

State-Space Modeling Based Model Predictive PMC Control Techniques of Wind Turbine Generators for Power System Studies

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Abstract: Wind energy plays a major role in the operation of wind turbine generators. Advancement in technology particularly in regard to wind energy has transformed the wind turbines from fixed speed to variable speed generators. This paper introduces a more innovative version of the wind turbine which uses the Model Predictive Control MPC approach. The advanced wind turbine has its control actions replaced with a technologically advanced controller. The replacement is instrumental since it conserves power originating from the wind turbines. This in turn reduces the time it takes to calculate the amount of energy released. Similarly, the advanced controller is able to monitor the Maximum Power Tracking, MPT, whose main objective is to capture energy form the wind. The proposed technology also reduces the constraints of the two main functional parts of the wind turbine; the full load and partial load segments. The pitch angle for full load and the rotating force for the partial load have been fixed concurrently in order to balance power generation as well as reduce the operations of the pitch angle. The advanced wind turbine generator also uses the mathematical modeling using statespace approach and leads to an improvement between power limitation and power optimization.

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Keywords—state-space; wind turbines; model predictive control; pitch control; power optimization.

1. Introduction:

Wind energy has become a widely used source of energy for the past many years across the world. It is one of the major sources of renewable energy, besides solar and biogas. It has become a topic of interest to many researchers [1]-[4]. A number of studies have been undertaken to determine the relationship between wind turbine and solar photovoltaic energy creation systems and grid power generation systems. Research is conducted whenever wind turbine plants produce high-level energy to determine whether their engineering systems are similar to other power generating systems [5]. Power that is expected to be generated by the wind is examined at the planning stage of the system. Studies also examine the system's stability, security, low-

voltage fault ride-through, energy profile, current movement, the short circuit flows and responsive power ability [6]. A few of the innovative machines are based on a relatively simple control design approaches. They use the dynamic modeling power system as well as the doubly-fed induction generator built on variable-speed wind turbine for power control [7]-[8]. The variable-speed wind turbine achieves a systematic approach of state-space modeling and design concerns controlled by predictive based load frequency [9]-[10].

The wind energy sector has recently experienced tremendous growth and continued growth is still expected in the future. The improved growth is as a result of innovative ideas incorporated in wind

turbine power systems. This has seen a reduction in the cost of energy generation and has also made wind energy the most preferred source of renewable energy. The variable-speed wind turbine plays a key role in the production of energy. It enhances energy production and reduces drive train rotations as well as the fluctuations existing in power production [11]-[12]. It is hard to control variable-speed wind turbine since they have non-linear features. Linear controllers are able to regulate wind turbines using the pitch angle. They are also extensively used together with quadratic Gaussian or quadratic regulator to control power. Varying suggestions have been made about the pitch angle and the quadratic regulator [13]-[14]. The design process undertaken for the Proportional Integral Derivative (PID) and the Proportional Integral (PI) has also been examined together with the regulators [15].

The gain scheduling (LQG) has been suggested as a way of introducing the linear features in the power systems [16]. Nevertheless, the LQG regulators are limited in terms of the level of performance they offer to the wind turbines which have non-linear features. The pitch angle was controlled by the traditional PID or PI controllers which controlled their output voltage. Also discussed in the paper is the power systems oscillation damping which are made by the robust synchronous voltage sources. It also deliberates regulation of the single fluctuating wind turbines and the utilization of a non-removable magnet matched generator [17]-[20]. The LQG generator has been recommended because it is able to handle the systems nonlinearity features [21]. As opposed to the use of the turbine which consists of a fixed wind speed, the variable wind turbine is able to produce high power levels as well as reduced levels of tension. The pitch angle controller is also an important aspect of the generation of energy using the linear regulator [22]-[26]. The use of PI and PID for power generation however, has a setback in their regulation outcome. In addition, STATCOM, which used to enhance performance of wind turbine plants, are able to manipulate wind turbine driven induction generators [27]-[29]. This has led to the creation of state-space models and regulations on the FACTS which enhance the damping in machines used to generate electricity to the national grid [30]-[33].

The creation of the WECS regulation method is a complex project. Complexity results from the numerous input and output (MIMO) systems which consist of robustly attached variables. The nonlinearity nature of the input power and the natural hindrances of the system differences also cause

difficulties to the regulation design creation [34]-[36]. Model predictive control (MPC) is one of the control methods that attracted researchers attention to improve the performance of the WECS. There are two sub-categories derived within the electrical area of the MPC drives. The first category is based on the advancement of the conventional field-oriented control in which changes are made to the internal current loops [37]-[38]. It is done with a MPC regulator without removing the modulator. In the second sub-category, the modulator in the first category is removed and the MPC controls the inverter [39]-[40]. Recently, the electric energy and the drive groups such as the power electronic have significantly identified with the MPC ideology. A different form of MPC is the Model Predictive Direct Torque Control (MPDTC). It is an old model and an addition to the DTC with improvement in the lookup table. It came about with the enhancement of the internet by regulating the torque as well as flux in the machines [41]. The MPC is a newer version which is responsible for controlling the machines stator currents [42]-[45].

