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Characteristic and Non-Characteristic Harmonics, Harmonic Cancellations and Relevant International Standards in Variable Speed Drives

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التوافقيات المميزة وغير المميزة ، الغاءات التوافقيات والمقياس الدولية المستخدمة في المحركات ذات السرعات المتغيرة

سيد اسلام

خلاصة : تقدم هذه الورقة مراجعة للتوافقيات في المقوم الموجي ذي الوجه الواحد وذي الثلاث اوجه ، وتناقش نتائج البحوث الحديثة في التعرف على مصادر التوافقيات وتضخيمها. وتعرض الورقة المقاييس الدولية المستخدمة في دراسة التوافقيات IEC61000-IEEE519-AS-2279 . أخيرا تعرض الورقة الطرق المستخدمة في التقليل من التوافقيات.

ABSTRACT: This paper will present a review of characteristic harmonics in both single phase and three phase drive front end rectifiers, discuss recent research findings in identifying sources and production of non-characteristic harmonics and amplification of harmonic levels when the front end rectifiers are fed from non-ideal supply conditions. Significant amount of triplens may be generated due to unbalances in utility supply voltage wave form and anticipated harmonic levels may vary widely. The paper will also discuss international harmonic standards such as the AS 2279, IEEE 519, and IEC 61000 series applicable to rectifier loads. Finally, the paper will present techniques to reduce harmonic levels by mixing of single phase and three phase non-linear loads resulting from mutual cancellations.

KEYWORDS: Harmonics, THD, 3rd harmonic, Triplen Harmonic, Supply Imbalance, Voltage Distortion, Non-Characteristic Harmonics, Harmonic Standards and Harmonic Cancellations.

1. Introduction

In variable speed drives (VSDs) both voltage and frequency conversions are necessary. VSDs typically converts in two stages: the front end rectifier stage and the inverter stage. The currents drawn from the supply by the VSDs are no longer sinusoidal and introduce harmonics. Proliferation of VSDs and other non-linear loads and resulting poor power quality is of prime concern to the supply network. Concerns and questions in the 90's regarding overloaded neutral conductors, overheating and failure of motors and transformers, frequent tripping of circuit breakers and capacitor failures, were often met with unacceptable answers and limited solutions. The IEEE 519-1992, AS 2279, and IEC 61000 series standards have been introduced to help combat the problem of poor power quality. Since this problem was an increasing one, it was assumed that newly introduced equipment was the likely cause.

The increased use of Variable Speed Drives (VSDs) in industry coupled with complaints about VSD shutdowns, together with the previous problems resulted in VSDs becoming one of the first targets as a cause of supply harmonic problems. It is easy to see why VSDs were blamed for harmonic problems, as they are normally high power devices, which inject high magnitudes of harmonic currents into the supply network. However we cannot disregard other low power devices such as computers and discharge lighting, as the large number of them can lead to a similar impact on the supply system. Any source of current harmonics can then cause an effect on other devices.

Due to the power quality problem, filters such as harmonic traps (Mark and David, 1999; Syed and Creg, 1995) are designed to reduce harmonic currents from VSDs and improve power quality. The design of such filters are based on the characteristic harmonic currents injected by VSDs (Gary and Wilson, 1998; Cyril, 1987; Mohan, 1995; Derek, 1996). These characteristic currents are usually generalised and based on an ideal supply. The effect of variation on harmonic currents could cause poor filter performance that may no longer meet standard specifications.

This paper explores the relationships between harmonic currents from VSDs and the associated supply. Characteristic harmonic currents of VSDs will be shown under perfect supply conditions, and then variations to the normal harmonic currents when the supply is non ideal will be developed with emphasis to the 3rd harmonic. Simulation and experimental results of these harmonic current variations will then be discussed along with the effects that can result from this distortion.

Harmonic currents from the single phase rectifiers and the three phase rectifiers may be anti-phasal and can cancel each other. This is an important phenomena and this paper addresses the issue.

The paper is set out in the following way: In section II of this paper, characteristic currents associated with VSDs that use 6-pulse rectifiers as the front end is given. Section III introduces the concept of how the triplen harmonics are produced; the effects of voltage reduction and voltage distortion are treated separately. In section IV, simulation results are presented showing the effect of voltage reduction on current distortion. Section V presents experimental results that verify the theoretical analysis. Section VI discusses the harmonic cancellation issues. Section VII presents some common harmonic standards applied to VSDs and other non-linear loads. Finally, some conclusions and recommendations resulting from this research are provided.

