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Power-Quality Management in New Zealand

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***Index Terms*—Harmonics, power quality (PQ), regulations.**

I. Introduction

NEW ZEALAND (NZ) is one of the most interesting countries for studying power quality (PQ) and, in particular, harmonics since it is a small island nation in which an extremely high proportion of generated electricity undergoes rectification. In fact, just two loads (Tiwai aluminium smelter and HVDC link) can constitute up to 28% of the peak generation for the country. This has resulted in documented harmonic problems since the mid 1960s. Moreover, there is always the challenge of ensuring that ripple control (which is used throughout New Zealand) operates reliably in the presence of background disturbance levels.

With the proliferation of equipment using power electronics, an increasing number of industrial loads are nonlinear and generate harmonics. Because of the importance of PQ and the concern regarding the possible impact of new technologies (such as widespread use of photovoltaic (PV) and electric vehicles), a three year project was initiated. This project was jointly funded by the NZ Government through FRST and the Electricity Engineers' Association (EEA).

This paper gives an overview of this project that was designed to manage the PQ levels into the future and especially with the challenges of new technologies. Details are given on how the project was conducted and the key outcomes.

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II. NZ Regulatory Framework

Before discussing the project, a few words on the N.Z. regulatory frame are necessary. In 1981, regulations were passed to limit harmonic levels in the NZ electrical network. This was at a time when there were only a few well-known sources of harmonics. The regulations dealt with voltage harmonics and telephone interference factors (EDV and EDI), and no allocation was given for emissions. These 1981 regulations are now encapsulated in the N.Z. Electrical Code of Practice (NZECP) No. 36 [1]. NZECP 36 was made mandatory by being cited by the electricity regulations. NZ has also adopted a joint AS/NZS 61000 series of standards that are based on the equivalent IEC 61000 standards. These differ significantly from NZECP 36; however, they are not binding unless cited.

However, in 2010, a dramatic departure occurred with the release of the *Electricity (Safety) Regulations 2010* [2]. Instead of NZECP 36 being the only means of compliance for harmonics, it was made as only one of several. Section 31 states:

> "compliance with whichever of the following standards is applicable is deemed to be compliance…"

but no guidance is given as to which standard is applicable.

Utilities that own and operate the distribution network (known as lines companies in NZ) also have grid connection codes which outline the technical requirements customers must meet for connections to the electricity distribution network. These have varied across the country. However, the objective of the PQ project is to have one common requirement across the country, which will result in standardization of solutions for equipment manufacturers and suppliers.

III. PQ Project

The project was entitled *Power Quality (PQ) in Future Electricity Networks (NZ)* (or *PQ project*) and the primary outcome was power quality (PQ) guidelines for the electricity industry in NZ [3]–[5]. These were promulgated through the EEA and used by their members as part of their connection codes. Other objectives were to:

1) identify mitigation techniques;
2) influence the standards to ensure poor devices are not deployed;
3) educate and disseminate information regarding PQ to the industry.

Fig. 1 illustrates the tradeoff that exists between emission limits and cost. Specifying low emission levels will result in a higher cost for equipment while the cost incurred by the system will be minimal. Allowing high emission levels will allow cheaper equipment to be deployed (although this might be countered somewhat by the need to have a higher immunity

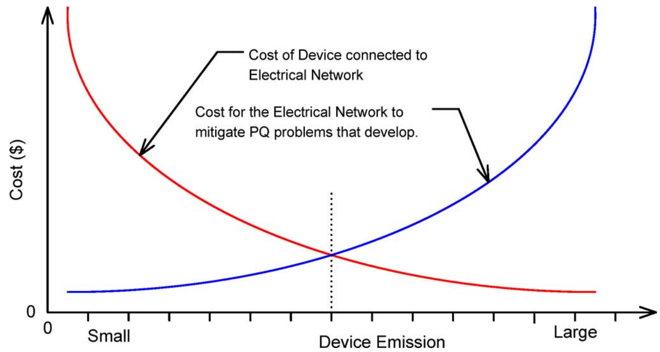

Fig. 1. Dependency of network and equipment costs on device emissions.

