The Power Quality trend in a New Zealand Distribution Company

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Abstract

Power Quality is an important aspect of network operation as poor power quality causes significant economic loss and disruption. As technology develops, the characteristics of equipment utilising the electrical system is changing. The question is whether this is affecting power quality on the network. The desire for more renewable generation and the drive for energy efficiency with smart appliances and equipment are all changing the equipment being deployed. In this paper an analysis of the trends in the different power quality indices that have occurred over the years is given. This is a difficult task as it requires significant amounts of data which can only be obtained by deploying many PQ monitors and monitoring the output over many years. Fortunately Orion had the foresight to start rolling out PQ monitors in 2007. Although this is only for one electricity distribution company, the trends are expected to be similar since the same technology is deployed throughout the country. How close the trends follow Orion's needs to be verified.

The power quality indices analysed were 3rd, 5th & 7th harmonic voltages, voltage Total Harmonic Distortion (THD) Absolute Voltage Deviation (AVD) and Voltage Unbalance Factor (VUF). It was found that the observed network does exhibit noticeable trends, particularly in the fall and rise of the 5th and 7th voltage harmonic levels respectively. This was found to be consistent with recent technological developments and their uptake. There is a need to continue to monitor the effects of emerging technologies so as to identify possible problems before they occur and mitigate potential problems by requiring minimum standards or restricting technologies that could have an adverse effect on the network and ensure adequate power quality levels are maintained.

1. Introduction

There is continual technological development which results in changes to the makeup of the electrical equipment being deployed in the electrical system. The question that arises is the impact this is having on the power quality, and in particular the voltage quality, throughout the power system. Power Quality is important as inadequate power quality will result in adverse effects being experienced, and for this reason it is important to have suitable limits and to assess the proximity to the limits and the direction the indices are trending [1, 2]. PQ disturbances can be broadly classified into two categories. These are *variations* and *events*. Of these variations is the focus of this paper, and are discussed in section 2.

2. Methodology

The raw power quality data was obtained from dedicated PQ monitors (conforming to IEC 61000-4-30:2008) that record 10 minute samples. To remove daily and seasonal variations and determine trends in the power quality levels over the years the data was grouped by year and the cumulative probability function was developed. An example of a daily variation for a complete year and by month is illustrated in Figs. 1 & 2, where the effect of loading on Voltage THD is evident. Gauge points are then used as measures for that particular year. For example CP95 represents the level in which 95% of the data points lie below. For the purposes of this investigation, each chosen index at each chosen site was assessed using its annual CP95 and CP99.5 values.

Since the system is three-phase, an overall index needs to summarise the levels in all three-phases. Furthermore, it is convenient to assess each index with respect to the defined limits. This is helpful for assessing how close each index is to its limit, therefore it is normalised. The process of normalisation and consolidation described in [3] was used to aggregate phases and obtain a relevant index. In summary the process of normalisation (dividing by the appropriate limit) is carried out on raw data values and is performed prior to consolidation. The process of consolidation is used for indices that do not automatically take into account multiple phases. The annual percentile values for each year are calculated for each phase and the highest percentile value of these is then taken as the value for the index in question for the given year.

