APPROPRIATE MEANS OF FREQUENCY MEASUREMENT FOR THE PROVISION OF INERTIAL RESPONSE FROM A WIND TURBINE

A. Giles, *University of Strathclyde, UK*
A. Roscoe & O. Anaya-Lara, *University of Strathclyde, UK*

ABSTRACT

A means of manipulating the power output of an individual wind turbine has been developed at the University of Strathclyde. This model takes into account the wind turbine dynamics. However, in order to enable such a control strategy to provide inertial response, the system needs to be coupled to control systems that monitor a power system. For inertial response, it is important that the wind turbine control strategy be made aware of changes in the power system as quickly as possible such that a change in power output (akin to inertial response) can be delivered in less than 200ms. This work focuses on monitoring power system frequency.

NOMENCLATURE

PCC	Point of common coupling
FRC	Fully Rated Converter
DFIG	Doubly-Fed Induction generator
SRF-PLL	Park transform phase-Locked loop
VCC	Vector-current control
PAC	Power adjusting controller
VSC-HVDC	Voltage-source converter
MMC	Modular-Multilevel-Converter
SOGI	2nd Order Generalised Integrator
f	System frequency
df/dt	Rate of change of frequency
H	System inertia
ΔP	Power imbalance
G(s)	SOGI transfer function
s	Complex argument
v_i	Voltage of phase i ($i = a,b,c$)
θ	Voltage phase (a)

1. INTRODUCTION

The UK is obliged to produce 20% of its total energy consumption from renewables by 2020. It is expected that the dominant contributor towards meeting this target will be wind turbines. The means by which a wind turbine exports power onto a power system is fundamentally different from the means by which a synchronous generator in a coal plant exports power onto a power system. A consequence of such is that the stability of the power system is reduced as more wind turbines offset conventional generator units such as coal and gas plants. Methods to boost system stability have been explored; these are covered in references [1-3]. However, these do not address the issue of measuring the status of a power system accurately and quickly.

This work investigates the measurement of power system frequency changes/power imbalances, with a long term aim towards demonstration of inertial response from an offshore wind farm connected via a HVDC link. Whilst this is an electrical control problem, solutions must take account of the aero-mechanical aspects of a wind turbine.

2. INERTIAL RESPONSE FROM A COAL PLANT

Classical power systems contained power plants whose electrical power was produced using the combination of fossil fuels, turbine systems and synchronous generators. In the UK, the power system frequency is nominally 50Hz. Because the mechanical torque produced in the rotor of a synchronous generator in a coal plant can be controlled, the synchronous generator can be directly coupled to the power system. Were it not controllable, the frequency of the electricity produced by the generator would be time-variant and a synchronous power system would not be possible. Of course, even with control mechanisms, the frequency of electricity produced by directly coupled synchronous generators is time invariant; this is because control mechanisms cannot react quickly enough to changes in the power system status. However, these changes are only small, so the magnitude of the changes in the frequency of such a generator is typically very small.

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Changes in the power system frequency are linked to the power imbalance between that being generated by the power plants and that being consumed by the load as expressed in equation 1:

$$\frac{df}{dt} = \frac{f\Delta P}{2H}$$

Inertia can be thought of as a form of energy storage; by virtue of the fact that the rotor in a synchronous generator is rotating, it has rotational kinetic energy. When the mechanical torque being applied by the prime mover is less than the electrical torque demanded at the stator windings, the rotational kinetic energy of the rotor is released, causing a reduction in the rotor speed and so a reduction in the frequency of the electrical power generated. Governor response is later employed to increase the mechanical torque supply and prevent a further reduction of the frequency. Equally, when the mechanical torque exceeds the electrical torque demand, the rotor speed increases, driving the frequency up.

