Development of PQ Guidelines for New Zealand

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Abstract

Any deviation of voltage or current from the ideal sinusoidal waveform is a power quality (PQ) disturbance. PQ disturbances can be broadly classified into two categories, Variations and Events. Variations are disturbances which have an effect on every cycle, such as harmonics or voltage unbalance. Events are disturbances which last for a time, from a fraction of a cycle to several cycles, and then may not repeat for several hours or days. Transients and voltage dips are examples of events.

It is not economically viable to eliminate PQ disturbances completely. However, they cannot be allowed to become too large, otherwise equipment costs would have to increase to account for the increased immunity required. The basic principles of EMC (electromagnetic compatibility) are used to develop a process by which equipment can be guaranteed to operate satisfactorily on the supply network. The basic idea is that, for each disturbance type, a value called the compatibility level is established and that:

- All equipment should have immunity levels greater than the compatibility level.
- The PQ disturbance level on the network has to be constrained to be less than the compatibility level.

This paper discusses the work undertaken to characterise the emission levels of equipment and electrical network and using this information devise PQ guidelines for the New Zealand electricity industry.

The management of emission levels is broadly similar for all disturbance types with some differences in detail. The treatment given in this paper is particularly relevant to harmonics, where a new voltage droop approach is presented. This basically determines a harmonic voltage allocation, which is then converted into a current allocation by assuming a given system harmonic impedance. Different approaches are adopted for LV and MV installations. The main principles are:

1. Time varying harmonic quantities are represented by their 95% values.
2. Diversity between independent sources is represented by the Summation Law.
3. The allocation should increase with customer maximum demand.
4. The allocation should be such that the largest harmonic voltage in the system should reach the planning level when all customers are connected and taking their full allocation.

1. Introduction

The electrical power system is designed to operate with sinusoidal voltage and current waveforms and any deviation of voltage or current from the ideal sinusoidal waveform is a power quality (PQ) disturbance. There are a large multitude of sources of PQ disturbances and it is not economically viable to eliminate PQ disturbances completely. Therefore equipment needs to be designed to have a certain level of immunity to PQ disturbances. By applying the principles of EMC (ElectroMagnetic Compatibility), a process by which equipment can be guaranteed to operate satisfactorily on the supply network can be developed. The basic idea (illustrated in Fig. 1) is that, for each disturbance type, a value called the compatibility level is established and that:

• All equipment should have immunity levels greater than the compatibility level.
• The PQ disturbance level on the network has to be constrained to be less than the compatibility level. This lesser value is the planning level, set by the network company to give a safety margin.

