PQSoft Case Study

Electric Utility Harmonic Study
Medium Voltage Filter Design

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Abstract:

This particular utility was experiencing voltage distortion levels throughout their distribution network that were exceeding IEEE Std. 519 limits. One customer, a plastic extrusion plant, was experiencing blown fuses in their switched capacitor banks along with capacitor failure. A harmonic evaluation study was performed on the 34.5kV/12kV network supplying this customer. The scope of the study was to investigate the impact of surrounding capacitor banks on voltage distortion levels and to make recommendations with regards to mitigating the harmonic problem. A medium-voltage harmonic filter was designed and simulated for mitigation effectiveness throughout the distribution system.

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RELATED STANDARDS

IEEE Std. 519

INTRODUCTION

The particular electric utility was experiencing voltage distortion levels throughout their distribution network exceeding IEEE Std. 519 limits. One customer, a plastic extrusion plant was experiencing blown fuses in their switched capacitor banks along with capacitor failure. This is believed to be the result of the high harmonic distortion measured throughout the network.

A harmonic evaluation study was performed on the 34.5kV/12kV distribution system that serves the facility and surrounding areas. The scope of the study was to investigate the impact of surrounding capacitor banks on voltage distortion levels. Of particular interest was the impact on harmonic distortion levels that resulted due to the interaction (resonance) between the capacitors and system impedance.

The scope of the harmonic evaluation study included:

- System model development
- Evaluation of system frequency response characteristics (resonance conditions) for various operating conditions
- Recommendations regarding follow-on field measurements for characterizing utility system and customer (nonlinear loads) distortion levels
- Model update to include nonlinear load characteristics
- Evaluation of harmonic distortion levels for various operating conditions
- Evaluation of possible solutions to excessive distortion levels, including the design and application of harmonic filters

A complete three-phase model of the distribution system supplied by the 69kV/34.5kV transformer was created using Electrotek's SuperHarm® program. The model was verified for accuracy and then used to perform the frequency scan analysis, distortion simulations, and ultimately the filter design.

System Description

The feeders experiencing problems are both fed from a 69/34.5kV wye-delta transformer, with three 34.5kV feeders feeding the local loads. There are no capacitors on the first two feeders, however, capacitor banks are located throughout one of the said feeders. The customer experiencing problems (plastics plant) has a 600 kvar, 12-step capacitor bank at the 480V level.

A one-line diagram of the system is shown in Figure 1.

