Fault Isolation in Parallel Coupled Wind Turbine Converters

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***Abstract*— Parallel converters in wind turbine give a number advantages, such as fault tolerance due to the redundant converters. However, it might be difficult to isolate gain faults in one of the converters if only a combined power measurement is available. In this paper a scheme using orthogonal power references to the converters is proposed. Simulations on a wind turbine with 5 parallel converters should a clear potential of this scheme for isolation of this gain fault to the correct converter in which the fault occurs.**

I. INTRODUCTION

As wind turbines increase in sizes and more wind turbines are installed offshore, the need for fast fault detection and accommodation increases. It is clearly preferable to detect occurring faults before they results in large faults and turbine break downs. It is even more beneficial if the wind turbine can be reconfigured in such a way that operation of the wind turbine can be continued even though it might be at lower rated power until next service of the wind turbine.

The purpose of a wind turbine is to convert wind energy to electrical energy. In this paper a three blades with a horizontal axis turbine is considered. The blades are facing the wind direction; these blades are connected to the rotor shaft. The wind acts on the blades and thereby rotating the shaft. A gear box is used to upscale the rotational speed for the rotor in the generator and converter.

In order to decrease the energy production costs and improves reliability fault detection, isolation and accommodation in wind turbines are of high importance. From a control point of view the wind turbine is operating by two controllers with different sample times, they are: wind turbine control and power electronics control.

Most faults in the converter are detected at best in the converter control system. In terms of fault detection in the wind turbine converters some examples are presented in [5], [6], [7] and [3].

One of the new trends in wind turbine designs is to use a number of converter, these are in the following denoted as power units operated in parallel with the same power reference, e.g. see [1]. A fault in the control of one of the power units might be difficult to detect internally in the power electronic controls, especially if only one power measurement is performed as combined one for the entire converter system.

In [4] frequency analysis of voltage measurements in parallel converters is presented. Another example of fault detection on a multi cell converter system used in a hybrid vehicle is presented in [2]. [8] presents some work on fault management in a parallel converter.

In this paper it is proposed to use additional orthogonal reference signals to each of the parallel converters to detect multiple faults in the converter control. The same references are subsequently convoluted on to the power measurements from eventually faults can be isolated to a specific converter.

The system is described in Section II, followed by the method description in Section III. In Section IV the simulation model is presented, and the simulation of the proposed scheme on this model is presented in Section V. Finally a conclusion is drawn in Section VI.

II. SYSTEM DESCRIPTION

The wind turbine converter system consists of a converter stack of more than one power unit, even or uneven. Notice that the power unit contains all three electrical phases. A specific example is considered consisting of 5 power units, as illustrated in Fig. 1. The system consists of a "Stack Control", 5 Power units, and Power Measurement unit. P_{ref} is the power reference to the entire converter system, $P_{\mathrm{ref},1}$, $P_{\mathrm{ref},2}$, $P_{\mathrm{ref},3}$, $P_{\mathrm{ref},4}$, $P_{\mathrm{ref},5}$ are the respectively power references to the 5 power units. P is the produced power, and P_{meas} is the measured power. Stack Control divides P_{ref} into the 5 references to each power unit.

III. FAULT ISOLATION USING ORTHOGONAL POWER REFERENCES

This scheme consist of two parts, in the first additional orthogonal power reference signals are generated and added to the power reference to each power unit, and in the second these orthogonal references are convoluted with the $P_{\mathrm{meas}}[n]$, which results a detection and isolation if one of the power units is not following the given reference. In case of no faults $P_{\mathrm{meas}}[n]$ would follow $P_{\mathrm{ref}}[n]$, in case of a fault in

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one power unit the orthogonal power reference to faulty power unit would be seen in$P_{\text{meas}}[n]$.

