Unresolved Problems in Power Quality

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ABSTRACT

The Power Quality Centre at the University of Wollongong has been in operation since 1996 and has made progress in many areas of power quality, with power system harmonics being a major focus. The paper will discuss some important issues in harmonics still needing to be resolved, including (i) the economic case for harmonic control, (ii) the setting of appropriate voltage limits, (iii) measurement of time-varying harmonics, (iv) the modelling of distorting loads, (v) allocation of harmonic current and (vi) the identification of harmonic offenders. There is brief mention of other important power quality issues still needing to be addressed.

1. INTRODUCTION

There has been a concentration on power quality research at the University of Wollongong since 1996 when the Integral Energy Power Quality Centre was formed. While many advances have been made in this time, for example harmonic allocation in distribution systems and the measurement of the sag immunity of equipment, however many other problem issues have emerged. This paper will cover some of these with particular emphasis on power system harmonics, with brief mention of some other areas.

First there is a need to establish some basic PQ (Power Quality) concepts. There are several definitions of PQ. We have adopted “The study of the sources, effects and control of disturbances that propagate via the electricity power supply”. These disturbances range from low frequency (voltage sags and flicker) to harmonics and impulsive transients. They may originate from various sources, for example from an upstream transmission system, the local supply, atmospheric disturbances, car accidents, and neighbouring customers or within the affected plant. Their effect on equipment can be subtle (short term overheating) or significant (destruction).

PQ disturbances can be classified into two major types – Continuous (or Variations) and Discrete (or Events). This is an important distinction – the two types differ in their causes, variation throughout the power system, effects and the way they are monitored and reported. Variations are present in every cycle of the waveform and include long term voltage variation, unbalance, flicker and harmonics. Their cause is downstream customer current and their effect is usually thermal (flicker a notable exception). Events occur as separate, independent short term disturbances and include voltage sags, swells, oscillatory and impulsive transients. These disturbances are caused by particular upstream events such as lightning strikes or fallen branches. Their effect is usually immediate, involving maloperation, tripping out or destruction of equipment.

To ensure that customer's equipment will operate with a minimum level of problems, standards need to be enforced. Australia's standards are based on the IEC which treats PQ as an EMC (Electromagnetic compatibility) issue. The network is characterised by voltage emission levels. Customer's equipment is characterised by an immunity level, that is the highest level of the disturbance which will not cause problems. Standards endeavour to define the compatibility level which is the boundary separating the highest acceptable network emission (planning level) and the lowest acceptable immunity level.

2. WHY LIMIT HARMONICS?

Australian Regulators are increasingly specifying PQ objectives for distributors. Since the management of PQ involves the expense of manpower, monitoring and mitigation, it needs to be established that poor PQ leads to problems which have an unacceptable cost.

In Europe, harmonics are considered the worst PQ problem, being near the limits at many sites [1]. The proliferation of power electronic equipment is giving an increase in harmonic THD levels of about 1% per decade.

Harmonics do not lead to immediate equipment malfunction and their importance can easily be underestimated in comparison with more immediate disturbances such as sags. It requires a study of the cost to the community to justify the added costs that harmonic limits entail. This is very difficult to do in any rigorous way as several simplifying assumptions need to be made. The report states that the additional cost to the community in terms of losses, equipment loss of life and mitigation has been estimated to be of the order of 0.5-2% of GDP per annum for four separate studies in different European countries! Astounding as this figure is, there is still a good case for controlling the level of harmonics if it is in error by a factor of ten.

Let us investigate by an order-of-magnitude calculation whether such figures could apply to Australia, assuming the costs are all concerned with additional losses. We have made harmonic measurements over about 150 LV sites in all eastern states in Australia and find that harmonic levels are about 60% of those in Reference [1]. Making the assumption that losses vary as voltage squared (as stated in Reference [1]), and taking the lower figure for cost (0.5% GDP) gives 0.2% GDP for Australia. Assuming a GDP of $400,000M [2] gives an annual cost of harmonics as $800M. To get a feel for this figure, it can be converted into kW-hr (assume 10 cents/unit) giving 8×10^9 kW-hr, equivalent to a constant power loss of 900MW. Assume now a maximum demand of 40,000MW, and the cost of harmonic losses is roughly equivalent to continuous power loss of 2% of maximum demand!

Reference [1] states that the costs are made up of equipment loss of service life and mitigation measures as well as losses. It is significant that costs in the range 0.5-2% GDP was obtained by four independent paper studies. It would be interesting to develop a more sophisticated model and make a more complete study for Australia.

More generally, there is a need to establish what is the major disturbance type for Australia. Could it be harmonics, as in Europe, sags as in USA, or maybe some other? Following this, there is a need to develop cost-benefit models so that the benefits of mitigation can be assessed. It also needs to be established whether the mitigation strategy should be applied to the network (reducing voltage emission levels) or in improvements in the immunity levels of customer equipment.