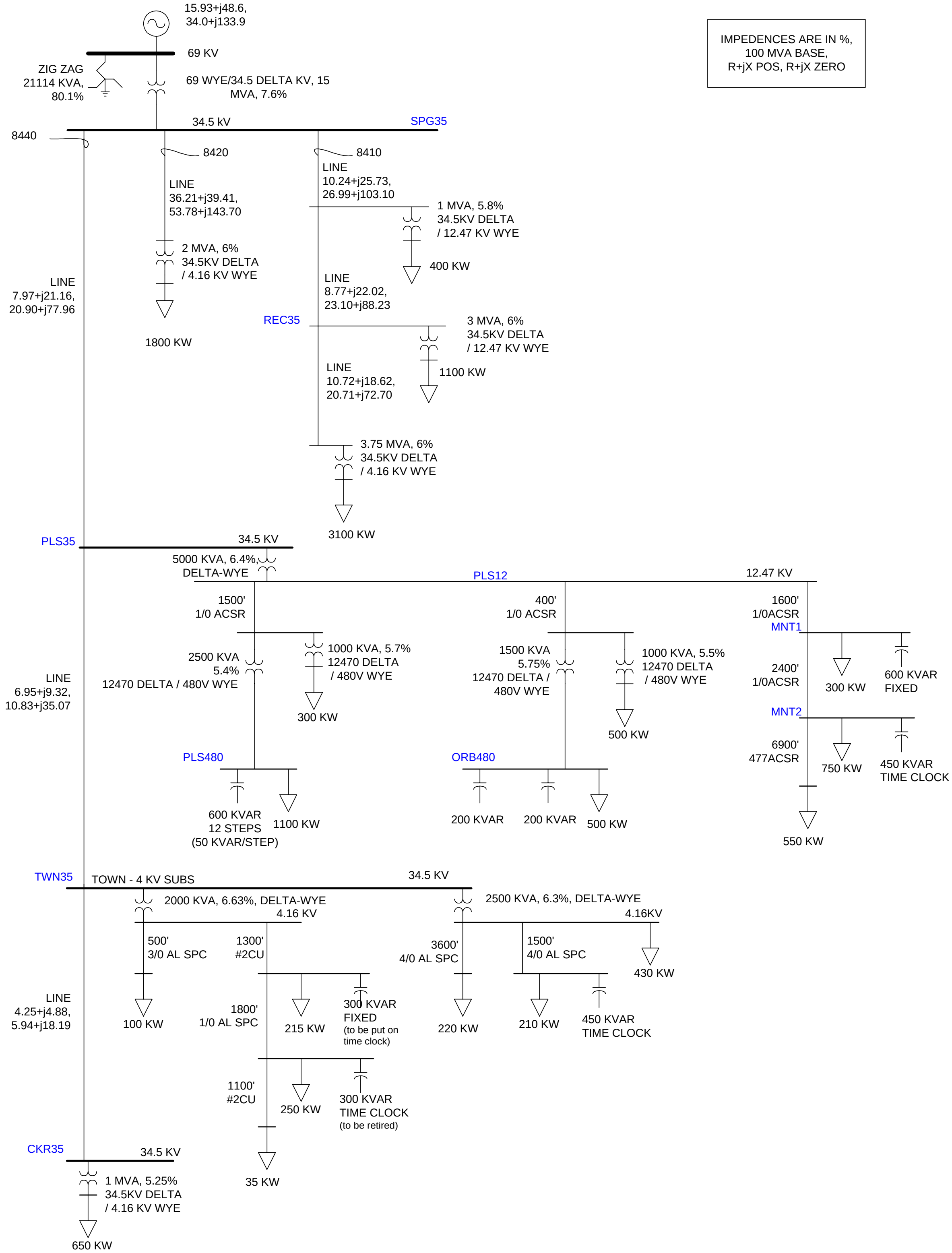


Figure 1 - System One-Line Diagram

The system model was implemented using the SuperHarm program. A three-phase model was used to accurately model the effect of transformer connections on harmonic cancellation. The model includes line and cable characteristics, transformers, substation and low voltage capacitors, load, and an equivalent representation of the adjacent system. All distribution and transmission lines were modeled using a three-phase positive/zero sequence impedance model. Linear load was included to provide a realistic amount of system damping for the distortion simulations. Without these loads, the simulation results would be too conservative, especially at or near system resonance.

Measured Data

The electric utility had previously performed measurements throughout the problematic system using a hand-held power quality meter. These measurements were taken between 4/1/99 and 8/12/99.
The surrounding distribution network experience voltage distortion levels exceeding IEEE Std. 519 limits of 5% THD, with some instances exceeding the 3% level for individual harmonics (5^{th} and 7^{th}).

FREQUENCY SCANS

Frequency response characteristics for various operating conditions were determined using the "Frequency Scan" capability of the SuperHarm program. These characteristics were evaluated to identify, if any, significant resonant conditions as the result of capacitor bank placement. The scans will demonstrate the expected harmonic voltage at the respective voltage level per amp of harmonic current injected into the system.

As shown in Figure 1, there are three fixed capacitors, three switched capacitors (time clock), and the 12-step, 600 kvar capacitor at the plastics plant. With these various switched capacitors, a very large number of possible capacitor combinations can be found. Using the Batch Mode function within SuperHarm, a multiple cases were run analyzing the effect each capacitor had on system resonance. Note: Unless otherwise noted, all frequency scans illustrated are under no-load conditions, thus providing worst than actual results.

Present Conditions

One worst-case scenario will be discussed in detail. For this scenario, the 600 kvar PLS480 capacitor bank is switched from 0 to 600 kvar in 100 kvar increments. The actual bank is switched in 50 kvar increments, but a resolution of 100 kvar is sufficient for illustrating the effect of shifting resonance. Each scan illustrates the driving point impedance seen at the PLS12 bus with one amp of current injection at the SPG35 bus.
The first scenario illustrates the resonance conditions seen at the PLS12 bus with the following capacitors online:

- MNT1 600 kvar
- ORB 400 kvar
- PLS480 200 kvar

Figure 2 illustrates the frequency response of the system seen at the PLS12 bus. The base case, no capacitor system is shown as a reference. As evident in Figure 2, resonance conditions occur at both the 5^{th}, 10^{th}, and 17^{th} harmonics. The extremely high resonance conditions found at the 5^{th} harmonic would explain the high amount of 5^{th} harmonic distortion measured on the system.

