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Inertia Support During Variable Wind Conditions

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***Abstract*—Wind variations are important to consider while designing inertia support strategies. A model has been evaluated but the findings should reflect issues with several control strategies utilizing a fixed inertia support pattern.**

Wind variability of 0.5 m/s from second to second is observed in real wind data. However, drastic changes in wind speed can occur within the duration of inertia support.

An improved inertia control algorithm has been presented allowing a stable delivery of inertia support from variable speed wind turbines (VSWT) subjected to realistic wind conditions. The controller improves the previously presented inertia algorithm and smoothly transitions from a locked operation window to MPPT-operation.

The impact of the utilized wind speed filter is described and its impact on the simulation found to be of great importance.

I. INTRODUCTION

With an increasing wind power penetration in power systems there is an increasing need for regulation from variable speed wind turbines (VSWTs) to provide support in the form of spinning reserve and for reducing frequency instabilities in the power system. This need originates from the lack of inertia response provided by VSWTs in their basic configuration [1]. Inertia support from VSWTs have been studied in for example [2] and [3]. The latter describing the issues due to the shape of the inertia support and its implications. Several other papers also consider the wind speed to be constant during a fixed inertia support period [4]–[7] and [8].

In [9] a fixed support is utilized for the de-acceleration phase, while the responsibility of re-acceleration is given to the maximum power point tracker (MPPT, although called OPPT). After providing 0.017 pu extra inertia support, from a production level of 0.17 pu, this re-acceleration strategy causes the the active power to decrease by -0.05 pu during a large re-acceleration transient. This re-acceleration transient could cause a large impact on the power system, especially in systems with low inertia and/or high wind power penetration.

[10] considers a variable wind speed. However, the wind speed is barley varying (changes 0.5 m/s during the 20 s window presented). Furthermore, the re-acceleration of the turbine is preformed based on having a MPPT-rotational reference speed derived from wind speed measurement on the turbine. This wind speed measurement is at a specific point (usually behind the turbine) and might prove difficult to rely on during real wind variations.

[11] provides valuable knowledge based on operational experience with the implementation of ENERCONs inertia support (ENERCON IE). Findings from a PSS/E simulation show different ability to deliver inertia support depending on the operational point of the turbine. The paper concludes that future modeling needs to consider the stochastic nature of the wind during the inertia support strategy.

This paper aims to evaluate the possible wind variance subjected to wind turbines when utilizing inertia support functions. The impact on wind variations on existing controllers is discussed and a solution is presented. The power response of the VSWT are studied under the assumption of constant wind and the impact if replaced with variable wind, ensuring the usability of previously mentioned papers. Furthermore, an improved controller is evaluated towards variable wind speed verifying its usability. Finally, conclusions and recommendations for future work are presented.

II. METHOD

A. Wind speed data

Wind speed data was acquired from measurements at Sheringham Shoal Offshore Wind Farm. The anemometer was installed at a mast at a height of 80 m where wind speed measurements were acquired at a sampling rate of 1 Hz. The wind speeds are then transferred to a hub height of 90 m (though it is site dependent) of the GE 3.6 MW turbine modeled by using the Hellmann approach [12] seen in (1) using α=0.11.

$$v_{wind,h} = v_{wind,ref} \left(\frac{h}{h_{ref}} \right)^{\alpha} \tag{1}$$

Where $v_{wind,h}$ is the wind speed at height h, $v_{wind,ref}$ is the wind speed at the measured height h_{ref} and α is the Hellmann exponent. Wind speeds averaged for a duration of 1000 s are extracted between 8.0 m/s to 11.2 m/s. This extraction results in 16 wind speed sessions used for evaluating variation in wind speed.

1) Wind speed filter: The wind does not hit the wind turbine identically across the swept area. Therefore, the wind speed is averaged out across the swept area of the rotor utilizing a linear filter $H_{\psi,0}(s)$ obtained from [13] that considers the power spectral density in the wind. Effort from the authors of [13] has been made to indirectly verify the model by wind measurements, power measurements and simulated power out-

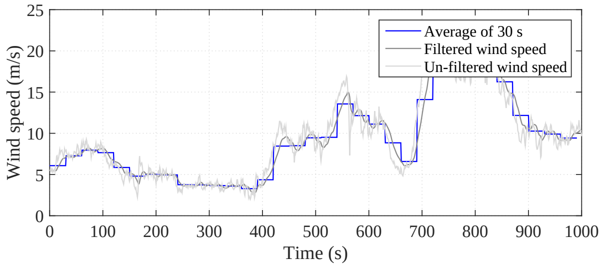


Fig. 1. Wind speed data, filtered and un-filtered, at Shoal wind power station during one wind speed session out of the 16 evaluated. The one wind speed session contains 33 averages of 30 s each.

