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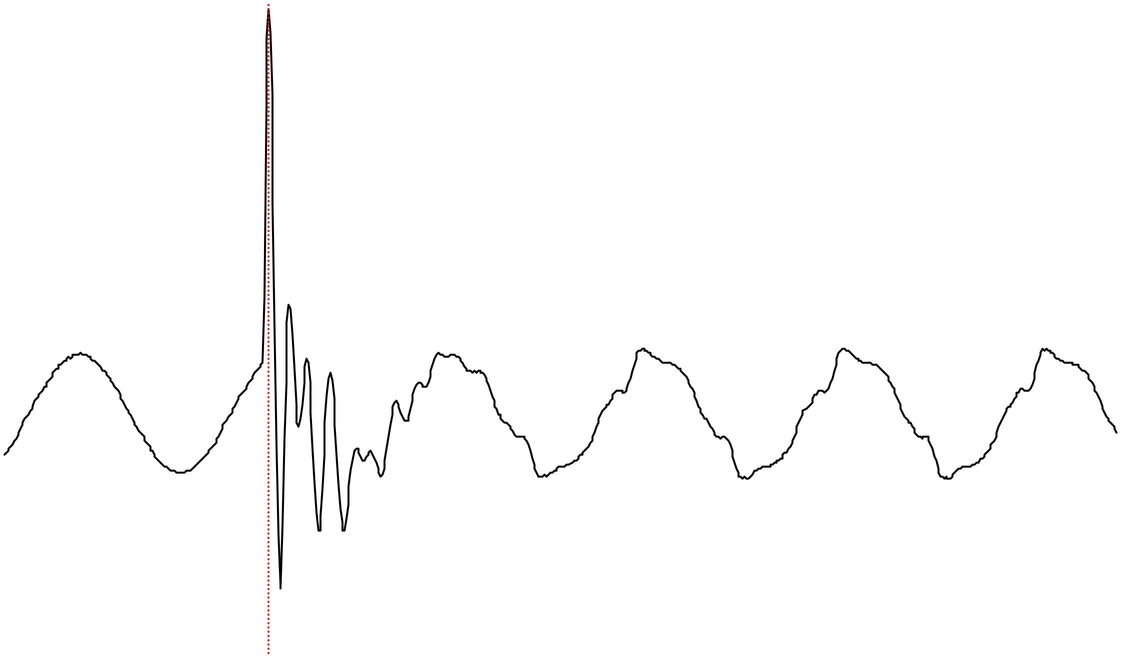
Harmonics and Transients Tech Notes



Issue # 99-3 ***November 1999*** ***Editor: Sandy Smith***

Project Manager: Tom Grebe

In this issue:

Letter from the Project Manager:

Dear PATH Members:

Welcome to another edition of *Tech Notes*. We hope you find this issue to be both informative and interesting. This issue features a case study on using SuperHarm to study the impact of a DC converter drive on various loads, an examination of using EMTP and TOP to simulate harmonic sources on a network, and a case study on a filter/compensation system for a steel plant.

Electrotek Concepts is pleased to announce the release of TOP 2000, the 32-bit version of TOP, The Output Processor. This new version features full integration with SuperHarm as well as the ability to read Power Quality Data Interchange Format (PQDIF) files and the capability to export to the Portable Network Graphics (PNG) format. You can download TOP 2000 from PATHWeb or from the Electrotek web site at www.electrotek.com/top.

We are holding off on shipping you TOP 2000 on disk because we are getting ready to release SuperHarm version 4.1. This upgrade fixes all of the bugs that you have reported on SuperHarm 4.0, and features a keyword generator for use in simulation studies. We anticipate shipping SuperHarm 4.1 by the first week of December, and will include TOP 2000 on this release, which will be shipped to you on CD-ROM. No more installations requiring multiple floppy disks. As with TOP, you will also be able to download SuperHarm 4.1 from PATHWeb.

We had a successful annual workshop and meeting, with excellent presentations from Garth Irwin of Manitoba HVDC Research Centre on PSCAD/EMTDC, Mississippi State University's Mark Halpin on simulation studies for distributed generation, a SuperHarm case study from Duke Power's Stephen Middlekauff, and a presentation on equivalent circuit models from Electrotek's Tom McDermott. Based on feedback from attendees, we are looking at revamping both the workshop and the meeting to place a greater emphasis on applications of simulation tools to address harmonics and transients, and to enable attendees to work through case studies. You will be seeing more on this proposed format in the next few months.

As we reach the end of another year, we want to express our wishes to you for a safe and happy holiday season, and our appreciation of your support of PATH.

Sincerely,

Thomas Grebe, P.E.
General Manager, Electrotek Consulting
PATH Users Group Project Manager

Using SuperHarm to Study the Effect of a DC Converter Drive on Power Systems and other Customer Loads

Durgesh P. Manjure and Elham B. Makram
Electrical and Computer Engineering Department
Clemson University

Introduction

SuperHarm and TOP, The Output Processor have been used to carry out harmonic analyses of power systems having nonlinear loads. More specifically, the effect of a DC converter drive on the power system and on other customer loads is studied. The DC converter drive injects harmonic currents into the system. It produces more distortion in the current waveform as compared to that in the voltage waveform. The entire system and the converter is modeled in the frequency domain using the models for various devices like BRANCH, MACHINE, VSOURCE, NONLINEARLOAD etc., available in the SuperHarm device library. The converter is modeled using NONLINEARLOAD, as a multiple frequency current source. The magnitude and phase angle of the current component at each frequency is specified. This model is more accurate as compared to the ISOURCE (multiple frequency current source) model, because it corrects the phase angles of each harmonic component with respect to the phase angle of the fundamental component automatically.

Various loading cases like single converter on the system, multiple converters (combinations of 6 pulse converters and 12 pulse converters) have been studied. The effect of replacing a linear load on the system by a dynamic load, on the harmonic quantities, is also observed. Two types of power systems are considered in the study; a 230 kV looped transmission system and a 13.8 kV radial distribution system.

The current injections at various frequencies required to simulate the converter in the SuperHarm program are obtained from the frequency spectrum analysis of the actual current waveform of a converter. This waveform is obtained from actual circuit simulation carried out in the time domain using the Alternative Transients' Program (ATP). The above mentioned study carried out in the frequency domain using the SuperHarm program is repeated in the time domain using ATP and the results obtained from the ATP simulations are consistent with those obtained using the SuperHarm program.

Simulation Results

Test System 1: 13.8 kV radial distribution system

A 13.8 kV, 13 bus radial distribution system as shown in Figure 1 was analyzed in the frequency domain, using SuperHarm and in the time domain using ATP.

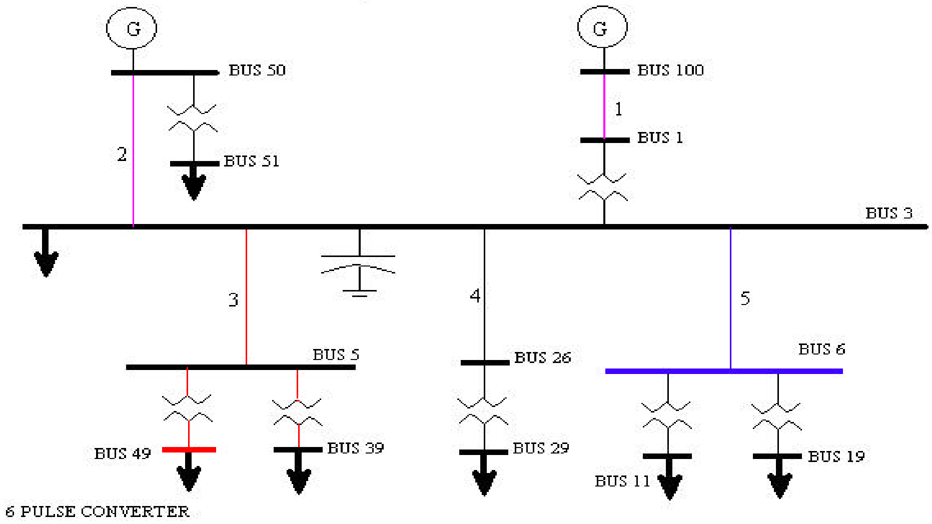


Fig.1 13.8 kV radial distribution system used for the simulations

Case 1: 6-pulse converter at bus 49

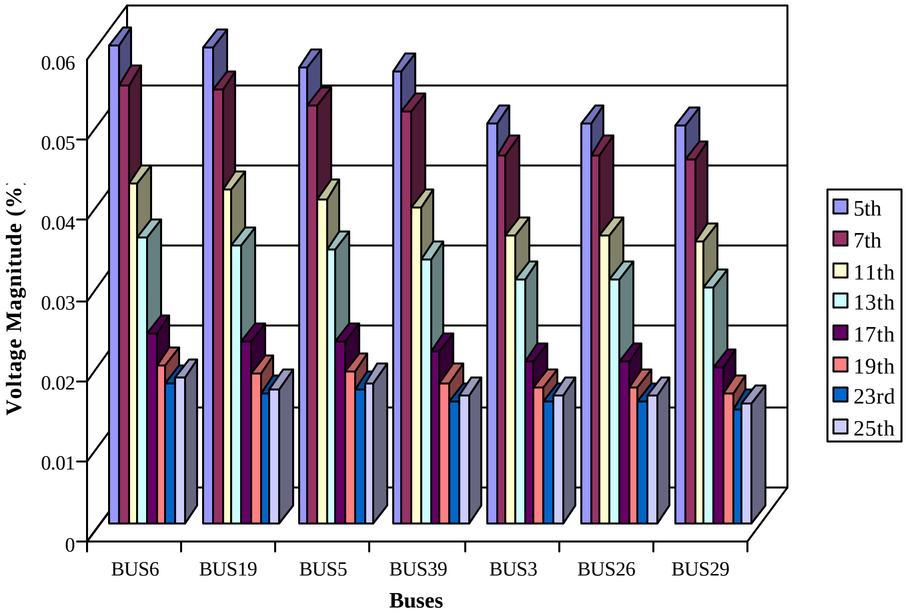


Fig.2. Harmonic voltages at the buses due to the converter at bus 49

A 6-pulse converter causes harmonic currents to flow through the system. It also causes voltage distortion, but the distortion in the current waveform is much more than that in the voltage waveform. It was observed that the voltages at all the buses other than those very close to the source buses have harmonic components as observed in Figure 2 above.