2. Characteristic Harmonic Currents Drawn by 6 Pulse Rectifiers

The complete 6-pulse rectifier circuit showing the DC link inductor used for most VSDs is shown in Figure 1. The current drawn from the source is given by

$$i_1(t) = \mathrm{I_{dc}} + \sum_{n=1,2......}^{\infty} (a_n Cos\ n\omega t + \mathrm{b_n\ Sin\ n}\omega \mathrm{t}) \tag{1}$$

The dc component is zero. The Fourier components a_n and b_n are given by

$$a_n = b_n = 0, \text{ for n} = 2,4,6....$$
$$\mathrm{a_n} = 0, \mathrm{b_n} = \frac{4I_a}{n\pi} Sin \frac{n\pi}{3} \text{ for } \mathrm{n} = 1,3,5...$$

The rms value of the ‘n’th harmonic component can be given by

$$I_n = \frac{1}{\sqrt{2}} (a^2{}_n + b^2{}_n)^{1/2} = \frac{2\sqrt{2}}{n\pi} I_a Sin \frac{n\pi}{3}$$

It is usually the case that the neutral of the supply is not connected to the rectifier and therefore the triplens are not present. Thus the first harmonic component present in the above analysis is the 5th harmonic current.

In general, characteristic harmonic currents drawn by a ‘p’ pulse rectifier are related to the pulse number. The following equation shows this relationship

$$h = p \times n \pm 1 \qquad (2)$$

where

h = the harmonic number, p = the pulse number of the rectifier and n = an integer having values of 1, 2, 3,…

This means that a 6-pulse rectifier at the front end of a VSD will typically have harmonic currents of the orders 5, 7, 11, 13, 17, 19, 23, 25, …etc. The magnitudes of the harmonic currents are theoretically the reciprocals of the harmonic sequence numbers as shown above. Thus 20% of 5th, 14% of 7th, 9% of 11th and so on. These theoretical harmonic current levels are based on a rectangular current wave of magnitude $\pm I_a$ or I_d, being drawn from the supply.

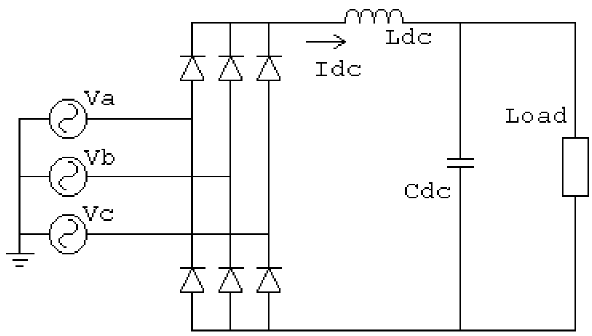


Figure 1. Complete circuit diagram of the 6-pulse rectifier.

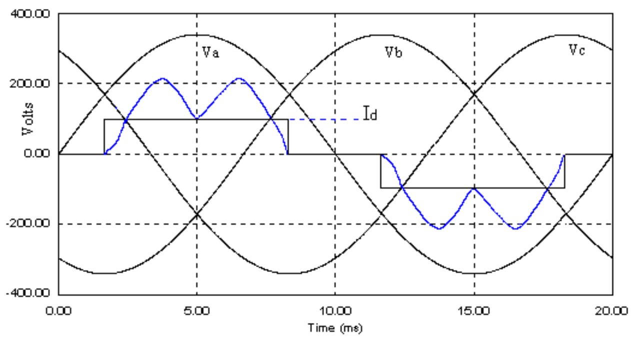


Figure 2. Theoretical representation of line current for an ideal 6-pulse rectifier.

The ideal rectangular current waveform is shown in Figure 2, the underlaying fact being that the current conducts between the cross over points of the phase voltages and is termed the conduction period. The Total Harmonic Current Distortion (THID) for this ideal current waveform is 29%. This distortion level is based on the fact that the supply voltage is ideal; that is the phase voltages are equal in magnitude and 120° out of phase with each other.

The case for a practical rectifier with a DC link inductor will have a current waveform shape characterised by two raised humps, also shown in Figure 2. The THID for a practical 6-pulse rectifier is 30% - 50% depending on the size of the source impedance and the DC link choke. The idealised rectangular wave is a useful approximation to give a good indication of how the conduction period will change with changes in the supply voltage waveforms.