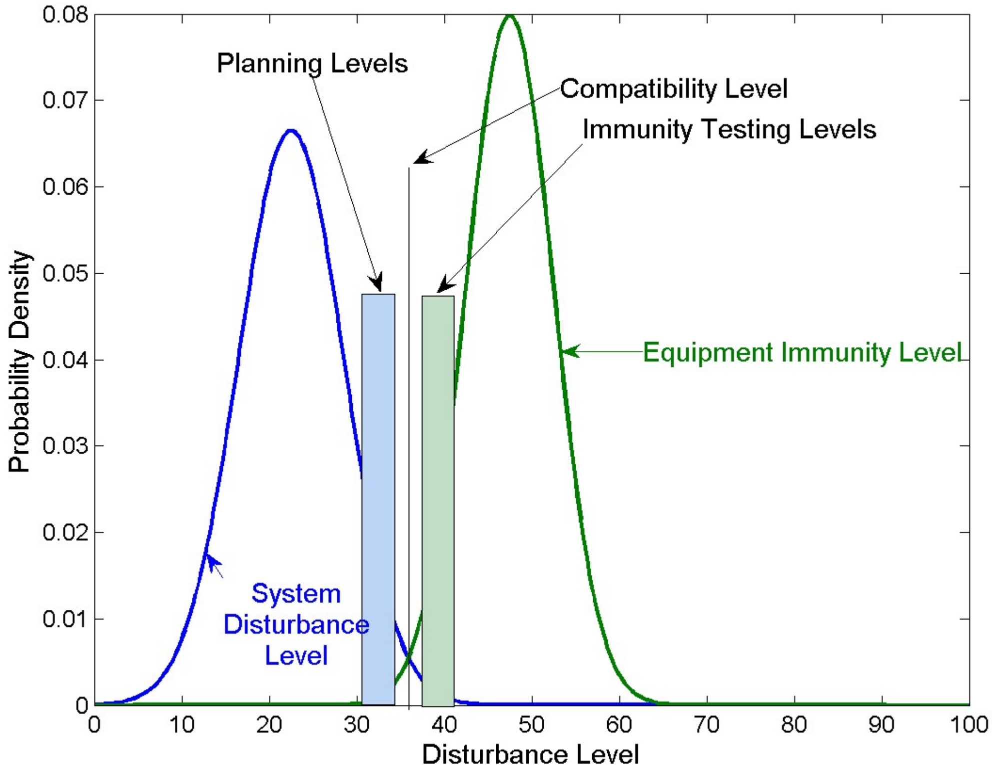

Figure 1. Concept of Compatibility and Planning Levels.

2. PQ Guidelines

The main goal of the FRST/EEA project is the development of PQ Guidelines for the electricity supply industry of New Zealand. In order for a guideline to be useful it must be simple enough so that it can be easily applied while not over-simplifying to the detriment of the results. The process of achieving this is outlined in the project overview diagram shown in Figure 2. The system disturbance level is determined by two factors; the emission level of equipment and the characteristics of the network (for a given emission level what disturbance level is generated). Therefore, the project was split into device characterisation and network characterisation. Emphasis will be on harmonics in this paper as an entirely new allocation method is proposed for harmonics. References [1-8] report on different elements of this overall PQ project. Some of the aspects covered in the PQ Guidelines include:

- typical characteristics of devices
- summary of findings on network characterisation
- PQ allocation techniques
- PQ Measurement and Management
- mitigation options
- recommended compatibility levels

3. Device Characterisation

A comprehensive campaign of measurements was made of a wide variety of equipment to characterise their emission levels. Measurements can only look at the here and now, while models allow futuristic scenarios to be investigated. Therefore the design of some equipment was investigated in more detail and models made and validated against measurements. This then allows planning studies to be conducted assuming certain equipment penetration in the future. This also showed the linkage between emission levels and circuit design and the cost of using a better, lower emission design. This work has led to one joint standard to be modified in 2009 (AS/NZS61000:3:2).

