Benchmarking Aspects of Power Quality of a Municipal Residential Network against International Standards

Wilfred Fritz, Deon Kallis

Abstract — In this paper the influence of domestic loads are discussed on voltage distortion in residential electrical networks. The effects of the resultant harmonics produced by different domestic load categories are reviewed. The source of harmonic generation by dimmable LED lamps, CFLs and ripple injection control, is elaborated on with resulting total harmonic distortion (THD) results. These harmonics may lead to unreliable energy delivery due to premature component and/or system failure as a result of the accretion of harmonic currents. Harmonic measurements that were data-logged in a case study in Beaufort West, a small town in South Africa, are analysed. Some of the standards addressing voltage distortion regarding power quality in electrical reticulation systems, such as the IEC61000 are compared to that of the network in the case study. The municipal network also has a number of grid-tied solar PV systems connected to the network. Some of the abovementioned voltage THD measurements are benchmarked against the IEC and other international power quality standards.

Index Terms— **power quality, harmonic control, pulse width modulation, ripple control.**

1 INTRODUCTION

There are two main categories of domestic loads that produce harmonics in residential networks. Firstly it is domestic loads that use switching control circuits and secondly hot water geyser ripple controls. Additional to these, solar PV rooftop systems also generate unwanted harmonics on the residential network. So the unfortunate situation that presents itself is that solar rooftop grid-tied inverters produce the most undesirable harmonics when there is a reduction in sunlight, coinciding with morning and evening peaks when non-linear switching household devices are used.

Domestic loads that use switching control circuits are light dimmers, LED lights, fluorescent tubes, compact fluorescent lamps (CFLs), mobile device chargers, microwave ovens, refrigerators, laptops and high power consuming motor drives such as washing machines and vacuum cleaners. These non-linear residential load implementation is on the increase due to the use of more efficient switch-mode power supplies. Inverters used in grid-tied solar PV systems operate at low power conditions when there is a decrease in irradiation patterns such as overcast conditions or during early morning and late afternoon. During this low power operation, an inverter produces more undesirable harmonics due to the use of pulse width modulation (PWM), in the voltage control process. Inverters are an integral part of solar PV grid-tied systems, and together with non-linear residential loads produce even more undesirable harmonics. The low order harmonic amplitudes increase with a decrease in PV inverter output power [1]. Low solar irradiance has a significant impact on deteriorating power quality of the output of a PV system [15]. According to Salvatierra et al it is even necessary to disconnect grid connected PV systems in the early hours of the morning in order not to effect the power quality of residential networks [16]. These harmonics may lead to unreliable energy delivery due to premature component and/or system failure as a result of the accretion of harmonic currents. The THD of these aforementioned household and commercial building devices should adhere to the IEC61000-3-2 standard that sets THD and harmonic limits [6].

For voltage harmonics, THD is defined as;

$$THD_u = \sqrt{\sum_{h=2}^{h=H} \left(\frac{U_h}{U_1}\right)^2} \tag{1}$$

where

$$U_h(\%) = 100\frac{U_h}{U_1} \tag{2}$$

Where the individual harmonic component U is defined as the percentage of harmonics for order h with respect to the fundamental U_1 at the fundamental frequency. The same applies to current harmonics. THD is the measure of the potential heating value of sub harmonics in relation to the fundamental frequency. It is also an indication of how much extra heat will be dissipated when a distorted voltage is fed to a resistive load. Another way of putting it is that it is an indication of additional losses due to current flow [20]. Small currents may have high THD and it may be misleading with capacitive loads. This has led to the referencing of the fundamental of peak-demand current in Total Demand Distortion (TDD) is defined as;

$$TDD = \frac{\sqrt{\sum_{n=2}^{H} I_n^2}}{I_L} \tag{3}$$

Where, I_n is the magnitude of individual harmonic components (rms) and I_L is the maximum demand load current at fundamental frequency (rms). The limits of TDD are based on the I_{sc}/I_L ratio, where I_{sc} is the short-circuit current at the point of common coupling (PCC) between the customer (load) and the utility (power supply).