3. INERTIAL RESPONSE FROM A WIND TURBINE

In the case of a wind turbine, the prime mover is driven by the power in the wind. The standard topology of a modern wind turbine from an aero-mechanical perspective is a pitch-regulated variable-speed horizontal axis wind turbine. Variable-speed operation refers to the fact that the rotor speed is varied as the wind turbine attempts to alleviate mechanical loads and increase energy capture. That being said, the rotor speed cannot be allowed to vary to such an extent that a natural mode of a component of the wind turbine is excited. Coupled with this are limitations on rotor speed imposed by noise considerations (for offshore this is not a constraint).

Of course, variable-speed operation implies that the generator rotor speed is time-variant. Consequently, for the overwhelming majority of modern wind turbines, the generator cannot be directly coupled onto the power system. Such a topology is shown in figure 1:

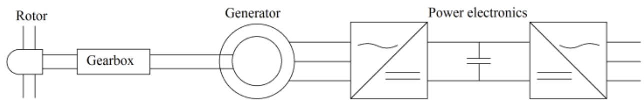

Figure 1: Common topology of modern wind turbines; the gearbox may or may not be present [4].

The exception to the rule is a wind turbine which employs hydraulic transmission systems to connect the turbine rotor to the generator rotor, such that the torque applied to the generator rotor is controlled. An example of such a turbine to employ a hydraulic transmission system is the Mitsubishi Sea Angel.

If it is assumed that a hydraulic transmission system is not employed, as is the case in the overwhelming majority of modern wind turbines, then the synchronous generator is connected to a transmission network via power electronics. For completeness, it is noted that induction generators are also featured in some wind turbines; these are DFIGs. However, the wind industry is moving towards topologies which employ synchronous generators. As such, future investigations into inertial response from wind farms by the authors will be constrained to FRCs.

The power electronics ensure that a signal compliant with the grid codes is exported onto the transmission power system. Synchronization with the power system is typically achieved using a PLL. By employing power electronics to export power onto the power system, which are controlled by a PLL coupled with the popular VCC, the wind turbine's output is not influenced by the status of the power system in the same manner as, say, a synchronous generator in a coal plant is. To be more specific, it does not provide inertial response. Rather, the power output of a wind turbine is defined by its central controller whose objective, from a power generation perspective, is to follow the black curve shown in figure 2:

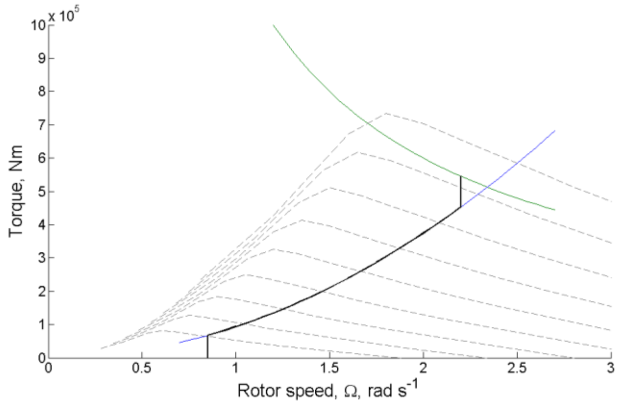

Figure 2: Torque-rotor speed diagram for a pitch-regulated variable speed wind turbine.

Consequently, as more wind turbines are integrated into the power system, the total system inertia is reduced. By equation 1, there is a bigger swing in frequency for a given power imbalance when the inertia is reduced. This is demonstrated in figure 3:

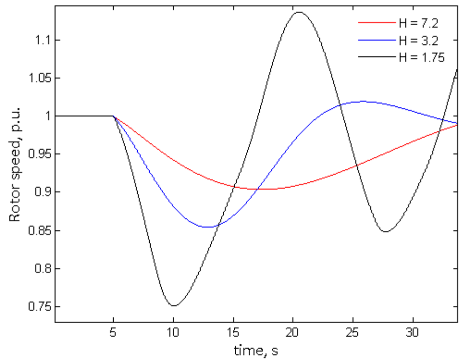

Figure 3: Influence of reducing the system inertia on frequency stability

As a result, multiple means of providing inertial response from a wind turbine have been developed in order to restore system stability. For completeness, these can be found in references [1-3]. However, some of these control strategies are specific to DFIGs, and so are not considered. The most appealing of those applicable to FRCs is [1]. This is because of the author's consideration of the interference between an external controller, whose aim is to manipulate the power output of a wind turbine, and the central controller of the wind turbine, which is of particular relevance in below-rated operation.