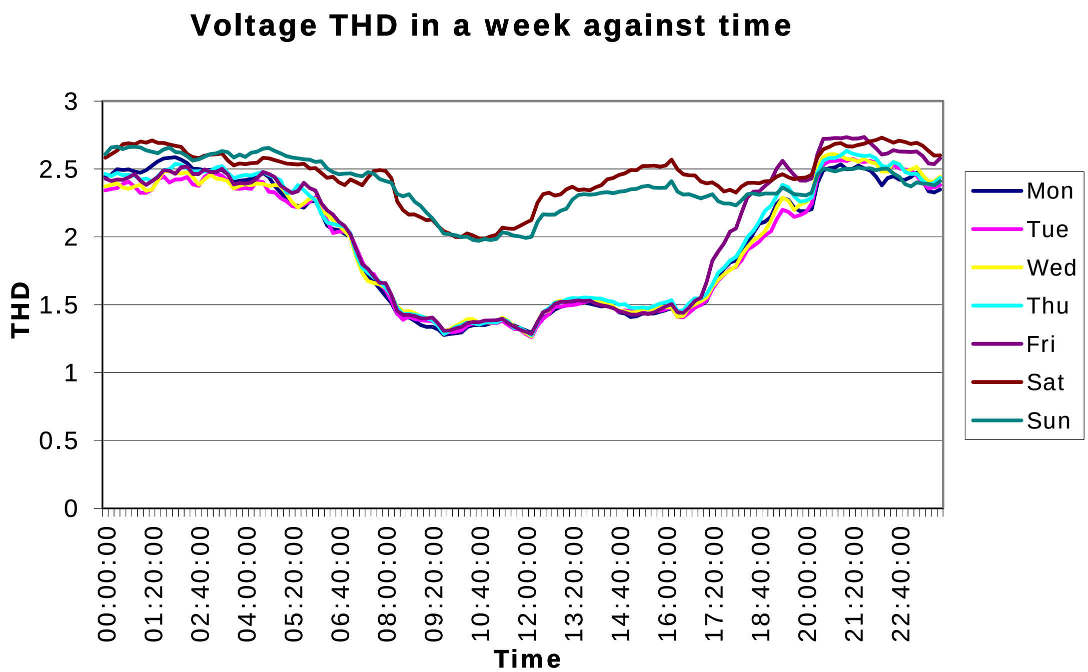

Figure 1: Example of a daily variation on a per day of the week basis

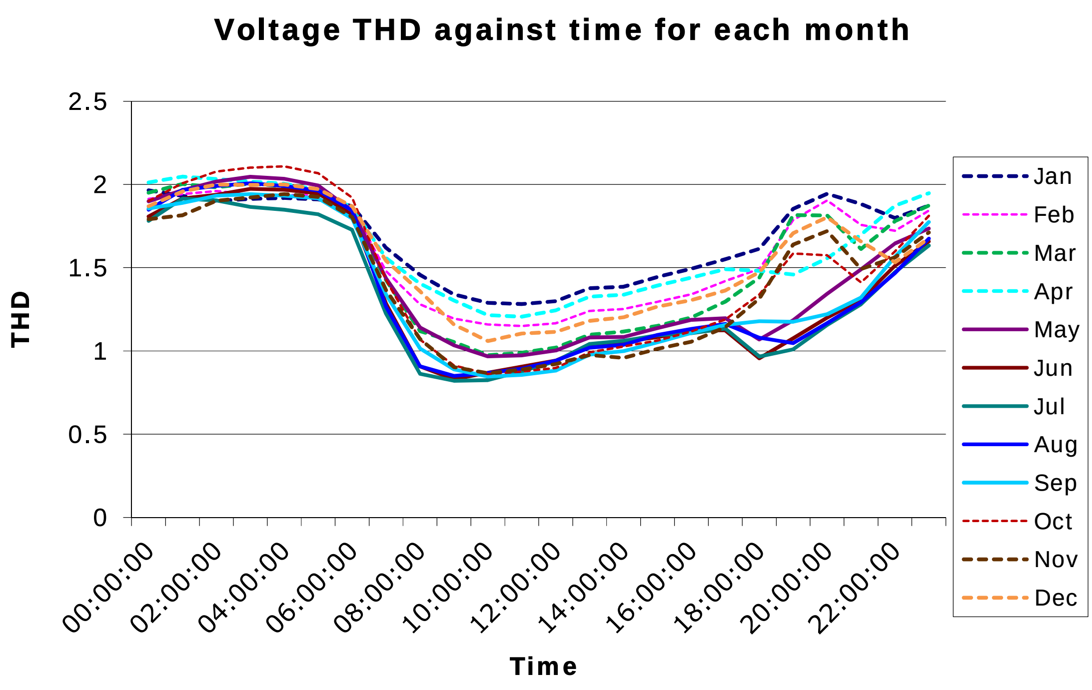

Figure 2: Example of a daily variation on a per month basis

From this process time series progressions of each index and annual summaries of each index were generated for analysis. The time series progressions were analysed partly using simple linear regression. Each index at each site was then categorised into five groups which indicates the direction and strength of the trend, that is: strong downward, notable downward, neutral, notable upward, and strong upward trends. Figs. 3 & 4 illustrate a strong downward trend and a notable downward trend. The classification each trend received was also influenced by recent local trends. This is the reason why some trends were classified as strong or notable despite having lower coefficients of determination. One example of this is seen in Fig. 4. It should be noted that data points for 2016 (in Figs. 3 to 8) are only for a small proportion of the year and therefore, due to seasonal variations, may not be a good indication of the overall year's statistic.