The IEC prefers that current harmonic limits be rigorously derived based on voltage limits and system impedance characteristics. The IEEE voltage harmonic limits are constant across all frequencies whereas the permissible voltage harmonic magnitudes decrease with frequency in the IEC [9]. The maximum demand load current of the fundamental frequency component and the short circuit current at the point of common coupling are used to determine the Total Demand Distortion (TDD) for calculation of the harmonic current distortion limits [17]. The TDD is the THD of current normalized to the maximum demand load current. The two would be the same at full load [18]. According to the IEC61000-3-6 harmonic limits standards, the MV and HV/EHV voltage THD limits are 6.5% and 3%, respectively and the LV voltage THD planning limit 5% [7] [9].

2 Harmonic generation by CFL and LED lamps

Research has proven that many undesired harmonics results from CFL and LED lamps. A decrease in current through dimming increases the voltage distortion, resulting in even higher THD. These types of indoor lighting systems increase PQ problems on the local network. These types of lighting will also be the de facto standard in residential households in the near future. Many shopping chains within South Africa have ceased selling incandescent lamps as their contribution toward energy efficiency.

Due to the high efficiency of LED lamps, they are becoming more and more popular as the price decreases due to economy of scales. With dimming, some of the methods to adjust the brightness are through regulation of the LED current, by current feedback control or through pulse width modulation (PWM) control. It is high frequency switching of the LED beyond the flicker threshold to a human observer. This leads to increased harmonic distortion transmission on the network feeders.

It depends on the quality of the lamps whether IEC61000-3-2 standard regarding THD is adhered to. LED lights that are dimmed, might result in a ripple frequency between 300Hz and 1300Hz, leading to flickering [5]. Bollen indicates that some LEDs are also prone to light output modulation when subjected to inter-harmonics [14].

Historically, CFLs were the first luminaires to be used as direct replacements for incandescent lamps. Due to the efficiency of CFLs over that of incandescent lamps, the increase in the use of the latter has a potential negative impact on the overall power quality of the grid, particularly when these devices are sourced primarily for their lower cost. The lower cost usually translates into a poorly designed control lamp system. One of the sources of the harmonics is the high frequency electronic ballast. Here an AC/AC power converter is used to increase the mains 50Hz to high-frequency AC power to supply the discharge lamp.

Due to these low cost rectifiers, a typical CFL has a very poor power factor and a large THD. Power factor correction and filtering is required to improve the power factor and to decrease the network harmonic pollution [2]. Various analysis on the harmonics generated from various dimmable and non-dimmable CFLs have been done through various tests. The study showed that dimmable CFLs have a higher distortion level, since they produce more harmonics compared to non-dimmable devices [3] [10]. On average the tests showed that the THD varies between 85%-93% with a prominent third harmonic component. The IEC61000-3-2 standard suggests lamps with active power below 25W should have a third harmonic current below 86% and fifth harmonic below 61% [13].

3 Harmonic generation by ripple injection control

Ripple injection control has been used by electrical utilities since the 1960s to control loads on the distribution network. These ripple signals are used to, amongst others, control streetlights, water pumps and hot water geysers during network peaks periods. Ripple control can also be used to signal high load periods to customers in order for them to reduce power consumption. A coded control signal is superimposed on to the normal 50Hz sine voltage waveform in the main on the MV side. A path for unidirectional communication to loads is created without the installation of new communications infrastructure. However, this leads to distortion of the 50Hz sinusoidal waveform on the network. The distortion lasts about 3 minutes per one-way communication event. The signals are detected by receiving relays, which switch loads on or off as required. [4]. This leads to power quality distortion such as noise or high level hum that is generated when a transformer or motor winding within an electrical appliance resonates with the 300Hz and 1300Hz ripple control frequency [5].