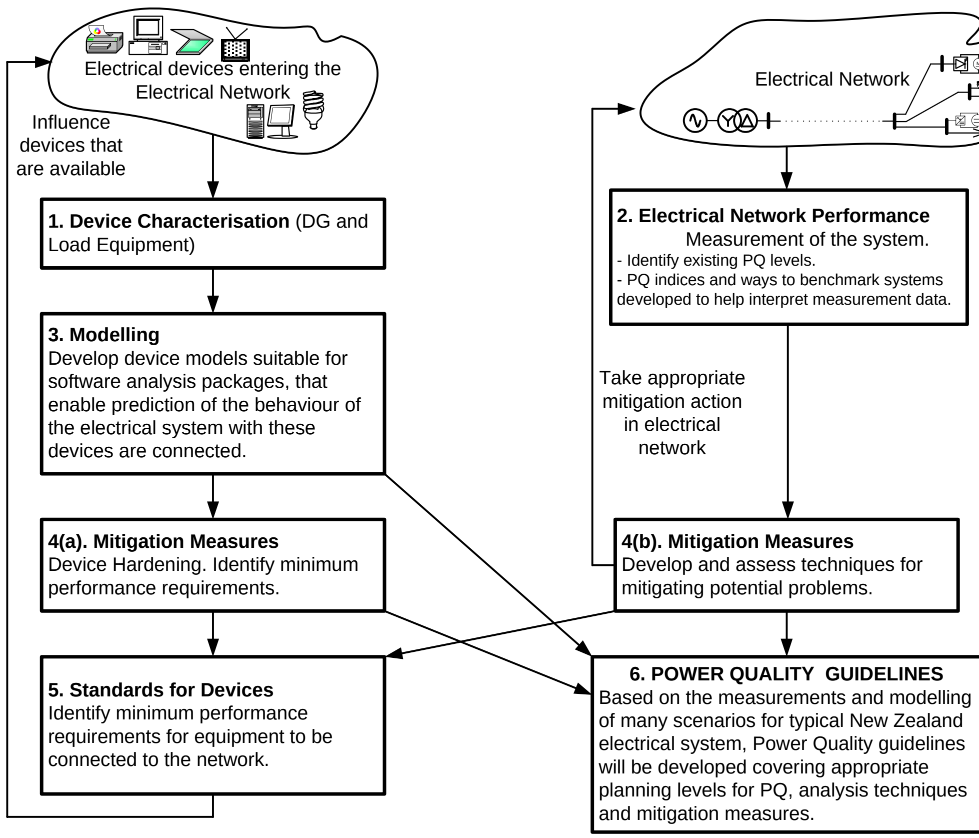

Figure 2. Overview of Project to Develop Power Quality Guidelines

4. Network Characterisation

The characterisation of typical New Zealand distribution systems involved both surveying Lines companies and by taking PQ measurements.

4.1 Transfer between Emission and Disturbance

The strength of the ac system determines the disturbance level generated for a given emission level. In the absence of resonances, the fault level is a good measure of the system strength. Therefore a survey gathered information on the fault levels at different levels of the distribution system. Survey results are depicted generically in Fig. 3. Figure 4 shows a plot of t fault levels for different parts of the distribution system in different utilities. As expected, the transformers have a more influential effect of fault level than the lines/cables. The survey information also differentiated whether primarily supplying rural, remote rural, industrial, commercial or residential load. There was a greater difference in fault level with type of load supplied at the higher voltage levels, with little difference at the lower voltages.

Although data for the 400V supply transformers was available, very little information was available for fault levels at the customer premises. Measurements were undertaken at three residential sites. These involved recording harmonic currents and voltages, change in levels with switching equipment on and off (for impedance calculations), loop tests and ball-park calculations. A figure of 0.183 + 0.179j Ohms was reached at one site (house near the end of LV feeder). Loop resistance was measured to be 0.162 Ohms.