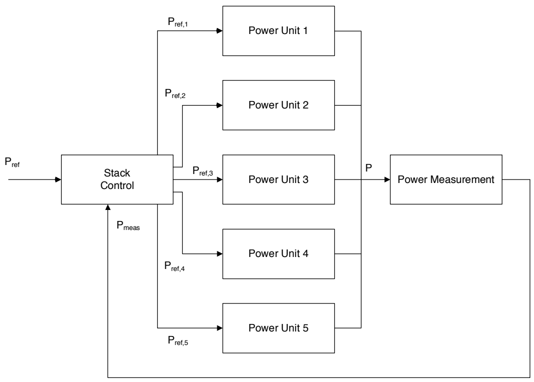

Fig. 1 An overview of the power electronic converter system in dealt with in this paper.

A. *Generation of orthogonal references*

The most basic way of dividing $P_{\text{ref}}[n]$ into $P_{\text{ref},1}[n]$, $P_{\text{ref},2}[n]$, $P_{\text{ref},3}[n]$, $P_{\text{ref},4}[n]$, $P_{\text{ref},5}[n]$ is given by

$$\begin{aligned} P_{\text{ref},1}[n] &= \frac{P_{\text{ref}}[n]}{5}, \\ P_{\text{ref},2}[n] &= \frac{P_{\text{ref}}[n]}{5}, \\ P_{\text{ref},3}[n] &= \frac{P_{\text{ref}}[n]}{5}, \\ P_{\text{ref},4}[n] &= \frac{P_{\text{ref}}[n]}{5}, \\ P_{\text{ref},5}[n] &= \frac{P_{\text{ref}}[n]}{5}, \end{aligned} \tag{1}$$

In this isolation scheme $P_{\text{ref}}[n]$ is separated into a part divided by the basic way, $\tilde{P}_{\text{ref}}[n]$, and a part given by orthogonal references to each power unit, $\hat{P}_{\text{ref}}[n]$.

The point is to use an orthogonal separation with a constant sum such that power follows the request at all time. Meaning that

$$\hat{P}_{\text{ref}}[n] = \sum_{i=1..5} \hat{P}_{\text{ref},i}[n] = k, \tag{2}$$

In which k is constant (power), chosen small in relation with maximal power reference. This also means that

$$P_{\text{ref}}[n] = \hat{P}_{\text{ref}}[n] + \tilde{P}_{\text{ref}}[n]. \tag{3}$$

The task is subsequently to construct orthogonal $\hat{P}_{\text{ref},i}[n]$s such that (2) is fulfilled.

An example of such a set of references is given by

$$\hat{P}_{\text{ref},1} = \left[1_{(L/2),1} 0_{(L/2),1}\right], \tag{4}$$
$$\hat{P}_{\text{ref},2} = \left[0_{(L/2),1} 1_{(L/4),1} 0_{(L/4),1}\right], \tag{5}$$
$$\hat{P}_{\text{ref},3} = \left[0_{(3\cdot L/4),1} 1_{(L/8),1} 0_{(L/8),1}\right], \tag{6}$$
$$\hat{P}_{\text{ref},4} = \left[0_{(7\cdot L/8),1} 1_{(L/16),1} 0_{(L/16),1}\right], \tag{7}$$
$$\hat{P}_{\text{ref},5} = \left[0_{(7\cdot L/8),1} 0_{(L/16),1} 1_{(L/16),1}\right], \tag{8}$$

and is shown in Fig. 2 - Fig. 6. The set of references could be constructed in other ways.

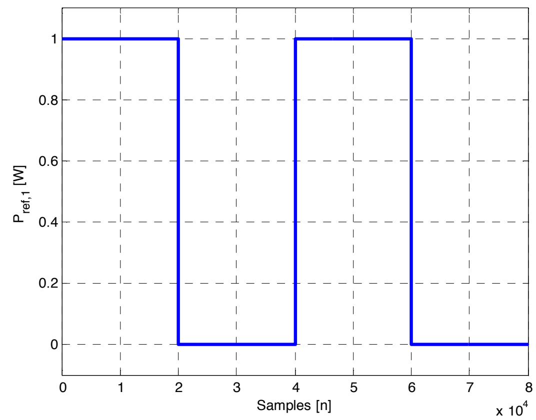

Fig. 2 $\hat{P}_{\text{ref},1}[n]$ in the example orthogonal reference set.