The amplitudes of the 1kHz ripple control signal levels on 11kV lines are approximately 300V. It is reduced to between 2 and 10V after propagation through 11kV/400V distribution transformers [4]. Adding capacitance or inductance in order to mitigate against these unwanted signals lowers or raises the resonant frequency. This may lead to amplification of dominant low order harmonics such as the 5th or 7th [4].

The effect of ripple-controlled hot water geysers also cause dimmed energy efficient light flickering or instability at low light settings.

4 Beaufort West case study: Harmonic measurements

PQ measurements were taken in a residential area in Beaufort West, a typical South African town with a 15MW municipal electrical demand. The town is located in the arid Karoo region of the Western Cape and has a population of approximately 34 000. Fig. 1 shows a map of the town layout, indicating grid connected rooftop solar PV plants ranging from 3kWp to 60kWp.

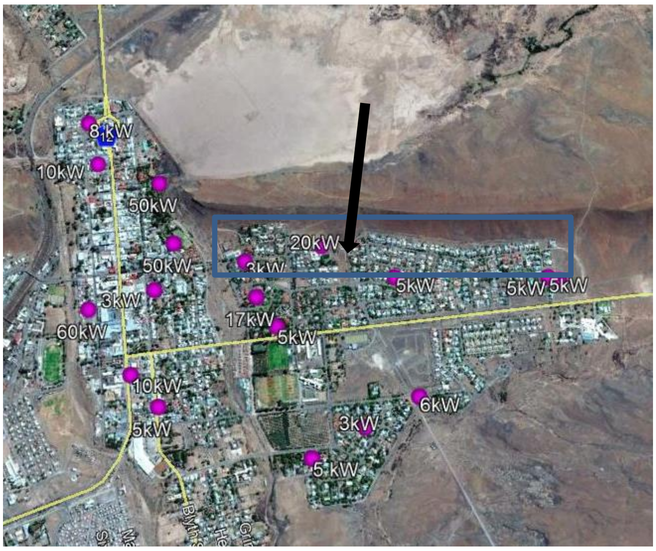

Fig. 1. Beaufort West town layout indicating rooftop solar PV generators

The encircled network of interest has a 3kW and 20kW solar PV systems connected to the LV side (400V bus) of the MV/LV Pieter Jacobs mini-substation. This LV feeder under test supplies a load of about 80 dwellings, a retirement village with about 40 apartments and about 10 municipal buildings. See Fig. 4. The load is in the main domestic appliances, lighting loads and office equipment.

4.1 Methodology

It is common practice to do PQ measurements at the point of common coupling (PCC) as shown in Fig. 2 and Fig. 3. The AC source impedance is $Z_s=R_s+jX_s$ and the harmonic source, V_{pcc} has harmonic components due to the harmonic current, I_h drawn by the load.

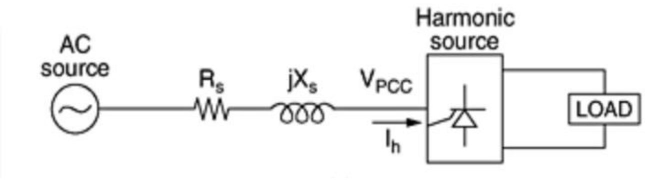

Fig. 2. Line diagram showing PCC [14].

The PCC can be located at either the primary or the secondary of a transformer. This is dependent on single or multiple customer interest, as shown in Fig. 3.

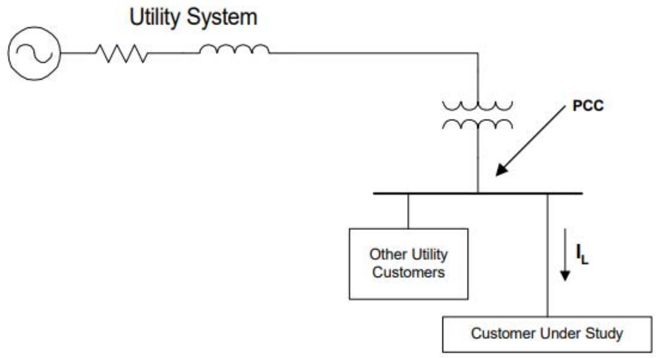

Fig. 3. Location of PCC with single customer cluster [17].

