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Development of a Quality Management System for Electric Power applied to Small Wind Turbines

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Abstract

This paper presents a methodology for calculating and monitoring power quality using discrete signal processing techniques, enabling the detection and quantification of electromagnetic disturbances in transient and steady state time periods. The limits of power quality disturbances that will be monitored are defined by international norm (IEEE 1159). Together with the power quality monitoring system, a power quality assessment was implemented by changing the input variables of the generator in order to restore the standards of the power grid (voltage, current and frequency). The proposed system is a management system, able to identify, quantify and monitor the power quality and can be used as a diagnostic tool for maintenance and a control system for decision-making to reestablish the generation system.

Key words

Alternative energy source, power quality management, voltage converter, wind generator.

1. Introduction

In a recent past, the characteristics of energy consumption were quite different than today. In those days it was possible to characterize consumers as residential, commercial and industrial. The demand for residential electricity consumers was composed almost entirely of resistive loads.

Today, all classes of consumers, including residential, have numerous electronically controlled loads that eventually distorts the network waveform. Turn, these loads are very sensitive to disturbances.

From the 90's began the analysis of Power Quality (PQE) with a focus on continuity service. The power quality was perceived by the consumer when supply interruptions or through equipment failure occurred.

Currently, electrical disturbances such as: voltage sags, harmonics, transient and fluctuation, among others, produce adverse effects on sensitive loads. It is therefore necessary to extend the PQE analysis to continuity of service including the electromagnetic disturbances mentioned [1]. Thus, this paper presents a method to calculate and manage key indicators of PQE applied to small wind turbines.

2. Power Quality

The PQE concept is related to a set of electromagnetic phenomena that can occur in the electrical system. By definition, is present in any event as voltage, current or frequency that results in failure or bad operation of equipment [1], [2].

The standardization of the power quality concepts is still development stage. Europe is one of the most advanced in relation to the normalization of the PQE, where norm is the EN 50160. In the United States, most utilities have used different reference standards such as IEEE 519. However, due to deregulation, in futures contracts the inclusion of PQE indexes should become norm [3].

In Brazil, the power quality is monitored by the electric utilities and by the regulatory agency, by means of indicators, which quantify some of the electrical disturbances provided. These indicators are defined by the ordinances and resolutions issued by regulatory agencies with the purpose of establishing goals, actions and deadlines to be met by utilities each year.

3. Wind Turbines: Basics Concepts

With the increasing scarcity of non-renewable sources of energy such as fossil fuels and the growth of ecological awareness, participation of renewable sources in electricity generation has increased in recent years. One way of generating electricity through renewable energy sources is to make use of wind turbines that capture the kinetic energy of the wind and transform it into rotational mechanical energy which is converted into electrical energy. Due to the increase of wind power generation, the turbines have a significant effect on the behavior of electric power systems, on all aspects including PQE [4].

A. Energy Conversion System

Wind turbines are machines that generate mechanical power from the wind. This power manifests itself through mechanical forces created on the surfaces of the blades, producing a net torque and a rotation the turbine [5].

In this operation of electromechanical energy conversion, the primary objective is of maximizing the generation of electricity, under constant amplitude and frequency. This process becomes complex because of certain characteristics of wind systems. In most, wind mechanical energy input is so buoyant as wind speed, and for each value of wind speed, there is a speed of rotation of the turbine which is the maximum wind energy capture.

Currently, generators operate in conjunction with power electronic converters and control system. There are several possible configurations of interconnections between the generator, converter and power grid, however, they can be classified into two main types: system with converter and output converter in feedback systems [6].

On systems with feedback converter in the stator windings of the doubly fed induction generator is connected to the network and the rotor windings are connected to the converter, as shown in Fig. 1.

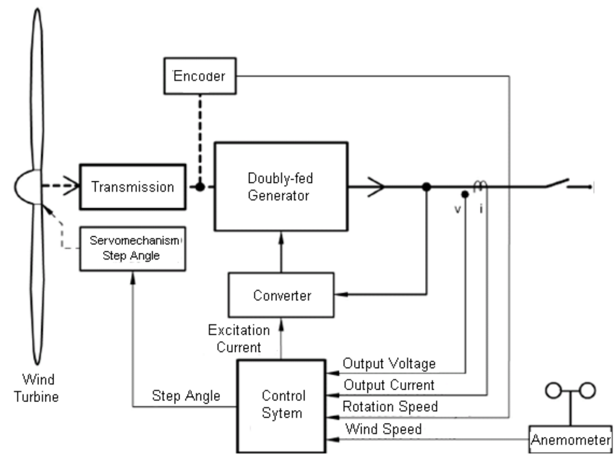

Fig. 1. Simplified diagram of the converter in the feedback systems [7].

