Power Quality Analysis of a Wind Turbine Using Optimal Iteration Process

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Abstract- Power quality performance analysis of a wind turbine is necessary to properly characterize the turbine before proceeding to grid integration. The analysis requires following strict guidelines stated in available international standards. This paper discusses the available international standards for power quality analysis along with the procedures used for different parameter calculations. The principal object of the paper is to demonstrate the difference between non overlapping block mode and sliding mode iteration methods during parameter calculations. Results indicate that the non overlapping block mode method is a faster iteration process with a similar accuracy to the sliding mode method during wind turbine characterization. The paper showed power quality parameters calculated using the non overlapping block mode method and also discusses the effect of a high number of samples on the overall analysis result. High resolution recorded data from a grid connected wind turbine in West Texas is used for the analysis.

Keywords- Power Quality, Grid Connected Wind Turbine, block mode, sliding mode, iteration process

1. Introduction

Renewable energy, especially wind powered generation resources are growing at a rapid rate in the United States power grid. The country is trying to reach the goal of acquiring 20% of its total power generation from wind dependent generators by the end of year 2030 [1]. Due to this huge demand and growing size of the wind turbines, power quality analysis of the generated output is very important. Normally, power generated from an intermittent source has a very random characteristic due to the variability of an input parameter, such as wind. The variable nature of the power output affects both the strong and weak grid, although the weak grid suffers more. Variable output can also trigger flicker emissions. Due to these facts, it is now highly recommended for the Wind Turbine (WT) manufacturers, that the turbines power quality parameters be tested and reported before proceeding to the grid integration.

Several parameters can be analysed for power quality assessment. One of the most common is Total Harmonic Distortion (THD). THD is common due to the ease of calculation and well defined boundary values for determining violation. Another widely accepted power quality index is the flicker coefficient, but the flicker coefficient needs rigorous calculation and extensive statistical analysis. Different approaches have been made in the past to analyse WT power quality. A method for flicker estimation of wind turbines by modelling the turbine in PSCAD/EMTDC is described in [2]. A module development process in Matlab/Simulink for voltage flicker measurement in the distribution power system is stated in [3]. Assessment of the wind power quality by measuring flicker coefficients implementing International Electrotechnical Committee (IEC) 61400-21 is shown in [4]. The power quality aspects of a wind power plant by measuring frequency, voltage variation, and harmonic content is highlighted in [5]. An alternative process to estimate the spectrum of the generating unit is mentioned in [6].

Previous works on wind turbine power quality analysis mainly focused on the calculation procedure and improvement of formulas, to increase the accuracy of the calculated parameters. Power quality analysis and wind turbine characterization involves a significant amount of recorded data. The iteration process becomes very important during the calculation process. The main scope of this paper is to identify an optimal iteration process and incorporate that with the available parameter calculation formulas. Results available from this paper will help to efficiently design power quality analysers. In this study, a power quality analyser has been developed using Matlab (A complete description of the Matlab model is out of scope for this paper. Formulas shown in Appendix A are implemented using the Matlab compiler). The analyser enables the user to calculate harmonics, THD, flicker coefficients, Root Mean Square (RMS) voltage, RMS current, positive sequence active/reactive power and power factor.

The paper begins with an overview of the available power quality standards in section 2, which includes information about IEC 61400 and IEEE 519. Section 3 discusses the data collected and the measured power quality parameters. Section 4 describes the two different iteration processes for parameter calculation. The results and comparison between the two different iteration methods, and the overall turbine characteristics are mentioned in section 5. Finally, the paper concludes in section 6 with the important findings from the study.

2. Power Quality Analysis Standards for a Wind Turbine

Wind turbine data analysis requires a specific set of rules and regulations to ensure proper collection, record, calculation and analysis of the data. IEC 61400 is one of the established standards accepted worldwide. Major wind energy producing countries, such as USA, Germany, Denmark, Netherland, India, and China, follow IEC 61400 guidelines. The standard has a series of different sub-standards [7]. Power quality characteristic indices measurement is described in the IEC 61400-21. The scope of IEC 61400-21 includes:

- Identifying the necessary power quality parameters required to characterize Wind Turbine
- Determining WT power quality quantities measurement procedure
- Identifying the assessment procedure of the measured quantities for compliance with power quality requirements [8]

Limits for harmonics and THD for different systems are mentioned in IEEE 519 standard [9]. This standard was first introduced in 1981 and updated in 1992. Initially, it was developed to mention limits for only voltage distortions, but in the 1992 revision, detailed limits for voltage and current distortions were included. Previously, the standard was developed considering the whole power system; that is the standard model for all linear and non linear loads of the system needed to consider during harmonic content calculation. But it is often hard to identify all the loads during the planning stage. Currently, the standard is used on an individual equipment basis. IEEE 519 defines the limits for depth of the notches, total notch area, individual voltage distortion, individual current distortion, total voltage, and total current distortion [10].

IEEE 1547 is a standard for interconnecting Distributed Resources (DR) with Electrical Power System (EPS). The standard was first published in 2003. The main scope of the standard is to provide a uniform requirement related to performance, operation, testing, safety and maintenance of the interconnected DR. The standard specifically mentions the requirement for voltage regulation, synchronization, inadvertent energizing, isolation and interconnection integrity. It also provides information related to the abnormal condition of the interconnected area and different kinds of tests. IEEE 1547 has four main sub sections. IEEE 1547.1 describes the test procedures for the equipment that is used for interconnecting DR. IEEE 1547.2 is a guide to understanding IEEE 1547 and its applicability. Monitoring, information exchange and control of DR is mentioned in IEEE 1547.3. Design, operation and integration of DR in islanded mode are described in IEEE 1547.4 [11].

