POWER QUALITY ASSESSMENT OF SOLAR PHOTOVOLTAIC INVERTERS

FINAL REPORT

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Toronto and Region Conservation for The Living City

POWER QUALITY ASSESSMENT OF SOLAR PHOTOVOLTAIC INVERTERS

The Living City Campus, Vaughan, Ontario

Final Report

Prepared by:

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

• monitor and evaluate clean water, air and energy technologies;

• assess barriers and opportunities to implementing technologies;

• develop tools, guidelines and policies, and

• promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

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EXECUTIVE SUMMARY

The *CAN/CSA-C22.2 NO. 257-06 (R2011)* and *IEEE 1547-2003* (these standards will be denoted by CSA 257 and IEEE 1547 within this report as shorthand) are the Canadian and U.S. standards that stipulate the tolerances for harmonic current emissions created by distributed resources, such as photovoltaic (PV) installations, connected to low-voltage electrical distribution systems.[1]

- *CSA 257* requires that any inverters used within a grid-connected PV installation be certified to *CAN/CSA-C22.2 NO. 107.1-01 (R2011)* (denoted by CSA 107.1 within this report as shorthand). In turn, *CSA 107.1* requires that an inverter has harmonic emissions below certain limits when the inverter is operating at 100% of its rated load.
- *IEEE 1547* requires that a PV installation obey the same general limits as *CSA 257*. However, in contrast, *IEEE 1547* requires instead that these limits be satisfied at the installation's point of common coupling to the area electrical power system when the installation is operating at 33%, 66% and 100% of the total rated load.

With either standard, the fact remains that an actual PV installation will see a much wider range of operating points, including frequent low-level and highly variable irradiance conditions and it is possible that there may be notable power quality issues outside of the recommended measurement conditions given within the standards.

This study used long-term monitoring to determine the power quality of solar PV inverters across a wide range of real-world operating conditions for four different installations in Vaughan, ON. Within the study, power quality analyzers were deployed for up to a year at the different installations, which ranged in size from approximately 6 to 40 kW. For each site, the total demand distortion (TDD) and individual harmonic distortion factors were determined across the measurement period and compared with the *CSA 257* and *IEEE 1547* harmonic current emission limits.

The harmonic current emission limits within these standards are given as a percentage of the rated load current of the inverter or installation. For example, an installation with a 100 A rated load current would need to have a third order harmonic current that is less than 4% of the rated current (i.e. the limit would be 4 A) when the inverter, or installation, is operating at either: (i) 100% of rated load as in the CSA standard, or (ii) 33%, 66% and 100% of rated load as in the IEEE standard. In contrast, this study looked at whether that 4 A limit, given in this example, was ever exceeded at <u>any</u> power output during both steady and transient conditions. This was done for all harmonic orders and the total harmonic current. The term "over-limit" is used to denote occurrences where the limits are exceeded, regardless of the current output, and similarly, the term "within limit" is used in a similar sense. It follows that "over-limit" does not necessarily mean non-compliance with the standards, simply because the standards say that the limits only have to be satisfied at specific operating points.

[1] *UL 1741 - Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources* is another important standard in this area.

There were four power quality meters in total deployed at partner sites. With a frequency greater than 99.99% of the time, two of the sites were within the *individual harmonic distortion factor limits*. The remaining two sites were within individual harmonic distortion factor limits greater than approximately 99% and 90% of the time that the inverters were producing power.

The presence of a specific brand of microinverters (termed within this report as Inverter D) was an important contributing factor to the over-limit occurrences. These occurrences were observed at part-load in steady irradiance conditions with a voltage THD below 5%. To be clear, Inverter D was certified to *CSA 107.1* and *IEEE 1547,* meaning that, individually, its harmonic current emissions were within the recommended limits at 33%, 66% and 100% of the rated load. Measurements taken on individual Inverter Ds within this study confirmed this compliance. However, Inverter D was measured to have very high harmonic content at less than 20% of the rated load (a power output level that is not considered by the standards).

If a fraction of the microinverters operating in parallel together on a given branch were shaded, or installed at a different orientation, it is feasible that the high harmonic emissions resulting from those few modules could pollute the whole branch to the extent where the *branch* would be over-limit, even when the total power output from the branch was relatively high (i.e. at or above the 33% rating point). This phenomenon was believed to have been the cause of the over-limit occurrences at installations containing Inverter D microinverters. The result was that, although (i) the installation was compliant with *CSA 257*, in that it used inverters that satisfied *CSA 107.1*, and (ii) the individual inverters were compliant with the limits in *IEEE 1547;* the entire installation would likely not have been compliant with *IEEE 1547* at all points in time. This was because individual harmonic distortion factor limits were exceeded when the inverters collectively were operating at 33% and 66% of the rated load. It is not currently known whether or not this effect is limited to Inverter D microinverters or if it also occurs across other inverter brands/topologies. This should be examined in future work and this specific issue may also warrant further consideration from standards development committees.

It should be stated explicitly that this report did <u>not</u> conclude that harmonic emissions should be considered as a notable barrier towards future deployment of PV. Power quality is a larger topic that extends far beyond PV power generation. For example, this study also documented the high harmonic currents produced by other non-linear loads. Whether the emissions come from loads or from generation, solutions to harmonic emission issues are available and typically involve some level of harmonic filtering.

ABBREVIATIONS

CSA 107.1	CAN/CSA-C22.2 NO. 107.1-01 (R2011)
CSA 257	CAN/CSA-C22.2 NO. 257-06 (R2011)
CT	current transducer
DR	distributed resource
EPS	electrical power system
LDC	local distribution company
PQA	power quality analyzer
TDD	total demand distortion
THD	total harmonic distortion

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1.0 INTRODUCTION

1.1 Background

Standards are necessary to ensure the safety and performance of photovoltaic (PV) system components and the PV system grid-interconnection. In Canada, the recommended practices for interconnecting an inverter-based distributed resource (DR), such as a PV installation, with a low-voltage electrical power system (EPS), are given in *CAN/CSA-C22.2 NO. 257-06 (R2011) - Interconnecting Inverter-Based Micro-Distributed Resources to Distribution Systems*. The comparable U.S. standard is *IEEE 1547-2003 - Standard for Interconnecting Distributed Resources with Electric Power Systems.*[2] Within this report, these standards will be denoted by *CSA 257* and *IEEE 1547* as shorthand. In general, both standards recommend that harmonic current injection into the utility EPS shall not exceed the limits specified in Table 1.1.

Table 1.1: *Harmonic current injection limits suggested by CSA 257 and IEEE 1547.*[3]

Individual Harmonic Order h (odd harmonics)*	H < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h	Total Demand Distortion (TDD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

* *Even harmonics are limited to 25% of the odd harmonic limits above.*

In order to verify that the harmonic current emissions are within the given limits, *IEEE 1547* stipulates that both the total demand distortion (TDD) and the individual harmonic distortion factors up to the 40th order should be calculated while the DR is operating at 33%, 66% and 100% of the rated load. In contrast, *CSA 257* states that the individual inverters that make up a DR system must use inverters which are compliant with *CAN/CSA-C22.2 NO. 107.1-01 (R2011)* (denoted by *CSA 107.1* within this report as shorthand). The current version of *CSA 107.1* does specify that the limits in Table 1.1 be satisfied, however, the only operating point in the testing procedure is at 100% of the rated load.

There is discussion towards updating that provision to 33%, 66% and 100%, as in the case of *the IEEE 1547*, in the next revision of *CSA 107.1*. However, until that time, manufacturers are able to test to both U.S. and Canadian requirements at the same time by using the procedures in *Technical Information Letter (TIL) No. I-43 - Interim Certification Requirements for Utility-Interconnected Inverters (2011)*, which introduces the additional 33% and 66% testing points. Inverter manufacturers are allowed to use the test methods in the *TIL No. I-43* or *CSA 107.1* until a new revision of the latter standard is available.

[2] *UL 1741 - Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources* is another important standard in this area.
[3] *The table was taken specifically from the IEEE 1547-2003.*

1.2 Overview

These standards seek to quantify the harmonic current emissions of grid-tie PV systems at a small number of different operating points to ensure that they are below recommended limits. This is both a reasonable and a practical stipulation. However, the fact still remains that these testing points do not fully represent a PV installation's wide range of real-world operating points.

Actual PV installations produce variable power from 0 to 100% of the rated capacity and furthermore, they are subject to periods of highly variable irradiance due to cloud cover or cloud lensing effects. Rapidly changing irradiance conditions can be both frequent and large in magnitude. Given these considerations, further research is necessary to probe whether or not the real-world harmonic emissions from grid-connected solar PV installations will always remain within recommended limits.

This research begins to fill that knowledge gap through the use of continuous long-term power quality monitoring. Within this study, power quality analyzers (PQAs) were installed at four different PV installations located in Vaughan, ON. Power quality data from each installation was collected for a period of time up to a year in duration. The monitoring data were analyzed for compliance with the harmonic current limits outlined in Table 1.1. Any situations where the power quality exceeded the recommended limits were identified and further analyzed to uncover the relevant contributing factors.

2.0 INSTRUMENTATION

Within this study, two different types of PQAs were used. The Yokogawa WT1800 is a high-end bench top PQA and was used to monitor a single installation at the STEP PV testing facility at The Living City Campus at Kortright. Lower-cost Acuvim IIW PQAs from Accuenergy were deployed at partner sites. This section provides a brief description of each PQA used in this study.

2.1 Yokogawa WT1800 PQA

The Yokogawa WT1800 (Figure 2.1) is a high-end bench-top PQA. It has direct inputs up to 50A and is capable of measuring both AC and DC power with a basic accuracy of ±0.1%. It is equipped with high-frequency waveform capturing, produces parameterized power quality metrics up to the 500th order and can operate with logging intervals as short as 50 ms.

Figure 2.1: *The Yokogawa WT180 PQA is a high-end bench-top PQA used in this study.*

The WT1800 is not designed specifically for continuous datalogging application but this functionality was obtained with the aid of a custom LabVIEW program that communicated with the device through the local area network and coordinated the writing and transfer of data files.

2.2 Acuvim IIW Custom Remote PQA

The Acuvim IIW (Figure 2.2) is a low-cost power meter designed with a wide-range of functionality useful for power quality measurement applications. It can act as a networked device, communicating using Modbus TCP/IP, or act as a standalone datalogger. It integrates with additional I/O modules, expanding its functionality beyond that of a power meter. It has waveform capturing that can be triggered manually or based on pre-configured power quality events. Importantly, it produces harmonic distortion parameters up to the 63rd harmonic. In this project, the Acuvim IIW was integrated into a portable instrumentation box with an uninterruptible power supply, IMT PV irradiance sensor and cellular modem, to be deployed at partner sites.

Figure 2.2: *The Acuvim IIW PQA was used to monitor power quality at partner sites.*

Models of this PQA are available for use with conventional current transducers (CTs) or Rogowski coils. To completely capture the distortion of the waveform, it is typically advisable to measure current using a direct input (as is the case with the Yokogawa WT1800) or a current shunt. However, the practical constraints of implementing either of these at external sites made both options prohibitively onerous. Open-core CTs were the most straightforward option.

Acuvim IIWs that use conventional open-core CTs have manufacturer claimed harmonic measurement accuracies of 1%. However, the effect of using conventional style CTs to measure high frequency harmonics, as is often done, does not seem well-established. Conventional CTs are not rated for high frequency and may affect the measurement in such a way that would be difficult to correct. For this reason, conventional open-core CTs were avoided in this project. Rogowski coil CTs were chosen instead because their measurement accuracy is claimed to be independent of frequency and they have a very wide current measurement range.

2.3 Verification

For the purposes of verification, the remote monitoring boxes using the Acuvim IIW PQA were used in parallel with the Yokogawa WT1800 to monitor the power quality of a PV installation at the Living City Campus (LCC). This is described in greater detail in Appendix B, which shows that there is good agreement between the Acuvim IIW and the Yokogawa WT1800 for all parameters except for the harmonic current measurements when the harmonic current magnitude is small. To improve the current harmonic distortion readings of the Acuvim IIW, STEP worked with Accuenergy to upload custom firmware to the Acuvim IIW devices and then one of two approaches were taken: (i) where possible, additional wire wraps around the CT were used, increasing the current magnitude; and (ii) where additional wire wraps were not possible, the flexible CT itself was wrapped around the wire an additional time, having the same effect. This is illustrated in Figure 2.3.

Figure 2.3: *The magnitude of the current was increased by either (left) wrapping the wire around the CT or (right) wrapping the CT around the wire.*

3.0 SITES

In total, four PQAs were installed at three different sites in Vaughan, ON:

1. The Toronto and Region Conservation Authority's (TRCA) Living City Campus (LCC) at Kortright,
2. The TRCA's Restoration Services Centre Facility, and
3. The Earth Rangers Centre for Sustainable Technology.

The Yokogawa WT1800 PQA metered one of the several PV installations at the LCC while the Acuvim IIW instrumentation boxes monitored the entire local EPS at the LCC (including several PV installations) as well as the PV installations at the remaining two sites. This section provides further details regarding each site.

3.1 Site 1: Living City Campus at Kortright

A high-level single line diagram (SLD) of the LCC at Kortright local EPS is shown in Figure 3.1.1. The generation is spread out across inverters from four different popular brands, denoted here as Inverters A to D (Figure 3.1.2). The primary load on the section of the EPS being monitored for power quality is an instrumentation hut (Figure 3.1.3). Total PV generation is 17.5 kW and the total rated current of all inverters is 72.9 A. Relevant inverter specifications are given in Table 3.1.1.

All inverters are split-phase 240 V. Loads are primarily connected to a single leg of the 240 V split-phase connection. The EPS is net-metered. The measurement of M1 is on the secondary side of the transformer rather than the primary because the transformer is the property of the LDC.

There are two different PQAs installed on the local EPS, denoted by M1 and M2 in Figure 3.1.1. M1 is a low-cost Acuvim IIW PQA using Rogowski coil CTs installed in February 2015. M2 is a Yokogawa WT1800 installed in March 2014. For the M1 current measurement, wires were wrapped three times around the CT to improve the current readings.