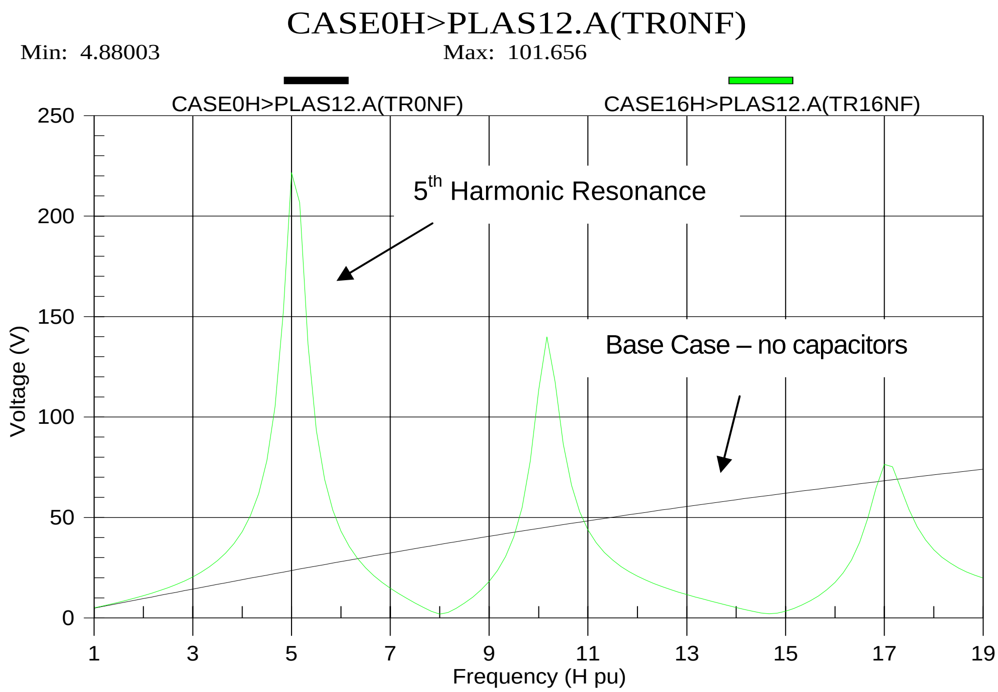


Figure 2 - Frequency Scan with 5th Harmonic Resonance

As the PLS480 capacitor banks are switched from 0 to 600 kvar, the 5th harmonic resonance shifts approximately 60 Hz (4.5th harmonic to 5.5th harmonic). Therefore, for cases in which the resonance normally occurs between the 4th and 6th harmonics, the switching of capacitors at PLS480 could result in a resonance shift such that it is tuned to the 5th harmonic.

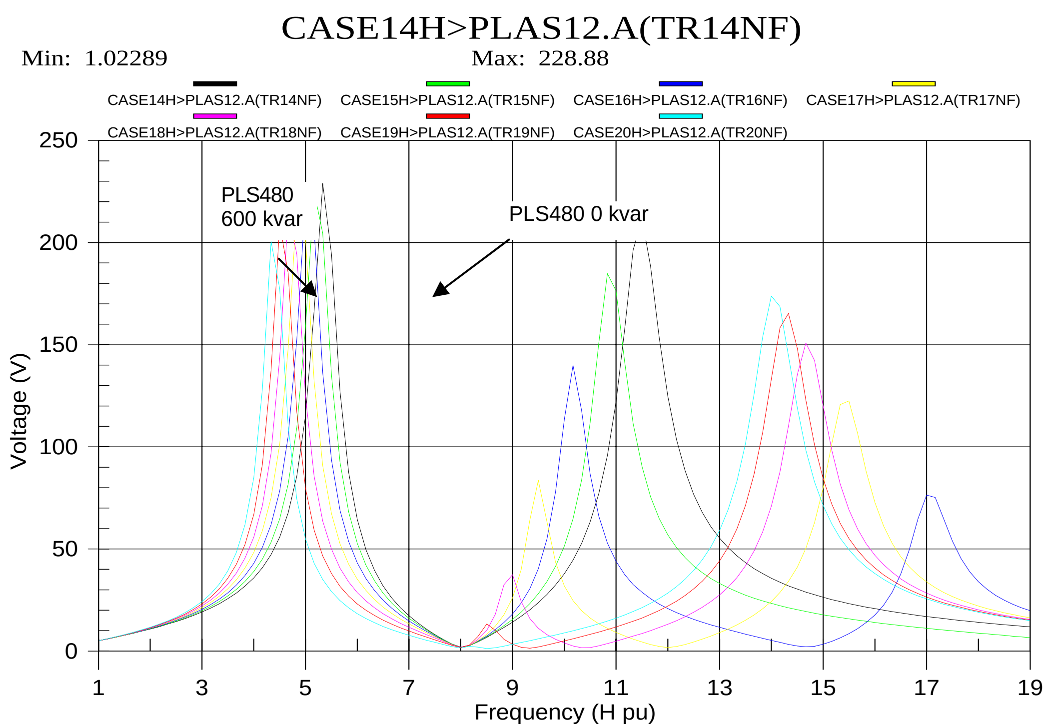


Figure 3 - Frequency Scan Results Illustrating 5th Harmonic Resonance

5th Harmonic Filter

A 5th harmonic filter was examined at multiple points in the system including

- SPG35 bus
- CKR35 bus
- PLS12 bus
- PLS480 bus
- REC35 bus
- PLS35 bus

Placing the filter at the PLS12 bus (MNT1 in Figure 1) provided the greatest amount of 5th harmonic suppression throughout the system. Using Figure 2 as an example, Figure 4 illustrates the suppression of 5th harmonic resonance as a result of placing a 1200 kvar filter at MNT1.