Fig 4 shows an equivalent line diagram of part of the network at Beaufort West. The arrow points to the PCC at the LV side of the 11kV/400V Pieter Jacobs transformer rated at 315kVA, where the measurements were made. The main Eskom utilty grid supplies 132kV. This is then stepped down to 22kV and 11kV respectively. The top part of the diagram shows the 11kV MV supply. The PCC is on the 400V side of the transformer that supplies a residential load. From 2014, the municipality embarked on an energy efficiency program where incandescent lamps were replaced with compact fluorescent and LED technology.

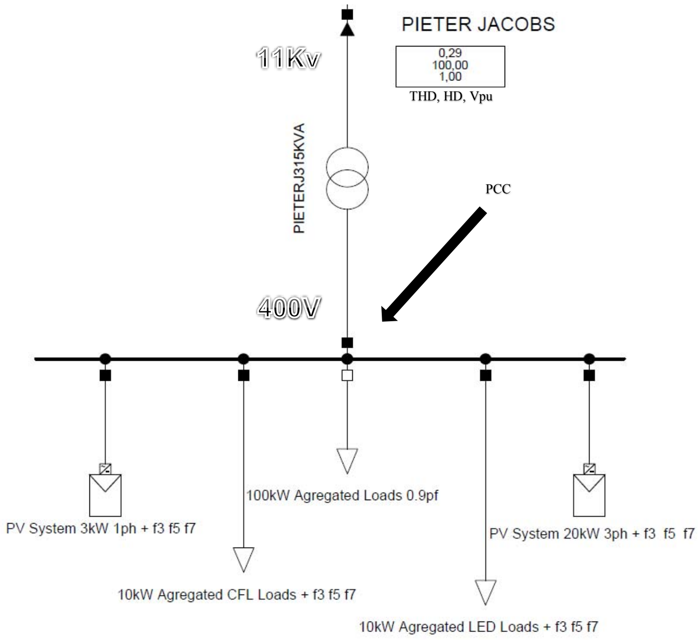

Fig 4. Equivalent network of part of the town grid used in PowerFactory Simulation

A Fluke 1735 Power Logger was used to measure the network characteristics. Measurements were made at a point in close proximity to the feed-in connections of a 20 kW and 3 kW grid-tied PV systems. The arrows in Fig. 1 and 4 shows the location and PCC on the LV side where the measuring instruments were installed.

Data was collected over the month of October 2017, with a sampling integration period of 10 minutes. The measuring device is capable of measuring up to the 50^{th} harmonic, with results indicating no measurable harmonics above the 25^{th}. Selected results are shown in Fig. 5 and Fig. 6. The average measured apparent power was 50kVA.

A harmonic flow simulation was done with DigSilent PowerFactory and the current THD was computed under different load conditions.