3. HARMONIC PLANNING LEVELS

A utility's harmonic planning levels are the voltage limits which it sets on harmonics. Reference [3] describes them as internal quality objectives with the onus on the utility to determine them as appropriate and manage customer loads to ensure they are not exceeded. They must be less than compatibility levels given in the standard.

Indicative planning levels for MV, HV and EHV voltage levels from Reference [3] are reproduced in Table I. We shall concentrate for now on the MV values which are shown in Figure 1. There is a general trend of harmonic limits reducing with increasing frequency. The table makes it clear that the harmonic orders are classified into three groups (i) the 6k±1 three phase characteristic harmonics (coloured red), (ii) the triplen or odd multiples of three (green) and (iii) the even (blue).

Even harmonics cause the positive and negative voltage half-cycles to be different, and full-wave rectifiers will draw different positive and negative half-cycle current waveshapes. This can lead to a dc component drawn from the supply. DC components are very undesirable as they can demagnetise transformers leading to high currents and possible damage.

The triplen harmonics are high in the LV system but are usually greatly reduced in MV systems because of the lack of a neutral winding and the use of delta-star connected transformers. If they do occur in an MV system, they must be unbalanced and they can be a symptom of a large imbalance in load. This may be the rationalisation for their low value at high harmonics. It is difficult to understand what is special about the low frequency harmonics, less than 10, where they are allowed to be as large as the characteristic ones.

Table I: Indicative Planning Levels
(Table 2 of Reference [3])

Odd harmonics non multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Order h	Harmonic voltage %		Order h	Harmonic voltage %		Order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1.6	1.5
7	4	2	9	1.2	1	4	1	1
11	3	1.5	15	0.3	0.3	6	0.5	0.5
13	2.5	1.5	21	0.2	0.2	8	0.4	0.4
17	1.6	1	>21	0.2	0.2	10	0.4	0.4
19	1.2	1				12	0.2	0.2
23	1.2	0.7				>12	0.2	0.2
25	1.2	0.7						
>25	0.2 + $0.5\frac{25}{h}$	0.2 + $0.5\frac{25}{h}$						
NOTE – Total harmonic distortion (THD): 6.5% in MV networks; 3% in HV networks.								

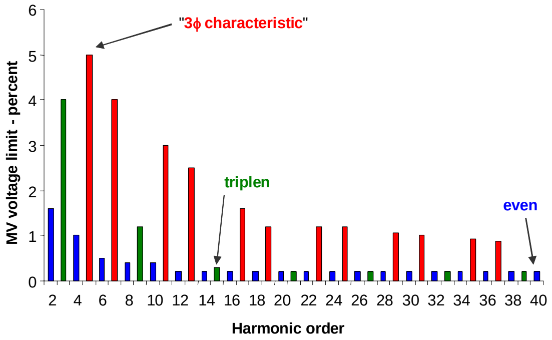

Figure 1: Spectrum of MV harmonic voltage limits

IEC standards evolve over many years, often being based on CIGRE or CIRED reports having little circulation. There is no obvious way of investigating the background of the present odd variation of planning levels with frequency. We shall attempt to determine the rationale for the characteristic ones since they are the largest harmonics appearing in a power system and are generated by most single and three phase loads. We shall investigate the limits falling with frequency for three types of loads - capacitors, induction motors and zero-crossover equipment affected by notching.

The main effect on capacitors is heating. To investigate this, we assume that the capacitor has an equivalent circuit as shown in Figure 2 including the equivalent series resistor R_{esr} representing capacitor losses. C and R_{esr} will be assumed to be constant. Let ω_o and h be the fundamental supply frequency and the harmonic order respectively.

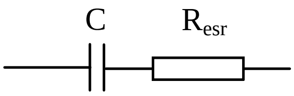

Figure 2: Capacitor equivalent circuit

The capacitor impedance is

$$Z_h \sim 1/hC\omega_o = X_{C1}/h \qquad (1)$$

The harmonic current is

$$I_h = V_h/Z_h \sim hV_h/X_{C1} \qquad (2)$$

The capacitor loss at the h^{th} harmonic is

$$P_h = I_h^2 R_{esr} \propto h^2 V_h^2 \qquad (3)$$

The total heating due to all harmonics is

$$P = \Sigma P_h = \Sigma h^2 V_h^2 \qquad (4)$$

This suggests that capacitors can be safeguarded if a limit is placed on the quantity $\Sigma h^2 V_h^2$. This is sometimes called the Weighted Total Harmonic Distortion (WTHD) because of its similarity with the THD. There are several possible forms for WTHD depending on the adopted weighting with harmonic order.

