LDC Tomorrow Fund Report

Correlation of Weather Conditions and Power Quality

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1. Introduction

Challenges currently facing local distribution companies (LDCs) include the increased number of renewable generation installations and non-linear loads within modern homes. As popularity of energy efficient appliances and renewable energy sources steadily increase within distribution grid, the number of variable frequency drives (VFDs) and solid-state converters add more challenges with respect to grid power quality. There has been significant research and investigation addressing the cause of harmonics, however, there is little experimental data covering the correlation between weather patterns and harmonic content generated by sources/loads of a modern grid. By assessing harmonics generated by renewable energy sources versus meteorological conditions, LDCs can better understand the impact of solid state devices and forecast the longevity of distribution assets.

2. Configuration

The Kortright Centre for Conservation - Living City Campus demonstrates sustainable technologies within two semi-detached houses. The site consists of a wind turbine (1.8 kW), photovoltaic (PV) (3.8 kW), modern loads (a variety of energy efficient appliances), and a level 2 electric vehicle (EV) charging station. The two houses are powered by a standard North American center-tapped 27.6 kV – 240/120 V, 50 kVA distribution transformer with a per unit impedance of 1.7%. Figure 1 represents a single line diagram (SLD) for the Living City electric supply services, including locations of power quality metering (PQM).

The location of each PQM (shown in Figure 1) depicts points of common coupling (PCC) for House A, House B, and PV installations respectively. The PCCs have been defined as the interface between the utility's distribution system and the customer's equipment [1]. Given that the LDC owns the distribution transformer feeding the Living City, all PCCs have been assigned on the transformer secondary.

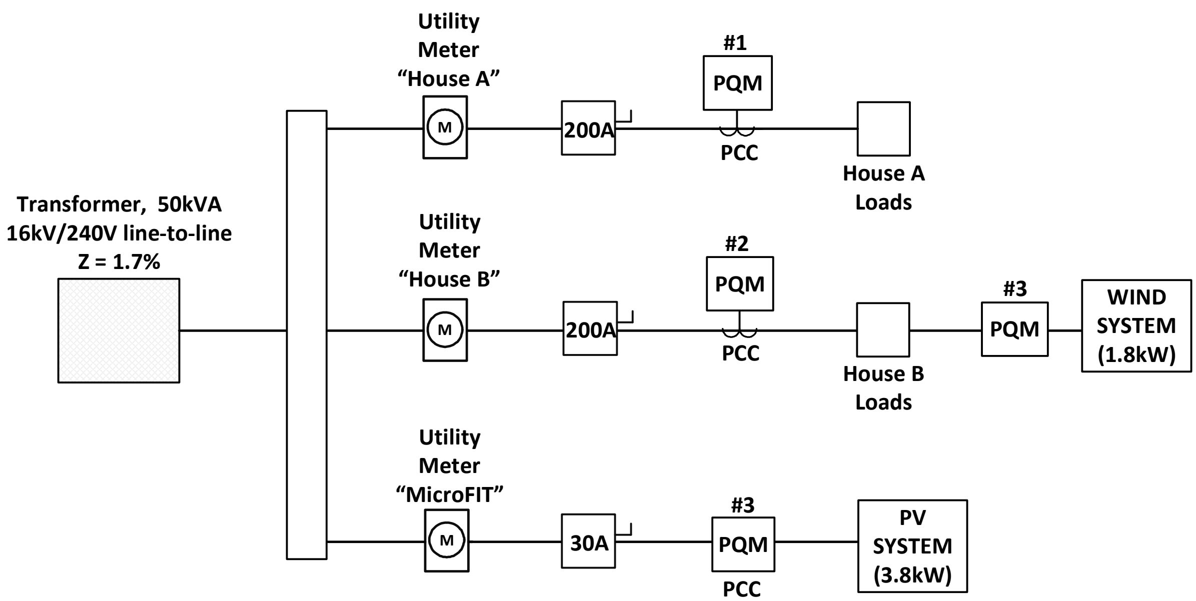

Figure 1 – The Living City Campus SLD

To evaluate harmonic content generated by the Living City loads, IEEE-519-1992 power quality standard has been applied. The harmonic limits were established based on "worst case" scenarios as governed by the standards (Table 1). The limits were determined by calculating the ratio of short circuit current compared to load current, expressed as I_{SC}/I_L [2].

