



Operational-Condition-Independent Criteria Dedicated to Monitoring Wind Turbine Generators

Preprint

W. Yang
National Renewable Energy Centre

S. Sheng
National Renewable Energy Laboratory

R. Court
National Renewable Energy Centre

*To be presented at the ASME 2012 International Mechanical Engineering Congress & Exposition
Houston, Texas
November 9–15, 2012*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5000-55195
August 2012

Contract No. DE-AC36-08GO28308

NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/help/ordermethods.aspx>

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721



Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

OPERATIONAL-CONDITION-INDEPENDENT CRITERIA DEDICATED TO MONITORING WIND TURBINE GENERATORS

Wenxian Yang
National Renewable Energy
Centre (Narec)
Blyth, Northumberland, UK

Shuangwen Sheng
National Renewable Energy
Laboratory (NREL)
Golden, Colorado, USA

Richard Court
National Renewable Energy
Centre (Narec)
Blyth, Northumberland, UK

ABSTRACT

Condition monitoring is beneficial to the wind industry for both onshore and offshore plants. However, due to the variations in operational conditions, its potential has not been fully explored. There is a need to develop an operational-condition-independent condition monitoring technique, which has motivated the research presented here. In this paper, three operational-condition-independent criteria are developed. The criteria accomplish the condition monitoring by analyzing the wind turbine electrical signals in the time domain. Therefore, they are simple to calculate and ideal for online use. All proposed criteria were tested through both simulated and practical experiments. The experiments have shown that these criteria not only provide a solution for detecting both mechanical and electrical faults that occur in wind turbine generators, but provide a potential tool for diagnosing generator winding faults.

INTRODUCTION

The wind industry continues to grow worldwide. In particular, offshore wind is attracting increasing interest because of its high and stable wind speed, and lack of significant visual impact and noise issues. Take the offshore wind resource in the United Kingdom (UK) as an example. With 18 sites and a total electric-generating capacity of 1.5 gigawatts (GW), the UK government launched the first round of offshore wind farm development plans in 2000. To date, 11 Round 1 offshore wind farms are fully operational, with a combined electric-generating capacity of 876 megawatts (MW). The 90-MW Teesside wind farm has been recently consented. Following Round 1, the government launched a plan for a second round of larger sites in 2003. In Round 2, 16 sites were awarded, totaling a combined capacity of up to 7.2 GW. Today, two Round 2 offshore wind farms (Gunfleet Sands II 64 MW and Thanet 300 MW) are fully operational, five are under construction, three were consented, and the other six are in planning. Subsequently, the UK offshore wind Round 3 scheme was announced in 2008, offering nine development zones and a

total electric-generating capacity of 32 GW—equaling one-fourth of the UK's electricity needs. From these data, it can be inferred that large megawatt-scaled wind turbines are being increasingly deployed offshore. Moreover, the locations where the wind farms are deployed tend to increase in size and distance from shore. Hence, wind turbine operators are very concerned about the reliability and availability issues of these offshore giants. The early experience of UK Round 1 offshore wind farms [1] shows that although these farms achieve satisfactory capacity factors (about 29.5%), their annual average availability is only 80.2%. This is fairly low in comparison to the average availability of UK onshore wind farms (97%).

Apparently, the low availability has become a barrier to reducing the cost of energy from offshore wind. For example, the Barrow site, a standard UK Round 1 offshore wind farm, includes:

- A rated power of 90 MW
- An annual average capacity factor of 29.5%
- A tariff rate of \$117 (USD) per megawatt-hour (MWh).

The annual revenue of this wind farm can be estimated by $90\text{MW} \times 365 \text{ days/year} \times 24 \text{ hours/day} \times 29.5\% \times 117\text{USD/MWh} \approx 27.2$ million USD. Then it can be readily inferred that this wind farm will yield \$272,000 USD more annual revenue if its production can be improved by 1%. For the future 32-GW UK Round 3 offshore wind development scheme, a 1% improvement in production could yield more than 9.7 billion USD per year. Undoubtedly, this is a significant economic profit to operators. In practice, there are many methods that can be used to improve wind turbine availability. Specifically, condition monitoring (CM) has been proven as one of the most efficient methods [2, 3]. The additional value of a proper wind turbine condition-monitoring system (CMS) is observable from detecting the incipient faults occurring in wind turbines and their subassemblies, protecting the defective parts from second-damage, and preventing fatal, catastrophic wind

turbine accidents. The additional value can also be justified by the following actual wind turbine operation and maintenance (O&M) data. In the commercial market today, the component replacement costs for a 5-MW turbine include the following [3, 4]:

- For a rotor: 1.9–2.3 million USD
- For a blade: 391–547 thousand USD
- For a blade bearing: 62.5–78.2 thousand USD
- For a gearbox: 628 thousand USD
- For a generator: 314 thousand USD
- For electronic modules: 16 thousand USD.

By contrast, the current average market price of a CMS is only around \$16,000 USD per unit. As a result, it may be worthwhile to equip offshore wind turbines with a CMS to ensure the turbine’s anticipated availability and economic return.

However, wind practice shows that the wind turbine CMSs that are currently available in the market have not been as successful as expected at improving wind turbine availability. The reasons are complicated [2], but one of the major reasons is that the available CMSs are using the general-purpose CM techniques, which are unable to provide reliable CM results for wind turbines. Because wind turbines operate at variable rotational speeds and are constantly subjected to varying loads, these influences and the effects of potential faults are combined in wind turbine CM signals, which makes it difficult to interpret the signals and reduces the reliability of the CM results. Although there have been some recent efforts [5, 6], frequent false alarms generated by the wind turbine CMS still overwhelm the operators and make them hesitant to use CMS extensively on their machines. Therefore, it is necessary to remove the negative influences of varying loads and rotational speeds on wind turbine CM results in order to use CMS to improve wind turbine availability. Two straightforward approaches could be taken for a solution: 1) introduce operational-condition decoupling procedures into the current wind turbine CM techniques, and 2) develop new operational-condition-independent wind turbine CM techniques. This paper demonstrates the second approach on monitoring wind turbine induction generators under continuously varying operational conditions. The details of this work follow.

OPERATIONAL-CONDITION-INDEPENDENT CONDITION MONITORING CRITERIA

To achieve a reliable CM technique that is dedicated for wind turbine induction generators that experience constantly varying operational conditions, the following criteria were researched.

Criterion δ

For a wind turbine induction generator, neither varying load nor potential faults are able to influence the primary frequency of its stator current signal. But the sub- or higher-order of fault-related harmonics will distort the time waveform of the stator current signal and thus disturb its zero-crossing

behavior. Whereas, the zero-crossing behavior of stator current signal is less dependent on load because varying load mainly affects the amplitude of the signal. Inspired by this knowledge, the first CM criterion, δ , was developed to describe the fault effect on the zero-crossing behavior of the stator current signal (see Figure 1). The figure shows the relative phase angles of the generator stator current signal with respect to the corresponding voltage signal in various scenarios. I_1 represents the line current signal measured at phase 1 of generator stator, V_1 represents the corresponding phase voltage signal, and Δt represents the leading/lagging time of I_1 , with respect to V_1 .

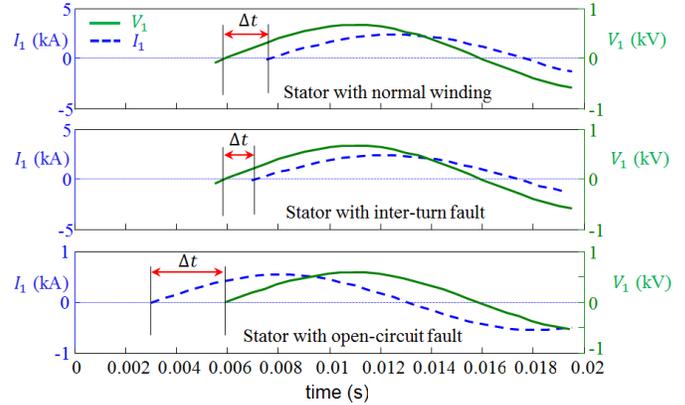


Figure 1: Zero-crossing behavior of the stator current signal in different scenarios