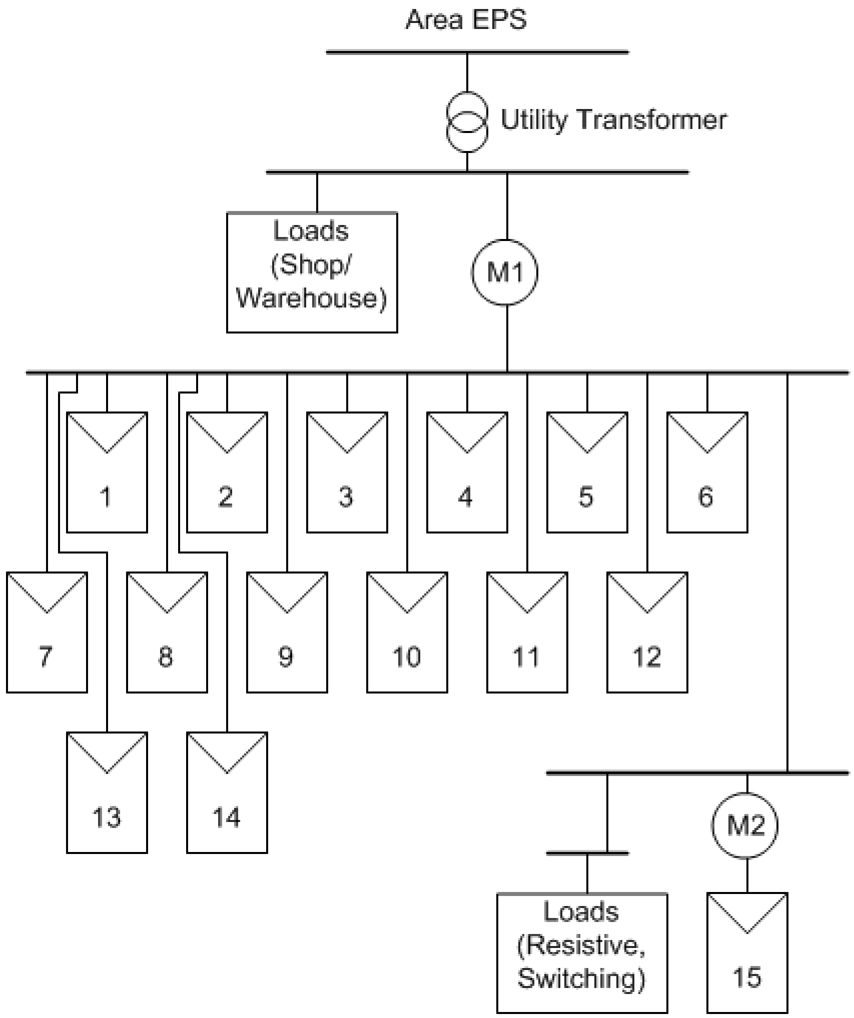

Figure 3.1.1: *Metering points M1 and M2, shown in the single-line diagram of LCC local electrical power system, monitor the power quality. M1 is an Acuvim IIW and M2 is a Yokogawa WT1800. The resistive/switching loads are housed in the hut shown in Figure 3.1.3. PV installations are comprised of that shown in Figure 3.1.2 and a number of other Inverter D microinverter installations.*

Figure 3.1.2: *Travelling clockwise from the top left, example PV arrays connected to Inverters A to D are shown, respectively. In the case of Inverters C and D, there are actually multiple inverters and therefore, those presented here are not exhaustive of all inverters on the property.*

Figure 3.1.3: *(Left) A small hut housing PV instrumentation is the primary load on the section of the EPS being monitored for power quality. (Right) The Yokogawa WT1800 is installed on a server rack within the hut.*

Table 3.1.1: *Specification of inverters at the LCC facility*

	Inverter A	Inverter B	Inverter C	Inverter D
Quantity of inverters on EPS	1	1	2	22
Maximum continuous output power per inverter [W]	3300	6000	2000	-
Maximum continuous current per inverter @ 240 V [A]	13.75	25	8.35	-
Inverter manufacture year (approximate)	2010	2011	2004	2010
Transformer within inverter	No	No	Yes	Yes
Notable features	Dual inputs with individual MPPT	Module-level DC-to-DC converters and MPPT	HF transformer with switchover	Microinverter
Total maximum continuous output power [kW]	17.5			
Total maximum continuous output current [A]	72.9			

Harmonic current limits for total PV capacity that is connected to the EPS are given in Table 3.1.2. The values were obtained by applying the percentage limits given in Table 1.1 to the total maximum continuous output current given in Table 3.1.1. Note that these limits apply only when there are no loads on the lines, which, as will be shown in Section 5.2, is the case for certain time periods.

Table 3.1.2: *Harmonic current limits for LCC EPS PV systems*

Harmonic order	Limit [A]
h <11 (odd)	2.9
h <11 (even)	0.73
11≤h≤17 (odd)	1.5
11≤h≤17 (even)	0.36
17≤h≤23 (odd)	1.1
17≤h≤23 (even)	0.27
23≤h≤35 (odd)	0.44
23≤h≤35 (even)	0.11
35≤h (odd)	0.22
35≤h (even)	0.055
Total harmonic current	3.6

Harmonic current limits for the Inverter B PV installation (metering point M2 in Figure 3.1.1) are given in Table 3.1.3. The values were obtained by applying the percentage limits given in Table 1.1 to the total maximum continuous output current for Inverter B given in Table 3.1.1.

Table 3.1.3: *Harmonic current limits for Inverter B*

Harmonic order	Limit [A]
h <11 (odd)	1.0
h <11 (even)	0.25
11≤h≤17 (odd)	0.50
11≤h≤17 (even)	0.13
17≤h≤23 (odd)	0.38
17≤h≤23 (even)	0.094
23≤h≤35 (odd)	0.15
23≤h≤35 (even)	0.038
35≤h (odd)	0.075
35≤h (even)	0.019
Total harmonic current	1.3

3.2 Site 2: TRCA Restoration Services Centre Facility

The TRCA Restoration Services Centre (RSC) Facility is located in Vaughan, ON. The rooftop PV installation was mounted in December, 2015 (Figure 3.2.1). The system is grid-connected under a feed-in tariff (FIT) contract and uses inverters from the same brand, although a newer model, as Inverter D in Section 3.1. For simplicity, the inverters used in this installation will also be referred to as Inverter D. These are single-phase inverters but they make a three-phase 208 V output by connecting them in a delta configuration where individual inverters provide 208 V across two of the lines. System specifications are given in Table 3.2.1.

Figure 3.2.1: *The Restoration Services Centre facility has a 38.9 kW rooftop PV array.*

Table 3.2.1: *RSC PV system description*

Specifications	
Quantity of inverters	181
Inverter model	Inverter D
Inverter manufacture year (approximate)	2014
Maximum continuous output power of installation [kW]	38.9
Peak output power [kW]	40.7
Maximum continuous output current per line in 3-phase connection [A][4]	108.0

Table 3.2.2 shows the maximum harmonic current limits per line of the three phase connection for this installation. These values were obtained by apply the percentage limits given in Table 1.1 to the maximum continuous output current per line given in Table 3.2.1.

Table 3.2.2: *Harmonic current limits per line of 3-phase connection for RSC PV installation*

Harmonic order	***Limit [A]***
h <11 (odd)	4.3
h <11 (even)	1.1
11≤h≤17 (odd)	2.2
11≤h≤17 (even)	0.54
17≤h≤23 (odd)	1.6
17≤h≤23 (even)	0.4
23≤h≤35 (odd)	0.65
23≤h≤35 (even)	0.16
35≤h (odd)	0.32
35≤h (even)	0.081
Total harmonic current	5.4

Instrumentation was installed on January 16th, 2015. The metering points are on the secondary side of the transformer, specifically, in the rooftop combiner panel, rather than the primary because the transformer is the property of the LDC. The PQA is an Acuvim IIW installed using Rogowski coil CTs. CTs were wrapped twice around each line of the three-phase connection. Irradiance sensor and PQA mounting is shown in Figures 3.2.3 and 3.2.4.

[4] Ampacity calculations per line were completed with the following equation:
Current (amps per branch) = (Maximum output power of microinverter) × (number of microinverters) ÷ (208 volts× 1.732)

Figure 3.2.3: *A plane-of-array irradiance sensor is installed on the roof-top adjacent to the AC combiner panel.*

Figure 3.2.4: *Sensor wires from the rooftop combiner panel penetrate through the roof to terminate at an instrumentation box mounted indoors.*

3.3 Site 3: Earth Rangers Centre for Sustainable Technology

The 30kW PV installation, completed in 2007, is installed on the rooftop of the aviary at the Earth Rangers Centre (ERC) for Sustainable Technology in Vaughan, ON (Figure 3.3.1). The system uses 6 single-phase inverters connected in a 3-phase 208 V configuration. System specifications are given in Table 3.3.1.

Figure 3.3.1: *The Aviary building of the Earth Rangers Centre for Sustainable Technology has a 30 kW rooftop PV installation.*

Table 3.3.1: *ERC PV system description*

Specifications	
Quantity of inverters	6
Inverter model	Inverter E
Maximum continuous output power per inverter [kW]	5
Maximum continuous current per inverter @ 208 V [A]	24
Inverter manufacture year	2007
Maximum continuous output power of installation [kW]	30
Maximum continuous output current per line in 3-phase connection [A][5]	83.3
Transformer in inverter	Yes

The harmonic current limits for this installation, per line of the 3-phase connection, are given in Table 3.3.2. They were obtained by applying the percentage limits in Table 1.1 to the maximum continuous output current per line, given in Table 3.3.1

[5] Ampacity calculations for a 3-phase power system:
Current (amps per branch) = (Maximum output power of inverter) × (number of inverters) ÷ (208 volts× 1.732)

Table 3.3.2: *Harmonic current limits per line of 3-phase connection for ERC PV installation*

Harmonic order	Limit [A]
h <11 (odd)	3.3
h <11 (even)	0.83
11≤h≤17 (odd)	1.7
11≤h≤17 (even)	0.42
17≤h≤23 (odd)	1.2
17≤h≤23 (even)	0.31
23≤h≤35 (odd)	0.50
23≤h≤35 (even)	0.12
35≤h (odd)	0.25
35≤h (even)	0.062
Total harmonic current	4.2

The remote monitoring PQA (Figure 3.3.3), was installed in March 2015. Data were acquired remotely using a cellular modem. The measurement is on the secondary side of the transformer rather than the primary because the transformer is the property of the LDC. Irradiance data were available from both of the other two sites installed on the same grounds, within approximately 1 km from each other, and therefore irradiance instrumentation was not installed at this location.

Figure 3.3.3: *The monitoring instrumentation is installed to the bottom left of the combiner panel. Current is measured using a Rogowski coil CTs wrapped twice around the wire.*

4.0 ANALYSIS

The Yokogawa WT1800 and three Acuvim WT1800s were deployed across the three sites discussed in Section 3, one of which having two metering points. High resolution data, at a logging interval of 200 ms, were collected from the Yokogawa WT1800 but the remaining three sites, using the Acuvim IIW PQAs, had a logging interval of 10 s. Logging was instantaneous. All the PQAs used in this study were equipped with internal analytics to produce parameterized values of the total and individual harmonic distortion factors or currents, alongside other power quality metrics. The PQAs were left in place to monitor various power quality metrics for up to a year and the data were subsequently analyzed. The following questions were investigated for each site:

1. Did the inverter(s) ever exceed total harmonic current limits (see Tables 3.1.2, 3.1.3, 3.2.2 & 3.3.2)?
2. Did the inverter(s) ever exceed individual harmonic distortion factor limits?
3. If yes to either, how frequently did this occur and under what circumstances?

It should be noted that the harmonic current emission limits given in Table 1.1 are expressed as a percentage of the rated load current of the inverter or installation. For example, an installation with a 100 A rated load current would need to have a third harmonic current that is less than 4% of the rated current (i.e. the limit would be 4 A) when the inverter, or installation, is operating at either: (i) 100% of rated load as in the CSA standard, or (ii) 33%, 66% and 100% of rated load as in the IEEE standard. In contrast, this study looked at whether that 4 A limit in this example was ever exceeded at any power output during both steady and transient conditions. The term "over-limit" is used to denote occurrences where the limits are exceeded regardless of the power output and similarly, the term "within limit" is used in a similar sense. It follows that "over-limit" does not necessarily mean non-compliance with the standards, simply because the standards say that the limits only have to be satisfied at specific operating points.

In order to answer the above questions, it was necessary to calculate the total demand distortion (TDD) and individual harmonic distortion factors ($IHD_{n,L}$) using the monitoring data from each site. It is important to note that, in contrast to the total harmonic distortion (THD), these are referenced to the rated RMS load current of the installation (I_L) rather than the RMS load current of the fundamental frequency at the time of measurement. This is shown in Equations 1 and 2. This report assumes that I_L is the rated current output of the inverter(s). I_n is the RMS value of the n^{th} order harmonic current.

$$IHD_{n,L} = \frac{I_n}{I_L} \cdot 100\% \tag{1}$$

$$TDD = \frac{I_H}{I_L} \cdot 100\% \tag{2}$$

Where,

$$I_H = \sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots} \tag{3}$$

Evaluating these equations using the data collected from the Yokogawa WT1800 was straightforward because I_n was logged directly for up to the 50th order. However, the low-cost Acuvim II W PQAs, used at external sites, did not output RMS harmonic current values directly. Rather, the output was the individual harmonic distortion factors for each of the nth harmonic orders (IHD_n) alongside the current total harmonic distortion (THD), both of which were based on the RMS value of the fundamental frequency (I_1) *at the time of measurement*. This is shown in Equation 4 and 5. Note that this is the convention used by the IEEE in contrast to the IEC convention that specifies harmonic based on the total RMS value of the waveform.

$$Current\ IHD_n = \frac{I_n}{I_1} \cdot 100\% \tag{4}$$

$$Current\ THD = \frac{I_H}{I_1} \cdot 100\% \tag{5}$$

I_n and I_H can be expressed in terms of THD and IHD_n using Equations 6 and 7, respectively.[6] Note that in these equations THD and IHD_n ought to be expressed as fractions rather than percentages and that "I" is the total RMS current.

$$I_H = \frac{THD \cdot I}{\sqrt{THD^2 + 1}} \tag{6}$$

$$I_n = \frac{IHD_n \ \cdot I}{\sqrt{THD^2 + 1}} \tag{7}$$

The distinction between TDD and THD is not relevant for voltage distortion. The total harmonic voltage distortion is given in Equation 8.

$$Voltage\ THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots}}{V_1} \cdot 100\% \tag{8}$$

Using this set of equations the harmonic current parameters output from Acuvim IIW PQAs (THD and IHD_n) could be transformed into I_H and I_n and used in Equations 1 and 2 to compare the current harmonics of each site against the limits specified in Tables 3.1.2, 3.1.3, 3.2.2 & 3.3.2.

The analysis for each site proceeded as follows:

- The PQAs were configured to log text data files on an LCC network drive.
- These data files were transferred from text files to a SQL database so as to facilitate large-scale analysis.