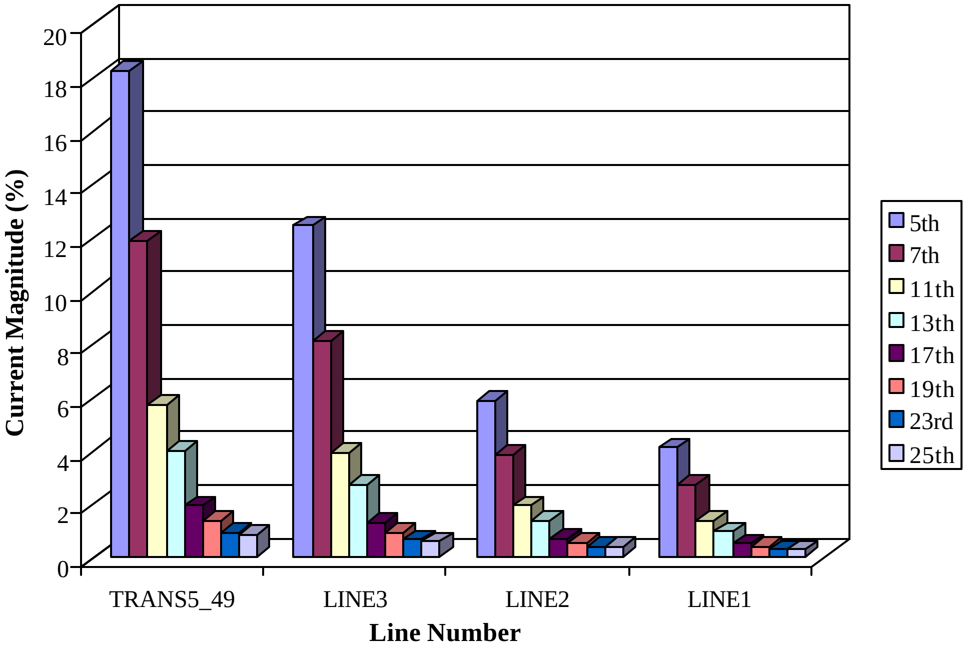


Fig.3 Harmonic currents in the system lines (TRANS5_49 is the transformer between bus 5 and bus 49)

Due to this 6-pulse converter, the lines connected in the path between the nonlinear load and the system source were the ones that showed current harmonics flowing through them. Also as we move away from the nonlinear load and toward the system source, the magnitude of the harmonics decreased as shown in Figure 3

Similarly, the linear loads on the system closer to the nonlinear load had a higher magnitude of current harmonics as compared to those far away from the nonlinear load as shown in Figure 4.

This case was also studied in the time domain using actual circuit simulation. The current injected by the converter was maintained the same in both the simulations as shown in Figure 5. The results obtained therefrom, were consistent with the ones obtained using the frequency domain method of analysis, the only difference being that the time domain simulation showed lesser harmonic propagation into the system and through the other linear loads on the system. Thus in a way, the frequency domain method gave pessimistic results as shown in Figure 6.

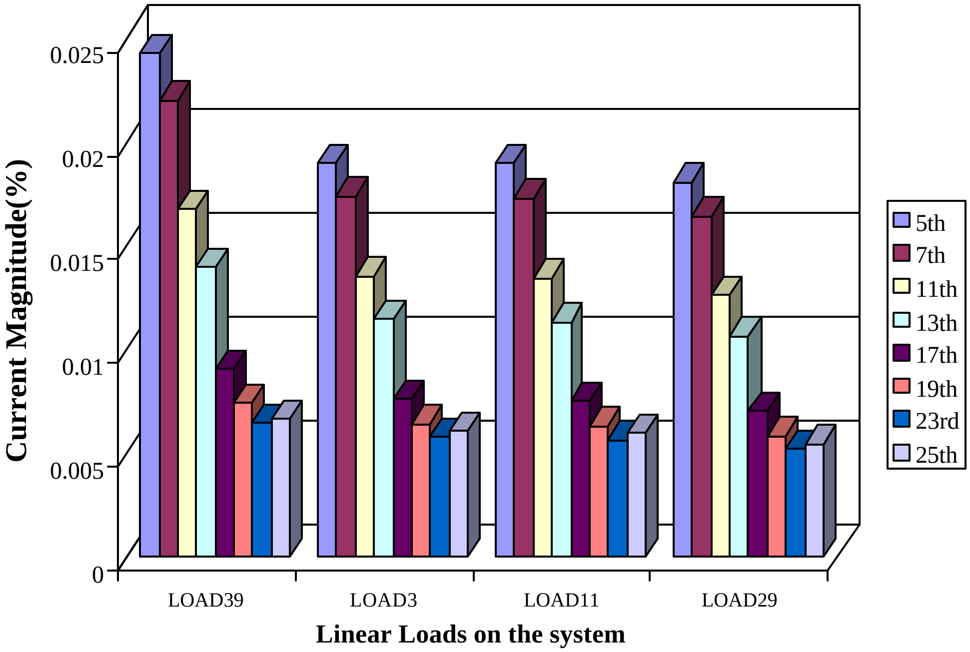


Fig.4 Harmonic currents through the linear loads on the system due to the converter at bus 49

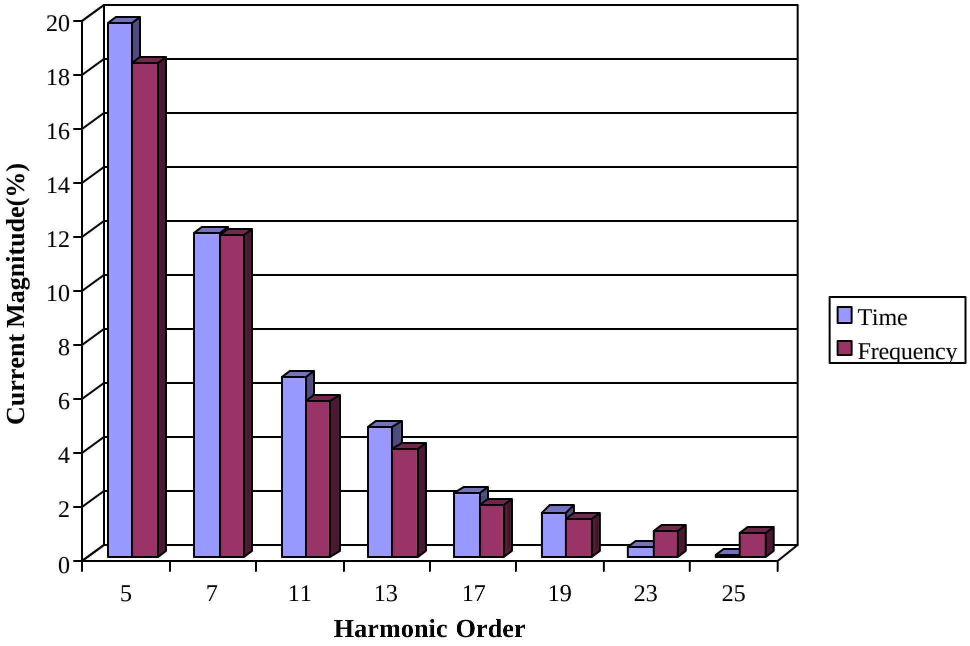


Fig.5. Comparison of the current injected by the converter used in the time domain and the frequency domain simulation