3. Production of Non-Characteristic (triplen) Harmonic Currents

3.1 Effect of Voltage Reduction

The normal current conduction period for a 6-pulse rectifier is 120°; this angle is determined by the cross over of the phase voltages ie for the A-phase current, voltage V_c to V_a and then V_a to V_b. The cross over points are typically 30° and 150° for the A-phase voltage.

The production of triplen harmonics occurs when there is a difference in the conduction period from the nominal 120°. Changes in the current conduction period can occur for two reasons; 1) due to a voltage reduction of one or two phases, 2) line voltage distortion of the supply, such as a clipped waveform. Ali and Geza (1991) use voltage unbalance to show a production of 3rd harmonic current. This analysis deals with phase controlled rectifiers, where the conduction angle can be controlled, to maintain a 120° conduction period for each phase current to minimise the effect of voltage imbalance and the production of a 3rd harmonic current.

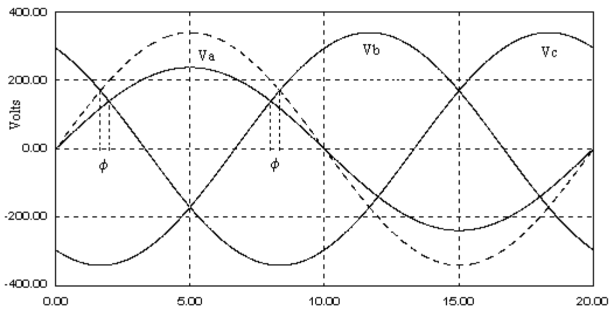


Figure 3. Effect of current conduction period with a change in voltage level.

Figure 3 shows that voltage V_a is reduced from the nominal value to a lower value. This results in a change of the conduction angle by 2 ϕ for the A-phase current. Using this result and Fourier analysis the amount of third harmonic current that will be produced from the A-phase voltage reduction can be found. The following Fourier transform is used taking into account quarter-wave symmetry.

$$I_h = \frac{4}{\pi} \cdot \int_{\frac{\pi}{6}+\phi}^{\pi/2} I_d \sin(h\omega t)\, d(\omega t) \tag{3}$$

where I_h = 'h' harmonic current magnitude, and I_d = Drive dc current level.

Solving this equation gives the result for the magnitudes of the line current harmonics of the rectifier. When expanded this gives the current spectrum of a 6-pulse rectifier.

$$I_h = \frac{4I_d}{h\pi} \cos\left[h\left(\frac{\pi}{6} + \phi \right) \right] \tag{4}$$

where h = 1, 3, 5, 7,..etc. In particular then the 3rd harmonic component is given by

$$I_3 = \frac{4I_d}{3\pi} \cos\left[3\left(\frac{\pi}{6} + \phi \right) \right] \tag{5}$$

From equation (3), when h = 3, 9, 15…etc and $\phi = 0$, the cosine value will be zero resulting in no triplen harmonic current. However when there is a change in the conduction angle ie ϕ is equal to some value other than zero, then the cosine value will no longer be equal to zero and triplen harmonic currents will be produced from the rectifier. The dominant component will be the 3rd as given by equation (5) but other odd order triplen harmonics, such as the 9th and 15th will be present but not as significant in magnitude as the third. These higher order triplens are divisible by 9 and 15, resulting in magnitudes that are 3 and 5 times smaller than the 3rd harmonic current.

What should also be noted from equation (4), is that for other values of h and for values of ϕ not equal to zero changes in the magnitudes of the characteristic harmonics will also occur. For an example of the 5th harmonic, if $\phi = 5°$ then the magnitude of the 5th harmonic will increase by almost 5%. This result has been determined using an ideal case for the current waveform. However the practical rectifier will give greater distortion levels due to the double hump waveform. Wilson and Randae, (1998) show a variation to harmonic currents under unbalanced supply conditions. Also discussed is an analysis to assess the harmonic propagation in each phase as harmonic currents change with voltage inbalance.

3.2 Effects of Supply Voltage Distortion

Effects of voltage distortions on the supply will have similar effects to that of voltage reduction. Again the current conduction period will change from the nominal 120°. The dominant harmonic voltages present on the supply are typically 3rd, 5th and 7th and the level of these harmonic voltages can be up to 4% of the fundamental value. These values have been taken from measured results in the laboratory. The total harmonic voltage distortion being approximately 3% but limited to 5% at the PCC by supply authorities for a commercial environment. Harmonic voltages can be attributed to existing harmonic producing sources such as computers, discharge lighting and VSDs.