Eqn(3) shows that the higher harmonics have a more severe effect on capacitors. This appears to provide a possible rationale for the decrease of the harmonic limits with frequency. However, it is now generally considered that capacitors should not be directly connected to the power system - a reactor should be connected in series with it to limit charging current and to prevent resonance with the power system. It is strange to limit the harmonic voltage levels on a power system to safeguard installations which follow unwise practices. In any case, a single limit on WTHD should suffice rather than limits on individual harmonic components.

We now look to induction motors to see if they can provide a more convincing rationale for the features seen in Figure 1. The harmonic behaviour is reviewed in Reference [4]. The fundamental and harmonic equivalent circuits are shown in Figure 3.

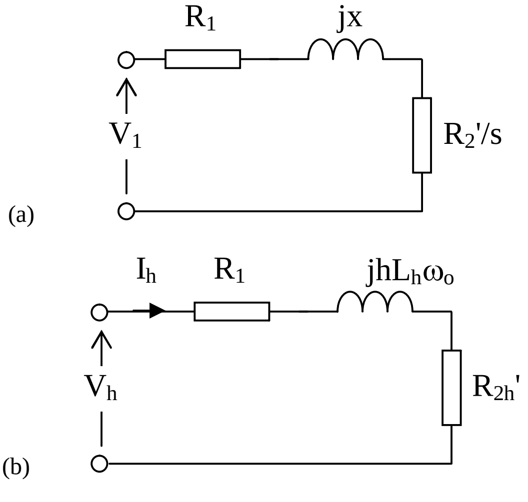

Figure 3: Induction motor equivalent circuits: (a) Fundamental, (b) Harmonic

The important resistive term is the rotor resistance with harmonic variation

$$R_{2h}' \propto h^{0.5} \qquad (5)$$

The motor inductance varies with frequency

$$L_h \propto h^{-0.35},\ X_h \propto hL_h = h^{0.65} \qquad (6)$$

Since the current is limited mainly by the harmonic reactance

$$I_h \sim V_h/X_h \propto V_h \times h^{-0.65} \qquad (7)$$

The loss at the h^{th} harmonic can be estimated from

$$P_h \propto I_h^2 R_{2h}' = V_h^2 h^{-1.3} h^{0.5} = V_h^2 h^{-0.8} \sim V_h^2/h \qquad (8)$$

The main harmonic effect is heating which can be expressed as

$$P = \Sigma P_h \propto \Sigma V_h^2/h \qquad (9)$$

This suggests that induction motors can be safeguarded if a limit is placed on a WTHD of the form $\Sigma V_h^2/h$. The equation shows that the lower harmonics have a more severe effect in this case. This is in contradiction to the variation of suggested planning levels.

Another possible explanation arises out of the impact of these limits on allowable notch depth and width. We note that notch depth is not covered explicitly in [3]; it was explicitly limited in the previous Australian standard AS 2279.2 [5] to 20% depth while notch area is limited in IEEE 519-1992 [6] to about 70 %-degrees.

To follow up this idea, a study has been made of the harmonic content of a notch with equal rise and fall time. It can be shown that, for a given harmonic content, the deepest notch is one having the form of Figure 4, with rise and fall time equal to its half-width.

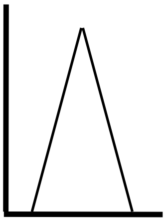

Figure 4: Notch giving greatest depth for given harmonic limits

Several notch widths were selected as shown in Table II (width given in degrees at 50Hz). For each width, the depth (in percent of nominal peak value) was increased until one of AS/NZS 61000.3.6 limits was exceeded. The depth and the corresponding limiting harmonic, together with the notch area, are also shown in the table. The depth is graphed in Figure 5.

Table II: Notch depth corresponding to harmonic limits for varying widths

width (deg)	depth (%)	limiting harmonic	Area (%-degrees)
0.1	450	49th	45
0.2	225	49th	45
0.5	91	49th	45.5
1	48	49th	48
2	29	49th	58
5	18	19th	90
10	22	19th	220
20	20	5th	400
40	25	5th	1000

For large widths, the low frequency harmonic limits of Table II restricts the notch depth to about 20% . For small widths, the high frequency harmonic limits

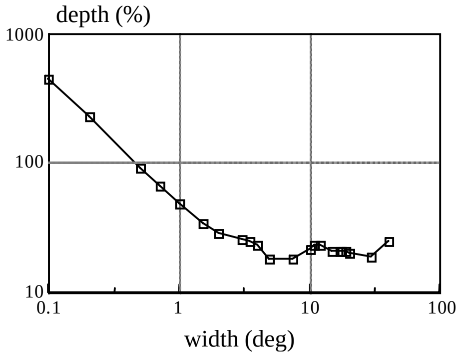

Figure 5: Notch depths from Table II

constrain the notch area to 45 %-degree. Could it be, then, that the variation of harmonic limits is solely oriented to an implicit limit on notching? If so, this would be an unsatisfactory situation. The equipment most commonly affected by notching is low power zero-crossover controlled light dimmers and digital clocks. It would be poor engineering to limit the harmonic emission of very high power equipment when it would be considerably less expensive to provide quality filtering at low power.