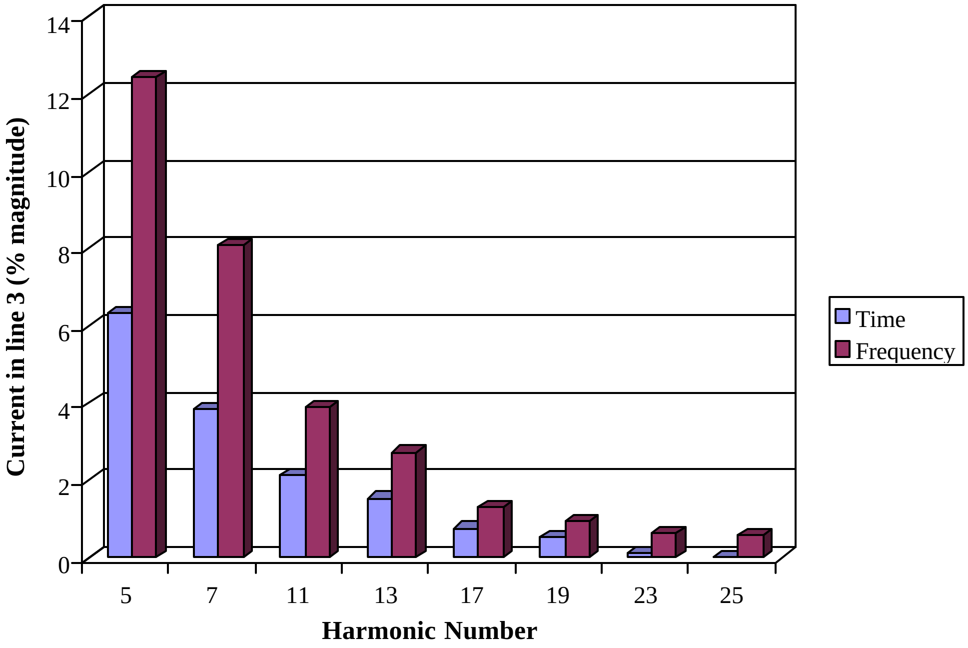


Fig.6. Comparison between the time domain and frequency domain simulation results

Case 2: A 6-pulse converter each at bus 49 and bus 11

With the addition of another 6-pulse converter at bus 11, it was observed that the lines in the path from bus 11 to the system source (line 5,2,1) experienced a change in the harmonic currents whereas the other lines were not affected. Figure 7 shows the harmonic currents in the lines with both the converters present, one at bus 49 and the other at bus 11.

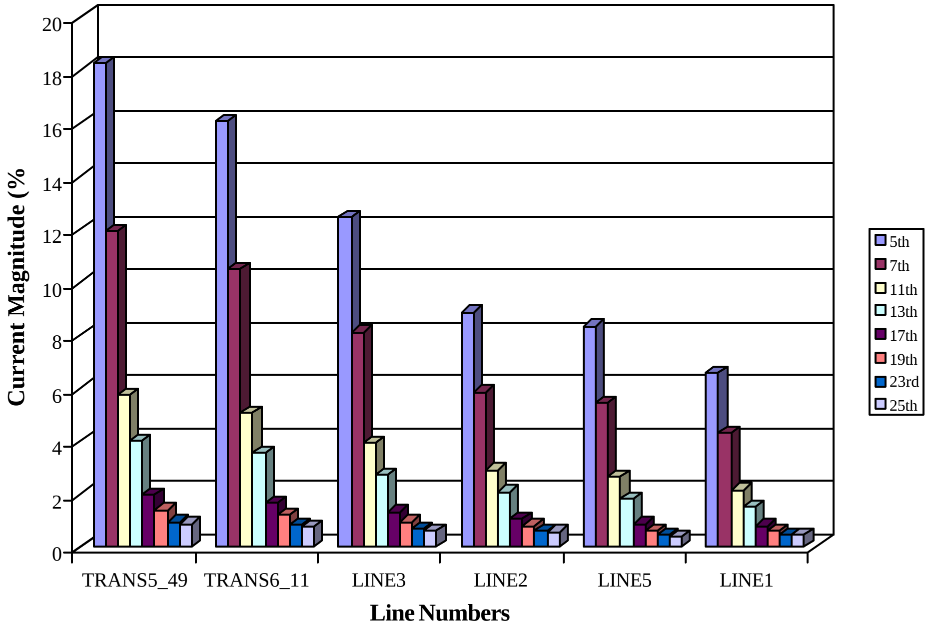


Fig.7. Harmonic currents in the lines with 6 pulse converters at bus 49 and bus11 (TRANS6_11 is the transformer between bus 6 and bus 11)

The harmonic content in the loads and at the buses increased and the buses and loads closer to the nonlinear load experienced a greater change than those away from the nonlinear load did.

This analysis was repeated in the time domain and here we observe that the converter at bus 49 affects line 3 as well. Figure8 shows the current harmonics in line 3 with one 6 pulse converter at bus 49 and with one 6 pulse converter each at bus 49 and bus 11.This is different from what was observed in the frequency domain simulation. There it was observed that only those lines that were in the path between the nonlinear load and the system source (lines 5,2,1) were affected. So the addition of another 6 pulse converter at bus 49 did not affect the current harmonics in line 3.

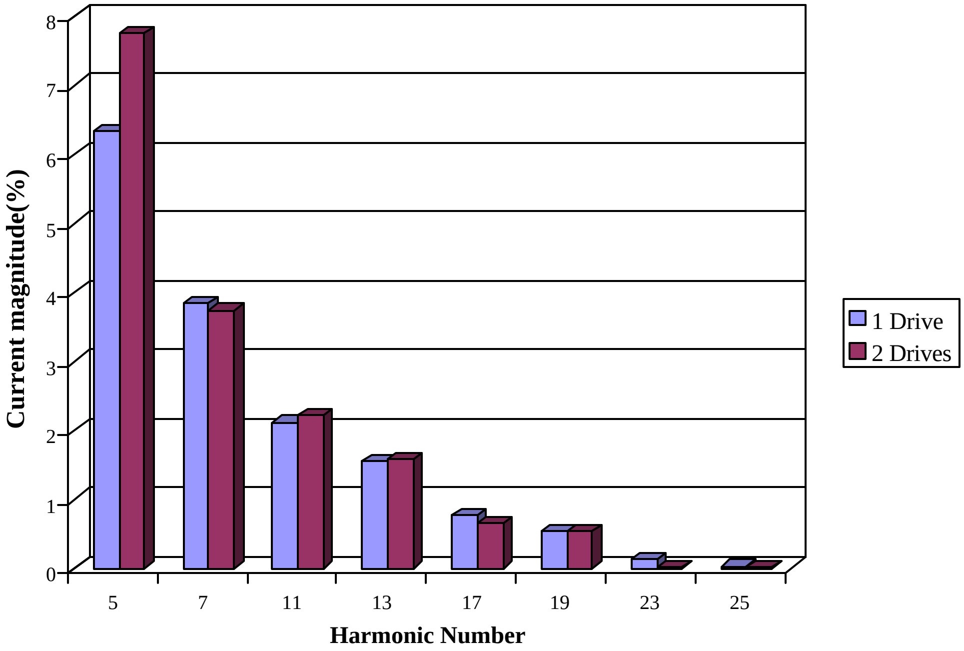


Fig.8. Comparison of harmonics in line 3 with a 6 pulse converter at bus 49 and with one at each, bus49 and bus11

Case 3: Varying the DC side load

In the frequency domain analysis there is no access to the DC side of the converter. Hence we cannot study the effect of the variation of the DC side load on the harmonics injected into the system. This is possible in the time domain simulation. The DC side load was varied and the effect of the variation was observed.

This simulation was carried under certain assumptions. The back-emf of the DC machine was assumed to be constant. The back-emf is proportional to the flux and the speed of the motor. Now this assumption can be valid only if the speed and flux both remain reasonably constant even under changing loading conditions. This is possible in case of a DC shunt motor.

We observe that the as the DC load goes on increasing the magnitude of the current harmonics goes on decreasing as shown in Figure 9.

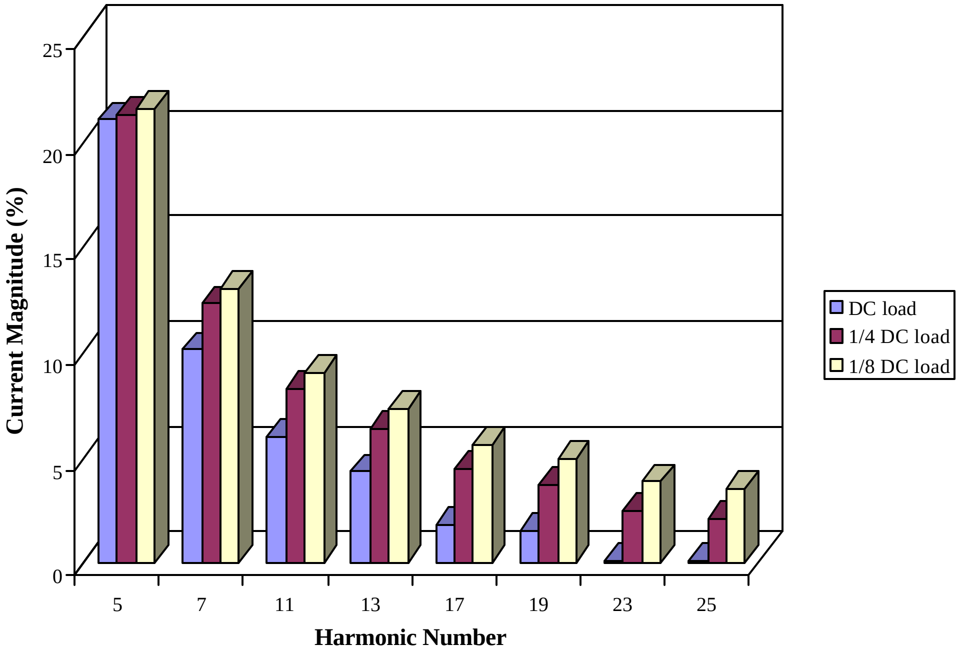


Fig. 9 Variation of the AC side harmonics with change in the DC side load.