In this paper, the MPC approach will be used, creating a reasonable regulator integrated in the system. There will also be the utilization of the mathematics concepts, MIMO and WECS for projection. The requested techniques have been validated by the use of Matlab/Simulink. Therefore, the objective of this paper to determine and standardize the apprentice MPC system set in contrast to the PID system. However, the PID does not take an active role in this paper. The paper will be divided into four sections, with section one giving a summary of the drive model. Section two will assess problems and recommend ways to achieve the highest level of wind turbine energy using the MPC system. The last chapter will display results and discussions regarding the regulation system and assessment of the entire process. Conclusion will include the resulting energy as well as speed originating from the rotation of the wind turbine.

2. WECS Model:

WECS changes electric energy from kinetic energy through a process where air streams are converted into electric energy. The conversation process takes place when wind causes the blades to rotate which in turn spins the turbines. The spinning rotor drives the machine which then produces electricity. Currently, many wind turbines are built on the lateral design and consists of either two or three blades as shown in

Figure 1 [2]. Energy transformation in the wind turbines takes place in four sub-systems as illustrated below [4]:

- Electric generator model – this works together with the basics required for local grid connection. MPC or PID controls the inputs to generator model and pitch actuator system to improve wind turbine efficiency.
- Aerodynamic model – These are the blades for the turbine. Input factor consist of the speed of wind, how fast the rotor spins and the pitch angle. Output on the other hand

consists of the rotation of the rotor which in turn produces electricity.

- Pitch actuator model – This part consist of mechanical servo that rotates the turbine blades against the wind to regulate the generator rotor speed.
- Drive train model – involves the speed shafts, the turbine hub, and the speed multiplier. The input in this section constitutes the rotor rotation and speed multiplier which drives the train model. The rotor speed and shaft rotation make up the output.

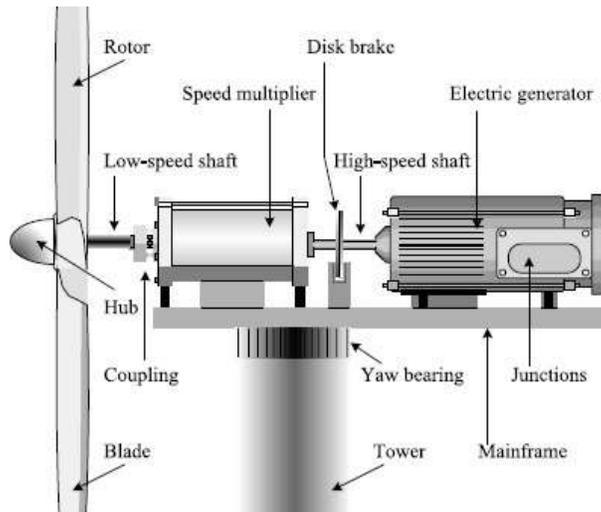


Fig.1. Elements of a two-bladed horizontal axis wind turbine

Figure 2 shows WECS modeled as a three fundamental system. It shows a standard practice in WECS control. Further explanations are given below. T_r and T_g are the rotor torque and generator torque input to drive train model, and ω_r , and ω_g consist of the revolving speed of the rotor and generator speed.

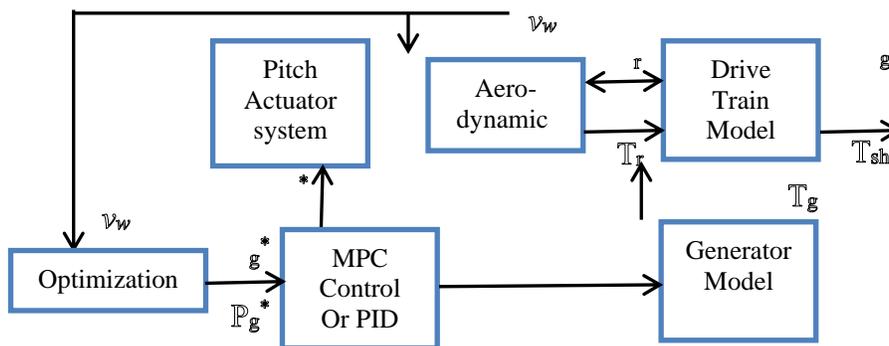


Fig.2. Aerodynamic, Mechanical, and Electrical model of the WECS

The enhanced wind turbine technology has improved the wind energy sector. It has caused a reduction in the cost of wind energy production and can now match other forms of electricity. The innovation has transformed wind turbine form the traditional constant speed to variable speed which is more efficient. There are assumptions that the wind turbines which generate high levels of energy more than the recorded speed are not cost effective. According to

Figure 3, the energy curve divides into three specific areas. Area 1 constitutes mild wind speed lower than the rated power of the turbines, therefore the turbine is operated at the highest possible level. Area 2 is the transformation area and responsible for reducing the level of noise. Lastly, Area 3 experiences high wind speed and it is where the turbine derives their highest level of power. At this level, the wind turbines are regulated within limits of the optimal energy.