Maximum Harmonic Current Distortion in % of I_L						
Individual Harmonic Order						
ISC/IL	**<11**	**11 < h < 17**	**17 < h < 23**	**23 < h < 35**	**35 < h**	**TDD**
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 1 – Current Harmonic Limits As Per IEEE-519-1992 [2]

To determine acceptable level of harmonics, the total demand distortion (TDD) was calculated as shown in Equation 1, where I_L is the maximum observed load current at the PCC, and I_n is the individual harmonic order.

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_n^2 \dots}}{I_L}$$

Equation 1 – Calculating TDD as per IEEE 519 [1]

System	I_L (Amps)	I_{SC}/I_L Ratio
PCC House A & B	40	306
PCC MicroFIT	15	< 20
Wind	5	< 20

Table 2 – System Summary

In this case, House A and B were monitored over a period of 7 months, and maximum load current was established to be 40 A for both houses. As shown in Table 1, each individual harmonic is to be evaluated in terms of ratio to the maximum measured load current (I_n/I_L). Based on IEEE-519 the short circuit current (I_{SC}) on the secondary of the transformer was calculated (12254 A) [1].

Using the maximum observable current, the current restraints for Houses A and B fall under the I_{SC}/I_L limit 100 < 1000. Both PV and wind systems fall under the category of generating equipment (I_{SC}/I_L < 20) [1]. It should be noted that although the wind turbine is not connected at the PCC, harmonic limits were still used for comparative purposes.

In order to determine total harmonics observed at the secondary of the distribution transformer, vector addition of individual harmonics is used as shown in equation 2.

$$\overrightarrow{I_{TransformerSecondary}} = \overrightarrow{I_{n_{HouseA}}} + \overrightarrow{I_{n_{HouseB}}} + \overrightarrow{I_{n_{Solar}}}$$

Equation 2 – Vector Addition

3. Measurement

In compliance with IEEE-519 standard, current harmonics were captured up to the 49th order, using Schneider Electric ION 7650 PQMs. Both line and neutral currents were measured at a sampling rate of 1024 samples per cycle, using a 3 second aggregate for filtering purposes [3]. Time synchronized measurements of the three PQMs were facilitated via a proprietary Ethernet protocol (accuracy +/- 16ms) [4]. PQMs #1 and #2 were installed to measure harmonics generated by Houses A and B respectively, while PQM #3 was assigned to capture harmonics generated by PV and the wind turbine (Figure 2).

Figure 2 – Installation of ION 7650 PQMs at the Living City

Meteorological conditions were recorded using two weather monitoring stations. The first weather station was installed on the mast of the 1.8 kW wind turbine (Figure 3). Conditions were measured every 15 minutes including: temperature (°C), solar irradiance (W/m^2), wind speed (m/s), gust speed (m/s), and wind direction. Data were then transmitted via cellular network to a centralized server accessible through the internet. The second weather monitoring station was installed on the roof of the semi-detached homes, and was custom built for the purpose of accurately collecting real-time meteorological conditions (1 sample per second).

Figure 3 – Weather Station Installed at Base of Wind Turbine

Figure 4 – Weather Station Installed at Base of Wind Turbine

A modular server platform (MSP) was installed at the test site allowing for automated data collection, scheduled backups, and remote monitoring for the PQMs. The MSP consists of a server, networking hardware, external (swappable) data storage and an uninterruptable power supply. The server's primary role is to host a structured query language (SQL) database where PQM and meteorological data are stored. To ensure simultaneous recording of both power quality and meteorological data, a custom software application was developed to activate triggering within the PQMs when a condition of interest is observed. In addition, a virtual private network (VPN) was established between the Living City and Mohawk College allowing for remote monitoring and data transfer.

Figure 5 – Installation of Modular Server Platform in Basement of House A

3. Observations & Test Results

Throughout the course of testing, a number of current harmonic measurements were conducted with varying meteorological conditions. These test results provide details which are representative of real-world conditions which affect a typical residential distribution grid. The following data can be used as an additional variable when determining the impact on distribution equipment due to poor power quality during varying weather conditions.

