Harmonic Survey of an MV Distribution System

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Abstract

The harmonic survey of a medium voltage distribution system involves three major aspects: (i) the choice of harmonic monitor, (ii) the choice of monitoring site, (iii) processing and presentation of results. As well as a discussion of the methodology for these aspects, the paper will discuss the harmonic levels measured, the minimum survey requirements for finding useful data and the harmonic parameters of residential, commercial and industrial loads.

1. INTRODUCTION

The objective of the study described was to investigate present day harmonic voltage levels in medium voltage distribution systems and to try to separate the contributions from the three accepted customer types, ie residential, commercial and industrial. There were three major aspects to the work

1. Testing of & selection of a suitable harmonic monitor
2. Selection of test sites
3. Processing of results.

Australia and New Zealand are about to adopt a new harmonic standard [1] based on the international standard IEC 61000.3.6. An important concept in this standard, to be used in this paper, is the assessment of time-varying harmonics is the 95% cumulative probability level.

Shuter [2] reports on a survey of 4.16 to 34.5kV circuits of the American Electric Power System. Voltage THD ranged from 1% to just more than 5% and was dominated by the 5^{th} harmonic. It is interesting that the high harmonic distortions were usually measured in the early hours of the morning. Etezadi-Amoli [3] gives the result of 1120 "spot" measurements on the Sierra Pacific Power Co at 120V. Maximum and average values of voltage and current distortion are given and the results suggest a 95% VTHD of 3%.

Emanuel [4] looks at 1 week measurements on the sending end of 5 New England Power Service Co feeders ranging 15-25 kV with samples taken every 3 minutes. VTHD was found to be 1.2%. Later phases of the project are reported in [5] and [6] concluding that VTHD is increasing at 0.1% per year. Hughes [7] gives voltage measurements at the 120V service entrance of some BC Hydro customers over a week. Residential, Commercial and Industrial customers were found to have 95% VTHD values of 2.9%, 1.9% and 3.9%.

Cavallini [8] takes a statistical analysis of 6 weeks' data recorded in Italy to determine the requirements for meaningful and consistent data. It is concluded that harmonic surveys should be taken over periods no shorter than 2-3 weeks but that sample rates as low as one per hour can give good estimates of 95% values.

The few harmonic surveys reported in the literature do not show a consistent approach. Very few report on both voltage and current or estimate the breakdown of load into residential, industrial and commercial components. Survey periods vary from spot readings to several weeks, with sampling periods ranging from 3 minutes to once per hour. Reported values of distortion can be average, 95%, 99% or maximum values. There appears to be further scope for developing a satisfactory methodology for harmonic surveys.

2. SELECTION OF HARMONIC MONITOR

The instrument selection is made difficult by the range of signal processing options which are available for making a frequency domain study of a time-varying system. The Australian standard for harmonic monitors[9] attempts to specify instrument operation but it is too new to be met by available instruments. Another complication is that the seven instruments involved were made available for different periods over the testing programme.

2.1 Requirements of AS/NZS 61000.4.7 [9]

This standard classifies the measurement requirements according to the rate of change of harmonics. Power system loads may change rapidly and "Fluctuating and rapidly changing harmonics" is the appropriate classification. This requires the sampling to be "strictly synchronised". The sampling window must be an exact multiple of periods in the range 4-8 cycles long. The sampling windows must not overlap and there must be no gaps, ie every cycle of the supply in the survey period must be sampled exactly once. Harmonics should be calculated up to the 50^{th}.

There are practical difficulties in meeting this standard with presently available instrumentation as it is relatively new, complex and in some parts not clearly expressed. Unlike the flicker meter standard [10], there are no benchmark tests which can be used to establish if a particular instrument meets the standard.

Most of the instruments were supplied on the basis of confidentiality and specific brand names cannot be mentioned in this paper. Hence the harmonic monitor testing is described form the point of view of methodology rather than to make a specific recommendation. In any case, this is a time of rapid developments in power quality monitoring and the instruments chosen may only have a short lifetime in the market.

2.2 Criteria for instrument selection

It is required that the monitor be accurate to the 20th harmonic, the highest harmonic considered by the present Australian harmonic standard AS 2279. If possible, accuracy should be retained to the 50th harmonic as required by AS/NZS 61000.4.7. The Integral Energy system is large and the University of Wollongong is situated at one extreme of the system. It was likely that the chosen sites would be some distance from the University and the capabilities for remote set-up, initiation and downloading were important.

Another important aspect of any instrument is the usability of the associated software. This usually requires a graphical interface and a well-structured "intuitive" menu system. All required parameters should be quickly accessible. Software usability needs to be examined for the following functions

1. Setting up sampling rates, thresholds etc
2. Initiation
3. Downloading
4. Post-processing
5. Data export to other applications such as spreadsheets.