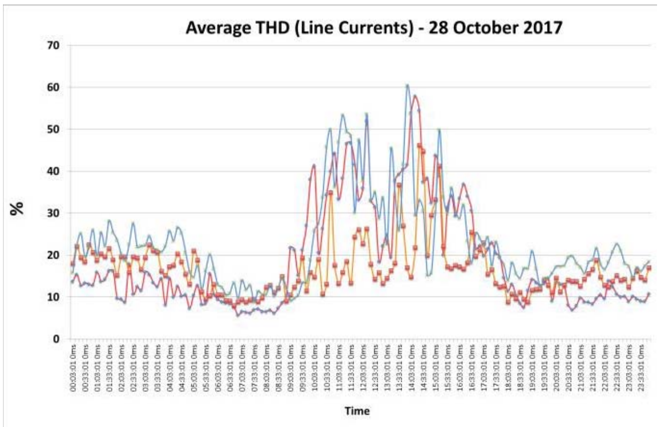

Fig. 5. Average THD_I 3-phases measured over 1 day

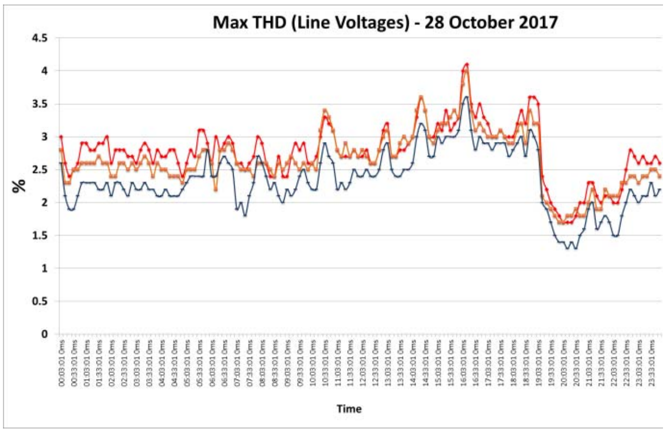

Fig. 6. Maximum THD_V 3-phases measured over 1 day

4.2 **Analysis of Test Results**

It is extremely difficult to classify power quality events due to the fact that numerous harmonic generating loads are connected to the same bus. The waveforms are a combination of different frequencies and magnitude variations. Table III displays the dominant harmonics due to various energy efficient household loads. CFLs, LEDs, microwave ovens, laptops and washing machines have high THD levels that exceed the limit [12]. Single phase nonlinear loads, such as domestic energy efficient lamps result in triple *n* frequencies (3rd, 9th, 15^{th} harmonics etc.). The aforementioned third harmonics on each phase ends up in the neutral, in a three phase circuit (Table 3).

TABLE III: Harmonics due to various energy efficient household loads. [12].

DEVICE	DOMINANT HARMONICS	THD
Laptop	3^{rd}, 5^{th}, 9^{th} 11^{th}, 13^{th} ,15^{th},17^{th} ,19^{th}	84.9
Printer	3^{rd}, 5^{th}, 9^{th} 11^{th}, 13^{th} ,15^{th},23^{rd}	84.4
CFL	3^{rd}, 5^{th}, 9^{th} 11^{th}, 13^{th} ,15^{th},17^{th}	74.9
LED	Harmonics up to 50^{th} are present	79.7
Refrigerator	3^{rd}, 5^{th}, 7^{th} ,9^{th} 11^{th} ,15^{th},17^{th} ,21^{st} , 31^{st}	60.3
Washing Machine	Harmonics up to 50^{th} are present	95.8
Desktop	3^{rd}, 5^{th} , 7^{th}, 11^{th}	36
Microwave	3^{rd}	24.9
AC	3^{rd} and 5^{th}	14.1
TV	3^{rd}	11.7

In a comparison between the analysis of harmonic distortion limits of the IEC and IEEE standards the grid THD_I is between 6% and 15% for LV and MV systems (Table IV). Given the integrated nature of the network under investigation, complete isolation of the selected renewable sources and therefore actual THD contribution to the overall network THD from said renewable sources is difficult. The THD_I is at a maximum between 10:00 and 16:30 (Fig. 6). The average 50% THDI is much higher than the limits of 6% and 15% listed in the IEC and IEEE (Table IV).

On a number of occasions over the measurement period, the current THD exceeded 50%. An extreme example of this is shown in Fig. 5 where the current THD exceeded 50% during the period 12h00 to 15h00 on 28^{th} October 2017. The major contribution to the high current THD during this period is suspected to be due to influence of the maximum irradiation on the solar PV inverters during this period. The measurements were during the month of October 2017 when it is sunny to partly cloudy and the minimum to maximum temperature varies between 11°C-26°C. During this month sunrise is at approximately 06:00 and sunset is at 19:00.