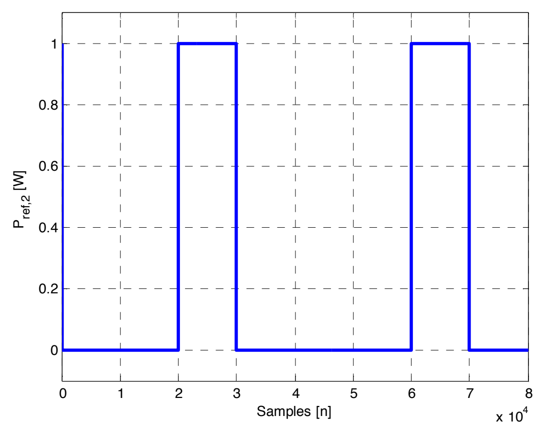

Fig. 3 $\hat{P}_{\text{ref},2}[n]$ in the example orthogonal reference set.

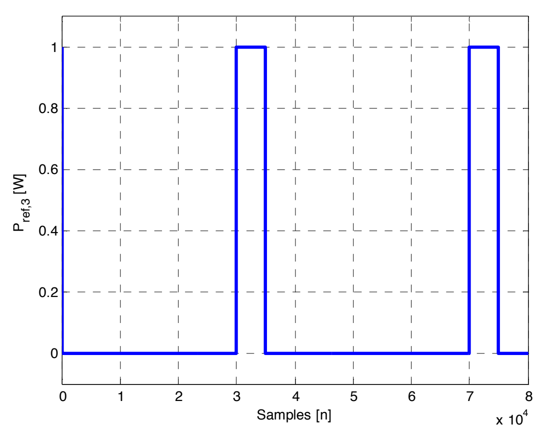

Fig. 4 $\hat{P}_{\text{ref},3}[n]$ in the example orthogonal reference set.

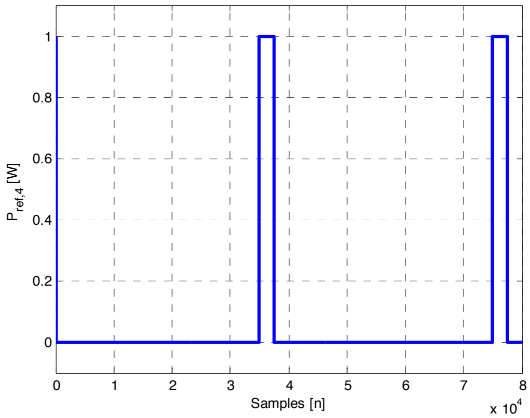

Fig. 5 $\hat{P}_{\mathrm{ref},4}[n]$ in the example orthogonal reference set.

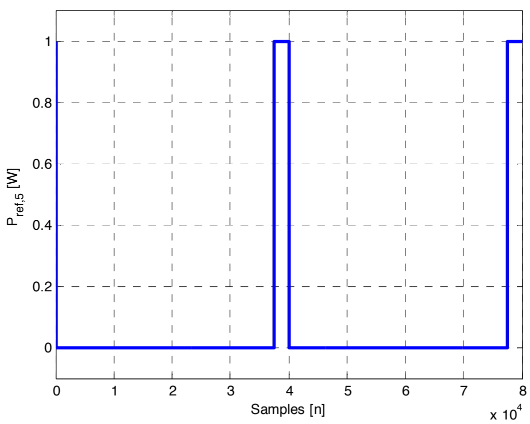

Fig. 6 $\hat{P}_{\mathrm{ref},5}[n]$ in the example orthogonal reference set.