As Figure 1 shows, the potential generator winding faults will either increase or decrease the value of Δt , thus disturbing the zero-crossing behavior of its stator current signal. So potentially Δt can be an indicator of the health of a wind turbine induction generator. However, Δt is not accurate enough to be a CM criterion. It only reflects the shift of the current signal, however, it does not exactly show how much the phase shift is with respect to the corresponding voltage signal. In other words, the same value of Δt might indicate a different level of phase shift of the current signal when the grid frequency is different [either 50 hertz (Hz) or 60 Hz, depending on the areas]. Therefore, an improvement of Δt occurs by normalizing Δt using the frequency of grid. Hence, a new CM criterion, δ , is designed as:

$$\delta = \frac{\Delta t}{T} \times 360^\circ \quad (1)$$

Where

$$T = \frac{1}{f_{grid}} \quad (2)$$

f_{grid} refers to grid frequency.

From a physics point of view, δ is less dependent on the external load applied to the generator because it is only related to the impedance status and the magnetizing behavior of the generator. However, the potential faults occurring in an induction generator will disturb its circuit impedance or ability to magnetize. In other words:

- Either an inter-turn or open-circuit winding fault occurring in the generator rotor or stator will change the impedance of the generator circuit, thus leading to the change of criterion δ
- The generator mechanical faults, usually related to rotor shaft, bearings, and air-gap eccentricity, will alter the rotor-to-stator air gap statically or dynamically. Then, the modified air gap will result in the change of the magnetizing current of the generator. As a consequence, criterion δ will change correspondingly.

Therefore, criterion δ should be able to send an alert of both electrical and mechanical faults occurring in the generator.

Criterion r

As mentioned above, both varying load and generator abnormalities will influence the power (and power quality) output from a wind turbine induction generator. The difference is that varying load can alter the power but not the physical performance of the generator, however, the generator abnormalities can alter both. For example, a generator winding fault can change the circuit impedance of an induction generator, whereas an external load cannot. So the circuit impedance of an induction generator is load-independent. However, it can be a challenge to accurately measure generator circuit impedance online. In addition, there is a lack of control over uncertainties related to slip rings or carbon brushes. The metering accuracy and sensitivity of the data acquisition instruments are also concerns. In response to these issues, an alternative criterion, r , was developed for the purpose of indicating the status of the circuit impedance of an induction generator. It is based on a statistical calculation of the generator stator line current and the corresponding voltage signals. The criterion $r(t)$, expressed in terms of line current $I_1(t)$ and the corresponding phase voltage $V_1(t)$, can be written as:

$$r(t) = \sqrt{\frac{\sum_{\delta t=-\tau/2}^{\tau/2} [V_1(t + \delta t)]^2}{\sum_{\delta t=-\tau/2}^{\tau/2} [I_1(t + \delta t)]^2}} \quad (3)$$

where, a sliding window with the width of τ is used in the calculation. Subscript '1' indicates the phase 1 of the generator stator. The criterion can also be assessed by using the electrical signals measured from phase 2 or phase 3 of the generator stator.

Inter-turn or open-circuit faults that occur in the winding of the generator rotor or stator will change the circuit impedance of the generator. Therefore, researchers believe that this change should be observable from criterion r . The generator shaft and bearing-related faults will statically or dynamically alter the rotor-to-stator eccentricity, which will affect the magnetizing current of the generator. As a result, criterion r will change as well.

In principle, criterion r is load-independent and valid for detecting both electrical and mechanical faults that occur in wind turbine induction generators.

Criterion e

Park's vector [7] successfully describes the three-phase phenomenon in a two-dimensional coordinate system that allows the pattern-based CM of three-phase induction motors [8]. This technique can be applied to the CM of three-phase induction generators. The current Park's vector components (i_d, i_q) can be calculated by:

$$\begin{cases} i_d = \sqrt{\frac{2}{3}}I_1 - \frac{1}{\sqrt{6}}I_2 - \frac{1}{\sqrt{6}}I_3 \\ i_q = \frac{1}{\sqrt{2}}I_2 - \frac{1}{\sqrt{2}}I_3 \end{cases} \quad (4)$$

where I_1 , I_2 , and I_3 represent the line currents measured from the stator of a three-phase generator/motor.

