, simulations were performed with the remaining two filters added to the secondary side of the transformers at customer #3 and #4. THD values from the simulations are tabulated in Table 5.2.

	Primary Filters In	Primary and Secondary Filters In
Customer #3	1.48%	1.45%
Customer #4	0.88%	0.84%

Table 5.2: Vthd Values

It can be seen from the values in Table 5.2 that the addition of the filters at customer #3 and #4 do not significantly change the THD values. The distortion evident with only the filters at customer #1 and #2 are within acceptable percentages. The effect on harmonic levels with the addition of the secondary filters can be seen in the frequency scans in Figure 5.3. The frequency scans were done on the high side of the transformer at customer #3. These filters succeeded in reducing the maximum harmonic resonance peak by 35%, yet the 5th and 7th harmonic notches remain at the same values. This accounts for the small decrease in the harmonic distortion.

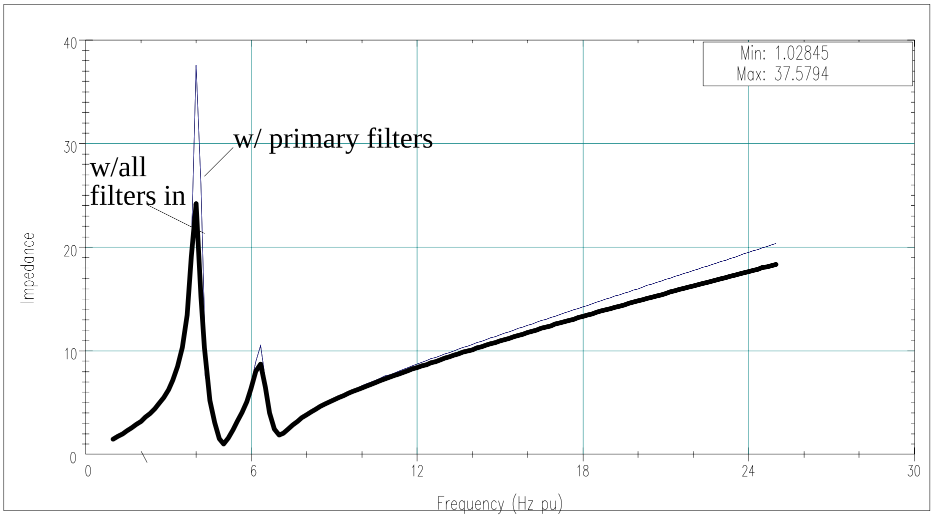

Figure 5.3: Frequency Scans at Customer #3

Section 5.3: 60 Hz Furnace with High Side Filters Installed

With the filters installed at the high voltage bus at customer #1, the harmonic currents are directed into the filters and not into the 60 Hz furnaces as shown in Figure 5.4. This reduces the low side voltage distortion to acceptable levels as shown in Figure 5.5. This should allow the 60 Hz furnaces to run at higher power ratings. The monitoring device will be used to verify the harmonic current and voltage levels and furnace operating conditions.