3. Power Quality Parameter Calculation

In this paper a grid connected wind turbine situated in West Texas was used for data collection and analysis. During the data acquisition process, three main parameters were recorded: three-phase voltage, three-phase current, and wind speed. Voltage and current parameters were collected using relatively high sampling frequencies (3.2 kHz & 51.2 kHz); whereas the wind speed was recorded using very low sampling frequency (1Hz). The data was collected for three continuous months.

Initial stages of this study required identification of the necessary power quality parameters, which would properly characterize the wind turbine. The power quality parameters selected for analysis were:

a) RMS Voltage & Current
b) Active, Reactive Power & Power Factor
c) Voltage & Current Harmonics
d) Total Harmonic Distortion
e) Flicker Coefficients

The calculation procedure for each of the power quality indices is explained in Appendix A. During the calculation, references [8], [12], [13], [14], [15], [16] and [17] were used.

4. Optimum Iteration Process for Measurement and Analysis of Power Quality Parameters

Total number of input samples in the recorded data set is huge due to the high sampling frequency of the voltage and current signal. A single value of a power quality parameter is calculated using a small set of input data. Therefore, to calculate the power quality parameters using the complete input data set, an iterative process needs to be followed. It is highly important to identify an iterative process which will provide optimum results along with the flexibility of fast calculation. Initially, two different methods were investigated:

- Non Overlapping Block Mode
- Sliding Mode

Details of the two methods are described in the following sub sections.

4.1. Non Overlapping Block Mode

In a non overlapping block mode, the input voltage and current signals are divided into several equal length consecutive blocks. The desired power quality parameter is calculated for each block. One block does not include or overlap samples from the previous or next block.

If the total number of samples in the complete recorded data set are N, and number of samples in a block is M, where N>>M, then the complete data set will be divided into N/M number of equal length blocks. Consider A and B are two consecutive blocks, where:

$$A = \{n_1, n_2, n_3 \dots n_M\} \quad (1)$$

$$B = \{m_1, m_2, m_3 \dots m_M\} \quad (2)$$

Here, $n_1, n_2, n_3 \dots n_M$ are the input samples in block A and $m_1, m_2, m_3 \dots m_M$ are the samples in block B. According to the non overlapping block mode method:

$$A \cap B = \{n_1, n_2, n_3 \dots n_M\} \cap \{m_1, m_2, m_3 \dots m_M\} = \emptyset \quad (3)$$

Advantages of using the non overlapping block mode method are the system needs to handle less number of blocks; the total number of iterations during parameter calculation will be less, as a result the computation time will be less. But this method has some disadvantages also, such as, the resolution of the calculated parameters will decrease, and it will be difficult to identify the impact of a particular input sample on the overall result.

4.2. Sliding Mode Method

In a sliding mode method, the input data set is divided into several equal lengths of overlapping blocks. Every block includes a certain number of samples from the previous block. During the power quality parameter calculation iteration, each new block is created by removing the first sample of the previous block and adding one new data sample at the end of the block. Suppose the total samples in the complete data set is N and each overlapping block contains M number of samples, where N>>M, then N-M+1 number of total blocks will be created during the power quality parameter calculation. Consider A and B are two consecutive blocks in the sliding mode method, then:

$$A = \{n_1, n_2, n_3, \dots, n_M\} \quad (4)$$

$$B = \{n_2, n_3, n_4, \dots, n_{M+1}\} \quad (5)$$

$$A \cap B = \{n_2, n_3, n_4 \dots n_M\} \quad (6)$$

An advantage of the sliding mode method is that the sampling frequency of the calculated power quality parameters remains the same as the input voltage and current recording sampling frequencies. Another advantage is it gives better resolution and identifies the effect of a particular input sample on the output results efficiently. However, this method also poses some challenges, such as, a high number of iterations, lengthy calculation time, and memory over usage for long data periods.

Table 1 shows the comparison between two methods in terms of computational time, and iteration numbers for different power quality parameters measured using Matlab. During the comparison, 10 minutes input data was used with a recording sampling frequency of 3.2 kHz. The example below shows the calculation procedure for the iteration numbers.

Total number of samples in 10 minutes input data=10*60*3,200=1,920,000

Block length for RMS calculation=0.2 seconds

Samples in block=0.2*3,200=640

The iteration number for the non overlapping block mode=total number of input sample/samples in block=1,920,000/640=3000

The iteration numbers for the sliding mode method= total number of input sample - samples in block + 1= 1,920,000-640+1=1,919,361

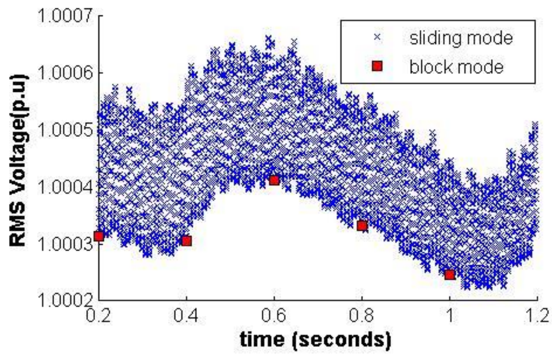
Table 1. Comparison between block mode and sliding mode iterative process