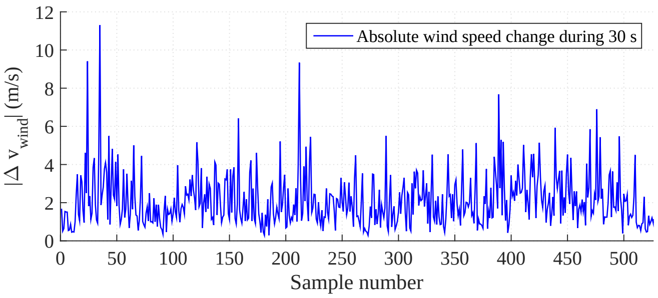


Fig. 2. The absolute change in wind speed during 30 s for all 16 evaluated wind speed sessions.

put. The model is also used for similar applications in [14]. The wind speed filter from [13] is presented in (2) below:

$$H_{\psi,0}(s) = \frac{0.99 + 4.79ds}{1 + 7.35ds + 7.68(ds)^2} \tag{2}$$

where s is the Laplace operator, $d = R_{wt}/V_0$ where R_{wt} is the radius of the wind turbine rotor and V_0 is the average wind speed of the wind speed session. The impact of the filter can be observed in Fig. 1. Furthermore, the average wind speed for a duration of 30 s is presented. This duration is equal to the time where the wind speed is assumed to be constant in for example [2]. From Fig. 1 a clear smoothing of the wind speed due to the filter can be observed. This would cause the mechanical power from the turbine to vary less compared to without the wind speed filter.

2) Wind speed variance: The variance of the wind speed within the 30 s is evaluated by considering the difference between the maximum and minimum wind speed for a 30 s window (for all of the 528 units of 30 s durations). The findings in the variation in wind speed for 528 of the 30 s windows can be observed in Fig. 2, where it can be seen that the wind speed can vary greatly during the time of locked operation. Furthermore, the average wind speed change for the evaluated 16 wind speed sessions is found to be 2.12 m/s. Moreover, it is observed that the second to second variation of the wind speed seldom is larger than 0.5 m/s as can be seen in Fig. 3. Even though the second to second variations are found to be small they will impact the variations in rotor speed seen by the wind turbine during the locked operation window, indicated in Fig. 5. These variations will become important when designing a controller that can handle variable wind speeds in an appropriate way. Furthermore, it is important to consider that these wind data are obtained from an offshore location, thus terrain roughness is kept at a minimum. It is reasonable to assume that an onshore wind turbine would be subjected to a larger variance in the wind speed. This variance would further increase the need for an adapted controller in order to deliver inertia support during realistic wind speeds.

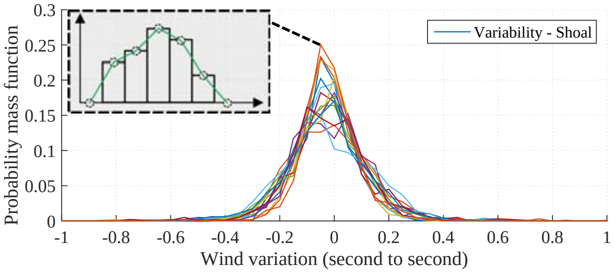


Fig. 3. Wind variance at Shoal wind power station during each of the evaluated wind speed sessions. The result of each of the 16 wind speed sessions probability mass is presented as exemplified by the miniature window.

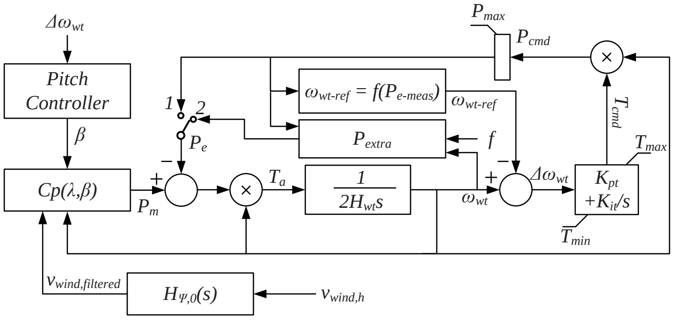


Fig. 4. Wind turbine model with the added functionality of inertia support within the P_{extra}-block.

B. Wind turbine modeling

A basic model of VSWT (GE DFIG 3.6 MW) is based on [2], [3] and [15] with the addition of the wind filter discussed in Section II-A. The model is presented in Fig. 4. The conversion from wind into mechanical power, P_m in Watt, can be represented by:

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3_{wind,filtered} \tag{3}$$

Where, ρ is the air density in kg/m^3, A the swept area by the blades in m^2, $C_p(\lambda, \beta)$ is the power coefficient of the turbine and $v_{wind,filtered}$ is the filtered wind speed subjected to rotor blades in m/s. The power coefficient, C_p, is determined by an analytical function seen in (4) [15].

$$C_p(\lambda, \beta) = \sum_{i=0}^{4} \sum_{j=0}^{4} \alpha_{i,j} \beta^i \lambda^j \tag{4}$$

TABLE I
PARAMETERS OF THE MODELED VSWT [15].

VSWT unit	
Parameter	Value
K_{pt}	3
K_{it}	0.3
T_{e-meas}	5 s
H_{wt}	5.19 s
T_{min}	0
T_{max}	0.833
P_{max}	1 pu

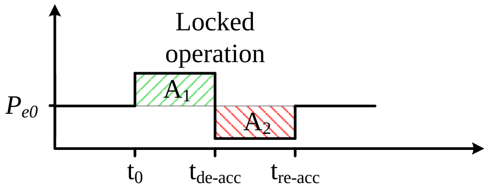


Fig. 5. Existing control strategy, Instant Power Support (IPS) [3].

Where λ is the tip speed ratio (TSR) of the turbine, β is the pitch angle of the blades and $\alpha_{i,j}$ are constants given in [2]. λ is obtained using (5).

$$\lambda = R_{wt}\frac{\omega_{wt}}{v_{wind,filtered}} \tag{5}$$

Where R_{wt} is the radius of the turbine and ω_{wt} is the rotor speed of the turbine. The speed reference,ω_{wt-ref}, of the turbine is generated with respect to the measured produced power in accordance with (6) when the output power is below 0.75 pu while above the speed reference is set to 1.2 pu.

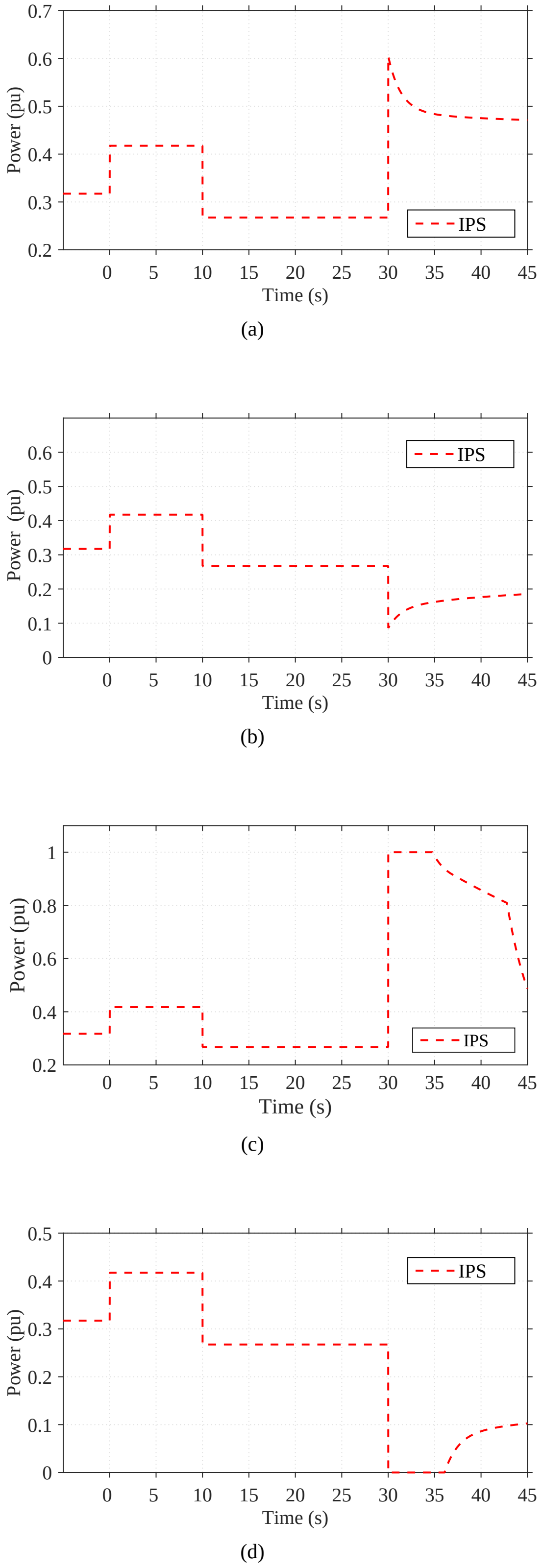
$$\omega_{wt-ref} = -0.67P^2_{e-meas} + 1.42P_{e-meas} + 0.51 \tag{6}$$

Where P_{e-meas} is the measured output power, acquired through a first order transfer function with a time constant T_{e-meas} of 5 s.

III. RESULTS

A. Existing controller during variable wind

Considering the fixed inertia support introduced in [2] and utilized in [3] (called Instant Power Support (IPS)). The strategy locks the operation of the maximum power point tracker (MPPT) of the VSWT during the disturbance, blocking the function during a locked operation window (before t = t_0 + t_{de-acc} + t_{re-acc} in Fig. 5). One of the main assumptions previously mentioned is that the wind speed is constant for during the activation of the strategy (here for 30 s) [3] where the strategy explained and evaluated in more detail. This section is meant to evaluate the effect of a wind speed step during the locked operational window and investigate the adoptions possible in order to improve the control strategy to handle these. Wind steps of Δv_{wind}= ± 1 m/s and ± 2 m/s were subjected to the VSWT when using IPS at 15 s after the activation, and its response in power output can be observed in Fig. 6. In the case of a wind increase it can be observed that since the controller expects the re-acceleration time (during



(a)

(b)

(c)

(d)

Fig. 6. The impact of the controller used in [3], [4] and [5] on power output during the various wind speed changes introduced at 15 s, a) Δv_{wind}= +1 m/s. b) Δv_{wind}= -1 m/s. c) Δv_{wind}= +2 m/s. d) Δv_{wind}= -2m/s.

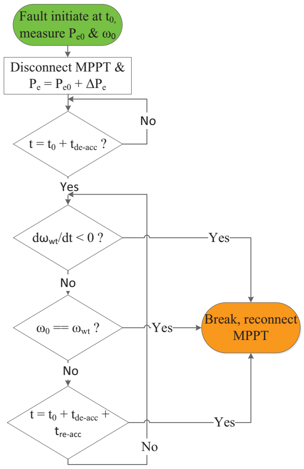


Fig. 7. The proposed controllers flow.

A_2 in Fig. 5) to be constant the controller does not expect the added mechanical power, which causes the rotor to accelerate faster, thus the rotation becomes higher than the pre-fault value. The speed error to the controller (once re-connected back to MPPT) is thus too big causing a big power burst when the turbine is de-accelerated down to MPPT-operation after the locked operation. This is done by requesting an increased amount of power (through the PI-controller) from the turbine thus reducing the rotor speed. For the case of a wind decrease during the locked operation window, this would cause the mechanical power to reduce. This in turn causes the rotation of the VSWT not to increase, even though re-acceleration power is consumed, especially if the wind step is big enough compared to that of the re-accelerating energy in A_2. However, at this operational point there is no similar necessity for the VSWT to regain its rotation. This since the wind decrease would any way cause the VSWT to reduce its power output to match the lower wind if in MPPT operation. At the transition to MPPT the speed deviation is too big compared to its initial point thus the control system tries to re-accelerate the turbine by consuming power from the power system causing zero power output for a short duration in response to Δv_{wind}= -2 m/s at 15 s.

B. *Proposed controller*

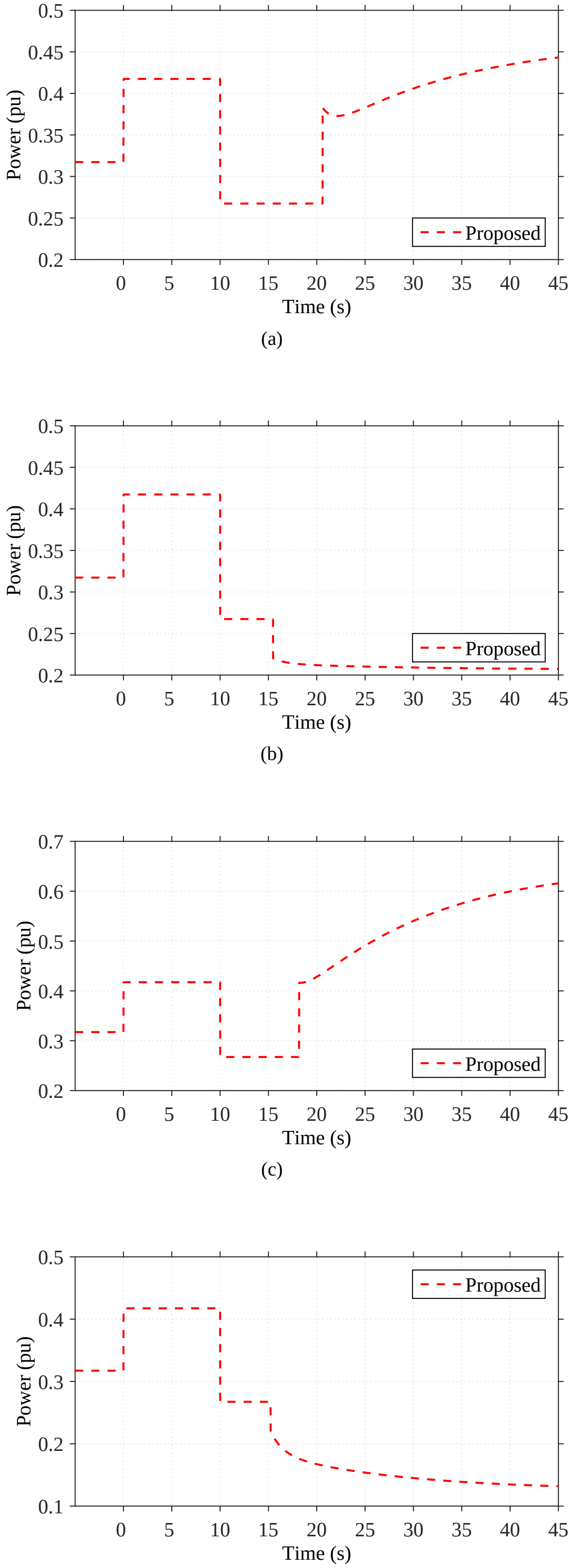
The implications on wind variations on the previous controller can be observed in Section III-A. In order to avoid the power bursts and allow the controller to deal with wind fluctuations an improved controller is presented in Fig. 7. The main inputs are rotor speed, electric power output from the turbine and the timings for the de-acceleration and re-acceleration of the IPS.

1) Controller function: The functionality of the proposed controller is hereby described; Assuming that the IPS is activated. If a wind increase do occur during the locked operation window of A_1 and A_2 in Fig. 5 the control system needs to remember its pre-fault value of rotation (ω_0 at t_0) in order to return to MPPT operation when it has re-accelerated to this value, further re-acceleration is not necessary. During a wind decrease, the control system needs to observe the derivative of the rotor speed of the VSWT. If the derivative is negative during the re-acceleration area A_2 (in Fig. 5), the controller is aware that the wind has decreased sufficiently not to provide its function (of re-acceleration) anymore. Thus, a MPPT operation is preferred. A filter on the rotor speed derivative allow for a temporary wind decrease of the turbine while still operating within the locked window, as could be seen in the Fig. 3 these variations would not be that big due to the small changes in wind speed from second to second. Hence, this filter is designed as a first order transfer function with a time constant of 1 s which reduces the number of accidental breaks from the locked operational window. Lastly, a very small wind decrease where the mechanical power does not drop as far as to cause a reduction in rotational speed the controller needs to continue to try to re-accelerate its rotor but still return to MPPT-operation if not able to re-accelerate before $t = t_0 + t_{de-acc} + t_{re-acc}$. The proposed controller was subjected to the wind steps presented and the impact on the power output evaluated.The improvements of the proposed controller can be observed in Fig. 8. For the cases of wind increase the re-acceleration time has reduced since the speed reaches its pre-disturbance value faster due to the increased mechanical power. For the case of a wind decrease, the controller notices that sufficient power is not provided to re-accelerate the rotor. Thus concluding that the mechanical power has decreased sufficiently enough therefor breaking out of the locked operation and returning to a MPPT-operation without the issues presented in Fig. 6.