3.1 Solar PV Generation

Measurements of the 3.8 kW PV system were conducted for all irradiance (200 W/m^2 to 1000 W/m^2) conditions. As shown in Table 3, maximum observable TDD and 3rd harmonic were 4.43% and 4.17% respectively, passing IEEE-519 harmonic limits. Remaining higher order harmonics (beyond the 5th) were observed to be less than 1% in all cases.

Irradiance (W/m^2)	I_{RMS} (Amps)	TDD (%)	Significant Harmonic Content I_n/I_L (%)			
			3rd	5th	7th	9th
Idle	0.17	0.21	0.17	0.06	0.02	0.03
200	2.83	2.10	1.74	0.62	0.29	0.22
400	4.22	2.42	2.10	0.55	0.26	0.22
600	7.37	2.75	2.43	0.05	0.21	0.27
800	9.06	3.34	3.00	0.22	0.32	0.43
1000	11.97	4.43	4.17	0.57	0.21	0.53

Table 3 – PV Harmonic Content

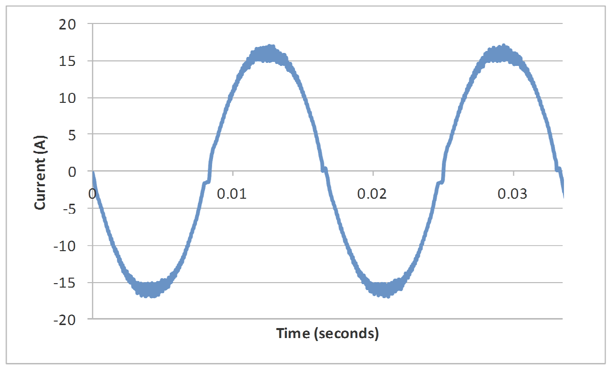

Figure 6 – PV Waveform at 1000 W/m^2

3.2 Wind Generation

Harmonic measurement of the 1.8 kW wind turbine was conducted during multiple levels of generation (Table 4). Typical current values generated by the wind turbine varied between 1 to 4 A. Observations showed the 5th and 11th harmonics steadily increase in magnitude as generation increased, while the 3rd harmonic was highest when approaching minimum and maximum generating levels. In contrast, the 9th harmonic was observed to typically decrease in magnitude as generation increased.

I_{Wind} (Amps)	TDD (%)	Significant Harmonic Content I_n/I_L (%)			
		3rd	5th	9th	11th
1	2.74	2.08	0.28	1.24	0.62
2	2.23	1.02	0.34	1.48	0.50
3	2.20	1.28	0.78	0.84	0.76
4	3.14	2.00	1.72	0.84	0.90

Table 4 – Wind Turbine Harmonic Content With No Solar Generation

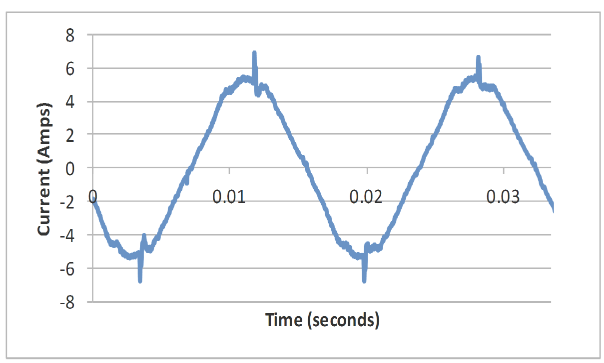

Figure 7 – Wind Turbine Waveform at 4 A Generation

Comparative testing was conducted with and without solar generation during varying levels of wind (Tables 3 and 4). A slight increase in TDD was observed when comparing Tables 4 and 5 during periods of solar generation. In contrast to Table 4, increased 5th harmonics were observed while wind and solar systems were operating in parallel. It is noteworthy that neither system produces significant 5th order content, implying that the 5th order harmonic is being generated as a consequence of parallel generation. Although an increase in poor power quality during high levels of generation was observed, TDD and individual harmonics passed IEEE-519 Standards.