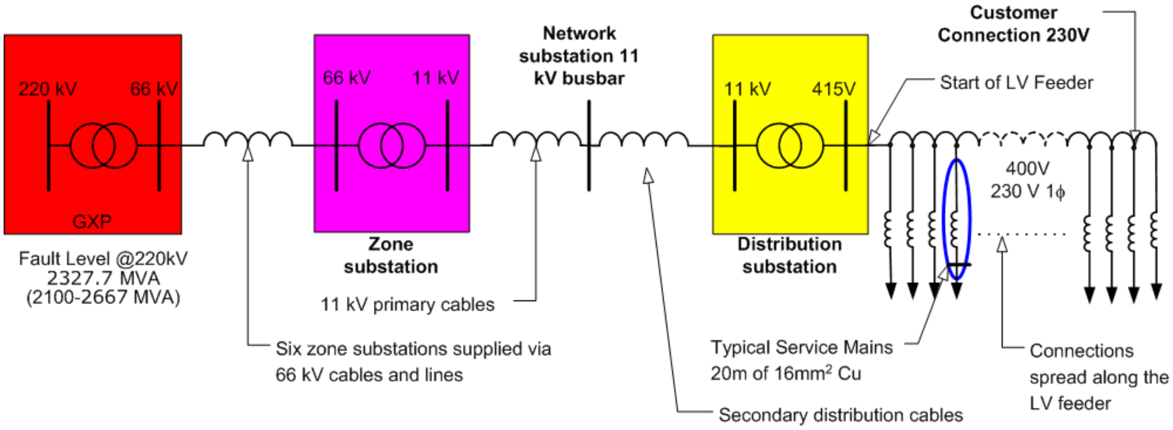

Figure 3. Generic view of the Electrical Power System

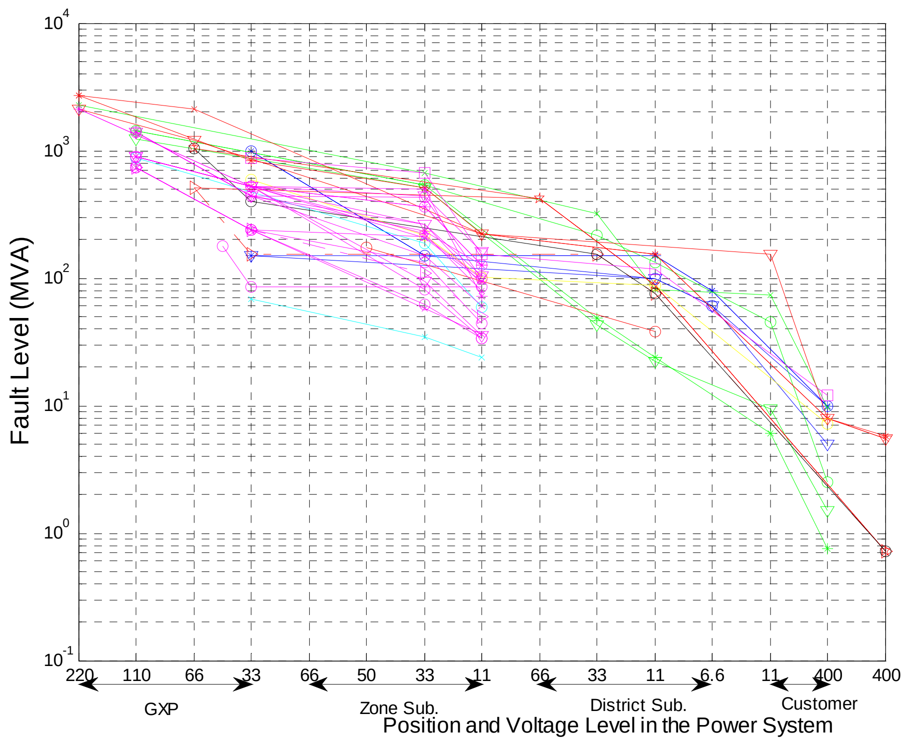

Figure 4. Variation of Fault Level for various parts of the Electrical Power System.

4.2 Existing Disturbance Levels

PQ disturbances can be broadly classified into two categories, Variations and Events. Variations considered in this project are:

- Steady-state voltage
- Voltage Unbalance
- Harmonics

The only events considered were Voltage Dips/Sags.

4.2.1 Steady-state Voltage

The 1st percentile and 99th percentile values were taken as the minimum and maximum levels for both the LV and 11 kV sites. The type of loads connected is clearly evident from the voltage distribution at the LV sites. Rural sites show the largest spread with 6.3 to 11% between the minimum and maximum voltages. Commercial sites have the lowest variation, of between 3.3 to 3.8%. Residential sites have 5.2 to 8.1% variation between their minimum and maximum values, with inmost 5.2 to 5.9% range. Industrial sites are very dependent on the type of operation and hence, the nature of their loads and the variation between minimum and maximum range from 3.3% to 5.3%. Even at the 11 kV sites, the spread of voltage at a rural location was clearly larger than the others. This is attributed to the large irrigation load being feed. The voltage variation at the 11 kV is considerably less with Urban 2.6% to 3.3%, Industrial 3.7% and Rural 7.5%

4.2.2 Voltage Unbalance

The two sources of Voltage unbalance are:

- the effect of drawing current through a electrical network with unbalanced electrical parameters
- unbalanced loading on the phases

In general, the voltage unbalance at commercial and rural sites is less than at residential and industrial sites at the LV level. This is to be expected as residential sites are an accumulation of single-phase loads. The uneven distribution of single-phase loads across the phases is a major cause of voltage unbalance. The voltage unbalance at the 11 kV sites is considerably less with none exceeding the 2% limit and 40% above 1% limit.