In this set of orthogonal references each power unit is not activated with the same time periods, meaning that they are not loaded equally, which could be of interest. In that case a sequence of orthogonal reference signals for each power unit is given by:

$$\hat{P}_{\mathrm{ref},i} = \left[0_{((i-1)\cdot L)/5,1} 1_{L/5,1} 0_{((5-i)\cdot L)/5}\right], \qquad (9)$$

In which L is the number of sample in one period of the reference sequence.

B. *Detection and Isolation of Power unit Faults*

The isolation of a fault in a power unit is given by a multiplication between a vector of interval of $P_{\mathrm{meas}}[n]$ and $\hat{P}_{\mathrm{ref},i}$.

Now define an isolation signal, γ, for each power unit. It is normalized with the power reference in order to compute a unit size isolation signal.

$$\gamma_i = \frac{1}{P_{\mathrm{ref}}[n]} \cdot \left[P_{\mathrm{meas}}[n-L+1] \cdots P_{\mathrm{meas}}[n]\right] \cdot \hat{P}_{\mathrm{ref},i}, (10)$$

Where $i \in \{1 \cdots 5\}$.

A power unit fault is detected and isolated if the corresponding power unit is active at the specific time and that $\|\gamma_i[n] - 1\| > \epsilon$, in which ϵ is a threshold found based on consideration on the ratio between false positive detections and false negative detections and isolations.

IV. SIMULATION MODEL

The isolation scheme is simulated on a full model of a three blade horizontal axis turbine which. It is controlled in two regions: in partial load of the wind turbine it is controlled to generate as much power as possible, this is achieved by keeping a specific ratio between the tip speed of the blades and the wind speed, which in turn is obtained by controlling the rotational speed through adjusting the power unit torque. In the full power region the power unit torque is kept constant and the rotational speed is adjusted by controlling the pitch angle of the blades which changes the aero-dynamical power transfer from wind to blades. This part of the wind turbine is illustrated in Fig. 7.

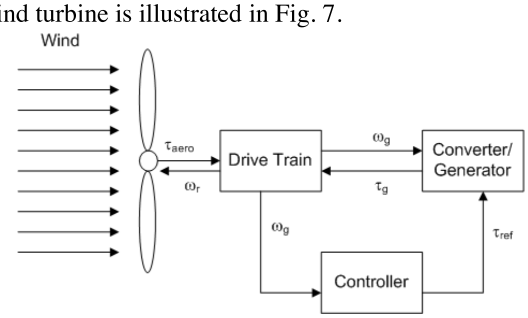

Fig. 7 Illustration of the principle of the wind turbine drive train. For illustrative purposes only two of the three blades are shown.

The wind turbine drive train in question has a number of measurements. $\omega_r[n]$ is a measurement of the rotor speed, $\omega_g[n]$ is a measurement of the generator speed, $\tau_g[n]$ is the torque of the generator controlled by the power unit which is provided with the torque reference, $\tau_{ref}[n]$.

A. *Model*

The model is first defined in continuous time and subsequently transferred to discrete time.

The aerodynamic model is defined as in (1)

$$\tau_{\mathrm{aero}}(t) = \frac{\rho A C_{\mathrm{p}}(\theta(t), \lambda(t)) v^3(t)}{2\omega_{\mathrm{r}}(t)}, \qquad (11)$$

Where ρ is the density of the air, A is the area covered by the turbine blades in its rotation, $\theta(t)$ is the pitch angle of the blades, $\lambda(t)$ is the tip speed ratio of the blade. (1) is used to estimate $\tau_{\mathrm{aero}}(t)$ based on an assumed estimated $v(t)$ and measured $\theta(t)$ and

A simple one body model is used to represent the drive train, see (12).