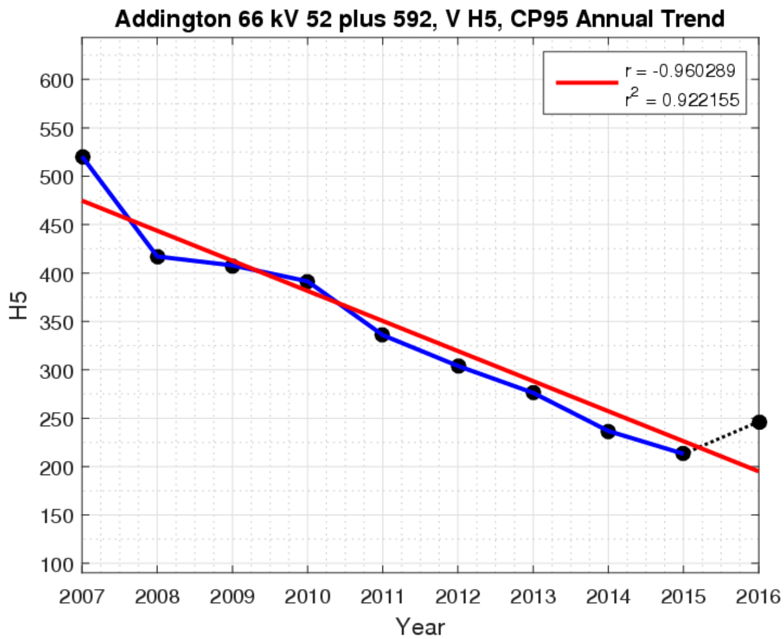

Figure 3: A strong downward trend at a High Voltage Site

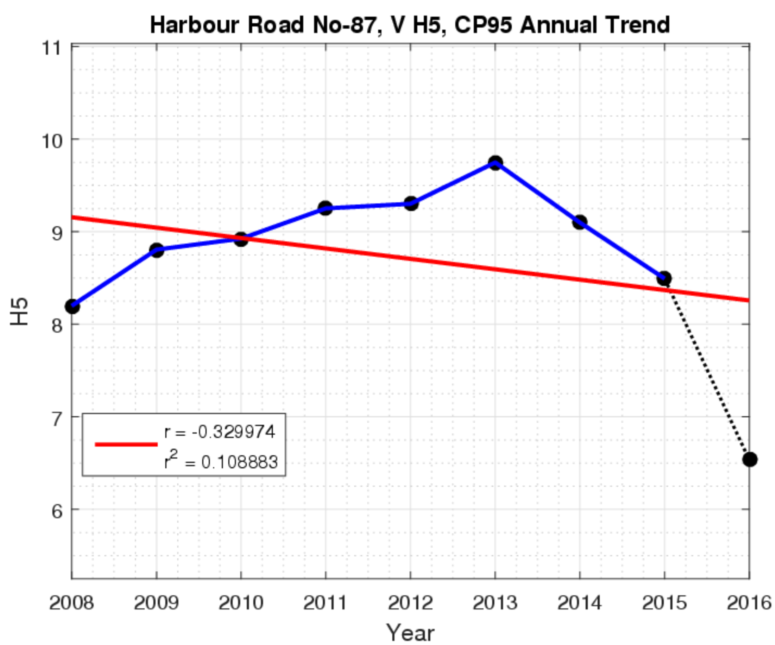

Figure 4: A trend categorised as a notable downward trend due to recent local trend

2.1 Power Quality Indices Assessed

Absolute Voltage Deviation (AVD)

This index was used to characterise steady-state voltages at a particular site. AVD measures the absolute difference of a voltage with respect to a reference voltage. The reference voltage was defined as the mean of the minimum and the maximum voltage limits. The reference voltage was very often defined to be the system nominal voltage. Steady-state voltage data was taken for each phase at each site where the absolute differences were calculated before being normalised and consolidated to form the AVD index. The AVD index is designed to be compatible with the standard CP percentile measure [3] and hence is designed to compactly represent the general deviation as one value.