Conclusions:

1. The linear loads on the system close to the nonlinear load are affected and have harmonic currents flowing through them, whereas the loads closer to the system sources do not show any current harmonics.
2. The total harmonic distortion through the loads, lines and at the buses increased in the presence of multiple converters on the system.
3. A nonlinear load injects harmonics into the lines connecting the nonlinear load to the system sources.
4. It affects the proximal lines more than those far away from the harmonic source. In this particular case one nonlinear load did not affect the other, since these loads traversed different paths to reach the system source.
5. The voltages at all the buses other than those close to the system source were affected by the nonlinear load. As with the linear loads on the system, the buses close to the nonlinear load had a higher voltage distortion as compared to those buses away from the nonlinear load

Filtering Dispersed Harmonic Sources on Distribution

Ward Jewell
Power Quality Laboratory
Wichita State University

Bill Miller
Southwestern Bell Telephone

Tom Casey
Kansas City Power and Light

Introduction

Telephone customers in a suburban area complained to the telephone company about noisy telephone service. Measurements by telephone company and electric utility personnel indicated 540 Hz current was coupling from the electric power system to the telephone system in an area where telephone and electric conductors shared a common right of way. This exposure, 1.5 miles in length, is shown in Figure 1.

No large harmonic sources were found on either of the distribution circuits sharing this right of way. Circuit 1 serves residential loads and a hospital. Circuit 2 serves residential loads.

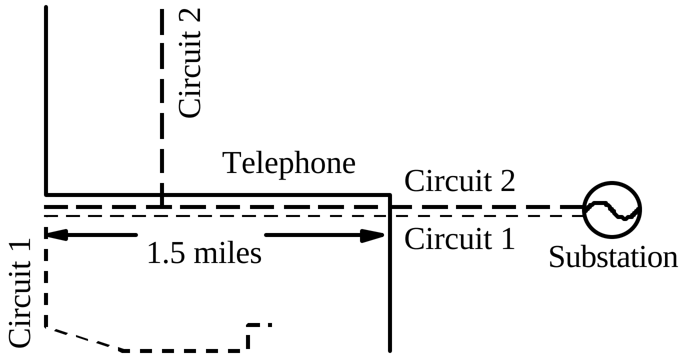


Fig. 1. Power and telephone circuits.

The telephone and electric power systems were in good condition. Grounding, shielding, and inductive coordination was all done properly on the telephone system. All power system fuses and the system neutral were good. No transformers were saturated. Power factor correction capacitors were not in resonance.

When all capacitors were removed from circuit 1, however, telephone noise dropped to acceptable levels. This indicated that 540 Hz current was being conducted to earth by power factor correction capacitors, and the earth currents were then coupling with the telephone system. It was concluded that the harmonic sources were many small, single-phase electronic loads dispersed throughout the distribution circuits. This conclusion was tested by developing a model of the system and simulating the system operation.

Modeling and Simulation

The distribution system of circuit 1, including neutral conductors and earth return, were simulated using the Electromagnetic Transients Program (EMTP). The simulation results were analyzed using TOP, The Output Processor.

System Model

The circuit models used in the simulation are shown in Figures 2, 3, and 4. Figure 2 shows the models for phase conductors, power factor correction capacitors, and connections to neutral and earth. Figure

3 shows the earth ground model, while Figure 4 shows the model representing lumped linear and harmonic loads.

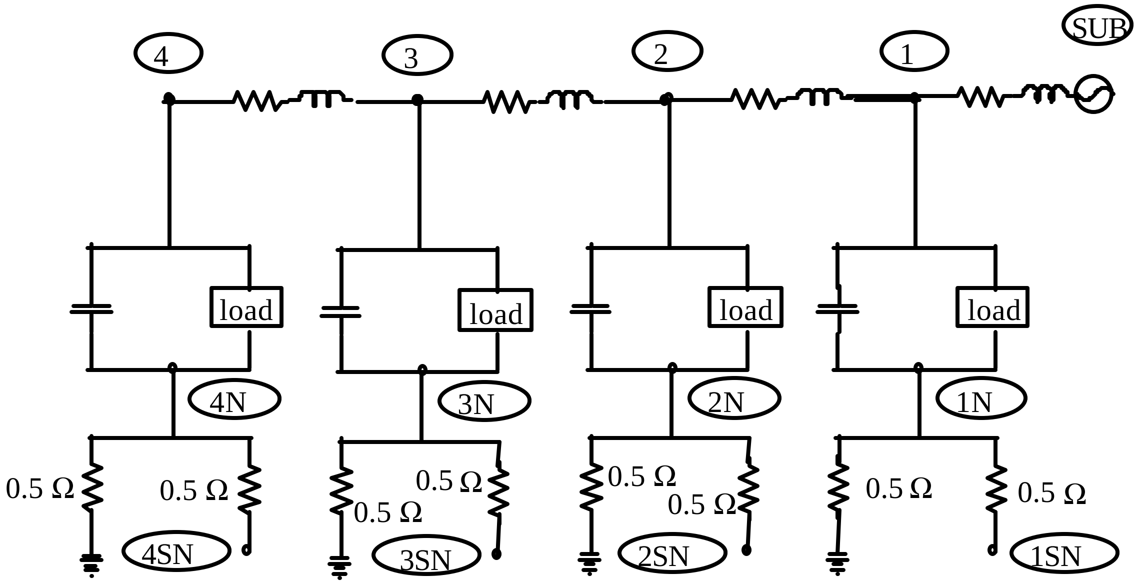


Fig. 2. Distribution system circuit model.

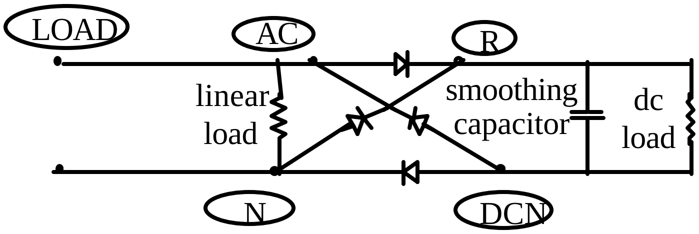


Fig. 3. Lumped load model.

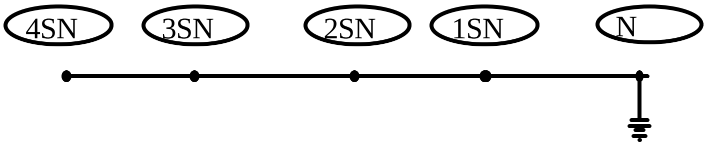


Fig. 4. Earth ground model.

The utility provided values of phase conductor impedances used in power flow and short circuit studies. These impedances were used in this circuit model. They are the reactance and resistances shown in Figure2 between main nodes, such as Substation to 1, or 3 to 4.

Because the model only needed to be accurate at relatively low frequencies, up to about 3000 Hz, the 50th harmonic of 60 Hz, these impedances were satisfactory. A higher frequency model would be needed for higher frequency studies, such as lightning or switching transients.

Power factor correction capacitors are shown in Figure 2 from the numbered node to the neutral “N” nodes, such as 1 to 1N, 2 to 2N, etc. Loads are modeled as lumped equivalents in parallel with the capacitors.

The load model, shown in Figure 3, combines linear resistive load with non-linear single-phase rectifier loads. This model can accurately simulate any combination of linear load and single-phase rectifier load. The values of linear load resistance, dc load resistance, and rectifier smoothing capacitance are calculated from measured current values, including harmonic currents, and from utility load estimates. No reactance was included in the linear load because it would have little effect on the relevant simulation results for this system. It could be included if needed, however.

In Figure 2 the resistance from the neutral “N” to the system neutral “SN” node, for example, 1N to 1SN, represents current flowing onto the system neutral from the loads and capacitors at the node. The resistance from the “N” node to ground represents earth current. The current is assumed to split evenly between system neutral and earth in this case, so the two resistances are equal.

The system neutral is then modeled as shown in Figure 4. This circuit allows the neutral current to be monitored as a simulation output.

Because neutral and earth current are assumed to be equal, the neutral current output can also be considered to be an earth current output. This is an extremely simplified model of earth current that assumes the earth current flows in a straight path parallel to the system neutral conductors. In reality, earth current spreads out over a wide geographic area as it flows. It will follow the shortest path, the path of least resistance, to return to its source. However, in this simulation we are concerned with the earth current that is coupling with the telephone cables in the same right-of-way as the system neutral and phase conductors, so this simple model works well.

Simulation Results

Initial simulations were run to compare the model’s results with actual conditions. In each case, simulation results were compared with measured values of currents and voltages on the phase conductors under similar conditions.