When the health condition of the generator is without any defect, (i_d, i_q) is characterized by a circle pattern that is centered at the origin of the coordinate system. The size of the circle is related to the power generated by the generator. For example, the larger the power, the bigger the circle. Apparently, the pattern depicted by (i_d, i_q) is load-dependent. So if i_d and i_q are applied directly to CM application (as done in [8]), it is hard to get a creditable CM result under a varying loading condition. To help alleviate this issue, a further improvement is provided below.

Because the external load will change the values of I_1 , I_2 , and I_3 , it will affect the values of i_d and i_q and the size of the pattern depicted by (i_d, i_q) . However, external load is unable to change the eccentricity and roughness of the pattern curve, which are only dependent on the balance status of the generator load (i.e., the balance of three phases) and the harmonics (either sub- or higher order) that are induced by the faults. Therefore, the pattern eccentricity and the roughness of its curve are load-independent and have the potential to be used for generator CM. To provide a comprehensive description of the pattern eccentricity and curve roughness, a new CM criterion, e , is developed:

$$e(t) = \frac{R_{max}(t) - R_{min}(t)}{\bar{R}(t)} \times 100\% \quad (5)$$

Where

$$\bar{R}(t) = \frac{1}{T} \int_{t-T/2}^{t+T/2} R(\tau) d\tau \quad (6)$$

$$R(\tau) = |i_d(\tau) + j \times i_q(\tau)| \quad (7)$$

$$R_{max}(t) = \max(R(\tau)), \tau \in [t - T/2, t + T/2] \quad (8)$$

$$R_{min}(t) = \min(R(\tau)), \tau \in [t - T/2, t + T/2] \quad (9)$$

T stands for the frequency period of grid.

FAULT SIMULATIONS

To verify the CM criteria, both inter-turn and open-circuit faults are simulated on the rotor and stator windings of an induction generator by using Simulink. The winding fault simulation model is shown in Figure 2, and the parameters of

the generator being simulated are listed in Table 1. In the experiment, the winding faults are simulated by introducing electrical asymmetry into the generator rotor and stator circuit, and the CM signals (i.e., line currents, phase voltages, and total power) are measured from the stator of the generator.

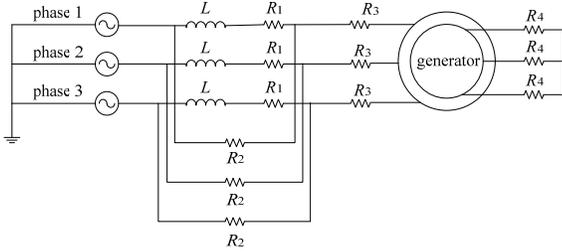


Figure 2: Model for simulating generator winding faults

In Figure 2, L refers to the inductance and R_1 refers to the resistance of the transmission line. $R_2 = 1e3\Omega$ represents the phase resistance to the ground. In the model, resistances R_3 and R_4 are specially designed to introduce electrical asymmetries into the stator and rotor of the generator. The initial values are $R_3 = 1.16e-3\Omega$ and $R_4 = 3.92e-2\Omega$ in the absence of electrical asymmetry.

Parameter	Value	Parameter	Value
Rated power, S_b	2 MW	Rotor leakage inductance, L_r^*	1.493e-1 p.u.
Line-line voltage, V_n	690 volts (V)	Magnetizing inductance, L_m^*	3.9527 p.u.
Rated frequency, f_b	50 Hz	Winding connection (stator/rotor)	Y-Y
Stator resistance, R_s^*	4.88e-3 p.u.	Turns ratio (N_s/N_r)	0.45
Stator leakage inductance, L_s^*	1.386e-1 p.u.	Inertia	32 Kg·m ²
Rotor resistance, R_r^*	5.49e-3 p.u.	Friction	2.985e-4 N·m·s

Table 1: The parameters used for simulating an induction generator [9].