I_{Wind} (Amps)	TDD (%)	Significant Harmonic			
		3rd	5th	9th	11th
1	2.98	2.00	0.32	1.30	0.34
2	2.64	1.44	1.08	1.36	0.82
3	2.72	1.70	1.12	1.10	0.72
4	3.58	2.44	1.84	0.86	1.24

Table 5 – Wind Turbine Harmonic Content With Solar Generation at 2kW

3.3 Temperature Profile

Research focused on the air source heat pump (ASHP) used for heating, ventilating, and air conditioning (HVAC) which is driven by a single phase VFD. The rated output capacity of the ASHP is 10 kW_{th} of cooling, and 11.7 kW_{th} of heating, with a full load amp (FLA) rating of 28 A. Heating functions within House A are assisted by an 8.8 kW_{th} electric boiler with an FLA rating of 15 A.

During the 7 month testing period, temperatures varied between -15°C and +30°C and TDD failed by exceeding 15% (Table 6). As outdoor temperatures fluctuated and reached extreme values, the increased load to the compressor (due to the VFD in the ASHP) caused an increase of current harmonics.

Measured data, shown in Table 6, provides a comparison between outdoor air temperature, TDD, and individual harmonics. Observations showed the 3rd, 5th, 11th and 13th harmonic orders varied the most relative to changes in outdoor temperature. Following IEEE-519 standard for an I_{SC}/I_L ratio limit of 100 < 1000, the Standard states that any harmonic below the 11th order shall not exceed 12% [1]. The 3rd order harmonic for House A continuously failed during outdoor temperatures of greater than 15°C and less than 0°C. As outdoor temperatures decreased below 0°C, individual harmonic distortion on the 3rd order was the most affected, with little change in the 5th order. These observations are likely due to the resistive heating load (electric boiler) utilized in both houses as it minimizes the average harmonic content. The visibly high crest factor in Figure 8 is expected due to previous analysis made using modern appliances, which utilized VFDs [2]. The current measurements of VFD appliances match those captured by the Advanced Power Quality Lab at Mohawk College [5].

Similar changes in both TDD and individual harmonics were observed on the neutral current for House A, as seen in Table 7. The 3rd, 5th, and 11th harmonic orders were the most impacted on the neutral conductor, with an increase of up to 8% on the 3rd order during temperatures above 15°C and below 0°C. Although the TDD did not fail harmonic limits, the TDD was observed to exceed 10% during varying outdoor temperatures.

The two peaks observed on the neutral waveform (Figure 9) are due to the high crest factor and DC offset of House A as shown in Figure 8. Due to the current imbalance of House A, magnitudes of the neutral peaks represent nearly a quarter of the maximum observed line current.

Toutdoor (C°)	IRMS (Amps)	TDD (%)	Significant Harmonic Content In/IL (%)			
			3rd	5th	11th	13th
-15	22.31	16.86	13.20	3.10	2.38	0.84
-10	21.20	16.41	12.81	2.93	1.64	0.52
-5	18.53	15.11	11.91	1.13	2.29	0.67
0	15.71	7.99	5.07	3.51	0.47	0.07
5	14.78	8.15	5.39	2.77	0.52	0.52
10	14.19	7.81	4.97	3.54	0.39	0.82
15	13.35	7.80	4.93	3.54	0.55	0.18
20	13.58	18.95	14.40	6.08	0.58	0.52
25	15.94	18.88	13.98	6.30	1.24	1.51
30	17.75	19.51	14.56	5.85	2.23	1.61

Table 6 – House A Harmonic Content (Line Current) (Highlighted Cell Repesent Failiures)