Figure 4 shows the effect of a 5th harmonic A-phase voltage with a lagging phase angle of 100°. The 5th harmonic voltage periodically adds and subtracts to the fundamental voltage. This will then change the current conduction period, for this case, so that the start of conduction will be less than 30° and the end of conduction will be less 150°. This situation does not allow the previous Fourier transform, equation (3) to be used, as quarter wave symmetry has now been lost.

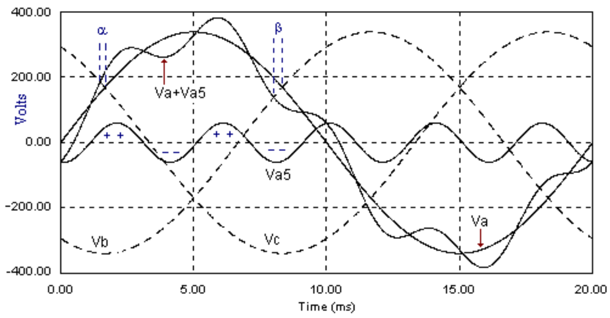


Figure 4. Effect of 5th harmonic voltage on rectifier current conduction angle. (note: scale for 5th harmonic current is greatly magnified).

This situation requires the Fourier transform with half wave symmetry. This is given in equation (5).

$$I_h = \frac{2}{\pi}\int_{\frac{\pi}{6}-\alpha}^{\frac{5\pi}{6}-\beta} I \sin(h\omega t)\, d(\omega t) \tag{6}$$

Solving this gives the following result.

$$I_h = \frac{-4I}{h\pi}\sin\left(\frac{h}{2}(\pi-\alpha-\beta)\right)\sin\left[\frac{h}{2}\left(\beta-\alpha-\frac{2\pi}{3}\right)\right] \tag{7}$$

Again from equation (7) we can see that if α and β are non-zero and h = 3 then there will be a production of the third harmonic current. The values of α and β will not necessarily be the same, and both values will change with a change in phase angle of the harmonic voltage. Also the other triplen harmonics will be produced but at lesser magnitudes, and variations of the characteristic harmonic currents will also occur.

For different magnitudes and phase angles of harmonic voltages in the supply, it is clear that the analysis will change considerably. As the supply becomes more distorted, by voltage harmonics and/or reduction in phase voltage, a simple mathematical solution will not be obtained easily. The best method of determining the THID is with the use of a suitable software simulation program.

4. Calculation of Harmonics

The reason for performing a harmonic analysis in a system would be to determine if the non-linear load on the system meets the requirements of the local supply authority, which is typically based on IEEE519-1992. If a system did not meet the requirements then measures would need to be taken to reduce the harmonics, for example using harmonic trap filters. Typical methods used for finding the total harmonic voltage distortion (THVD) use ideal supply conditions. The effect of supply distortions, if not taken into account in the initial design, could result in poor performance.

4.1 Effect of Voltage Imbalance

PSpice simulation program has been used to determine 3rd harmonic current levels from a 6-pulse rectifier by reducing the A-phase voltage. The model is simulated using a circuit simulation program. The circuit used is the same as of that shown in Figure 1. The results of this are shown in Figure 5. Phase A voltage is only reduced up to 5% of its nominal value to coincide with the typical allowed value for volt drop in a system.

The results show a significant amount of 3rd harmonic current produced in the line current for a supply voltage imbalance. Initial values of 3rd harmonic current are at 2% for phase A and C and 1% for phase B. The currents then reached a value of 39 and 40% for phase A and C respectively and 23% for phase B. The initial levels of 3rd harmonic for 0% voltage reduction are due to calculation errors in the software as the tolerance has been reduced to speed up the simulation. The results also show that all three line currents are affected but not by the same amounts but by the decrease of only one of the phase voltages.

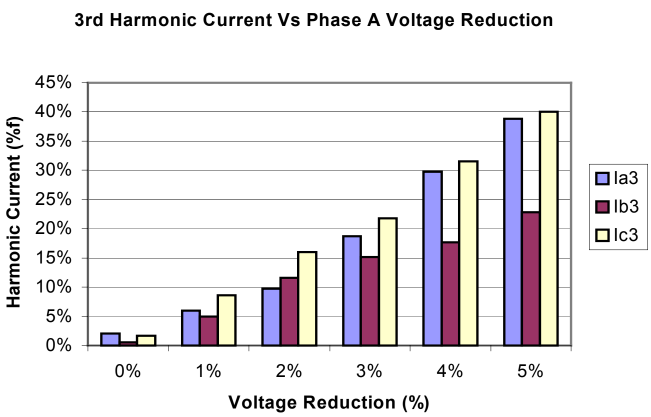


Figure 5. Effect on 3rd harmonic current with varying A-phase voltage.