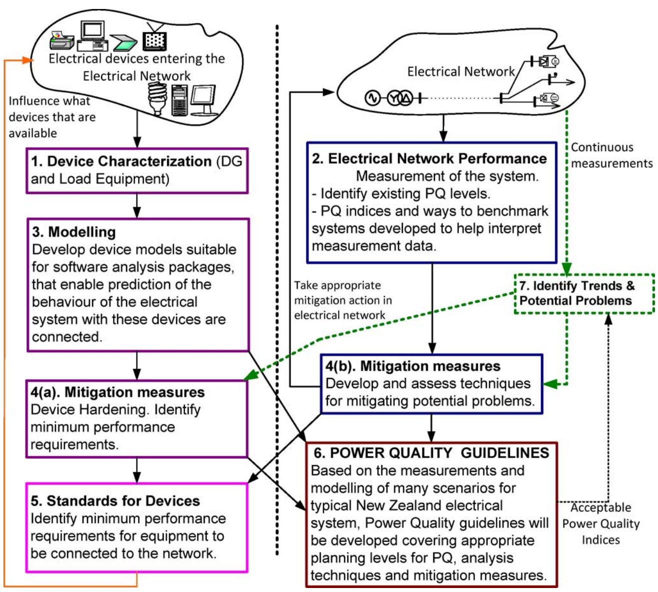

Fig. 2. Overview of the PQ project to manage PQ levels in NZ.

level), but a higher cost will be incurred by the system (in extra losses, loss of equipment lifetime and mitigation).

IV. Project Plan

There were two main streams to the project: 1) device side and 2) electrical network side (depicted in Fig. 2) [3]–[5]. The device side first involved characterizing the emission and immunity of devices. In many cases, their circuits were analyzed and computer models were then developed, which enabled simulations to be performed to see what the likely the PQ levels would be if widespread deployment occurred. This gave insight into mitigation methods (design changes to enhance performance) and their feasibility. This led to minimum performance standards for devices entering the NZ market, resulting in the modification of AS/NZS61000.3.2.

The electrical network side characterized: 1) existing disturbance levels and 2) sensitivity of the disturbance levels to emissions. That is, for a given emission level, what is the impact on the disturbance levels? This is linked to the system's impedance and is also influenced by resonance conditions.

The management of utility emission levels is similar for all disturbance types. The treatment given below is particularly relevant to harmonics, where one of the main PQ problems is addressed. The average low-voltage (LV) customer cannot be expected to understand or implement measures to limit emissions. Instead, equipment/device emission limits are defined by the relevant device standards. These limits are designed to ensure that equipment connected to the LV network will not lead to PQ levels which exceed compatibility limits. It is the responsibility of the manufacturer to design and construct equipment to meet these limits.

At medium-voltage (MV) (and for some LV customers), installation limits are determined by the utility following the PQ guidelines. The customer attempts to meet this limit by the specification of appropriate equipment, sometimes with additional filters or other mitigation measures.

V. Device Characterization

A. *Emission Levels*

Letters were sent to retail outlets asking for their permission to measure the harmonic emissions from all appliances on their shop floor. This represents the devices presently entering the system. Monitoring equipment as well as a CHROMA arbitrary waveform generator were transported to the stores and four tests were performed on each device. The first three were with a sinusoidal waveform (230 V, 230 V−6%, 230 V+6%) and 230 V with harmonics (flat-top waveform) [6], [7]. A small representative sample of devices was purchased and taken to the laboratory for further testing (voltage dip/sag testing and in-rush testing [8]). This was necessary due to the stress that such testing puts on the device and there is the possibility of damage. In-situ PQ measurements were taken of irrigation pumps, dairy factories, PV installations, etc. PQ data were also gathered from installations and networks which already have PQ monitors installed (mainly windfarms and two utilities).

The desire for energy efficiency has resulted in the government-subsidized campaigns to replace incandescent lamps with compact fluorescent lamps (CFLs). Although each device is small, the combined effect of millions is significant [9]. Heat pumps are another energy-efficient technology that is rapidly being adopted. Subsidies (as well as the Canterbury earthquakes) have resulted in an incredibly large number entering the system in recent years. In the rural sector, high prices for dairy products and low prices for wool and lamb have resulted in many cropping and sheep farms converting to dairy farming. Often, these farms are situated in dry areas where intense irrigation is required to maintain adequate grass growth for the herds. The irrigators use submersible pumps that are fed from variable speed drives (VSDs). Due to the size of these pumps, typically 100 kW up to 2.2 MW, some type of soft starting is required. VSDs are selected rather than soft-starters due to the additional features they provide and the incremental cost. These VSDs have caused harmonic problems, including interference with protection and control equipment in the rural network [7], [8]. Many other devices, such as LED street lights, electric-vehicle chargers, etc., have been tested. This has shown that many manufacturers comply with the letter of the regulations rather than the essence of the regulation. Since equipment is to be tested at rated power, the waveshape conditioning circuitry is