According to Figure 4, the variable-speed variable-pitch WECS is made up of two operating areas. First, the partial load regime consists of all the different wind speeds and rotors of the wind turbine responsible for achieving the highest level of performance. Secondly, the full load regime consists of wind turbines which are run when the speeds level are high or below the v_{co} .

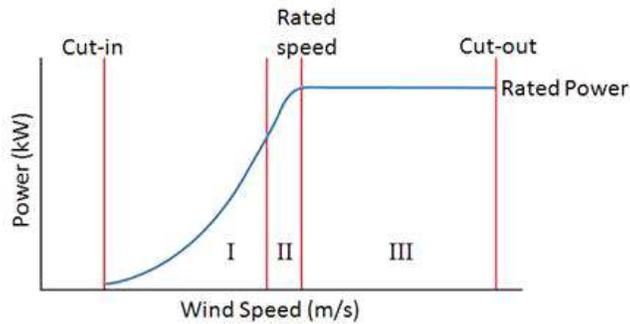


Fig.3. Ideal WT Power Curve

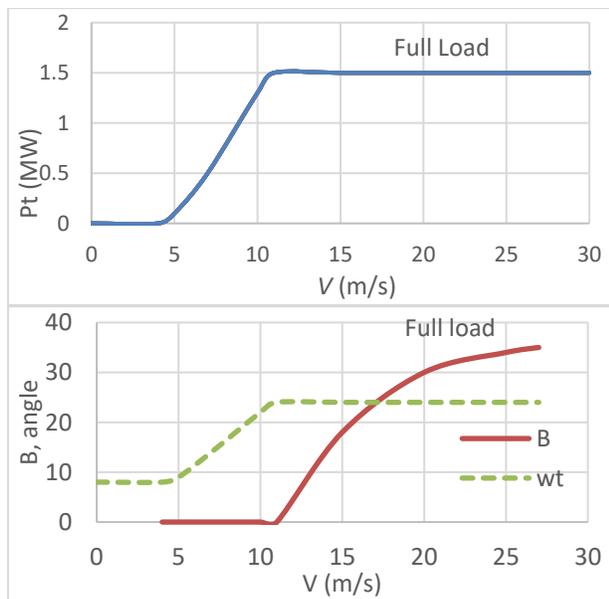


Fig.4. Variable-speed variable-pitch WECS power curve.

The control systems in this area controls output energy and the speeds of generator based on their expected speed levels. In Figure 5, the energy coefficient forms the wind turbine. It is known as the ratio of recorded output of energy to the free stream-like power flowing in the same area. The tip speed ratio λ is defined as the speed of the wind turbine at the highest part of the blade to the free stream speed of wind. The speed on the tip of the blade has to reach a certain speed so that the wind turbine can generate maximum energy [10]-[13]. Utilizing an efficient control technique such as MPC will produce this desirable outcome. The highest output energy released does not flow in the same direction as the highest torque level. Both follow different laws with the output energy following the cube law while the torque takes the square law [15].

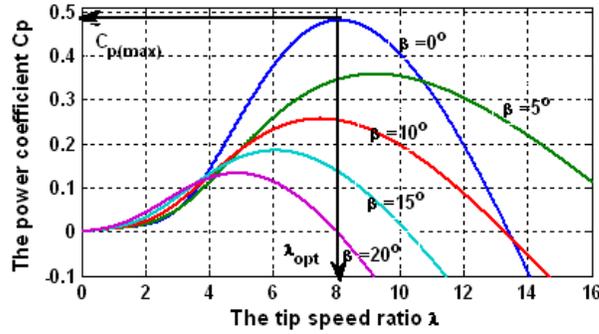


Fig.5. WECS power coefficient vs tip speed ration

2.1 Wind Turbine Aerodynamics System

The aerodynamic system converts wind energy into useful mechanical energy. A thorough discussion about wind turbine aerodynamics can be found by reading [16]-[20]. It is important to understand the equations about the torque and how power is captured by the blades. Figure 6 illustrates three aspects (wind, energy curve, and responsiveness to wind fluctuations) of capturing wind energy. The energy and torque derived from the wind is shown in the equations below

$$P_w = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 v_w^3 \tag{1}$$

$$T_a = \frac{1}{2} C_T(\lambda, \beta) \rho \pi R^3 v_w^2 \tag{2}$$

where

- P_w is power extracted from the wind.
- T_a is aerodynamic torque of the rotor.
- ρ is the density of air.
- R is the radius of the blades.
- v_w is the wind velocity.
- C_p is the power coefficient.
- β is pitch angle of the rotor blades.
- C_T is aerodynamic coefficient.