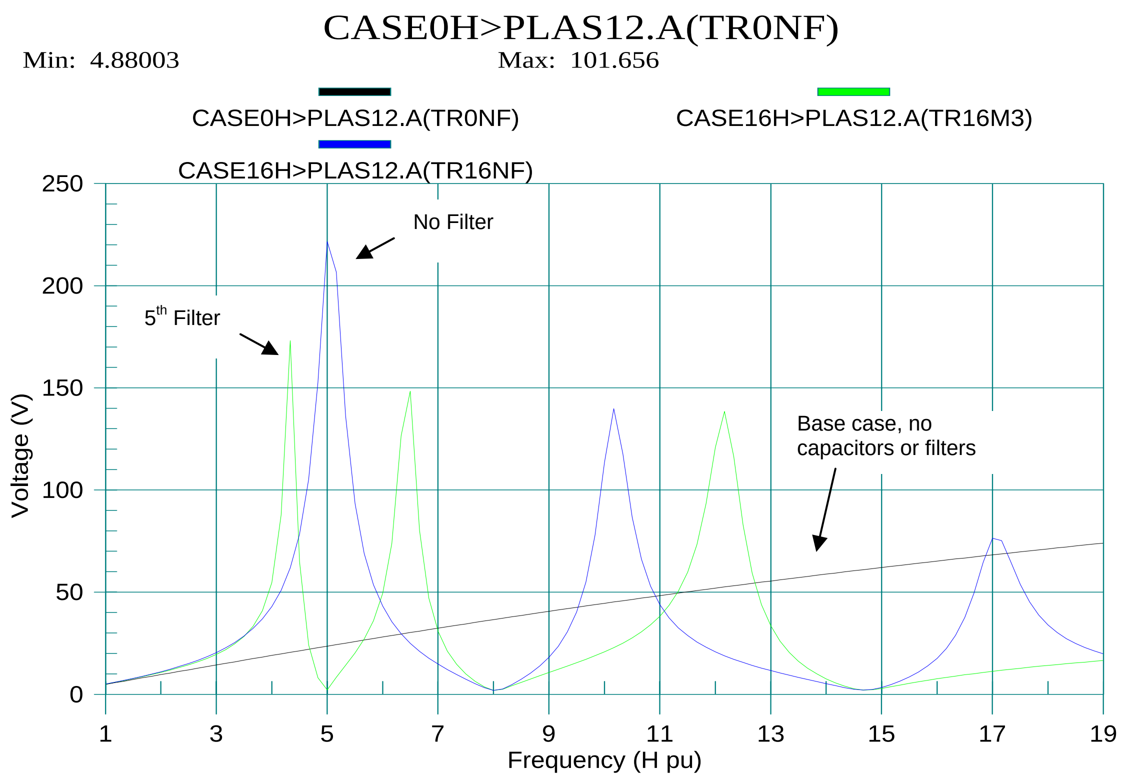


Figure 4 - Frequency Scan with 5th Harmonic Filter at PLS12 Bus (MNT1)

As shown in Figure 4, the 5th harmonic filter creates a short circuit at the 5th harmonic (300 Hz), thus providing a sink for 5th harmonic distortion. Note that at the fundamental frequency, the filter will act as a standard shunt connected capacitor, providing reactive power to the distribution system.
Also note that the filter also produces a parallel resonance at approximately 390 Hz (6.5th harmonic).

Using the PLS480 switched bank as a variable (as in Figure 3), this resonance can be shifted towards the 7th harmonic (see Figure 5).