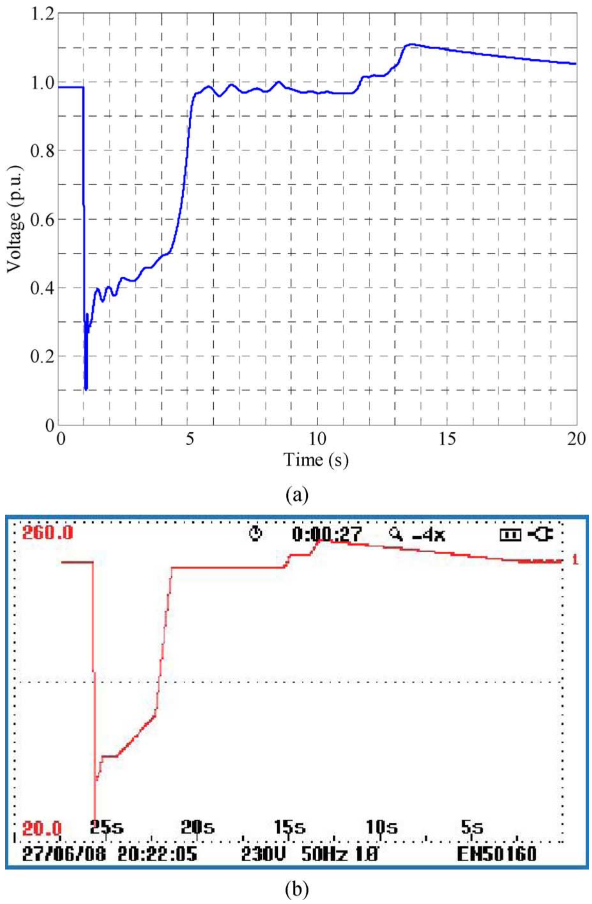

Fig. 3. Voltage profile for hard fault. (a) Supplied profile for a hard fault. (b) Waveform from an arbitrary waveform generator.

often switched out at lower power levels, resulting in a very poor waveform [10].

B. Immunity

Testing of immunity to voltage dips/sags has been performed as well as quantifying the improvement in immunity with extra dc bus capacitance. Moreover, two voltage dip/sag profiles supplied by Transpower NZ Ltd. were used for testing heat-pump performance. Fig. 3(a) shows the supplied profile for a low-impedance fault based on measurements of these events while Fig. 3(b) displays the digitized representation that the arbitrary waveform generator applies for the device under test (DUT).

Testing has also been performed at sites where malfunctions have been blamed on poor PQ.

Initially, simulations were performed using a scenario-based (case study) approach, as so many of the papers published recently. These studies are based on measured characteristics and typical electrical systems from the authors' country. Although these studies give some useful insights, they are generally of limited applicability (due to the specifics of the case analyzed). This project required what could be called a regulatory-based study, as depicted in Fig. 4(b). This is based on acceptable disturbance levels and the characteristics of the electrical network (which will be different for different countries), and from this, the performance requirements of electrical devices are obtained. In the regulatory-based approach, a specific network was not

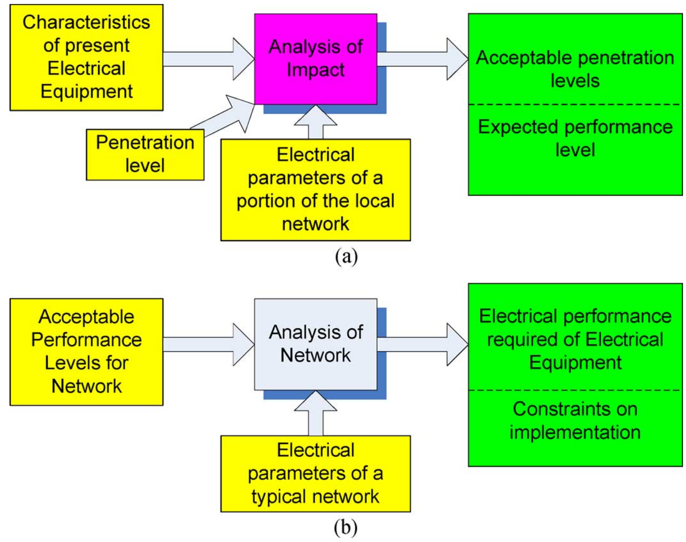

Fig. 4. Types of studies: (a) scenario based and (b) regulatory based.

used but five representative networks. These representative networks were distilled from a survey of all distribution companies in NZ. Hence, they were a statistical representation of the NZ networks rather than any particular one.

VI. Electrical Network Characterization

A. Existing Disturbance Levels

A national survey of existing PQ disturbance levels has been undertaken at MV and LV levels. Monitoring was also performed at customer premises. Each lines company receives a report on their PQ disturbance levels on their network. Once the national survey has been completed, a report will be produced, benchmarking the different networks. The identity of lines companies will be anonymous.

B. System Impedance

With the help of the EEA, the lines companies were surveyed to obtain information on typical network topologies and fault levels. Estimation of the supply impedance at harmonic frequencies was obtained via a change in disturbance level with a change in injection and capacitor switching. Resistive loop testing (performed by the utility) and ballpark calculations were also used to verify the supply impedance.