C_p and C_T are nonlinear functions with respect to the tip speed ratio and the pitch angle and have the following relation, $C_p(\lambda, \beta) = \lambda C_T(\lambda, \beta)$, λ is tip speed ratio. The ratio between blade tip speed and wind speed upstream the rotor.

$$\lambda = \frac{\omega_r R}{v_w} \tag{3}$$

Where: ω_r is the rotational speed of the rotor in (rad/s) and v_w is effective wind speed (m/s).

$$\delta T_a = -\beta_w(\omega_r, v_w, \beta) \delta \omega_r + -\beta_v(\omega_r, v_w, \beta) \delta v_w + -\beta_\beta(\omega_r, v_w, \beta) \delta \beta \tag{4}$$

$$\beta_w(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta \omega_r} |_{(\omega_r, v_w, \beta)} \tag{5}$$

$$\beta_v(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta v_w} |_{(\omega_r, v_w, \beta)} \tag{6}$$

$$\beta_\beta(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta \beta} |_{(\omega_r, v_w, \beta)} \tag{7}$$

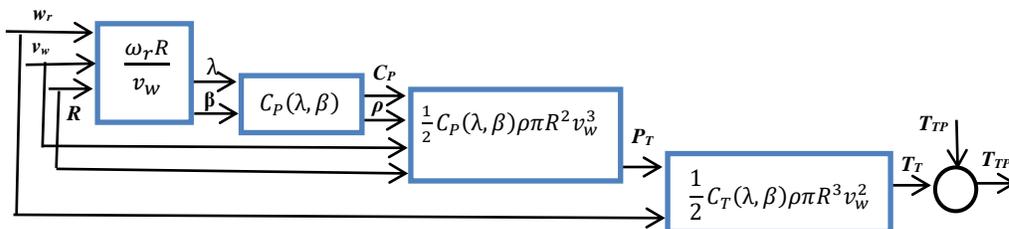


Fig.6. Block diagram of the aerodynamic wind turbine model

The blades are designed to ensure the highest energy coefficient outcome at the best speed on the tip speed ratio λ_{opt} . The energy coefficient is based on the speed at the tip and will fall under $0 \leq C_p \leq 0.4$. However, it will not be able

to attain the maximum value C_p , referred to as Betz Limit, $C_p < C_{p-Betz}=0.593$. [8]. The equation below illustrates utmost collected energy and aerodynamic torque of the wind turbine:

$$P_{max} = \frac{1}{2} C_{p,max}(\lambda_{opt}, \beta) \rho \pi R^2 v_w^3 \quad (8)$$

$$T_{a,max} = \frac{1}{2\lambda_{opt}^3} C_{p,max}(\lambda_{opt}, \beta) \rho \pi R^5 \quad (9)$$

2.2 Pitch Actuator System:

This is a non-linear system that rotates the blades of the wind turbine. It is created using the saturation of the amplitude which can be modeled as a first-order or second-order dynamic equations [23]. Figure 7 demonstrates the first-order system of the actuator.

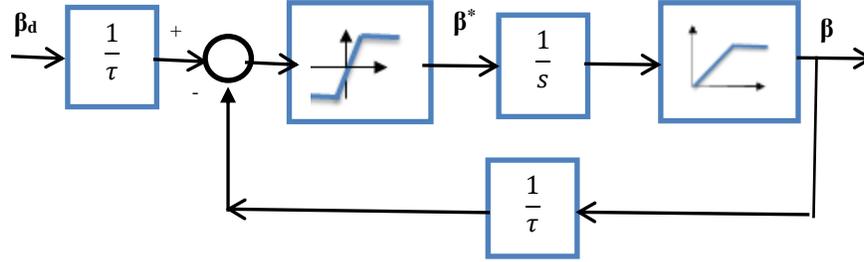


Fig.7. Pitch angle actuator model

The equation below illustrates the changing performance of the pitch actuator.

$$\beta^* = \left(\frac{1}{\tau}\right) \beta_d - \left(\frac{1}{\tau}\right) \beta \quad (10)$$

Where:

$$\beta_{min} \leq \beta \leq \beta_{max}$$

$$\beta_{min}^* \leq \beta^* \leq \beta_{max}^*$$

β is actual pitch angle (0-45°), with $\pm 10\%$ max.

β^* is desired pitch angle

After calculating the desired pitch angle, the error in the closed loop has to go through a pitch angle limiter to bound the rate of change on the blades angle which results in increasing the blades lifetime [24].