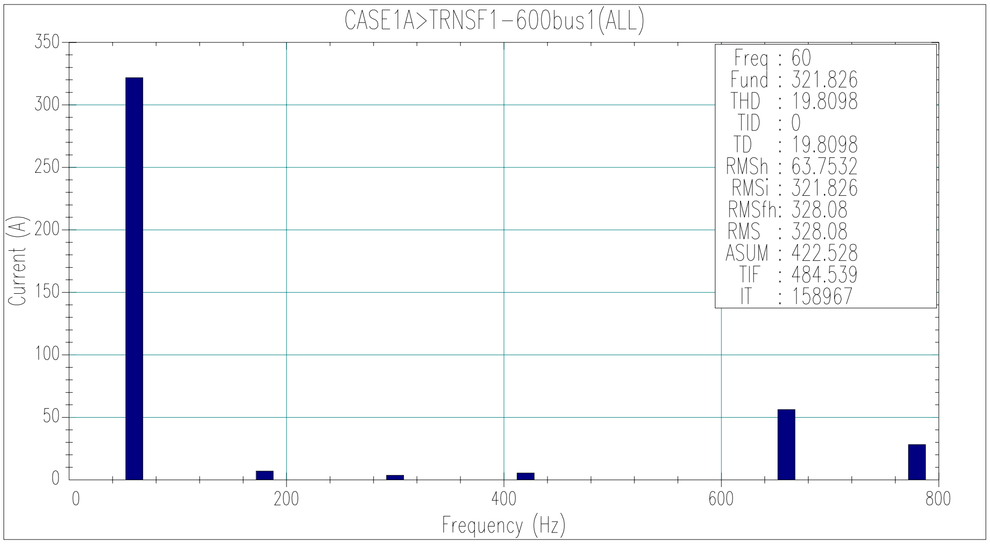

Figure 5.4: 60 Hz Furnace Current with Filters Installed at Customer #1

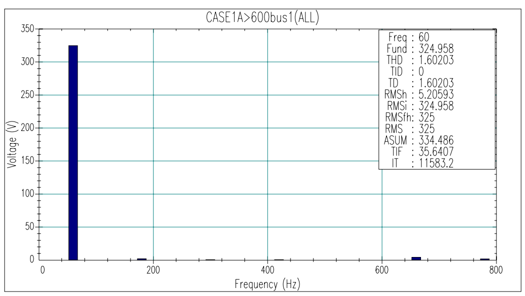

Figure 5.5: 60 Hz Furnace Low Side Voltage Distortion with Filters Installed at Customer #1

Section 5.4: Required Ratings

The proposed design of the filters were found to be effective in reducing the total harmonic distortion in the system. However, to achieve reliable system performance it is necessary to insure that the required reactor and capacitor ratings are not exceeded. Several different contingencies were studied with various filters in and out of service and with filter tolerances varied.

In one of the contingencies studied, one of the filter reactors exceeded its limits. This contingency investigated the situation of all filters in except at customer #1. The result of this was the 7th harmonic filter at customer #4 exceeds its rated reactor current by 9.39%. This demonstrates the system's dependence on the filters at customer #1. Due to the excessive distortion and harmonic currents present at that customer, it is necessary to insure the reliability and operation of these filters. In another case, with the filter capacitors at customer #1 and #2 set 10% higher than specified, both the 5th and 7th harmonic filters at all the customer locations are within specified reactor ratings. This verifies that the reactor current limits will not be exceeded with a kVAr increase of up to 10%.

Section 6: Conclusions and Recommendations

Harmonic currents may be prevented from flowing on to the power system by the effective use of filters. The fundamental approach to efficient filter design involves the examination of the filter response, including the effect of tolerances in the capacitor and the reactor values. The proposed filter designs for this power system were investigated in this approach and the following conclusions were made:

- Harmonic simulations showed that the filters effectively reduce the total harmonic distortion.

- The installation of the secondary filters reduce the total harmonic distortion at customer #3 and #4 (primary voltage level) by a minimal percentage. These filters are definitely not necessary to control harmonic levels on the distribution primary. The removal of the filters at customer #1 from the system allows the current ratings of the reactor of the filters at customer #4 to be exceeded. This demonstrates the systems dependence on the efficient and reliable operation of the filters at customer #1. A way to prevent this is to re-design the low side 7th harmonic filter to allow for the excess current or to insure the continuous operation of the filters at customer #1.

- The monitor should be installed at the substation to measure both harmonic distortion levels and disturbance events.

- One monitoring device should be installed at the high voltage side of customer #1 to view harmonic current and voltage distortion.

- Since he filters at customer #3 and #4 have been received and will be installed first, one monitoring device should be installed at each location on the low voltage side. Measurements should be taken for at least two weeks prior to the installation of the filters in order to get a base value of the harmonic currents present in each facility. The filters should be installed and energized when the system load level is low. The current into the filters should be monitored closely especially the first few days to insure that the filters are not overloaded and drawing excessive harmonic currents from the utility system.

- After monitoring is completed at customer #3 and #4, the monitoring devices at each location should be moved to customer #1. One 60 Hz furnace and one induction furnace should be monitored on the low voltage side. These monitors along with the high side monitor should provide valuable information when problems occur.

- The 60 Hz furnace monitoring device is very important. This furnace was modeled using an equivalent parallel RLC circuit. The furnace is very difficult to model because three different parameters can vary. These parameters include the tap changing autotransformer, furnace coil, and furnace power factor correction capacitors. The furnace parameters modeled represent one estimated operating condition. This condition resulted in severe voltage distortion at the furnace 600 V bus. A series resonance draws harmonic currents down from the high voltage bus at customer #1, and a parallel resonance causes magnified voltage distortion. The simulations also showed that with the filters at customer #1 installed, the harmonic currents are directed into the filters and not into the 60 Hz furnaces. This reduces the low side voltage distortion to acceptable levels, which should allow the 60 Hz furnaces to run at a higher power rating. The monitoring device will be used to verify the harmonic levels and furnace operating conditions.

- The plant also operates conventional loads on a bus that is fed from another substation. Problems arise when there are voltage sags or outages on either circuit because the whole plant must be shutdown. Therefore, reliability is reduced. Simulations indicate that when the filters are installed at customer #1, the voltage distortion at the bus will be reduced to well below 5%. After this has been verified with measurements, and the voltage distortion is still below 5%, the conventional load bus could be transferred back to the feeder and should operate without problems. The transformer and conventional loads will not draw much harmonic current because this bus will appear as a high impedance and the harmonic current will still want to flow into the filters.