Clearly, providing synthetic inertia from a wind turbine operating below rated power will cause rotor speed (turbine sense) variations which will be viewed as disturbances by the central controller. The central controller will then attempt to eliminate the disturbance, modifying the torque demand at the generator-side converter, thus negating the provision of synthetic inertia. In [1], dummy signals are used to 'fool' the central controller into believing that there is no change in rotor speed during the provision of inertial response. In addition, relative to other control strategies such as [3], the energy capture of the wind turbine is not significantly reduced.

A block diagram of the controller, named the PAC, is presented in figure 4:

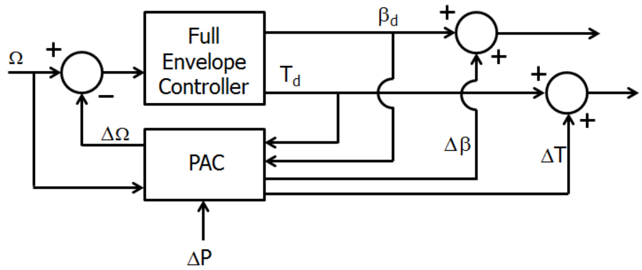

Figure 4: Block diagram of the PAC.

The input into the PAC is the change in power output, ΔP, required from the wind turbine by the power system. Other methods accept measurements of system frequency, or changes in system frequency. By equation 1, the two are equivalent.

4. MONITORING THE STATUS OF A POWER SYSTEM

The logical step in following on from this work would be to assess the ability of an offshore wind farm to provide inertial response. Offshore wind farms are of particular importance due to the amount of power that they will be exporting onto the power system, and indeed their potential to provide additional power if needed (studies show that the large wind turbines that will be found in offshore wind farms are better suited to the provision of inertial response). Of course, a wind farm has added complexity such as the influence of wake effects: manipulating the power output from a wind turbine will influence its wake, which would, at some later time, influence the performance of a wind turbine operating downstream of the first wind turbine. However, the length of time that is required for a change in the wake brought about by manipulating the

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performance of the front wind turbine is sufficiently long that, for inertial response investigations, the wake can be treated as frozen.

To demonstrate inertial response from an offshore wind farm, the first task is a proper investigation into how does one measure frequency changes or power imbalances both accurately and quickly (it must be measured and delivered to the PAC and the power exported onto the power system within 200ms of an event beginning). This work focuses on this issue.

An offshore wind farm located far offshore, for economic reasons, will most likely be connected to a mainland power system by a VSC-HVDC link. Indeed, such links are already found in real life systems, such as SAPEI, a transmission system connecting Sardinia with the Italian mainland.

Using a HVDC transmission system means that the power system status is potentially measured far from the location of the wind turbines, and fed-forward to the offshore wind farm. Optical fibres can be employed to ensure fast relaying of measurements made on mainland.

Four methods of power system status monitoring have been considered in this work: the first is zero-crossing; the second is the use of a SOGI; the third is with a SRF-PLL; and the forth is a PMU.

4.1 ZERO-CROSSING METHOD

This method is the simplest of all; the frequency is inferred from measuring the time between crossing events. However, such a method is highly sensitive to noise in a signal. High frequency content in a signal can lead to incorrect frequency measurements. Such a method is not widely used.