The effect of the voltage reduction will also have an effect on the other current harmonics as outlined previously.The effect can be shown by examining the change in THID of each line current for a change in phase A voltage. These results are given below in Figure 6.

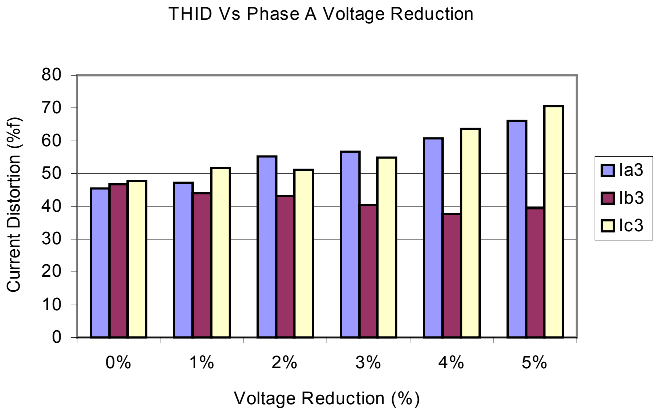


Figure 6. Effect on total harmonic current distortion with varying phase A voltage.

These results show that in fact there is an increase in THID for phase A and C current and a reduction of THID for phase B current. The increase of THID is not just associated with an increase in the 3rd harmonic current. Phase A and C THID have increased by 21 and 23%, respectively, which is quite significant as this could cause a reduction in performance of a trap filter designed to reduce the THID from a VSD.

4.2 Effect of Voltage Distortion.

Line voltage distortion due to harmonic voltages in the supply will cause similar effects to the conduction angle as with line voltage imbalance. Large variations of magnitudes and phase of harmonic voltages are possible and therefore a simple analogy is not feasible and a more realistic approach is to see the effect of "real world" voltage distortion on a VSD. To determine the distortion level of a supply it is then necessary to perform a harmonic analysis of the supply. This can be done easily with a harmonic analyser that allows for time recording. Measurements can then be taken over a period of time ie. hours or even days, which will then give an indication of the level of THVD.

5. Experimental Results

Laboratory tests have been performed to verify that the above theoretical results do occur in a real world situation. An ideal case will be looked at for comparison with the non-ideal case. To obtain an ideal voltage supply, a small synchronous alternator connected to a dc motor (prime mover) was used. This source is still not perfect in the sense that there was a small amount (1%) of 3rd harmonic voltage present at no-load, however at full load the effect was negligible. This test set up is shown in Figure 7.

The harmonic voltage supply or distorted supply is based on the laboratory power supply, which is fed from a main transformer that also feeds other buildings in the University. The transformer is fed from the local utility. The existing amount of voltage harmonics present on the distorted supply has been measured using a harmonic analyser. The level of harmonics that are on the supply would be attributed to discharge lighting, computer loads and any distortion already present on the high voltage side of the transformer.

The tests on both supplies have been performed using a 3kW VSD with a DC link reactor. The VSD has been run at the full load rating for all tests as the THID changes with variation of load and increasing with a decrease in load. The reactance of both supplies varies and this also changes the THID, which decreases with an increase in supply reactance. The measured results for the VSD harmonics for the ideal case are given in Table 1.

Table 1: VSD harmonic currents from ideal voltage source.

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	0.5	29.4	8.0	0.0	6.5	31.5

Figure 7. Experimental test set up.

These results clearly show that there are no triplen harmonic currents, the small percentage of 3rd harmonic current can be neglected, as this would be attributed to the small amount of 3rd harmonic voltage present at the alternator terminals. The 5th harmonic current is approximately 10% higher whereas the 7th and 11th harmonics are slightly lower than the ideal square wave spectrum. However the overall THID is in close agreement with the ideal case.

The laboratory power supply (distorted supply) was measured and the results of the harmonics present are given in Table 2. These results have not been averaged and represent one time instant of the supply voltage. Averaging of the harmonic voltages, magnitude and phase can in fact cause a reduction of the current harmonics, as cause-effects of the true values are not represented. The voltage supply contains the dominant harmonics and also a reduction of the phase A voltage.