2.3 Testing program

The University had available a Voltech PM3000A harmonic monitor of high accuracy but inadequate to record time-varying harmonics over an extended period. A harmonic generator described in [11] could produce constant harmonic voltages over the required frequency range. This capability suggested two series of tests

1. Comparison tests involving simultaneous logging by the available monitors over a day: the supply chosen was the power laboratory and probably reflected the harmonic conditions of a typical commercial site dominated by computers and fluorescent lights with some specialised equipment. This test was intended to check the ability of the instrument to give reasonable results in a situation close to field conditions.
2. Logging of constant harmonics from the harmonic generator and a comparison with the PM3000A.

Fig. 1 shows results for from the first stage of testing of 3 instruments A-C for the day survey test. The graph shows the a-phase voltage 5th harmonic reading of each instrument. The results for instrument C appear to be very much in error

- there are rapid falls to zero not shown by the other instruments
- the general trending is different over much of the time period

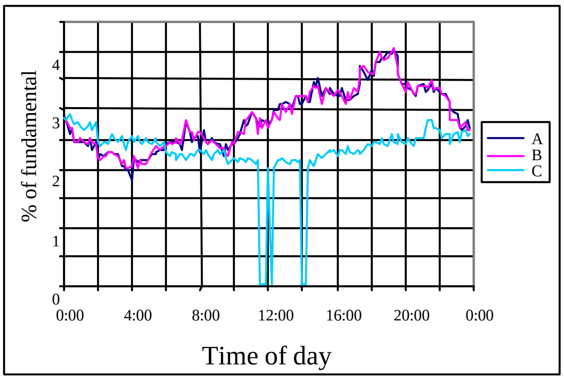

Fig. 1: Laboratory daily 5th harmonic voltage trend

At the 19th harmonic, further differences can be seen as shown in Fig. 2. Instrument C gave a reading of zero throughout and is not shown on the graph. Instrument A has sudden peak readings which are believed to be highly unlikely and instrument B appears to be the best of this particular batch. Readings were also taken of the 9th harmonic, to show the situation half way between the lowest and highest harmonics recorded. This showed the trend of instrument C giving zero readings at lower levels and instrument A showing and increased number of spikes at higher harmonics.

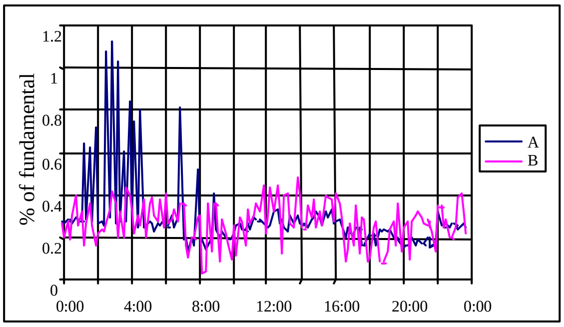

Fig. 2: Laboratory 19th harmonic voltage trend

2.4 Other aspects of monitor selection

Most instruments had limited memory capabilities with 4MB being considered large by most manufacturers. This is a pity as memory is relatively cheap and gives increased flexibility in the use of the instrument.

The setting up of some instruments seemed unnecessarily complicated. Some used software which was not easy to use. Some were not menu-driven and required a knowledge of a programming language.

Instrument prices varied over the range $1,500-$9,000. There was little correlation between price and performance.

After all tests were run, two harmonic logging instruments were found to be acceptable, one at $7,000 and one at $1,500. The first was a full power quality monitor with more facilities than were required. The second was intended primarily as a tariff meter with a large volume market, but was adequate for the proposed harmonic survey and was the instrument finally selected. Its memory limitation determined that only three harmonics and THD could be logged over the survey period. The three harmonics chosen were

1. 5th harmonic: should dominate at MV
2. 19th harmonic: highest harmonic of importance for the present Australian harmonic standard AS 2279.2-1991 [12]
3. 49th harmonic: highest harmonic of importance for the forthcoming Australian harmonic standard AS/NZS 61000.3.6 [1]

3. SITE SELECTION

Sites close to each other in the Integral Energy MV system had to be identified. We hoped to be able to make future measurements at regular intervals to investigate the growth of harmonics due to changes in load type rather than the growth in load. This suggested a location that was almost fully loaded and where the network was unlikely to change over the next few years. We decided to look for a zone substation having all sites on its 11 kV side. We hoped to find a substation having one feeder which was almost completely industrial, another one which was commercial and one residential; the others could be some mixture but we wanted to have some idea of what the mixture was.