Based on the parameters listed in Table 1, the transmission line impedance can be estimated as:

$$R_1 + jL = 0.01Z_{sb} + j \times 0.1L_{sb} \quad (10)$$

where

$$Z_{sb} = \frac{V_{sb}}{I_{sb}} \quad (11)$$

$$V_{sb} = \sqrt{\frac{2}{3}} V_n \quad (12)$$

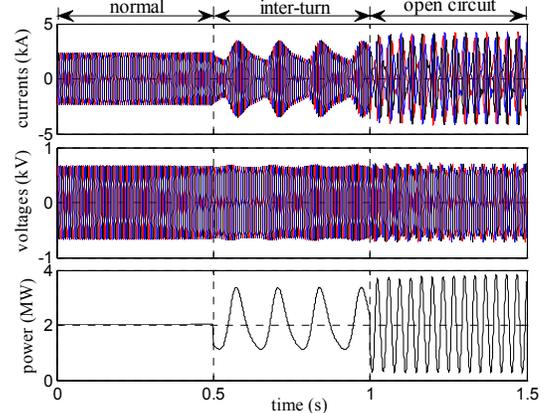
$$I_{sb} = \sqrt{\frac{2}{3}} \times \frac{S_b}{V_n} \quad (13)$$

$$L_{sb} = \frac{Z_{sb}}{2\pi f_b} \quad (14)$$

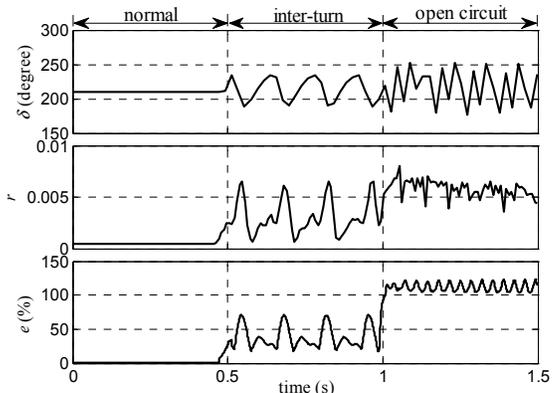
By submitting (11)-(14) into (10), obtain $R_1 = 2.3805e-3\Omega$ and $L = 7.6e-5H$.

Winding faults in rotor

The inter-turn and open-circuit faults are simulated first in the generator rotor by setting the resistance in the second phase to $R_4 = 3.92e-3\Omega$ and $R_4 = 3.92e-1\Omega$. The resulting electrical signals and the corresponding CM results are shown in Figure 3.



(a) Electrical signals



(b) CM results

Figure 3: Simulation and CM of generator rotor winding faults

Figure 3(a) shows that both the inter-turn and open-circuit faults that occur in the rotor significantly distort the time-waveforms of stator current signals, but have less of an effect on the time-waveforms of stator voltage signals. This is because the generator voltage is mainly dominated by the grid's voltage, whereas the generator stator current is a different matter. The generator stator current is not only dependent on the generator's external load and operational condition, but on its actual health status. Researchers also noticed that the total power signal appears in direct current (DC) form when the generator is healthy and without any winding defect, and appears in alternating current (AC) form time-waveforms in the presence of either inter-turn or open-circuit winding faults. In addition, researchers found that the power signals that were collected in two fault scenarios show distinctly different pattern features, for example, the power fluctuates slowly along time in the presence of an inter-turn fault, but fluctuates quickly in the presence of an open-circuit fault. The similar phenomena can

also be observed from the time-waveforms of the current signals. The two types of rotor winding faults have different characteristic frequencies in generator electrical signals. This could be important information, not only to the generator's CM but also to its fault diagnosis.

Figure 3(b) shows that all three proposed CM criteria are aware of the presence of both types of rotor winding faults, although the faults display different variation characteristics in different scenarios. The CM results shown in Figure 3b prove that the winding faults that occur in the generator rotor will:

- Disturb the zero-crossing behavior of generator stator current signal (characterized by criterion δ)
- Change the circuit impedance of the generator (characterized by criterion r)
- Cause load imbalance to the generator (characterized by criterion e).

Winding faults in stator

The inter-turn and open-circuit faults are simulated in the stator of the generator by setting the resistance in its second phase to $R_3=1.16e-4\Omega$ and $R_3=1.16e-2\Omega$. The electrical signals and corresponding calculation results of CM criteria are shown in Figure 4.