C. Mitigation

Mitigation of the intolerably high 5th harmonic levels in rural areas was studied [11]. Although harmonic filters were investigated, the preferred solution was the use of zig-zag transformers (Dnz0) [12]. These were deployed and the harmonic levels monitored to verify the improvement. Dairy factories that convert milk to milk powder use a large number of VSDs and create significant harmonics. Dnz0 transformers have been used here also. Other mitigation methods have been: 1) limiting equipment entering the market based on their performance; 2) ensuring the diversity of equipment entering the system; 3) design changes that improve performance; 4) harmonic filters; and 5) switching energy source (e.g., electricity to gas).

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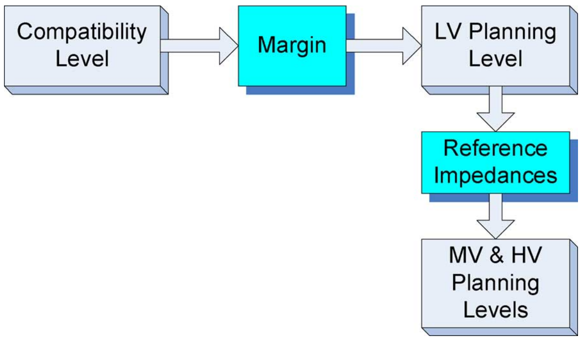

Fig. 5. Setting planning levels.

TABLE I
COMPATIBILITY LEVELS FOR HARMONIC VOLTAGES (RMS VALUES AS A PERCENTAGE OF RMS VALUE OF THE FUNDAMENTAL COMPONENT) IN LV AND MV POWER SYSTEMS

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 %
5	6	3	5	2	2
7	5	9	3.0	4	1
11	3.5	15	2.0	6	0.5
13	3	21	1.5	8	0.5
17≤ h ≤49	2.27×(17/h)-0.27	21< h ≤45	1.5	10≤ h ≤50	0.25×(10/h)+0.25
Note: Total Harmonic Distortion (THD): 8%					

VII. HARMONICS

A. Setting of Compatibility and Planning Levels

Since equipment is now sold on a world market, most of the equipment being used will be designed in terms of emissions and immunity for conformity to international standards. Therefore, the new set of limits for LV systems is better aligned with international standards. The new compatibility levels for harmonic voltages are shown in Table I. The planning level at LV is set to 90% of the compatibility level. The difference between the planning levels at different voltage levels sets the allowed emission at the voltage level and is a function of system impedances. From the survey work, five typical network configurations were identified and typical impedances were obtained. These were then used to develop the planning levels at all other voltage levels [13]. This is depicted in Fig. 5. Of note is that the triplen harmonic levels in Table I are significantly higher than those specified in IEC standards. Measurements on the NZ system showed some triplen harmonic levels that are already twice the IEC limits and with no adverse effects. The reasons for having lower triplen harmonic levels would have to be coupled to the fact that they are zero sequence. Telephone interference would be one obvious consideration. There has been a long history of telephone interference with analog circuits in NZ, but with modern technology, this problem has largely disappeared. Therefore, triplen and nontriplen odd harmonics are not distinguished in terms of approach and formulae used in the PQ guidelines.

The developed planning levels for LV, MV, and HV were compared to other existing, and draft, international standards and limits (e.g., IEC, ER G5/4, NRS048, EN50160, AS/NZS & IEEE 519, France, Hydro Quebec) to see how they compared.

B. Allocation of Emissions

Any allocation method needs to have a sound technical basis and be:

- fair;
- well defined;
- practical.

The voltage droop philosophy has be adopted for this [14]–[16].

Customers and equipment manufacturers can control the time variation of their installations/products better than utilities can control their harmonic voltages. Because of this, it is justified to compare the installation or devices' 100% (maximum) current with the allocated value whereas the harmonic voltage is based on the 95% level.

The allocated harmonic voltage contribution for an installation is

$$E_{Vhi} = \frac{L_h}{(V_d \mathrm{SCR})^{1/\alpha}}. \tag{1}$$

where

L_h relevant planning level;
SCR short-circuit ratio;
V_d voltage droop (proxy for the system impedance) $[V_d = \max(0.3, 2/\mathrm{SCR})]$.

The harmonic current allocation is

$$E_{Ihi} = \frac{E_{Vhi}}{X_{ih}}. \tag{2}$$

In the absence of resonances and if not a triplen harmonic, the impedance can be approximated by

$$X_{ih} = \frac{h}{FL_i} \tag{3}$$

where FL_i is the fault level at the ith load, giving

$$\frac{E_{Ihi}}{S_i} = \frac{L_h \mathrm{SCR}^{(1-1/\alpha)}}{h {V_d}^{1/\alpha}}. \tag{4}$$

The voltage droop method is not restricted by whether the system is radial or meshed. Of more importance is the fault level, which is largely determined by the number of voltage transformations. Additional guidance is given on the application of the voltages droop method where there are resonances. Rather than using (3) as a proxy for harmonic impedance, the actual harmonic impedance, as assessed from computer simulation, is used instead.