Power Quality Parameter	Number of iteration		Computational time	
	Non overlapping	Sliding mode	Non Overlapping	Sliding mode
RMS	3,000	1,919 ,361	5.5 seconds	64 seconds
Active, Reactive Power& Power factor	35,556	1,919,947	9 seconds	213 seconds
Single order Harmonics	3,000	1,919,361	6 seconds	141 seconds
Total harmonic Distortion	3,000	1,919,361	42 seconds	7,351 seconds
Flicker Coefficient**	2	1,920,001	24 seconds	13,675 second

** Due to the huge time consumption, flicker coefficient for sliding mode is calculated for 10 seconds

5. Results & Analysis

Field data collected from the wind turbine was used during the power quality parameter calculation and comparison between two iterative methods. The power parameter indices which were calculated using the non overlapping block mode and sliding mode method are shown in Figure 1. Figure 1(a through e) indicate that the number of samples in the power quality parameters calculated using the sliding mode method is higher than the parameters calculated using the block mode method. Within a fixed time frame, the sliding mode method plotted more output values than the non overlapping block mode method. In figure 1(a through e), the output parameters calculated using sliding mode had a sampling frequency of 3.2 kHz; whereas the non overlapping block mode changed the sampling frequency of the output parameters into a much lower value (5Hz for RMS and Harmonics; 60 Hz for active and reactive power; 1.666 mHz for flicker coefficient). Due to better resolution, the sliding mode method helps to identify the impact of a particular input's effect on overall output. The variation in the output values is clearer in the case of the sliding mode method. The non overlapping block mode fails to identify a single input effect; rather it shows the effect of a collective set of input on the output value.



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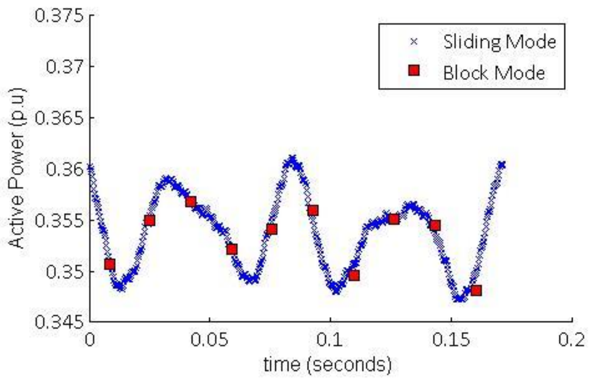

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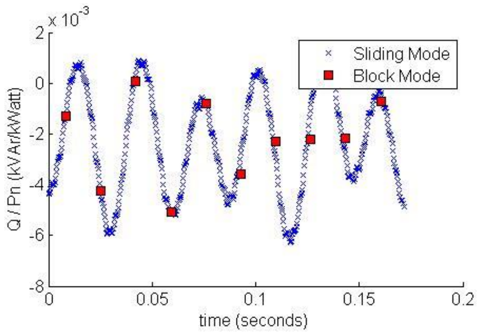

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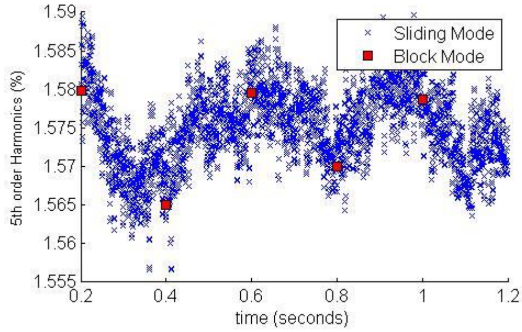

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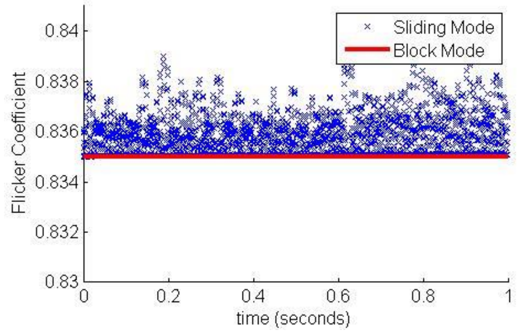
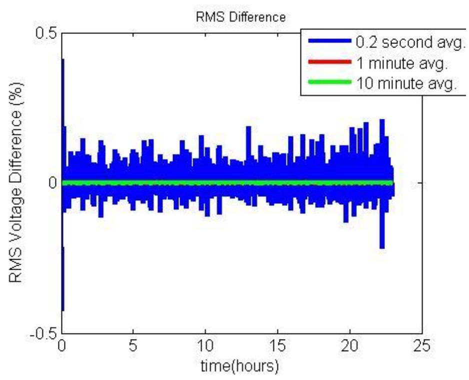


(e)

Fig. 1. Power Quality Parameters Calculated using Block mode and Sliding mode (a) RMS Voltage (b) Active Power (c) Reactive Power (d) 5^{th} harmonics (e) Flicker Coefficient

Once the power quality parameters are calculated, they are transferred into 0.2 second, 1 minute and 10 minute average data set. These average data sets are used to analyse the power quality performance of the wind turbine [13]. During the study, the average values available from the two iterative methods, were compared to identify the overall impact of a method on the characterization of the turbine. The parameters chosen to show the difference includes: RMS voltage, active power, reactive power, and 5^{th} harmonics. Earlier analysis indicated that 5^{th} harmonics is the dominant harmonics, and the THD value depends mostly on the 5^{th} harmonics for this turbine [18]. Therefore, to save time and computation, instead of showing the THD values, only the 5^{th} harmonic's value is compared. Figure 2 shows the differences between the average values available from the sliding mode method, and non overlapping block mode method using one full day's data.