In summary, the rationale for decreased high frequency harmonics appears to come from the harmonic effects on capacitors and zero-crossover equipment. It can be argued that it would be cheaper for the community if this equipment had better immunity. A better argument could be based on induction motor heating. Effort is needed to identify the major harmonic problem in power systems and develop limits which are more appropriate.

4. HARMONICS AND INTERHARMONICS

In the steady state, there is a clear distinction between a harmonic and an interharmonic. With harmonics, each cycle is distorted equally. Interharmonics give a distortion which is different for adjacent cycles. If a waveform repeats over N cycles, it can be unambiguously resolved into harmonics of the supply frequency and interharmonics which are harmonics of the N-cycle frequency. For example, if a waveform repeats every 3 cycles, it can be resolved unambiguously into (i) harmonics of the supply frequency, (ii) interharmonics of one third of the supply frequency, namely

- the subharmonics of order 1/3, 2/3
- interharmonics 4/3, 5/3, 7/3,8/3 etc

The situation is different if the waveform never repeats. This can be interpreted in several ways

(i) the harmonics vary from cycle to cycle
(ii) there are interharmonics which are all multiples of an extremely low frequency
(iii) a mixture of time-varying harmonics and interharmonics

Without some additional information, it is not possible to separate the two types of distortion. This can be seen in the example of Figure 6 which repeats over two supply cycles

(i) the first made up of 100% fundamental
(ii) the second having 100% fundamental and 30% 3rd harmonic

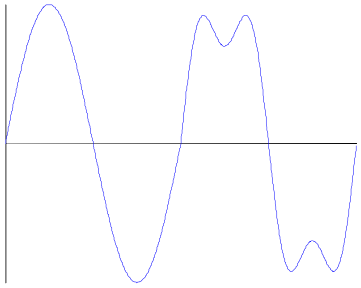

Figure 6: Waveform with 3rd harmonic in second cycle

The spectrum of each supply cycle is shown in Figure 7(a) and (b). This can be interpreted as a constant 100% fundamental component with a 3rd harmonic which increases from 0% to 30%.

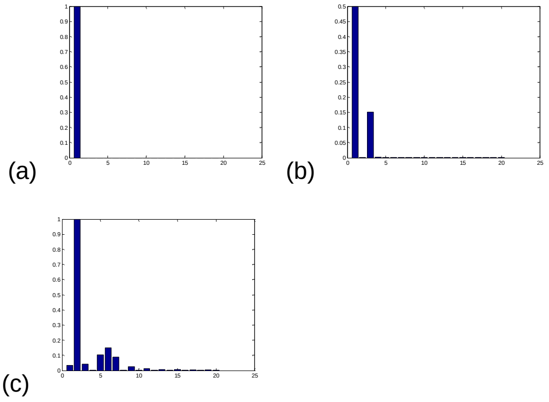

Figure 7: Spectrum of Figure 6 waveform:
(a) first cycle, (b) second cycle, (c) both cycles combined

Suppose the two cycles are subject to FFT analysis. This type of analysis can only find time-invariant components which have a fundamental frequency of half the supply frequency as shown in Figure 7(c) and summarised in Table III.

Table III: Alternative views of component frequencies for Figure 6 waveform

Harmonic of $f_s/2$	"Harmonic" of f_s	Magnitude (%)
1	0.5	3
2	1	100
3	1.5	4
4	2	0
5	2.5	10
6	3	15
7	3.5	9
8	4	0
9	4.5	3

The frequency is shown in the first column as a multiple of the two-cycle frequency, 25Hz. It is also shown in the second column as a multiple of the single-cycle frequency 50Hz. There are three types of entry

- The unshaded rows 2, 4, 6, 8 correspond to the fundamental and the 2nd, 3rd and 4th harmonics. It is noted that the even harmonics are zero. The 3rd harmonic has the value to be found from averaging over the first and second cycles

- The darker shaded row 1 is a subharmonic at 25Hz with a magnitude of 3%.

- The lightly shaded rows 3, 5, 7, 9 correspond to interharmonics of magnitude 3-10%

Note that the resolution of the interharmonic frequency is $0.5f_s$, corresponding to the 2 cycle window.

This raises the issue of what is a suitable Window width for measurement of time-varying harmonics. The use of a wider window would give harmonics which are constant over a longer time period and interharmonics having finer resolution. This shows that the distinction between time-varying harmonics and interharmonics is artificial. Since the limit on harmonics is well defined while that for interharmonics is poorly defined, Window width can be important in determining whether a site is acceptable or not. Without a standard definition of Window width, harmonic monitors may give different results under time-varying conditions although they might agree in the steady state. Figure 8 shows differences we have observed in measurements of the 19th harmonic with two different instruments [7].