The recorded results for the test performed using the distorted supply are given in Table 3. These results show that there is a large production of 3rd harmonic current and to a lesser extent the 9th harmonic in all 3 line currents. Results also show that the other characteristic harmonics have increased as well, resulting in the THID increasing between 23% and 35% from the ideal test result. This increase can also be attributed to the decrease in supply reactance on this supply compared with the synchronous alternator used for the ideal case. The ideal THID for this supply could be in the order of 40%. This, however, cannot be measured to verify the result and has only been simulated. This then represents an increase of THID between 8% to 20%, which is quite significant.

Table 2: Voltage supply harmonics.
(a) phase A, (b) phase B, (c) phase C.

H No.	1	3	5	7	THVD
Voltage	236.1	4.6	2	2.7	2.4%
% f	100.0	1.9	0.8	1.1	
Angle	0	145	152	-56	

(a)

H No.	1	3	5	7	THVD
Voltage	239.3	2.9	4	3	2.4%
% f	100.0	1.2	1.7	1.3	
Angle	0	151	-170	-56	

(b)

H No.	1	3	5	7	THVD
Voltage	239.1	3.5	2.2	2.8	2.1%
% f	100.0	1.5	0.9	1.2	
Angle	0	144	166	-54	

(c)

Table 3: Measured results for current harmonics using the distorted voltage supply. (a) phase A, (b) phase B, (c) phase C.

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	11.7	44.1	36.8	4.2	12.5	60.7

(a)

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	11.2	40.9	30.8	1.2	7.7	53.5

(b)

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	18.1	48.5	37.2	3.1	12.0	65.6

(c)

Figure 8 shows the measured current waveform under the distorted supply. It can be seen that the peaks are no longer the same height, and the conduction period has changed slightly during this time period.

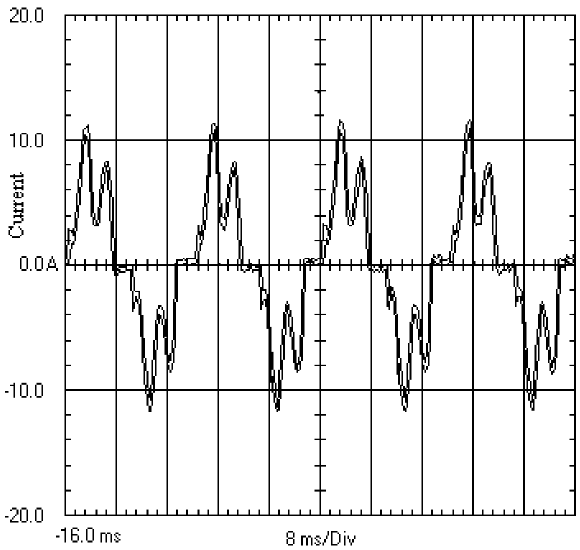


Figure 8. VSD line current fed from a distorted supply.

A simulation has been performed using a suitable VSD model (circuit model as in Figure 1) and the distorted supply to compare the results of the software program with the practical case. Microsim's PSpice circuit simulator has been used for the simulation.

The output results for the harmonic currents are given in Table 4. These results show that the THID is in close accord with the measured results for phases A and B, with the harmonic components within approximately 5% of the measured result. However the phase C result has a large error associated with it, and represents a reduction of 15% in THID and up to 15% error of the harmonic currents from the measured result.

These errors could be due to following reasons: 1. incorrect measurements were recorded, 2. a large change in the supply distortion occurred during the testing, and 3. inaccurate modelling/simulation of the practical VSD model. The main cause for the error would most likely be due to 2 as the test system is open, and outside influences cannot be monitored easily.

To further increase the accuracy of results between measured and simulated tests; a closed system would need to be used to ensure consistency of measured practical results so that the simulation model for the system can be accurately developed.

Table 4: Simulated results for current harmonics using the distorted voltage supply. (a) phase A, (b) phase B, (c) phase C.

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	13.8	49.2	31.5	3.5	9.3	61.6

(a)

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	6.2	41.1	32.7	3.7	8.0	54.8

(b)

H No.	**1**	**3**	**5**	**7**	**9**	**11**	**THID**
Current (%)	100.0	13.1	42.2	23.3	3.6	6.9	51.1

(c)

6. Harmonic Cancellation

Multi-pulse methods involve multiple converters so that the harmonics generated by one converter are cancelled by harmonics produced by other converters. If two six pulse converters are fed through two transformers of Δ-Y and Δ-Δ configurations, then the secondary voltage of the first one will have 30^0 phase shift compared to the second one. In this case, the 5^{th} and 7^{th} harmonic currents will be anti phase to each other and will cancel in the line current giving rise to 11^{th} and 13^{th} as the first pair of harmonics which have much less amplitudes and therefore much smaller filters will be required to clean the input current waveform should this be necessary. In general, then the required minimum phase shift is 60^0/number of converters for harmonic cancellations.