Thus, the power flows through the converter reduced to only what is consumed by the generator excitation. The doubly-fed generator consists usually of an induction machine with wounded rotor, which is mechanically driven by the turbine and is electrically excited by the three phase winding. The access to the rotor winding is through slip rings, which can apply voltage direct current (DC) or alternating current (AC) [8].

B. Control Strategy of Wind Turbines

Due to the set standards of power quality norms, the turbines are forced to deliver the electricity generated within certain limits of current, voltage and frequency. For this it is necessary to make use of an effective control of the generation unit, in order to minimize fluctuations in the supply of electricity caused by the change in kinetic energy provided by wind turbine. Thus, the system must be compensated for these oscillations by controlling the excitation current and the machine rotation. Also, a frequency converter connected to the induction generator to eliminate the variations in the phase voltages and the output frequency can be considered, so that the mechanical power swings not affect the PQE [9]. Thus, the rotor of the doubly excited induction machine is connected to a three-phase inverter as shown in Fig. 2.

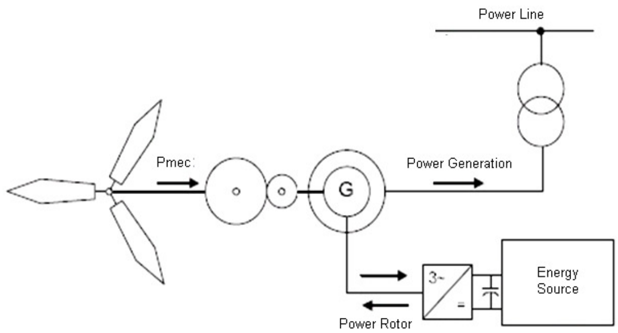

Fig. 2. Basic structure for a variable speed wind turbine with doubly fed induction generator [7].

4. Proposed Methodology for Disturbances Calculation

The proposed algorithm in initiated by voltage and current signals obtained at the output of the wind turbine analysis, which are acquired through A/D converters. The capacity to detect disturbances is limited by project constraints, mainly on the sampling rate, scan rate, rate of data transmission, and storage capacity.

A. Voltage Steady

To characterize the steady state voltage is used the root mean square voltage value (V_{rms}) of a voltage signal obtained by the expression [10]:

$$V_{rms} = \sqrt{\frac{\sum_{i=1}^{N} V_i^2}{N}} \quad (1)$$

where, V_i is the instantaneous value of the sampled voltage and N is the number of samples per measurement window.
The estimation of the effective value of the sampled signals is performed with algorithms windows of 1/2 and 1 cycle, updated by 1/8, 1/4, 1/2 and 1 cycle. The steady state voltage is monitored to verify that V_{rms} is within the tolerance limits. If exceeded the limit, the occurrence of a disturbance is considered.

B. Voltage Variation

The voltage variation of short or long duration is obtained through the value of voltage V_{rms}. The main parameters to characterize the voltage variation are the magnitude and duration of the disturbance. The root mean square voltage or *rms* voltage, V_{rms}, is constantly monitored. Therefore, when a voltage value exceeds the tolerance limits, the algorithm begins to acquire the voltage signal at time t_{in}. On the other hand, it is considered the end of event when the voltage is restored within tolerance ($0.9 < V_{rms} < 1.1$ p.u.), when time t_{end} is recorded. Fig. 3 shows a typical collapse and the parameters to be measured.

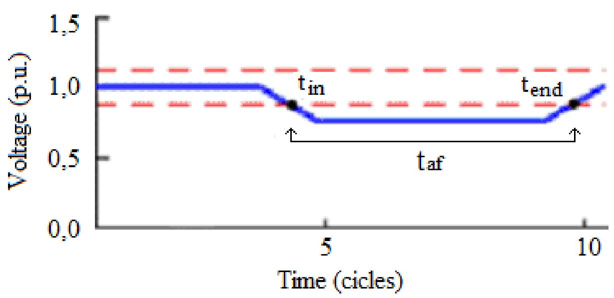

Fig. 3. Short Voltage Sag.