$$J_r\dot{\omega}_r(t) = \tau_r(t) - K_{dt}\theta_\Delta(t) - (B_{dt}+B_r)\omega_r(t) + \frac{B_{dt}}{N_g}\omega_g(t), \qquad (12)$$

$$J_g\dot{\omega}_g(t) = \frac{\eta_{dt}K_{dt}}{N_g}\theta_\Delta(t) + \frac{\eta_{dt}B_{dt}}{N_g}\omega_g(t) - \left(\frac{\eta_{dt}B_{dt}}{N_g^2} + B_g\right)\omega_g(t) - \sum_{i=1\ldots5}\tau_{g,i}(t), \qquad (13)$$

$$\dot{\theta}_{\Delta}(t) = \omega_r(t) - \frac{1}{N_g}\omega_g(t), \quad (14)$$

Where

$$\dot{\tau}_{g,i}(t) = p_{gen}(\tau_{\mathrm{ref,i}}(t) - \tau_{\mathrm{g,i}}(t)), \quad (15)$$

$$\tau_{ref,i}(t) = \frac{P_{ref,i}(t)}{\omega_g(t)}, \quad (16)$$

J_r is the moment of inertia of the low speed shaft, K_{dt} is the torsion stiffness of the drive train, B_{dt} is the torsion damping coefficient of the drive train, B_g is the viscous friction of the high speed shaft, N_g is the gear ratio, J_g is the moment of inertia of the high speed shaft, η_{dt} is the efficiency of the drive train, and $\theta_{\Delta}(t)$ is the torsion angle of the drive train. The fault in terms of lower drive train efficiency is model by another parameter η_{dt2}. p_{gen} is the generator model parameter. In addition measurement noise is added to the measurements, with relevant variances.

V. Results

The isolation scheme is applied on the described simulation of the wind turbine, with two faults in the power units. Power unit 1 has a gain factor of 1.01 and Power unit 4 has an offset at 10% of the power reference to the power unit. In the simulation the following reference was given to all power units:

$$\hat{P}_{\mathrm{ref},i}[n] = 2 \cdot 10^5\mathrm{w} \cdot \sin[n \cdot T_s] + 7 \cdot 10^5\mathrm{w}, \quad (17)$$

$\tilde{P}_{\mathrm{ref},i}[n]$ is described by (4)-(8) multiplied with a factor of $100\mathrm{kw}$.

The detection signals $\gamma_i[n]$ can be seen in Fig. , from which it can be seen that the fault in Power unit 1 is detectable and thereby isolable, while the offset fault in Power unit 4 is not detectable, and thereby not isolable. Consequently this test shows that the proposed scheme can detect and isolate gain errors in one of the power unit even though that only one combined power measurement is available.

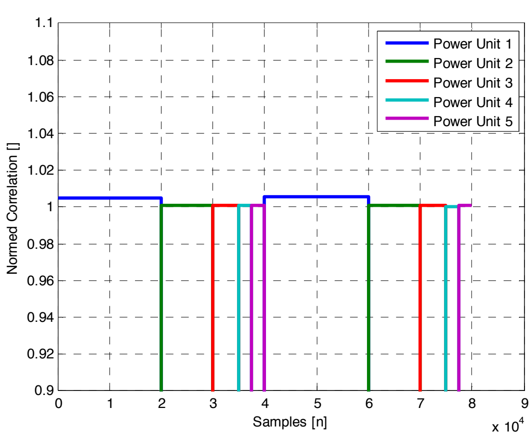

Fig. 8 Plot of $\gamma_i[n]$ for the 5 power units.

A. Offset Isolation

It is not possible to isolate an offset error to a specific power unit using these orthogonal references, the only possible way under these conditions is to switch off the power units one of the time and then determine which switch off removes the power offset. Consequently, the faulty power unit is detected.

VI. Conclusions

In this paper a scheme for detection of gain faults in parallel power units used in a wind turbine, with only one combined power measurement, is proposed using orthogonal references to each of the power units. Simulations on a model of a wind turbine with 5 parallel power units, shows the potential of this scheme in terms of isolating gain faults in the individual power units.

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