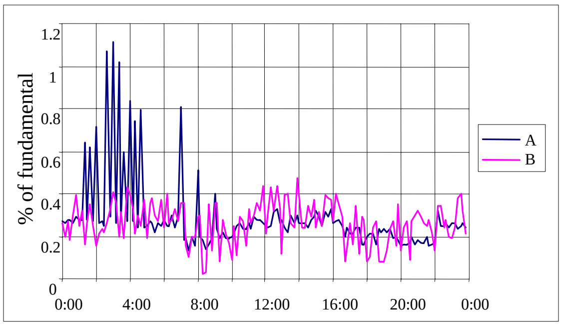

Figure 8: Comparison of time-varying harmonics measured with two different instruments [7]

Standards [8] specify a 10 cycle window. It is appropriate to ask if this should always be the case. For example, it might be possible to have *a priori* knowledge of interharmonic frequencies - eg cycloconverter with known operating details, in which case they can be extracted and the remaining components treated as time-varying harmonics. In most LV systems, it is difficult to see what would be a source of interharmonics, and a case could be made for one cycle windows, with some smoothing of the resulting spectrum.

5. MODELLING HARMONIC SOURCES

It is commonly stated in harmonic studies that pfc capacitors should not be directly connected to power systems because of the risk of a resonance with the power system at a harmonic frequency and the amplification of harmonic voltages above their normal levels. Recently, in order to confirm this, we analysed some harmonic measurement results for Integral Energy at their Greystanes zone substation where a 5MVAr bank was directly connected without detuning reactor [9]. Measurements were made of the 11kV voltage and the downstream current over a one hour period with the capacitor being switched in and out every 10 minute as shown in Figure 9.

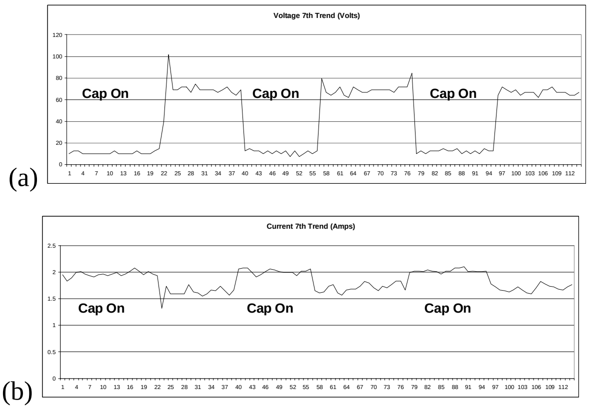

Figure 9: Waveforms of 7th harmonics during switching of pfc capacitor: (a) 11kV bus voltage, (b) feeder current

We shall concentrate discussion on the 7th harmonic. The results were surprising in two respects. Firstly the harmonic voltage fell rather than increased, and by a significant amount, 80%. Secondly, the combined feeder current increased by about 30%! This indicated that we had poor understanding of both how capacitors interact with the power system and the harmonic behaviour of loads.

Further study uncovered the behaviour of the capacitor. A mains signal blocking filter was connected in series with the capacitor. The filter consists of a parallel LC circuit tuned at the ripple control frequency of 1050Hz. At the 7th harmonic this behaves inductively and therefore partially fulfils the role of a detuning inductor. Calculation showed that this resonates with the pfc capacitor to give series resonance at very close to the 7th harmonic, explaining why the 7th harmonic voltage fell by such a dramatic amount. Explaining the increase in feeder currents requires a discussion of harmonic source modelling.

A couple of decades ago, one dominant harmonic source was the dc variable speed drive, having a thyristor rectifier as the power electronic front end. Filtering of the load current was by means of the dc motor inductance, possibly with series inductance for additional smoothing. The other dominant harmonic source was the aluminium smelter. It too had a significant series inductance on the dc side.

Both circuits behave similarly, with a line current having a quasi-square waveform. For three phase systems, the line current harmonics are those of the form 6k±1, with the h^{th} harmonic varying as 1/h. The important lower frequency harmonics were only slightly affected by the system impedance. Hence it was standard practice for many years in harmonic analysis to represent harmonic sources by ideal current sources with a spectrum following the 1/h relation.

There is a growing realisation that this representation is not relevant today. Modern harmonic sources are mainly electronic/digital devices at LV and ac variable speed drives at MV. The front end is a rectifier, with filtering on the dc side being by means of a shunt capacitor rather than a series inductor. This gives a more peaky type of current waveform such as shown in Figure 10 [10].