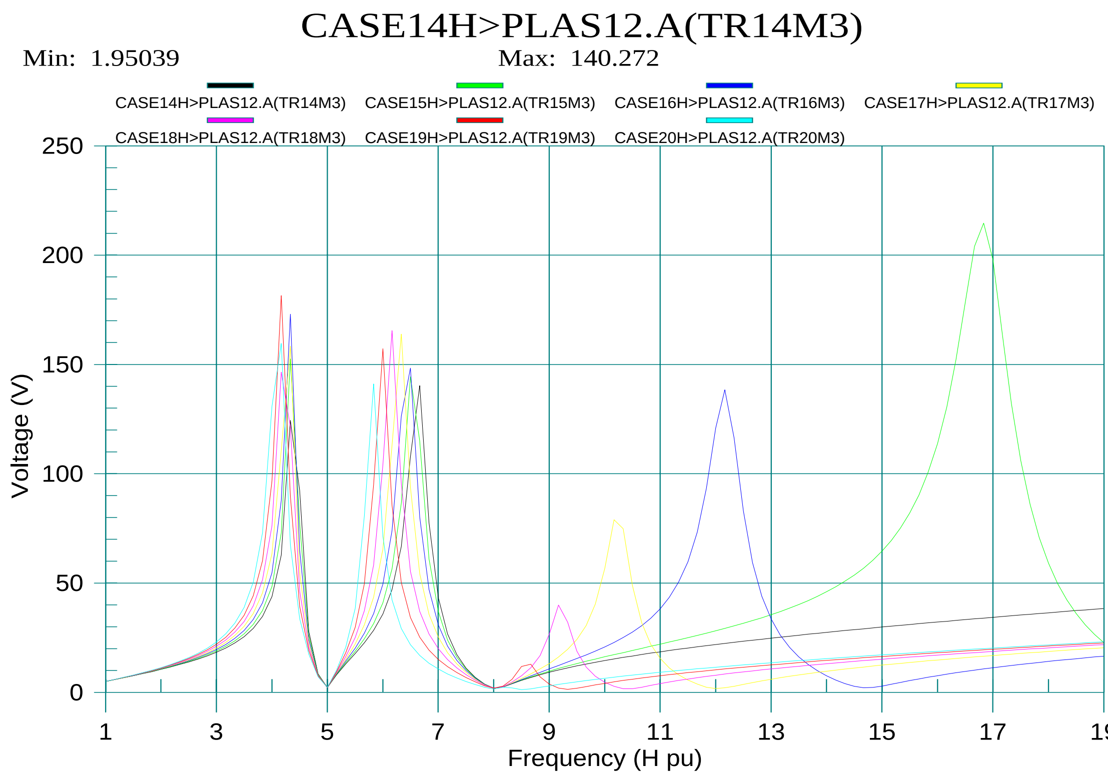


Figure 5 - Frequency Scan with 5th Harmonic Filter at MNT1 (PLS480 0-600 kvar)

5th and 7th Harmonic Filter

As a result of the possible shift in resonance to the 7th harmonic, a second filter was considered at this same bus. A 600 kvar 7th harmonic filter was included in the model, and the results are shown in Figure 6 (same cases as shown in Figure 3 and Figure 5).

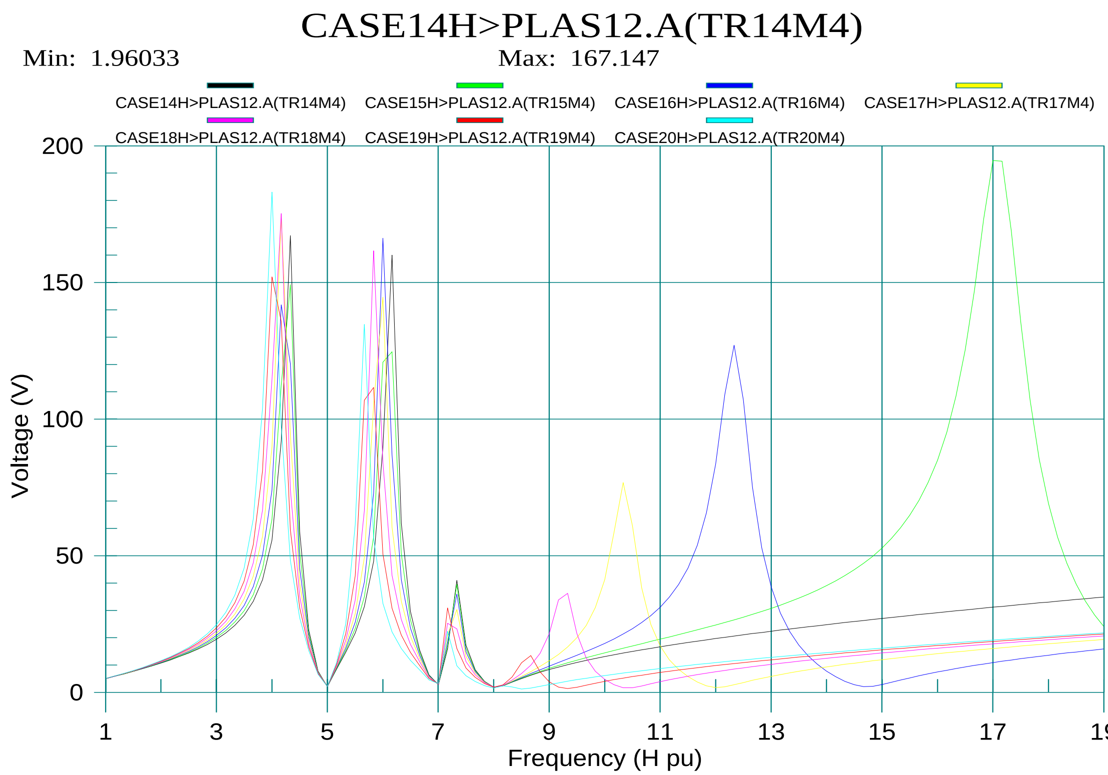


Figure 6 - Frequency Scans with 5th and 7th Harmonic Filtering at Mont1

The combination of 5th and 7th harmonic filtering provides a sink for both 5th and 7th harmonic distortion. As a result of installing both filters, the natural resonance at the 5th harmonic is eliminated at MNT1 along with the potentially adverse 7th harmonic resonance that occurs with the 5th harmonic filter.