4.2 SOGI

A control system known as the SOGI is used for grid-synchronization. An illustration of such is presented in figure 5:

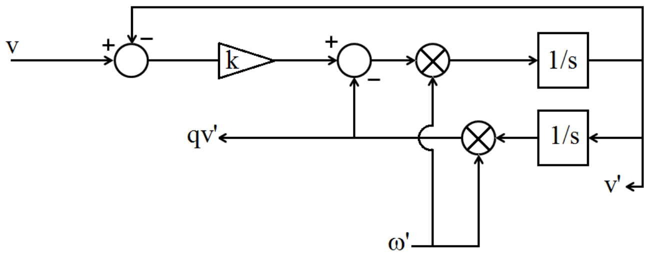

Figure 5: Block diagram representation of a SOGI [5]

The transfer function of the SOGI can be expressed as follows [6]:

$$G(s) = \frac{\omega' s}{s^2 + \omega'^2}$$

The important feature to note is that the SOGI has a resonant characteristic. That is, if the input signal is decomposed into its constituent frequency components, most of the frequencies will be attenuated whilst one will be amplified. This can be seen from equation by letting the input frequency equal the resonant frequency of the SOGI.

When a single-phase is used as the input, the output of the SOGI is two orthogonal signals. This is when only one voltage is used as the input. For this reason, SOGI systems have been popular in single-phase systems.

Naturally, the resonant frequency of the SOGI needs to be frequency adaptive; were it not, it would not be able to function properly. As such, a frequency-locked loop is coupled to a SOGI as was implemented in [5]. This gives rise to the following structure:

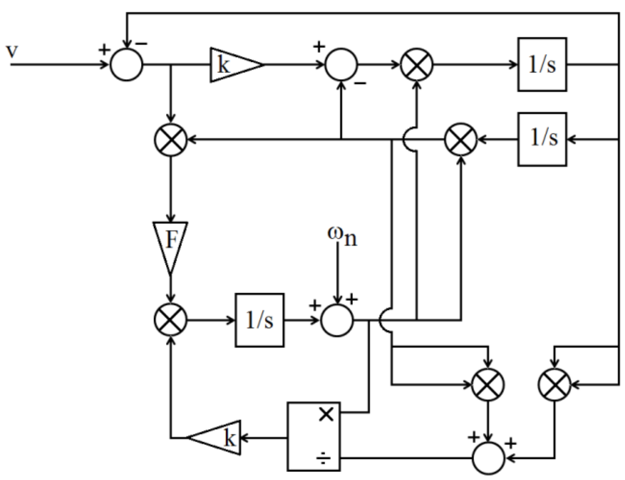

Figure 6: Block diagram representation of SOGI-FLL [5]

The gains of this control system were as recommended by the paper from which this measurement technique was taken. Note that in simulations, the integrators were discrete-time integrators using the forward Euler technique.

4.3 SRF-PLL

The dominant control strategy employed is VCC following the success of its application in DFIG wind turbines and other devices featuring power electronics.

As with the wind turbine, a VCC control strategy applied to a HVDC link requires the use of a PLL in order to achieve synchronism with the power system. Typically, SRF-PLL systems are used.

The SRF-PLL operates in the dq0 frame, a rotating reference frame. The transformation of a three-phase voltage from a stationary reference frame (abc) to the dq0 frame is given by equation 3:

$$\begin{pmatrix} v_d \\ v_q \\ v_0 \end{pmatrix} = \boldsymbol{T} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}$$

where

$$\boldsymbol{T} = \begin{pmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{pmatrix}$$

The control objective of the PLL is to establish the angle θ such that the component v_q is nominally zero. When such an objective is met, the PLL is phase-locked with the power system voltage at the PCC. This, by extension, allows a measurement of frequency to be made. A block diagram of a PLL is presented in figure 7:

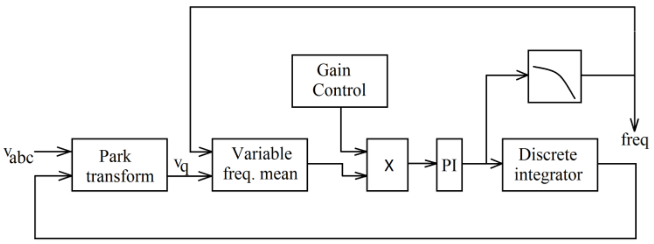

Figure 7: Block diagram of PLL

4.4 PMU

A pure sinusoid may be described completely by its amplitude and phase. A phasor is a complex quantity which is such. Of course, since it operates on pure sinusoids, in power systems it is chosen to operate on the fundamental frequency component. The use of phasors in synchronization and frequency tracking has recently gained a significant amount of interest. Phasor estimation of a signal is usually achieved using the discrete Fourier transform [7].