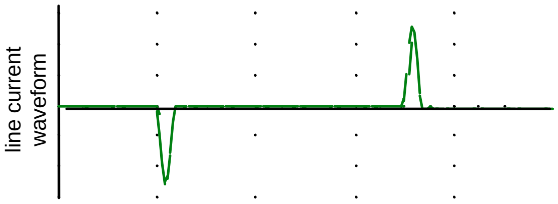

Figure 10: Capacitor-filtered rectifier line current waveform

The harmonics of this type of circuit were determined in Reference [9] from simulation and, unlike the inductor-filtered rectifier, were found to vary significantly with system impedance. One result is shown in Figure 11 for chosen values of SCR (short-circuit ratio) with the 1/h relationship shown for comparison. The harmonic magnitudes fall off more slowly for low values of h and more quickly for large values of h. These graphical relations can be well approximated by the expression

$$I_h(SCR) = \frac{1}{1+\left(\frac{h}{a\log SCR}\right)^b} \qquad (10)$$

where the best fit is achieved with a = 3 and b = 2.7.

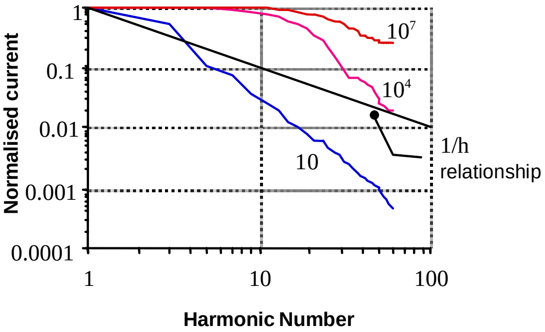

Figure 11: Variation of harmonic components with SCR [9]

We also note that the harmonic current decreases as the SCR decreases, that is as the system impedance increases. This suggests that the load behaves as a non-ideal current source, that is a Norton equivalent circuit such as shown in Figure 12. This is confirmed by the increase in harmonic current with decreased system impedance observed at Greystanes.

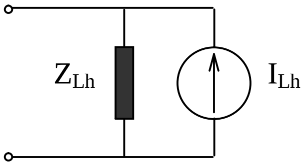

Figure 12: Norton equivalent circuit of common distorting loads

It is possible to estimate the value of Z_{Lh} from the results in Figure 10. For each value of SCR, I_7 is determined from eqn(10) above. The system impedance X_1 is also determined, from which X_7 can be found. Multiplying by I_7, the voltage V_7 across the load is then found. It is then necessary to make a least squares fit to find I_{L7} and Z_{L7}, assumed to be inductive for simplicity. This can be done using Solver in Excel. Results in per unit, based on the rectifier rating are $I_7 = 0.76$pu, $Z_{L7} = 0.09$pu. We note that I_7 is much higher than would be expected from the 1/h model of 0.14. The internal impedance of 0.09 corresponds to a fundamental SCR of about 100, meaning that the current is sensitive to system impedance for SCRs in the range of 10-1000.

Further work may give a load model giving a good quantitative explanation of the Graystanes measurements. This will involve a more rigorous approach to developing the load model and allowing for the feeder impedance also. It is clear that the 1/h ideal harmonic current source model is less useful in present day harmonic studies.

6. HARMONIC ALLOCATION - IMPACT OF DG

As stated earlier, harmonic THD is increasing about 1% every decade [1]. It is becoming more important for utilities to control the current allocation to MV customers to keep harmonic levels within acceptable limits.

Figure 13 shows a case study to illustrate the harmonic allocation problem. We shall make some substantial simplifications in order to highlight the main issues. A zone substation with capability S_t supplies loads connected directly to the MV busbar. We shall ignore the contribution of harmonics from upstream and the contribution from LV loads. It is required to find the harmonic current of order h to be allocated to load "i" having maximum demand S_i. Let the transformer impedance be x_t. The maximum harmonic voltage allowed at the MV bus is the planning level, assumed to be V_h.

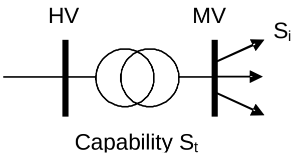

Figure 13: MV zone substation with particular installation "i"

The principles to be used in harmonic allocation are given in the Australian standard [3]. Each load is to be given a share of the harmonic voltage in proportion to its maximum demand. The allocation is to be made so that the MV busbar reaches the planning level value when all present and future loads take their full allocation. There is a method given to handle diversity, but this will be ignored.

The approach to determining the allocation to load S_i is to first allocate it a harmonic voltage at the MV bus proportional to its rating

$$V_{ih} = \left(\frac{S_i}{S_t}\right)V_h \qquad (11)$$

This is then converted into a current using the transformer impedance, assumed to be inductive

$$x_{th} = hx_t \tag{12}$$

$$I_{ih} = V_{ih}/x_{th} \tag{13}$$

Without consideration of DG (Distributed generation), S_t is known and the current allocation to load "i" can be determined without knowledge of future loading. The possibility of the connection of DG at the MV bus changes all of this.