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[6] See Appendix A for a derivation

- The data were filtered to include only those data points with a voltage THD below 5%. The purpose of this was to eliminate any harmonic currents that may have been caused by harmonic voltages unrelated to the inverter operation. Data points with no power production were also excluded so as to speed up computation times.
- The total harmonic current (I_H) was calculated for each data point using Equation 3 or Equation 6 and the TDD was calculated using Equation 2. The total harmonic current dataset was then plotted as a function of the inverter power production and compared against the 5% TDD limit specified in the *CAN/CSA-C22.2 NO. 257-06 (R2011)* and *IEEE 1547-2003* standards outlined Tables 3.1.2, 3.1.3, 3.2.2 & 3.3.2.
- The individual harmonic currents were calculated using Equation 7 or obtained directly from the monitoring data. The maximum values observed within the monitoring period were compared against the limits specified in Tables 3.1.2, 3.1.3, 3.2.2 & 3.3.2.
- If either the TDD or individual harmonic distortion factors were larger than the recommended limits, the frequency of over-limit occurrences was determined. Such occurrences were also probed further to better understand the situations that gave rise to the high levels of harmonic currents.

5.0 RESULTS

5.1 The Living City Campus (Single Installation)

Metering point M2 in Figure 3.1.1 monitored the power quality of Inverter B using the Yokogawa WT1800. Data were collected at 200ms intervals from March 2014 to April 2015. This resulted in 150,000,000+ rows of data, across several hundred parameters. Data were then analyzed with the aid of an SQL database.

Figure 5.1 plots the total harmonic current (I_H) as a function of the fraction of rated inverter power for March 1st/2015 to March 15th/2015. The rated current of the inverter is 25 A. Each data point represents 200 ms of operation. Note that the fraction of rated inverter power is simply the power produced by the inverter at a given point in time divided by the rated power. A small window of time was used in this plot because Microsoft Excel is limited to plotting approximately a million data points. At no point in time during this period did the harmonic current exceed the recommended limit.

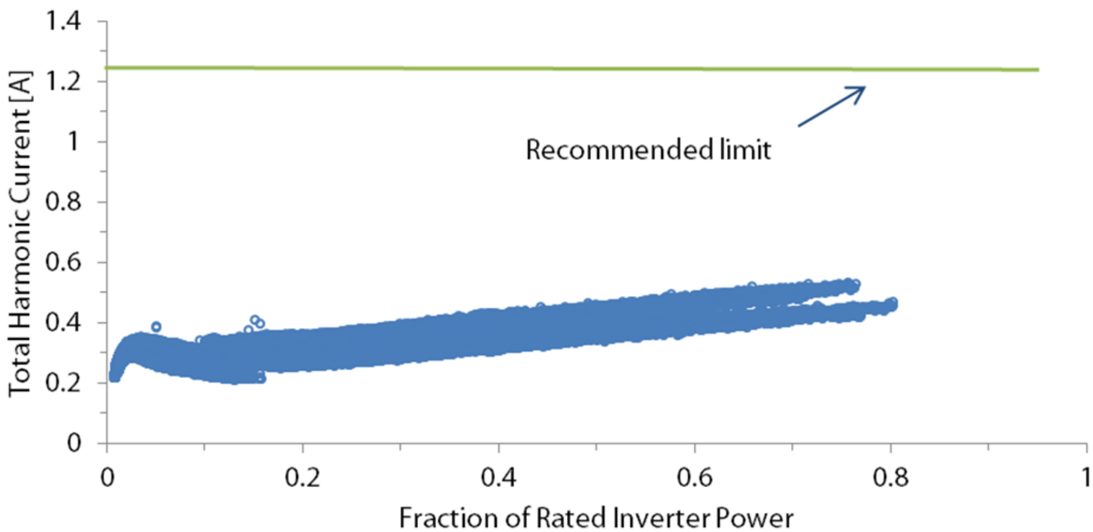

Figure 5.1: *The total harmonic current limit specified in Table 3.1.3 is never exceeded between March 1st/2015 to March 15th/2015. Note that the rated current is 25 A. This is plot is representative of the entire one year monitoring interval.*

Similar plots were generated for a two week period within each month during the monitoring period. Within those time periods, the TDD never exceeded the recommended value, provided the voltage THD was below 5%. However, an interesting power quality event occurred in March 2014 (Figure 5.2). During this month, there were sporadic events (on the scale of 200 ms in duration) where the total harmonic voltage distortion on the network increased to between 53 and 91%. This resulted in the inverter producing correspondingly large current harmonic emissions. This is shown in Figure 5.2 as outliers that are increasing approximately linearly with the fraction of rated inverter power. To be clear, this is not demonstrating a failure of the inverter, rather, it is showing the inverter response to a specific power quality event (i.e. high voltage distortion on the EPS).

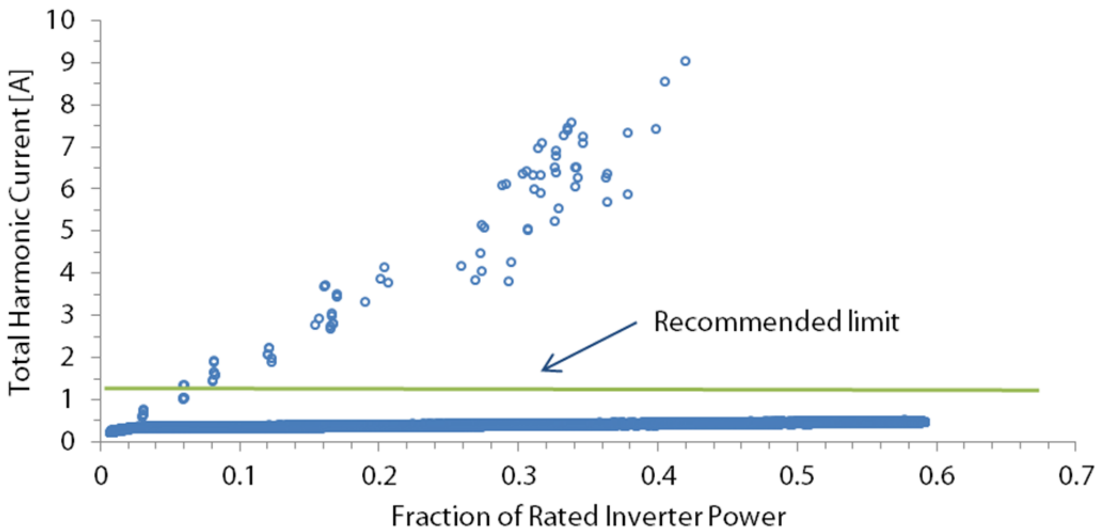

Figure 5.2: *There were a small number of occurrences in March 2014 where the total harmonic current exceeded recommended limits. This happened in short (approximately 200 ms) intervals during a two-day period and was due to very high harmonic voltages on the network.*

Figure 5.2 plots the maximum observed individual harmonic current up to the 40th harmonic order observed during March 2015 and compares it to the suggested limits shown in Table 3.1.3. The maximum measured value, shown in green, exceeds the suggested limit for several harmonics that are above the 23rd order. However, across all months, this occurs with a frequency less 0.006% of the time. There is an apparent discrepancy in that Figure 5.3 shows a 3rd order harmonic current as high as 1.5 A while Figure 5.1 shows a total harmonic current that does not exceed 0.6 A. This is due to the fact that 3rd order harmonic currents this large are extremely rare and Figure 5.1 only plots a two week window of time. Within this window, the 3rd harmonic never exceeded the recommended limit. When the third order harmonic current reaches 1.5 A, it would in fact push the total harmonic currents passed recommended limits – this was just never caught by only looking at two week subsets from each month as was done in the analysis.

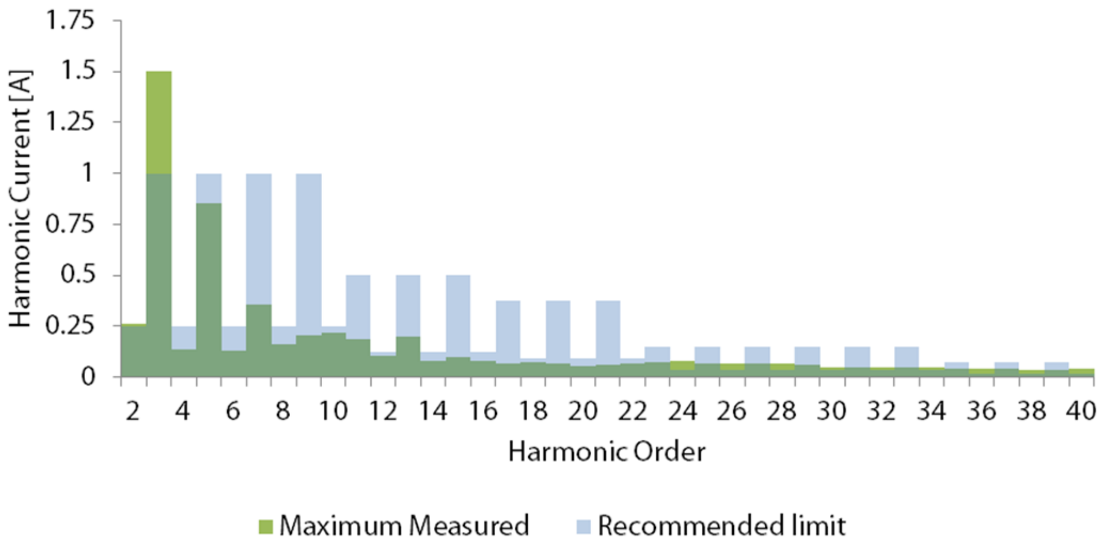

Figure 5.3: *For March 2015, the maximum measured harmonic current (green) up the 40th order is compared with the recommended limits from Table 3.1.3 (blue). The maximum value exceeded the recommended limit for some harmonic orders but this occurs less than 0.006% of the time for any given month.*

It should be noted that the dataset was filtered to only include those points with a voltage THD that was less than 5%. It is feasible that the voltage THD could be below 5% while still having prohibitively high voltage harmonics at higher harmonic orders. High harmonic voltages could result in a high harmonic currents provided the inverter was operating at a large percentage of its rated capacity (as demonstrated in Figure 5.2) and this could possibly explain the current harmonic emission over-limit occurrences illustrated in Figure 5.3 that occur at higher orders. In essence, these occurrences might be related to harmonic voltages on the network but this was not explored further simply because they occur so infrequently and are likely not significant.

It should be noted as well that the over-limit occurrences for the third harmonic order could not be explained in terms of harmonic voltages on the network. This is because further analysis showed that the high 3rd order harmonic current emissions occurred when the voltage THD was approximately 3.5%. Since 1.5 A of 3rd order harmonic current would on its own represent a current TDD of 6% for this installation, it is not plausible that this high level of current harmonic emission could be explained by a correspondingly low-level of voltage distortion. To summarize, the inverter itself is responsible to some degree for over-limit occurrences but such occurrences are extremely infrequent.

5.2 The Living City Campus (Entire EPS)

Data were collected between February 17th/2015 and June 22nd/2015 at metering point M1 in Figure 3.1.1. Within this time period, approximately 994 hours of data were collected. Figure 5.2.1 shows the power production and current THD for each phase of the 240 VAC split-phase connection over the course of a given day (March 28th/2015). It is clear from the overnight power consumption (displayed as positive power) that there are both loads and generation on Line A while it seems for Line B there is primarily generation. Further inspection showed that there is actually an air-conditioner on Line B that begins to cycle on and off after April 1st/2015.

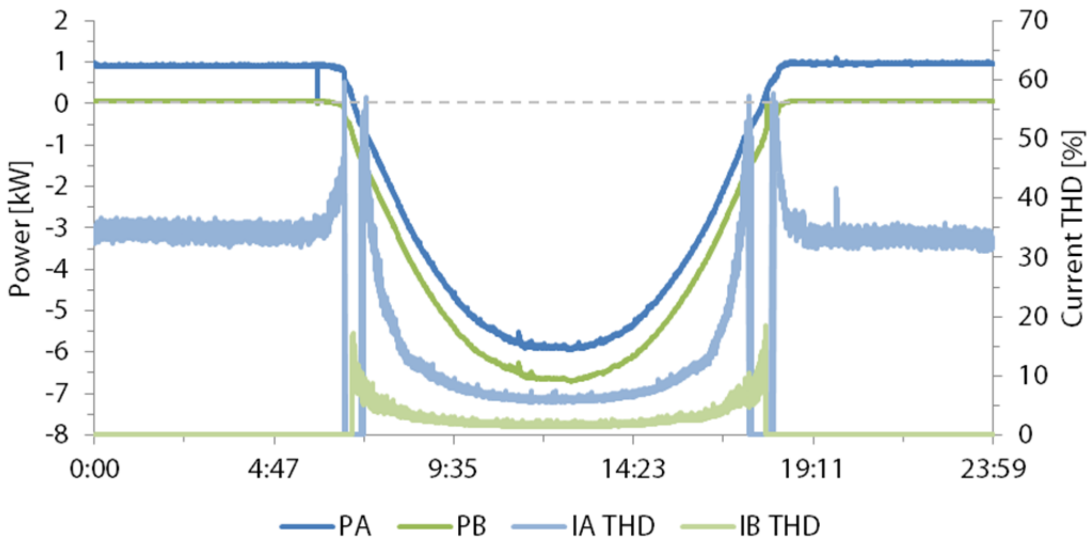

Figure 5.2.1: *The overnight power consumption shows that the loads are connected to Line A. Line B does not have any apparent load until an air-conditioner begins to cycle on-and-off after April 1st/2015.*

Line B is useful for looking at the combined harmonic emissions of multiple inverters operating in parallel with only generation on the line. Figure 5.2.2 plots the total harmonic current as a function of the fraction of rated power at which the inverters are operating. The data have been filtered to include only daytime operation with voltage total harmonic distortion less than 5%. Data between February 17th and March 30th were used because during this time there were no loads on this phase of the connection. Collectively, the inverters operate at well under the 5% TDD limit (shown in green) illustrated in Table 3.1.2. Note that the rated current of all inverters is 72.9 A.