2.3 Drive Train System:

Figure 8 shows the model made up of two mass mechanical models which are connected using a shaft with damping and stiffness coefficients. This shaft can be modeled as a torsion springs connecting two masses; the turbine inertia and the generator inertia [26].

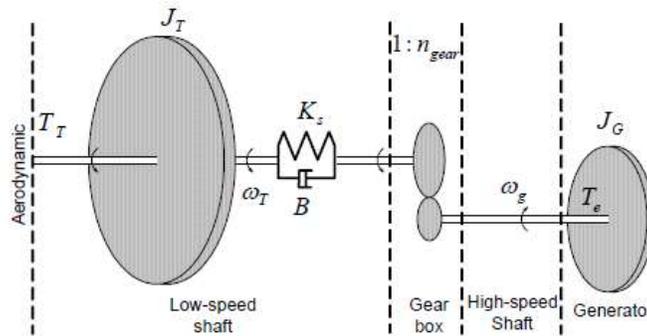


Fig.8. Two mass model for the driven train

The mechanical model can then be described by the motion laws:

$$\omega_T = \frac{1}{J_T} (T_T - (K_s \delta \theta + B \delta \omega)) \quad (11)$$

$$\delta\dot{\theta} = \delta\omega \tag{12}$$

$$\omega_g = \frac{1}{J_g} \left(\frac{1}{n_{gear}} (K_s \delta\theta + B \delta\omega) - T_g \right) \tag{13}$$

$$\delta\theta = \theta_T - \theta_g \tag{14}$$

$$\delta\omega = \omega_T - \frac{\omega_g}{n_{gear}} \tag{15}$$

2.4 Generator System:

It is important to model only the generator side converter considering the control system design of the wind turbine. The following equation represents the overall component of the generator torque control action by the generator side for second-order dynamic systems:

$$\frac{T_g(s)}{T_g^*(s)} = \frac{\omega_{ng}^2}{s^2 + 2\xi_{ng}\omega_{ng}s + \omega_{ng}^2} \tag{16}$$

Where: T_g^* is the generator torque command
 $(\omega_{ng} \approx 40 \text{ r/s})$ is the natural frequency
 and $(\xi_{ng} \approx 0.7)$ is the damping ratio of the generator dynamics.

3. Linearize WECS Model:

According to the rotor, the aerodynamic rotation, and non-linear function of wind speed, rotor speed and pitch angle can be formulated into a linear equation as below:

$$\delta T_a = -\beta_w(\omega_r, v_w, \beta) \delta w_r + \beta_v(\omega_r, v_w, \beta) \delta v_w + \beta_\beta(\omega_r, v_w, \beta) \delta \beta \tag{17}$$

Where: $\beta_w(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta w_r} |_{(\omega_r, v_w, \beta)}$

$$\beta_v(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta v_w} |_{(\omega_r, v_w, \beta)}$$

$$\beta_\beta(\omega_r, v_w, \beta) = \frac{\delta T_a}{\delta \beta} |_{(\omega_r, v_w, \beta)}$$

For state space equation:

$$\dot{X} = AX + BU + GW \tag{18}$$

$$Y = CX \tag{19}$$

Where:

$$X = [\delta w_r \quad \delta v_w \quad \delta T_{sh} \quad \delta T_g \quad \delta \beta]^T$$

$$U = [\delta T_g^* \quad \delta \beta^*]^T$$

$$Y = [\delta v_w \quad \delta P_g]^T$$

Then:

$$A = \begin{bmatrix} \frac{\beta_w}{J_T} & 0 & \frac{-N}{J_T} & 0 & \frac{\delta\beta_\beta}{J_T} \\ 0 & 0 & 0 & 0 & 0 \\ K_D N + \frac{N D_{sh} \beta_w}{J_T} & -K_{sh} & -\left(\frac{N^2 D_{sh}}{J_T} + \frac{D_{sh}}{J_g}\right) & 0 & \frac{N D_{sh} \beta_\beta}{J_T} \\ 0 & 0 & 0 & \frac{-1}{\tau_g} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{\tau_r} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\tau_g} & 0 \\ 0 & \frac{1}{\tau_r} \end{bmatrix}, \text{ and } G = \begin{bmatrix} \frac{\beta_v}{J_T} \\ \frac{N D_{sh} \beta_v}{J_T} \\ 0 \\ 0 \end{bmatrix}$$

And:

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & \tau_r & 0 & 1 & 0 \end{bmatrix}$$

Equation (17) shows the wind speed model based on equation (21). And is explained on [21] The model consists of tower shadow, wind shear and rotational sampling effects. The working positions are ascertained by the regulatory strategy. However, it has limitations such as energy, rotor, wind speed and pitch angle [22]. Equations (18) and (19) establish, increase and assess the various wind speeds. It later creates equation 18 and 19 which are the linear model of the entire system. The state vector and the regulatory input are the assessed results. The system is then described as MIMO which has a changing dynamics whenever there is a change of wind speeds.