HARMONIC DISTORTION SIMULATIONS

Because detailed current measurement data was unavailable for representing the nonlinear sources within the system, accurate distortion simulations could not be performed. However, by injecting harmonic current into the SPG35 bus, the needed voltage distortion for illustrating the effectiveness of filtering could be achieved. In order to produce the needed voltage distortion, harmonic current was injected into the system using a multiple frequency source (ISOURCE). 11.65A at 300 Hz (5th harmonic) and 4.66A at 420 Hz (7th harmonic) was injected. This current injection produced worst than measured voltage distortion, ranging from 4 to 10% THD; thus providing conservative results.
Note that the harmonic distortion simulations were performed under loaded conditions, thus providing reasonable damping throughout the system.

The following three cases illustrate the harmonic distortion seen at the PLS12 bus, PLS480 bus, and the SPG35 bus for the following conditions:

- No filtering
- 1200 kvar 5th harmonic filter at MNT1
- 1200 kvar 5th and 600 kvar 7th harmonic filters at MNT1

A summary table of these results is shown in Table 1.

H	PLS12 (12.47kV			PLS480 (480V)			SPG35 (34.5kV)			IEEE 519
	No Filter	5th filter	5th & 7th filter	No Filter	5th filter	5th & 7th filter	No Filter	5th filter	5th & 7th filter	Limits
Vthd	9.60	2.49	0.32	10.81	2.29	0.39	4.80	2.05	2.26	5%
5th	9.56	0.29	0.29	10.76	0.33	0.33	4.74	1.99	1.99	3%
7th	0.85	2.47	0.14	1.10	2.27	0.20	0.72	0.51	1.08	3%

Table 1 - Summary of Harmonic Distortion Calculations

At the PLS12 12kV bus the 5th harmonic filter reduces the total harmonic distortion (THD) below the IEEE Std. 519 limits of 5% at 2.5%, with the 5th harmonic distortion falling below the 3% limit at 0.3%. However, as noted in the previous section (see Figure 5), the 5th harmonic filter can produce resonance near the 7th harmonic. This is evident with the increase in 7th harmonic distortion seen at the PLS12 bus, from 0.8% to 2.5%. With the addition of the 600 kvar 7th harmonic filter, the total harmonic distortion is reduced to 0.3%, with the 7th reaching 0.14%.

The harmonic distortion seen at the PLS480 bus are very similar to that found at the PLS12 bus. The THD is reduced to 2.3%, with a rise in the 7th harmonic. Similarly the THD and 7th harmonic voltage is reduced significantly as the result of the 7th harmonic filter, 0.4% and 0.2% respectively.

The filter has a varying effect on the SPG35 bus. The additional 5th harmonic filter reduces the THD from 4.8% to 2%, the 5th harmonic from 4.75% to 2%, and the 7th harmonic from 0.7% to 0.5%. The additional 7th harmonic filter actually increases the 7th harmonic voltage seen at the SPG35 bus, from 0.7% to 1.1%.

FILTER DESIGN

This section provides the specifications needed for the filter design.

Based upon discussions with the electric utlity engineers, the 34.5kV/12.47kV substation does not have the physical space necessary for a filter installation. Therefore the filter will have to be placed on the distribution network. Simulations were performed with the filter located at the MNT1 bus (see Figure 7). The filter will serve as a replacement for the 600 kvar and 450 kvar capacitors at MNT1 and MNT2 respectively.

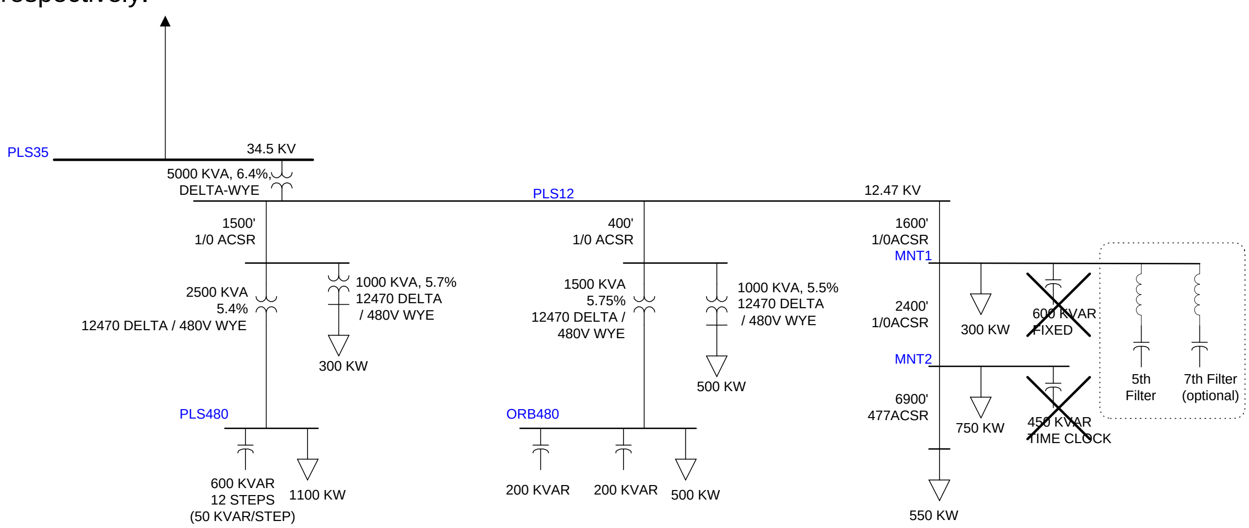


Figure 7 - Oneline Diagram of Filter Location

Using the Filter Design spreadsheet, the following tables provide the necessary specifications for both a 5th and 7th harmonic filter.