Embedded generation is considered as a load for harmonic allocation purposes. This necessitates consideration of the probability distribution for the embedded generation, hence the network's ultimate supply capacity, including embedded generation. Without this consideration, full allocation is given to the

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embedded generation, thereby restricting the allocation for all other loads, even though it may seldom reach its full generation potential.

C. Short-Term Harmonics

For short-term harmonics, the major limitation is not thermal effects but interference with neighboring equipment. The compliance, based on a 10-min reading, can allow intolerably high harmonic levels for a short time. For this reason, voltage harmonics and current harmonics have short-term limits that are separate to the statistical limit of 10-min readings taken over 1 week. The short-term harmonic voltage limit is 150% of the steady-state value. Many instruments give for each 10-min reading, the ratio of the maximum 3-s value to the average; hence, the maximum 3-s value is available. Each 3-s recording must be below 150% of the steady-state limit.

In order to limit the short-term total harmonic distortion (THD) level, the short-term harmonic current emission must be limited. The multiplication factor for short-term harmonic current emission is

$$F = \frac{20}{1 + 19 * \left(\frac{S_i}{S_t}\right)} \tag{5}$$

where S_i/S_t is the ratio of the installation size to supply capacity. With an aim of limiting the harmonic voltage to 1.5 times the steady-state limit, 1 in 6 sample periods is 1.5 times the steady-state limit and the rest is at the steady-state limit, then the average of the rms values is approximately 1.05 times the steady-state limit. This is then weighted by the relative size of the load (F). Therefore, if a load is very small, then F is approximately 20 and the short-term harmonic current limit is $20 \times 1.05 = 21$ times their steady-state limit. If a load is very large, F is approximately 1 and the short-term limit is $1 \times 1.05 = 1.05$ times their steady-state harmonic current limit.

D. Interharmonics and Higher Frequency Emissions

Due to the negative consequences, interharmonics need to be limited. The main frequency divisions are:

$<$50 Hz (subharmonics);
50 to 2.5 kHz;
2.5 to 9 kHz;
9 to 150 kHz;
$>$150 kHz.

Disturbances in the frequency range 2.5 to 150 kHz are classified as narrowband, broadband, or recurring oscillations. For frequencies between 100 Hz to 2.5 kHz, although a level of 0.5% may be tolerable, this may need to be reduced for frequencies within 8.8 Hz of harmonic frequencies due to light flicker, and possible interference with PLC if present and the frequency coincides. When considering a band of frequencies and using a 200-Hz bandwidth, the reference value which should not be exceeded is 0.3%.

The reference value is determined by considering the following impacts:

- light flicker–this involves looking at the frequencies generated and the perceptibility of these frequencies;
- acoustic noise and vibrations—in the frequency range 1 kHz to 9 kHz the limit is 0.5%; although the level of disturbance depends on the type of equipment and frequency, above this value, the disturbance is likely to be noticeable;
- compatibility with ripple control;
- interference with and malfunction of equipment;
- destruction of thyristor-based equipment due to false triggering.

In NZ, ripple control is widely used and these use harmonic and interharmonic frequencies. Therefore, compatibility with ripple control is important. Ripple receivers may respond to as little as 0.3% of the nominal supply voltage; therefore, the reference limit is set to 0.1% of the nominal supply voltage. Any interharmonic with a level close to or above 0.3% is likely to cause interference when its frequency coincides with the operational frequency of the receivers. This limit is location specific as different regions will have different ripple frequencies.

One issue was whether control signals, such as ripple control, should be called out as an exception to the limits or made to comply with the short-term emission limits. The latter approach was taken. This seemed prudent as ripple control signals are known to interference with equipment when the signal level is high; hence, it should be restricted also.

VIII. Other PQ Issues

The EEA PQ guidelines also address (to varying degrees):

- steady-state voltage;
- voltage unbalance;
- voltage fluctuations and flicker;
- voltage dips/sags;
- voltage swells;
- frequency deviation;
- telephone interference;
- dc current injection;
- wiring and contact defects.

For these PQ issues, either international or local standards have been drawn upon.

A. Steady-State Voltage

Except for momentary fluctuations, the voltage magnitude supplied to an installation must be kept within $\pm$6% of the nominal voltage (230 V for phase-to-neutral LV). Hence, the maximum range is 216.2 to 243.8 V. The immunity of equipment is expected to be $\pm$10%, giving a margin between the disturbance level and immunity level. Assessment is made of the 99th percentile and 1st percentile of 10-min rms readings over a one-week period.