Voltage Unbalance Factor (VUF)

This index is used internationally to characterise steady-state voltage unbalance. The VUF is defined as the ratio of the negative sequence voltages to the positive sequence voltages [4].

The overall limit was set at two percent. VUF is an example of an index that automatically aggregates phases since it considers the sequence components. Therefore the process of consolidation did not need to be applied to this index.

Voltage Total Harmonic Distortion (THD)

The Voltage THD index was used as a general measure to characterise harmonic distortion at a particular site. The limit for THD depends on the nominal voltage of the site. These were taken from the EEA Power Quality Guidelines [1].

Harmonic Voltages

These refer to individual harmonic levels found at each site. Three harmonic levels were analysed during this investigation; these were the 3^{rd}, 5^{th}, and 7^{th} harmonic voltages. Higher harmonic levels were not analysed in this investigation due to the absence of some of this data. The limits for harmonic voltages depended on what the nominal voltage of a site was. These were taken from the EEA Power Quality Guidelines.

2.2 Power Quality Indices Not Assessed

Dips/sags and swells

Event based indices such as these were not assessed in this investigation due to a lack of complaints related to this received by the lines company from customers. The lines company has identified the performance of protection equipment and infrastructure as being the leading factor behind the vast majority of dip/sag and swell events. Furthermore these events currently cannot be conveniently presented in a useful form for trending.

Flicker

The present flicker index is based on voltage measurements and is a measure of the flicker severity when a 60W incandescent lamp is connected to the electrical grid. The flickermeter incorporates the characteristics of the incandescent lamp and human perception (eye-brain response). Although new lighting technologies such as compact fluorescent lamps (CFLs) and LED lighting do exhibit flicker, the flicker index is unsuitable due to the fact it is tailored for an incandescent lamp. Due to the marked decrease in customer complaints because of flicker (probably due to the significant change in the lighting technology used) the traditional flicker index was not considered.

3. Results

The data from 31 permanent PQ monitors deployed in the Orion network was analysed. Of these 18 were classified as Low Voltage (LV) sites, 8 were classified as Medium Voltage (MV) sites (all were 11 kV) and 5 were classified as High Voltage (HV) sites. An overview of the trend in all the sites is given in Appendix A, while only the strong and notable CP95 trends are summarised in Tables I - VI.

Out of 18 LV sites, 6 were located within Christchurch city, 6 were located in surrounding towns, 4 were located in rural areas, one was in a remote location and one was located within a red zoned area. Of the 6 Christchurch city sites, one exhibited a strong upwards trend in the 7th harmonic voltage while four sites were deemed as notably increasing. However, 2 sites showed a strong trend downwards in the 5th harmonic voltage. Two of the 4 rural sites exhibited a strong upward trend in all harmonics and THD.

There appears to be a general slight downward trend in VUF across the LV sites.

Seven of the MV sites were located on the secondary side of various zone substation transformers across the network while the remaining site was located within a mainly business area of Christchurch. Of the 7 substation sites, 4 exhibited a strong downward trend in the 5th harmonic voltage, one site showed a strong upward trend in the 7th harmonic voltage and two showed a notable upward trend in the 7th harmonic. Two sites showed strong downward trends in THD while 2 other sites showed strong upward trends in AVD. The Christchurch business area site showed a strong increase in the 7th harmonic trend.

The HV sites were all located on the high voltage side of various zone substation transformers and grid exit points around the network. Of these sites, 2 were located within Christchurch while the others were located in the surrounding region. All sites showed a strong downward trend in the 5th harmonic. All Christchurch sites also exhibited strong downward trends in 3rd harmonic and voltage THD while one of the Christchurch sites showed a notable increase in the 7th harmonic.

