



HAL
open science

Method for computing efficient electrical indicators for offshore wind turbine monitoring

Georgia Cablea, Pierre Granjon, Christophe Bérenguer

► **To cite this version:**

Georgia Cablea, Pierre Granjon, Christophe Bérenguer. Method for computing efficient electrical indicators for offshore wind turbine monitoring. CM 2014 - MFPT 2014 - 11th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, Jun 2014, Manchester, United Kingdom. 12 p. hal-00979124

HAL Id: hal-00979124

<https://hal.science/hal-00979124>

Submitted on 17 Jun 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Method for computing efficient electrical indicators for offshore wind turbine monitoring

Georgia Cablea, Pierre Granjon and Christophe Bérenguer
Gipsa-lab, Grenoble University, France
{georgia.cablea, pierre.granjon, christophe.berenguer}
@gipsa-lab.grenoble-inp.fr

Abstract

Offshore wind turbines availability is an important issue if such wind farms are to be considered a reliable source of renewable energy for the future. Environmental conditions and the low accessibility of such wind farms have contributed to the decrease of the availability of the wind turbines, compared to the onshore ones. In order to improve the reliability, condition monitoring systems and the implementation of scheduled maintenance strategies are a must for offshore power plants.

This paper proposes a method of computing efficient electrical indicators using the available three-phase electrical quantities. These indicators are then to be used to obtain fault indicators for fault detection and diagnosis. The electrical indicators are obtained by using the instantaneous symmetrical components decomposition, a well proven method in power networks design and diagnosis. The new quantities are able to fully describe the whole electrical system and provide an effective mean to quantify the balance and unbalance in the system. The method uses the electrical three-phase quantities measured at the output of the generator in a wind turbine to obtain the indicators. The performance of this method is illustrated using both synthetic and experimental data.

1. Introduction

Wind power plants are a rather new and promising way of providing renewable energy. Moreover, as technology evolves, their reliability improves with time and modern wind turbines achieve a quite high availability⁽¹⁾. However, unscheduled wind turbine failures most often result in high maintenance efforts, production losses and economical costs.

To further decrease losses and costs, efficient maintenance strategies have to be developed according to each wind farm's specific needs. This need is further emphasized by offshore deployment of wind farms. The offshore turbines have much lower accessibility⁽¹⁾ so maintenance work has to be planned well in advance. To correctly plan a maintenance strategy, condition monitoring of systems and subsystems is needed.

Several condition monitoring techniques have been developed and implemented in wind turbines⁽²⁾ like vibrations, acoustic emissions, or oil analysis. Most of them are intended to monitor blades or mechanical parts (bearings, gears, shafts...), which are considered as critical wind turbines subassemblies. However, wind turbines electrical generators also have a high failure rate and generate a very high amount of downtime⁽¹⁾. For such three-phase electrical systems, new approaches using electric signals have to be developed.

Raw three-phase electric signals contain a great quantity of information on the system they are part of, but are complex and difficult to interpret. In order to extract relevant features, the whole electrical information has to be split into different and specific indicators. One method used to separate such electrical information into meaningful quantities is the symmetrical components decomposition⁽³⁾. This method has been first developed by Fortescue in 1918⁽⁴⁾ and has since been widely used, for example in power networks calculations⁽⁵⁾ (network modeling and control, power quality monitoring, fault detection...). Symmetrical components decomposition approaches have also shown good results in monitoring three-phase electrical motors⁽⁶⁾⁽⁷⁾. In this paper, this decomposition is used to analyze electric quantities measured at the output of a three-phase generator. The associated estimation algorithm provides several electrical features that can be further processed or directly used as fault indicators dedicated to the generator. The adopted sample per sample approach allows its online implementation, and reaches good estimation and tracking performance in stationary and non-stationary case.

The theoretical considerations behind this method are presented in the next section where the electrical features to be estimated are defined. Then, section 3 gives an overview of the algorithm used to estimate these quantities. The proposed algorithm performance is next studied in section 4 thanks to synthetic and experimental data measured on a small-scale wind turbine test bench. Finally, the conclusions and future works are summarised in section 5.

2. Method of electrical signature analysis for wind turbine monitoring

Electrical sub-assemblies used in wind turbines such as electrical generators are three-phase systems. One efficient way to take into account the whole information contained in such systems is to use the symmetrical component decomposition, as it is customary for power networks⁽⁵⁾. From these symmetrical components, the design of fault indicators dedicated to the monitoring of such subassemblies can be expected. This idea is further develop in this second section, where the definition of symmetrical components is first given, followed by the proposition of some wind turbine electric features that can be used to elaborate fault indicators.