B. Voltage Unbalance

A compatibility level of 2% has been adopted, and the indicative planning levels per IEC 61000-3-13 are used (Table III).

C. Voltage Fluctuations and Flicker

The compatibility levels of P_{st} and P_{lt} for LV power systems of 1.0 and 0.8 were adopted (as in IEC 61000-2-2). The indicative planning levels of AS/NZS61000.3.7, shown in Table IV, were also adopted. It is acknowledged that this approach is inappropriate for newer technologies, and flicker based on direct

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TABLE II
-Interharmonic and High-Frequency Limits' Indicative Planning Levels

Frequency	Applied to	Reference Level ($\%V_1$)
0 – 100 Hz	Inter-harmonics (Discrete frequencies)	0.2%
Ripple frequency	(Discrete frequencies)	0.1%
100 Hz to 2.5 kHz	Inter-harmonics (Discrete frequencies)	0.5%
	Harmonics	Already stipulated
2.5 to 9 kHz	Harmonics/ inter-harmonics (Discrete frequencies)	0.2%
	Band of frequencies	0.3%
9 to 150 kHz	Harmonics/ inter-harmonics (Discrete frequencies)	0.2%
	Band of frequencies	0.3%

TABLE III
Indicative Planning Levels

Voltage level	VUF - Planning level (%)
MV	1.8
HV	1.4
EHV	0.8

TABLE IV
Indicative Values of Planning Levels for P_{st} and P_{lt} (L_{Pst} and L_{Plt})

	MV	HV & EV
L_{Pst}	0.9	0.8
L_{Plt}	0.7	0.6

light measurements has been developed but not yet at a stage ready for incorporation into standards or regulations.

Flicker problems have been experienced due to interharmonics. Power-electronic converters act like a modulator that couple frequencies between the ac and dc sides. For example, 175-Hz ripple signal can cause a 25-Hz component in the light from fluorescent lights. The strength of this coupling between a 175-Hz ripple signal and 25-Hz light fluctuation is design dependent and choosing a different model of ballast often removes the problem. However, flicker in incandescent lamps, due to sources such as arc furnaces, can often be solved by replacing them with CFLs. The characteristics of the voltage fluctuations and the lighting technology (hence, transfer from voltage fluctuations to light fluctuations) determine the level of light flicker experienced. For this reason, a light-based flickermeter has been developed.

D. Voltage Dips/Sags

The ITIC curve is a voltage tolerance curve which shows the region for which equipment should tolerated. It covers voltage dips and voltage swells. Therefore, the lower limit of the ITIC curve is a measure of the voltage dip/sag that the equipment should withstand. Although designed for computer and electronic business equipment (its predecessor was the CBEMA curve), the immunity of other equipment is often tested against the ITIC curve. This is due to the lack of internationally accepted limits for immunity of other classes of equipment to voltage dips (the one exception is SEMI 47).

TABLE V
Voltage Dip/Sag Limits

Duration of Event	Deviation from Nominal		Retained Voltage	
	Immunity (ITIC Curve)	Planning Level	Immunity (ITIC Curve)	Planning Level
< 2 ms	100%	90%	0%	10%
20 ms to 0.5 s	30%	27%	70%	73%
0.5-10 s	20 %	18%	80%	82%
> 10 s	10%	9%	90%	91%

Many sources of voltage dips are unplanned events in which an emission allocation is inappropriate. However, for events for which an emission allocation is appropriate (e.g., motor starting), in accordance with the practice of 10% margin between the compatibility limit and planning level, the deviation from nominal voltage is multiplied by 0.90 to give a planning level as a deviation from nominal voltage. This is then converted to a retained voltage limit (see Table V). Both voltage dip/sag time and phase aggregation are dealt with. Of particular note is the work on voltage dip/sag characterization, propagation, and limits of the CIGRE/CIRED/UIE Joint Working Group C4.110, IEC, Eskom and others [17]–[20].

The PQ measurement of existing disturbance levels has clearly shown that faults cause voltage dips to be outside the voltage dip/sag limits, and this is due to the speed of the power system protection equipment.

E. Voltage Swells

Voltage swells occur when the rms voltage rises to more than 110% of nominal for a period of 1 min or less. As with voltage dips/sags, many sources of voltage swells are unplanned events for which an emission allocation is inappropriate. However, there are some events for which an emission allocation is appropriate (e.g., load rejection). In accordance with the practice of 10% margin between the compatibility limit and planning level, the deviation from nominal voltage (from ITIC curve) is multiplied by 0.90 to give a planning level as a deviation from nominal voltage. This is then converted to a percentage voltage-level limit (as is done for voltage dips/sags). There are four timeframes: 0.1 to 1 ms, 1 to 3 ms, 3 ms to 0.5 s, and > 0.5 s, as based on the ITIC curve timeframes.