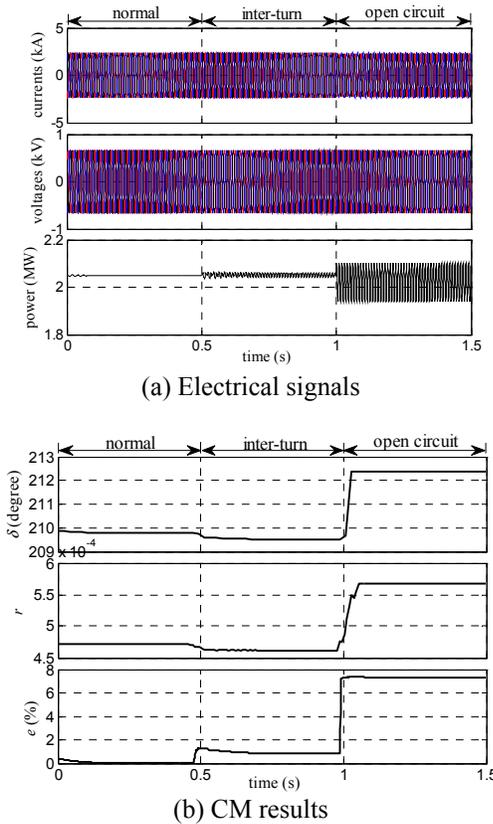


Figure 4: Simulation and CM of generator stator winding faults

Figure 4(a) shows that, compared to the winding faults that occur in the generator rotor, both inter-turn and open-circuit faults that occur in the generator stator do not have a significant effect on the time-waveforms of stator current and voltage signals. However, like a generator rotor winding fault, they create a load imbalance in the generator, which is characterized by the AC form of power signal.

Figure 4(b) shows that all three proposed CM criteria are equally sensitive to both types of stator winding faults. For example:

- An inter-turn circuit fault decreases the value of criterion δ , while an open-circuit fault increases it. This finding further supports the phase shift phenomena of the current signal shown in Figure 1.
- An inter-turn circuit fault decreases the circuit impedance of the generator, while an open-circuit fault increases it.
- Both inter-turn and open-circuit faults change the pattern depicted by Park's vector (i_d, i_q) , thus changing criterion e .

VERIFICATION EXPERIMENTS

The verification experiments were conducted on a 30-kilowatt (kW), three-phase, four-pole induction generator, which was driven by a 54-kW, DC-variable speed motor through a two-stage gearbox with a gear ratio of 1:5. To emulate faults, the rotor circuit of the generator was coupled to an externally connected, three-phase resistive load bank (see Figure 5). As a result, electrical asymmetry could be readily applied to the generator rotor by adjusting the phase resistances of the load bank. The test rig was instrumented and controlled using LabVIEW, allowing researchers to apply a variety of wind speed inputs to the test rig via the DC motor. The rotational speed of the DC motor was controlled by a mathematical model that incorporates the properties of natural wind at different wind speeds and the mechanical behavior of a 2-MW wind turbine operating under closed-loop control conditions. More details about this test rig are provided in [10]. In the experiment, both fixed and variable rotational speeds were applied to the DC motor and generator to verify the capabilities of the three proposed CM criteria under various loading conditions.

Researchers verified and applied the CM criteria when monitoring the generator at a fixed rotational speed of 1,750 revolutions per minute (rpm). In addition, researchers periodically applied a winding fault to the generator's rotor by repeatedly adjusting the phase resistances of the load bank. The electrical signals were collected from the generator terminals by using a sampling frequency of 5 kilohertz (kHz). The time-waveforms of the electrical signals and the corresponding CM results are shown in Figure 6. In the figure, normal represents electrical symmetry and abnormal represents electrical asymmetry.

