

# Adaptive Envelope Protection Control for the below and above Rated Regions of Wind Turbines

Mustafa Sahin, İlkyay Yavrucuk

**Abstract**—This paper presents a wind turbine envelope protection control algorithm that protects Variable Speed Variable Pitch (VSVP) wind turbines from damage during operation throughout their below and above rated regions, i.e. from cut-in to cut-out wind speed. The proposed approach uses a neural network that can adapt to turbines and their operating points. An algorithm monitors instantaneous wind and turbine states, predicts a wind speed that would push the turbine to a pre-defined envelope limit and, when necessary, realizes an avoidance action. Simulations are realized using the MS Bladed Wind Turbine Simulation Model for the NREL 5 MW wind turbine equipped with baseline controllers. In all simulations, through the proposed algorithm, it is observed that the turbine operates safely within the allowable limit throughout the below and above rated regions. Two example cases, adaptations to turbine operating points for the below and above rated regions and protections are investigated in simulations to show the capability of the proposed envelope protection system (EPS) algorithm, which reduces excessive wind turbine loads and expectedly increases the turbine service life.

**Keywords**—Adaptive envelope protection control, limit detection and avoidance, neural networks, ultimate load reduction, wind turbine power control.

## I. INTRODUCTION

THE life span of wind turbines depends on their operating conditions. Excessive loads are not desired on wind turbines. Thus, a multitude of control studies examines methods to reduce loads in terms of both fatigue [1]-[4] and ultimate loads [1], [5]-[8]. The current work focuses on ultimate load reduction and proposes a wind turbine EPS algorithm that adapts to turbines and their operating points and intervenes only with the blade pitch controller output whenever an envelope violation is detected throughout the below and above rated regions.

Power reduction is a useful method to alleviate turbine loads [9]. For instance, in [7], power reduction is achieved to avoid excessive turbine loadings both around the rated wind speed, and throughout the entire turbine operational regions. Thus, the turbine is consistently kept within the pre-defined safe envelope limits. An online optimization-based procedure is used for following up the current wind and turbine states that predicts wind speed variations and simultaneously controls turbine response to prevent exceedance of safe operation boundaries. A predicted wind speed, referred to as envelope wind speed, and the actual wind speed are used to

determine the turbine excessive loading and therefore a suitable power reference is selected. On the other hand, [6] focuses on the optimal soft cut-out control strategy during storms. In the soft cut-out strategy, when the turbine operates below allowable limits, the power reference is increased and vice versa. Therefore, depending on the current turbine loadings, power reference is adjusted by varying the rotor speed reference while keeping generator torque at its rated value. In [8], the optimization-based algorithm is re-investigated with a generalized formulation for Region II, Region II<sup>1/2</sup>, Region III, and the optional Region IV under the name of envelope protection control. The optimization-based algorithm in [6]-[8] is an add-on to the baseline power control algorithms; generator torque and collective blade pitch controllers. A similar approach related to the soft cut-out is examined by [10], but an assumption is required on wind characteristics. Therefore, an incorrect assumption may result in excessively low power reference or high loads. This inevitably requires online monitoring of wind characteristics for proper performance [6].

In this study, an approach to envelope protection for wind turbines is presented. Unlike the protection algorithm in [6]-[8], the proposed approach adapts to turbines and their operational points. Further, it has a different theoretical approach. The idea of the proposed system is inspired by the adaptive EPS algorithm used for manned/ unmanned aircraft as in [11]-[13]. The approach uses an online learning neural network for the adaptation of unmodelled dynamics. Therefore, learning is realized in real time and does not require an a priori training of neural networks as well as excessive computation. However, the idea of aircraft EPS algorithm, as in [11]-[13], cannot be directly utilized for wind turbines without vital modification/ assumptions since aircraft and turbines are different systems with different states and inputs along with being exposed to different operational conditions.

In the proposed algorithm, the neural network weights are updated in real-time, depending on an update law based on Lyapunov analysis [12]. A Linearly Parametrized Neural Network (LPNN) is used to approximate the nonlinear dynamics of the limit parameter. Weight update laws are designed such that the neural network output eliminates the modeling uncertainty of the approximate limit parameter dynamics model. The proposed adaptive EPS algorithm is independent of the algorithms for baseline turbine controllers. The avoidance by the current proposed adaptive EPS is realized through the variation of the blade pitch reference only, thereby changing the blade pitch angles throughout the

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below and above rated regions. In [6]-[8], however, the turbine avoids excessive loading by adjusting blade pitch and generator torque in the below rated region, while varying the rotor speed reference by keeping generator torque constant at its rated value in the above rated region. Therefore, unlike the optimization-based algorithm in [6]-[8], the currently proposed algorithm is an add-on to the baseline blade pitch controller only. It monitors both wind and turbine states, adapts to the changes in turbine operating point by adjusting learning weights to estimate accurate limit parameter dynamics and simultaneously calculates the envelope wind speed. By comparing the envelope wind speed with the actual wind speed, a proper protection/avoidance action is applied to the output of the blade pitch control system. This reduces the turbine power output and eventually prevents the turbine from abandoning the safe operation. In addition, the proposed algorithm is more straightforward in implementation than the optimization-based protection algorithm in [6]-[8]. That algorithm requires the knowledge and separate addition of each baseline controller algorithm to the corresponding reduced order turbine model for the below and above rated region. Here, this issue is solved with the currently proposed EPS algorithm, which does not require any knowledge about the employed turbine controllers. Furthermore, the avoidance through the change of blade pitch reference, i.e. blade pitch angle, is much simpler to implement since there is no intervention with the generator torque controller, i.e. power electronics.