F. Transients

Transients can be classed in different ways. Common classifications are:

a) shape of transient (oscillatory or impulsive);
b) source of energy for the interaction (electromagnetic transient or electromechanical transient);
c) timescale of the phenomenon (fast, medium, or slow transient), which is linked to the objective of the analysis (insulation coordination, switching study, overvoltage study, transient stability).

Transient effects can be attributed to three mechanisms:

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TABLE VI
RECOMMENDED LIMITS ON PEAK VOLTAGES

Peak as percentage of normal steady-state crest voltage	Duration of event
200	< 1 ms
140	1 to 3 ms
120	3 ms to 0.5 s
110	> 0.5 s

TABLE VII
DROPOFF FREQUENCIES FOR AUFL

	Block 1		Block 2	
	SI	NI	SI	NI
Frequency (Hz)	47.5	47.8	45.5	47.5

1) increased component and insulation stress due to elevated crest voltage; this will cause degradation of the insulation and components in equipment; repetition of these events will shorten the lifetime of equipment;
2) malfunction due to high dv/dt;
3) multiple zero-crossings causing timing issues.

Due to the diversity of transient responses, there is no straightforward way of specifying and imposing transient limits. As a first step for switching transients, the peak voltage should not exceed the recommended levels shown in Table VI.

The frequency of oscillation needs to be estimated and dv/dt compared to the immunity of all equipment subjected to it. Likewise, the immunity of equipment to multiple zero crossings needs to be ascertained.

Management of switching transient peak voltages has been through: design of equipment (e.g., detuning reactors on capacitor banks), point-on-wave switching on circuit breakers (CBs and, in one case, the addition of an RC filter to an 11-kV busbar (to limit dv/dt as supplying thyristor-based equipment).

G. Frequency Deviations

The frequency is to be maintained within 1.5% of 50 Hz, except for momentary fluctuations. The momentary fluctuation clause is to cover those inevitable system events (fault or loss of generation) over which there is no control. The expected frequency swing in a major event is $\pm 10\%$. This has been borne out by system events that have seen the frequency in one island going to 55 Hz and the other to 45 Hz. Both spinning reserve and automatic underfrequency load shedding (AUFL) are essential to maintain transient stability since NZ has no neighboring electrical systems to interconnect with. Historically, a minimum of two 16% blocks of load in each island could be automatically disconnected to ensure restoration of the system. Since the nature of the power system is changing over time, it is essential that the AUFL be reviewed periodically. Due to the makeup of the generation in each island and historical reasons, the trip frequencies are different, as shown in Table VII.

The ability of generation to remain connected when the frequency drops due to a real power deficit is essential to maintain stability. Historically, the frequency swing of the North Island was 45 to 55 Hz; however, with deregulation and investment in generation coming from companies, a noncompliant plant has been built (particularly, a combined-cycle thermal plant). This has necessitated the need to reduce this frequency range.

IX. PUBLIC CONSULTATION PERIOD

The PQ project was extended for 1 year after the PQ guidelines were released (at the end of the three-year mark). In this consultation period, the following actions were performed:

- Electricity industry personal were educated on how to use the PQ guidelines through workshops and ongoing communication.
- Feedback was sought on improvements.
- Additional studies were performed on identified issues (impact of harmonic resonances).

This was definitely beneficial and the final EEA PQ Guidelines were issued in early 2013 [21].

The idea of point of compliance or point of evaluation (POE) was introduced. For most customers, the point of common coupling (PCC) will be the point of compliance; however, for some customers, this does not give enough certainty. This is because the location of the PCC will depend on the location of the nearest neighbor, which can change over time and a customer has no control over where the PCC is, and when it changes. This arose because of a new factory being built in a rural area. Transmission lines were installed from the closest substation. The PCC was at the substation but it was acknowledged that other customers will be connected to the line over time. Therefore, it makes sense to make the POE at the end of the MV line and design the installation for this.

A clarification of what fault level is to be used for allocation purposes was made. The MVA fault level will fluctuate based on system loading and most utilities, when asked, give the maximum fault level since this is what they are geared up for; yet, it is the normal minimum that should be used for harmonic allocation. Hence, the fault level to be used is *"the minimum fault level that occurs over a reasonable percentage of the time. (less than one week a year should be ignored)."*

Initially, the PQ guidelines had a two-stage allocation process so that all installations had to comply regardless of size. There was a consensus to realign the stages in the PQ guidelines to AS/NZS and IEC three stages. This means allowing connection if the SCR is sufficiently high (i.e., $S_i/S_{SC} < 0.2\%$).