One method of harmonic cancellation is to mix single phase and three phase non-linear loads. It is seen that the 5^{th} and the 7^{th} harmonics produced by three phase loads and single phase loads are almost diametrically opposite in the phase plot. Since, harmonics are added vectorially not arithmetically, this leads to significant cancellations. Figure 9 shows the phase plot of the 5^{th} and 7^{th} harmonics for both single phase and three phase loads as a function of short circuit impedance.

The impedance of the secondary side of the distribution transformer plays an important role in determining the magnitude and phase of the predominant harmonics discussed above. The phase angle of the 5^{th} harmonic for typical single phase rectifier load lies in the sector of 45^0 to -65^0 and for three phase loads in the region of 110^0 to -135^0or $+215^0$ (Steffan, Peter and Blaabjerg, 2000). These two regions are almost opposite to each other resulting in cancellations. If the loads are completely balanced then exact cancellation may occur.

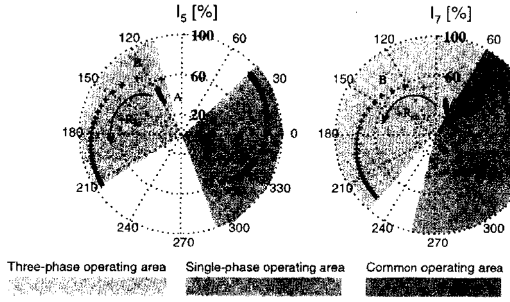
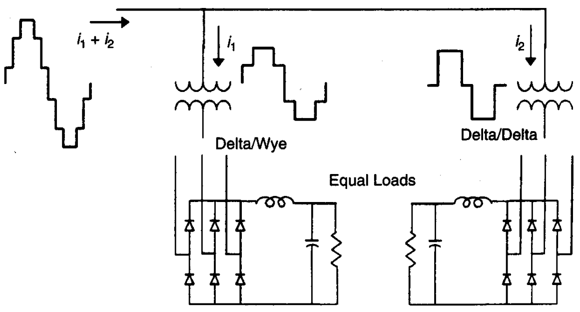


Figure 9. Polar plots for 5th and 7th harmonics for various short circuit ratios and argument of short circuit impedance equal to 80^0.

Another method of harmonic cancellation is to employ different transformer connections to supply the three phase converters as discussed above.



$$i_1(\omega t)\,\alpha\,\frac{2\sqrt{3}}{\pi}\left(\cos\omega t-\frac{\cos 5\omega t}{5}+\frac{\cos 7\omega t}{7}-\frac{\cos 11\omega t}{11}\cdots\right)$$

$$i_2(\omega t)\,\alpha\,\frac{2\sqrt{3}}{\pi}\left(\cos\omega t+\frac{\cos 5\omega t}{5}-\frac{\cos 7\omega t}{7}-\frac{\cos 11\omega t}{11}\cdots\right)$$

Figure 10. Two separate six pulse rectifier currents combine to a twelve pulse rectifier current.

Figure 10 shows two six pulse rectifiers one fed by a delta/star transformer and the other fed by a delta/delta winding transformer. In this case the secondary star winding voltage will be 30^0 phaseshifted from the secondary delta connected side. This will result in currents in the delta, star and input line as shown in Figure 10 (Derek, 1996).

The resulting line current clearly will have no 5th and 7th harmonic currents as shown (i_1+i_2) in Figure 10 and is similar to the current drawn by a twelve pulse converter. Thus the first harmonic component of the current will be 11th and then 13th of amplitude 1/11th I_{Fund} and 1/13th I_{Fund} respectively.

7. Harmonic Standards

Harmonics generated by non-linear loads such as the variable speed drives are regulated by various international standards. Harmonic limits are normally associated with background voltage distortions and varies from transmission to distribution systems and country to country. Figure 11 shows the allowable distribution voltage %THD for various countries.