The magnitude of the event is obtained as the minimum value reached by voltage sag divided by the nominal voltage.

$$Magnitude = \frac{V_{af}}{V_n} \qquad [p.u.] \tag{2}$$

where V_{af} is the minimum value of the root mean square voltage during the sag and V_n is the rated rms voltage of the system.
The duration of the event is the time interval in which the rms voltage remains below the threshold voltage (V_{af}).

$$Duration = t_{end} - t_{initiall} \qquad [s] \tag{3}$$

where $t_{initial}$ is the time instant at which the voltage exceeds the reference value and t_{end} is the time instant when the voltage to returns within the zone to be considered normal.
This methodology for monitoring of voltage V_{rms} in real-time systems, with the appropriate changes, can be used to characterize the following disturbances: overvoltage, under-voltage and disruption.

C. Voltage Imbalance

The detection of voltage imbalances is accomplished also through the *rms* voltage value. Thus, it is calculated the difference between the *rms* voltage of each phase divided by the average of the *rms* voltages [1].
The signal acquisition and the *rms* voltage calculation are performed according to (1). Next, using the *rms* voltage of each phase, one can calculate the voltage imbalances as:

$$\Delta V_{RS} = \frac{V_R - V_S}{\left(\frac{V_R + V_S + V_T}{3}\right)} \qquad [\%] \tag{4}$$

When the result in (4) is higher than the limit (per example 0.5%), a counter is started for the duration of the disorder and it is considered finished when the result of (4) is less than the reference value [1].
The parameters used to characterize voltage imbalances are the maximum value calculated from (4) and the duration of the disturbances.

D. Transient Events

For detection of transients events it is used an envelope of the voltage waveform as a trigger for registration of the disturbances, as shown in Fig. 4.

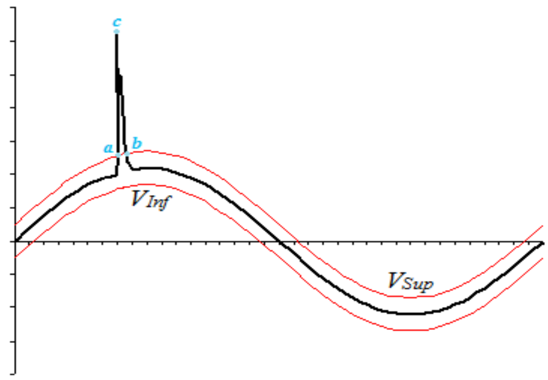

Fig. 4. Voltage waveform and its envelope (trigger).

The proposed methodology consists of the constant monitoring of the instantaneous values of voltage through its envelope in order to ensure that voltage values are within limits ($V_{inf} < V_I < V_{sup}$). Thus, when the voltage exceeds the threshold (a), the methodology begins to acquire the voltage value corresponding to the transient (impulsive or oscillatory). It is considered the disorder as terminated when the voltage is restored within the tolerance value (b).
Impulsive transients are characterized according to the duration time (peak value and tail) and the peak value of voltage (c), while the oscillatory transients are characterized by the spectral content of their predominant frequency, duration and amplitude [1].

E. Harmonics and Inter-harmonics

The characterization of harmonics and inter-harmonics in the electrical system is realized through the decomposition of the signal voltage or current by Fourier series. Thus, the harmonic distortion levels are characterized by the harmonic spectrum, with amplitude and phase angle for each individual component. In the proposed algorithm is used the following equations:

$$\mathrm{F}(u)=\sum_{x=0}^{N-1} f(x)\cos(2\pi ux/N)+j\sum_{x=0}^{N-1} f(\mathrm{x})\mathrm{sen}(2\pi\mathrm{ux/N}) \quad (5)$$

$$f(x)=\sum_{x=0}^{N-1} \mathrm{F}(u)\cos(2\pi ux/N)+j\sum_{x=0}^{N-1} \mathrm{F(u)sen}(2\pi\mathrm{ux/N}) \quad (6)$$