The first case simulated was with all capacitors energized and daytime light-load conditions, with normal levels of rectifier load dispersed throughout the circuit. Following this, capacitors were removed one at a time, beginning with node 1, and moving out through nodes 2, 3, and 4, until all capacitors were off. Figure 5 shows the location of capacitors on circuit 1. The results agree with the field measurements, in which noise levels stay high until all capacitors are removed from the system. When all capacitors are off, 540 Hz noise drops significantly.

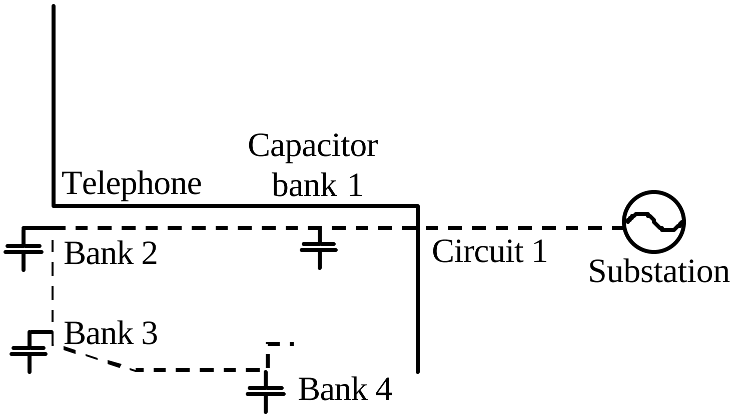


Fig. 5. Capacitors on circuit 1

These simulation results supported the conclusion that the telephone noise was caused by small, dispersed single-phase electronic loads throughout the distribution system, especially on circuit 1.

The total earth current and the 540 Hz component were recorded for each case. The 540 Hz component with all capacitors energized was equated to the high noise levels measured at the affected customer for the same conditions. The noise calculated for the case with all capacitors off was equated to the acceptable noise levels measured during that condition. These values were then used in subsequent simulations to judge the telephone noise levels. Relative noise values, both simulated and measured, for these first five cases are presented in Table I. The noise value for the base case, all capacitors energized, is used as the per unit base, so that noise is presented as 1.0.

Table I. Simulation base case results

540 Hz noise in power/phone exposure			
	Simulated		Measured
	(A)	p.u.	dBrnC
Base	2.2	1.0	92
Cap 1 off	3.4	1.5	90
Caps 1,2 off	6.2	2.8	92
Caps 1,2,3 off	4.8	2.2	93
All caps off	1.2	0.5	80

In the next series of simulations the capacitors were energized, but the neutral point on each bank was disconnected from the system neutral and earth. This blocks the flow of harmonic current into earth. The results of these simulations are presented in Table II.

Table II. Simulation results: open capacitor neutral

540 Hz noise in power/phone exposure		
	Simulated	
	(A)	p.u.
Base	2.2	1.0
Neutral 1 open	3.3	1.5
Neutrals 1,2 open	5.4	2.5
Neutrals 1,2,3 open	6.5	3.0
All cap neutrals open	2.3	1.0

These results indicate that removing the ground connections from the capacitor banks will not accomplish the desired telephone noise reduction. By the time this result was available the utility had already considered this solution and rejected it. A safety problem for line crews occurs when capacitor grounds are opened. The capacitor neutral point, which has always before been at earth potential, can no longer be assumed to be at that low voltage. It must now be assumed to be at any voltage up to full line voltage, and line crews must be retrained to assume this.

The next set of simulations installed a harmonic suppression reactor (HSR) in the neutral of each capacitor bank. While there was no resonant capacitor, the common use of HSRs, it was thought that the additional reactance might decrease the harmonic earth current to acceptable levels. Table III shows the resulting noise levels, which were still unacceptably high.

Table III. Simulation results: harmonic suppression reactors

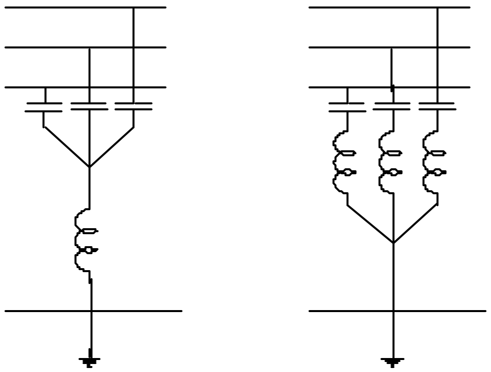
540 Hz noise in power/phone exposure		
	Simulated	
	(A)	p.u.
Base	2.2	1.0
HSR at cap 1	3.5	1.6
HSRs at all caps	1.9	0.9

The next step, then, was to consider installing a shunt filter to reduce the harmonic currents in the earth exposure between the distribution lines and telephone cables.

Filter Design

A shunt harmonic filter provides a low impedance path to neutral for currents at the tuned frequency. This is accomplished by placing an appropriate reactance in series with existing capacitors. Because this retunes the whole distribution system, it is necessary to simulate the filter under varying conditions during the design process.

Figure 6 shows two designs for a shunt filter on a three-phase bank. Design (b) is recommended, with one reactor per phase. But the telephone company and electric utility already had experience with harmonic suppression reactors, which are installed as shown in design (a), so this design was used.



Design (a) Design (b)

Fig. 6. Shunt filter designs.

To tune the filter in design (a) for low impedance at frequency “f,” the inductance is

$$L = \frac{1}{3(2pf)^2 C}$$

Two different 7200 V capacitor sizes were installed on this circuit; 1200 kVAR (20.5 μF), and 600 kVAR (10.2 μF). The inductance required to tune the 1200 kVAR capacitor to 540 Hz is 1.4 mH. The 600 kVAR requires 2.8 mH. Three cases were simulated:

1. Filters at all four capacitor banks.
2. Filter at bank 2 only.
3. Filter at bank 3 only.

The results are shown in Table IV.

Table IV. Simulation results: 540 Hz shunt filter

540 Hz noise in power/phone exposure		
	Simulated	
	(A)	p.u.
Base	2.2	1.0
Filter at all caps	1.0	0.5
Filter at cap 2 only	0.6	0.3
Filter at cap 3 only	0.6	0.3

Applying filters at all four banks reduces the harmonic noise to an acceptable level. Filtering at only bank 2 or 3 produces even lower noise than filters at all four. A filter at bank 2 or 3 removes from the exposure much of the 540 Hz current generated between banks 2 and 4, while not drawing a significant harmonic current from the other end of the exposure. On this circuit it was physically impractical to install a filter reactor on the pole at bank 2, so the filter at bank 3 was chosen for further study.

All combinations of capacitors on and off the system were then simulated with the shunt filter installed at bank 3. Higher load levels were also simulated. The noise levels remained at acceptable levels for all conditions.

The simulated values of currents through the capacitor bank were analyzed to insure the bank would not be overloaded by the increased 540 Hz current it was carrying. The current through the filter reactor was used to specify the current capacity of the reactor itself.

Filter Test

The shunt filter was tested at bank 3. A harmonic suppression reactor of the correct inductance was temporarily installed in the capacitor neutral. Telephone noise levels were monitored at the affected customers. Capacitor and filter reactor current and voltage were also recorded.

Before the reactor was switched in, the 540 Hz noise at the affected telephone customers was 95 dBrnC. When the reactor was switched in, the noise level dropped to 87 dBrnC, an acceptable level. Capacitor and reactor voltages and currents were within their ratings and design ranges.

The steady-state current ratings of the harmonic suppression reactor used in the test were too low to permanently install it as a filter reactor; it is intended to block currents, so its ampacity is relatively low. An oil filled reactor was ordered from a transformer manufacturer and was permanently installed at bank 3. The permanent reactor produced the same noise reduction as the test reactor. Noise levels on the telephone circuit have stayed within acceptable ranges ever since.

Case Study of Filter/Compensation System for a Steel Manufacturing Facility

Milan Graovac, Xiaolin Wang and Reza Iravani
Department of Electrical and Computer Engineering
University of Toronto

Abstract

Power System Harmonics are increasingly present in industrial networks today. Nonlinear magnetic loads, electronic power switching devices and different arcing type devices (electric arc furnaces, fluorescent lighting) cause harmonic distortion of the load current. In the modern steel manufacturing facility, the problem is usually combined with unacceptably low power factor that affects the productivity of an electric arc furnace operation. Power factor correction using simple capacitor banks may interact with harmonic currents leading to equipment failures. To avoid this, problems of increasing the power factor and reducing harmonics should be solved simultaneously. This paper addresses some of the important issues that are often missed in the filter design process. EMTP and SuperHarm will be used for getting the system resonant conditions, simulating switching transients and obtaining current and voltage harmonics of the system under study.

Introduction

Filter design process is usually based on achieving two goals: minimizing THD while providing sufficient reactive power to the system. When the load changes in a broad range, reactive power requirements change accordingly and it is often needed that some filters or capacitors to be switched off/on to maintain acceptable voltage level on all busses. This leads to a number of filter/load scenarios that should be carefully studied to identify possible parallel resonances.

In this paper, special attention is brought to even order harmonics that are often neglected (primarily 4th and 6th). Such harmonics (2nd, 4th, 6th ...) are generated during transformer energization due to transformer core nonlinearity. Switching transients can result in harmonic currents that are flowing through power factor capacitors or harmonic filters and are being magnified by the resonances. Serious overvoltages and overcurrents will result, possibly leading to equipment failure. It will be shown how computer simulation may be used to predict possible problems during the filter design stage.

Circuit under Study

A typical steel plant power system considered in this paper is shown in Figure 1. The system power factor without any compensation varies between 75 and 80%. The system contains two main sources of harmonics:

- Electric Arc Furnace (EAF) that generates almost a continuous spectrum of harmonic currents of both integer and non-integer order.
- Six- and twelve-pulse DC drives that generate even order harmonics (5th and higher)

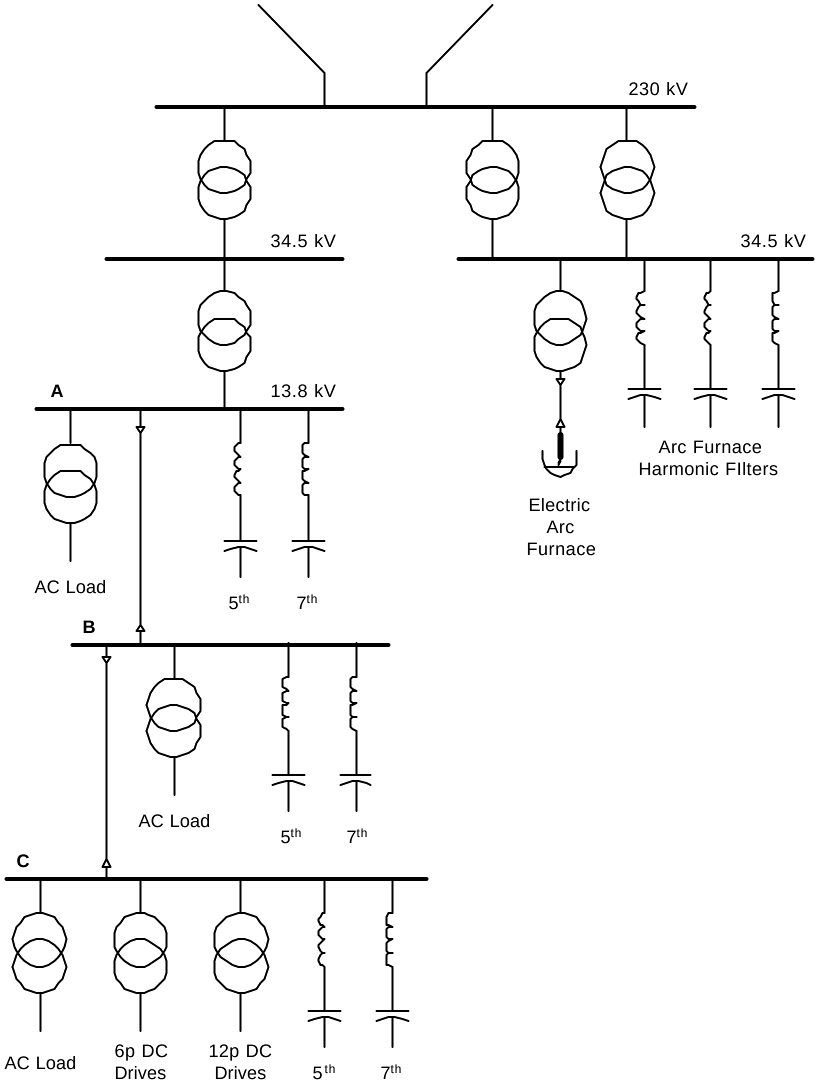


Fig. 1. One-line diagram of a steel manufacturing facility power system (study system)

In terms of harmonic generation, two periods of the EAF operation are of interest: Initial melt and refinement. Table 1 shows the current harmonic content for a typical arc furnace during each of these periods (according to IEEE Std.519-1992).

Table 1
Harmonic Content of Arc Furnace Current
at two Stages of the Melting Cycle (IEEE Std 519-1992)

Furnace Condition	Harmonic Current % of Fundamental				
	Harmonic Order				
	2nd	3rd	4th	5th	7th
Initial Melting (active arc)	7.7	5.8	2.5	4.2	3.1
Refining (stable arc)	0.0	2.0	0.0	2.1	0.0

Measurements show that in some cases harmonic content may be significantly higher than that of Table 1. According to [1] 3rd harmonic current can be as high as 20% and 5th harmonic current is around 10%. These harmonic levels depend on a number of factors, many of which are not electrical in nature. Arc furnace operation is often further complicated by the frequent energization of the large arc furnace transformer (1000-30000 times/year [2]). For arc furnace transformers, a pre-insertion resistors or inductors are successfully used to eliminate overcurrents and overvoltages as will be assumed in our example. Smaller transformers in the steel mill plant usually do not use any devices for limiting inrush current. This paper shows that in some cases this may be a reason for concern.

Three-phase DC drives generate odd harmonics of order **6*n* ± 1** where ***n*** is an integer value. The magnitudes of these harmonics depend, in addition to other factors, on the control strategy used. Table 2 shows example of harmonic measurement results obtained for a six-pulse current source inverter (CSI) and a six-pulse voltage source inverter (VSI) as well as twelve-pulse VSI [3]. When twelve-pulse inverters are used 5th, 7th, 17th and 19th harmonics are greatly reduced. The remaining 11th and 13th are close to those generated by a similar six-pulse inverters.

Table 2
DC Drives Input Current Harmonic Content

Type of Inverter	Harmonic Current % of Fundamental					
	Harmonic Order					
	5th	7th	11th	13th	17th	19th
Six-Pulse Current Source Inverter	21	13	9.0	7.8	5.6	4.8
Six-Pulse Voltage Source Inverter	44	19.6	8.0	4.5	3.7	2.1
Twelve-Pulse Voltage Source Inverter	0	0	6.4	3.3	0	0

Filters shown in Figure 1 provide adequate reactive power to keep power factor above 0.95 under all conditions. The total reactive power that is provided by 13.8 kV filters may cause the voltage of the bus to exceed the prescribed limit (1.05 per unit) under reduced load conditions. To keep the voltage of the 13.8 kV bus within limits, 5th and 7th harmonic filters are connected to bus **A**. These filters are designed so that can be individually switched on and off when needed. The load normally changes within a wide range, resulting in a number of configurations for harmonic studies.

Obtaining Resonant Conditions in the Power System

An important part of a filter/compensation design process is to obtain adequate frequency response at all major busses in the system and for all relevant system configurations. Primary concern is to make sure there are no parallel resonances at harmonic frequencies. Both EMTP and SuperHarm are well suited for this purpose. For any given configuration of the system, the frequency scan is readily available.

It is important to note that the load level may seriously affect the result. The damping is higher when the load is higher, resulting in lower amplification due to parallel resonances. Higher load also indicates that reactive power requirements are higher, requiring more capacitors (or filters) in service than during light load conditions. Sample frequency scans obtained with EMTP and SuperHarm are shown on Figure 2.

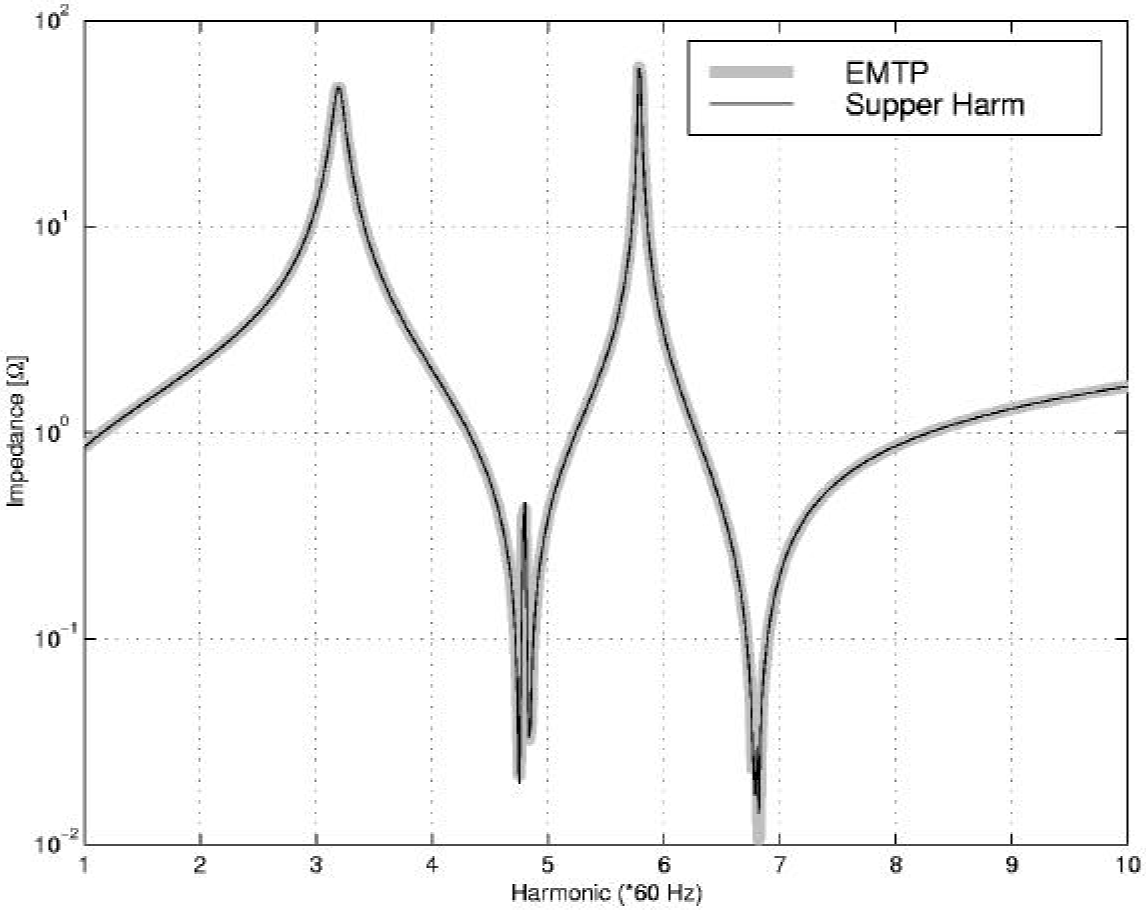


Fig.2. Frequency scan from the 13.8 kV bus with all filters in service (average load)

The filters are chosen to provide adequate reactive power when the plant works with the average load and to provide reduction of the 5th and 7th harmonics. The frequency scan of Figure 2 shows that there are no parallel resonances at integer harmonics, so it appears that the solution is acceptable. Changing the load condition from the average load to a light load would require filters on bus **A** to be disconnected to keep the bus voltage below 105 % of the rated value. Figure 3 shows changes in the frequency scan under light load and average load conditions.

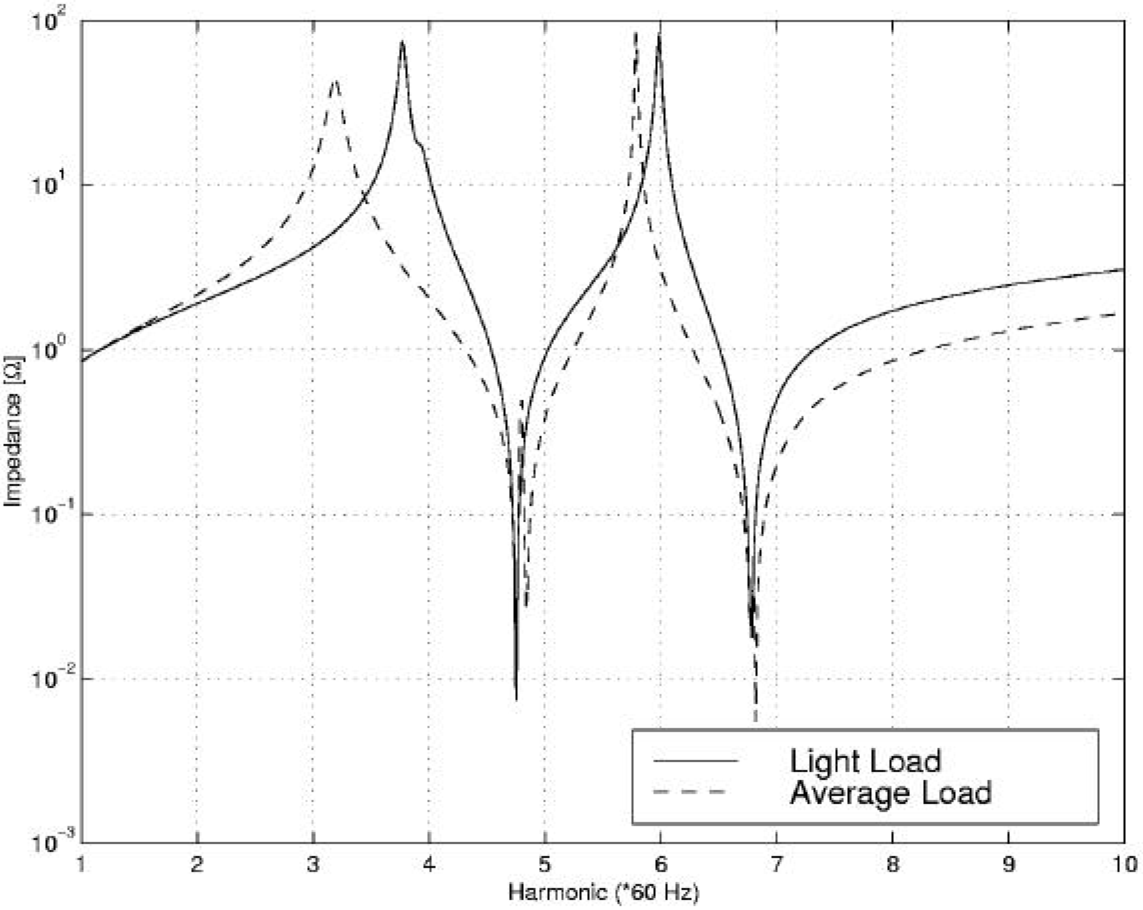


Fig. 3. Frequency scan from the 13.8 kV bus under average load to the light load (including appropriate filter switching) conditions

The frequency scan of Figure 3 shows that the load reduction resulted in a significant increase in the system impedance for all integer harmonics except the 3rd. The main point of concern, however, is the parallel resonance that is extremely close to the 6th harmonic frequency. Papers dealing with the filter design process usually quote 2nd, 3rd, 4th and 5th harmonic currents as potential source of problems [1]. Our study shows that during transformer energization there is enough of the 6th harmonic inrush current to produce serious overvoltages if resonant condition exists. Figure 4 shows the frequency analysis of the transformer magnetization current during the transformer startup.

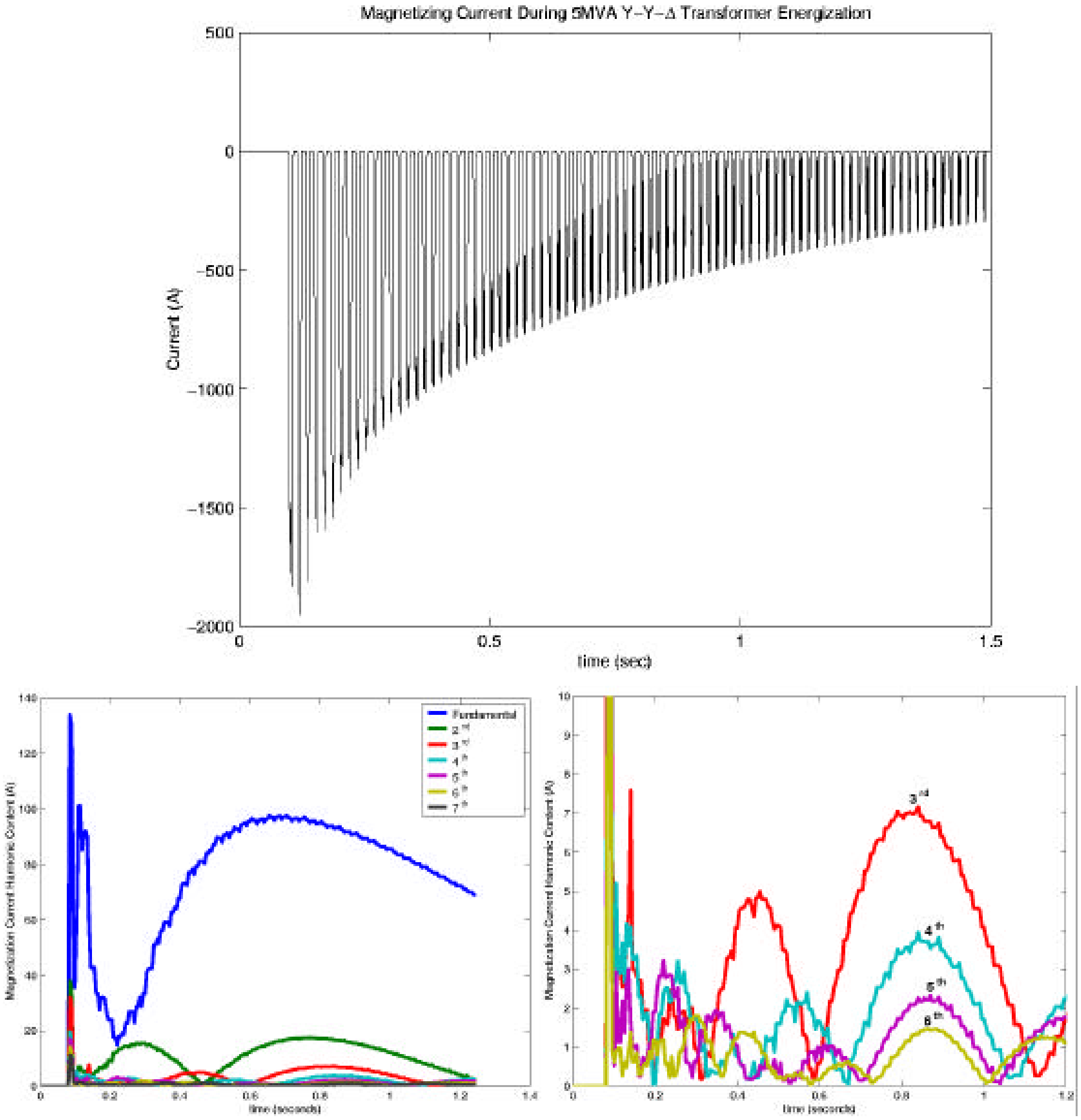


Fig. 4. Transformer inrush current waveform and associated harmonic currents
(based on EMTP simulation results)

Transformer Energization Transients

Checking for overvoltages during switching transients is an important part of filter design process. Frequency analysis is based on the steady-state calculation and it is not always possible to foresee all the problems that may arise during energization transients. It was shown in the previous section that there was a serious concern about 6th harmonic parallel resonance under light load conditions. Transient analysis should show whether this actually is the concern or not.

Figure 5 shows voltages of the 5th and 7th harmonic filter capacitors when the 5MVA transformer is energized under average load conditions. Overvoltages do exist, but they are well within the limits prescribed by [2]. Energization under light load conditions, however, results in much higher overvoltages, as shown in Figure 6. Critical voltage values are reached approximately 0.7 seconds after transformer energization. Harmonic contents of filter capacitor voltages at this time are shown in Figure 7. Exceptionally high 6th harmonic voltage is due to the parallel resonance that is exactly at the 6th harmonic (Figure 3), combined with the transformer 6th harmonic magnetizing current (Figure 4).

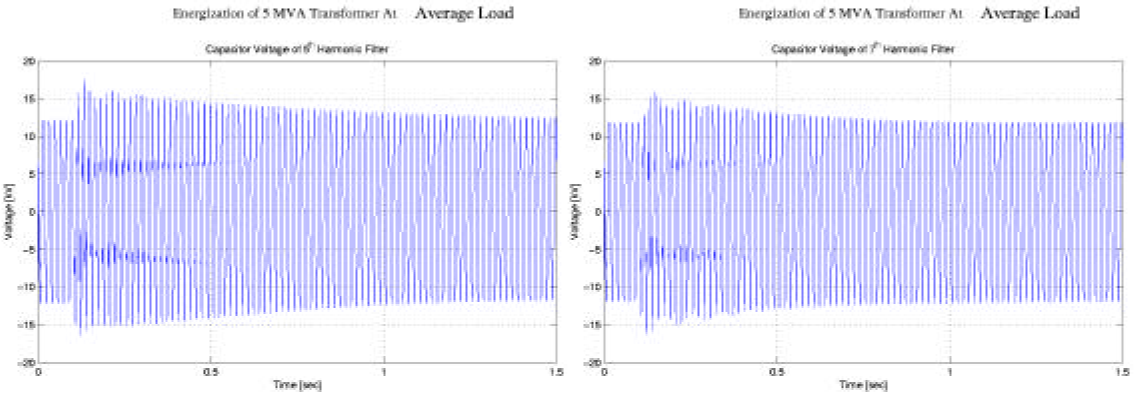


Fig. 5. Voltages on filter capacitors during transformer energization under average load conditions (based on EMTP simulation results)

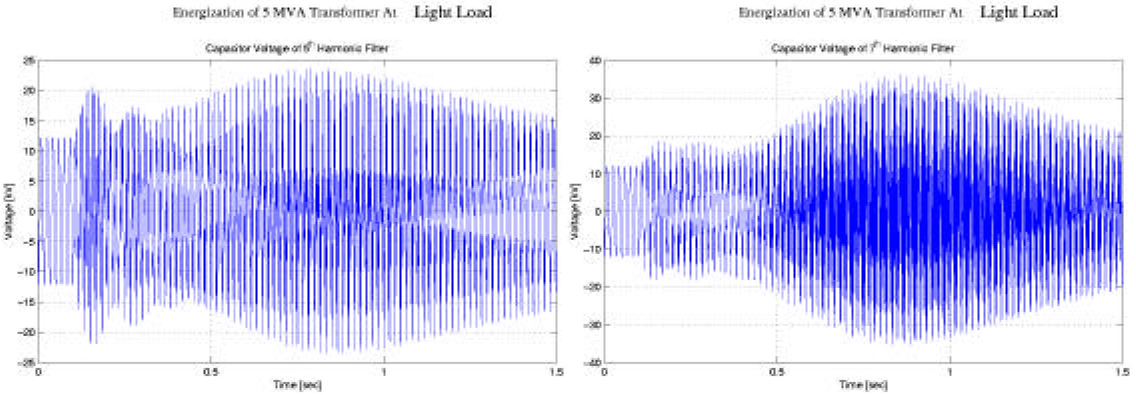
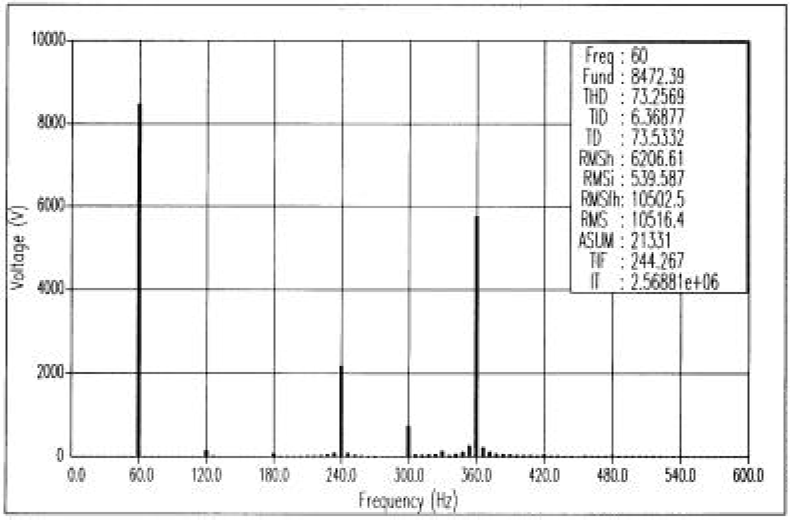
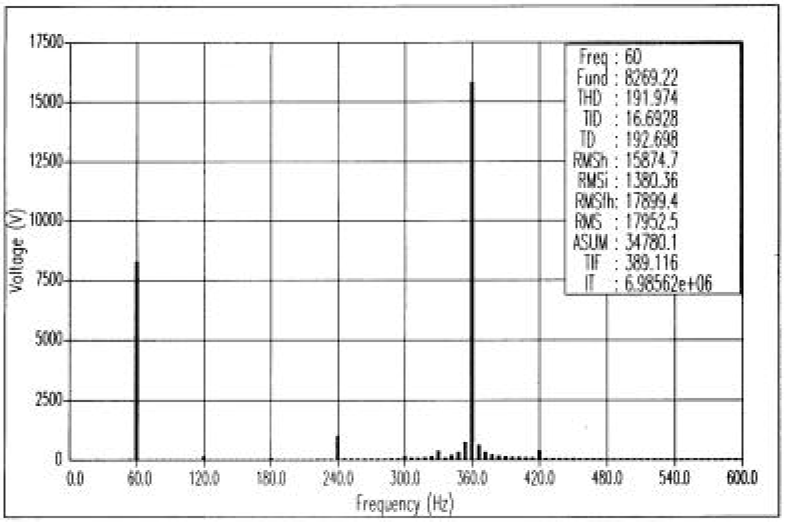


Fig. 6. Voltages on filter capacitors during transformer energization under light load conditions (based on EMTP simulation results)

Figure 7 shows that the 6th harmonic current is amplified to the point that, in the case of the 7th harmonic filter capacitor, it exceeds two times the magnitude of the fundamental. This results in an overvoltage that is approximately 3 per unit, while allowable limit is 2.5 per unit [2].



(a) 5th harmonic filter



(b) 7th harmonic filter

Fig. 7. Harmonic contents of filter capacitor voltages 0.7 seconds after energization under light load conditions (based on EMTP simulation results)

This resonant condition cannot be tolerated. Either harmonic filter design should be modified, or transformer energization procedures should be modified. It should not be allowed to energize a transformer without appropriate precaution when there is a parallel resonance at any of the lower integer harmonics (up to 11th).

Conclusion

Harmonic filter design procedures are primarily dealing with limiting harmonics under normal operating conditions. Power factor correction is another common goal. This paper shows that the design process should not be limited to a small number of steady-state operating conditions. System should be carefully studied for all the cases when transformer or filter energization may be expected. Omission to perform such analysis may lead to serious consequences if parallel resonance is encountered.

Filter design process is the task that makes excellent use of power system simulation packages like SuperHarm and EMTP. Frequency scans obtained by these two programs mach well for the system under study. SuperHarm is well suited for steady-state harmonic flow analysis that is required for filters component rating. EMTP is required for transient studies to reveal whether parallel resonances that exist in the system can cause unacceptable scenarios. This paper shows the case where transient studies are essential for proper harmonic filter design.

References

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