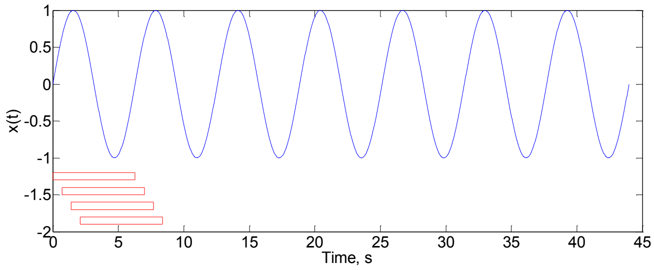

Figure 8: Moving window (red box) used for discrete Fourier transform.

A single phase PMU device is illustrated in figure 9:

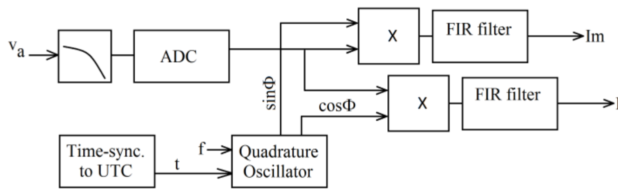

Figure 9: Single phase PMU [8]

This concept can be developed into a three-phase system with fault tolerance. Such a system is illustrated in figure 10:

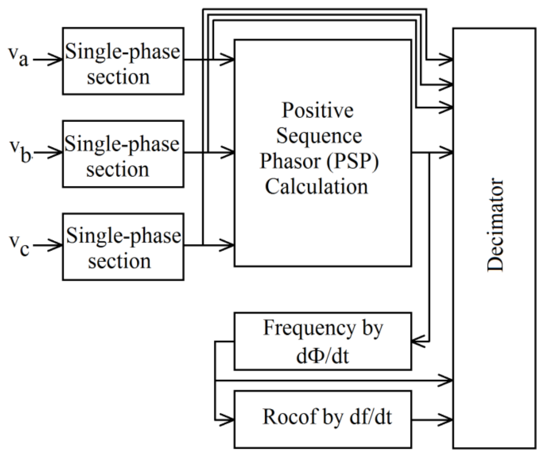

Figure 10: Three-phase PMU [8].

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PMUs can be split into two classes: M-class and P-class. The difference between the two is the structure of the filters. In a P-class PMU, a fixed-length triangular-weighted symmetric filter of length 2 cycles is used. In an M-class PMU, a fixed-weight filter is used with a substantially greater length than found in a P-class PMU. Further details can be found in [8].

4.5 COMPARISON OF METHODS

Using MATLAB, two simulations were conducted with the first using a simple power system model to assess the different frequency measurement algorithms. The simplicity of the model did mean that there was no harmonic content in the system, which favours the performance of the zero-crossing method. An illustration of the simulation is provided in figure 11:

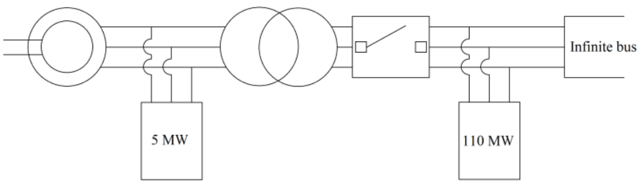

Figure 11: Simulation setup.