Table I: 3rd Harmonic Trend

3rd Harmonic CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	0%	22%	28%	11%
MV (8 sites)	0%	38%	13%	0%
HV (5 sites)	60%	20%	0%	0%

Table II: 5th Harmonic Trend

5th Harmonic CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	17%	39%	22%	11%
MV (8 sites)	50%	25%	0%	0%
HV (5 sites)	100%	0%	0%	0%

Table III: 7th Harmonic Trend

7th Harmonic CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	6%	6%	33%	11%
MV (8 sites)	0%	13%	25%	25%
HV (5 sites)	0%	20%	20%	0%

Table IV: Voltage THD

Total Harmonic Distortion (THD) CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	11%	17%	28%	11%
MV (8 sites)	25%	25%	13%	0%
HV (5 sites)	80%	20%	0%	0%

Table V: Voltage Unbalance Factor

Voltage Unbalance Factor (VUF) CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	22%	44%	6%	0%
MV (8 sites)	0%	25%	0%	0%
HV (5 sites)	20%	20%	0%	0%

Table VI: Absolute Voltage Deviation

Absolute Voltage Deviation (AVD) CP95				
	Strong Down	Notable Down	Notable Up	Strong Up
LV (18 sites)	6%	39%	11%	0%
MV (8 sites)	0%	38%	0%	25%
HV (5 sites)	20%	40%	0%	0%

4. Discussion

Historically, the 5th harmonic has been the main harmonic issue on the network, particularly in rural areas. This was due to the 5th being the predominant harmonic current injected by 6-pulse converters [5]. Significant upwards trends were found in rural areas where irrigation pumps has historically been a major contributor to harmonics. However, only 2 rural sites now show this and the others now a slight downward trend. There is a mixture of increasing levels and decreasing levels of 5th harmonic voltage in the Christchurch sites. The 5th harmonic voltage is clearly trending downwards at the MV and HV sites. The trend in rural areas (see Figs. 5 & 6), coupled with other recordings, suggests that since the problem with irrigation pumps has been identified the steps taken to address it are working (use of Dzn0 transformers and requirement to limit harmonic current injections) [6].