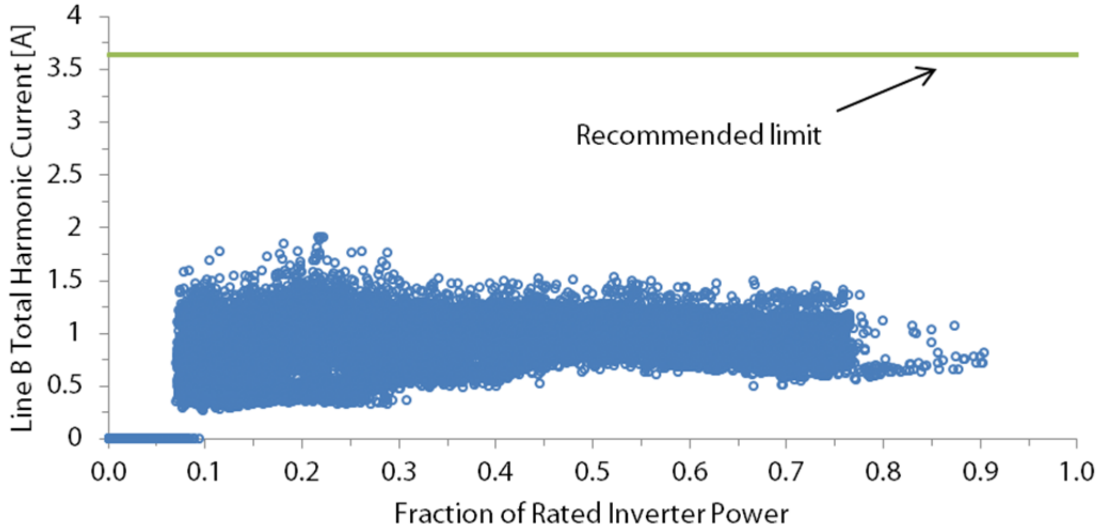

Figure 5.2.2: *The total harmonic current from the various inverters installed on Phase B of the LCC EPS never exceeds the recommended limit.*

Figure 5.2.3 plots the total harmonic current on Line A during the same time period. Line A includes multiple switching and resistive loads housed in the testing hut shown in Figure 3.1.3. The collection of points at approximately 1 kW is due to the loads operating overnight. The space between the adjacent collection of points to the right is due to a discrete jump in power consumption when an electric heater turns on. The loads create a larger harmonic current than the PV inverters and they appear to be the primary contributor to the combined harmonic current when there is net generation (evident from comparing Figure 5.2.3 to 5.2.2).

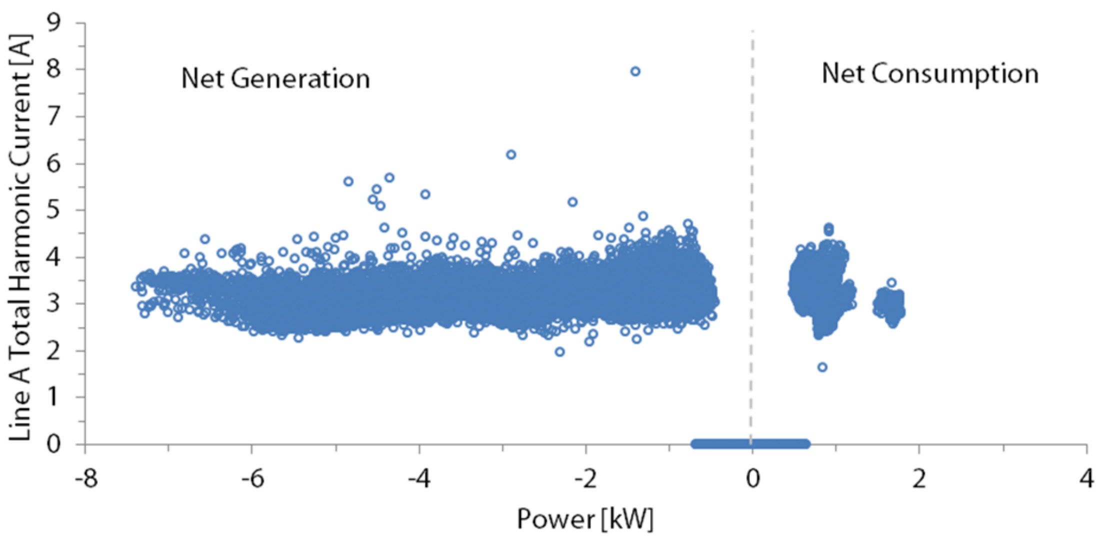

Figure 5.2.3: *On Phase A, the harmonic current due to the loads is high. It is the main contributor to the combined harmonic current when there is both consumption and generation. This is clear from the much lower total harmonic current observed when there is only generation on the line (Figure 5.2.2).*

The harmonic current of each individual harmonic order on Phase B from February 17th and March 30th (ie. when there are no loads) was assessed against the recommended limits (Table 3.1.2) in Figure 5.2.4. This figure plots both the recommended limit (blue) and the maximum observed harmonic current measured (green) during the monitoring period. The second harmonic order was the only harmonic order observed to exceed the recommended limit and this occurred approximately 0.7% of the time. It was also found that there were no second order harmonic voltages present on the EPS that might have contributed to the second order harmonic current emissions – pointing to the fact that these current emissions are in fact due to inverters on the network.

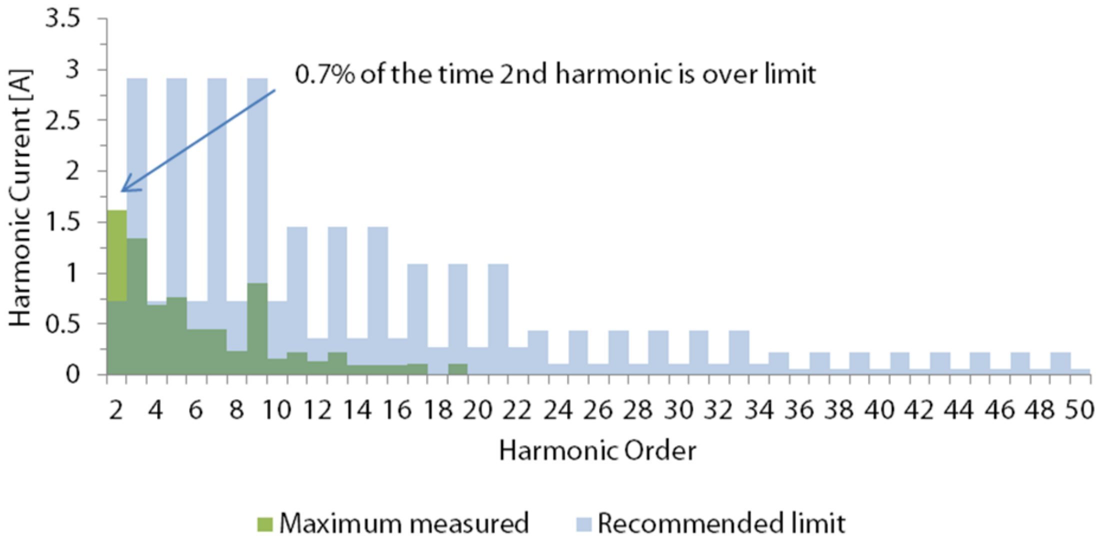

Figure 5.2.4: *The* <u>*maximum*</u> *measured harmonic current for each harmonic order is compared against the recommended limits in the IEEE 1547. The 2nd order harmonic current exceeds recommended limits 0.7% of the time.*

To better understand those situations in which the 2nd harmonic order exceeded the recommended limit, Figure 5.2.5 plots the Line B second order harmonic current as a function of the fraction of rated power at which the inverters were operating. Again, data points were instantaneous, taken every 10 s. High harmonic currents were most frequently observed at less than 30% of the rated power.

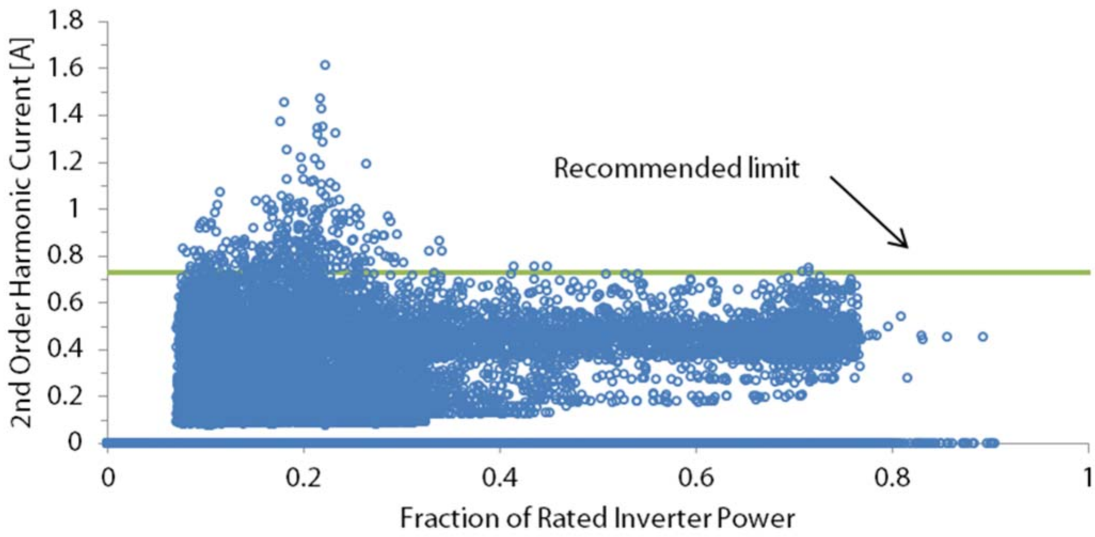

Figure 5.2.5: *The 2nd order harmonic current is sometimes exceeded when the inverters are operating at less than 30% of their collective rated power.*

Figure 5.2.6 plots the second order harmonic current over the course of a clear sky day. The harmonics are most pronounced in the morning and evening but they are also observed periodically throughout the day in steady irradiance conditions, although during the day they were still under recommended limits.

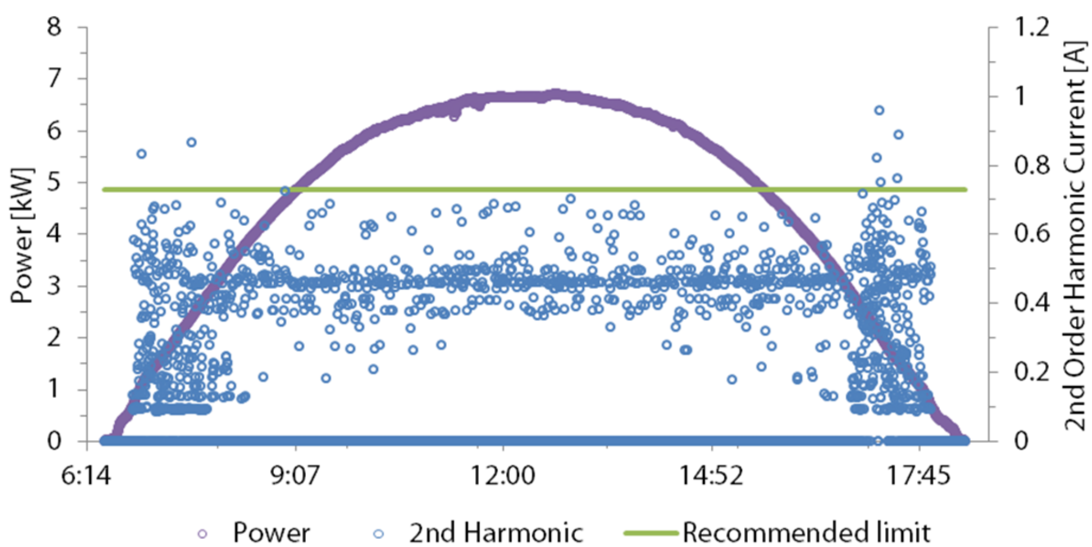

Figure 5.2.6: *Second order harmonics are worst under low power generation conditions but do appear periodically throughout the day.*

In addition to the power quality testing, a power outage event was simulated by throwing the main circuit breaker for the local EPS. The waveform capturing of the Acuvim IIW was used to record the voltage waveform from all inverters on the EPS as they transitioned to anti-islanding mode. The result is shown in Figures 5.2.7 and 5.2.8. It is clear from the current waveform that at approximately 32 ms, the breaker was turned in the off position. As an example, HydroOne requires that DRs disconnect within 500 ms when islanded.[7] As Figure 5.2.8 shows, the voltage waveform peak value has decreased by more than 80%, 100 ms after disconnection, and by more than 95%, 200 ms after disconnection. The waveform capture did not extend past approximately 250 ms after disconnection.

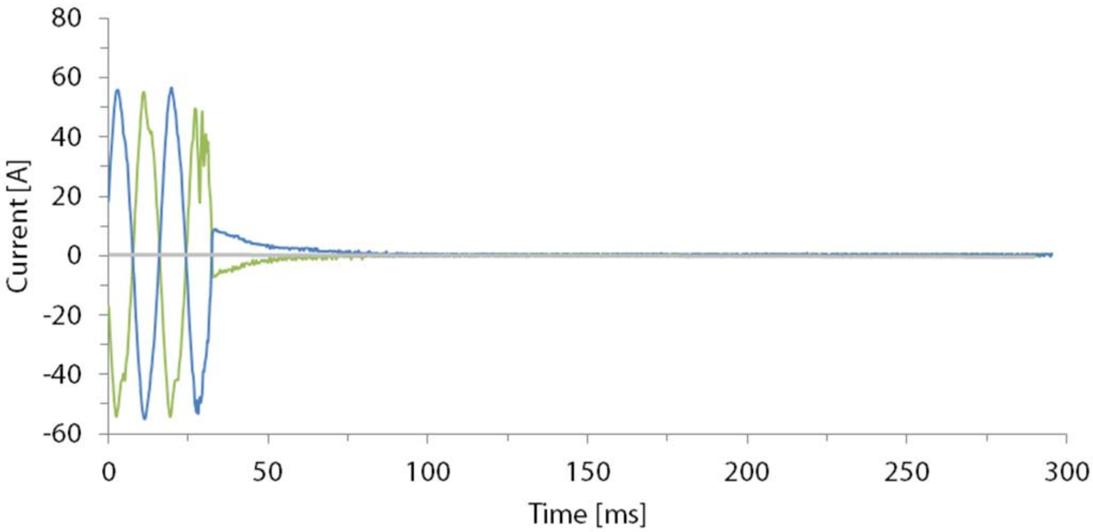

Figure 5.2.7: *The main breaker to the LCC EPS was thrown to the off position (at approximately 32 ms) to simulate a power outage.*

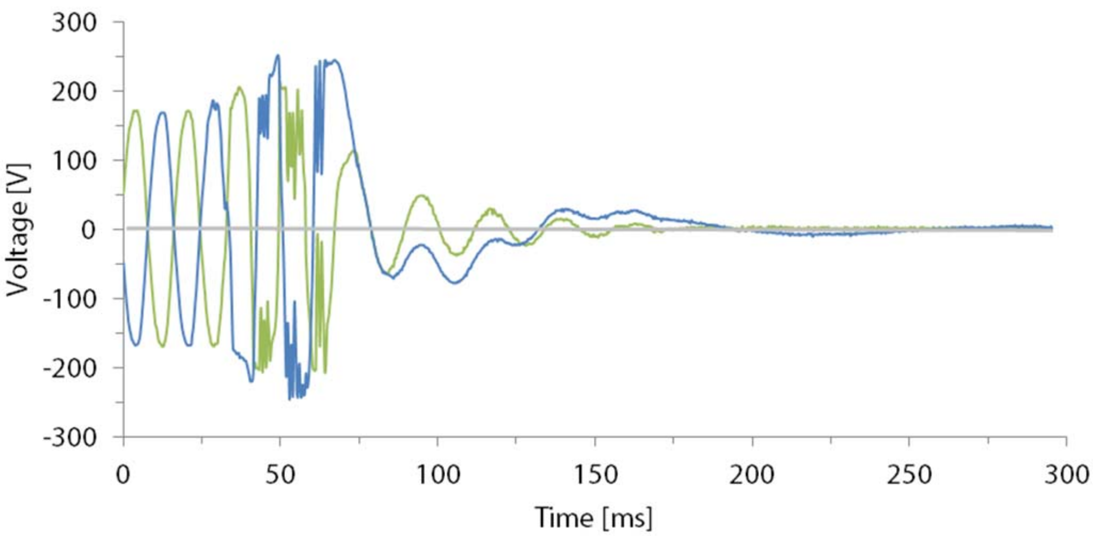

Figure 5.2.8: *The corresponding voltage waveforms to Figure 5.2.7 show that the inverters quickly operate in anti-islanding mode. Voltage was measured line-to-neutral.*

[7] Hydro One, 2013. Distributed Generation Technical Interconnection Requirements at Voltage 50 kV and Below. Accessed online October 10/2015: http://www.hydroone.com/generators/pages/technicalrequirements.aspx

5.3 Restoration Services Centre Facility

Data were collected between February 10th, 2015 and June 22nd, 2015. Data were filtered to remove those points that occurred during the night or those that had a voltage THD greater than 5%. This left approximately 725,000 data points at 10 s intervals, representing 2000+ hours of operation.