(i) Although DG is a power source, it can be a distorting load at harmonic frequencies, and also deserves a share of the harmonic allocation. If the DG rating is S_{DG}, the voltage allowance for load "i"

$$V_{ih} = \left(\frac{S_i}{S_t + S_{DG}}\right)V_h \tag{14}$$

(ii) Secondly, the DG can have shunt impedance which reduces the harmonic impedance of the system.

$$x_{sh} = x_{th} \| x_{DGh} \tag{15}$$

where x_{sh} is the overall system impedance at the MV busbar

The effect described by eqn(14) reduces the current allocated to load "i" while that described by eqn(15) will increase the allocation, depending on the DG technology. Unfortunately, the technology and the rating of DG which might be connected to a particular bus is unknown. There is a need to move away from the principles of [3] to allow for this uncertainty. One possibility is to add some margin and then fine-tune allocations based on monitoring of existing harmonic levels.

7. IDENTIFICATION OF THE HARMONIC OFFENDER

When harmonic voltages are too high, there is a need to determine the customer or customers who are causing it. First it is important to have a harmonic allocation determined as discussed in the previous section. It might be thought that it is then only necessary to determine which customer is exceeding their current allocation. This argument is considered too simple-minded when a major customer has filters installed as will be explained using the equivalent circuit of Figure 14(a).

I_L is the harmonic current due to a particular customer and Z_f the impedance of filters connected at the plant to reduce harmonic current injected into the system. V_s represents the background harmonics due to other sources and Z_s the system impedance. It can be seen that harmonic current I will be measured flowing between the plant and the system even when the current source I_L is zero because the filters will absorb harmonic current from the system.

The system can be converted into the equivalent circuit of Figure 14(b) by current-to-voltage source conversion. Superposition can show that the current I has two components I_{sL} (left to right) due to the background harmonics and I_{Ls} (right to left) due to the customer's equipment.

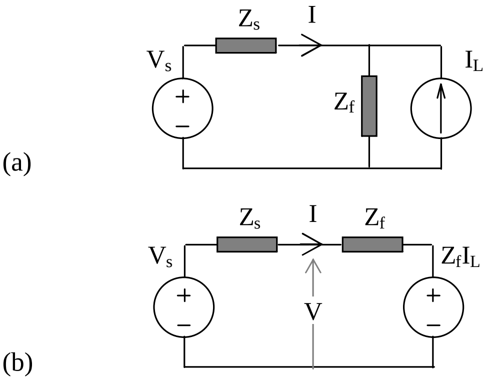

Figure 14: System and harmonic installation:
(a) Norton equivalent circuit,
(b) Thevenin equivalent circuit

$$I_{sL} = \frac{V_s}{Z_s + Z_f} \tag{16}$$

$$I_{Ls} = \frac{Z_f I_L}{Z_s + Z_f} \tag{17}$$

$$I = I_{sL} - I_{Ls} \tag{18}$$

Since other customer are causing the first component of current, it is considered by many experts that the allocated current is only the term I_{Ls}. This causes complications in identifying harmonic offenders since the allocated quantity cannot be directly measured but has to be inferred from measured quantities using mathematical models such as Figure 14(a) containing parameters about which there can be disagreements.

A technique which has been suggested for identifying the offender without this difficulty is to use harmonic power. The h^{th} harmonic power is defined for a voltage V_h and current I_h having relative phase angle ϕ_h as

$$P_h = V_h I_h \cos\phi_h \tag{19}$$

It needs to be emphasised that this power is a constant quantity in a balanced three phase system as with fundamental power. It is conserved separately at each frequency. A passive load can only absorb it, and the only sources can be generators or distorting loads.

Figure 15(a) shows a triac circuit feeding a resistive load and waveforms at $\alpha = 90°$. The sinusoidal source cannot generate or absorb power at any frequency other than the fundamental. The current waveform through the load is distorted and contains all odd harmonics, as does the voltage. The load must therefore absorb harmonic power at each odd harmonic, as well as at the fundamental. Since harmonic power is conserved, this must be generated by the triac. However, the triac cannot absorb net power, and so must absorb fundamental power to make up for the generated harmonic power. The power flow at the different frequencies is shown in Figure 16.