The turbine operating point changes during turbine operation due to the change in wind speed. Therefore, the change in wind speed alters the turbine states, i.e. rotor speed, blade pitch angle, etc. The proposed system adapts to these changes and carries out an avoidance action when a pre-defined limit exceedance is about to occur. In this study, the thrust force is selected as the parameter to be limited since it is a vital design driving load on some important turbine components. Thrust force is directly obtained as an output from the MS Bladed Model. However, in actual implementation on turbines, it can be taken from the turbine root load sensors. In order to show the effectiveness of the proposed EPS algorithm, two example simulations, one for the below rated region, and one for the above rated region, are investigated using the MS Bladed Wind Turbine Simulation Model [14], [15] for the NREL 5 MW wind turbine equipped with a standard generator torque controller and a gain-scheduled proportional and integral (PI) strategy-based collective blade pitch controller.

The outline of this paper is as follows: Section II includes information about the MS Bladed Wind Turbine Simulation Model. Section III defines the baseline controllers for the NREL 5 MW Turbine. Section IV explains the idea and the theory behind the proposed adaptive EPS, which includes the estimations of linear parameter dynamics, envelope wind speed, excessive loading and, lastly, the limit avoidance method. Section V focuses on the proposed algorithm implementation and evaluates the simulation results, i.e., adaptation to the changes in operating point and protection.

Simulations are evaluated with and without the envelope protection algorithms under normal turbulent wind speeds of 7 m/s and 15 m/s. Finally, the conclusions are added in Section VI.

## II. MS BLADED WIND TURBINE SIMULATION MODEL

The MS Bladed Wind Turbine Simulation Model is based on the Blade Element Momentum (BEM) theory. Aerodynamic calculations of the MS Bladed Simulation Model are similar to those of [16]-[18]. The simulation model has the aerodynamic corrections such as rotor hub and blade tip losses, turbulent wake state, and skewed wake rotation, etc. The model has properties of nacelle yawing and blade pitching; collectively or individually. In addition, the model permits the user to define a desired precone and a nacelle tilt angle.

The turbine model considers rigid turbine structures and employs a variable torque electrical generator as well as a gearbox between the rotor and the generator. Thus, the turbine dynamic system model is constructed on:

$$J_t \dot{\Omega} = \tau_a - \tau_{gen} \quad (1)$$

$$J_t = J_r + N_{gear}^2 J_{gen} \quad (2)$$

where  $\Omega$  represents the rotor speed,  $\tau_a$  is the aerodynamic rotor torque,  $\tau_{gen}$  is the generator electromagnetic torque, the  $N_{gear}$  is the gearbox ratio, whereas  $J_t$  stands for the total inertia of the turbine system,  $J_r$ , turbine rotor inertia, and  $J_{gen}$ , electrical generator inertia. The rotor speed is utilized for control purpose, rather than that of the generator.

Lastly, the turbine simulation model includes a first order blade pitch actuator model with a time constant of 0.2, a rate limiter of 8 deg/s, and a saturation limit to the optimum pitch angle. The generator torque actuator dynamics is neglected. However, a rate limiter and a saturation limit are added to the generator torque control system.

More information about the MS Bladed Wind Turbine Simulation Model is available in [14], [15].

## III. WIND TURBINE BASELINE CONTROLS

The NREL 5 MW turbine is equipped with a generator torque controller and a blade pitch controller respectively for Region II and Region III. The block diagram for these controllers is given in Fig. 1.

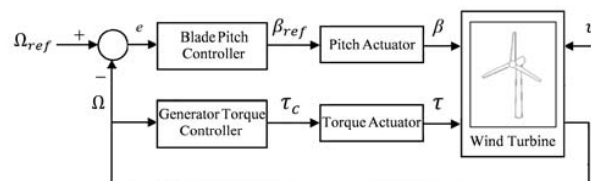


Fig. 1 Block Diagram for Baseline Controllers

For the maximum power production in Region II, a typical

nonlinear generator torque controller is employed based on the following control law [16], [17], [19]:

$$\tau_c = K\Omega^2 \quad (3)$$

where  $\Omega$  is the rotor speed, i.e LSS of the gearbox, whereas  $K$  is the torque controller gain and is defined as:

$$K = \frac{1}{2} \rho \pi (R \cos \Phi)^5 \frac{C_{pmax}(\lambda_*, \beta_*)}{\lambda_*^3} \quad (4)$$

where  $\rho$ ,  $R$ ,  $\Phi$ ,  $\lambda_*$  and  $\beta_*$  are air density, rotor radius, precone angle, optimum tip speed ratio (TSR), and blade pitch angle, respectively.