It was decided to install 7 monitors

1	Measure total voltage and current at the 11 kV zone substation busbar
2-4	Measure the voltage and current at the sending end of each of the residential, commercial and industrial feeders
5-7	Measure voltage and current at typical residential, commercial and industrial sites along the feeder

Measurements at locations 1-4 were made by means of the substation voltage and current transformers. [9] suggests that there should be no problems with the VTs used as they were of the magnetic type. Previous work had established that the CTs would have adequate bandwidth for these measurements [13]. V_{ab}, V_{cb}, I_a and I_c were recorded. It is clear from Fig.3 that the voltage readings at sites 1- are identical.

The chosen monitor was not weatherproof and had to be connected at an enclosure. The MV side of distribution transformers is not accessible. Instead Sites 5-7 were monitored at the LV side of 11kV/415V distribution transformers using direct connection for the voltage leads and clip-on CTs intended for harmonic measurements for the current sensing. All three line-to-neutral voltages and line currents were recorded.

The zone substation chosen, in consultation with Integral Energy, was Homepride, a typical 33/11kV zone substation in the Liverpool area of Sydney and supplying ten 11kV radial feeders. The substation load was about 40MVA and the short-circuit level at the 11kV busbar was 213MVA. Fig. 3 details the schematic layout of the system test area. Sites

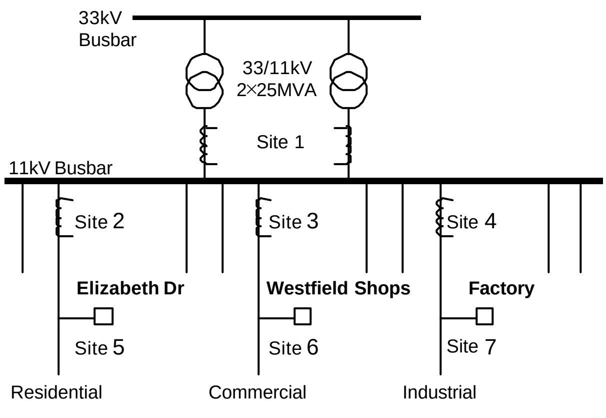

Fig. 3: Layout of Test Area

Sites 1-3 are all within the substation at the sending end of feeders identified as being of a predominant load type. Site 5 was the last enclosed type substation (padmount) along the feeder route located approximately 2 km from Homepride. The remaining 2 km of feeder is overhead with pole-top mounted transformers. The site fed a recently developed residential area. Site 6 supplies a Westfield shopping centre with a couple of large supermarkets and many small shops. Site 7 supplies a factory manufacturing paper products such as paper towels, toilet paper and tissues.

The three feeders in question have an estimated proportioning of load type as follows (with R, C and I standing for residential, commercial and industrial respectively):

- "Residential" Feeder – 85% R, 15% C
- "Commercial" Feeder – 10% R, 90% C
- "Industrial" Feeder – 5%R, 20% C, 75% I

The load breakdown of the three LV sites is estimated to be.

- Site 5: Residential Transformer – 90% R, 10% C
- Site 6: Commercial Transformer – 100% C
- Site 7: Industrial Transformer – 100% I

4. SURVEY RESULTS

4.1 Voltage trends

Fig.4 shows a typical recording of the substation 11kV harmonic voltage over a week averaged over the two line-to-line values. The 5^{th} harmonic and VTHD are very close to each other showing that the 5^{th} harmonic is the dominant distortion. The 19^{th} harmonic is low (about 0.1%), towards the limit of resolution of the instrument. The 49^{th} harmonic recorded was insignificant. The remainder of the discussion will be limited to the 5^{th} harmonic.

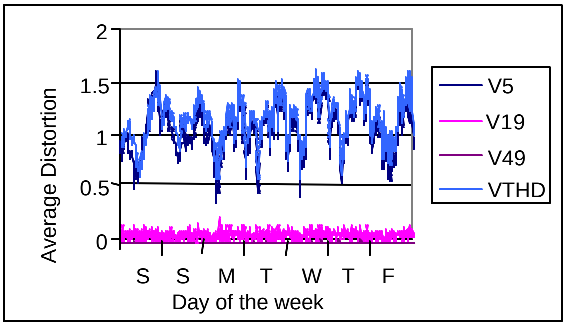

Fig. 4: Homepride Zone Substation 11kV harmonic voltage trend

4.2 Cumulative probability

Cumulative probability distributions of the 5^{th} harmonic voltage are given in Figs 5-8 for the zone substation 11kV busbar and the three low voltage sites. The 95% values of 5^{th} harmonic voltage at the Zone substation is 1.56%, well below the recommended Planning Level of 5% [1]. The LV values are