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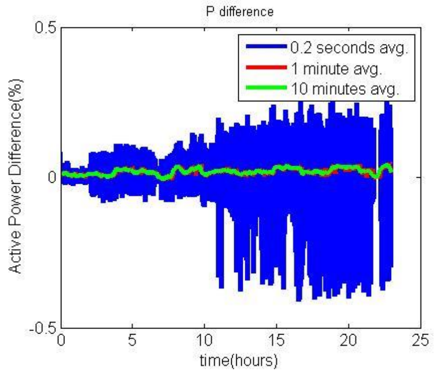

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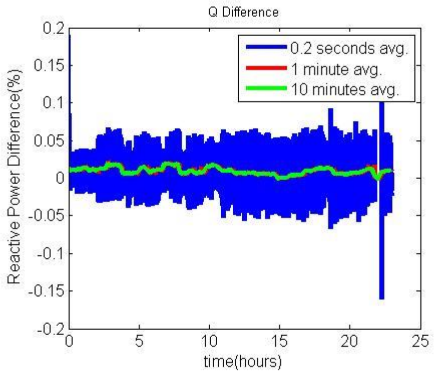

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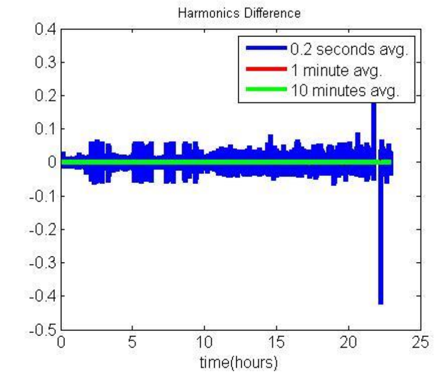


(d)

Fig. 2. Difference between average values calculated using Block mode and Sliding mode methods (a) RMS Voltage (b) Active Power (c) Reactive Power (d) 5th Harmonics

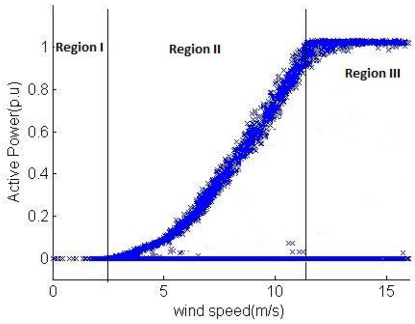
From figure 2(a through d), it is clearly visible that for 0.2 seconds average data, the two iterative methods produced notable differences. The values shown in figure 2(a through d) is a percentage of the nominal values (considering the high nominal values of the parameters, even 0.1% is a considerable amount in the actual unit). But the figure 2(a through d) suggest, as 1 minute and 10 minute average data are considered, the difference between the output values reduces. In Table 2, the maximum differences between the average values for different power quality parameters are listed. The table's data indicate that the maximum difference in 1 minute and 10 minute average values for two different methods are negligible. Especially for 10 minute average values, the difference between the power quality parameters are very close to zero. Generally during characterization of a wind turbine, 10 minute average values of the parameters are used. Results suggest that the non overlapping block mode method can characterize and analyze the power quality in a faster way, with relatively similar accuracy of the sliding mode method. The sliding mode method is suitable to analyze data for a short period, but for long term data, non overlapping block mode method provides better flexibility.

Table 2. Maximum Difference in parameter values calculated using non overlapping block mode and sliding mode

Power Quality Parameter	0.2 second average (% of nominal value)	1 minute average (% of nominal value)	10 minute average (% of nominal value)
RMS Voltage	0.42	0.0028	0.00042
Active Power	0.41	0.05	0.04
Reactive Power	0.19	0.02	0.02
5th Harmonics	0.42	0.0036	0.00034

One major challenge during wind turbine characterization arises from the fact that the harmonics calculated using the recorded voltage and current signal represents harmonic contents available from the wind turbine as well as background noise. The background noise harmonic content is mainly generated by other generating units and non linear loads. To identify the wind turbines effect solely on harmonic generation, special tests and data recording processes need to be followed. At the Point of Interconnection (POI) between the grid and the wind turbine, the current and voltage signals are recorded while the wind turbine remains switched off. The harmonic filter of the turbine remains online. Harmonic contents calculated using this set of recorded data gives the general characteristics of the grid harmonics. Finally, the harmonics generated by the wind turbine is identified by subtracting the grid harmonic values from the combined harmonic values.

Normally, a limited set of data points are considered during characterization of the wind turbine. According to IEC 61400, at least five samples from each wind speed bin (each wind speed bin has 1m/s width) is required to characterize the turbine. Generally, the steady state and fault free values are considered. These values are considered as sorted values. However, in a continuous system of data collection and analysis, it might not always be possible to identify the transient and faulty values. Possible effects of unsorted and an unnecessarily high number of samples on overall characterization of the WT were investigated. RMS values are normally not too much affected by short term faults or over voltages. If the fault sustains for a long period of time, then there is visible changes in the RMS voltage level. Active and Reactive powers are very important parameters for characterization. Considering too much unsorted samples can misrepresent the relation between wind speed and power. Due to grid faults or control need, the turbine often produces less power than the expected, which in turn affects the overall power curve of the turbine. Figure 3(a and b) depicts the normalized power curve and reactive power curve of the turbine. The power curve has been developed using unsorted data and it can be seen that even for wind speeds greater than the cut in speed (3 m/s), the turbine produces zero kWatt active power in several incidents. As a result, the average wind speed for -0.05 to 0.05 nominal power (P_n) range is 8.32m/s, which is way more than the cut in wind speed, and wrongly characterizes the turbine. Also, in the reactive power versus active power graph, there is an unusual vertical straight line at the -0.5P_n to 0.5P_n range.