In Australia, the harmonic standards are in three stages. In stage 1, automatic acceptance are given to non-linear single and three phase loads of less than 0.3% of short circuit capacity at Point of Common Coupling (PCC), between 5-75 kVA for secondary distribution systems and 50-500 kVA for primary distribution systems. In stage 2, loads greater than 75 kVA for secondary distribution systems and 500 kVA for primary distribution systems are considered. In this case, connection is permitted according to the relation between the converter rated power and the system short circuit level, provided that the distortion level is within 75% of the permitted limits shown in Table 5:

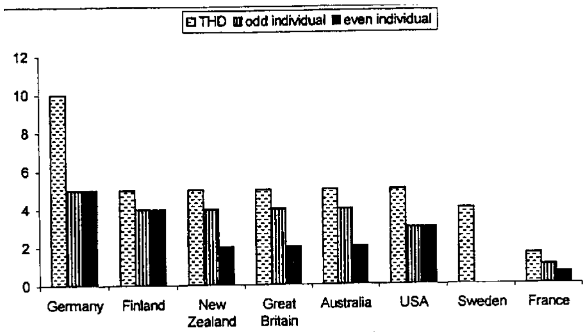


Figure 11. Comparison of national standards.

Stage 3 applies to all loads that do not meet above conditions that is, loads greater than given in Figure 12 and where voltage distortion is greater than 75% of Table 5. Stage 3 also requires detail analysis of the system and load according to a procedure described in the standard.

Harmonic distortion produced by the new load should be estimated before connection and should not exceed values given in Table 5. If more than one customer is supplied at PCC then the supply authority can limit distortion to an equitable value between them. Connection at transmission and sub-transmission level is also required to carry out detailed analysis including resonances.

Table 5: THD limits for equipment under stage 2, (AS2279).

	System Volts	%THD	Odd	Even
Primary and Secondary Distribution Systems	Up to 33 kV	5	4	2
Transmission And Sub-transmission	22, 33 and 66 kV	3	2	1
	>110 kV	1.5	1	0.5

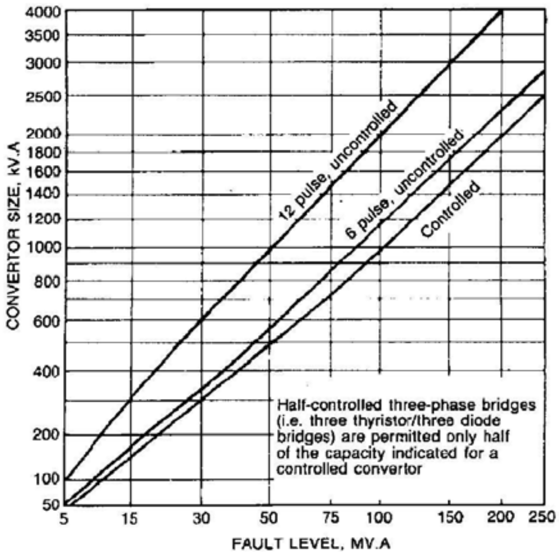


Figure 12. Equipment size in stage 3 (AS 2279).

The basic philosophy of the IEEE 519-1992 (currently under revision) is to limit:

- Harmonic current injected into the power system
- Utility responsible for maintaining voltage distortion

Current distortion limits are given in Table 6.

Table 6: IEEE 519 current limits.

SCR= I / I_1	<II	II<h<17	17<h<23	23<h<35	35<h	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The IEC 61000 series is an internationally accepted set of standards and comprise IEC 61000-3-2, 61000-3-4, 61000-3-6, 61000-3-3, and 61000-3-5. However, IEC 61000-3-4 is the most relevant one for industrial installations.

8. Conclusions

The increased use of 6-pulse VSDs will cause an increased level of harmonic currents in the supply network. These harmonic currents are characterised typically by the odd harmonics without the triplens. The analysis presented here has shown that these characteristic harmonics will vary and a production of the triplen harmonics will occur in the presence of an unbalanced or distorted voltage supply. The balance of harmonic currents will also be lost as shown from the results.

A detailed study of existing voltage levels and distortion on a system to where a VSD or VSDs are to be connected should be performed, as this will affect the current distortion from the VSDs. The impact of the analysis presented the following; the THID will be increased leading to a possible case where harmonic current levels may not meet IEEE519-1992; if harmonic trap filters are used to meet IEEE519-1992 they may not reduce harmonic levels adequately to meet the specification.

The paper also outlines the technique for minimisation of harmonic currents by mutual cancellation techniques. Finally, relevant standards are also included.

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