In the proposed method, it is made the acquisition of the waveform with windows of a cycle, and then applies the Discrete Fourier Transform (DFT), which calculates the harmonic components of the discrete signal. As the harmonic distortion is a steady state phenomenon, it is necessary to analyze the set of average values of the harmonics, captured periodically and during an interval of 10 minutes, in order to characterize the disturbances in an appropriate and consistent [11]. Harmonic distortion levels are characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. The Total Harmonic Distortion (THD) is a measure of the magnitude of harmonic distortion (IEEE 519) and is calculated as [11]:

$$THD=\frac{\sqrt{\sum_{h=2}^{\infty}(Vh)^2}}{v_n}\times 100\% \quad (7)$$

where V_h is the *rms* voltage values of harmonic components, h is the order of harmonic, v_n is the *rms* value of fundamental voltage.

F. Voltage Fluctuation

The voltage fluctuation can be obtained by adjustment of the tension, demodulation, frequency relevance score, mean square, and statistical analysis [12]. This sets out the short-term indicator (Pst - "Short-term probability") and long-term indicator (Plt - "Long term probability"), as described and recommend in IEC 61000-4-15.
The short-term indicator (P_{st}) represents the flicker severity levels associated with fluctuations of voltage in a continuous time period of 10 minutes [11].
The long-term indicator (P_{lt}) represents the flicker severity levels associated with voltage fluctuation measured in a continuous period of 2 hours and calculated from the records of P_{st} [13]:

$$P_{lt}=\sqrt[3]{\frac{1}{12}\sum_{i=1}^{12}\left(P_{sti}\right)^3} \quad (8)$$

G. Variation of frequency

In this paper was used the PLL (phase locked loop) based on the instantaneous vector calculus - CVI [14]. The principle of operation of the PLL method is to synthesize a signal $U(\phi,\ \omega)$ in steady state that satisfies the orthogonality condition with the fundamental voltage sign (V_n), i.e., $V.U=0$. While the algorithm seeks to satisfy the orthogonality condition, the PI regulator converts the error of the scalar product in a frequency correction signal ($\Delta\omega$) that enables the detection of input signal frequency (ω).
The initial dynamic response of the PLL is the variable $\omega_{ff}=2\pi f_n$, where $f_n = 60\ Hz$. Therefore, when the output value of PI is constant, this output represents the frequency of the input signal (ω) [14]. The choice of this method is due to its fast answer, being robust and immune to noise transients in the input.

5. Analysis and Algorithm Validation

In this section it is presented the main simulations for performance analysis of the proposed algorithm emphasizing typical and adverse situations that may occur during the operation of Electric Power Systems (EPS). In order to improve, quantify and qualify the validation of the algorithm were analyzed disturbances from the simulated data and then actual measurements of a power company.
The synthesized data were of great importance for development and improvement of the algorithm, besides understanding the operation, improvement in routines and overall software were possible. While the actual data served to validate the performance of the methodology for monitoring the PQE.
The voltage variation was estimated using (1) with window of ½ cycles. The event duration is detected by means of calculation (p.u.) between a sample signal and a sample synthesized with a nominal value of the system. Thus, the algorithm detects the sample in which the disturbance begins or ends, avoiding the error caused by windowing the data. The results of voltage changes are shown in Table I.

Table I. – Comparison of the Magnitude and Duration of Voltage Variation

Voltage Variation					
Amplitude (p.u)			Duration (ms)		
Actual	Read	Error (%)	Actual	Read	Error (%)
0.5	0.5	-9.80E-11	8.33	8.33	-8.00E-11
0.1	0.1	-4.10E-11	12.5	12.5	-6.67E-11
0.8	0.8	-9.25E-11	16.67	16.67	-1.88E-11
0.9	0.9	-4.00E-11	66.67	66.67	-1.72E-11
1.1	1.1	-5.45E-11	500	500	-1.94E-11
1.2	1.2	-1.67E-11	3,000	3,000	-1.88E-11
1.4	1.4	-2.93E-11	60,000	60,000	-1.94E-11

It can be seen in Table I that the error generated in this algorithm is due to the "rounding" of the software. Note that the maximum error resulting from estimation algorithm of length variation is equivalent to the sampling period (Ts=1/fs). Thus, lower Ts, the smaller the error.
The algorithm performance for the estimation of voltage imbalances, equation (4), is based on the calculation of V_{rms} showed the following results in Table II.