Table 2 provides specifications for the 1200kvar/14.4kV, ungrounded-wye connected filter tuned to the 5th harmonic. Table 3 also provides specifications for a similar filter tuned to the 7th harmonic.

Due to possible distribution system changes in the future (e.g., transformer upgrades, increased motor load, capacitor reconfiguration, etc.), it is recommended that the filter reactor have taps allowing variable tuning. Two 5% taps will be sufficient, providing ±10% variability.

Table 2 - Filter Design Spreadsheet for 1200 kvar 5th Harmonic Filter

Filter Calculations: **1200kvar, 5th harmonic filter**

SYSTEM INFORMATION:

Filter Specification:	5	th	**Power System Frequency:**	60	Hz
Capacitor Bank Rating:	1200	kVAr	**Capacitor Rating:**	14400	Volts
Rated Bank Current:	48	Amps		60	Hz
Nominal Bus Voltage:	12470	Volts	**Derated Capacitor:**	900	kVAr
Capacitor Current (actual):	41.7	Amps	**Total Harmonic Load:**	1.50E+03	kVA
Filter Tuning Harmonic:	5	th	**Filter Tuning Frequency:**	300	Hz
Cap Impedance (wye equivalent):	172.8000	Ω	**Cap Value (wye equivalent):**	15.4	uF
Reactor Impedance:	6.9120	Ω	**Reactor Rating:**	18.3347	mH
Filter Full Load Current (actual):	43.4	Amps	**Supplied Compensation:**	937	kVAr
Filter Full Load Current (rated):	50.1	Amps			
Transformer Nameplate:	5000	kVA	**Utility Side Vh:**	5.00	% THD
(Rating and Impedance)	6.40	%	*(Utility Harmonic Voltage Source)*		
Load Harmonic Current:	20.00	% Fund	**Load Harmonic Current:**	13.9	Amps
Utility Harmonic Current:	36.2	Amps	**Max Total Harm. Current:**	50.1	Amps

CAPACITOR DUTY CALCULATIONS:

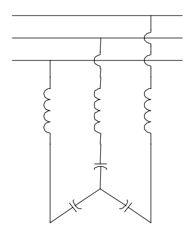
Filter RMS Current:	66.3	Amps	**Fundamental Cap Voltage:**	12989.6	Volts
Harmonic Cap Voltage:	2999.2	Volts	**Maximum Peak Voltage:**	15988.8	Volts
RMS Capacitor Voltage:	13331.3	Volts	**Maximum Peak Current:**	93.5	Amps

CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	⟵⟶	111%
Current:	180%	⟵⟶	138%
KVAr:	135%	⟵⟶	128%
RMS Voltage:	110%	⟵⟶	93%

FILTER CONFIGURATION:

12.47kV bus
Xl = 6.912 ohms
1200 kvar @
14400 Volts (L-L)



FILTER REACTOR DESIGN

Reactor Impedance:	6.9120	Ω	**Reactor Rating:**	18.3347	mH
Fundamental Current:	43.4	Amps	**Harmonic Current:**	50.1	Amps

Note: The supplied compensation provided by the 5th harmonic filter is approximately 940 kvar. The total combined compensation at PLS12 is 1050 kvar (600 kvar at MNT1 and 450 kvar at MNT2). By retiring these two capacitor banks, the 1200 kvar filter will deliver the needed compensation (less 100 kvar). However, unlike the 450 kvar switched bank, the filter must be permanently fixed.

Table 3 - Filter Design Spreadsheet for 600 kvar 7th Harmonic Filter

Filter Calculations: **600kvar, 7th harmonic filter**

SYSTEM INFORMATION:

Filter Specification:	7	th	**Power System Frequency:**	60	Hz
Capacitor Bank Rating:	600	kVAr	**Capacitor Rating:**	14400	Volts
Rated Bank Current:	24	Amps		60	Hz
Nominal Bus Voltage:	12470	Volts	**Derated Capacitor:**	450	kVAr
Capacitor Current (actual):	20.8	Amps	**Total Harmonic Load:**	1.50E+03	kVA
Filter Tuning Harmonic:	7	th	**Filter Tuning Frequency:**	420	Hz
Cap Impedance (wye equivalent):	345.6000	Ω	**Cap Value (wye equivalent):**	7.7	uF
Reactor Impedance:	7.0531	Ω	**Reactor Rating:**	18.7088	mH
Filter Full Load Current (actual):	21.3	Amps	**Supplied Compensation:**	459	kVAr
Filter Full Load Current (rated):	24.6	Amps			
Transformer Nameplate:	5000	kVA	**Utility Side Vh:**	2.50	% THD
(Rating and Impedance)	6.40	%	*(Utility Harmonic Voltage Source)*		
Load Harmonic Current:	20.00	% Fund	**Load Harmonic Current:**	13.9	Amps
Utility Harmonic Current:	12.9	Amps	**Max Total Harm. Current:**	26.8	Amps

CAPACITOR DUTY CALCULATIONS:

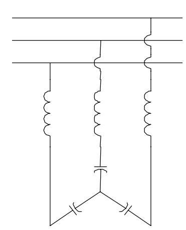
Filter RMS Current:	34.2	Amps	**Fundamental Cap Voltage:**	12729.8	Volts
Harmonic Cap Voltage:	2293.8	Volts	**Maximum Peak Voltage:**	15023.6	Volts
RMS Capacitor Voltage:	12934.8	Volts	**Maximum Peak Current:**	48.1	Amps

CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	←——→	104%
Current:	180%	←——→	142%
KVAr:	135%	←——→	128%
RMS Voltage:	110%	←——→	90%

FILTER CONFIGURATION:

12.47kV bus
Xl = 7.0531 ohms
600 kvar @
14400 Volts (L-L)



FILTER REACTOR DESIGN

Reactor Impedance:	7.0531	Ω	**Reactor Rating:**	18.7088	mH
Fundamental Current:	21.3	Amps	**Harmonic Current:**	26.8	Amps

Note: The total combined compensation from the 5th and 7th harmonic filters totals approximately 1400 kvar. If both filters are to be installed, the combined compensation will provide increased kvar over what is currently installed (1050 kvar).

The existing 600 kvar and 450 kvar capacitors located at MNT1 and MNT2 respectively can possibly be used for the filter. This will be a decision made by the utility and the respective filter manufacturer. However, the voltage rating for either capacitor must be rated at 13.3kV or above (e.g. 13.8kV, 14.4kV, etc.). If not, the capacitor limits according to IEEE Std. 18 will be exceeded (for most filter designs, a capacitor should be rated at least 10% higher than nominal bus voltage).

With the filter located on the distribution feeder, the filter will need to be pole-mounted. These filters typically are available with: air-core reactors, vacuum switches, capacitors, rack for mounting between two poles, capacitor fuses, blown fuse detection system, control power transformer, and surge arresters. The typical price for a 1200 kvar filter at 12kV is $35,000.

SUMMARY

A complete three-phase model of the distribution system supplied by the 69kV/34.5kV transformer was created using Electrotek's SuperHarm® program. The model was verified for accuracy and then used to perform the frequency scan analysis, distortion simulations, and filter design.

Frequency scans were performed on the system to identify possibly resonance conditions that, when excited, could be causing the increased voltage distortion measured throughout the distribution system. Many different system conditions are possible due to the 12 step, 600 kvar capacitor bank at the plastics plant, in addition to the three switched banks that are on a time clock.

Therefore, frequency scans were performed for approximately 100 different capacitor configurations. This large number of scans were performed in order to identify possible capacitor configurations that, when avoided, could result in acceptable voltage distortion. Unfortunately, these scans illustrated that a particular "combination" was not the culprit, and that each capacitor could contribute to a parallel resonance that could easily be tuned to the 5th or 7th harmonic switching the 12-step, 600 kvar capacitor at the plastics plant.

Various filtering options were considered for eliminating the high voltage distortion. Frequency scans were performed with filters placed throughout the distribution network, with the goal of identifying a location that provides the most effective harmonic mitigation. Utility engineers were also consulted with regards to installation barriers concerning possible filter locations. Considering said factors, a 1200 kvar filter tuned to the 5th harmonic is recommended to be installed on the 12 kV feeder (MNT1), in place of the existing 600 fixed capacitor bank. With the installation of the 1200 kvar filter, both the 600 kvar and 450 kvar capacitor banks along that feeder can be retired (in addition to offering filtering, the filter will also provide needed reactive power compensation along the feeder).

Harmonic current was injected into the simulation model and distortion simulations were performed to analyze the effectiveness of the 5th harmonic filter. The filter was found to provide the needed harmonic mitigation throughout the distribution network. As a result of the 5th harmonic filter, possible resonance could occur near the 7th harmonic, thus causing increased voltage distortion at that frequency. Simulations demonstrated that this the distortion at the 7th harmonic could approach IEEE Std. 519 limits of 3% THD. Therefore, additional simulations were performed using both 5th and 7th harmonic filters. The additional 7th harmonic filter provided the necessary harmonic mitigation.

REFERENCES

IEEE Std. 519-1992 "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems."