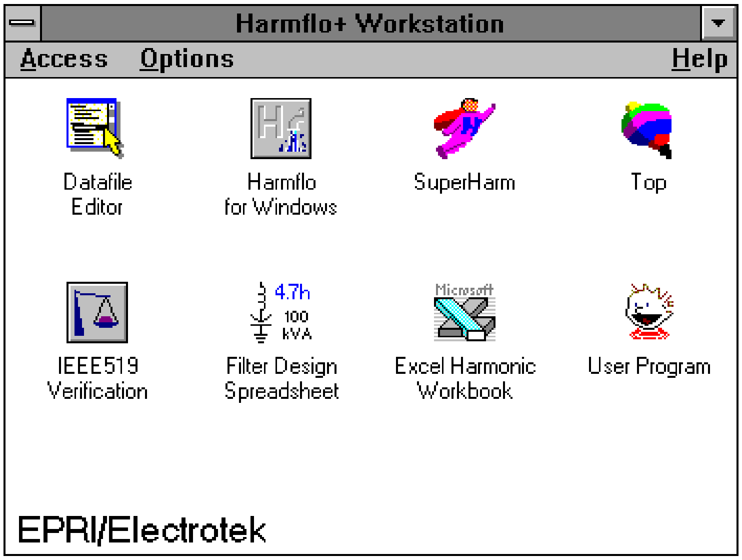
HarmFlo+ Tech Notes



for users of the EPRI/Electrotek HarmFlo+ Workstation

Issue # 95-2 ***December, 1995*** ***Editor: Susie Brockman***

Project Manager: Tom Grebe

in this issue:

Letter from the Editor:

This is the sixth issue of *HarmFlo+ Tech Notes*. The technical newsletter provided to members of the HarmFlo User's Group. It was developed as a technical bulletin for exchanging information between members of the group. We are constantly seeking new information to share. Following is a list of the types of articles you may want to submit.

Technical articles
Modifications / enhancements to the code
Case studies / unique simulations
Research projects
SuperHarm / HARMFLO data preparation / model development
Include / library files developed for distribution on the BBS
Letters to the editor / User's Group
Technical paper abstracts
Questions for members of the User's Group

If you feel you have an article which is appropriate, or may help another member of the group with harmonic analysis, please send us a copy for review. We feel the exchange of information is one of the most helpful resources the group can provide.

Sincerely,

For more information concerning the newsletter or to submit a contribution please contact:

Susie Brockman
Electrotek Concepts, Inc.
408 North Cedar Bluff Road, Suite 500
Knoxville, Tennessee 37923
Phone: (423) 470-9222 x141 FAX: (423) 470-9223
e-mail: susieb@electrotek.com

Multiple Paralleled AC Drives

Resonant Interaction and Additive Harmonic Effects of Multiple Paralleled AC Drives in Forest Products Processing

Abstract

A forest products company proposes installing a 100 HP adjustable speed drive for fans in its drying kilns. Utility engineers identify a resonance problem by using an elementary model and readily available software. The utility proposes a simple and effective solution: remove an existing capacitor bank designed for power factor correction, but retain a fifth harmonic filter to meet current distortion standards. The company does so and obtains satisfactory performance from the drive. Expansion to seventeen identical drives proceeds quickly and reliably.

Introduction

In recent years, the adjustable speed drive for alternating current machines has become both economical and practical. Driving pumps and fans with an adjustable speed AC drive, instead of employing single speed induction motors and regulating the flow mechanically, provides the promise of substantial energy savings. The responsiveness of the drive to closed loop control also promises substantial improvement over former, often mechanical, methods.

These improvements come with a new set of issues for engineers. Old reliable methods, such as installing capacitor banks for power factor correction, meet significant and possible unexpected difficulties when left in place after the installation of an adjustable speed drive. Such a situation occurred when a forest products company proposed using an adjustable speed drive for the fans in their drying kilns. Fortunately, the company contacted the utility before installing the drive. Utility engineers predicted a resonance problem and proposed a simple and effective solution. The company was able to quickly and reliable expand from the single drive they initially proposed to seventeen such drives. However, other customers served by the same utility, particularly farmers who added adjustable speed drives to their irrigation systems, have seen the same resonance phenomenon damage their equipment.

Resonance between adjustable speed drives and capacitor banks occurs predictable. Software is available to predict such problems and to check proposed solutions.. In this paper, the causes of this problem are identified and practical solutions are proposed and verified.

Problem Description

In 1994, a large forest products company considered the advantages of converting to adjustable speed drives for a large number of electrically-driven fans in their lumber drying kilns. Previously, these ten-horsepower fan loads had been directly driven from a 480 Volt line. For reasons not presented in this paper, including economic benefits and practical advantages of closed loop flow control, they decided to proceed. Being reasonably cautious, they chose to verify their strategy by first installing only one adjustable speed drive. If it performed acceptable, then they would consider expanding to seventeen drives, all working from the same feeder.

A one-line diagram of a portion of the plant's distribution system, including the proposed single adjustable speed drive, is shown in Figure 1. The point of common coupling is the distribution transformer's 69 kV primary connection. Power flows through a 12.47 kV feeder and another step-down transformer to an adjustable speed drive. The adjustable speed drive consolidated ten of the 10 HP fan loads at the end of the feeder. Before the drive and filter were proposed, the fan loads were connected directly to the 480 Volt bus. Power factor correction capacitors, appropriate for a load consisting of several induction motors, straddle the secondary of the low voltage transformer. The drive is already known to have unacceptable high fifth harmonic current in stand-alone applications, so a fifth harmonic filter is assumed.

Before installing the first drive, the company contacted the utility. They asked whether a 100 horsepower adjustable speed drive having ten induction motors as its load could be added to the plant's distribution network. They were particularly interested in whether the drive could be reliable and whether it would interact adversely with other equipment in the plant.

Figure 1 - System Diagram

Should the utility discover any difficulties, the customer wanted the utility to recommend appropriate general remedies. In addition to this, the utility was interested in whether the proposed filtering would be adequate to meet standards for voltage and current harmonic content at the Point of Common Coupling. These standards are found in IEEE519-1992.[3] The customer initially wanted to install a single drive, but clearly stated that they would expand to seventeen drives if the first one proved to be satisfactory.

Modeling the System

A model for the system proceeds from the one-line diagram shown in Figure 1. The notation in that diagram is from SuperHarm, a power system harmonic analysis software package.[1] The distribution elements are modeled as shown in Table 1. Series impedance of the lines is considered negligible. This model is fairly simple, but addresses each significant element of the circuit in a desirable manner. This model fits nicely into a harmonic analysis software package, in this case SuperHarm.

Table 1
Synopsis of Element Models

Element	Modeled As	Value
transmission system	V source & series Z	69 kV (1.0 pu)
transformers	series Z	7.74%
transformer	series Z	5.80%
choke	series Z	5.0%
capacitor bank	capacitance	2 kVAR
filter capacitor	capacitance	345.4 uF
filter reactor	inductance	0.9222 mH
plant load	source	5235 kVA @ 85% pf
ASD & load	current source	given in Appendix 1

For the adjustable speed drive, the current source model's values are assumed to be its nominal values of each harmonic current at rated operating conditions. This gives its harmonic distribution and waveform as shown in Figure 2. Modeling the drive as a current source with harmonic components places emphasis on the harmonic current behavior of the system, giving a reasonable accurate estimate of it. The simulated drive operated near full load because the voltage drops at fundamental frequency are relatively small under the model conditions.

Modeling the plant load a s a source can be shown to be a reasonable assumption. The currents distribute themselves quite reasonable, given the transmission voltage being modeled as a voltage source. The model ignores nonlinear effects of voltage harmonics on the drive itself, an unfortunate, but not disabling, disadvantage. Experimental results presented later in this paper confirm the correctness of these assumptions. For a more exact representation, an analysis software such as ElectroMagnetic Transients Program (EMTP) should be considered.

Figure 2 - Harmonic Spectrum and Analog Waveform of Adjustable Speed Drive Current at Rated Conditions.

Simulation

Simulation of this system employs SuperHarm, a package contained within the HarmFLo+ software by Electrotek. [1] Simulation reveals the existence of a resonance cure, as shown in Figure 3. On this resonance curve, the effect of the fifth harmonic filter produces a characteristic notch at 300 Hertz. More important, however, simulation predicts a much stronger resonance in the system neat the eleventh harmonic. An attendant simulation for zero sequence (results not shown) indicates a zero sequence resonance near the fifteenth harmonic. Because the circuit is fairly simple a hand calculation verifies these results: From the perspective of the 480 Volt bus, a lumped positive sequence source impedance Z_{source} can be determined. A resonance between Z_{source} and the rest of the circuit, primarily influenced by the bus capacitors then can be calculated.

Figure 3 - Resonance Curve

The origin of this resonance can be explained by considering Figure 4. The equivalent source impedance Zsource, dominated by a reactance, is interacting with the capacitor bank to form a tank circuit. IF the resonant frequency of this tank circuit is near one of the harmonic currents generated by the adjustable speed drive (a nonlinear load), then there will be a significant current component excited in the tank. In this case, eleventh harmonic indeed fits this requirement and Figure 3 indicates that there is also significant gain on the thirteenth harmonic. Figure 5 shows SuperHarm's estimate of this current in the 12.47 kV/480V distribution transformer. In this waveform, the eleventh harmonic current is 5.5% of the fundamental current and the thirteenth harmonic current is 4.4% of the fundamental current. The capacitor bank shows components of similar amplitude.

Figure 4 - Resonant Subcircuit

Harmonic voltage components, on the other hand, do not appear to be a problem. Due to the topology of the system, nearly all of the harmonic voltage was dropped inside the plant. Little appeared at the point of common coupling, satisfying utility standards.

Figure 5 - Distribution Transformer Current Waveform

These harmonic currents lead to significant problems, First, the transformer must be derated for harmonic current reasons. In this case, the derating is only 97% with a load K-factor of 1.8, but this is derating nonetheless. Second, the capacitors must be considered as a sink for the harmonic current. This causes increased heating and dielectric stresses. Through requirements of IEEE Standard 18-1992, this still could shorten the life of the capacitor.[2] If this problem occurs with one drive, it will be of greater concern with the proposed seventeen drives. A worst case model of seventeen drive case calls for seventeen time the harmonic current in the same two capacitors. Third, this level of harmonic current in the distribution transformer exceeds the standards of IEEE Standard 519-1992.[3] However, the point of common coupling is the larger distribution transformer, which carries the plant load also. The magnitude of the plant load is so much greater than the drive current as to make meeting IEEE Standard 519-1992 guaranteed. This relationship is true even for the case of seventeen drives, though considerations for cogeneration at this plant (not addressed in this study) could complicate the harmonic issue substantially.

Proposed Solution

A simple solution to this problem is to remove the capacitor banks. Its original purpose was to provide power factor correction in the presence of the induction motor load. However, the fundamental displacement factor of an adjustable speed drive is typically very near unity. Therefore, there is no need for power factor correction if the load consists completely of adjustable speed drives.

After removing the capacitor bank and the filters from the model, a model in SuperHarm again simulated the system's operation. As expected, the impedance shows no resonance, even with 17 drives; see Figure 6. Current and voltage waveforms from this simulation, at the drive input and at the transformers, show no evidence of resonance, either.

Figure 6 - Positive Sequence Impedance: Capacitor Bank and Filters Removed

Unfortunately, without the filters, SuperHarm predicts the fifth harmonic current at the point of common coupling to be 5.2% in the seventeen drive case, exceeding IEEE 519-1992 standards.[3] Total current distortion also exceeds limits of IEEE 519-1992. Installing fifth harmonic filters in a SuperHarm simulation brings predictions of both fifth harmonic current and total current distortion well within limits. The customer proceeded to install the drives with filters, removing the capacitor bank in the process.

Experimental Results

After the customer installed all seventeen drives and placed them in operation, experimental verification of the final configuration was obtained while the kilns services by the subject drive system were actually in production. In Figure 7, current at (a) the drive input, (b) the filter capacitor, and (c) the filter choke are shown. These are quite similar to those predicted by SuperHarm.

Figure 7 Experimental Results: Drive System Currents

There is substantially less of the higher frequency harmonic currents on a percentage basis, in the seventeen-drive total current waveform (Figure 7d) than there is in a single drive current waveform. This follows from theory stated in reference [4].

Because this is a working plant, there is no reasonable opportunity to safely verify the predictions of resonance. However, experience at the same utility with farmers who installed adjustable speed drives for irrigation pumps informally verified the notion that resonance does indeed occur if capacitor banks are not removed. Typically, diode failure in the rectifier section of the drive occurs within a few weeks of installation. Capacitor banks must be removed and appropriate filters must be installed to meet standards. When these measures are taken and after the drive is repaired, the problem disappears.

Conclusions

A forest products company proposed using variable speed drives for its induction motor-driven fans, asking the utility to determine the requirements necessary to do so. Upon modeling the customer's distribution system and simulating the model using SuperHarm, a resonance condition became obvious. The customer had installed power factor correction for the induction motor load long ago. Simulations predicted that harmonic currents generated by adjustable speed drive would resonate in a tank circuit formed by the capacitor bank and the series reactance of the transmission system and distribution transformers. Derating of transformers and capacitor bank would be necessary.

SuperHarm accurately revealed the resonance problems and verified the practical solution: remove the capacitor bank and, in light of a proposed expansion to seventeen identical drives, install fifth harmonic filters. Adjustable speed drives normally do not require displacement power factor correction, but can interact adversely if added between a motor load and a bus having power factor correction capacitors. Resonance indeed disappeared when the capacitor banks were removed, but a fifth harmonic filters remained necessary to meet standards for current harmonic content and current distortion. SuperHarm predicted that installing the filters would lead to an acceptable performance, which proved in practice to be true. The same solution was extended to seventeen drives with quite satisfactory results. SuperHarm was a useful tool in this analysis, giving predictions that proved to be quite valid. It did not give the detail of accuracy of such tools as EMTP, but did give a good indication quickly of whether the proposed solution would work.

Acknowledgments

Boise Cascade Corporation provided the motivation for this study and graciously permitted data collection at their Emmett plant while the kilns served by the subject drive system were actually in production. Darren Beasley, an engineer with Idaho Power, arranged access to the Emmett plant to gather data. Idaho Power Company provided the SuperHarm software for the simulation portion and provided the instrumentation for the experiments.

Appendix 1
Nominal Current Harmonic Content of Adjustable Speed Drive

Harmonic	Frequency	Amps
1	60	92.0
3	180	1.55
5	300	27.89
7	420	8.0306
9	540	0.0
11	660	5.636
13	780	3.24
15	900	0.0

References

[1] "HarmFlo+^{TM} Harmonic Analysis Workstation Users Guide Version 2.0," Electrotek Concepts, Inc.
[2] IEEE Standard 18-1992.
[3] IEEE Standard 519-1992.
[4] A. Mansoor, W.M. Grady, A.H. Chowdhury, and M.J. Samotyj, "An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-Phase Power Electronic Loads," IEEE Transmission and Distribution Conference, Chicago, April 1995.

*This paper was presented at the PCIM Conference in Long Beach, CA 1995

Vern Padaca
Idaho Power Company

Case Study

Blown Fuses and Arresters, What's the Story?

This is an outline of the presentation Jim Rossman made at the Users Group meeting in Knoxville. For more information, please contact Jim at TVA.

Customer 1 Problems:

Metal Processing Plant with induction heater loads was experiencing 13 -kv feeder breaker interruptions, erratic operations of process controls, and unexplained furnace shutdowns.

Customer 2 Problems:

Woodworking plant with minimal non-linear load is experiencing fuse operations associated with three-480V capacitor banks. These banks are on different services and normally the fuses operate at night or during weekends. This plan is located across town from the metal processing plant.

Distributor Problems:

The distributor serving this customer experienced sagging 13-kV feeder conductors, surge arrester failures, and distribution capacitor fuse operations as well as unexplained line operations.

Recent System Changes:

The distributor recently installed a 1200-kVAR capacitor bank near the plant site and this bank was routinely blowing fuses and making noise when in operation.

Studies Performed

Harmonic monitoring was performed at both plant sites over time. A SuperHarm model was built and the results were used to verify the quality of the simulation's base case. Once the model was fine tuned, multiple cases were run to determine all possible system tuning conditions. The measured currents and voltages were compared to IEEE 519 guidelines as follows:

Table 1
Metal Processing Plant Meter Point Current Summary

	THD	**< 11 harmonic**	**11 -16 harmonic**	**17-22 harmonic**
IEEE 519 (<20) limits	5.0% limit	4.0 limit	2.0 limit	1.5 limit
Measured Results	3.2%	0.9% (5th harmonic)	2.6% (11 harmonic)	0.1% (19 harmonic)
Does it exceed limits?	Under limit	Under limit	Over limit	Under limit

Table 2
Metal Processing Plant Meter Point Voltage Summary

	THD	**Maximum Individual Harmonic**
IEEE 519 Limit	5.0%	3.0%
Typical measurements during the day	2.3%	1.1% (13th harmonic)
Typical meaurements during the night	12.8%	11.2% (11th harmonic)

In Resonance - Typically at night when system is lightly loaded.

Typical conditions when system loading is high enough to warrant 5400 bank

Simulation results - At woodworking location - 480-V capacitor

Actual waveform shown below of service entrance - 480-V level woodworking location

Solution:

One of the 5400-kVAR capacitors is presently switched on (manually) and left on to detune the system from the 11th harmonic. Other alternatives considered were installing a filter at the plant, removing the 1200-kVAR bank at the plant, and in the long run serving the plant from a dedicated substation.

Lessons Learned from this Study:

- Series harmonic resonance conditions may be caused by parallel resonance conditions some distance away.
- Harmonic studies must account for daily and seasonally loading possibilities.
- Twelve pulse rectification helps reduce the 5th and 7th harmonics but the 11th and 13th are still problems.
- Make sure you understand the problem fully before you try to detune the system.
- Changing fuse types to slower blowing fuses only masks the root cause.
- Arresters can quickly be destroyed if peak of the sine wave exceeds the arrester turn on level.
- SuperHarm is an accurate and wonderful tool for harmonic analysis.

Jim Rossman
Tennessee Valley Authority

Harmonic Concerns

Operational and Harmonic Concerns Associated with a Semiconductor

Abstract - This paper clarifies the harmonic problems associated with the application of a semiconverter. A comprehensive explanation of the harmonic generation and an analysis of converter operation with different firing angles is provided. Voltage and current waveforms showing the distortion characteristics of input and output quantities are presented. The performance of a 2nd harmonic filter to reduce even harmonic injection into the system and to improve power factor is evaluated using the Electromagnetic Transient Program (EMTP).

Introduction

A semiconverter, or half-controlled three-phase bridge rectifier, is occasionally used to serve industrial loads up to several hundred kilowatts. The circuit configuration of interest is shown in Figure 1. The semiconverter is supplied from a 480 V ac voltage source through a delta/wye connected isolation transformer. The load of the converter is represented by an RL series branch.

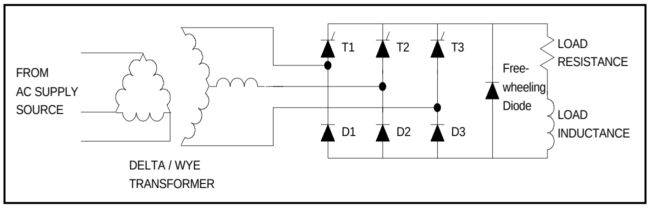


Figure 1: Semiconverter AC to DC Conversion System

Discussions of the semiconverter operation under idealized conditions can be found in power electronics texts[1][2][3]. Three controlled devices are used in conjunction with three diodes. By using three diodes, the cost and complexity of the control circuit for the semiconverter can be greatly reduced when compared with a full controlled bridge converter. This makes the semiconverter very attractive in applications where only one-quadrant operation is required. The authors have noticed applications of the semiconverter in large ac generators, built in the 90's, where the semiconverter supplies the dc exciter current. The most common application of the semiconverter is for dc motor drives.

While recognizing the advantages of the semiconverter, problems associated with its use should be identified. Semiconverter use can inject an excessive amount of even harmonics into the ac power system. This occurs particularly when the converter is operated with a large firing angle and the freewheeling diode of the converter carries a significant current. The asymmetry of the ac line current, with respect to the current zero level, distinguishes the harmonic distortion caused by a semiconverter from other types of power electronics. The frequency spectrum of the semiconverter current is rich in even harmonics. Typical measured voltage and current waveforms from a semiconverter application are presented in Figure 2 to illustrate the discussed waveform distortions.

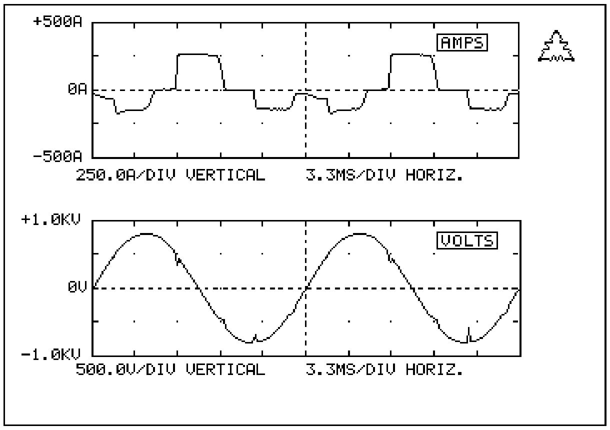


Figure 2: Measured Waveform of Line-to-Line Voltage and Line Current.

The waveforms in Figure 2 were measured at the supply side of the isolation transformer feeding the semiconverter. The voltage waveform clearly indicates a three-pulse operation (three voltage notches) and the current waveform shows the dramatic asymmetry of the line current with a rich even harmonic content.

Although similar waveforms have been frequently observed in practice, the lack of published information regarding this issue has hindered the formation of the problem. And, therefore, it has not been comprehensively understood by many electrical engineers who work at the front line of industries and electric utilities. The objective of this paper is to provide a clear explanation of the operating principles of the semiconverter, to illustrate its performance characteristics, and to demonstrate an approach which can be used to reduce the current distortion seen by the ac power system.

Operation Principle

A semiconverter can be considered as a series combination of phase-controlled half-wave converter (the upper bridge) and an uncontrolled half-wave rectifier (the lower bridge). If the upper bridge thyristors are fired at natural commutation points, the semiconverter operates exactly as a full-wave diode bridge rectifier. The EMTP simulated ac line-to-neutral voltage (Va), the ac line input current (Ia), the dc output voltage (Vdc) and the dc load current (Idc) for the system shown in Figure 1 under such firing conditions are illustrated in Figure 3. This results in the traditional harmonic current spectrum with odd, non-triplen terms only.

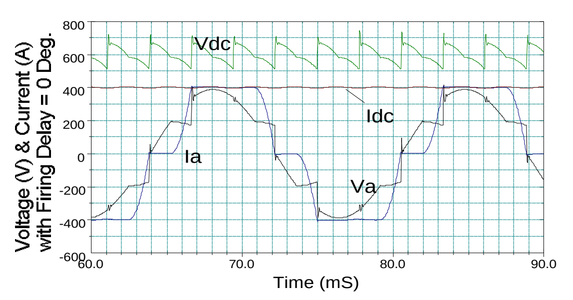


Figure 3: Input / Output Quantities of Six-Pulse Operation.

The transformer primary line-to-line voltage is 480 V_{rms} and the ratio of the delta/wye isolation transformer is 1:1. Consequently, the line-to-neutral peak voltage of the wye-connected secondary is $392V_p$. The load of the converter consists of 1.5 Ω resistance in series with 10 mH inductance. In the simulation, properly sized source and transformer impedances as well as carefully selected snubber circuits were used. The impedance of the supplying system causes the phase current commutation to be completed within a finite period of time as opposed to jumping from zero to the full load level as in an ideal circuit. The symmetry between the three phase currents and the symmetry of each individual phase current with respect to the zero crossing points prevents any triplen or even harmonics from appearing in the ac line current under this operating condition [2][3].

When the thyristors are fired with a time delay, the converter can have two basic operation modes; six-pulse and three-pulse. The lower bridge is completely uncontrolled and always acts as a half wave diode rectifier. The operating mode of the semiconverter depends only on the firing control of the upper bridge. Before the delay angle reaches $\pi/3$ radians, the converter is in six-pulse mode. After the delay angle reaches and exceeds π/3 radians, the converter starts and stays in the three-pulse mode.

The transition from six-pulse operation to three-pulse operation is gradually completed as a firing angle increases from 0 to 60 degrees. The waveforms of the dc output voltage with firing angles of 0, 30, and 60 degrees are presented in Figure 4, Figure 5, and Figure 6 respectively to illustrate this transition.

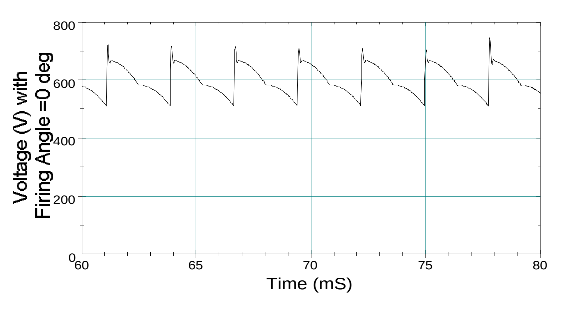


*Figure 4 **-**Firing Angle = 0 Deg.*

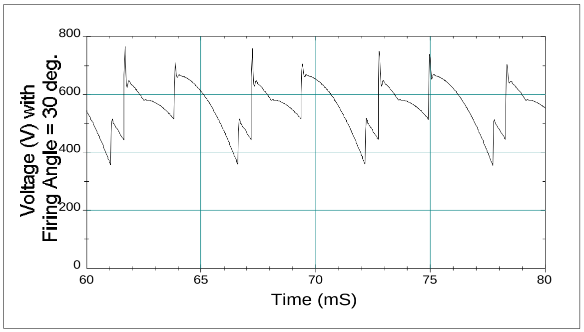


Figure 5 -Firing Angle = 30 Deg.

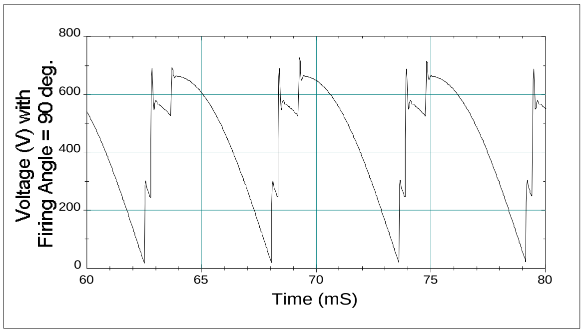


Figure 6 - Firing Angle = 60 Deg.

The formation of a dc output voltage wave shape can be better explained with the help of the graphic illustration of Figure 7.

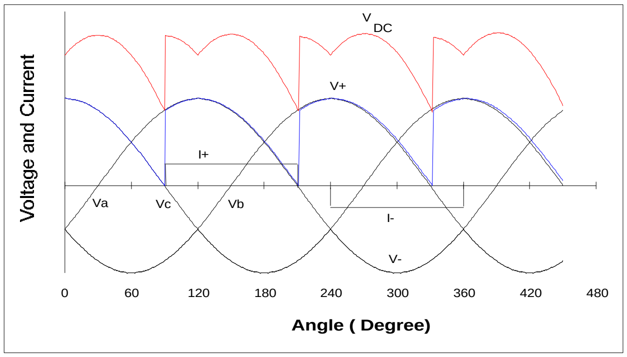


Figure 7 -Formation of DC Output Voltage of Semiconverter.

In Figure 7, three line-to-neutral voltages are shown. Because there is no control over the firing angle on the lower bridge of the converter, the potential on the common anode of the diodes (negative dc pole V-) always follows the bottom envelope of the line-to-neutral voltages. For the upper bridge, the potential of the common cathode of the thyristors (positive dc pole V+) is controlled with the firing angle.

Theoretically, the thyristors can be fired at any delay angle α between 0 and 180 degrees. Namely, for the thyristor T1 of phase-a, the conduction can occur any time between the commutation point of T3 and T1 (positive Vc and Va intersection) and the commutation point of D1 and D2 (negative Vc and Va intersection). As T1 conducts, the potential of the positive dc pole is the same as the potential of the transformer terminal of phase-a. The output voltage of the converter (Vdc) is the difference between the top envelope, consisting of the segments of the phase-to-neutral voltages corresponding to the conduction period of each phase thyristor, and the bottom envelope of the line-to-neutral voltages. Figure 7 illustrates the formation of the dc output voltage waveform and the ac line current waveform with a 30 degree firing angle. The difference noticed between this dc voltage waveform and that given in Figure 5 is due to the inclusion of practical considerations in the simulation. For a balanced three-phase system, the maximum conduction period of each thyristor is 120 degrees.

Note that if a firing angle is less than 60 degrees or if the converter operates in the six-pulse mode, the output voltage is continuous. The thyristor or diode of each phase conducts for a fixed period of 120 degrees. Therefore, the output current is continuous and the freewheeling diode connected across the dc positive and negative buses carries no current and plays no role in the circuit operation.

The phase-a input current waveforms of the converter for firing angles of 0, 30, and 60 degree are given in Figure 8. In order to illustrate where the current starts and ends with respect to the phase voltage, the phase-a line-to-neutral voltage waveform is plotted. This voltage waveform corresponds to a converter firing at 60 degrees.

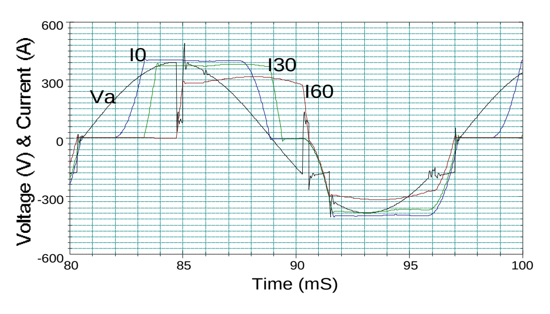


Figure 8 - Waveforms of Phase A Current with a=0, 30, And 60 and Phase A Voltage with a=60

Figure 8 illustrates that when the converter firing angle increases from 0 to 60 degrees, not only is there a reduction in the current magnitude, but the starting and ending points of the positive conduction period are delayed. Conversely, the starting and ending points of the negative conduction period remain unchanged.

When the firing delay increases beyond 60 degrees, the converter operates in the three-pulse mode and the output voltage becomes discontinuous. Figure 9 shows the output voltage waveforms of the semiconverter for firing angles of 90, 120, and 150 degrees respectively.

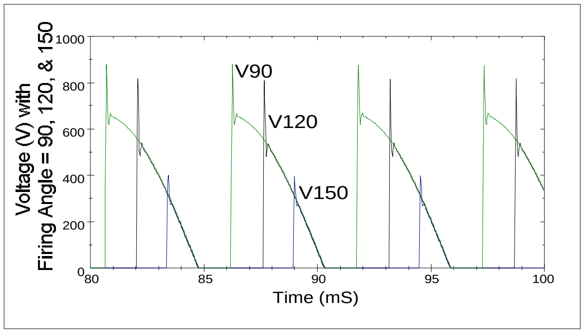


Figure 9 - Waveforms of Output Voltage With Firing Angle = 90, 120, and 150 degrees.

In fact, when the delay angle becomes greater than 90 degrees, the phase-controlled upper bridge half-wave converter starts to act like an inverter. In other words, its contribution to the output voltage becomes negative. With the ideal voltage waveforms shown in Figure 7 and considering the semiconverter as the series connection of an uncontrolled half wave rectifier with a phase controlled half wave converter, the average dc output voltage can be expressed as the summation of two parts [2].

$$V_d = \frac{3\sqrt{6}}{2p} V_f (1 + \cos \boldsymbol{a}) \qquad (1)$$

Where the constant term is the contribution of the uncontrolled half-wave rectifier and the α dependent term is the contribution of the phase-controlled half-wave converter. As shown by Figure 4, Figure 5, Figure 6, and Figure 9 and as indicated by Equation 1, when the firing angle increases from 0 to 180 degrees, the average output voltage decreases from the maximum to zero. The spikes appearing at the front edges of the voltage pulses (Figure 9) reflect transients caused by simulated power electronic switching. This type of overshooting can be controlled by adjusting parameters of the snubber circuit.

A distinctive characteristic of three-pulse operation is the ending points of the phase conduction on both positive and on negative current flowing directions are fixed. As a result, a further firing delay beyond 60 degrees makes the thyristor and diode of each phase carry current for a period of less than 120 degrees. The current waveforms resulting from 90, 120, and 150 degree firing angles are shown in Figure 10.

To supply an inductive load, the freewheeling diode is used to provide a path for the load current. Otherwise, the thyristors will fail to stop conduction at the specified times.

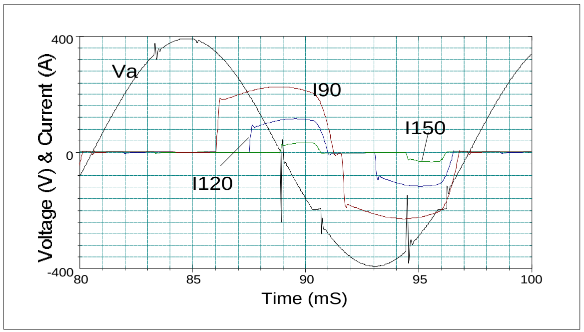


Figure 10 -Waveforms of Input Currents with a= 90, 120, 150 Deg. and of Input Voltage with a=150 Deg.

Figure 11 illustrates the relationship between the semiconverter input current (Ia), the load current (Idc), and the current flowing through the freewheeling diode (Id) with a firing angle of 90 degrees.

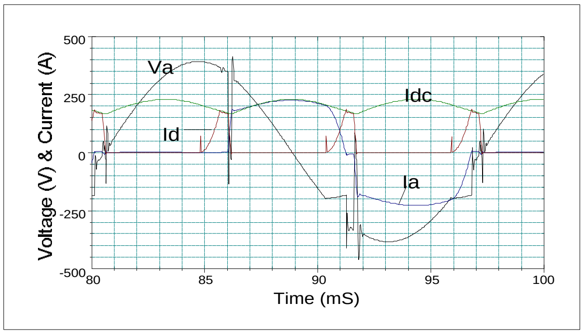


Figure 11 - Phase A Voltage, Input Current, Output Current And Freewheeling Diode Current.

Harmonic Characteristics

Regardless of the firing angle, it is clear that the mechanism of the semiconverter operation does create an asymmetry of the line current. This means that the semiconverter does not generate a dc component of the input current. However, as being illustrated, for any non-zero firing delay, the line current waveform is asymmetrical with respect to the voltage zero crossing of the phase voltage. The degree of the asymmetry changes with the firing angle. Although the balance of three phases still prevents generation of any triplen harmonics, this asymmetry does create a series of even harmonics. The current waveforms for a firing angle smaller than and equal to 60 degrees and the waveforms for a firing angle greater than 60 degrees can be classified into two basic patterns as previously shown in Figure 8 and Figure 10 respectively. If the current waveforms are idealized, the pattern shown in Figure 8 should consist of the 120 degree movable positive current pulse and the 120 degree standstill negative current pulse. The pattern shown in Figure 10 has the pulse width of both the positive and negative pulses, varied with the firing angle. But the conduction pulses of either polarity end at the natural commutation points. Although these two described conduction patterns are different, it was found that the Fourier expansions for these two current patterns have the same sets of Fourier coefficients. Therefore, the input line current can be written as:

$$i(t) = \sum_{1}^{\infty} a_n \cos nwt + \sum_{1}^{\infty} b_n \sin nwt\,, \qquad (2)$$

where:

$$a_n = \frac{1}{p} \int_{0}^{2p} I_{dc} \cos(nwt)\, d(wt)$$

$$b_n = \frac{1}{p}\int_0^{2p} I_{dc}\sin(nwt)d(wt)$$

for n=1, 2, 3, ...

Derived from these integrals, the coefficients for the current Fourier expansion obtained are:

$$a_{n=2m} = \frac{2I_{dc}}{np}\sin(n\frac{p}{6})(1-\cos na) \qquad (3)$$

$$b_{n=2m} = \frac{-2I_{dc}}{np}\sin(n\frac{p}{6})\sin(na) \qquad (4)$$

for n = 2, 4, 6, ...

$$a_{n=2m+1} = \frac{-2I_{dc}}{np}\cos(n\frac{p}{6})\sin(na) \qquad (5)$$

$$b_{n=2m+1} = \frac{2I_{dc}}{np}\cos(n\frac{p}{6})[1+\cos(na)] \qquad (6)$$

for n = 1, 3, 5, ...

These Fourier coefficients indicate that the semiconverter does not generate any triplen harmonic as long as a balanced three-phase system is maintained. However, the even harmonic generation is an inherent characteristic of the semiconverter.

Equation 2 and Equation 4 can be combined to obtain the magnitude of an even harmonic, as shown in Equation 7.

$$\begin{aligned}\left|C_{n=2m}\right| &= \sqrt{a_n^2+b_n^2} \\ &= \frac{2\sqrt{2}I_{dc}}{np}\sin(n\frac{p}{6})\sqrt{1-\cos(na)}\end{aligned} \qquad (7)$$

for n = 2, 4, 6, ...

This expression reveals that the even harmonic current components reach their maximum when nα = 180 degrees. Therefore, the peak of the 2nd is expected at 90 degrees and the two peaks of the 4th harmonic are expected at 45 and 135 degrees, respectively, with maximum magnitudes of approximately 55% and 28% of the dc load current I_{dc}.

In order to provide a more vivid illustration of the harmonic variation with firing angle, an EMTP model of the circuit shown in Figure 1 was developed. The firing angle of the semiconverter was increased linearly from 0 to 165 degrees. The resultant line current waveforms on the transformer secondary are presented in Figure 12.

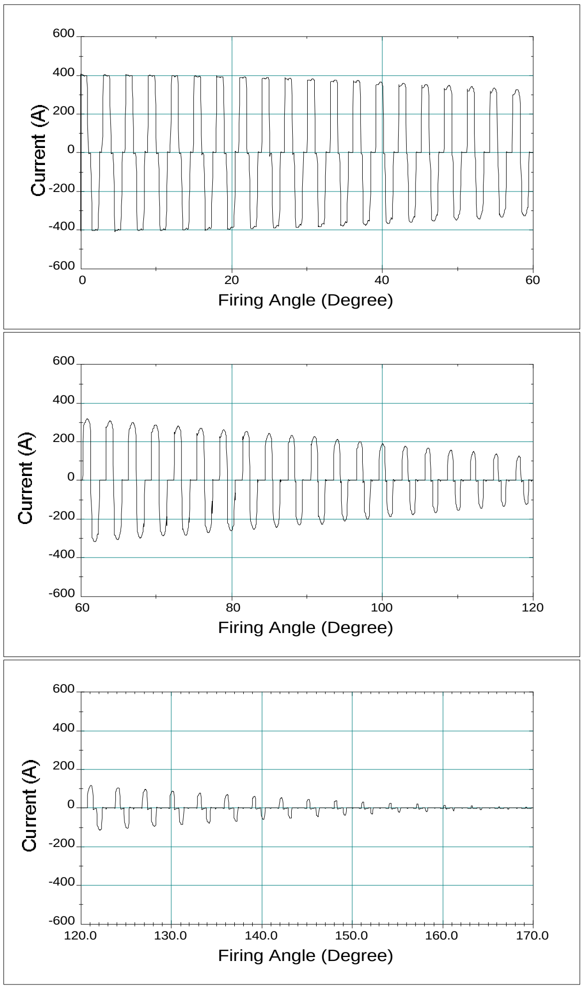


Figure 12 - Line Current Waveform of Wye-Winding Side.

In Figure 12, the horizontal axis marks the value of the firing angle in degrees. To emphasize the dramatic change in the magnitude of the current with the change in firing angle, the magnitude scales of the current plots were kept constant.

The line current appearing on the primary of the delta-connected transformer is simply the resultant value produced by the subtraction of the two corresponding line currents of the secondary of the transformer. The primary current shows double humps on the positive half cycle and a single hump on the negative half-cycle. The magnitude of the peak on the negative half-cycle is twice that of the positive half-cycle. The changing waveform of this current with the changing firing angle is illustrated in Figure 13. Although the primary current waveform appears to have a greater asymmetry than that of the secondary current waveform, even harmonic content of the primary current is the same as that of the secondary current.

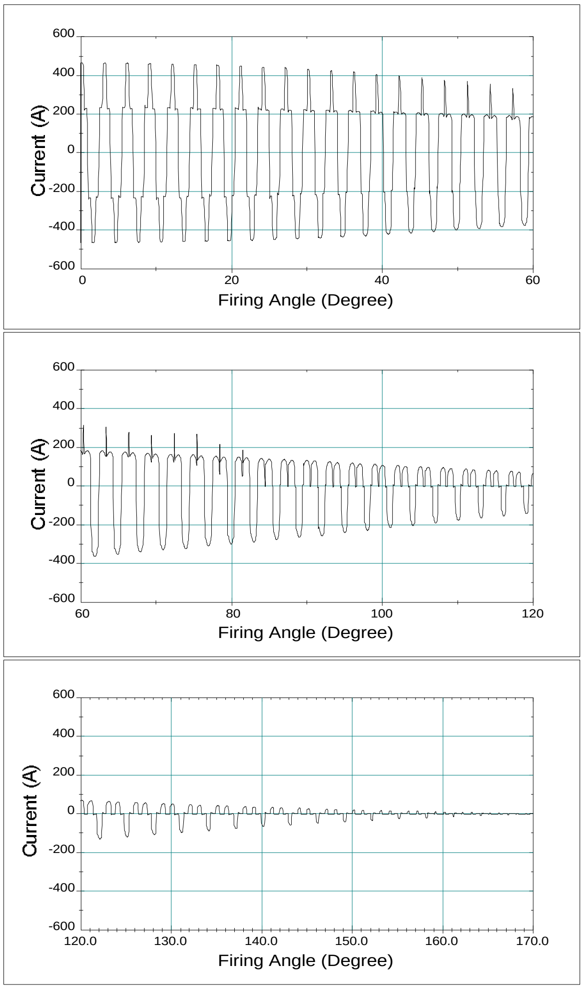


Figure 13 - Line Current Waveform of Delta-Winding Side

The curves given in Figure 14 illustrate the trends of the fundamental (I1), the 2nd harmonic (I2), and the 4th harmonic (I4) currents throughout the full range of the firing angle. The firing angle is also displayed for reference

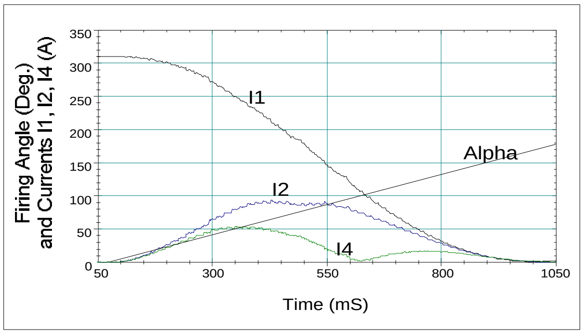


Figure 14 - Fundamental and Even Harmonics and Firing Angle.

Due to the source impedance and a finite load inductance, the practical commutation has made the simulated current pulses different from perfect square waves, which were assumed for simplifying theoretical derivations. As a consequence, the harmonic peaks obtained from the simulations were shifted from the times determined according to Equation 7.

Figure 15 illustrates the changes of the 5th and the 7th harmonics with the change of the firing angle. Comparing Figure 14 with Figure 15, it is realized that in a practical operating range of the firing angle, the magnitude of the 2nd harmonic is about two to three times the magnitude of the 5th harmonic. The harmonics of most concern for a semiconverter are the lower order even harmonics.

As previously mentioned, for an inductive load, the freewheeling diode carries current during an interval in which the out-going thyristor has stopped conducting and the in-coming thyristor has not been fired.

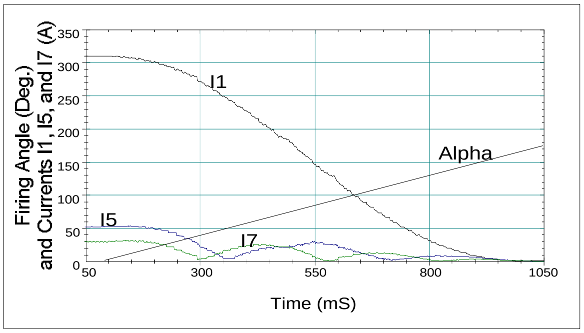


Figure 15 - Firing Angle and Fundamental, 5th, and 7th Harmonics of Semiconverter Current.

The freewheeling diode current and the load current for a firing angle between 60 and 170 degrees are plotted in Figures 16a and 16b. The freewheeling diode conduction interval increases with the firing angle. The magnitude of the current reaches a peak around 90 degrees. If the freewheeling diode is not connected, the load current will force the out-going thyristor to maintain conduction until the in-coming thyristor is fired. This results in a lower power factor.

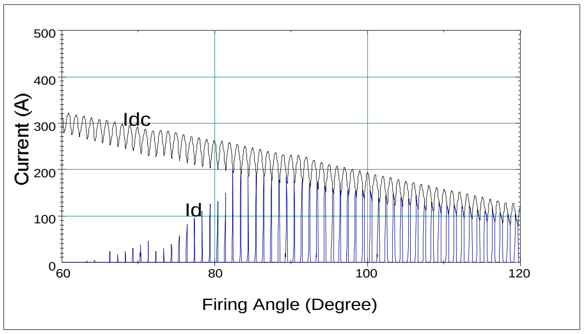


Figure 16a - Current through Freewheeling Diode

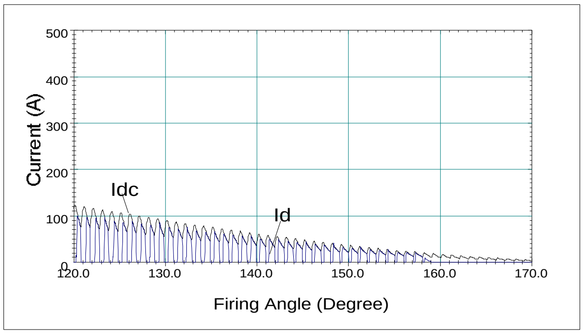


Figure 16b - Current through Freewheeling Diode.

Harmonic Reduction & P.F. Correction

Although a power factor problem associated with the semiconverter application has not been discussed in detail in this paper, it can be logically deducted that the power factor associated with the application is a function of the firing angle and tends to decrease when the firing angle increases. The statement is supported by the fact that the line current is getting out of phase with respect to the voltage as the firing angle increases.

A perspective approach which can benefit both the power factor correction and the harmonic reduction is to install a capacitor bank as a tuned filter at the converter input terminals. Usually, filter installations for each and every significant harmonic components are not practical. Therefore, the recommended practice is to install a single second harmonic filter with a relatively large capacity.

An EMTP simulation has been conducted to investigate the effectiveness of the proposed solution. For the converter with a dc output rating of 260 kW, a three-phase filter of 250 kVAr is connected on the transformer secondary. The waveforms of the phase voltage and the input current of the transformer primary obtained from the simulation with the worst firing angle of 90 degrees are presented in Figure 17.

To illustrate the improved power factor, the current waveform without the filter has also been given in Figure 17. It is clear that the capacitor compensation has made the line current change from significantly lagging to leading. This is because the actual kVAr provided by the filter at 60Hz is much greater than 250 KVAr. The harmonic filtering effects are illustrated in the chart given in Figure 18. After the 2nd harmonic filter was connected, the fundamental component of the current increased by approximately 85% and the magnitude of the second harmonic was reduced to the 18% of its original value. The magnitudes of the 4th and 5th harmonics were slightly reduced. As a consequence, the Total Harmonic Distortion (THD) of the line current was reduced from 70.6% to 13.7%.

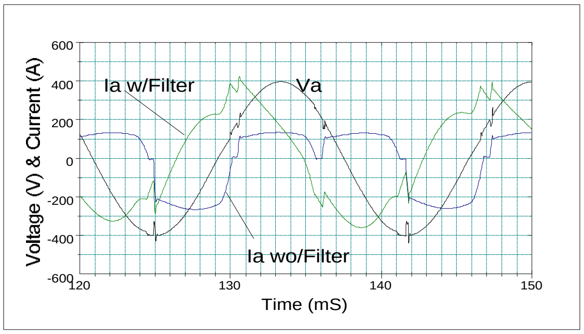


Figure 17 - Phase Voltage and Current Waveforms With and without Filter.

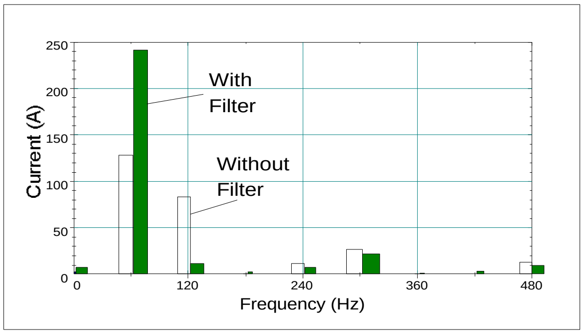


Figure 18 - Comparison between Current Spectrums Obtained With and Without 2nd Harmonic Filter.

Conclusions

A semiconverter has two operating modes, six-pulse operation and three-pulse operation. As the firing angle increases from 0 to 60 degrees, the converter changes from the six-pulse operation to the three-pulse operation. With a further increased firing angle beyond 60 degrees, the converter remains in three-phase mode of operation with the increased input current and output voltage discontinuity.

Even harmonic generation is the inherent characteristic of the semiconverter. The worst even harmonic peak occurs when the firing angle is around 90 degrees.

The power factor of the semiconverter varies with the firing angle. In a range of practical firing delay, the power factor is poor and decreases as the firing angle increases.

A capacitor bank tuned as a second harmonic filter can effectively reduce even harmonics and it can greatly improve the power factor of the system. However, a second harmonic filter is quite expensive due to the capacitor derating required.

References

[1] Ned Mohan et al., Power Electronics: Converters, Applications, and Design. John Wiley & Sons, Inc. 1989, pp. 41-62.
[2] JMD Murphy & FG Turnbull, Power Electronic Control of AC Motors, Pergamon Press, 1988, pp. 73-90.
[3] Muhammad H. Rashid, Power Electronics: Circuits, Devices, and Applications, Prentice-Hall, Inc., 1988, pp. 77-100.