Figure 5.3.1 plots the total harmonic current as a function of the fraction rated inverter power for Line 1 of the 3-phase connection. The rated continuous output current for each line is 108 A. The current values have been adjusted to account for the presence of the wire wraps. It should be noted that 99.992% of the data lies below the 5% TDD limit shown in green. The data points that exceed the limit are most commonly found at less than 30% of the rated power. Results were similar for Line 2. Line 3 also followed a similar trend but all points were under a TDD limit of 5%.

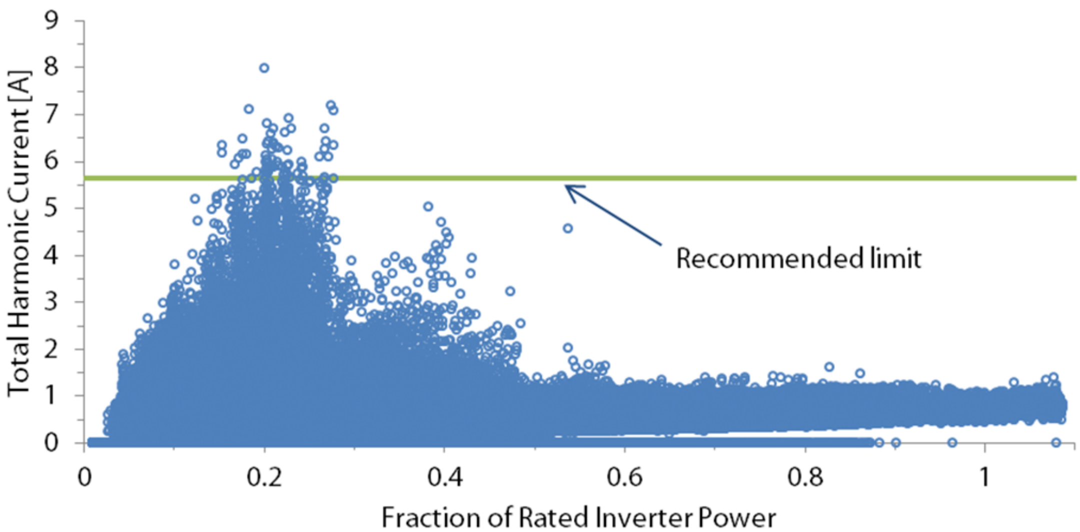

Figure 5.3.1: *The total harmonic current is within the recommended limit 99.992% of the time.*

Figure 5.3.2 compares the individual harmonic orders against the recommended limits in Table 3.3.2. It plots the maximum harmonic current observed during the monitoring period. Where the maximum is greater than the recommended limit, the figure notes the frequency that the data exceeds the limit. This percentage is in reference to daylight hours where power was being produced and the total harmonic voltage was below 5%. The 2nd, 24th and 28th harmonic currents exceed recommended values approximately 4.1%, 1.7% and 10.2% of the time, respectively. These occurrences did not coincide with corresponding voltage harmonics on EPS, at each of the given orders, and are therefore related to the inverter operation rather than harmonic voltages on the EPS.

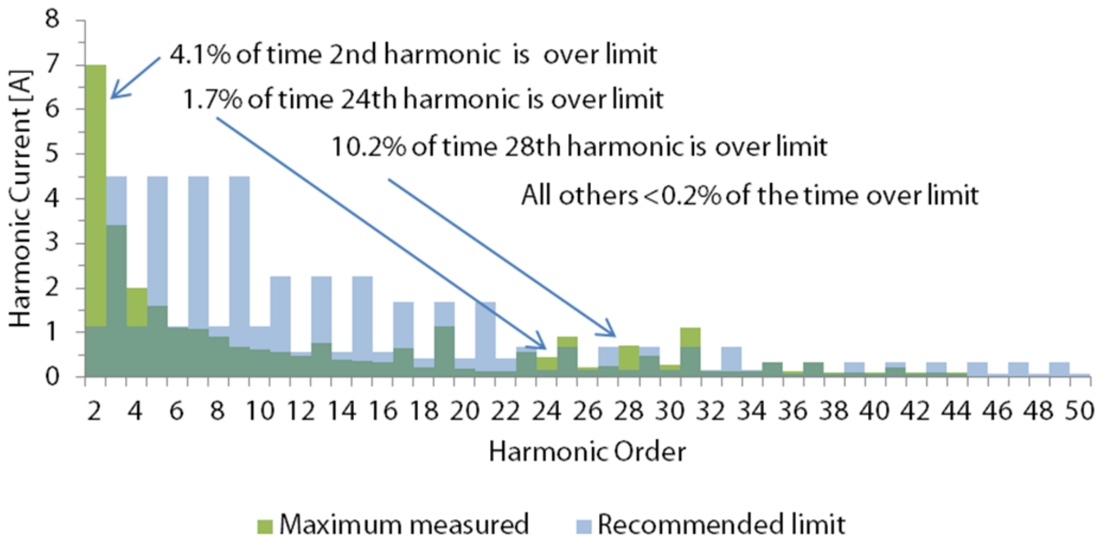

Figure 5.3.2: *The maximum observed harmonic current is compared against the recommended limit for each harmonic order. The limits are surpassed for several harmonic orders.*

Figure 5.3.3 plots the 2nd harmonic order as a function of the fraction of inverter rated power at which the inverters were operating. It should be noted that 96% of the data actually reside below the green line signifying the recommended limit. The occurrences are greatest when the inverter is operating at less than approximately 50% of its rated power.

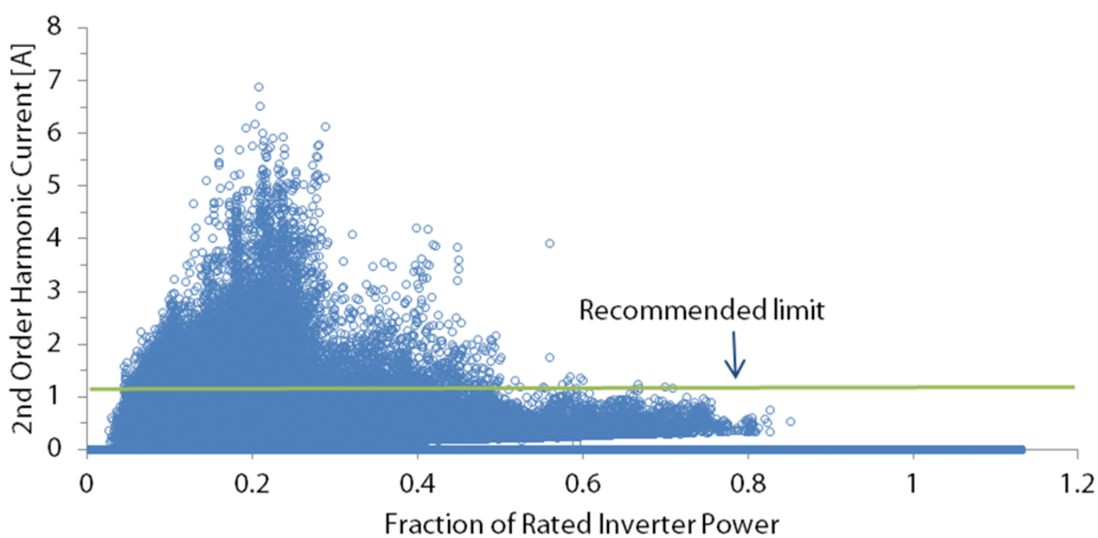

Figure 5.3.3: *The second order harmonic current is within the recommended limit 96% of the time.*

Figure 5.3.4 plots a similar trend for the 28th order harmonic current. In this plot, approximately 90% of the data resides below the green line that signifies the recommended limit.

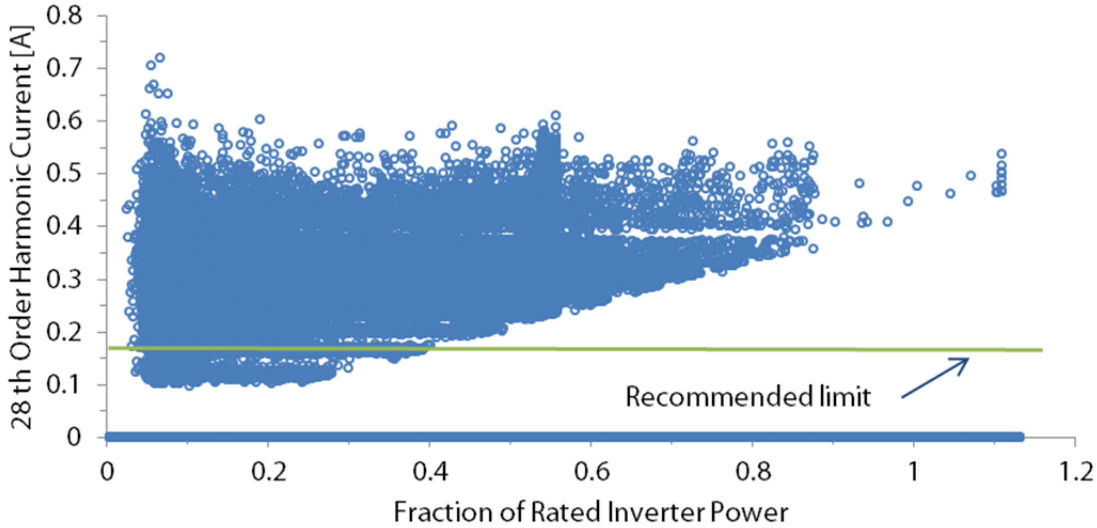

Figure 5.3.4: *The 28th order harmonic current is within the recommended limit 90% of the time.*

Figure 5.3.5 plots the 2nd and 28th harmonic order over the course of a clear sky day.

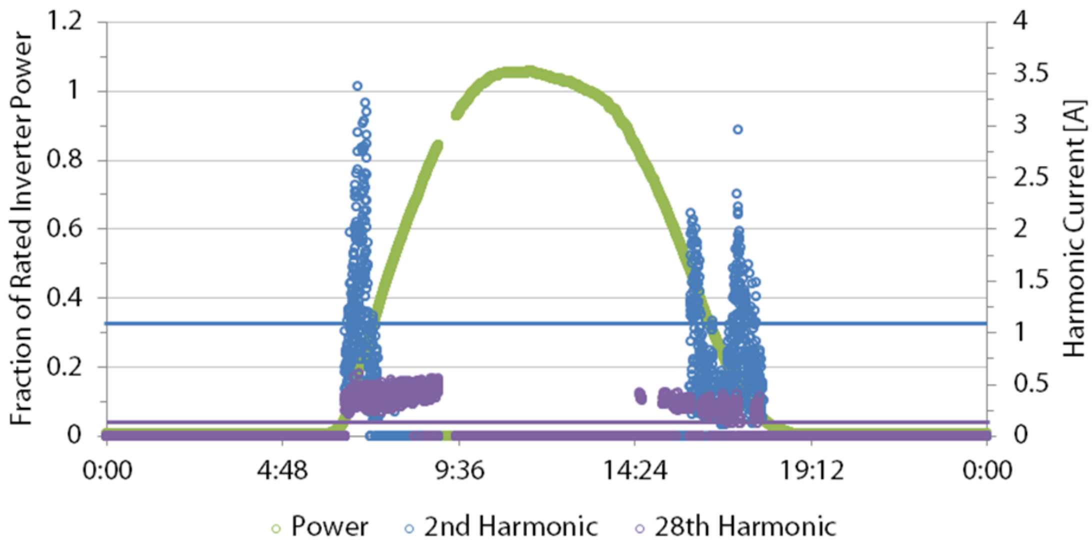

Figure 5.3.5: *The recommended limit for the 2nd and 28th is shown as blue and purple lines respectively. The 2nd harmonic occurs only at low values of power production. The 28th order harmonic does not appear to occur at all once the inverters exceed approximately 80% of their collective rated power.*

Waveform captures were used to further confirm the harmonic emissions measurements. Figure 5.3.6 shows a current waveform capture with very low harmonic content. It appears to be nearly perfectly sinusoidal (a pure sine wave is plotted as well for a guide). In contrast, Figure 5.3.7 shows a waveform captured at low operating power with a high harmonic content. Higher order harmonics of low magnitude cause the rippling of the waveform and lower order harmonics of higher magnitude have deformed the second crest and trough of the wave. These plots are meant to demonstrate that the measured harmonic emissions are in fact a real phenomenon for this installation.