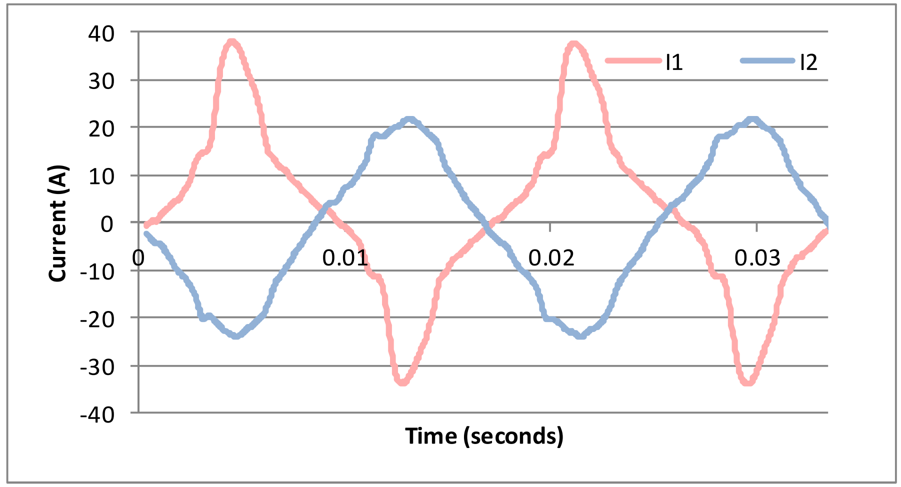

Figure 8 – Sample Waveform (Line Current) of House A at 30 °C as Seen in Table 6

Toutdoor (C°)	IRMS (Amps)	TDD (%)	Significant Harmonic Content In/IL (%)			
			3rd	5th	11th	13th
-15	6.55	8.89	7.62	3.79	1.38	0.78
-10	6.31	7.92	6.74	3.59	1.16	0.57
-5	5.33	7.21	6.12	3.18	0.98	0.07
0	3.30	3.01	2.49	1.37	0.20	0.07
5	3.51	3.53	2.88	1.67	0.11	0.11
10	4.12	4.75	3.56	2.70	0.26	0.17
15	3.11	3.08	2.18	1.53	0.21	0.35
20	4.07	10.08	8.35	5.04	1.31	0.56
25	4.02	8.36	7.10	4.47	1.39	0.86
30	4.64	9.64	8.05	4.52	1.34	0.80

Table 7 – House A Harmonic Content (Neutral Current)

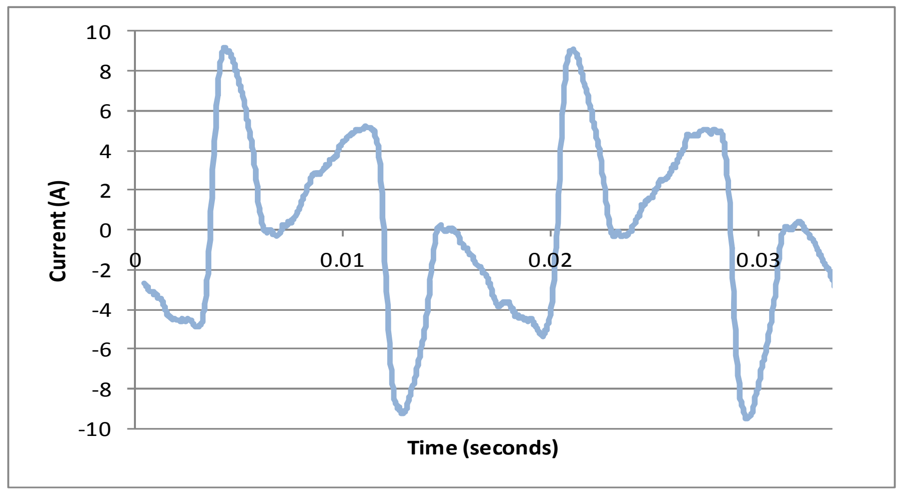

Figure 9 – Sample Waveform (Neutral Current) of House A at 30 °C as Seen in Table 7

3.4 Distribution Transformer Harmonic Content

To determine the level of poor power quality at the transformer secondary, the PCC power quality data (House A, House B and Solar) were summed via simple vector addition. Table 8 represents the calculated vectors of the three PCC locations against the same temperature profiles as seen in Table 6 (of significant interest due to the IEEE-519 limit failures of House A observed in this range).

Using calculated vector values for line current, the TDD ranged between 6% and 13% (Table 8), barely passing IEEE 519-1992 limits for the distribution transformer. Calculations showed the 3rd and 11th harmonics steadily increased during extreme outdoor temperatures, while the 5th order decreased in magnitude during cooler temperatures.

The same calculation was made for the neutral current at each PCC (Table 9). All individual harmonics (most importantly the 3rd and 5th), increased when nearing extreme cold and hot outdoor temperatures. The data shown in Table 9 compliment that of Table 7, where the increase in individual harmonics is seen to be very similar.

In contrast with House A, all calculated data for the distribution transformer pass IEEE-519-1992 limits. The values in Table 8 can be attributed to the ground source heat pump (GSHP) being out of service for House B, which instead, used resistive space heaters and alternative cooling as a replacement during the year of 2014.