It might be expected that similar ideas held at the system level. In a system with one distorting load such as shown in Figure 17, harmonic power can only flow from the distorting to the linear loads. Some have extrapolated

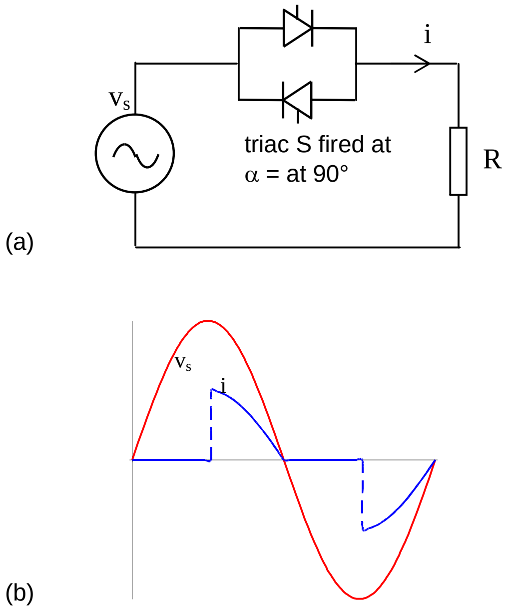

Figure 15: Triac circuit with resistive load:
(a) Circuit, (b) Waveforms

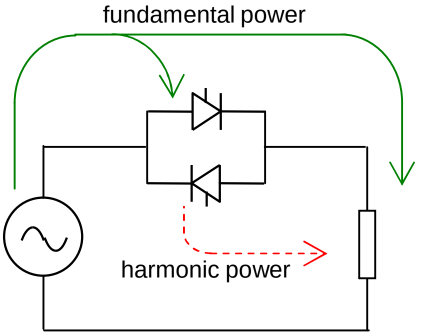

Figure 16: Flow of fundamental and harmonic power in triac circuit

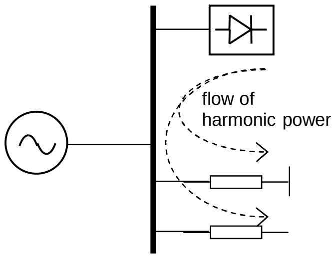

Figure 17: Harmonic power flow with one distorting load

from this that when there are many distorting loads, it will flow from the largest.

However, this intuitive argument is wrong. We have studied some situations in Reference [11] and shown that the flow of harmonic power depends on more than just the magnitude of the source. In any case, it is not the source with the largest magnitude which is the offender, but the one with the largest magnitude relative to its allocation that needs to be identified.

Another difficulty can be seen in relation to Figure 14(b). Suppose that, at a particular harmonic frequency, the system impedance Z_s is inductive and the filter impedance Z_f is resistive. Putting I_L to zero, we see that harmonic power can only flow into Z_f; Now putting V_s to zero, we see that no harmonic power due to the load can flow at the point of connection. In other words, there is no harmonic power at this pint due to the distorting load no matter how large it is.

There are regular publications on this topic. One recent suggestion is the use of harmonic reactive power rather than power as an identification tool [12].

8. OTHER ISSUES

This paper has concentrated on harmonic problems but there are other problems concerning some other aspects of power quality.

- Voltage in Australia is subject to absolute limits, unlike harmonics and flicker which have limits on the 95% cumulative probability levels. Also voltage has both an upper and lower acceptable range. These aspects make it difficult to develop simple voltage indices for sites allowing them to be ranked in a simple manner for mitigation work.
- When determining the distorting current allowance for large flicker loads such as arc furnaces, one needs to determine the effect at LV where affected incandescent lamps are to be connected. An assumption is normally made that the flicker will propagate downstream with little attenuation. It is now known that this is too pessimistic an assumption and it can lead to unnecessary mitigation expense. Work is needed to determine more realistic values for the flicker transfer coefficient and the factors which determine it [13].
- Sag durations in distribution systems are mainly determined by protection settings and are of the order of 0.5 sec [14]. However, IEC standards suggest much shorter times for equipment immunity tests [15]. There needs to be a standard which is more representative of what most LV equipment will have to face.
- Transients have a high frequency component and are not easy to measure. They are supposedly responsible for much equipment damage. There needs to be standards and practices developed to reduce unnecessary damage.

9. CONCLUSIONS

The paper has given a detailed discussion of harmonic power quality problems. Some unresolved issues include

(i) Establishing the true cost of poor harmonic levels
(ii) Developing a solid basis for power system harmonic limits and reviewing present values
(iii) Resolving limits on interharmonics in association with the development of measurement protocols
(iv) Determining improved models for distribution system harmonic loads able to be used for a wide range of system impedances such as when there are resonances
(v) Developing techniques for allowing for the uncertainties of DG on harmonic current allowances
(vi) Determining more convincing tests customers exceed their harmonic allowance.

The Eurelectric report indicates that poor power quality can be a high cost on the community. EPRI work on the effect of voltage sags has reached similar conclusions. There is still much interesting power quality research required to allow utilities to take up effective management of power quality issues.

10. ACKNOWLEDGMENTS

I thank my colleagues Dr Sarath Perera, Dr Vic Smith, Dr Duane Robson & Mr Sean Elphick of the Integral Energy Power Quality and Reliability Centre for their advice on this paper.

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