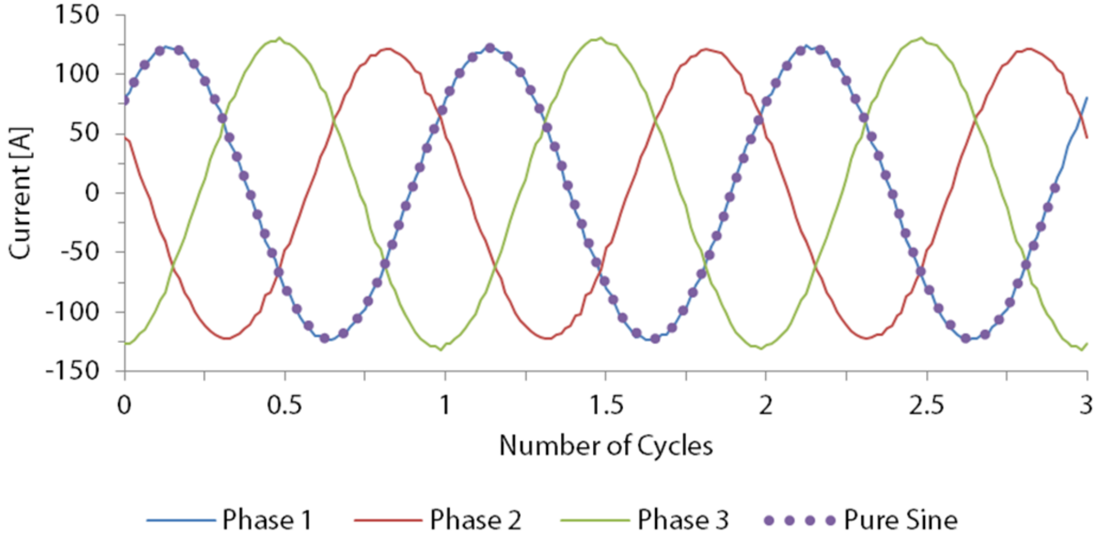

Figure 5.3.6: *A waveform capture, taken at high operating power, from the Restoration Services Centre Facility shows very low harmonic content.*

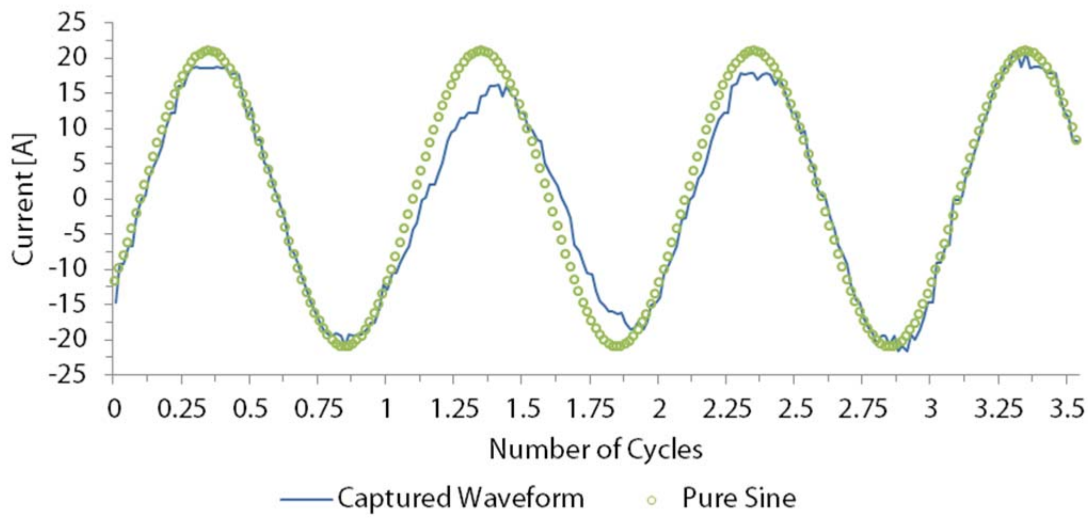

Figure 5.3.7: *A waveform capture, taken at low operating power, from the Restoration Services Centre Facility shows high harmonic content. The rippling is caused by small magnitude higher order harmonics while the waveform deformation is due to lower order, higher magnitude, harmonic content within the waveform.*

To gain a better understanding of this phenomenon, and to confirm the observations with a second instrument, the power quality of two microinverters operating in parallel was monitored at the LCC PV test facility using the Yokogawa WT1800 PQA. These microinverters were the same brand as Inverter D but an older model. The rated current of the two inverters operating in parallel at 240 V is 2 A. Current was measured using the direct inputs of the Yokogawa WT1800. The limit on the 2nd order harmonic current, according to Table 1.1, is 0.02 A (i.e. 1% of 2 A).[8] Figure 5.3.8 shows the 2nd order harmonic current as a function of the fraction of rated power at which the inverters are operating. Each data point represents 200 ms of operation. The 2nd order harmonic current of the inverters is below the recommended limit for the 33%, 66% and 100% of rated power operating points required by IEEE 1547. However, below 20% of rated power the 2nd order harmonic is as much as an order of magnitude higher than that limit. Note that, with the exception of approximately a 1 s time span during the monitoring period, the total harmonic voltage distortion was below 5%.

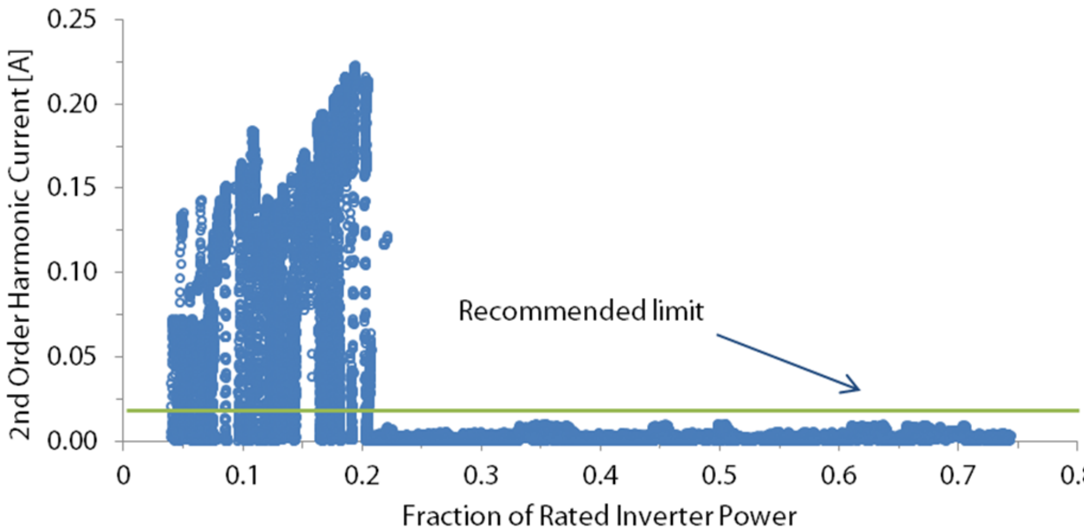

Figure 5.3.8: *The second order harmonic current of two Inverter D microinverters operating in parallel, as measured by the direct current input of a Yokogawa WT1800, is very high at less than 20% of the rated load.*

Figure 5.3.9 shows the 28th order harmonic as a function of the fraction of rated power from the same time period. According to Table 1.1, the 28th order harmonic current should not be greater than 0.15% of the rated current. It follows that for the 2 A rated inverter current, the 28th order harmonic current should be limited to 0.003 A. The same trend as in Figure 5.3.8 is present. The harmonic current is generally below the recommended limit above 20% of rated load but can be as much as approximately 4 times the recommended limit below 20% of rated load. These measurements were taken with a voltage total harmonic distortion that was below 5%.

[8] Note that even harmonics should be limited to 25% of the odd harmonic limit for the given range.

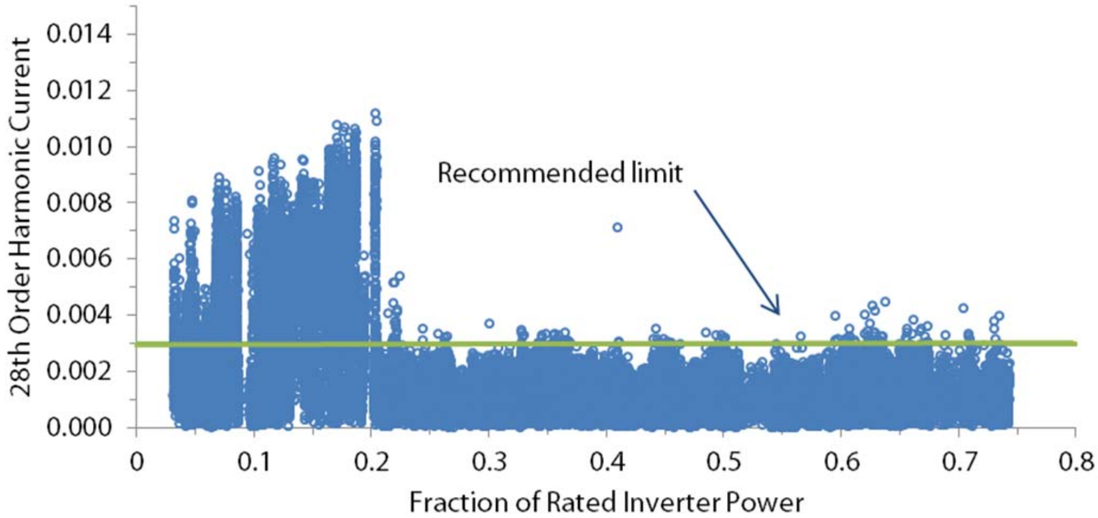

Figure 5.3.9: *The 28th order harmonic current of two Inverter D microinverters operating parallel is very high below 20% of the rated load.*

As an example, a screen capture of the high harmonic emissions observed at low power is given in Figure 5.3.10. Shown are both the voltage and current waveforms. The voltage waveform is sinusoidal with low harmonic content but the current waveform has very high harmonic content. The current waveform is non-sinusoidal and the RMS current value, as taken over the time range given in the waveform capture, would need to be determined using integration. However, a simple inspection shows that the waveform peaks at instantaneous current values of +/- 1 A. It follows that a notable distortion of waveform is occurring at non-negligible current values.

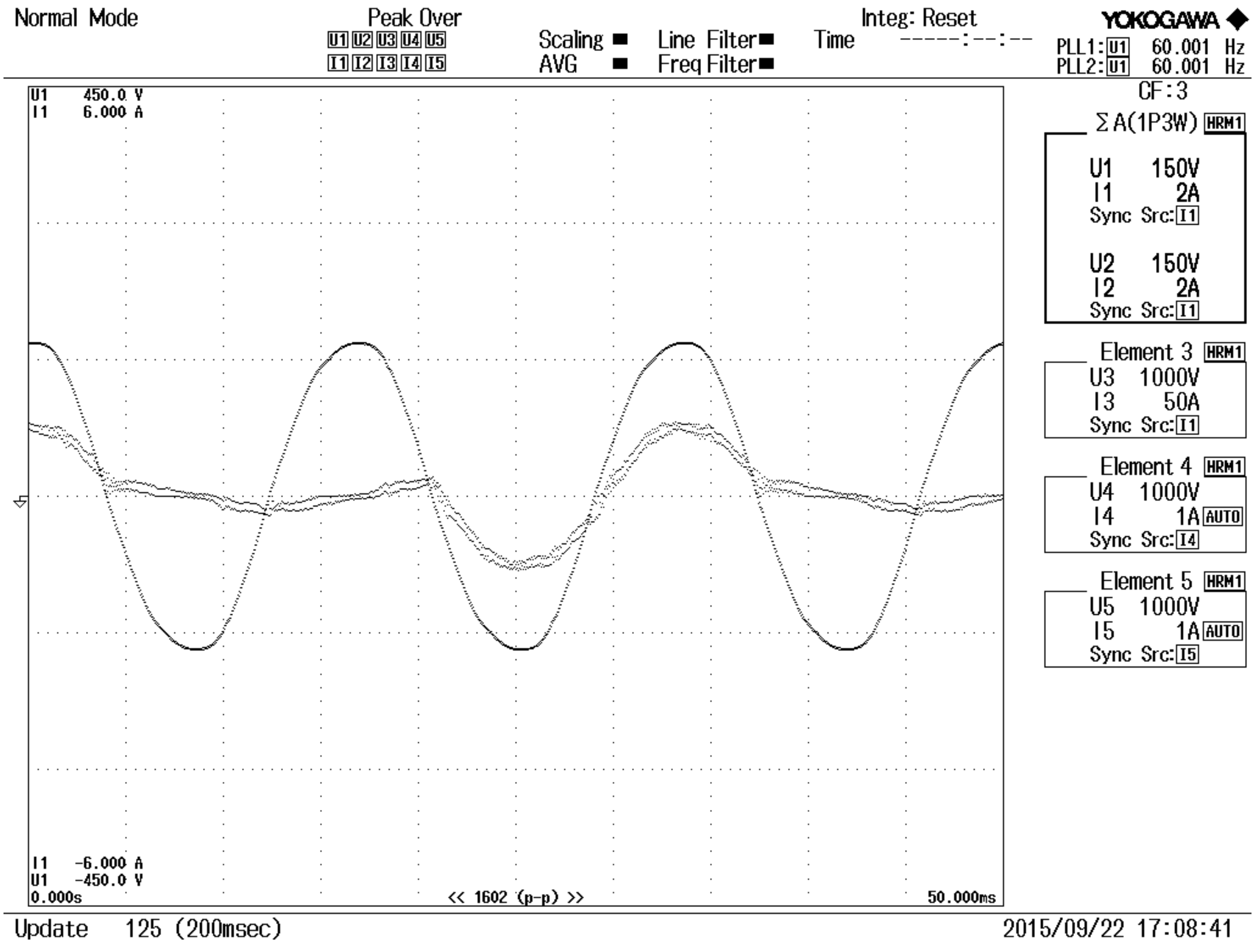

Figure 5.3.10: *A snapshot of the current and voltage produced by the two Inverter D brand microinverters demonstrates that the current waveform has high levels of harmonic distortion at low load. Voltage is measured from the neutral to one leg of the split-phase connection and is shown to be approximately sinusoidal.*

Figures 5.3.8 to 5.3.10 provide additional insight towards understanding the results presented in Figures 5.3.1 to 5.3.4. The high harmonic emissions shown in Figures 5.3.1 to 5.3.4 were observed in steady irradiance conditions with low harmonic voltage content, across a large range of inverter power outputs. Yet, the inverters are listed as compliant with both *IEEE 1547* and *CSA 257*. This installation is clearly showing harmonic emissions above what should be expected and at first glance it is not clear why. Figures 5.3.8 and 5.3.9 confirmed to some extent that the <u>Inverter D microinverters are in fact compliant with the power quality limits at 33%, 66% and 100% of rated load</u>. However, it was shown that the harmonic emissions are very high below 20% of rated load.

The high emissions observed in Figures 5.3.1 to 5.3.5 can be explained by noting the fact that the Restoration Services Centre Facility PV installation has modules oriented both vertically on a curtain wall and also at shallow tilt angle on the roof. As a result, the microinverters are not all producing the same level of power. It is feasible that as the sun position changes or if there is shading, some modules will be producing above 20% of the rated load and some, below 20% of rated load, even though the total combined power output itself may be much higher than 20% of rated load.

It would seem that the very high harmonic emissions from a small fraction of microinverters operating at a low power are enough to make the combined emissions from a branch of microinverters exceed recommended limits. Put differently, inverters which are individually compliant with recommended harmonic emissions limits may actually produce combined harmonic emissions that are in excess of those same limits when installed alongside other inverters in a PV installation provided that: (i) there are high levels of harmonic emissions at low operating powers and (ii) modules are installed at different orientations within the array, or there is notable shading. This seems to be the only reasonable explanation for the high harmonic emissions observed at this installation but this finding should be confirmed through monitoring at other installations in future work.