4. Problem Description:

The main task is to regulate the rotor speed of the turbine which will in turn enhance the smoothness in the turbines making them efficient; especially at the limited load regime. The process however has a limitation which occurs during the creation of the regulator. The regulator is able to completely enhance the changed efficiency while at the same time reducing the temporary loads. The outcome indicated that variances existed between two objectives which required a balancing position [34]. The objective of regulation when operating at full load regime is to control the generator resulting energy and equally control the generator at set standards. The greatest limitation at this point is the big percentages of variations in the turbines energy. The percentages are caused by fluctuations in wind speed. The limitation also leads to a fluctuation in the drive train torsion torque as well as output electric power delivered to the grid. This power must be regulated thereby reducing the WECS apparatus and the flicker troubles [36].

Power Maximum WT

Ordinary tests on the full load and partial regimes occur when the systems dynamics are not linear and viable variations occur at the operational center. Another test occurs when the system has cyclic aerodynamic torque difference and the turbine blades are rotating at three times their speed. This occurrence is known as the rotation sampling effect which is caused by uneven wind. Similarly, regulatory systems must identify regulatory goals kept at a certain level when facing limitations. For example, the highest level 1 is based on amplitude, speed pitch servos, generator energy and the speed of the turbines. Normally, variable speed and pitch consist of two working areas. The first is undertaken in partial load region with the aim of deriving the highest level of energy by regulating the turbine rotor speed. The second working area is the full load region where regulatory processes are able to alter the resulting energy as well as the speed of the generator at standardized figures. This creates difficulties especially in the WECS design since the MIMO system is not linear. In addition, factors such as the stochastic and sustainable differences of the speed of the wind and the restrictions by the system limit must be considered. The model illustrated above provides further complications to the regulatory design process. When assessed in the same level as the fixed speeds wind turbines, the variable speeds wind turbine has greater benefits such as increased production of energy on lower costs [44].

MPC control method can alter, regulate and predict perceptions of predictive models. It can also alter limitations and different weights. When varying scenarios are run on the system, which could either be linear or non-linear, the MPC can assess the regulatory performance. This can be seen in the altering of chemical processes and electromechanical systems. It is most beneficial when used in predictive model and is relevant in deriving regulatory actions by reducing certain functions which are objective. MPC optimization takes into consideration reduction of the variances existing in the predicted and reference parameters. The regulatory attempt is also based on the determined limitations.

The MPC takes the following approach:

- The expected outputs for the anticipated prospect n , are predicted at each instant, t using the process model. These predicted outputs $y=(t+k(t))$, for $k=1, \dots, n$, depends on the known values up to instant t (past inputs and outputs) and on the future control signals $u=(t+k(t))$, $k=0, \dots, n-1$, is calculated out of the process.
- The set of future control signals is calculated by an enhancing categorization in order to keep the process as close to the reference trajectory $w=(t+k)$, which can be the set point itself or a close approximation of it. This standard typically takes the appearance of a quadratic role of the errors between the predicted output signal and reference trajectory.
- The regulatory indication $u(t)$ is taken to the system while the next regulatory indicator calculated rejected, since the next sampling instant $y(t+1)$ is already known and step 1 is repeated with this new value.

The MPC model is vital in the prediction of future outputs arising from current values and expected future regulation action based on general composition as illustrated in Figure 9. When using the linear model, over prediction are based on open and compulsory answers. The optimizer allows for the selection of the most beneficial regulation systems hence reducing cost functions. This is carried out by getting the weighted sum of the square predicted inaccuracy as well as square predictable regulatory figures. They are calculated at the high and low predicted possibilities and are known as the regulation perspective. The regulatory perspective allow the reduction allow the reduction in the predicted regulation based on the $\Delta u(k+j)$ for $J \geq N_u$. The $w(k+j)$. This signifies the location route over the regulatory perspective N .