The effect of harmonic resonances caused by power-factor capacitor banks was investigated since this will influence allocations. These studies looked at straight capacitor banks as well as capacitor banks with a 7% detuning reactor. The effect of power-factor correction capacitors on the 317-Hz ripple frequency has also been looked at.

REFERENCES

[1] NZECP 36:1993, New Zealand Electrical Code of Practice for Harmonic Levels Energy and Resources Division, Ministry of Commerce. Wellington, New Zealand, 1993. [Online]. Available: http://www.med.govt.nz/energysafety/legislation-policy/electricity-acts-regulations-codes/standards-and-codes-of-practice/new-zealand-electrical-codes-of-practice

[2] Ministry of Business, Innovation, and Employment (MBIE) (Govt. of New Zealand), Wellington, New Zealand, Electricity (safety) regulations, Rep. no. SR 2010/36, 2010. [Online]. Available: http://www.legislation.co.nz/regulation/public/2010/0036/latest/DLM2763501.html

[3] N. R. Watson, S. Hardie, V. Gosbell, S. Elphick, and S. Perera, "Development of PQ guidelines for New Zealand," presented at the EEA Conf. Exhibit., Auckland, New Zealand, Jun. 23–24, 2011.

[4] N. R. Watson, S. Hardie, J. Lawrence, B. Heffernan, T. Scott, and S. Hirsch, "Power quality management in New Zealand," in *Proc. CIGRE*, Paris, France, Aug. 22–27, 2010.

[5] N. R. Watson, "Power quality: A New Zealand perspective," presented at the Power Qual. Symp., Kuala Lumpur, Malaysia, Jul. 2010.

[6] N. R. Watson, T. Scott, and S. Hirsch, "Implications for distribution networks of high penetration of compact fluorescent lamps," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1521–1528, Jul. 2009.

[7] S. Hardie and N. R. Watson, "Power quality implications of new residential appliances," presented at the EEA Conf., Christchurch, New Zealand, Jun. 17–18, 2010.

[8] M. Schinkelshoek, N. R. Watson, and B. Heffernan, "The characteristics of CFLs, beyond the harmonics," presented at the Australasian Univ. Power Eng. Conf., Christchurch, New Zealand, Dec. 5–8, 2010.

[9] S. Hardie and N. R. Watson, "The effect of new residential appliances on Power Quality," presented at the Australasian Univ. Power Eng. Conf., Christchurch, New Zealand, Dec. 5–8, 2010.

[10] W. J. B. Heffernan, N. R. Watson, R. Buehler, and J. D. Watson, "Harmonic performance of heat-pumps," *IET J. Eng.* Sep. 2013. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/joe.2013.0012

[11] S. Hardie, N. R. Watson, and V. Gosbell, "An investigation of excessive rural network harmonic levels caused by particular irrigation pumps," presented at the EEA Conf. Christchurch, New Zealand, Jun. 19–20, 2009.

[12] N. R. Watson, S. Hardie, T. Scott, and S. Hirsch, "Improving rural power quality in New Zealand," presented at the EEA Conf. Christchurch, New Zealand, Jun. 17–18, 2010.

[13] N. R. Watson, J. R. C. Orillaza, and S. Hardie, "Harmonic planning levels in New Zealand: Medium voltage networks," presented at the Int. Conf. Harmonics Qual. Power Hong Kong, China, Jun. 17–20, 2012.

[14] V. J. Gosbell and R. A. Barr, "A new approach to harmonic allocation for MV installations," in *Proc. 20th Australasian Univ. Power Eng. Conf.*, 2010, pp. 1–6.

[15] V. J. Gosbell and R. A. Barr, "Harmonic allocation following IEC guidelines using the voltage droop concept," in *Proc. 14th Int. Conf. Harmonics Qual. Power*, 2010, pp. 1–6.

[16] R. A. Barr and V. J. Gosbell, "Introducing power system voltage droop as a new concept for harmonic current allocation," in *Proc. 14th Int. Conf. Harmon. Qual. Power*, 2010, pp. 1–5.

[17] Voltage dip immunity of equipment and installations, Working Group C4.110, CIGRE rep. no. 412, Apr. 2010.

[18] *Electromagnetic Compatibility (EMC) Part 4.11: Testing and Measurement Techniques – Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests*, IEC 61000-4-11, IEC, 2004.

[19] *Electromagnetic Compatibility (EMC) Part 4.34: Testing and Measurement Techniques – Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests for Equipment With Mains Current More Than 16 A per Phase*, IEC 61000-4-34, IEC, 2009.

[20] M. H. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*. New York, USA: Wiley/IEEE, 1999.

[21] *"EEA Power Quality (PQ) Guidelines,"* Electricity Engineers' Association (NZ), 2013. [Online]. Available: http://www.eea.co.nz/tools/products/details.aspx?SECT=publications&ITEM=2577

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