4.2.3 Harmonics

Measurements at residential sites showed that the voltage harmonic levels of triplen order (odd multiples of 3) are considerably higher than expected and breach IEC limits (summarized in Table 1). The 15th and 21st limit of IEC are considerably lower than the odd harmonics on either side and considering the actual levels that occur this should not be the case.

Table 1: Voltage Harmonics (95% Percentile levels)

Harmonic Order	Range (% Fundamental)	IEC Limit
3rd	0.6 -1.9	5
5th	1.4 -3.3	6
7th	0.9 -1.4	5
9th	0.2 -1.2	1.5
11th	0.4 -0.6	3.5
13th	0.2 -0.5	3
15th	0.2 -0.7	0.3
17th	0.1 -0.3	2
19th	0.1 -0.3	1.5
21st	0.1 -0.3	0.2
23rd	0.10 -0.15	1.5
25th	0.10-0.13	1.5

4.2.4 Flicker

No untoward flicker levels (P_{st}) were observed although the rural flicker levels were higher than the urban.

4.2.5 Voltage Dips/Sags

These were collected for 230V, 11kV, 33 kV & 66kV. These follow the protection curve with the 1 second clearing time being more evident at the high voltage. The depth varied depending on the distance to fault location and fault impedance.

5. Harmonic Emission Allocation

A new method for allocating harmonic emission, known as the Voltage droop method [11,12], is proposed in the PQ Guidelines. The voltage droop approach basically determines a harmonic voltage allocation. This is converted into a harmonic current allocation by assuming that the system harmonic impedance is inductive and linearly increases with harmonic order "h". This requires that all transmission lines are sufficiently short and that all capacitors are detuned. If these requirements are not met, the determination of harmonic current allocation is difficult and no guarantees can be made that the allocation can be kept unchanged in the future. This difficulty arises not just with the voltage droop method of harmonic allocation but with all other methods as well. The new method links harmonic voltage drops to fundamental voltage droop so the former is held within limits providing the later has been properly considered. This link removes the requirement for extensive harmonic studies for each harmonic allocation. The approach can be applied to MV installations, LV installations, and as a reasonable first estimate for newer LV equipment harmonic current limits in cases where equipment standards might not yet be developed. Unlike other methods, it is easy to extend to the allocation of THD and the approach can be further refined to use field measurement data to take account of previous allocation policies.

5.1 Principles

This method has been adapted to conform, as much as possible, to the IEC allocation principles without incurring a large data collection and calculation burden. The main principles are:

1. Time varying harmonic quantities are represented by their 95% values.
2. Diversity between independent sources is represented by the Summation law. If V_{1h} and V_{2h} are the 95% values of independent harmonic voltages at frequency h, the 95% value of the combined effect (V_{Th}) is given by:
$$V_{Th} = \sqrt[\alpha]{V_{1h}{}^{\alpha} + V_{2h}{}^{\alpha}} \qquad (1)$$
The summation exponent "α" is chosen according to the order of the harmonic. $\alpha = 1$ for $h < 5$, $\alpha = 1.4$ for $5 \le h \le 10$ while $\alpha = 2$ for $h > 10$.
3. The allocation should increase with customer maximum demand.
4. The allocation should be such that the largest harmonic voltage in the system should reach the planning level when all customers are connected and taking their full IEC allocation.

5.2 Overview

The load short-circuit ratio (SCR_i) is the ratio of the fault level at the point of connection to the maximum demand of a load. The load voltage droop (V_{di}), in p.u., is approximated by the inverse of the load short circuit ratio.

$$V_{di} = \frac{1}{SCR_i} \qquad (2)$$

The maximum voltage droop when full loaded (V_d), ignoring the tap-changes on transformers and voltage regulators, is required for harmonic allocation. It has been estimated to be about 10% for each voltage level where voltage regulation (usually by tap-changer) takes place. A value of 30% is recommended for most studies. This has been confirmed by comparison of the harmonic current allocations given by the voltage droop approach with those given by IEEE 519. However, where supply substations are heavily loaded, it is recommended that a larger value be used. Simulations suggest that a suitable value is found by first determining the substation SCR, defined as the ratio of the output fault level to the firm capacity.