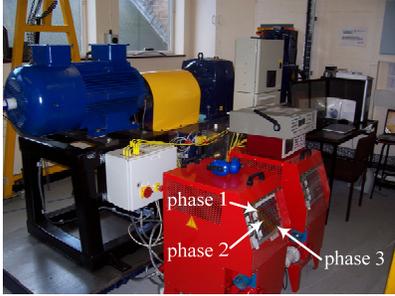
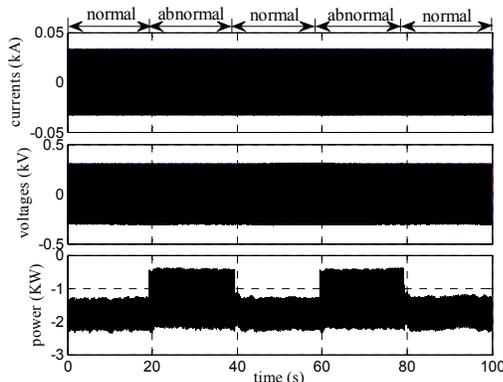
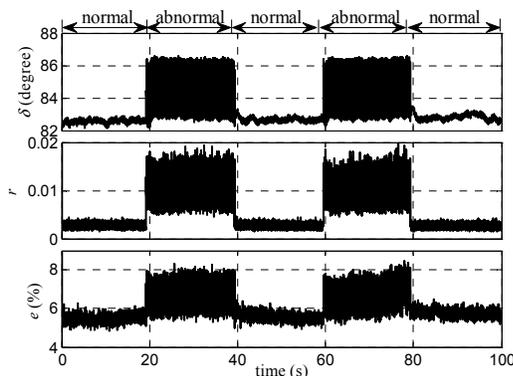


Figure 5: Test rig for conducting verification experiments (Source: Narec)



(a) Electrical signals



(b) CM results

Figure 6: CM when generator rotates at constant rotational speed

Compared to Figure 3(a), the emulated rotor winding fault shown in Figure 6(a) does not disturb the time-waveform of the stator current signal as anticipated. This is because the asymmetry that is introduced by the load bank is too small to be observable from the measured current signal. To confirm this, the current signal shown in Figure 6(a) was amplified 40 times. The amplified time-waveform of the current signal is shown in Figure 7, from which the waveform distortion that was caused by the asymmetry has already been clearly visible. So it is demonstrated, once again, that the winding fault that occurs in the induction generator's rotor distorts the time-waveform of its stator current signal. Compared to the effect of the winding fault on generator stator current signal, the effect of the

distortion on generator total power is much more significant. In Figure 6(a), a big distortion of generator power signal happens as soon as the fault occurs, and the power returns back to its normal waveform immediately when the fault goes away. This suggests that, in comparison to the stator current signal, the generator total power signal is more alert to the fault. This is why the generator power signal, rather than the stator current signal, was adopted in [6] for wind turbine condition monitoring, even though the majority of existing motor/generator CM techniques are based on the analysis of stator current signals [11].

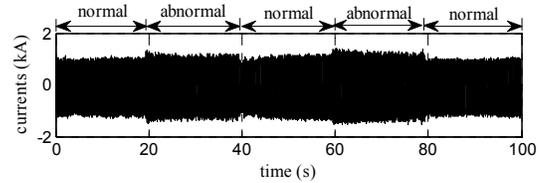
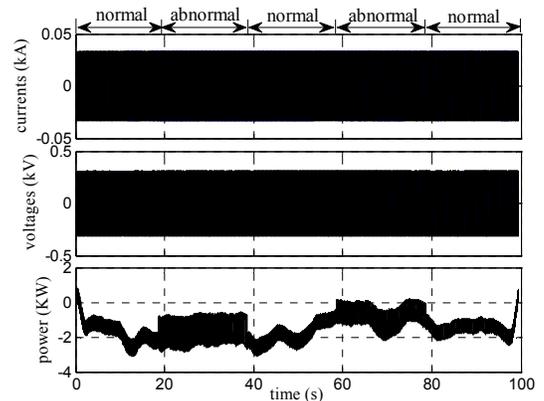


Figure 7: Amplified time-waveform of the stator current signal

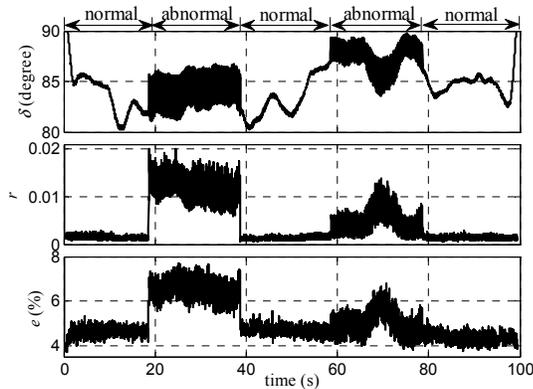
In Figure 6(b), the winding fault has been successfully detected by all three proposed CM criteria, although these criteria are developed based on the analysis of the stator current and voltage signals.