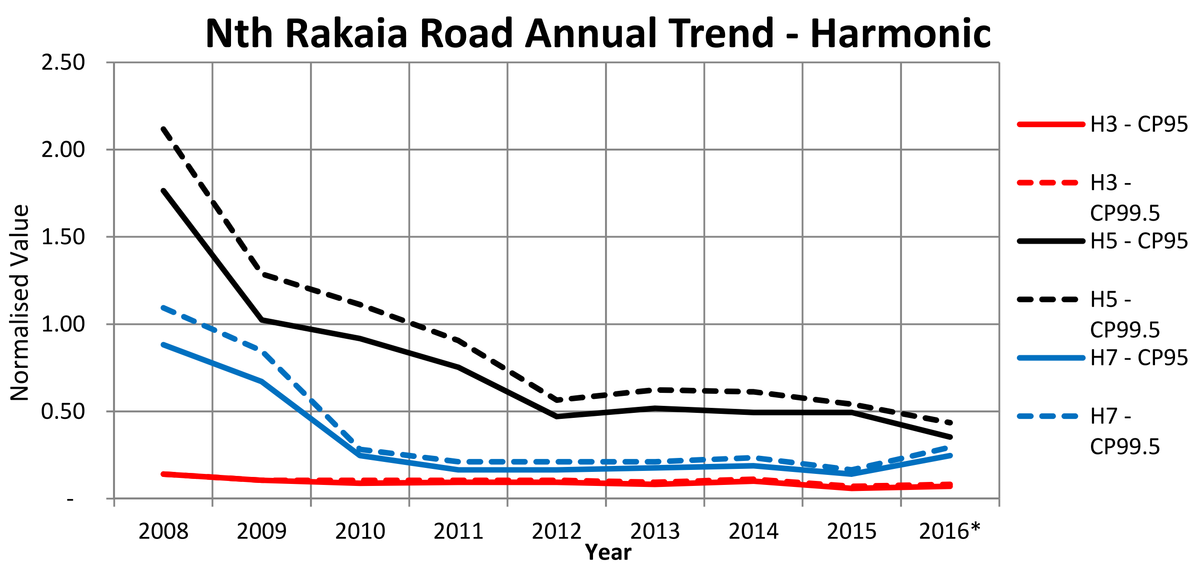

Figure 5: Individual Harmonics at a Rural Site

The 7th harmonic voltages consistently exhibit a higher proportion of upward trends compared to downward trends across all voltage levels. This suggests that increases in the 7th harmonic voltage may be the emerging topic for the future as new technologies become more widely adopted. Photovoltaic installations are known to cause increases in its nominal feeder voltages and in the 7th harmonic. The consequences of allowing widespread implementation of PV embedded generation are also well known to electricity distribution companies. Tests on PV inverters has shown a similar 5th and 7th harmonic current emission levels for some which, due to the higher reactance at the 7th harmonic, results in the 7th harmonic voltage being similar or larger than the 5th harmonic voltage. This was identified in a national survey of harmonic levels.

One LV site in Christchurch was available to represent the behaviour of a feeder with PV loads. It had the greatest number of PV installations connected to one feeder. Figure 7 shows the increase in AVD and Fig. 8 the 7th harmonic for this site. Although the trend could be due to PV installations, without more measurements at the PV installations themselves it is impossible to conclusively draw this conclusion.

The restriction on low order harmonics is resulting in equipment using active front-ends which use higher switching frequencies. This moves the distortion to high frequencies and is of increasing concern both here and internationally.