5.4 Earth Rangers Centre for Sustainable Technology

Data were collected from the Earth Rangers site between March 31st, 2015 and June 22nd, 2015. Poor cellular reception at the site meant that data loss was intermittent. The data were filtered to include only those data points collected during the day-time with a voltage THD less than 5%. In total, approximately 87,000 data points, at a 10 s interval, were collected. This represented 240+ hours of inverter operation with sufficient breadth to adequately cover the power production range of the inverter.

Figure 5.4.1 shows the measured total harmonic current as a function of the fraction of inverter rated power for one line of the 3-phase connection. Results were comparable across all lines. The total harmonic current is highest when the inverter is operating between 0.1 and 0.15 of the rated power. The 5.0% TDD limit prescribed in Table 1.1 is shown in green given the rated current of 83.3 A. It was never exceeded.

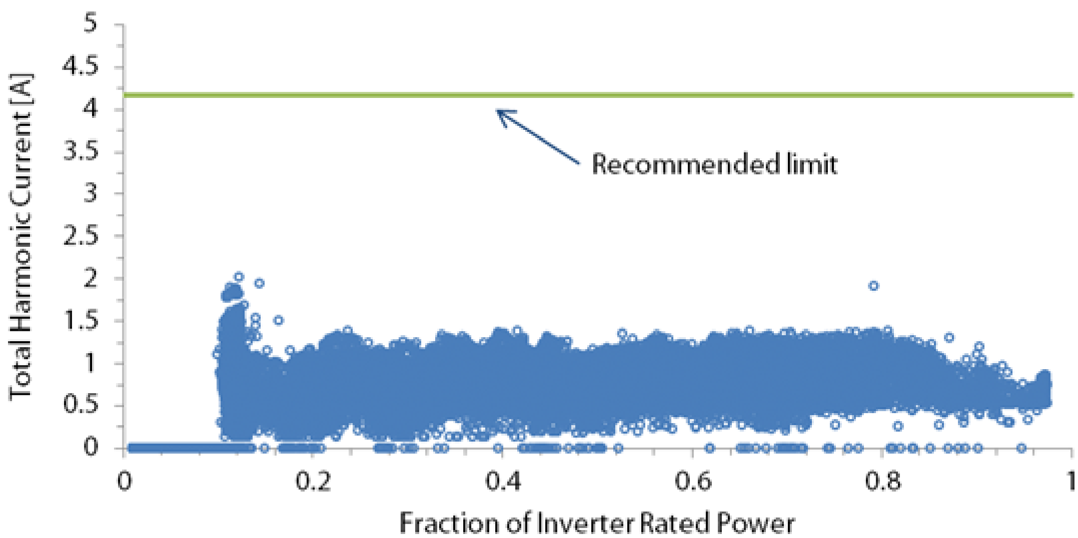

Figure 5.4.1: *The total harmonic current is well under the 5% recommended limit.*

Figure 5.4.2 evaluates the individual harmonic distortion factors against the recommended limits in the Table 3.3.2. It demonstrates that all values are within recommended limits at all times.

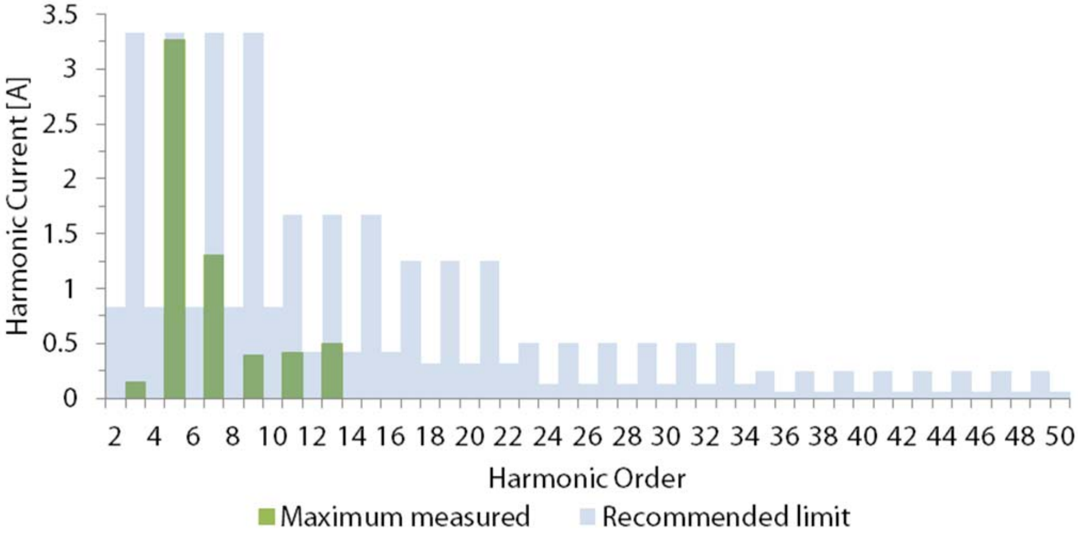

Figure 5.4.2: *The recommended harmonic current limits for each harmonic order (Table 3.3.2) are compared against the maximum harmonic current measured for each harmonic order during the monitoring period. All harmonic currents were within recommended limits at all times.*

6.0 DISCUSSION AND CONCLUSION

6.1 Overview

CSA 257 is the Canadian standard which stipulates the power quality constraints for PV installations connected to the utility electrical distribution network. This standard requires that installations use inverters which are compliant with *CSA 107.1*. Compliant inverters must produce harmonic emissions less than limits given in Table 1.1 when operating at 100% of rated load. This requirement is similar to the comparable U.S. standard, the *IEEE 1547 (or UL 1741)*, with the exceptions that *IEEE 1547* requires additional testing points at 33% and 66% of the rated load and that the power quality measurements should be taken at the point of common coupling to the utility EPS.

This study examined the power quality of real-world installed solar PV installations with respect to the limits given in these standards. Operating points at loads across the entire power-producing spectrum of the inverter were examined and, included in this, were any potential transient effects associated with the variable solar resource.

Table 6.1 summarizes the four sites that were monitored with power quality instrumentation long-term. The analysis determined whether or not the real-world TDD or individual harmonic distortion factors ever exceeded the recommended limits of *CSA 257* and *IEEE 1547*, and, if so, the frequency and nature of the occurrences were examined.

Table 6.1: *Summary of PV installation sites used for power quality monitoring*

Site	Inverter(s)	Total Rated Power [kW]	PQA
Living City Campus (Single Installation)	Inverter B	6	Yokogawa WT1800
Living City Campus (Entire EPS)	Inverters A to D	17.5	Acuvim IIW
TRCA Restoration Services Centre Facility	Inverter D	38.9	Acuvim IIW
Earth Rangers Centre for Sustainable Technology	Inverter E	30	Acuvim IIW

6.2 Total Demand Distortion

The TDD at each site was compared against the recommended limits. The findings are organized in Table 6.2.

Table 6.2: *TDD findings from PV installation sites*

Site	Findings
Living City Campus (Single Installation)	The TDD never exceeded recommended limits at any point in time.
Living City Campus (Entire EPS)	The TDD never exceeded recommended limits at any point in time.
TRCA Restoration Services Centre Facility	The TDD was within recommended limits 99.992% of the time during those hours where the inverters were producing power. Occurrences where the TDD exceeded the recommended limit appeared to be associated with high levels of 2nd order harmonic current that occurred when the inverters are operating at less than 50% of the rated power.
Earth Rangers Centre for Sustainable Technology	The TDD never exceeded recommended limits at any point in time.

6.3 Individual Harmonic Distortion Factors

The individual harmonic distortion factors measured at each site were compared against the recommended limits. The findings are outlined in Table 6.3. Note that over-limit occurrences listed in Table 6.3 were not accompanied by voltage harmonic distortion on the network. It follows that the current harmonic emissions are therefore a result of the inverters themselves rather than the conditions on the EPS. Also note that, as explained in Section 4.0, over-limit does not necessarily mean non-compliance with the standards. In some of the cases accounted for in Table 6.3 the installations are, in fact, still compliant because the over-limit occurrences were observed at fractions of rated load which are below 33%.

Table 6.3: *Individual harmonic distortion factor findings from PV installation sites*

Site	Findings
Living City Campus (Single Installation)	The individual harmonic currents were within the recommended limits 99.993% of the time that inverter was producing power.
Living City Campus (Entire EPS)	The 2nd order harmonic current was over limit 1.1% of the time and all others were always within recommended limits at all times. Based on the observations at the Restoration Services Centre Facility, it seems likely that the cause of these occurrences is related to the Inverter D microinverters in the installation, although this was not confirmed directly.
TRCA Restoration Services Centre Facility	It was observed that 4.1% of the time the 2nd harmonic order was over limit, 1.7% of the time the 24th harmonic order was over limit and 10.2% of the time the 28th harmonic order was over limit. These occurrences were observed on clear sky days in steady conditions.
Earth Rangers Centre for Sustainable Technology	The recommended harmonic limits for individual orders were never exceeded at any point in time.

6.4 Discussion

The results for the Restoration Services Centre Facility had a discrepancy. High levels of harmonic emissions were observed when the installation was operating at greater than 33% of rated load in steady irradiance conditions with a low voltage THD on the EPS. This was observed despite the fact that the microinverters were listed as compliant with *CSA 107.1* and *IEEE 1547*. Measurements on specific Inverter D microinverters showed that, while the harmonic content at operating powers above 20% of the rated load were within limit (or very close), the harmonic content below an operating power of 20% were very high.

The only available explanation for the high harmonic content at the RSC Facility was that, since some modules on a given branch were mounted nearly horizontal and others, nearly vertical, at certain points in time there would be some microinverters within the branch operating at a low fraction of rated power. These modules produced a sufficiently high harmonic current to push the combined harmonic current of the whole branch over the limits suggested in the above standards. This could have also occurred due to module shading. This lead to the somewhat counterintuitive conclusion that inverters which are individually compliant with recommended harmonic emissions limits may actually produce combined harmonic emissions that are in excess of those same limits when installed alongside other inverters in a PV installation.

This study sought to, in-part, identify whether or not transient irradiance conditions might be associated with power quality disturbances. The only notable power quality issues uncovered within this study were associated with Inverter D microinverters operating at part-load in steady-state conditions. Prohibitively high harmonic emissions resulting from transient irradiance conditions were not identified.

Certain study limitations should be noted. Measurements in this study were on the customer-side of the utility transformer and it is likely that the harmonic emission measurements on the utility-side may differ somewhat. However, harmonics on the customer-side are still important because it is possible for multiple customers to be connected to the same utility transformer; and the intent of the power quality constraints in the grid- interconnection standards is to limit the degree to which one customer might pollute the power used by others on the network.

While it is important to perform studies such as these on the existing stock of PV installations, it is also important to note that inverter technology is continually improving and results from inverters that are several years old may not be completely indicative of the performance of newer models from the same brand. However, in the case of Inverter D, which yielded the most interesting results, the most recent model was tested.

This study also demonstrated how power quality is a larger topic that extends beyond PV power generation. It was seen that non-linear loads may produce high levels of current harmonic emissions greater than that associated with PV installations of comparable size.

6.5 Conclusion

In general, the PV inverters examined within this study performed in compliance with the power quality limits outlined in the grid-interconnection standards. Deviations from this behaviour were infrequent. As such, the power quality of solar PV inverters is not considered as a barrier towards future deployment of PV. However, with one specific microinverter brand (Inverter D), it was observed that the power quality was poor at operating points not currently considered by the grid-interconnections standards. This created potentially problematic levels of current emissions when many Inverter D microinverters were installed alongside each other in an installation.

This has only been seen with one brand of microinverter and it is not clear whether or not other microinverter brands would have the same issue. This should be the topic of future work. In general, this phenomenon also merits further investigation – particularly by standards development committees that define the power quality constraints for grid-connected inverters. It is feasible that this loophole could be closed with more stringent requirements but whether or not that is the right course of action needs to be evaluated against the corresponding drawbacks and benefits of doing so. Individual LDCs do have the power to set their own power-quality constraints and ultimately, any problematic current harmonic emissions could be mitigated with filtering if deemed appropriate.

6.6 Future Work

- This work examined a limited number of inverter models, manufacturers and topologies. Future work might go to greater extents to take similar measurements on the most common inverter manufacturers and make comparison between the different inverter topologies.
- It was observed that Inverter D had high harmonic current at low load. Right now this effect has only been observed from a single brand, Inverter D. It remains to be seen whether or not there are other inverter topologies/brands also have high levels of harmonic emissions at low load. This should be further investigated.
- Further power quality measurements should be taken to confirm the explanation for the high harmonic emissions observed at the RSC Facility.
- Grid-interconnection standards development committees might wish to determine whether or not the situation of very high harmonic currents at low load should be addressed in future standard versions, especially as microinverter topologies gain in popularity and are deployed at "solar-farm" levels.
- Inverter D manufacturer should be engaged in an attempt to rectify the observed power quality issues and also to further explore the extent to which it is, in fact, an issue.

APPENDIX A - DERIVATIONS

Equations A.1 to A.3 show how the RMS harmonic current (I_H) can be expressed in terms of the total RMS current (I) and the RMS current of the fundamental frequency (I_1).

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots} \tag{A.1}$$

$$I = \sqrt{I_1^2 + I_H^2} \tag{A.2}$$

$$I_H = \sqrt{I^2 - I_1^2} \tag{A.3}$$

Equations A.4 to A.6 show how I_1 can be expressed in terms of THD and I.

$$THD = \frac{I_H}{I_1} \tag{A.4}$$

$$THD = \frac{\sqrt{I^2 - I_1^2}}{I_1} \tag{A.5}$$

$$I_1 = \frac{I}{\sqrt{THD^2 + 1}} \tag{A.6}$$

Rearranging equation A.4 gives Equation A.7. Equation A.6 substituted into Equation A.7 gives Equation A.8. This the total harmonic current expressed in terms of known quantities from the Acuvim IIW PQA.

$$I_H = THD \cdot I_1 \tag{A.7}$$

$$\boxed{\boldsymbol{I_H = THD \cdot \frac{I}{\sqrt{THD^2 + 1}}}} \tag{A.8}$$

Similarly, the harmonic current for any n^th harmonic order is shown in Equation A.10.

$$I_n = IHD_n \cdot I_1 \tag{A.9}$$

$$\boxed{\boldsymbol{I_n = IHD_n \cdot \frac{I}{\sqrt{THD^2 + 1}}}} \tag{A.10}$$

APPENDIX B - VERIFICATION

To verify the power quality measurements from the low-cost Acuvim IIWs, the devices were connected in parallel with the Yokogawa WT1800 and all monitored the power quality of a PV installation at the LCC PV testing facility. Results are shown for one device only but are similar across all Acuvim IIW devices used. Figure B.1 plots the current measured by the Acuvim IIW as a function of the current measured by the Yokogawa WT1800 over the course of the day on Sept 9th/2014. The installation was small (<5kW), so to increase the accuracy of the Acuvim IIW in the low current range, multiple wire wraps around the Rogowski coil were used. The "Unadjusted" current measured is the raw current measured by Acuvim IIW that has not been adjusted to take into account the number of wire wraps. The "Adjusted" current is the actual current, calculated by dividing the "Unadjusted" value by the number of wire wraps. As shown by the line of best fit, there is a 1-to-1 relationship (to within 1%) between the current measured by the Yokogawa WT1800 and the "Adjusted" current measured by the Acuvim IIW.