- Residential: 1.5%
- Commercial: 2.6%
- Industrial: 1.7%

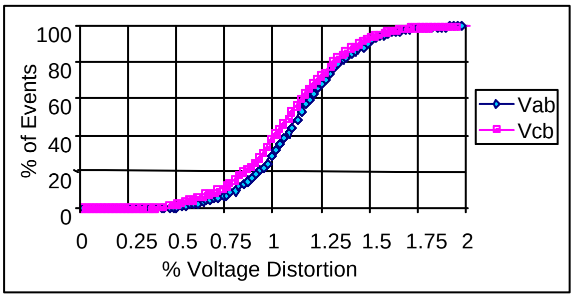

Fig.5: Homepride Zone Substation 11kV cumulative probability

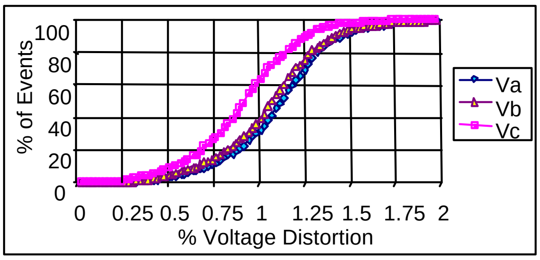

Fig. 6: Residential site LV cumulative probability

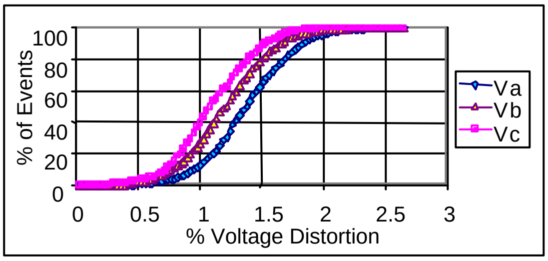

Fig. 7: Industrial site LV 5^{th} harmonic voltage cumulative probability

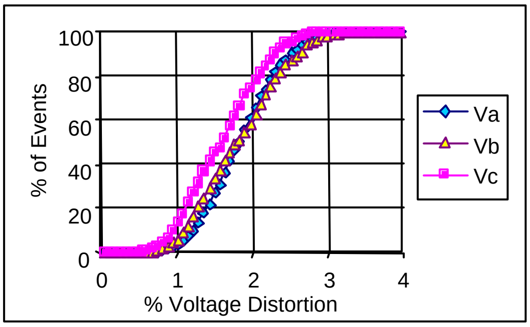

Fig.8 Commercial site LV cumulative probability

4.3 Minimum survey requirements

The information recorded was over 4 weeks and allows the minimum surveying requirements to be estimated. Fig.5-8 show some differences between the different phases, but these are not significant considering that an acceptable accuracy for harmonic surveys is not high, being possibly 0.2% at the 5^{th} harmonic. It appears that acceptable accuracy could be obtained by measurements on one phase alone. This is confirmed by Figs. 9 and 10 which are scattergraphs of two of the phase readings for the MV and one of the LV sites respectively. Fig. 10 is especially interesting if one assumes that most of the harmonic voltage is produced downstream by single phase residential loads.

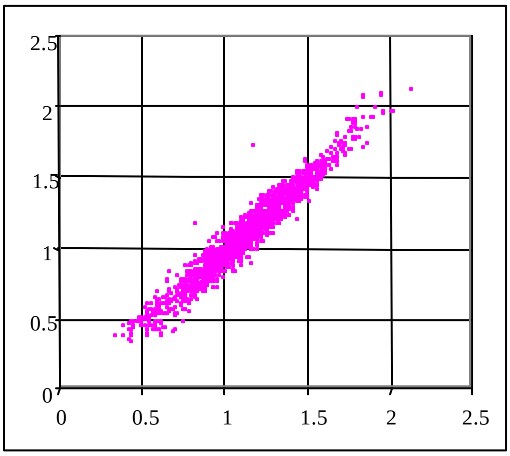

Fig.9: Scattergraph of 5^{th} harmonic voltages V_{ab} versus V_{cb} at Homepride zone substation