At 25s, an islanded system is formed whereby the only means of powering the load is by the synchronous generator. Figures 12 and 13 illustrate the performance of all the methods under such an event:

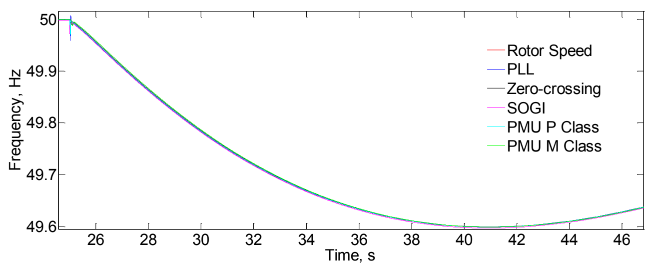

Figure 12: Frequency tracking performance of the discussed algorithms when an island is formed.

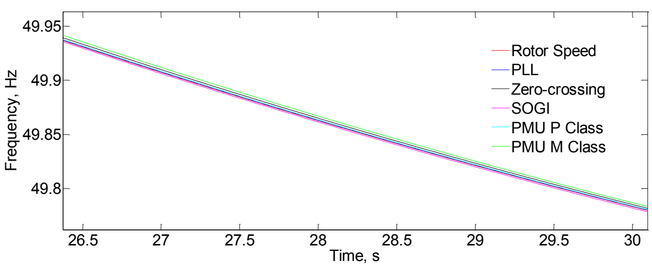

Figure 13: Close-up of figure 11.

From above, it can be seen that all algorithms are in agreement. However, as already stated, the power system setup is an ideal system.

In light of the simplicity of the first simulation, a second test was conducted whereby a fault was applied, using real data corresponding to a fault event in the West of Scotland.

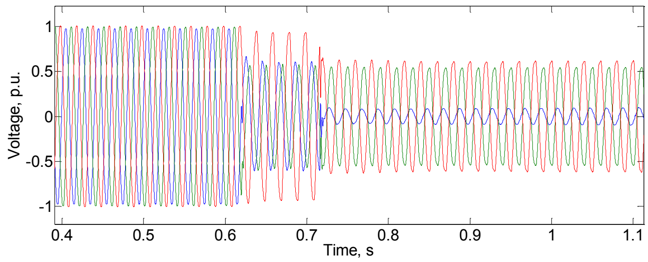

Figure 14: Voltage waveforms during fault.

The performance of the different algorithms during the fault has been split into two graphs. This is because the SOGI-FLL was found to be highly sensitive to the fault and made observations of the performance of the other methods difficult.

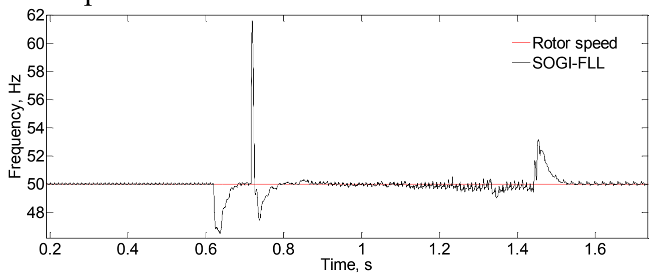

Figure 15: Performance of the SOGI-FLL during the fault

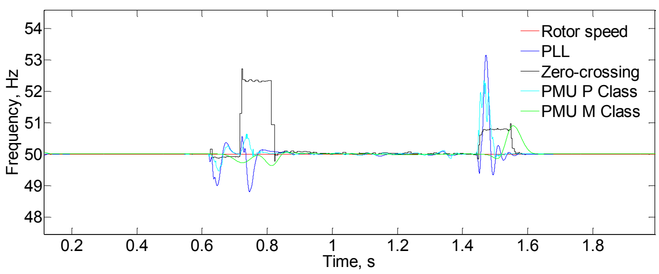

Figure 16: Performance of all other algorithms during the fault.

5. CONCLUSIONS

Frequency tracking has been investigated using a number of algorithms. The sensitivity of the algorithms was tested by subjecting them to a fault. It was found that the frequency-adaptive SOGI performed worst in the event of a fault. In terms of

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percentage error, the M Class PMU performed with the best accuracy in the fault study, suggesting it would be the preferable means of frequency tracking. Further improvements could be made using a multitude of locations for frequency measurement in order to provide robustness against faults.

ACKNOWLEDGEMENTS

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