To regulate the turbine output power in Region III, the following gain-scheduled PI-based collective blade pitch controller is employed:

$$\beta_{ref}(t) = K_p^{GS} e(t) + K_I^{GS} \int e(t) dt \quad (5)$$

where  $K_p^{GS}$  and  $K_I^{GS}$  denote the gain scheduled PI gains of the blade pitch controller, respectively.  $e(t)$  is the error between rotor speed reference and the actual rotor speed measurement.  $\beta_{ref}(t)$  is, on the other hand, the controller output. Controller gains are scheduled using a gain correction factor [20]. The actuator dynamics is modeled with a first order transfer function with a time constant,  $\tau$  of 0.2 as follows:

$$\frac{\beta}{\beta_{ref}} = \frac{1}{\tau s + 1} \quad (6)$$

where  $\beta$  is the blade pitch angle input to the turbine. In addition, transition region torque controllers are employed for Region I<sup>1/2</sup> and Region II<sup>1/2</sup>, which are linear and depend dynamically on the rotor/generator speed [8], [21].

#### IV. WIND TURBINE ENVELOPE PROTECTION

The duty of a wind turbine envelope protection control system is to keep a machine within its pre-defined safe operational limits and thereby protecting turbines from severe damages. For a wind turbine, these limits may be excessive loadings, rotor speed, blade tower oscillations, or other limits considered critical for the turbine. An EPS algorithm always checks how close the turbine is to the envelope of safe operational region and tries to keep the system response within the safe region. This is ensured if the critical loads stay within the pre-defined envelope limits. Through the currently proposed EPS algorithm, wind and turbine states are constantly monitored. Using measurable data, the EPS algorithm detects the unsafe operational state and carries out a protective/avoidance action whenever the envelope limits are about to be violated. By doing so, it ensures that the turbine operates within the pre-defined safe limits at all times. When implemented properly, the proposed EPS algorithm can limit any other critical turbine parameters.

#### a) Estimation of Limit Parameter Dynamics with Neural Network

A limit parameter dynamic is typically a nonlinear function of turbine system states and inputs. This function alters whenever the turbine operating point or configuration changes. Here, the proposed approach uses a linear approximate limit parameter model along with a neural network to estimate the limit parameter dynamics [13]. Fig. 2 depicts the block diagram for the online estimation of limit parameter dynamics. Therefore, a nonlinear wind turbine system may be represented as:

$$\dot{x} = f(x, u), x \in R^n, u \in R^p \quad (7)$$

$$Y = g(x, u), y \in R^q \quad (8)$$

where  $x$  represents the turbine states such as rotor speed, blade pitch angle, etc., whereas  $u$  is the input to the turbine such as wind speed, etc., and  $Y$  is the system output. Let  $y_l \in Y$  be a limit parameter with the following nonlinear equation:

$$y_l = h(x, u) \quad (9)$$

where  $x$  the turbine are states and  $u$  are the inputs. The states can be divided into fast and slow states. During a transient response, the fast states are those that predominantly influence the limiting parameter dynamics, whereas the slow states change slower and therefore have a negligible effect on the transient response. Thus, the equations for the turbine fast and slow states may be written as [13]:

$$\dot{x}_s = f_1(x_s, u), x_s \in R^l \quad (10)$$

$$\dot{x}_f = f_2(x_f, u), x_f \in R^{n-l} \quad (11)$$

The limit parameter for a given input,  $u$  may be represented by,

$$y_l = h(x_s, x_f, u) \quad (12)$$

In order to obtain an online estimate of limit parameter dynamics, the time derivate of  $y_l$  is taken for a constant input,

$$\dot{y}_l = h_{x_s} \dot{x}_s + h_{x_f} \dot{x}_f \quad (13)$$

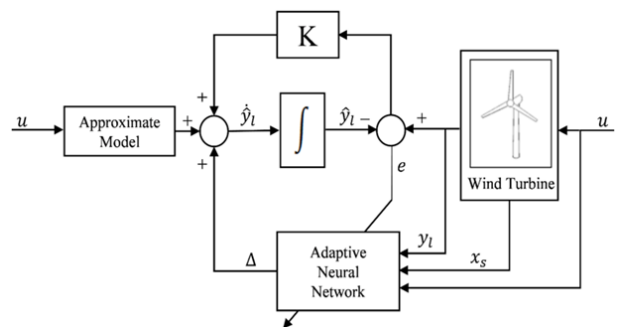


Fig. 2 Online estimation of the limit parameter dynamics

Using (10) and (11), the limit parameter dynamics can be written as:

$$\dot{y}_l = r(x_s, x_f, u) \quad (14)$$

Assuming that the limit parameter dynamics are as fast as the fast states, the limit parameter dynamics can also be written as:

$$\dot{y}_l = r(y_l, x_s, u) \quad (15)$$

The above equation is assumed to be a representation of the limit parameter dynamics. An approximate linear model is used to estimate the dynamics of (15):

$$\hat{y}_l = A\hat{y}_l + Bu \quad (16)$$

The “^” symbol represents the approximate model. Therefore,  $\hat{y}_l$  represents the output of the employed approximate linear model. Also,

$$\dot{y}_l = \hat{r} + \xi(y_l, x_s, u) \quad (17)$$

where  $\xi(y_l, x_s, u)$  corresponds to the modeling error in the limit parameter dynamics, and therefore:

$$\xi = r - \hat{r} \quad (18)$$

Since the approximate linear model in (16) does not represent the actual limit parameter dynamics, it is augmented with an adaptive neural network to improve the limit parameter estimation. The resulting dynamics of the estimate is obtained [12]:

$$\dot{\hat{y}}_l = \hat{r} + \Delta(y_l, x_s, u) + K(y_l - \hat{y}_l) \quad (19)$$

where  $K$  is the observer gain matrix. The error dynamic is constructed between the actual and estimated limit parameters. The error is defined as:

$$e = y_l - \hat{y}_l \quad (20)$$

When (19) is subtracted from (17), the error dynamics is,

$$\dot{e} = -Ke + \xi - \Delta \quad (21)$$

If  $\xi$  and  $\Delta$  eliminate each other, the error,  $e$  reaches to zero asymptotically for a Hurwitz  $K$  matrix. Otherwise, the term  $\xi - \Delta$  in (21) behaves as a forcing input to the error dynamics [12]. Here,  $\Delta(y_l, x_s, u)$  is obtained using an LPNN:

$$\Delta = W^T \delta(\mu) \quad (22)$$

where  $W, \beta, \mu$  and  $\Delta$  are the neural network weights, basis functions, input vector and, the output, respectively. The network weight update law is given as [12]:

$$\dot{\hat{W}} = \Gamma(\delta e^T P - k\hat{W}\|e\|) \quad (23)$$

where  $k$  is the gain of e-modification term,  $\Gamma$  is the learning rate of the neural network,  $e$  is the error and  $P$  is the solution of the following Lypunov equation.

$$(-K)^T P + P(-K) = -I \quad (24)$$

and the network input vector,  $\delta$  is defined as follows:

$$\delta(y_l, x_s, u) = D_1 \oplus D_2 \quad (25)$$

where  $\oplus$  represents the Kronecker product,  $D_1$  and  $D_2$  are the vectors defined as follows considering 1s as the bias term:

$$D_1 = [1 \ y_l \ x_s] \quad (26)$$

$$D_2 = [1 \ u] \quad (27)$$

#### b) Estimation of Envelope Wind Speed and Potential Excessive Loading

Envelope wind speed is an estimated wind speed that pushes the turbine to a pre-defined envelope boundary. This wind speed is calculated depending on the turbine current operating conditions as well as the limiting parameter value. In this study, it is estimated using the concept of unsteady dynamics, where the time derivative of fast state (and therefore the time derivative of the limit parameter) is kept in the EPS algorithm. This is because the turbine limit parameter, i.e. turbine thrust force, has an unsteady behavior under the turbulent wind. In a supportive way, both turbine fast and slow states are almost always in their transient phases in almost all turbine operations. Thus, they do not reach their steady-states during turbine operations unlike fast states reaching their steady-state values whereas slow states are still changing in dynamic trim concept. The estimated envelope wind speed can be very much different from an actual wind speed. Here, it is just used for determining whether the turbine potentially operates with excessive loadings or not. Using the limit parameter dynamics in (19), the approximate model in (16) and the error in (20), the following is obtained [12]:

$$\dot{\hat{y}}_l = A\hat{y}_l + Bu + \Delta(y_l, x_s, u) + Ke \quad (28)$$

Thus, when the desired value,  $y_{ld}$  of the limit parameter is used in (28) and solved for  $u$ , the envelope input,  $u_{env}$  which takes the turbine to the limit value,  $y_{ld}$  is obtained as:

$$u_{env} = -B^{-1}(Ay_{ld} + \Delta(y_l, x_s, u) + Ke - \dot{\hat{y}}_l) \quad (29)$$

In this paper, the thrust force is chosen as the limit parameter,  $y_l$  wind speed is the input,  $u$  to the turbine. Therefore,  $u_{env}$  is the envelope wind speed. In (29),  $\dot{\hat{y}}_l$  is kept to reflect the transient behavior of the limit parameter. Due to the turbulent nature of wind, turbine states do not reach their steady-states and stay mostly in transient phases. Although the slow states are assumed not to change much, the fast states, therefore the limit parameter is assumed to still change due to the turbulent nature of the wind.