$T_{Outdoor}$ (C°)	I_{RMS} (Amps)	TDD (%)	Significant Harmonic Content I_n/I_L (%)				
			3rd	5th	9th	11th	13th
-15	44.69	10.05	9.52	2.14	0.48	1.10	0.42
-10	41.64	9.95	3.27	2.71	0.63	0.99	0.25
-5	37.12	8.99	7.41	2.17	0.51	0.79	0.20
0	31.80	6.65	4.82	4.14	0.62	0.15	0.33
5	26.76	7.17	3.23	2.68	0.91	0.25	0.24
10	26.21	6.77	5.78	3.23	0.70	0.54	0.17
15	18.71	7.16	5.83	3.56	0.50	0.31	0.19
20	23.71	11.53	10.22	4.90	0.24	0.30	0.39
25	27.50	11.55	10.50	4.49	0.25	0.60	0.75
30	32.94	12.19	11.07	4.65	0.50	1.13	0.72

Table 8 – Distribution Transformer Harmonic Content (Line Current)

$T_{Outdoor}$ (C°)	I_{RMS} (Amps)	TDD (%)	Significant Harmonic Content I_n/I_L (%)				
			3rd	5th	9th	11th	13th
-15	14.26	7.46	6.79	2.74	0.70	0.96	0.51
-10	13.84	7.10	6.40	2.81	0.72	0.85	0.42
-5	12.46	6.23	5.74	2.03	0.88	0.70	0.23
0	8.89	3.67	3.03	1.82	0.41	0.30	0.17
5	7.17	3.35	2.78	1.64	0.39	0.34	0.14
10	6.51	2.24	1.72	1.23	0.40	0.15	0.10
15	5.15	3.30	2.56	1.81	0.37	0.22	0.16
20	6.75	7.17	6.12	3.29	0.54	0.92	0.41
25	6.89	7.22	6.20	3.26	0.59	0.93	0.64
30	7.79	8.09	7.05	3.67	0.60	0.95	0.52

Table 9 – Distribution Transformer Harmonic Content (Neutral Current)

3. Conclusions and Recommendations

Based on the findings of this study, wind turbine and PV outputs did not exceed harmonic standard limits (Table 1). Although renewable energy passed IEEE limits, harmonic content for wind (3rd, 5th, 9th, and 11th orders) and PV (3rd order) was nevertheless present, with an amplification of the 5^{th} harmonic when both solar and wind run in parallel. The increasing popularity of renewable energy installations introduces an additional injection of current harmonics to the residential grid. This is due to the solid-state converters, and grid synchronization which requires the use of power electronics (as seen in a switch mode inverter). As a result of switching techniques used in these inverters, harmonic disturbances will always be present for installations requiring power conversion.

HVAC system operation was directly related to both changing weather patterns and power quality. This relationship is not unexpected given that HVAC system loading is nearly entirely dependent on external meteorological conditions. Noteworthy however was the impact on power quality during extreme temperatures, primarily due to changing power levels in the VFD which drives the ASHP. This continuous use of the ASHP led to the failure of IEEE-519 limits for House A. Harmonic content during temperatures ranging between 0°C and 15°C was significantly less, with the TDD being observed to be less than 10% in most cases. The slight improvement in power quality during colder outdoor temperatures is due to the resistive boiler (linear load) which was used in combination with the ASHP during heating cycles. Continued measurement of the neutral current within the homes is of significant interest due to the observed current imbalances caused by the ASHP and miscellaneous equipment which may be detrimental to the longevity of the distribution transformer feeding the Living City Campus.

The injection of current harmonics by VFDs is due to solid-state devices used to simulate a sinusoidal wave in order to control the speed and torque of an electric motor. These solid-state devices are used for switching applications (non-linear) which are the primary source of the injected current harmonics and explain the observed crest factor in figure 4. Recommendations to mitigate the observed poor power quality due to the VFD include the use of line reactors, passive filters, and/or active filters.

With the installation of the high-speed weather monitoring station, the automated triggering of power quality measurements and the analysis of current harmonics will allow for increased measurement accuracy, specifically for the 1.8 kW wind turbine. Since small scale wind generation is heavily affected by wind gusts, the use of the high-speed weather station will assist in capturing high resolution data.

4. References

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