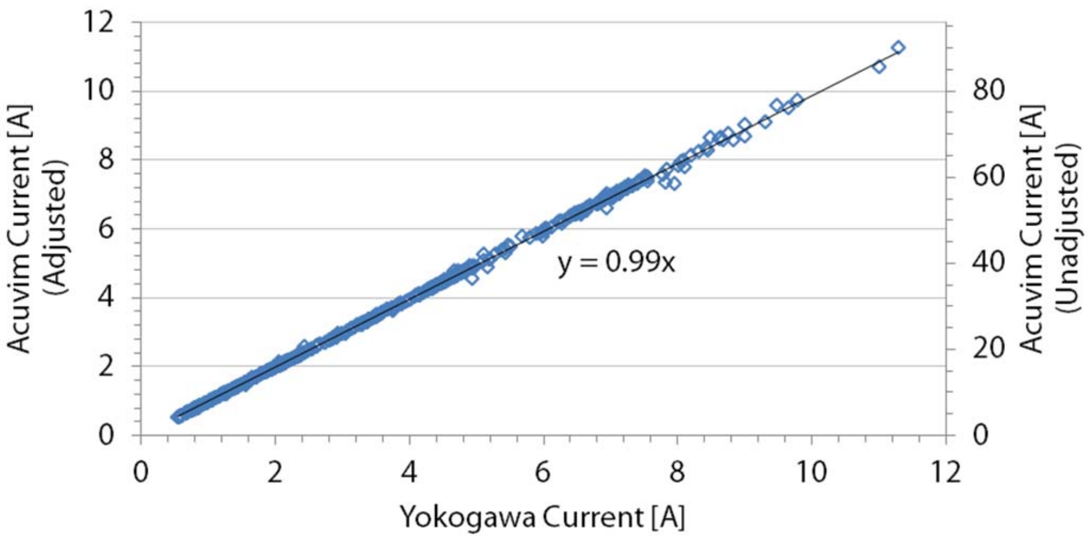

Figure B.1: *The current measurements of the two instruments agree to within 1%. Wire wraps around the Acuvim IIW's Rogowski coil CT were used to increase the devices accuracy in the low current range. The "Unadjusted" values are the raw measurements read by the Acuvim IIW while the "Adjusted" value is the actual current (i.e. the "Unadjusted" value divided by the number of wire wraps).*

Figure B.2 shows the total harmonic current (I_H, see Equation A.3) measured by the Acuvim IIW as a function of that measured by the Yokogawa WT1800 over the course of the day on September 16th/2014. Equations A.6 and A.7 were used to calculate I_H from the Acuvim IIW's THD and RMS current measurements. Again, the "Unadjusted" value is the raw value read by Acuvim IIW while the "Adjusted" value is the "Unadjusted value" divided by the number of wire wraps. At the given level for the "Unadjusted" total harmonic current, between 4 and 8 A, the total harmonic current measured by the Acuvim IIW is approximately 15% lower than that measured by the Yokogawa WT1800.

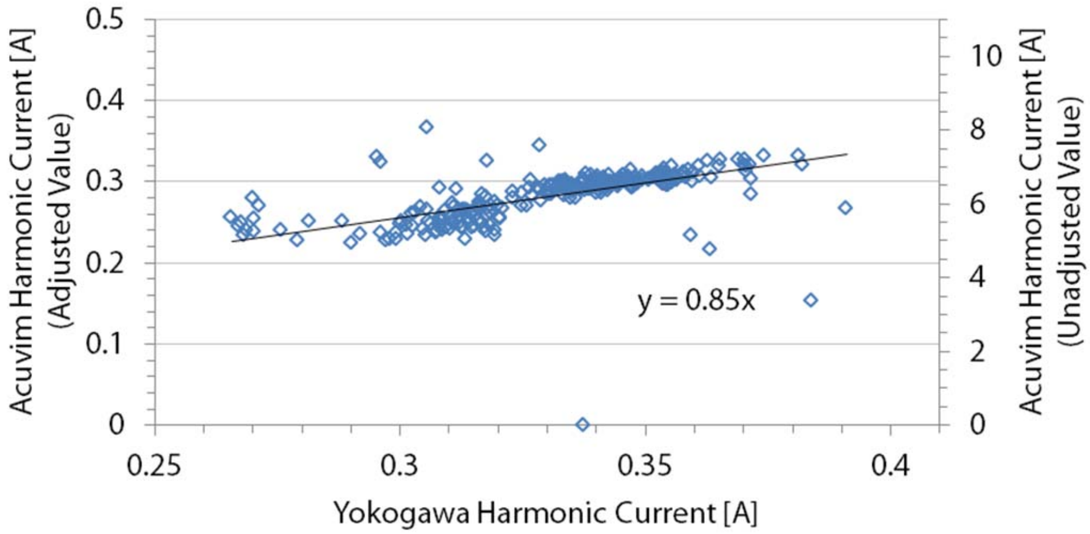

Figure B.2: *The total harmonic current measurement of the Acuvim IIW is approximately 15% lower than that from the Yokogawa WT1800 when the unadjusted harmonic current is between 4 and 8 A.*

The disagreement illustrated in Figure B.2 decreases as the total harmonic current increases. This is illustrated in Figure B.3. This plot was obtained by measuring the power quality of a linear and non-linear load operating in parallel. Wire wraps were used to progressively adjust the current magnitude, and the measured harmonic current was compared against the estimated actual value. The estimated actual value was calculated using the THD measured in the limit of very large current (where the difference between measured and actual is assumed to be small). The difference is such that <u>the Acuvim IIW always measures less than the actual value</u>, likely because it is less sensitive to smaller signals. The plot shows that below 3 A the harmonic current measurement is heavily attenuated. As an example, when the Acuvim IIW measures a total harmonic current of 3 A, the actual value is likely closer to (3 A)*(1+0.2) = 3.6 [A], where the 0.2 was estimate from Figure B.3 (i.e. the difference is approximately 20%). This characterization method was simple and intended to be rough check on the Acuvim IIW's behaviour. A more rigorous characterization would look at a wide range of harmonic currents across each of the individual harmonic orders within device's measurement range (up to the 63^{rd}). This was beyond the scope of this study and the rough measurements described in Figure B.3 are sufficient towards interpreting the Acuvim IIW power quality results from the various sites.

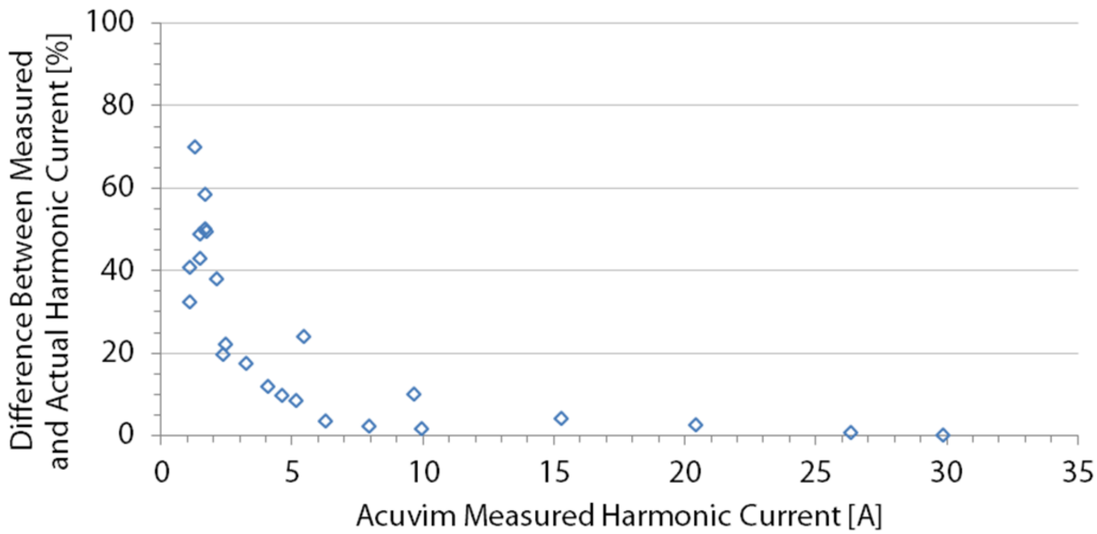

Figure B.3: *The difference between the estimated actual total harmonic current and that measured by the Acuvim IIW is large when the magnitude of the measured total harmonic current is small. The Acuvim IIW always reads lower than the actual value. Below a total harmonic current of approximately 3 A the Acuvim IIW's total harmonic current measurement is heavily attenuated.*

Figure B.4 shows the 3rd harmonic measured by the Acuvim IIW as a function of that measured by the Yokogawa WT1800 over the course of the day on September 16th/2014. It is worth noting that the two devices were not controlled using the same time server. The timing was synchronized manually. This may not have been sufficiently precise in transient conditions, and this may have resulted in the outliers of the dataset. Figure B.4 shows that between 1 and 4 A the 3rd harmonic current measured by the Acuvim is, on average, 11% less than that measured by the Yokogawa WT1800.

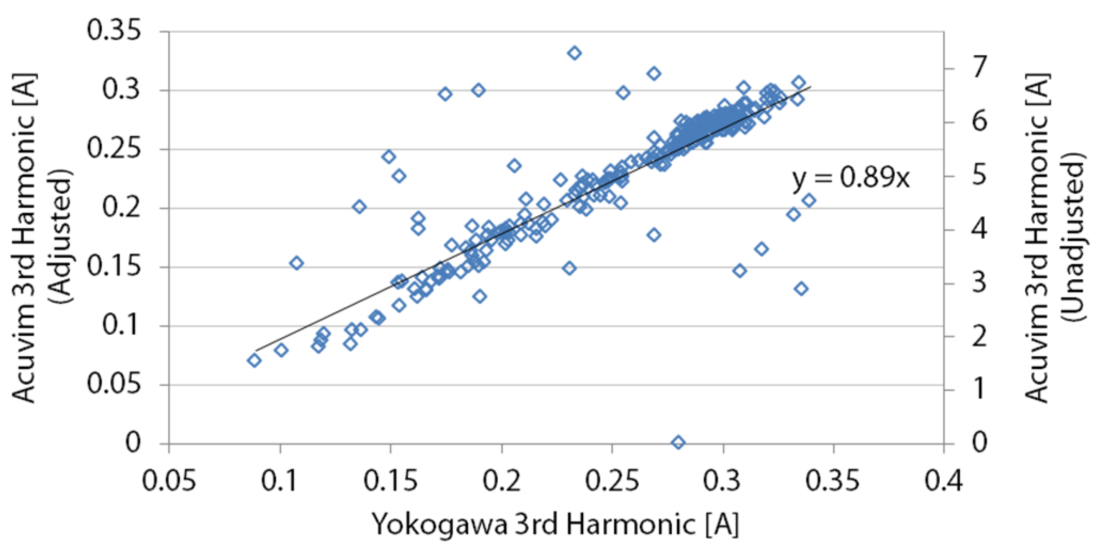

Figure B.4: *The 3rd order harmonic current measurement of the Acuvim IIW is approximately 11% lower than that from the Yokogawa WT1800 when the unadjusted harmonic current is between 1 and 7 A.*

Figure B.5 shows the 5th harmonic measured by the Acuvim IIW as a function of that measured by the Yokogawa WT1800 over the course of the day on September 16th/2014. It is clear that due to the lower "Unadjusted" current the Acuvim IIW's measurement is more heavily attenuated.

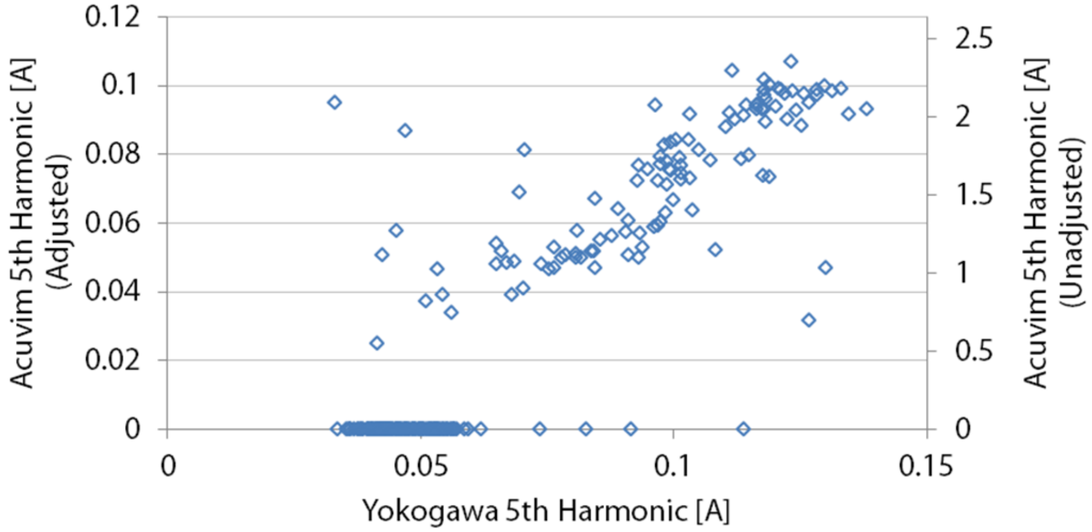

Figure B.5: *The 5th order harmonic current measurement of the Acuvim IIW is notably attenuated from the Yokogawa WT1800 when the unadjusted harmonic current is between 0.5 and 2.5 A.*

It is clear that the current harmonics measured by the low-cost Acuvim IIW using Rogowski coil CT's do not completely agree with that measurements of the high-end Yokogawa WT1800 with direct inputs for all cases. This was not unexpected since the there is wide difference between the cost of the two instruments. However, Figures B.1 to B.5 have helped to identify those conditions where the measurements will disagree as well as the extent of the disagreement. This will help to provide additional insight to the Acuvim IIW's measurements where necessary.

POWER QUALITY ASSESSMENT OF SOLAR PHOTOVOLTAIC INVERTERS

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