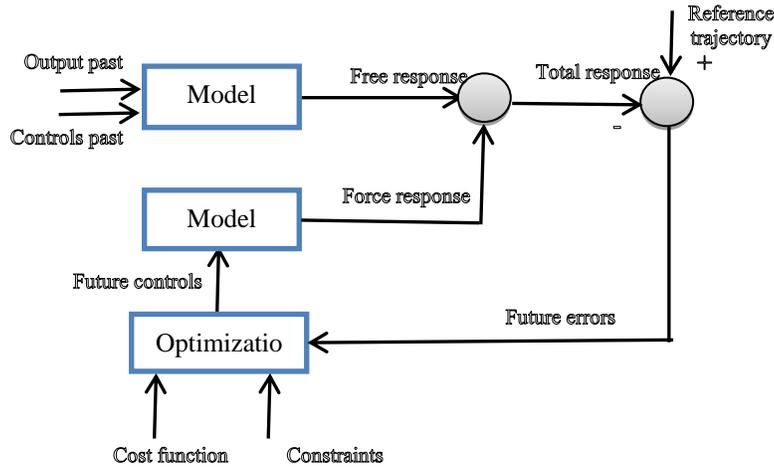


Fig.9. MPC Controller

Limitations placed on the regulatory indicators, the outputs, and regulatory indicator varying can be included in the following equation:

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \beta(j)(y(k+j) - w(k+j))^2 + \sum_{j=1}^{N_u} \lambda(j)(u(k+j) - 1)^2 \quad (20)$$

If N_1 , N_2 fall at the bottom and highest prediction level on top of the results, then N_u is the regulatory possibility, $\beta(j)$, $\lambda(j)$ are weighting variables. Limitation on the regulatory indicators, results as well as regulatory indicators varying can be included in equation below:

$$\begin{aligned} u_{min} &\leq u(k) \leq u_{max} \\ \Delta u_{min} &\leq \Delta u(k) \leq \Delta u_{max} \\ y_{min} &\leq y(k) \leq y_{max} \end{aligned} \quad (21)$$

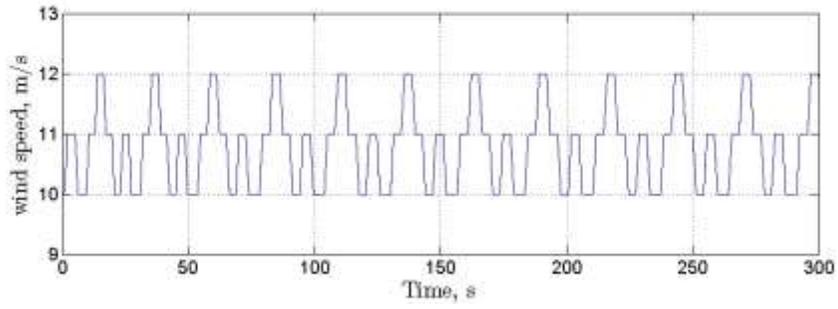
The outcome of Eq. (20) derives the best order of regulation indicators based on the perspective N and at the same time recognizing limitation on Eq (21). The MPC has many benefits such as the ability to control different systems, easy to use on complex systems, and offer prediction even if the outcome is delayed. Similarly, it can bring about the predicted results in systems which are closed loop. It can also be used to achieve the best outcomes with recognition of limitations. Although the benefits are diverse, it requires skills for anyone to model the system and handle its limitations. The MPC model is more complex as compared to PID since it requires more calculations.

5. Results and Discussions:

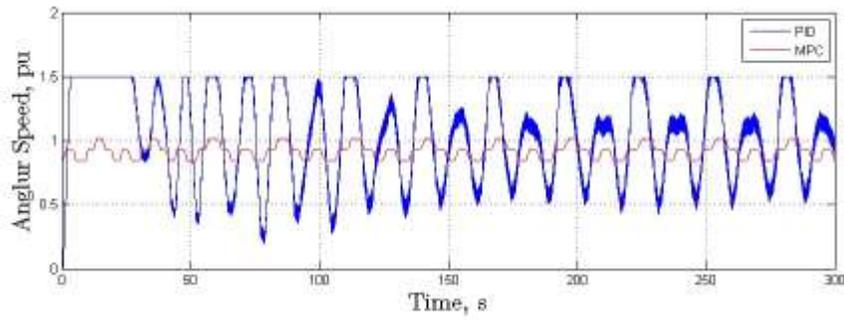
The considered 600 KW turbine consist of three blades and pitch regulator. The feature of the MPC is an advantage over conventional linear controller PID including nonlinear control action. It can also reduce the noise, disturbance and parameters variations. The results for partial and full load operation, MPC and PID controllers are similar in their limitations. They include wind velocity, angular momentum, pitch angle, generator power as well as torque output for 300 esc. The system parameters are shown in Appendix.