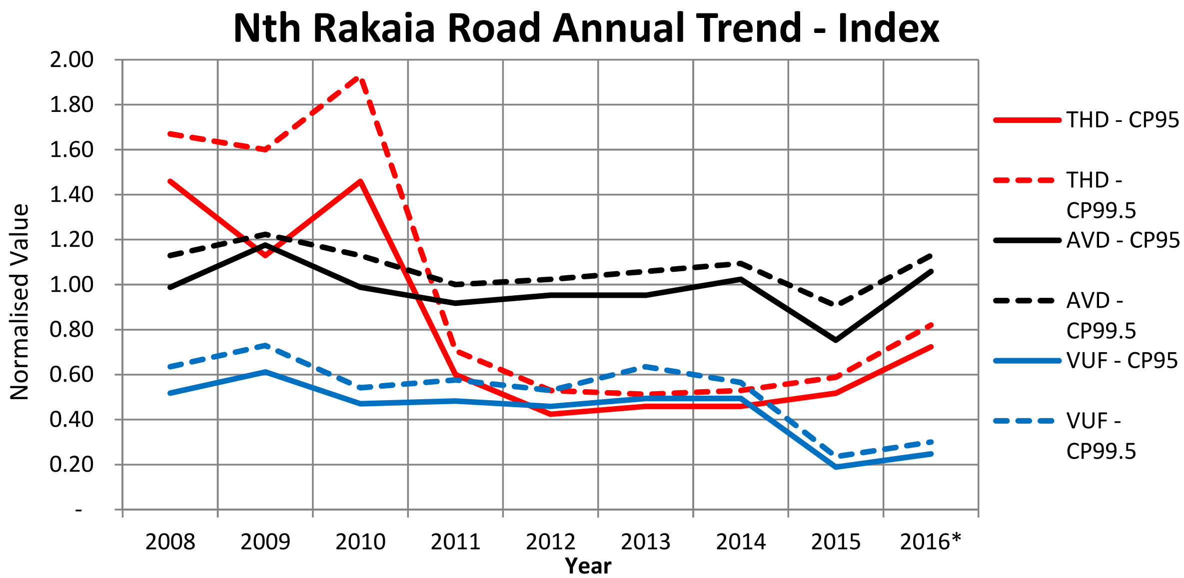

Figure 6: THD & AVD at a Rural Site

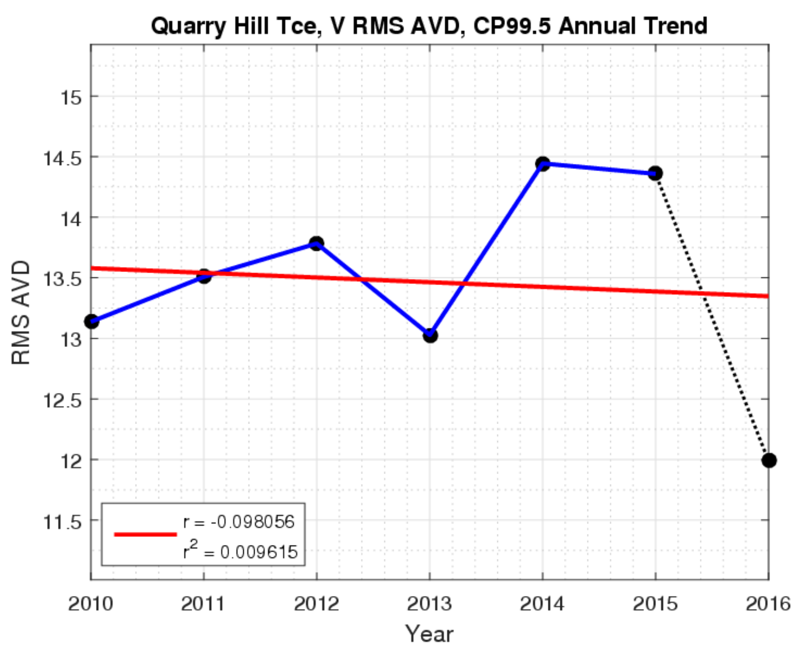

Figure 7: AVD Trend at Christchurch PV site

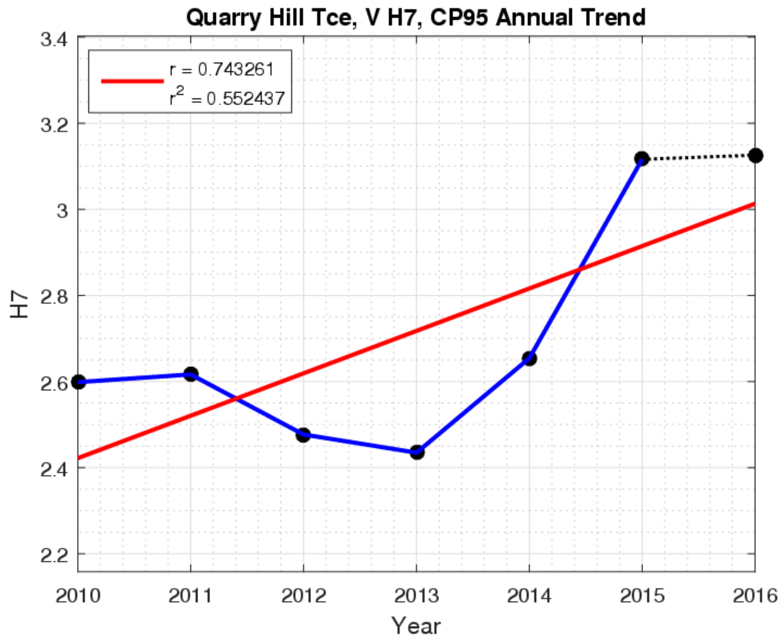

Figure 8: 7th harmonic trend at Christchurch PV site

5. Conclusions

This survey of PQ indices has identified some trends that have occurred over the years. It is clear that new technologies being deployed will influence the voltage quality, and will become more pronounced as the number increases. The 5th harmonic issue is not increasing as it once was and the 7th harmonic is the main harmonic increasing at present. Higher frequencies (2.5-9 kHz) need to be monitored as equipment with switching frequencies in this range is now entering the system.

