Mitigation of interharmonics using a switched filter scheme

Wilsun Xu1*, Thavatchai Tayjasanant2, Guibin Zhang3 and Richard Bahry4

1Electrical and Computer Engineering, ECERF, 9107-116 street, 2nd floor, University of Alberta, Edmonton, AB, T6G 2V4, Canada
2Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Patumwan Bangkok, 10330, Thailand
3ATCO Electric Ltd., Po Box 2426 Sin Main, Edmonton, AB, T5J 2V6, Canada
4FortisAlberta Inc., 320 17 Ave SW, Calgary, AB, T2S 0A8, Canada

SUMMARY

This paper presents a real-life case where variable frequency drive is identified as an interharmonic source that causes flickers. Through field measurements and system studies, the mechanism of light flicker production is revealed. After investigating various options to mitigate the problem, a simple switched filter scheme is recommended as the solution. Field measurement results have confirmed the effectiveness of the proposed scheme. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: power quality; light flicker; interharmonics; variable frequency drive

1. INTRODUCTION

VARIABLE frequency drives (VFDs) are well-known harmonic sources. Unfortunately, some of the drives are also interharmonic sources [1,8]. Interharmonics are spectra components whose frequencies are not multiple of the fundamental frequency. The beating between interharmonic components and the fundamental frequency component results in light flicker [2].

This paper presents a real-life case where a VFD is identified as a flicker source. The case involves a 3 MW VFD of a pipeline compressor station. The mechanism of light flicker generation is revealed. Unfortunately, mitigating the flicker problem is a challenge since frequencies of the interharmonics produced by the drive varies with the drive speed. Common passive filters become ineffective to solve the problem. As a result, a switched filter scheme is proposed. The filter scheme has been implemented and field test results confirmed its effectiveness. Although conceived for a specific industry case, the proposed switched filter is a general and effective scheme to mitigate interharmonics produced by variable frequency drives, especially for those used by the pipeline industry. This paper also presents the process of problem identification, system studies, and solution evaluation. It serves as a case study example of flicker troubleshooting and mitigation.

2. VFD-CAUSED INTERHARMONICS AND FLICKER

A VFD, especially the current-source inverter-based medium voltage drive, can be considered as a frequency converter. It converts a 60 Hz input into an output with a different frequency. Technically speaking, the system can be considered as bi-directional, meaning the motor side voltages and currents can also be converted to the supply system side as shown in Figure 1 [1].

For example, if the motor is running at 43 Hz, the inverter will ‘convert’ the motor voltage into a DC component with ripples. The ripple has a frequency of 43 Hz times the pulse number of the inverter. As a result, the current of the dc link actually contains both 60 Hz caused ripples (due to the supply voltage) and 43 Hz caused ripples (due to the motor voltage). Since the supply side current is related to the dc link current through the rectifier, the 43 Hz caused ripples will penetrate into the supply side and present as
interharmonics because $43 \times (\text{pulse number})$ is not a multiple of 60 Hz. If the interharmonic frequencies coincide with the system resonance frequency, voltage, and current interharmonics can be amplified.

If a voltage waveform contains interharmonics, the peak, and RMS magnitudes of the waveform will fluctuate. This is because the periods of the interharmonic components are not synchronous with the fundamental frequency cycle. This fluctuating magnitude is essentially a form of voltage flicker [2]. Figure 2 shows the waveform composed of a 175 Hz component and a 60 Hz component. It can be seen that the envelope of the waveform appears fluctuating. If the fluctuation magnitude is sufficiently large and the fluctuation frequency is in a range perceptible by human eyes (0.5 to 30 Hz), light flicker can occur. It has been documented that the voltage fluctuation magnitude as small as 0.33% of the fundamental magnitude at frequency 8.8 Hz can cause visible light flicker [2]. As a result, devices that produce interharmonics are a major source of light flicker [3]. A detailed analysis of the relationship between interharmonics and flickers is documented in Reference [4].

### 3. A REAL-LIFE VFD-CAUSED FLICKER CASE

This case involves a 25 kV distribution feeder typically seen in rural North America (Figure 3). The feeder length is about 30 miles and total feeder load is about 10 MVA. Customers A and B are the largest loads supplied by the feeder. Both customers use VFDs for pipeline compressors. Customer A’s VFD uses old current source inverter technology, which has a 12-pulse rectifier interfacing to the supply system and a 6-pulse inverter supplying a large induction motor. Customer B uses the newer pulse width modulation (PWM) inverter technology. Since the installation of Customer A load several years ago, light flicker problems have been reported at various locations in the system, including Customer A site, the town center, and Customer C. Frequent customer complaints have made it necessary for the supply utility to identify the causes of the problem and to find solutions.

The starting point of investigation is the consistent observations that Customer A is somehow related to the complaints. One would first suspect that the load of Customer A fluctuates since such loads normally cause flickers. Discussion with the customer revealed this is not the case since compressor load is not a fluctuating load. One may note that the load is a harmonic-producing type. However, harmonics do not lead to flickers. In addition, the plant is well-equipped with harmonic filters. There is no indication that excessive harmonic currents entered the supply system.

Preliminary conclusions drawn from the above analysis are (1) the voltage in the area must contain some forms of fluctuation in order to cause flicker and (2) Customer A should be monitored. Since the problem is related to unknown causes, one should capture the raw waveforms at the customer site for analysis. Furthermore, as the problem is related to flicker, the waveforms collected must contain many cycles so that the fluctuation pattern of the waveform magnitude can be identified.
4. MEASUREMENT RESULTS

The supply utility has several power quality monitors. Unfortunately, the meter cannot take waveform snapshots longer than four cycles. Four cycles are not sufficient to detect voltage fluctuation. The utility has used the monitors in the past to troubleshoot the flicker problem. However, the findings revealed high even harmonics and no meaningful conclusions could be drawn. For the current project, an alternate PQ monitor was selected for the monitoring work. This monitor can take waveform snapshots for several seconds. The monitors are placed at the two sites, Customers A and C.

Multiple waveform snapshots were taken at the two sites. They correspond to different drive speeds (i.e., output frequencies) of the Customer A load. A sample snapshot is shown in Figure 4. It can be seen that the waveform has a fluctuating magnitude. This characteristic is known as flicker. One can also see that a 4-cycle snapshot reveals nothing about the voltage fluctuation (Figure 4b).

Using a 60-cycle windowed Fourier analysis, the spectra contents of the waveform were obtained. The results are shown in Figure 5. They reveal that the waveform contains harmonics and two dominant interharmonics. The frequencies of the interharmonics are 117 and 237 Hz, respectively. It is these interharmonics that cause the voltage fluctuation. These two interharmonics are close to the even harmonics. If 4-cycle window is used for Fourier analysis, they will appear as even harmonics. This explains the findings of the monitors originally used by the supply utility.

After determining the cause of the flicker problem, it becomes necessary to find where the interharmonics are originated. One of the techniques used to answer this question is to check the direction of interharmonic power. Since it is rare for a system to contain multiple interharmonic sources at the exactly same frequency, the interharmonic source should be located on the side where the interharmonic power is generated. A sample result of such analysis is shown in Figure 6. The figure also shows the 60 Hz power. It can be seen that the interharmonic powers have the opposite signs to the 60 Hz power. Since the 60 Hz power flows from the supply system to Customer A, the interharmonics must come from the customer. One can thus conclude that the drive at the customer site is the source of the interharmonics. For the project, the correlation between the interharmonic frequencies and the drive speed was also conducted. The results shown in Figure 7 reveal that there is a strong linear correlation between the two quantities, which further confirms that the drive is indeed the interharmonic source. The equation between the interharmonic frequencies on the supply side and the drive speed can be derived from References [1,8]

\[ f_{IH} = (p_1 k \pm 1)f_1 \pm np_2f_d \]  

where \( p_1 \) and \( p_2 \) are pulse numbers of the rectifier and inverter respectively, \( f_1 \) and \( f_d \) are supply system fundamental frequency and drive frequency, \( k \) is a positive integer including zero (0, 1, 2, \ldots) and \( n \) is positive integer (1, 2, 3, \ldots). The measurement results fully agree with the theoretical results.
5. SYSTEM STUDY RESULTS

The interharmonic currents produced by the drive are actually quite small as shown in Figure 8. The high interharmonic voltages observed in the field is due to the parallel resonance between the customer harmonic filter and the supply system. Figure 9 shows the full arrangement of the drive system in compressor station. There are four harmonic filters. One of the 11th filter is switchable to maintain adequate power factor when the drive operates at a high load level. The drive operating frequency is in the range of 30–55 Hz. The load level is almost in proportion to the square of the drive frequency (i.e., the motor speed). The configuration shown in Figure 9 is common for large VFDs applications. Harmonic filters are essential for the VFD facility to meet the harmonic current injection limits [5].

All filters in the facility are single tuned filters. A single-tuned filter consists of a capacitor in series with a reactor. At the tuning frequency, the capacitor and reactor have the same reactance so they cancel out. It results in a small impedance for the filter branch and harmonics near the tuning frequency are sunk by the branch. This situation is shown in Figure 10. At frequencies below the tuning frequency (say 4.2 harmonic for the 5th harmonic filter), the impedance of the capacitor is larger than that of the reactor. So the filter behaves as a capacitor. Furthermore, as shown in the figure, there is always a frequency where the filter curve intersects with the system (reactive) impedance curve. This intersection leads to the formation of a parallel resonance and a high combined system-filter impedance is produced. Since the filter is capacitive and the system is reactive below the filter tuning frequency, there is always a parallel resonance [6]. If the drive injects an interharmonic current at that frequency, a high interharmonic voltage will result. This is the reason why the flicker is observed at the facility and other locations.

When a system has multiple filters and components, frequency scan analysis needs to be conducted to identify the resonance points. Figure 11 shows the combined system and filter impedance, i.e., the impedance seen by the drive, at different frequencies.
Figure 5. Spectra of the voltage waveform (a) overview, (b) detailed view around 120 Hz, and (c) detailed view around 240 Hz.
There are two curves each representing a different filter combination. The result shows that there is a parallel resonance when interharmonic frequencies reside in zones 1–4. (The 80 V threshold is used for an illustrative purpose only). To check if these resonance zones do result in a flicker problem, we need to verify the following two factors:

1) The drive’s feasible operating points do produce interharmonics whose frequencies coincide with the resonance zone. This can be checked through the relationship between the interharmonic frequency \( f_{IH} \) and the drive frequency \( f_d \) [4]. The equation for dominant interharmonics \( (k = 0 \text{ and } n = 1 \text{ in Equation (1)}) \) of the current 12-pulse input and 6-pulse output drive is

\[
f_{IH} = |f_1 \pm 6f_d|
\]

(2)
2) For the operating points where the interharmonics do coincide with the resonance zone, the interharmonic frequencies have to be such that they will result in beat frequencies and associated light flickers that are visible to human eyes. The range of human perception is 6–17 Hz. The equation to compute the beat frequency is as follows

\[ f_{\text{beat}} = \left| f_{IH} - f_h \right| \] (3)

where \( f_h \) is the harmonic frequency closest to \( f_{IH} \) [4].

By taking into account the above two factors, Figure 12 is produced. This figure relates the flicker frequency with the drive frequency. It also plots the combined system and filter impedance seen by the drive at various drive frequencies (for the dominant
interharmonic component and the $5 + 7 + 11$ filter configuration). As a flicker frequency in the range of 6–17 Hz is most irritating to human eyes, this frequency range is shown as a horizontal shaded band in the figure. The corresponding drive frequencies (i.e., drive frequencies that are most likely to produce visible flicker) are 31–33 Hz, 37–39 Hz, 41–43 Hz, and 47–49 Hz etc. It can be seen that when the drive operates between 41–43 Hz, the impedance is the highest. Accordingly, the flicker is most noticeable at this drive frequency.

Figure 11. System impedance seen by the VFD.

Figure 12. Flicker frequency and system impedance as functions of drive frequency.
frequency range. One may argue that the drive frequency range of 57–59 Hz also corresponds to high impedance values and a flicker could also be observed. The field experience did not show this is the case. The reason is the following: the interharmonics produced in this range have higher frequencies. They produce less voltage fluctuation for the same amount of interharmonic magnitude [2,3]. As a result, the operating point of concern is around 41–43 Hz. This analysis has a good agreement with field measurements. Figure 13 shows the measured magnitude of the dominant interharmonic component. The star points are the drive operating conditions where light flicker was observed in the field.

6. MITIGATION METHODS

Although the customer should reduce the interharmonic voltages at all drive operating points below certain limits, this approach was not taken since standards on interharmonic limits were not available. More importantly, the solution can be very costly and the benefits are not tangible. For the goal of eliminating the light flicker, several mitigation options are considered. They are summarized below:

1) Increase the size of the DC link reactor: this measure deals with the source of the problem. An increased DC link reactor will reduce the coupling between the supply side and the motor side. Consequently, less motor harmonic current will penetrate into the supply system side as interharmonics.

2) Eliminate or retune the 5th harmonic filter: this option is based on the consideration that the 5th harmonic filter causes the resonance in zones 1 and 2. By eliminating this filter, the resonance point could be moved to a higher frequency. It is hoped that the resonance caused visible flicker problem could be avoided this way. Alternatively, the filter can be modified by adding a series resistor. This approach will reduce the magnitude of the filter-system resonance.

3) Low frequency filter: this filter is expected to reduce the intensity of resonance in zones 1 and 2. The filter may be tuned to the 3rd harmonic. Since the filter will create a new parallel resonance point below its tuning frequency, a damping resistor is often needed. As the filter is tuned to a low frequency, the losses on the damping resistor can be high. Reference [7] suggests that a capacitor can be inserted in series with the resistor to reduce the fundamental frequency losses. It results in a filter configuration shown in Figure 14a which has been used to mitigate interharmonics from a cycloconverter [7]. Figure 14b illustrates another design of the low frequency filter evaluated for a facility that had a DC arc furnace and cycloconverters [3]. The filter is tuned to the third harmonic. The series LC in parallel with the resistor is tuned to the power frequency to minimize losses. So the filter behaves as a capacitor in series with the damping resistor at the fundamental frequency.

4) Switched filter schemes: this idea is conceived from the following observation: the interharmonic frequencies vary with drive conditions and are predictable. If we can dynamically adjust the filter configuration in response to the drive operating speed, it
becomes possible to prevent the interharmonics from exciting the resonance points. The idea is illustrated in Figure 15. In this figure there are two filter configurations. Configuration A has a resonance point around the 3.5 harmonic and configuration B has a resonance point around 4.6 harmonic. If a drive operating in a speed range that produces interharmonics in the frequency range of X to Y, we can use configuration A. Once the drive operating point goes below point X or above point Y, the filter configuration is changed to B. In this way, the resonance points of both configurations will not be encountered by the drive.

The effectiveness of option 1, increasing DC link reactor, was investigated using time-domain simulation. The results shown in Figure 16 reveal that the DC link reactor is already quite large. Further increase of the size can be helpful but it is unlikely to result in significant reduction on interharmonic currents.

For option 2, eliminating the 5th filter, the driving point impedance results are shown in Figure 17. It can be seen that resonance frequency for the 5th + 7th + 11th filter case is moved from the 3.3 to 4.2 harmonic. The resonance frequency for the 5th + 7th + 2 × 11th case is moved from 2.7 to 3.3 harmonic. Although there is an improvement for the one 11th filter case, the case of two 11th filters (2 × 11th + 7th) still encounters resonance around 3.3 harmonic, which corresponds to a drive speed of 43 Hz. As a result, this option cannot solve the problem. Since eliminating the 5th harmonic filter is unlikely to solve the problem, the option of re-tuning the 5th filter will be even less effective.

Option 3 could eliminate the resonance in zones 1 and 2 if the filter tuning frequency can be selected properly such as tuning the filter to the 3.3 harmonic. This option, however, will result in a resonance point below the 3.3 harmonic, say 2.8. The original 5th filter caused resonance point still exists. Its frequency will reside between the tuning frequencies of the 3rd and 5th filter. These two resonance points are very likely to cause the light flicker problem at other drive operating frequencies. In addition, a 3rd harmonic filter is expensive due to large component sizes. There is no space to add the filter. In view of these issues, this option is not a viable solution.

There are two possible variations for the switched filter option. One is the switchable 5th and 7th filter scheme and the other is the switchable 11th filter scheme. Figure 18 shows the impedance seen by the drive for three operating scenarios: all filters are in service, one 11th filter is switched off and both 5th and 7th filters are switched off. It can be seen that if the interharmonic frequencies
are below approximately 3.2 harmonic, switching off one 11th filter or both 5th and 7th filter will result in smaller system impedance. When the interharmonic frequencies are above 3.2, all filters should be in service since the impedance is lowest (up to the 4.5 harmonic). Thus the switched filter scheme will provide lowest impedance for all interharmonic frequencies of concern.

The results show that both switched filter schemes are almost equally effective. Since one 11th filter is already switchable, the switchable 11th filter scheme is the preferred choice, as this will reduce the implementation cost. To determine the drive frequency where the switching should take place, the Equation (2) can be used with $f_d = 60$ Hz. For the 3.2th harmonic, the drive frequency calculated is 42 Hz. In view of all the options available, a drive speed triggered switchable 11th filter appears to be the most suitable solution to the problem. This option was recommended for implementation.

Figure 16. Impact of DC link inductor on the interharmonic currents.

Figure 17. Driving point impedance without the 5th filter.
7. FIELD VERIFICATION RESULTS

Although the frequency scan study has identified the point of filter switching, it is important to verify or refine this point through field measurements. This is because the accuracy of the frequency scan analysis depends on the quality of feeder model and model data. The tool is good at predicting the existence of resonance points and the approximate resonance frequencies. It has limitations to

Figure 18. Impedance for three operating scenarios.

Figure 19. Field results on the drive switching frequency.
MITIGATION OF INTERHARMONICS

predict precise frequency for filter switching. There is therefore a need to fine-tune the switching frequency through field experiments.

Extensive field measurements were conducted at different drive operating frequencies for the purpose of determining the precise switching frequency. The main results are summarized in Figure 19. This figure shows the 1st dominant interharmonic voltage magnitude at various drive frequencies for two filter configurations. The flicker-producing operating points are marked with star symbols. It can be seen that if the 11th filter is switched on at these points, the interharmonic voltages will drop by 1.5–2.5%, which eliminates the flicker problem. With the switched filter scheme, the overall interharmonic voltage level is less than 2.3% which occurs at the switching point. According to the result, the switching frequency is refined to 46 Hz. The recommended scheme was implemented about four years ago, since then no flicker problem has been reported.

8. CONCLUSIONS

This paper has presented a real-life case where VFD causes voltage flicker and a switched filter scheme is proposed to solve the problem. The main conclusions of this paper are summarized as follows

- The flicker problem is caused by interharmonics generated from a VFD. The interharmonic frequency depends on the drive output frequency.
- The harmonic filters installed at the drive site interact with the system impedance causing a parallel resonance at a frequency that coincides with the interharmonic frequencies produced by the drive.
- The resonance magnifies the impact of the interharmonic currents from the VFD, causing high interharmonic voltages in the system. The interharmonic voltage beats with the 60 Hz voltage and produces flicker.
- The proposed solution is to avoid filter-system parallel resonance using a switched filter scheme. The scheme involves two or more filter configurations or combinations. Depending on the drive speed, the configuration that produces the smallest impedance at the interharmonic frequency is switched on.

9. LIST OF SYMBOLS AND ABBREVIATIONS

PWM pulse width modulation
VFD variable frequency drive
\( p_1 \) pulse numbers of the rectifier
\( p_2 \) pulse numbers of the inverter
\( f_1 \) supply system fundamental frequency
\( f_d \) drive frequency
\( k \) a positive integer including zero (0, 1, 2, \ldots)
\( n \) a positive integer (1, 2, 3, \ldots)
\( f_{IH} \) interharmonic frequency
\( f_{beat} \) beat frequency
\( f_h \) harmonic frequency closest to \( f_{IH} \)

REFERENCES