Table II. – Comparison of Voltage Imbalances

Voltage Imbalance						
Actual (p.u)	Phase (R-S)		Phase (S-T)		Phase (T-R)	
	Read	Error(%)	Read	Error(%)	Read	Error(%)
-0.025	-0.025	-7.92E-11	-0.025	-7.92E-11	-0.025	-7.92E-11
0.000	0.000	2.00E-11	0.000	2.00E-11	0.000	2.00E-11
-0.075	-0.075	-2.57E-11	-0.075	-2.57E-11	-0.075	-2.57E-11
0.087	0.087	2.19E-11	0.087	2.19E-11	0.087	2.19E-11
0.100	0.100	1.90E-11	0.100	1.90E-11	0.100	1.90E-11

Using the proposed algorithm to determine the harmonics level obtained the individual harmonic distortion (DIT). The results are showed in Table III.

Table III. –Comparison of DIT

Individual Harmonic Distortion - DIT			
Index	Actual	Read	Error (%)
1	5.0000	5.0000	-2.85E-03
2	4.0000	4.0000	-6.82E-05
3	2.0000	2.0000	-1.36E-04
4	0.5000	0.5000	-2.85E-03

Since the total harmonic distortion (THD) some results are presented in Table IV.

Table IV. – Comparison of DHT

Total Harmonic Distortion - DHT			
Index	Actual	Read	Error (%)
1	11.225	11.225	-2.22E-13
2	7.4162	7.4116	-1.78E-13
3	5.4772	5.4772	3.33E-13
4	3.70	3.71	-3.33E-14

It is observed that the network frequency remained constant during the measurements, since the efficiency of the algorithm depends on the frequency synchronization. The algorithm needs N points with the constant sampling rate per cycle, emphasizing the importance of an algorithm to detect the frequency.

The flickering light is measured by the adequacy of the voltage modulation index of relevance in frequency, mean square, and statistical treatment and estimating the short-term indicator (P_{st}) and long-term indicator (P_{lt}). These indicators represent the severity levels of flicker associated with fluctuations in voltage at a predetermined time period. Table V presents results of simulations.

For detection of frequency variations, it is used the PLL algorithm based on instantaneous vector calculus - CVI. Numerous tests were performed varying and estimating the signal frequency. Some results are presented in Table VI. It is observed that the algorithm used obtained highly accurate results.

Table V. – Comparison of Luminous flickers

Flickering Luminous - P_{st}		
Actual	Read	Error (%)
0.025	0.026	-3.90
0.050	0.051	-1.56
0.100	0.101	-1.41
1.000	1.014	-1.38
2.500	2.548	-1.86
5.000	5.100	-1.96
10.000	10.231	-2.26

Table VI. – Comparison of frequency ranges

Fundamental Frequency - Regime		
Actual (Hz)	Read (Hz)	Error (%)
58.00	58.00	5.11E-13
59.00	59.00	1.55E-13
59.09	59.09	3.55E-13
60.01	60.01	3.33E-13
60.10	60.10	3.33E-13
61.00	61.00	3.33E-13

6. Final Considerations

Considering the current scenario of PQE regulations, technological advances in equipment, monitoring and control of power quality, measurement and quantification of disorders have become a necessity for electricity companies.
This work presented the first identification of parameters which are most convenient to evaluate comprehensively the power quality. For this purpose, it was developed a methodology for detecting and analyzing key indicators of PQE. The algorithm was developed in Matlab platform.
The developed methodology was used to detect changes in voltage, frequency variation, voltage unbalance, voltage fluctuation, transient and steady state voltage waveform distortion. The characteristics (amplitude and duration) of events were estimated, and classified according to the IEEE 1159. Thus, the methodology serves as a tool to help the detection and analysis of electromagnetic phenomena in PQE.
The proposed system management is a methodology for monitoring the PQE at the output of wind turbine that will serve as input data to proportional control system. The later will perform the management of PQE in order to correct variations in voltage and frequency changing of the wind turbine by controlling the excitation current and rotation of the machine with power electronics. Moreover, the very classification of disorders serves as a tool to identify the possible root causes of the disturbance.

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