TABLE IV: LV & MV Harmonic current emission limits: Comparison between IEEE519 and IEC61000-3-6. [21]

	Maximum Harmonic Current in percent of the fundamental frequency component				THD (%)
	Harmonic Order				
	5	7	11	13	
IEC 61000-3-6 ($50<Isc/I_L\leq 1000$)	5	3	1.5	1	6
IEEE 519 ($50<Isc/I_L<100$)	10	10	4.5	4.5	12
IEEE 519 ($100<Isc/I_L<1000$)	12	12	5.5	5.5	15

The maximum voltage THD (Fig. 6) for the same day also briefly exceeded 4% but is within the limit of 5%, according to Al Ain [7]. It (THD_V) is far below the recommended grid voltage THD values in electrical power systems of 8%, according to the supply voltage requirements according to the EN50160 Voltage Disturbances and Voltage Characteristics in Public Distribution Systems standards.

It is noted that Beaufort West is a participant in the South African government's Energy Efficiency and Demand Side Management Programme (EEDSM), with efficient lighting interventions being one of the strategies used to lower overall demand. The replacement of conventional municipal building lighting with CFL and LED lights has resulted in an overall reduction in demand, but with the possible negative impact on PQ. More detailed analysis was done in the form of harmonic flow studies with PowerFactory. The simulated results with different loads as shown in Fig. 4 are shown in Table V.

TABLE V: Pieter Jacobs min-substation simulated MV THD_I under various household loads

Load	Load Type	THD_I (%)
1	10kW Aggregated CFL load with dominant f3, f5, f7 harmonics according to [12]	0.14
2	10kW Aggregated LED load with dominant f3, f5, f7 harmonics according to [13]	0.08
3	Two solar PV systems (23kW), with dominant f3, f5, f7 harmonics according to [1]	0.1
Loads 1,2 & 3	20kW CFL & LED loads plus 23kW Solar PV systems	0.29

In summary, the measured 4% average THD_V of the LV supply voltage of the town network is below the 8% limit of the South African utility (ESKOM) Technology Standardization Department (TSD) (NRS 048-2:2003) [8]. The voltage distortion level on LV and MV systems according to the IEC is 8% and should not be exceeded more than 5% of the time [17] [19] [20]. The simulated results show a total contribution of 0.28% current THD by 20kw aggregated energy efficient lamps and a 3kW and 20kW solar PV system. The actual current THD measurements peaked 4 hours after sunrise and 4 hours before sunset. The approximately 7 hour THD_I "peak", coincides with:

- office hours when the retrofitted energy efficient municipal office lighting are switched on,
- optimal irradiation hours when solar PV systems operate at its extreme.
- warm water geysers are sequentially being switched on with ripple control, after the morning peak and before the evening peak and

- the daytime use of household appliances with dominant high order harmonics, such as washing machines and vacuum cleaners.

Harmonic reduction methods could be amongst others, the installation of series inductance or chokes on the dc side of semiconductor bridge circuits, reactors on the AC lines, harmonic trap filters, broadband and active filters.

5 CONCLUSION

Measurements made within a small town having a number of grid-tied renewable sources show an overall compliance with voltage THD limits, with the few reported anomalies regarding maximum current THD levels that require further investigation. The simulated MV THD values are relatively low compared to the measured LV THD values. This is due to damping of the harmonics by the transformer windings. Another anomaly is the current THD that has a long daily midday peak. Follow up research will be conducted with models to see whether there is a correlation between load power, regional irradiation and harmonic levels over the same time window. This would indicate whether the long midday peak is being derived by the dominant inverter harmonics of solar PV generators, the dominant triple *n* frequencies of domestic household equipment, the harmonics of office energy efficient non-linear lamps and of ripple control injection onto the network.

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