Comparing the estimated envelope wind speed,  $u_{env}$ , with the actual wind,  $u$ , gives information about the turbine loading, i.e. excessive thrust force. Here, the actual wind speed may be obtained by a wind speed sensor, a wind speed estimator, or a LIDAR device on turbines. When the actual wind is less than the estimated envelope wind speed, the turbine is considered safe, i.e., operating below the envelope boundary with low loads. However, once the actual wind speed becomes greater than the envelope wind speed, the turbine potentially operates with excessive loadings. This requires an avoidance action in order not to allow the turbine to exceed the envelope boundary, i.e. pre-defined limit value. Comparison of the envelope and actual wind speeds is realized by the following relation:

$$\Delta u = u_{env} - u \quad (30)$$

### c) Wind Turbine Limit Avoidance

In this work, control limiting [11] is used both for the below and above rated region, which covers Region I<sup>1/2</sup>, Region II, Region II<sup>1/2</sup>, and Region III. This is realized through the collective blade pitch control system, i.e., limiting the controller output,  $\beta_{ref}$  (

Fig. 3). There is no intervention with the baseline generator torque controller. The avoidance both in the below and above rated regions is obtained by reducing the turbine power output by increasing the blade pitch reference, and thus, the pitch angle. This intervention of EPS algorithm with the blade pitch controller output corresponds to a change in turbine operating point.

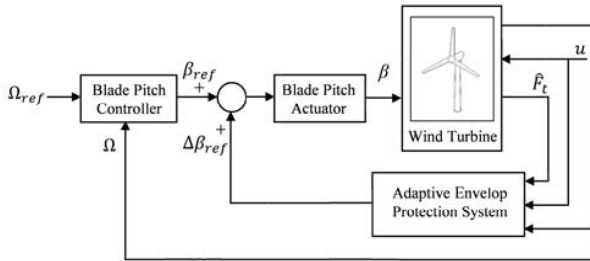


Fig. 3 Limit avoidance via control limiting for VSVP wind turbine

Fig. 3 depicts the general block diagram for the proposed EPS algorithm which intervenes with the output of the blade pitch control system and adjusts the blade pitch angle reference whenever a limit parameter violation is predicted. The thrust force,  $F_t$  is the limit parameter and is assumed to be known.

The adaptive EPS algorithm estimates the amounts of blade pitch angle reference,  $\Delta\beta_{ref}$ , to be adjusted in order to protect the turbine from exceeding its pre-defined limit. Here,  $\Delta\beta_{ref}$ , is estimated at each instant of time and is obtained by:

$$\Delta\beta_{ref} = \varepsilon\Delta u \quad (31)$$

where  $\varepsilon$  is a design parameter for effective limit avoidance.

## V. IMPLEMENTATION AND SIMULATION RESULTS

The proposed protection algorithm is implemented using the MS Bladed Wind Turbine Simulation Model with the properties of the NREL 5MW turbine [21]. The approximate model in (16) is constructed for the thrust force,  $\hat{F}_t$ , as:

$$\dot{\hat{F}}_t = a\hat{F}_t + bu \quad (32)$$

where  $a = -0.24$ ,  $b = 0.0175$  are approximate values and  $u$  is the actual wind input. When the above approximate linear parameter dynamics in (32) is augmented using (19), the following is obtained for the accurate estimation of the desired thrust limit dynamics:

$$\dot{\hat{F}}_t = a\hat{F}_t + bu + \Delta(F_t, \Omega, u) + K(F_t - \hat{F}_t) \quad (33)$$

where the turbine rotor speed,  $\Omega$ , and blade pitch angle,  $\beta$  are considered as the slow state and fast state, respectively.

TABLE I  
DESIGN PARAMETERS FOR THE ADAPTIVE EPS

Observer Gain, $K$	50
Learning Rate, $\Gamma$	25
e-modification term, $k$	0.02
Parameter, $P$	0.01
Design parameter, $\varepsilon$	-2.5

The effect of fast state, i.e., the blade pitch angle,  $\beta$ , is introduced to the thrust force dynamics as a function of limit thrust value,  $F_t$ . The other design variables for the LPNN based adaptive EPS algorithm are given in Table I. Also, for the current implementation, the vectors in (26) and (27) are adopted as follows:

$$D_1 = [1 \ F_t \ \Omega] \quad (34)$$

$$D_2 = [1 \ u] \quad (35)$$

The envelope wind speed,  $u_{env}$ , is calculated by writing (29) for the limit thrust value,  $F_t$  and it becomes as in:

$$u_{env} = -b^{-1} \left( aF_t + \Delta(F_t, \Omega, u) + Ke - \hat{F}_t \right) \quad (36)$$

where  $F_{t_d}$  is the pre-defined thrust limit value. The above predicted wind speed,  $u_{env}$ , is compared with the actual wind speed,  $u$ . This comparison is realized by (30) for the below and above rated regions, respectively. A positive estimation of  $\Delta u$  corresponds to a turbine operation within the pre-defined safe envelope limit, while a negative value of  $\Delta u$  corresponds to an operation outside the envelope limit, i.e., with excessive loadings. Therefore, in that case, a proper avoidance action must be realized in advance as defined in Section IV c. This is realized by (31) with a negative  $\varepsilon$  value.

Wind series are obtained using a program called SWIFT developed by ECN according to the IEC61400-I normal turbulence model for a class IA wind turbine [22]. The effectiveness of the proposed adaptive EPS algorithm is

explored under normal turbulent wind conditions with different mean values both for the below and the above rated regions. Namely, two different turbulent winds with means of 7 m/s and 15 m/s are utilized. The turbine thrust force,  $F_t$ , is limited to 0.55 MN. Two example simulation cases, adaptation to changes in operating points for the below and above rated regions and protection are examined. All simulation results are given for a duration of 50 s and the EPS algorithm is activated at the 10 s of the simulation time. The neural network weights

are started from zero initially. Therefore, just at the beginning of the simulation, weights are automatically adapted online to the turbine operating point in few seconds. The simulation results have shown a promising capability for both cases. Therefore, by adaption to the changes in turbine operating point, the proposed EPS algorithm has managed to keep the turbine within the predefined thrust limit, resulting in reduced turbine thrust force. The followings are the details of these simulations.

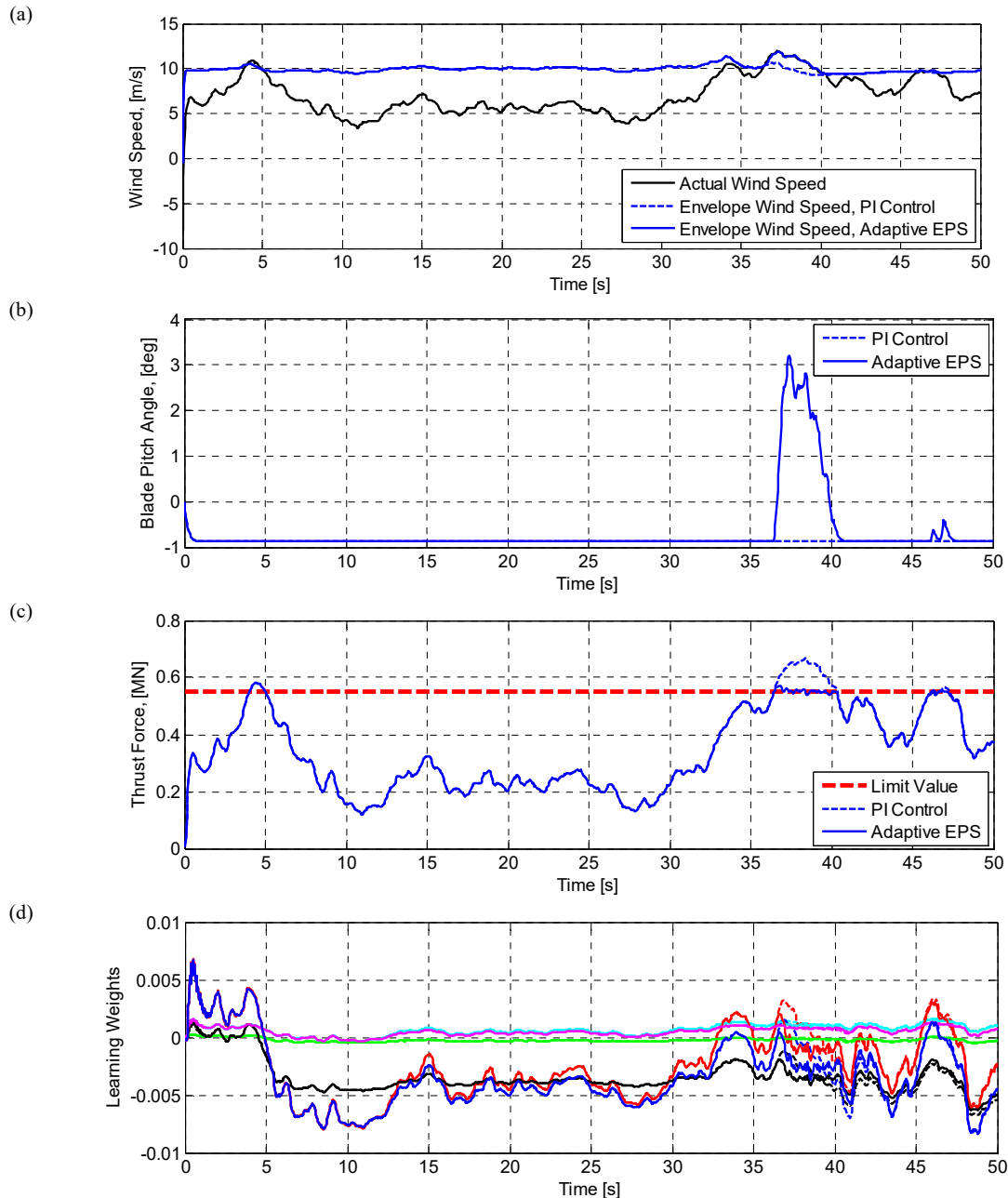


Fig. 4 Below Rated Region Simulations (a) Actual/envelope wind speed, (b) Blade pitch angle, (c) Thrust force, (d) NN weights

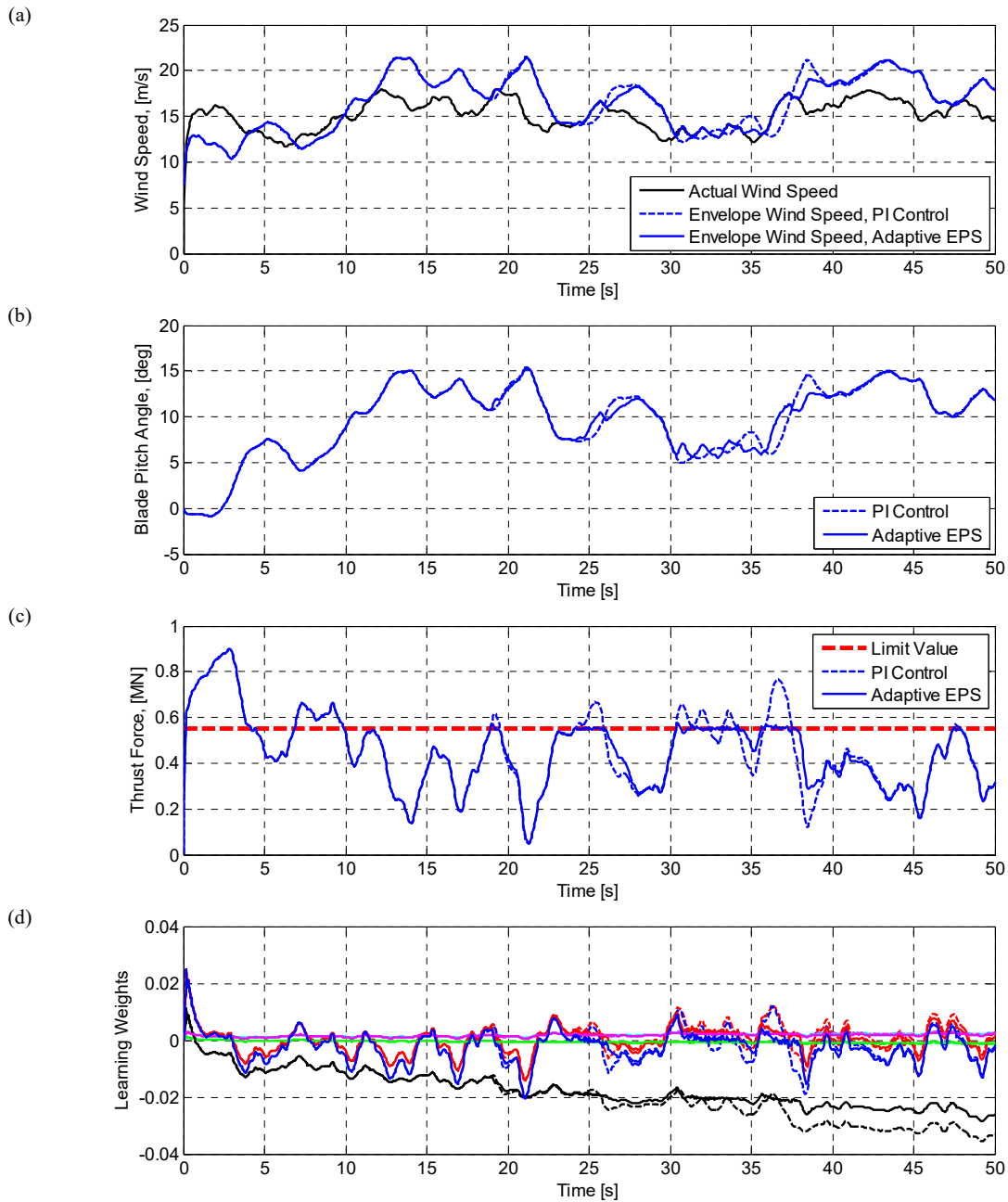


Fig. 5 Above Rated Region Simulations (a) Actual/envelope wind speed, (b) Blade pitch angle, (c) Thrust force, (d) NN weights

#### a) Adaptation to Turbine Operating Point in the Below Rated Region and Protection

This simulation case is given for the below rated region, or Region II to show the proposed algorithm being adapted to the variations in operating point and estimating the limit parameter dynamics as well as realizes a proper protection action whenever a safe operation is about to be abandoned.

Fig. 4 shows the simulation results for the NREL 5 MW wind turbine with and without adaptive EPS algorithm under a normal turbulent wind with a mean of 8 m/s. Figs. 4 (a)-(d) show the changes in estimated envelope/actual wind speed,

blade pitch angle, thrust force and the online learning weights in time, respectively.

When the turbine operates with baseline control system, the thrust of the turbine (Fig. 4 (c)) exceeds the pre-defined thrust limit of 0.55 MN. This occurs around  $t = 4$  s, 36.5 s and 46.6 of the simulation. At those time instants, the estimated envelope wind speed crosses and becomes lower than the actual turbulent wind (Fig. 4 (a)). This corresponds to an excessive loading situation and the turbine is thought to be in danger because the thrust force has exceeded the pre-defined thrust limit of 0.55 MN (Fig. 4 (c)). After the activation of

adaptive EPS algorithm at  $t=10$  s, the system starts automatically detecting the thrust limit exceedance, and carries out an avoidance action when required, i.e. at around 37 s and 47 s of the simulation. Therefore, the system does not allow the turbine to cross the pre-defined thrust boundary and rides the turbine at the boundary (Fig. 4 (c)). Here, the avoidance is carried out by interacting with the output of the closed-loop blade pitch control system, i.e. increasing the blade pitch angle reference, thereby increasing the blade pitch angles. This increment in blade pitch angle for the protection action is seen in Fig. 4 (b). Fig. 4 (d) shows the changes in neural network weights with (solid) and without (dashed) adaptive EPS algorithm.

#### b) Adaptation to Turbine Operating Point in the above Rated Region and Protection

This example case is prepared for the above rated region, or Region III to show the effectiveness of the proposed algorithm being adapted to the changes in turbine operating point and how it does prevent the turbine from exceeding the pre-defined thrust limit. Similarly, the simulation results are given for the NREL 5 MW wind turbine with the baseline controllers and with the adaptive EPS algorithm under normal turbulent wind with a mean of 15 m/s. Figs. 5 (a)-(d) show the variation in the estimated envelope/ actual wind speed, pitch angle, thrust force and adaptive NN weights in time, respectively. When the turbine operates with only baseline pitch control system, the thrust of the turbine (Fig. 5 (c)) exceeds the pre-defined thrust limit of 0.55 MN. This occurs at the beginning, around  $t=6.85$  s, 18.9 s, 24.1 s, 30.3 s, 33.25 s, 35.85 s and 47.45 s of the simulation. At these instants, the estimated envelope wind speed crosses and stays below the actual turbulent wind speed for some time (Fig. 5 (a)). This indicates an excessive loading situation because the turbine thrust force has exceeded the limit value of 0.55 MN (Fig. 5 (c)). However, after the adaptive EPS algorithm is engaged at  $t=10$  s of the simulation, and once the system detects the thrust limit exceedance, it carries out an avoidance action. Thus, it prevents the turbine from crossing the pre-defined thrust limit and rides the turbine at the thrust force boundary (Fig. 5 (c)). This is realized by increasing the blade pitch angle reference, thereby increasing the blade pitch angles for the turbine protection (Fig. 5 (b)). (Fig. 5 (d)), on the other hand, shows the changes in neural network weights with (solid) and without (dashed) adaptive EPS algorithm.

## VI. CONCLUSIONS

This paper introduces a wind turbine EPS algorithm for the below and above rated regions of VSVP horizontal axis wind turbines. In the algorithm, a neural network monitors current wind and turbine states, adapts to the changes in turbine operating point and simultaneously predicts an envelope wind speed that would lead the turbine to a pre-defined envelope limit, when necessary, applies an avoidance action to prevent the turbine from having high thrust forces. The envelope wind speed is calculated by the introduced concept of unsteady dynamics for which all the turbine states are in transient,

therefore the time derivative of (fast state) the limit parameter is kept in the algorithm. Comparing the envelope wind speed with the actual wind speed, the algorithm determines if an excessive thrust force occurs on the turbine or not. The proposed algorithm realizes the avoidance action by intervening with the pitch controller output only, so increasing the turbine blade pitch angles and thereby reducing the power output.

In this paper, the proposed EPS approach is tested for the adaptation to the changes in turbine operating point and protection for the below and above rated regions. Therefore, it is tested under normal turbulent wind speeds with means of 7 m/s and 15 m/s using the MS Bladed Model for the NREL 5 MW turbine with baseline generator torque and blade pitch controllers. By simulations, it is proven that the proposed EPS algorithm can adapt online to the changes in turbine operating point in both operation regions and effectively realizes protection action when required. Therefore, through the proposed system, the NREL 5MW turbine is kept within a pre-defined thrust limit of 0.55 MN. Thus, dangerous thrust forces are prevented and an increase in turbine service life can be expected. Here, the thrust force is selected as limit parameter. However, this may be expanded to any other turbine critical variables.

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