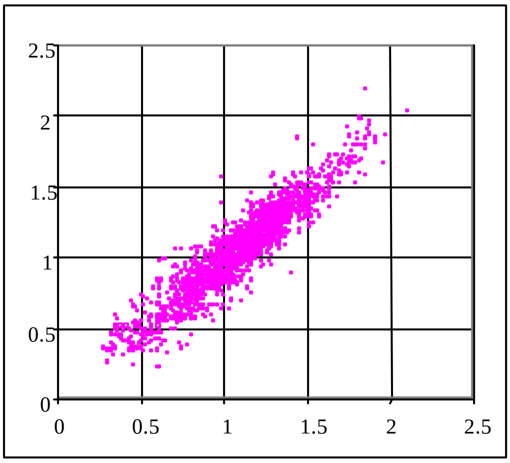

Fig.10: Scattergraph of 5^{th} harmonic voltages V_a versus V_c at Site 5 (Residential LV)

The minimum survey period can found by breaking the 4 week survey period into four separate records as shown in Table I for the MV readings. It can be seen that the maximum deviation of a reading from the overall reading of 1.56% is 0.12% which is within acceptable accuracy. Thus a reading over a period as short as 1 week gives useful information without being biased too much by short term trends. Note that there may be additional large long term seasonal trends about which this survey can give no insight. Table II again reinforces the balance of the system with different phases sharing similar trends.

Table I: Weekly 95% cumulative values for MV 5^{th} harmonic voltage

	Week 1	Week2	Week 3	Week 4
Vab	1.48	1.68	1.61	1.45
Vcb	1.46	1.66	1.56	1.45

The weekly readings have been further broken down into daily 95% cumulative values in Table II. The following can be noted:

- The weekend always has high harmonic levels although the first Sunday has one of the lowest levels recorded.
- Friday always has about the lowest level
- No one day is typical of the week as a whole
- Some trials suggest that the smallest subset of days giving useful results is Sunday-Tuesday which has an average differing from the week value by about 0.6%.

Table II: Daily 95% cumulative values for MV 5^{th} harmonic voltage V_{ab}

	S	S	M	T	W	T	F	Total
Week 1	1.44	1.28	1.35	1.45	1.56	1.53	1.47	1.48
Week 2	1.73	1.90	1.55	1.53	1.32	1.26	1.24	1.68
Week 3	1.76	1.75	1.50	1.54	1.35	1.44	1.37	1.61
Week 4	1.58	1.50	1.34	1.41	1.52	1.43	1.34	1.45

Maximu m harmonics occurred Monday-Friday at 4-5 and 7-9 pm, different to what is reported in [2]. However the high harmonic levels on Sunday and the above results are consistent with higher harmonic levels occurring away from the peak loading periods. This may reflect harmonic loads such as personal computers and lighting being on for a relatively long time of the day and the effect of other loads absorbing harmonics at peak load periods.

4.4 Harmonic characteristics of different load types

Table III summarizes survey results for the 95% cumulative values for the fundamental and 5^{th} harmonic current for the three LV sites. The subscript "1CP95" indicates the fundamental component 95% cumulative probability level. It is required to characterize the load types so that 95% cumulative levels of harmonic distortion can be predicted from known network impedances and load magnitudes and compensations. Assuming that similar load compositions at any power level will have the same spectrum, each load type can be characterised conveniently by the ratio I_{5CP95}/I_{1CP95} as shown in the right hand column. This shows that the residential load has much less distortion than the commercial and industrial types as would be expected. These will have to be considered as preliminary results, with further extensive harmonic surveying required to establish figures have a wide ranging validity.

Table III
Fundamental and 5th harmonic current 95% cumulative values (A)

Harmonic Monitor Site	I_{1CP95}	I_{5CP95}	I_{5CP95}/I_{1CP95}
Site 5 - Residential	143	3.01	0.02
Site 6 - Commercial	648	44.7	0.07
Site 7 - Industrial	1310	137	0.10

5. CONCLUSIONS

The paper has discussed the methodology used for a harmonic survey of part of a MV distribution system.

It appears that presently available harmonic monitors are not able to give a consistent measure of harmonics under changing conditions. A combination of stationary tests with laboratory grade instrumentation and comparison tests on a normal supply can be used to eliminate most instruments simplifying choice.

Factors in site selection have been listed allowing the separate determination of the harmonic characteristics of different load types.

The results show that the MV system has a large capacity for absorbing growth in harmonic loads. The same conclusion cannot be made about the LV system as measurements were made very close to the distribution transformer. It should be realised that for most LV customers, most of their impedance drop is in the LV distributor. There is also the additional complication of triplen harmonics which are largely absent from the MV system.

It has been shown, in common with overseas studies, that the 5th harmonic is the one of greatest concern and the following conclusions below relate solely to this harmonic order. It appears that useful harmonic data can be obtained from the readings of just one phase over a period as short as three days.

The three conventional load types for harmonic studies have been characterised in a way that should allow the development of mathematical models for the predictions of harmonics.

6. ACKNOWLEDGEMENTS

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