V_d = maximum(30%, 200/SCR)

Considering diversity, the allocated contribution to harmonic voltage for load *i* at harmonic *h* (E_{Uhi}) is given by:

$$E_{Uhi} = L_h \left(\frac{V_{di}}{V_d} \right)^{1/\alpha} \quad (3)$$

L_h is the LV voltage planning level for harmonic order *h* (which can be expressed as proportion or percentage). When all the loads are using their allocation this level should be just reached. Using eqn (2) gives:

$$E_{Uhi} = \frac{L_h}{\left(V_d \times SCR_i\right)^{1/\alpha}} \quad (4)$$

Assuming the harmonic impedance increases linearly with *h,* then the allocated harmonic current injection for load *i* at harmonic *h* (E_{Ihi}) is (in pu or %):

$$\frac{E_{Ihi}}{I_i} = \frac{L_h \times SCR_i^{(1-1/\alpha)}}{hV_d^{(1/\alpha)}} \quad (5)$$

Where I_i is the agreed maximum demand for load *i*. If L_h is expressed in % then E_{Ihi}/I_i will be the harmonic current allocation as a percentage of fundamental current. If L_h is expressed as a proportion, then E_{Ihi}/I_i will be a fraction.

As an illustrative example consider the 5^{th} harmonic current allocation of a 75 kVA load connected to a 11kV/400V transformer. If the system fault level is 6500 kVA, then the SCR is 86.667. The maximum fundamental current is 108.25 Amps. If the Planning level is 0.04 (that is 4%) then I_5= 6.765% or 7.32 Amps. When the load is drawing less than the agreed maximum demand then I_5 can exceed 6.765% as long as it does not exceed 7.32 Amps. This allocation assumes a diversity factor of 1.4 in the 5^{th} harmonic. If it is known that the other loads connected are similar in nature with no diversity then this must be considered. For example, if another block of 75 kVA load has the same characteristics, then an allocation for 150 kVA is made and the allocation split between the two 75 kVA blocks. This gives a 5^{th} harmonic current allocation of 5.549 % (or 12.0 Amps) for the 150 kVA block and hence there is an allocation of 6.0 Amps for each of the two 75 kVA loads. This assumes there is diversity between these two blocks of load and the remaining load. If all the connected loads are similar then the harmonic diversity can simply be changed to one to reflect this. As a further illustration let us assume a planning level of 4% for odd order harmonics and 2% for even harmonics. Figure 5 shows the allocation as a function of load SCR assuming these planning levels. This can be converted to an allocation based on load power as illustrated in Figure 6.

5.2 Compatibility Level

Equipment manufacturers are designing equipment to meet IEC compatibility levels so their products can be sold in Europe. Therefore it is reasonable to assume equipment imported into New Zealand is manufactured to have immunity levels that meet the IEC requirements. It is therefore proposed that similar compatibility levels are used in New Zealand, except for the triplen harmonics for the reasons outlined previously. Planning levels are then set lower than these to give an adequate safety margin.