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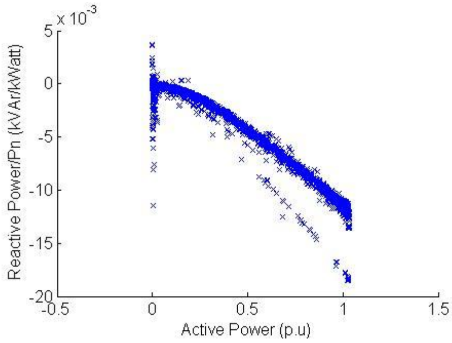


(b)

Fig. 3. Wind Turbine Power Curve using unsorted data (a) Active power vs. Wind speed (b) Reactive power vs. Active power

Flicker coefficient gets severely affected from the grid voltage variation and frequency deviation. Calculation of the flicker coefficient requires fault free voltage and current signals; in case of faulty values, the turbine produces unusual high values for the flicker coefficient. Generally, the turbine used in this project produces flicker values within a range from 0.0 to 5, but in the case of faults it can go as high as 250. Obviously, it is not the true characteristics, but these faulty values can be useful to detect short term faults in the power system. Short term faults are not often detected by using the 0.2 seconds, 1 minute or 10 minute average RMS value; in that case high flicker coefficient values can come into help. It can direct the analyzer to the time window where faulty values are suspected. A three phase to ground fault for 15ms was artificially created. Figure 4 shows the fault.

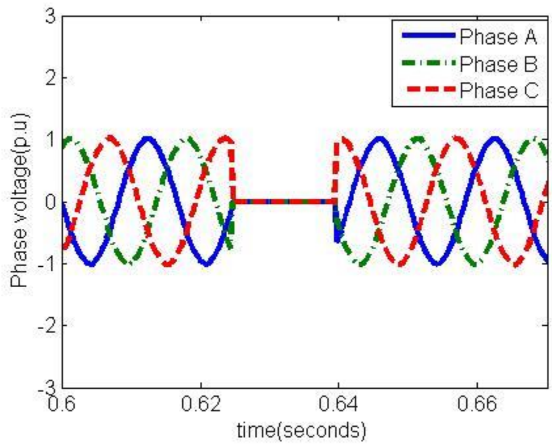


Fig. 4. Three phase to ground fault (simulated)

The RMS voltage values calculated during the faulty period produces slight deviations. During fault, 0.2 second average value of RMS voltage shows a maximum deviation of 4% from the nominal value. Similarly, 1 minute and 10 minutes average value of RMS voltage shows a maximum deviation 0.78% and 0.04% respectively. The deviations are within normal operating limits (+/- 5% of nominal) so no grid faults can be suspected. But the flicker coefficient produces a value of 63.4459 considering the faulty values, which is higher than the flicker coefficient values during normal operating condition (2.1245). Due to this huge deviation in the flicker coefficient value, short term grid faults are suspected.

Finally, the normalized power quality parameters, calculated using the non overlapping block mode method is shown in the following figures. Figure 5 showed the RMS voltage value for the whole analysis period. The values were within the normal operating limit (+/- 5% of nominal) for most of the time with few outliers. Maximum and minimum values of the RMS voltage calculated were 102.79% and 0.3% of nominal value.

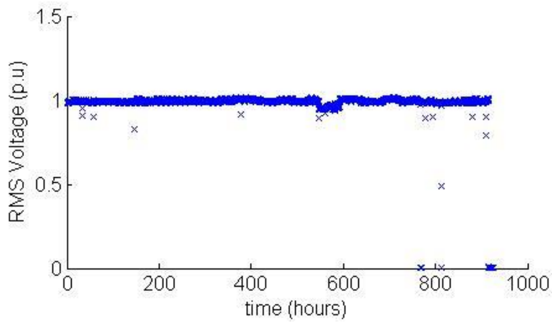
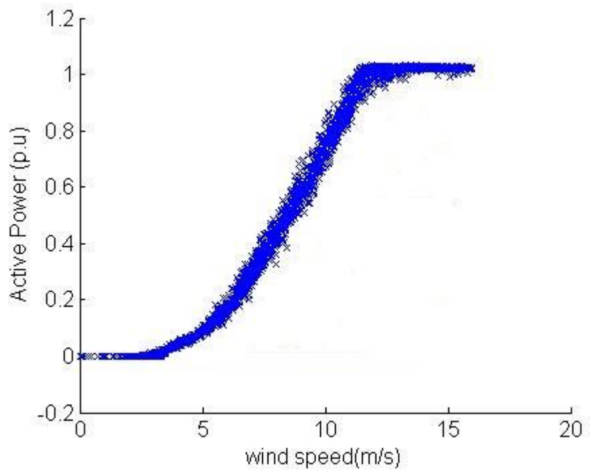


Fig. 5. RMS Voltage of the WT

Figure 6(a and b) shows the normalized power curve and reactive power curve of the WT using sorted data. The maximum and minimum of the active power value calculated during the analysis period were 103.4% and 0% of the nominal power; whereas the maximum and minimum reactive power was 0.0185 VAr/Watt and 0.0037 VAr/Watt.