2) Proposed controller during real wind conditions: In order to evaluate the proposed controller it is combined IPS and subjected to variable wind. The results are presented in Fig. 9. In order to ensure that the controller could handle the severe wind speed variations the wind speed filter described in Section II-A1 was not used. This causes, as discussed, greater power variations during the locked operational window, hence causing larger stress on the controller. As can be observed in Fig. 9 the re-acceleration area, A_2, is shortened by the increase of mechanical power during the re-acceleration phase followed by the average wind increase during the period 7-13 s. After the reconnection there is a small period where the output power increases following MPPT-operation before the overall wind decreases again. Noted during the initial seconds of the activation of the support strategy an increase of the rotor speed above the pre-fault value is observed, however the controller is set to deliver the full 0.1 pu of extra power for 10 s and since the rotor speed at 10 s is not up to pre-fault the re-acceleration is started.

IV. CONCLUSION

Wind variability subjected to a VSWT in an offshore location are evaluated. The average maximum wind speed change during a 30 s window is found to be 2.12 m/s and even though second to second variations of the filtered wind



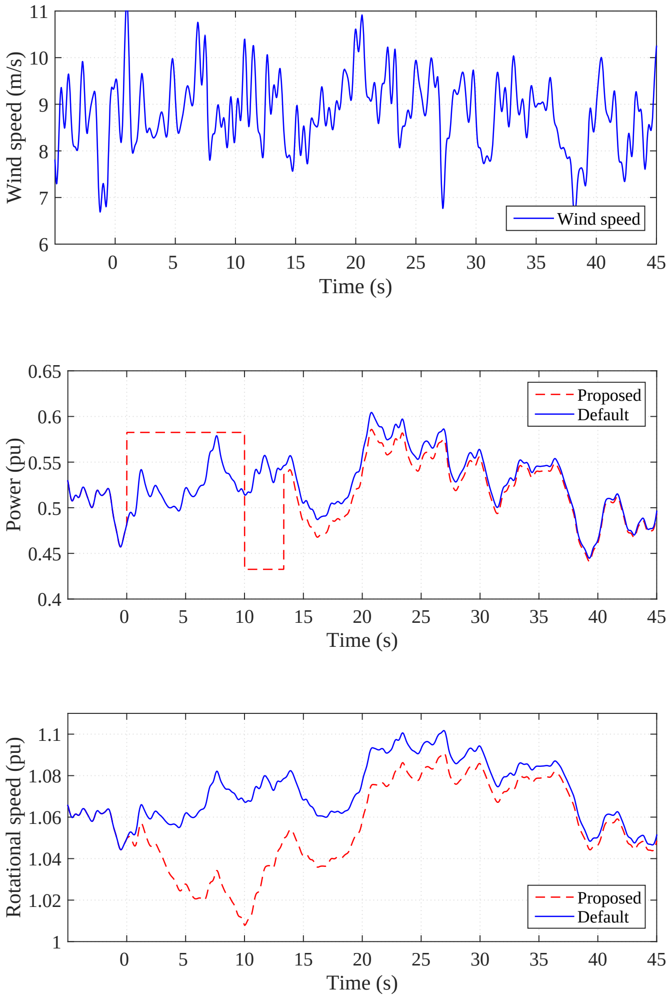
(a)

(b)

(c)

(d)

Fig. 8. The impact of the proposed controller used in on power output during the various wind speed changes introduced at 15 s, a) Δv_{wind}= +1 m/s. b) Δv_{wind}= -1 m/s. c) Δv_{wind}= +2 m/s. d) Δv_{wind}= -2m/s.



(c)

Fig. 9. a) Wind speed subjected to the wind turbine. b) Power output of the wind turbine with the proposed controller together with a turbine in default MPPT operation. c) Rotational speed of the turbine.

speed is maximum 0.5 m/s. These wind variations are expected to worsen if the VSWT is considered to be placed onshore. The previous designs flaws in handling variable wind has observed and evaluated. It is important to consider realistic wind conditions when providing inertia support. The impact of the utilized wind speed filter needs further attention, since this affects the wind speed data drastically. Improvements to the instant power support strategy in order to provide fast active power support during variable wind is proposed and evaluated. The filter of the rotor speed derivative is based on the second to second variations in the wind. It has been shown that the proposed controller is able to handle rough wind variations and deliver a stable response. The controller is evaluated through fixed steps in wind speed and variable wind speeds. To evaluate the filter of the rotational derivative is vital for it to handle variable winds and should be evaluated in future research. The benefit of being able of acting on the market is however still very important, a fixed amount of power support could be sold and traded on a market that allowed for such an action. The proposed strategy could be utilized by previous mentioned papers and the variability in the wind could be a base for future control strategies in order to considering variable wind speeds and inertia support from VSWT.

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