To further verify the CM capability of the proposed criteria under varying loading conditions, as observed from real wind turbines, researchers repeated the experiment when the DC motor was controlled to operate at constantly varying speeds. As part of this process, the electrical signals (i.e., stator current, voltage, and total power) were collected from the generator terminals by using the same sampling frequency of 5 kHz. The time-waveforms of these CM signals and the corresponding results are shown in Figure 8.

Figure 8(a) shows that, not only is the winding fault undetected by the time-waveforms of the stator current and voltage signals, but it is undetected by the generator power signal, due to the negative influence of varying loads. Nonetheless, the fault is detected successfully by using the three proposed CM criteria [see Figure 8(b)]. However, the result of criterion δ is not completely load-independent, therefore a de-trending process is necessary.



(a) Electrical signals



(b) CM results

Figure 8: CM when the generator rotates at a varying rotational speed

CONCLUSIONS

In this paper, researchers first discussed the influences of various types of winding faults on an induction generator. Three operational-condition-independent condition monitoring (CM) criteria were researched to achieve a reliable CM of a wind turbine generator that is usually subject to constantly varying loads. Based on this work, researchers came to the following conclusions:

- Winding faults that occur in a generator rotor will distort the time-waveform of the generator stator current signal, but the faults have less influence on the stator voltage signal.
- Compared to the stator current and voltage signals, the generator total power signal is more alert to the presence of generator faults.
- All three proposed CM criteria are able to successfully detect the generator winding faults, despite the loading conditions. However, experimental results indicate that criterion δ is not completely load-independent. Under varying loading conditions, an additional de-trending of the criterion could be necessary to further improve its fault detection capability.
- Experimental results suggest that different types of rotor winding faults show different characteristics in the stator current signal. This is potentially important information to both CM and fault diagnosis of the induction generator.

ACKNOWLEDGMENTS

The work described above was supported by the United Kingdom National Renewable Energy Centre (Narec) and

China Natural Science Foundation, with project reference number 51075331.

REFERENCES

- [1] Feng, Y., Tavner, P., Long, H., 2010, "Early experiences with UK Round 1 offshore wind farms," *Proceedings of the Institution of Civil Engineers: Energy*, **163**(4), 167–181.
- [2] Yang, Wenxian, Tavner, P., Crabtree, C., Feng, Y., Qiu, Y., 2012, "Wind turbine condition monitoring: Technical and commercial challenges," *Wind Energy*, In Press.
- [3] McMillan, D., Ault, G.W., 2007, "Quantification of condition monitoring benefit for offshore wind turbines," *Wind Engineering*, **31**(4), 267–285.
- [4] BVG Associates, 2011, "A guide to an offshore wind farm."
- [5] Yang, Wenxian, Court, R., Tavner, P., Crabtree, C., 2011, "Bivariate empirical mode decomposition and its contribution to wind turbine condition monitoring," *Journal of Sound and Vibration*, **330**(15), 3766–3782.
- [6] Yang, Wenxian, Tavner, P., Crabtree, C., Wilkinson, M.R., 2010, "Cost-effective condition monitoring for wind turbines," *IEEE Transactions on Industrial Electronics*, **57**(1), 263–271.
- [7] Cardoso, A.J.M., Saraiva, E.S., 1993, "Computer-aided detection of airgap eccentricity in operating three-phase induction motors by Park's vector approach," *IEEE Transactions on Industry Applications*, **29**(5), 897–901.
- [8] Nejari, H., Benbouzid, M.E.H., 2000, "Monitoring and diagnosis of induction motors electrical faults using a current Park's vector pattern learning approach," *IEEE Transactions on Industry Applications*, **36**(3), 730–735.
- [9] Xiang, D., Ran, L., Tavner, P., Yang, S., 2006, "Control of doubly fed induction generator in a wind turbine during grid fault ride-through," *IEEE Transactions on Energy Conversion*, **21**(3), 652–662.
- [10] Yang, Wenxian, Tavner, P., Court, R., "An online technique for condition monitoring the induction generators used in wind and marine turbines," *Mechanical Systems and Signal Processing*, In Press.
- [11] Tavner, P., 2008, "Review of condition monitoring of rotating electrical machines," *IET Electric Power Applications*, **2**(4), 215–247.