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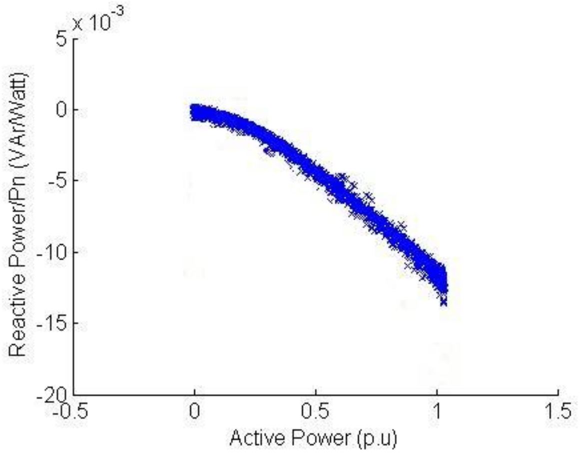
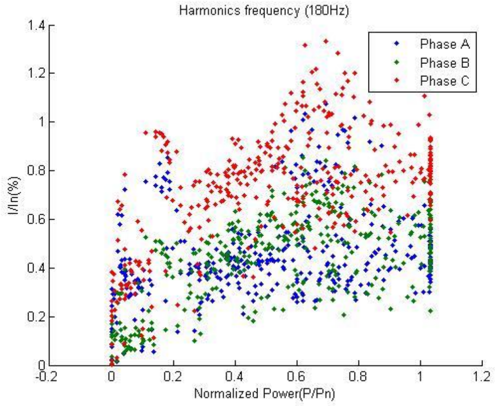


(b)

Fig. 6. Normalized Power Curve of the WT, (a) Active Power vs. Wind Speed (b) Reactive Power vs. Active Power

Figure 7(a through d) shows the 3rd, 5th, 7th and 9th harmonic values of the WT current. Although, up to the 50th order harmonics was calculated, only the major four harmonics are shown. The harmonic analysis shows that the 5th harmonics were the dominant, with a maximum value of 2.25% of the nominal current. The maximum value for the THD was calculated as 2.52% of the nominal current.



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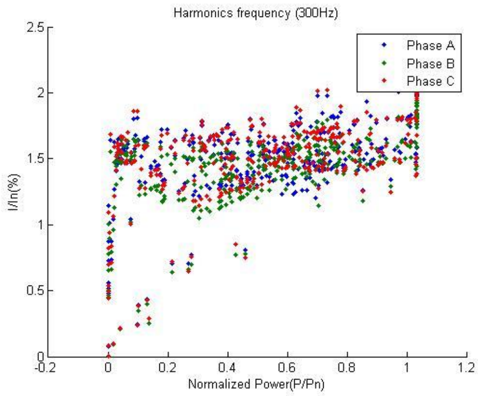

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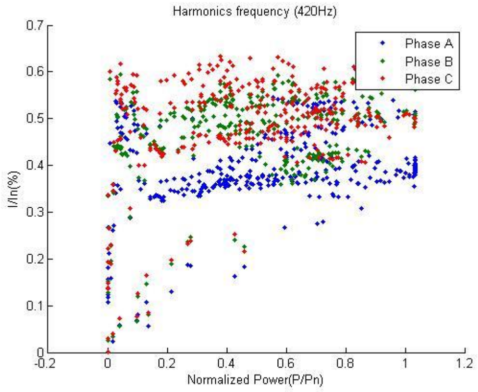

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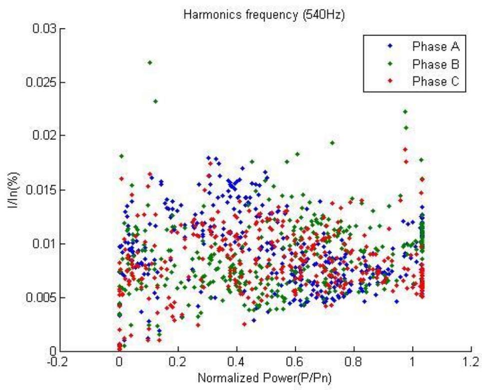
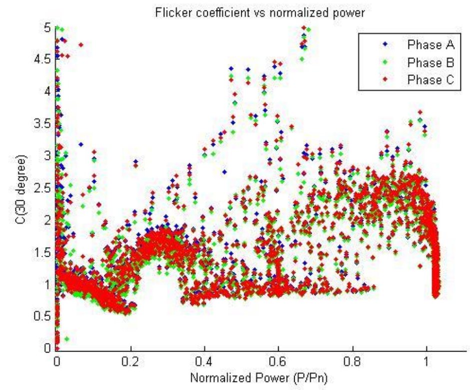


(d)

Fig. 7. Current Harmonics of the WT, (a)3rd Harmonics(180 HZ), (b) 5th Harmonics (300 Hz), (c)7th Harmonics (420 HZ), (d) 9th Harmonics (540 Hz)

Figure 8(a through d) shows the flicker coefficient variation of the WT for different network angles (30^0, 50^0, 70^0 and 85^0). Normally, the flicker coefficients value varies within 0 to 5, but the most populated area is within the values of 0.5 to 2.5. During this study the flicker coefficient was calculated by considering that the turbine was connected to a fictitious grid. For a specific site, the limits for P_{st} and P_{lt} can be calculated using the requirement of the particular grid.



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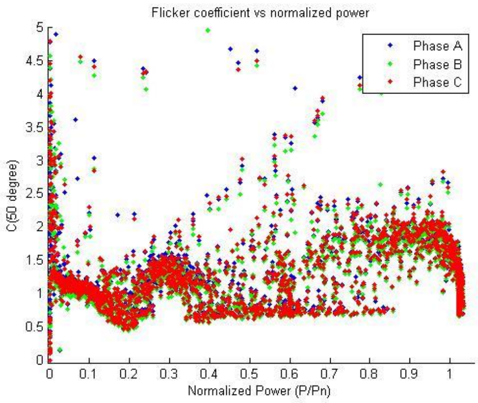

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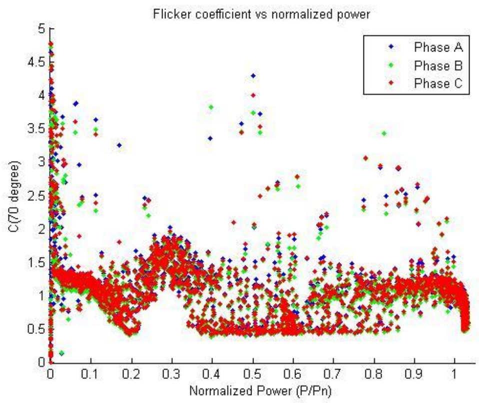

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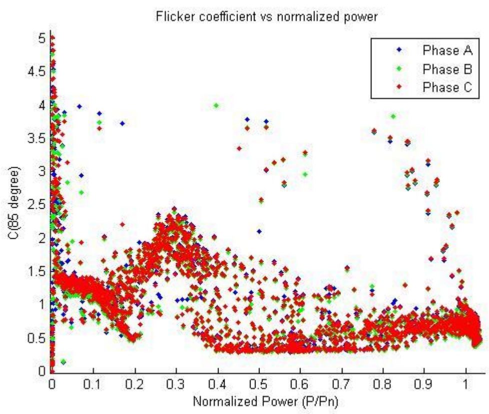

(d)

Fig. 8. Flicker Coefficient vs. nominal power for (a) 30^0 network angle, (b) 50^0 network angle, (c) 70^0 network angle, (d) 85^0 network angle

6. Conclusion

The paper demonstrated results for different power quality indices calculated using the data recorded from the wind turbine. The power quality analyser developed during the project is not site or wind turbine model specific, and can be used with recorded data from any wind turbine. The paper also demonstrated two different iterative methods for parameter calculation and compared the results. The results available from the study indicated that the non overlapping block mode method provides similar results during the characterization of the wind turbine in a faster time. Long term power quality analysis and WT characterization should be done using the non overlapping block mode method. The sliding mode method can be used during the short term analysis of the turbine data for better resolution. Finally, in this study, the wind turbine power quality parameters have been calculated and analysed using the non overlapping block mode method. This comparison will help to develop the power quality analyser in an efficient and faster way. This study also showed that the data analysis using an unusually high number of unsorted output values can affect adversely and wrongly characterize the turbine. The measured power quality can be used during the grid integration of a new wind turbine. The turbine manufacturer can supply the results to the Independent Service Operators (ISO) and Transmission Service Operators (TSO). It will help the ISO and TSO to provide better system and protection planning.

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Appendix A

A.1. RMS Voltage & Current

Root Mean Square or RMS is the quadratic mean of a time varying signal. RMS value is calculated using Eq. (6) [12]

$$U_{rms} = \sqrt{mean(U(t) * U(t))} = \sqrt{\frac{U_1{}^2+U_2{}^2+U_3{}^2+\cdots+U_n{}^2}{n}} \quad (6)$$

Where, U_{rms}= RMS value of the varying signal, $U(t)$= time series values for the signal,U_1, U, U_3,..., U_n= Signal values for different sample, n= number of total samples

From Eq. (6) it is clear that from n number of input samples one RMS value is calculated. During the RMS calculation process, 0.2 seconds time window has been selected to calculate each RMS value. The number of samples for calculating one RMS value is then described by Eq. (7)

$$n = 0.2 * f_s \quad (7)$$

Where, f_s= Data recording sampling frequency.

A.2. Active, Reactive Power & Power Factor

Active, Reactive power and power factor provides a clear idea about how the injected power from the WT is affecting the power quality of the grid. The power quantities were calculated using the positive sequence voltage and current signal. To calculate the positive sequence values, fundamental component of three phase voltage and current signals are measured for each cycle. Each cycle contains $n = \frac{f_s}{f_1}$ number of data samples; where f_s is the data recording sampling frequency and f_1 is the system fundamental frequency (60 Hz in the US power grid). Finally, active, reactive power and power factor quantities are calculated using Eq. (8) – Eq. (10)

$$P_{1+} = \frac{3}{2}(U_{1+,cos} * I_{1+,cos} + U_{1+,sin} * I_{1+,sin}) \quad (8)$$

$$Q_{1+} = \frac{3}{2}(U_{1+,cos} * I_{1+,sin} - U_{1+,sin} * I_{1+,cos}) \quad (9)$$

$$cos\varphi_{1+} = \frac{P_{1+}}{\sqrt{P_{1+}{}^2+Q_{1+}{}^2}} \quad (10)$$

Where $V_{1+,cos}$, $I_{1+,cos}$, $V_{1+,sin}$, $I_{1+,sin}$ are the Cosine and Sine coefficients of the positive sequence voltage and current, P_{1+} is the active power, Q_{1+} is the reactive power and $cos\varphi_{1+}$ is the power factor [8]. Once these parameters are calculated they are saved to 0.2 seconds average data, 1 minute average data and 10 minute average data by block averaging. The highest values in each time format are used to characterize the wind turbine [13].

A.3. Harmonics & Total Harmonic Distortion (THD)

Normally non linear loads, rectifier and inverters inject harmonics into the power system. Double Fed Induction Generator and Permanent Magnet Synchronous generator based wind turbines both use rectifier and inverters, so there is a strong possibility of harmonics injection from the wind turbine to the grid. Harmonic parameters in this project were calculated using the IEC 61000-4-7 substandard [14]. Up to the 50th order of the harmonics were calculated for analysis. The values are presented as a percentage of the nominal value of the current and voltage signal. Eq. (11)-Eq. (13) is used to calculate harmonic content [15]

$$U_h = U_{dc} + \sum_{1,2,....}^{50} a_n \cos(2\pi f_1 nt) + b_n \sin(2\pi f_1 nt) \tag{11}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} U(t)\sin(2\pi f_1 nt)dt \tag{12}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} U(t)\cos(2\pi f_1 nt)dt \tag{13}$$

Where, U_h is the Harmonics value, U_{dc} is the D.C. component of the input signal (normally zero for sinusoidal grid voltage and current), f_1 is the system fundamental frequency, n is the harmonics order and a_n, b_n are the cosine and sine coefficients of the input signal. Once the harmonic values are calculated, Total Harmonic Distortion value is calculated using Eq. (14)

$$THD = \sqrt{\frac{\sum_{h=2}^{50} U_h}{U_n{}^2}} * 100 \tag{14}$$

Where, U_n is the nominal value of the signal.

IEC 61000-4-7 recommends at least 10 cycles (50 Hz system) or 12 cycles (60 Hz system) of voltage or current data should be considered for calculating one harmonics value. Both the required cycles refer to 0.2 seconds of recorded data. The WT is characterized by using the 10 minute average harmonic values and considering the maximum average value of each harmonic order.

A.4. Flicker coefficients

Flicker coefficient is a measurement of variation in the voltage signal. Cyclic variation in the voltage magnitude can cause changes in illumination intensity of the light sources. WT produces flicker due to light variation in wind speed. The basic idea behind the flicker coefficient is to artificially develop the lamp-human eye reaction scenario by using the simulator [13, 16]. Short and long term flicker emission are defined as

$$P_{st} = P_{lt} = C(\psi_{k,} V_a) * \frac{S_n}{S_k} \tag{15}$$

Where, P_{st} and P_{lt} are the short and long term flicker emission, C is the flicker coefficient, ψ_k is the network angle, V_a is the wind speed, S_n is rated apparent power and S_k is the short circuit power at point of common coupling [8].

According to IEC 61400-21, calculating the flicker coefficient includes three main steps

Calculating network parameters (Resistance and Inductance), Rfic and Lfic for different network phase angles, ψ_k (00, 300, 500, 700 and 850). The parameters depend on the short circuit apparent power (Sk, fic). Eq. (16) and Eq. (17) are used for the calculation [8]

$$\tan(\psi_k) = \frac{2\pi f_1 L_{fic}}{R_{fic}} = \frac{X_{fic}}{R_{fic}} \tag{16}$$

$$S_{k,fic} = \frac{U_n{}^2}{\sqrt{R_{fic}{}^2 + X_{fic}{}^2}} \tag{17}$$

Calculating a fictitious grid voltage (Vfic) using instantaneous values of the measured voltage and current signal. In a power system several nonlinear and flicker producing loads are present, a fictitious grid voltage measurement is necessary to identify the flicker emitted by the wind turbine separately. Eq. (18) indicates the fictitious grid voltage

$$U_{fic} = U_0(t) + R_{fic} * I_m(t) + L_{fic} * \frac{dI_m(t)}{dt} \tag{18}$$

Where, $U_0(t)$ is the ideal voltage and $I_m(t)$ is the measured instant current value. The ideal signal should be completely free from fluctuations and should have the same angle as the fundamental of measured voltage [16].

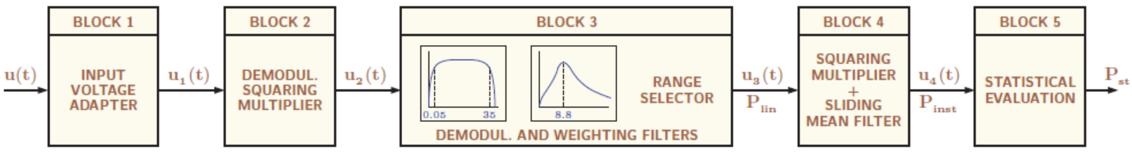

Figure 9. Digital Flicker Meter according to IEC 61000-4-15 [12]

Developing the digital flicker meter according to the IEC 61000-4-15 standard by using previously calculated fictitious voltage and measured grid current [17]. The digital flicker meter is shown in Figure 9.

After implementing all the blocks, the short term flicker coefficient for the desired time period (10 minute average data required to calculate single flicker coefficient value) are obtained.