2.1 Three-phase electrical system analysis

2.1.1 Balanced three-phase systems

Most often, electrical signals and systems are analysed around their fundamental frequency f_0 . Indeed, the most relevant part of the whole electrical power is located around this particular frequency, where a lot of information is accessible. Following this consideration, electrical signals are often considered as pure sine waves of frequency f_0 with constant amplitude and original phase. A convenient notation for such single-phase electric signal $x(t)$ is its phasor notation $\underline{x}(t)$ defined in Eq. (1), where $x(t)$ stands for a generic electric signal, either a voltage or a current.

$$\underline{x}(t) = Ae^{j(2\pi f_0 t + \alpha)} = Xe^{j2\pi f_0 t} \quad (1)$$

In that case and for a known frequency f_0 , the complex amplitude $X = Ae^{j\alpha}$ is then sufficient to completely characterize the original signal at f_0 , which is linked to its phasor through the simple relation $x(t) = \text{Re}[x(t)]$.

This approach can be easily extended to three-phase electrical signals $x_1(t), x_2(t), x_3(t)$ that can be represented at their fundamental frequency by three complex amplitudes X_1, X_2, X_3 . In the case of a balanced three-phase system, the three electrical signals have the same amplitude and are shifted from each other by the same angle of $\frac{2\pi}{3}$ radians. This leads to the following phasor representation:

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} e^{j2\pi f_0 t} = X \begin{bmatrix} 1 \\ e^{-j\frac{2\pi}{3}} \\ e^{-j\frac{4\pi}{3}} \end{bmatrix} e^{j2\pi f_0 t}. \quad (2)$$

Eq. (2), clearly shows that for a known fundamental frequency, the balanced three-phase system is fully represented by the single complex amplitude X , as in the single-phase case of Eq. (1).

2.1.2 Unbalanced three-phase systems and symmetrical components

However, real electrical three-phase systems are never perfectly balanced. Consequently, Fortescue⁽⁴⁾ proposed in 1918 a method to decompose any n -phase unbalanced system in a set of n balanced systems called symmetrical components. As described in the previous section, the resulting set of balanced systems can be regarded as n single-phase systems, completely characterized by a set of n complex amplitudes. Following this approach, any unbalanced three-phase system can be resolved at its fundamental frequency into a sum of three balanced systems:

- the positive-sequence component: three phasors equal in magnitude, shifted by $\frac{2\pi}{3}$ radians and in the same phase sequence as the original system,
- the negative-sequence component: three phasors equal in magnitude, shifted by $\frac{2\pi}{3}$ radians and in the reverse phase sequence of the original system,
- the zero-sequence component: three phasors equal in magnitude and with no phase shift between them.

In matrix form, the three complex amplitudes X_1, X_2 and X_3 of the original system can be related to the ones of the corresponding symmetrical components thanks to the simple linear relations:

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} X_+ \\ X_- \\ X_0 \end{bmatrix} \quad \begin{bmatrix} X_+ \\ X_- \\ X_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix}, \quad (3)$$

where X_+, X_- and X_0 are the complex amplitudes of the positive-, negative- and zero-sequence components respectively and $a = e^{j\frac{2\pi}{3}}$ is called the Fortescue operator modelling a phase shift of $+\frac{2\pi}{3}$ radians. It can be noticed that in the algorithm presented in Fig. 1, a factor of 2 has to be applied in the right-hand side of Eq. (3) to obtain amplitude invariance between the original system and the symmetrical components.

One major interest in using symmetrical components is that they provide the means to analyse general three-phase quantities at a given frequency by splitting them into balanced and unbalanced parts. Indeed, in case the original system is balanced, it only consists of a positive-sequence component, while the negative- and zero-sequence components are zero. On the contrary, the existence of negative- and/or zero-sequence components means that there is an unbalance in the three-phase system at the studied frequency. Therefore, the amplitude X_+ of the positive-sequence component quantifies the amount of balanced signal, whereas X_- and X_0 can be used to precisely quantify the unbalance in the original system.

Several methods exist to estimate the symmetrical components of a three-phase system from the measured electrical signals, among which the most popular is obviously the discrete Fourier transform⁽⁸⁾ (DFT). However, this approach is usually implemented on blocks of data, and cannot easily compute instantaneous values of symmetrical components at each new measured sample. One way to overcome this problem is to use the instantaneous symmetrical component transform first introduced by Lyon⁽⁹⁾. This transform simply applies the same matrix appearing in the right-hand side of Eq. (3) to the three-phase electrical signals $x_1(t)$, $x_2(t)$, $x_3(t)$ instead of the complex amplitudes of Eq. (3). As a result, we obtain three complex-valued signals $x_+(t)$, $x_-(t)$, $x_0(t)$ named the instantaneous positive-, negative- and zero-sequence component respectively. By selecting the content of these signals around the fundamental frequency f_0 , it has been shown⁽⁶⁾ that we obtain the classical symmetrical components of the original three-phase system at f_0 . This last method is used in the algorithm described in part 3.

2.2 Wind turbines electrical features

Electrical quantities acquired on real electrical systems are usually voltages and/or currents, measured on a single phase or on all three phases. Such signals are very rich in content and it is difficult to isolate meaningful and clear electrical information using raw data. In this paragraph, the previous ideas and definitions are used to propose simple three-phase electrical features, highlighting particular and precise electrical information such as electrical unbalance, signal distortion or quality, electrical powers, *etc.* Afterwards, the proposed features can either be used directly or be further processed to obtain efficient fault indicators.

In order to propose well-defined features, several preliminary assumptions must be made. Firstly, the monitored electrical system is supposed to be star connected with a connected neutral wire, and the measured electrical quantities are line to neutral voltages and line currents. Nonetheless for the case of symmetrical components systems, the quantities can be easily converted from line to phase quantities and vice-versa⁽³⁾. Moreover, measured electrical signals are studied at their fundamental frequency f_0 , even if the same analysis could be made at any frequency. This means that in the following, all phasors and complex amplitudes are computed at f_0 . Finally, due to wind speed and direction fluctuations, wind turbines most often run under non-stationary conditions and generate non-stationary electrical quantities. Therefore, the electrical signals must be considered as non-stationary, and the simple phasor model given in Eq. (1) must be adapted to take into account amplitude and frequency variations of the fundamental component⁽¹⁰⁾:

$$\underline{x}(t) = A(t)e^{j\theta_0(t)} = |X(t)|e^{j\theta_0(t)}, \quad (4)$$

where $X(t) = A(t)e^{j\alpha}$ (time varying positive magnitude multiplied by a complex number) and the instantaneous phase $\theta_0(t)$ is related to the instantaneous fundamental frequency $f_0(t)$ by:

$$\theta_0(t) = 2\pi \int_0^t f_0(u) du. \quad (5)$$

It has also been shown⁽¹¹⁾ that in electromechanical systems, most mechanical faults generate amplitude and frequency modulations in electrical quantities. This also justifies the signal model adopted in Eq. (4), where $x(t)$ stands for voltage or current signals, either their measured values or their symmetrical components in the three-phase case.

2.2.1 Narrow band electric features

The previous model shows that at a given frequency, electric signals are fully described by their instantaneous amplitude and frequency. Eq. (4) and (5) show that the instantaneous amplitude can be easily obtained as the absolute value of the phasor, and the instantaneous frequency can be extracted from the time derivative of its phase angle. This is summarized by Eq. (6).

$$\begin{aligned} A(t) &= |\underline{x}(t)|, \\ f_0(t) &= \frac{1}{2\pi} \frac{d\theta_0(t)}{dt} \quad \text{where } \theta_0(t) = \angle \underline{x}(t). \end{aligned} \quad (6)$$

For the three-phase scenario, the instantaneous frequency is computed as in Eq. (6) using only the instantaneous positive sequence component phasor $\underline{x}_+(t)$. The reasoning behind this is that this component usually has the larger magnitude, and that in case of a perfectly balanced symmetrical system, only the positive sequence component would be non-null.

The method of symmetrical components provides the means to easily describe electrical unbalance in a three-phase system. Indeed, an obvious unbalance indicator is the ratio between the unbalanced part and the whole part of a three-phase signal at a given frequency. Using the instantaneous symmetrical components phasors, this simply expresses as:

$$u_x(t) = \sqrt{\frac{|\underline{x}_-(t)|^2 + |\underline{x}_0(t)|^2}{|\underline{x}_+(t)|^2 + |\underline{x}_-(t)|^2 + |\underline{x}_0(t)|^2}} = \sqrt{\frac{|X_-(t)|^2 + |X_0(t)|^2}{|X_+(t)|^2 + |X_-(t)|^2 + |X_0(t)|^2}}. \quad (7)$$

This indicator belongs to the interval $[0,1]$, where the ideal case of a perfectly balanced system would yield $u_x = 0$ and the worst case to 1.

2.2.2 Wide band electric features

An electric signal is not distorted or of “perfect quality” if it is constituted by a pure sine wave of frequency f_0 . One way of quantifying this “quality” is then to compute the ratio between the amount of signal contained at the fundamental frequency over the

total amount of signal. A simple way to quantify the amount of a signal $x(t)$ being its mean power $P_x = \lim_{T \rightarrow \infty} \frac{1}{T} \int |x(t)|^2 dt$, the following feature gives an instantaneous image of the signal quality:

$$\text{SQ}_{\underline{x}}(t) = \frac{P_{\underline{x}}(t)}{P_x(t)}. \quad (8)$$

where $P_{\underline{x}}(t)$ and $P_x(t)$ are local estimates of the mean power at the fundamental frequency and for the whole signal.

If this indicator equals 1, the signal can be considered a pure sine wave of frequency f_0 . On the contrary, if this feature equals 0, no component is present at f_0 . Finally, $\text{SQ}_{\underline{x}}(t)$ can be interpreted as the fraction of signal localized at the fundamental frequency.

This feature can be easily extended to the three-phase case noting that the mean power of a three-phase signal is the sum of the signal powers on each phase. Therefore, in terms of symmetrical components, the following relationship exists:

$$\begin{aligned} P_{x1}(t) + P_{x2}(t) + P_{x3}(t) &= \frac{1}{2} \left(|X_1(t)|^2 + |X_2(t)|^2 + |X_3(t)|^2 \right) \\ &= \frac{3}{4} \left(|X_+(t)|^2 + |X_-(t)|^2 + |X_0(t)|^2 \right), \end{aligned} \quad (9)$$

and such relations can be used in Eq. (8) to measure the quality of three-phase signals.

2.2.3 Electrical powers and phase shift

If both voltages and currents are available (either on one phase or on all three phases), the electrical powers and the phase shift between voltages and currents are interesting features to characterize relationships between these two electrical quantities. Once again, the following features are defined only at the fundamental frequency f_0 .

The single-phase instantaneous complex electric power at frequency f_0 is given by:

$$\underline{p}(t) = \underline{v}(t) \underline{i}^*(t) = \frac{1}{2} V(t) I(t) e^{j\varphi_0(t)}. \quad (10)$$

In terms of real and imaginary parts this complex power leads to active and reactive powers, while in terms of magnitude and phase angle it leads to apparent power and phase shift between voltage and current:

$$\begin{aligned} P(t) = \Re \{ \underline{p}(t) \} &= \frac{1}{2} V(t) I(t) \cos(\varphi_0(t)) & Q(t) = \Im \{ \underline{p}(t) \} &= \frac{1}{2} V(t) I(t) \sin(\varphi_0(t)) \\ S(t) = | \underline{p}(t) | &= \frac{1}{2} V(t) I(t) & \varphi_0(t) &= \angle \underline{p}(t) \end{aligned} \quad (11)$$

In practice and in the algorithm described in the next section, the power factor $\cos(\varphi_0(t))$ is considered instead of the phase shift $\varphi_0(t)$.

The complex power defined in Eq. (10) for single-phase signals can be easily extended to the three-phase case thanks to instantaneous symmetrical components. Indeed, in that case this quantity expresses as:

$$\underline{p}(t) = \frac{3}{2} \left[\underline{v}_+(t) \underline{i}_+^*(t) + \underline{v}_-(t) \underline{i}_-^*(t) + \underline{v}_0(t) \underline{i}_0^*(t) \right], \quad (12)$$

where phasors at f_0 of the voltages and currents instantaneous symmetrical components are used.

Considering that healthy electrical systems should only develop positive sequence power, the proposed feature for the complex three-phase power only considers the positive sequence components⁽⁶⁾:

$$\underline{p}_+(t) = \frac{3}{2} \underline{v}_+(t) \underline{i}_+^*(t). \quad (13)$$

In healthy systems, this would give an almost ideal approximation of the total three-phase power. Once again, real and imaginary parts or magnitude and phase angle can be used to obtain active, reactive, apparent powers and power factor in the three-phase case.

Eq. (6), (7), (8), (10), (11) and (13) form a set of electric features that can be used to describe in detail the electrical content of one-phase or three-phase electrical signals measured for example on wind turbines.

3. Estimation algorithm

The goal of this section is to briefly describe the general structure of the algorithm used to estimate the electric features previously proposed.

Figure 1 depicts the part of the algorithm dedicated to estimate features defined for one electrical quantity (voltage or current). The input is either a single- or a three-phase electrical quantity, and the outputs consist in the different per-quantity features defined in the previous section. Both single-phase and three-phase indicators are presented in this figure in order to emphasise the similarities in computing the indicators for the different scenarios. Operations depicted in purple are specific to the three-phase scenario, while blue parts are applicable in both cases.

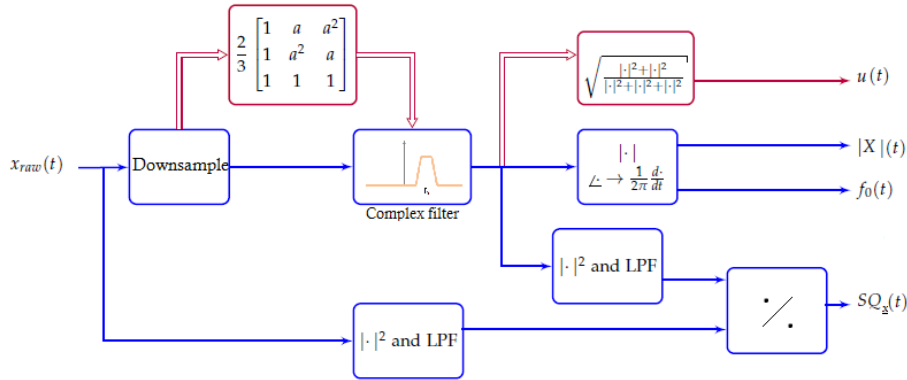


Figure 1. Estimation algorithm for instantaneous electrical features dedicated to one electrical quantity (LPF stands for lowpass filter)

This structure has been chosen to obtain a “sample per sample” algorithm, able to update the features at each new input sample. It is organized around a complex bandpass filter⁽¹²⁾ used to select the content of its input around the fundamental frequency. Thanks to its complex-valued coefficients, this filter avoids the symmetry around the zero frequency, thus only selecting the content around $+f_0$ and not the one

located at $-f_0$. Therefore, the output of such a filter consists in complex phasors such as the ones defined in Eq. (1) or (4). As in ⁽⁶⁾, this filter is implemented in the time domain with a finite impulse response structure. The down-sampling operation located in front of the complex filter is used to minimise the number of filter coefficients. By using a time-invariant filter for selecting the frequency content, computational time is kept low at the cost of limitation on the variations of the fundamental frequency. This limitation is given by the bandwidth of the filter. Simple and instantaneous operations are then applied to the obtained phasors in order to estimate the desired electrical features.

Figure 2 depicts the part of the algorithm dedicated to the estimation of features defined when voltages and currents are available: electric powers and power factor. Here also, these features can be computed for both single- and three-phase cases. The inputs are phasors obtained thanks to the complex bandpass filter, on which simple and instantaneous operations are applied to obtain instantaneous values of active, reactive, apparent power and power factor at the fundamental frequency.

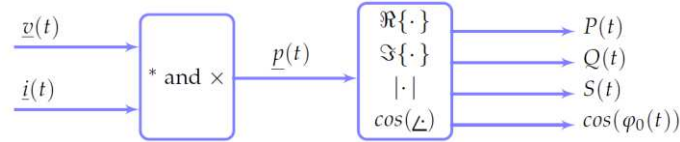


Figure 2. Estimation algorithm for instantaneous electrical features dedicated to two electrical quantities

It is worth noting that all the operations described in the two previous figures (the filters and the different instantaneous operations) can be real-time implemented, leading to a real-time sample per sample estimation algorithm.

The performance of this algorithm is illustrated in the next section on synthetic and experimental electric signals.

4. Results

In this section two sets of results will be presented. The first set is obtained using synthetic data in order to compare the estimated features with their theoretical values and measure the performance of the proposed estimation algorithm. The second set is obtained using experimental data obtained from a test-bench running under non-stationary conditions, highlighting the tracking capabilities of the algorithm.

4.1 Synthetic results

A set of synthetic signals is generated in order to illustrate the behaviour and performance of the proposed electrical features and estimation algorithm. These three-phase electrical signals are considered to be line-to-line voltages (their zero-sequence component is then null) and line currents. The three-phase currents are perfectly balanced with a positive sequence of 10 Amps. The three-phase voltages are perfectly balanced with a positive sequence of 100 Volts, except between 10 and 17 seconds where a 1% increase in magnitude has been generated on phase 1 only, leading to a local voltage unbalance of 0.5%. The voltages also contain non-stationary high frequency components between 20 and 45 seconds to illustrate the signal quality feature. At 20s, a high frequency component was added to the voltages with the same magnitude as the fundamental component, and was divided by two at 33s and cancelled at 45s. For each quantity, the same 2% random variations are introduced on the

fundamental frequency of 50 Hz. Finally, the phase shift between the positive-sequence components of voltages and currents is kept constant throughout the simulation.

The results obtained by the proposed method are presented in Fig. 3. Theoretical values are in light blue while estimated ones are in dark blue, and the delay of 0.38 seconds (775 samples) due to the bandpass filter used in the algorithm has been cancelled. Features associated to the voltages are represented in Fig. 3(a) to 3(e) (positive- and negative-sequence magnitudes, unbalance, instantaneous frequency and quality). The magnitude of the current positive sequence component is plotted in Fig. 3(f), followed by active and reactive powers (Fig. 3(g) and 3(h)).

Fig. 3 clearly shows that the proposed algorithm globally reaches very good performance. Estimation errors are small for stationary and non-stationary parts of each feature. The influence of the increase of phase 1 voltage is perfectly highlighted and quantified, either thanks to voltage features (see for example the voltage unbalance feature in Fig. 3(c)) or thanks to powers (see active and reactive powers in Fig. 3(g) and 3(h)). Even the random fluctuations of the fundamental frequency are correctly estimated and followed. This means that whatever the feature, this sample per sample algorithm presents at the same time good estimation and tracking performance.

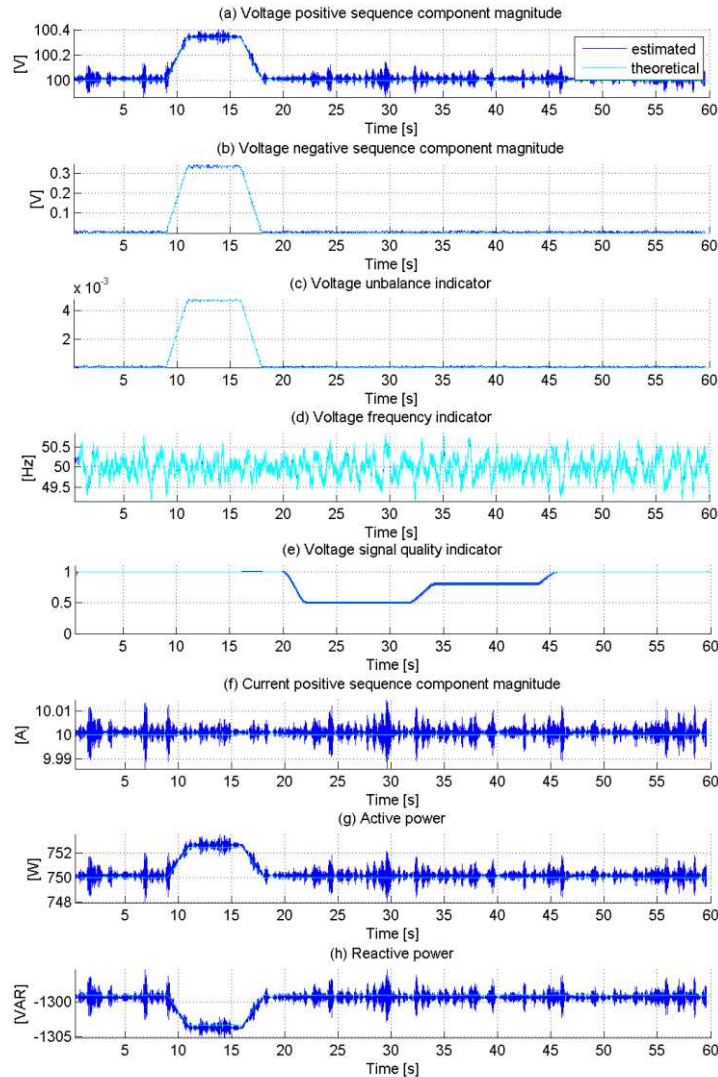


Figure 3. Results obtained on synthetic data

4.2 Experimental results

A test bench located in the CETIM laboratory (Senlis, France) has been used to generate a set of three-phase electric signals under stationary and non-stationary operating conditions. This test bench, depicted in Fig. 4, has been elaborated in the context of the KAStrion European project in order to simulate the operation of a real wind turbine. At the input of the structure, a geared induction motor drives a low-speed shaft connected to a gearbox used as a multiplier. The high-speed shaft at the output of the multiplier drives an induction three-phase generator connected to the power network through a PWM power converter. The user can specify the desired speed profile thanks to an inverter supplying the input geared motor. Electric quantities are measured at the output of the generator using 3 current probes and 3 voltage probes. Measured quantities are the three line currents and the three line-to-line voltages. Sampling frequency is 40 kHz.

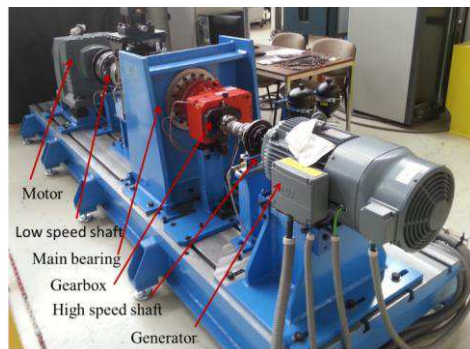


Figure 4. Experimental test bench

The results presented in Fig. 5 have been obtained by applying the proposed algorithm on the electric quantities measured for two different operating states. In each state, the speed of the low-speed shaft (LSS) is considered as the input of the whole system. State A represents steady state operating conditions with a constant LSS speed of 20 rpm. On the contrary, State B represents non-stationary operating conditions with a LSS speed of 20 rpm added with some small linear variations. This speed profile was used in order to simulate typical wind turbine behaviour.

Fig. 5(a) depicts the two speed profiles of the low speed shaft (constant for state A and time-varying for state B). Fig. 5(b) depicts the estimated instantaneous fundamental frequency of the electric signals computed from the positive sequence component of the measured voltages. The strong correlation between the speed profiles and the estimated frequency observed in these two first figures highlights the good estimation and tracking performance of this algorithm. Fig. 5(c) depicts the magnitudes of the positive sequence component for voltages, while Fig. 5(d) shows the magnitudes of the positive sequence component for currents. These magnitudes are computed around the fundamental frequency of the signals and show, as expected, variations correlated with the speed profiles. The estimated values of active and reactive powers are depicted in Fig. 5(e) and 5(f), and are also closely linked to the speed variations. The voltage unbalance indicator is represented in Fig. 5(g). Considering that there was no electrical unbalance at the generator stator, the value of this indicator is very close to zero, whatever the state. Nonetheless, it is worth mentioning that this indicator is independent on the operating conditions of the system. Indeed, the speed variations of the shaft, depicted in Fig. 5(a), do not induce any correlated variations in the evolution of this particular indicator. The voltage signal quality indicator is presented in Fig. 5(h). The spectrum

analysis of the measured signals has shown that the PWM converter connected at the output of the generator is responsible for high harmonic distortion, thus confirming the poor signal quality obtained by the algorithm.

From all these results, it can be concluded that the proposed electrical features successfully describe the electric quantities generated at the output of the test-bench, and that the proposed algorithm successfully estimates their values and follows their variations.

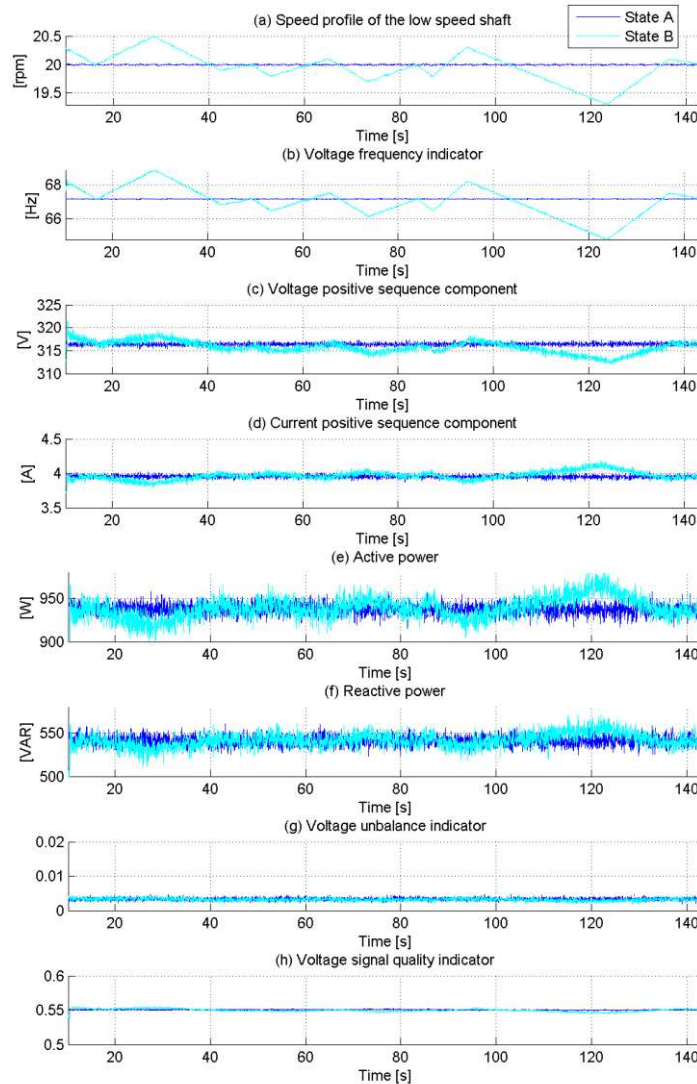


Figure 5. Experimental results

5. Conclusions

In this paper, a method generating meaningful electrical features from electric measurements is presented. In the beginning of this paper the definition of electrical features was given. These features are able to describe the whole electrical information contained in both single- and three-phase electrical systems. The second part of the paper proposed an algorithm to efficiently estimate such quantities. The algorithm is able to process signals sample per sample and is suited for online implementation. The results were validated using both synthetic and experimental signals. This approach gives good results in terms of features estimation and tracking.

Future work implies the evaluation of the proposed algorithm using real wind turbine data. This will also enable the definition and validation of fault indicators specific to wind turbines. Nonetheless, the algorithm to obtain the faults indicators could be extended to other electrical systems. Furthermore, the algorithm can be improved by implementing adaptive filtering for the fundamental frequency selection step.

Acknowledgements

The authors would like to thank CETIM (*Centre Technique des Industries Mécaniques*) for providing the test-bench and experimental data.

References

1. P. J. Tavner, *Offshore wind turbines reliability, availability and maintenance*. London, U.K.: Institution of Engineering and Technology, 2012.
2. F. P. García Márquez, A. M. Tobias, J. M. Pinar Pérez, and M. Papaelias, "Condition monitoring of wind turbines: Techniques and methods," *Renewable Energy*, vol. 46, pp. 169–178, Oct. 2012.
3. J. E. Hobson, "Symmetrical components," in *Electrical transmission and distribution reference book*, Westinghouse Electric Corp., 1964.
4. C. L. Fortescue, "Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks," *Transactions of the American Institute of Electrical Engineers*, vol. XXXVII, no. 2, pp. 1027–1140, Jul. 1918.
5. G. C. Paap, "Symmetrical components in the time domain and their application to power network calculations," *IEEE Transactions on Power Systems*, vol. 15, no. 2, pp. 522–528, May 2000.
6. P. Granjon, "Condition Monitoring of Motor-Operated Valves in Nuclear Power Plants," in *8th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, Cardiff, United Kingdom, 2011, vol. 1, pp. 109–119.
7. T. Vaimann, A. Kallaste, and A. Kilk, "Using Clarke Vector Approach for Stator Current and Voltage Analysis on Induction Motors with Broken Rotor Bars," *Electronics and Electrical Engineering*, vol. 123, no. 7, Sep. 2012.
8. T. Tarasiuk, "Comparative Study of Various Methods of DFT Calculation in the Wake of IEC Standard 61000-4-7," *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 10, Oct. 2009.
9. W. V. Lyon, "Transient Analysis of Alternating-Current Machinery", The Technology Press of M.I.T. and John Wiley & Sons, New York, 1954.
10. B. Boashash, "Estimating and Interpreting the Instantaneous Frequency of a Signal", *Proceedings of the IEEE*, vol. 80, no. 4, April 1992.
11. M. Blodt, P. Granjon, B. Raison and J. Régner, "Mechanical fault detection in induction motor drives through stator current monitoring - Theory and application examples Fault Detection", Wei Zhang (Ed.), 2010.
12. A. Reilly, G. Frazer, and B. Boashash, "Analytic signal generation-tips and traps," *IEEE Transactions on Signal Processing*, vol. 42, no. 11, pp. 3241–3245, Nov. 1994.