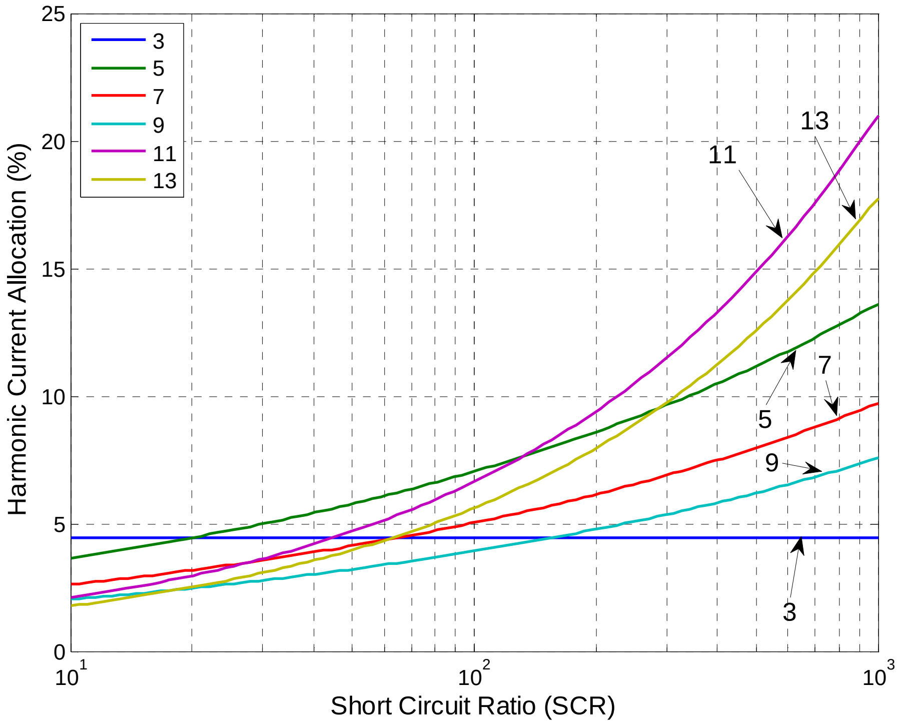

Figure 5. Harmonic Current Allocation as a function of SCR

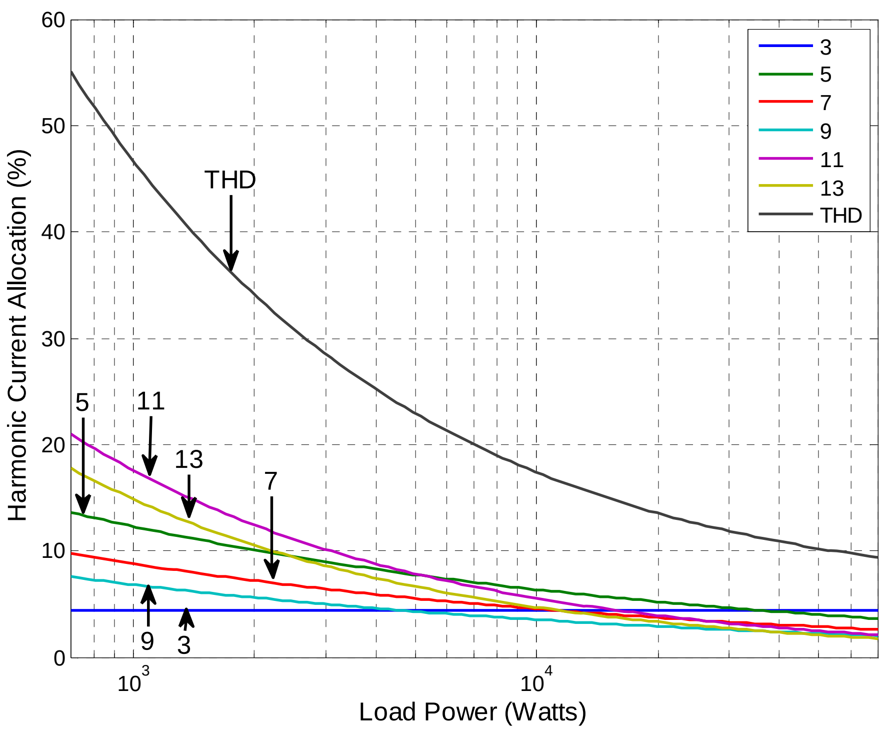

Figure 6. Harmonic Current Allocation as a function of Load Power

6. Conclusions

This paper has discussed the two tracks used for developing PQ Guidelines for New Zealand, namely Device Characterisation and Network Characterisation. The principles of Electromagnetic Compatibility have been discussed and specific details given of a new harmonic allocation method, known as the Voltage droop method.

7. Acknowledgements

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