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Appendix A:

Table A.1: Overview of Trends

Low Voltage												
Site Name	**AVD**	**AVD**	**VUF**	**VUF**	**THD**	**THD**	**H3**	**H3**	**H5**	**H5**	**H7**	**H7**
Christchurch												
Armagh Street No.30	48		7740	7502	2261	1941	4270	2528	143	752	3895	4450
Garden Road No.31 Kiosk	3481	3536	6393	6489	6432	5009	41	474	9162	8572	9256	8568
Northcote Rd No.123	1892	1720	274	198	3148	3710	3	64	3375	3449	847	998
Quarry Hill Tce.	264	96	6950	6559	2284	579	4852	2634	1654	721	5524	5081
Rudds Rd No.18	6325	4969	1311	690	9177	9630	4	3	8875	8303	346	640
Wairakei Rd No.292	1681	146	8027	7565	5668	4239	2682	534	5529	3790	447	599
Rural Urban												
Beach Rd AK4-22	5695		288		8677		6375	4423	9172	9114	130	229
Gerald St Supermarket Lincoln	366		623	1123	799	267	5480	5193	43	1614	2931	1014
Rolleston Supermarket	5504	6567	5047	6160	171	869	5960	4710	4977	5956	5998	328
Rolleston T1 Incomer							1631	230	5861	5841	3048	5350
Shands Rd Sawmill R15-201	3266	5942	3027	4676	1539	1743	161	853	129	474	2792	3153
South Tce. Darfield Kiosk	6182	6729	798	957	6850	5123	2488	1913	7895	6487	48	4811
Redzoned												
Harbour Road No.87	7808	6911	8710	8811	3559	2141	4947	4281	1089	289	6433	4819
Rural												
Nth Rakaia Rd SE9-61	1349	2523	6150	5847	5444	5666	1555	3321	7391	7699	5189	5283
Rakaia Huts Kiosk	6369	6370	9062	9063	9402	6111	9377	6450	8875	6665	5944	5415
Rakaia Island HU6-10	3350	5055	2853	4281	9822	9859	9941	8576	9738	9137	9279	8777
Terrace Downs FH4-19	29	221	6956	7193	87	8	32	277	1302	376	3234	2271
Remote												
Ontrack Arthurs Pass	7144	4886	5297	82	4607	2750	7080	186	1602	51	8912	3000

Medium Voltage

Site Name	AVD	AVD	VUF	VUF	THD	THD	H3	H3	H5	H5	H7	H7
Brookside T1 (66/11 kV)	6934		5376		112		5831	5549	80	5700	8283	2151
Darfield 11 kV Incomer	7700		1586		7968		2658		8397	7816	958	1092
Dunsandel 11 kV Incomer 110	9669				7809		467	334	8369	8097	6158	7203
Duvauchelle T1 11 kV Incomer	2220				9144		3524	3586	9454	9342	2396	1416
Duvauchelle T2 11 kV Incomer	144	96	366	613	9121	9832	3674	2190	9372	9068	5537	6026
Kimberley 11 kV Incomer 110	3957		7610		3107		5245	6655	4109	8014	4787	6818
Kimberley 11 kV Incomer 120							4262	6017	3610	7720	6411	7242
Langdons Road 11 kV	891	197	3924	3695	3906	2217	6636	4446	1207	825	9230	8714

High Voltage

Site Name	AVD	AVD	VUF	VUF	THD	THD	H3	H3	H5	H5	H7	H7
Christchurch												
Addington 66 kV 52 plus 592	826	4167	5516	3860	8636	8102	9035	9227	9222	8807	550	903
Bromley 66 kV 492 T5	7391		6678		8909		8580	8441	8686	1578	3821	676
Rural												
Hororata 33 kV	6012		54		8779		428	1431	8873	7820	79	1598
Hororata 66 kV CB52	1795		98		9096		4852	3243	9359	8176	4005	2957
Springston 33 kV Incomer	1493		333		6678		7374	8076	7996	8635	1002	633

Trend

- Strong Downward
- Notable Downward
- Neutral
- Notable Upward
- Strong Upward
- Obscure

The values in the boxes are the coefficient of determination (R^2) multiplied by 1000. The coefficient of determination is a key output of regression analysis and measures the variance from a predicted outcome. With a value of 0 to 1, the coefficient of determination is calculated as the square of the correlation coefficient (R) between the sample and predicted data.