5.1 Partial Load Operation:

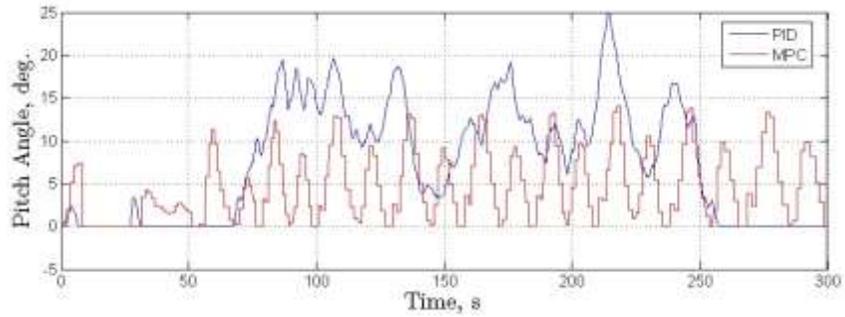
Figure 10 shows the results from the reputation exercise conducted for 300 seconds of partial load WECS process. The outcomes reveal that the MPC and the PID regulators had identical tracing performance as observed in the speed of the generators. The MPC and the PID was seen to have similar energy production capability. However, the energy output from the MPC was more stable. The generator energy variations and the rotation of the generator were reported to be similar for both MPC and PID. This resulted from the consistency of the return speed from the generator in tracking the maximum point tracking. Nevertheless, amounts of these variations reduce with the use of the MPC control strategy.



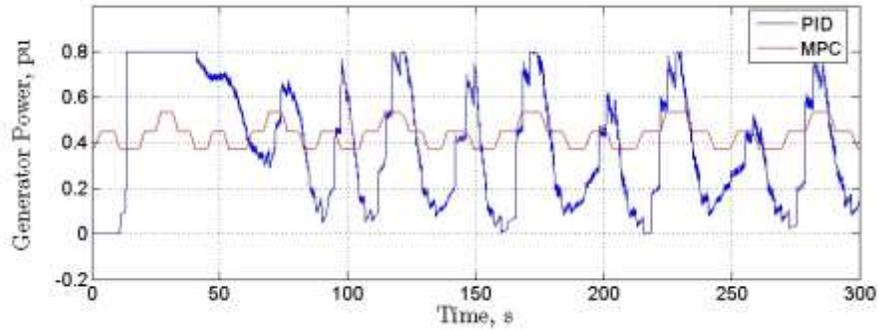
(a) Wind speed, m/s



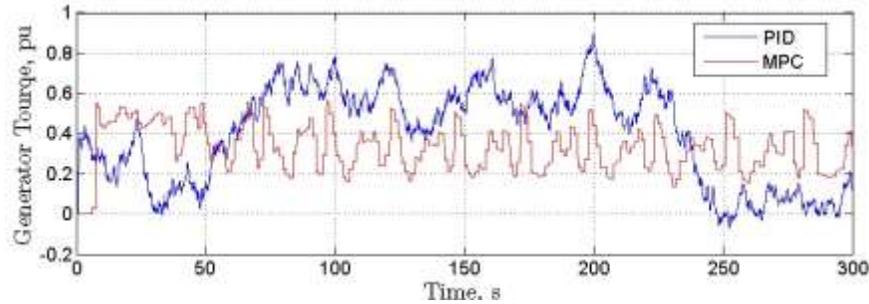
(b) Angular speed, pu.



(c) Pitch angle, deg.



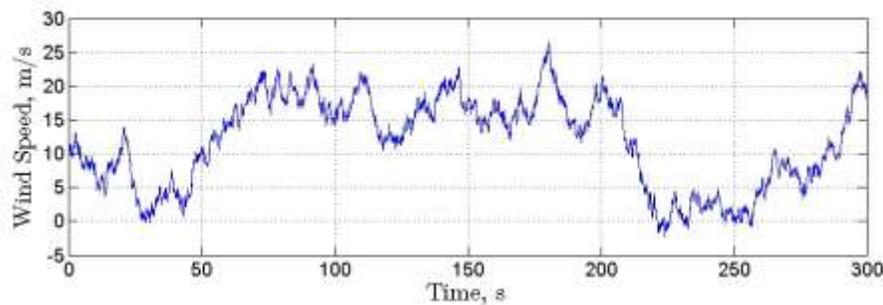
(d) Generator power, pu



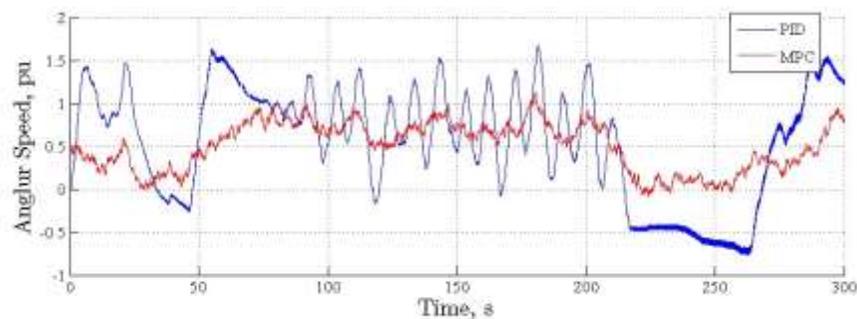
(e) Generator torque, pu.
Fig.10. Partial load operation

5.2 Full Load Operation:

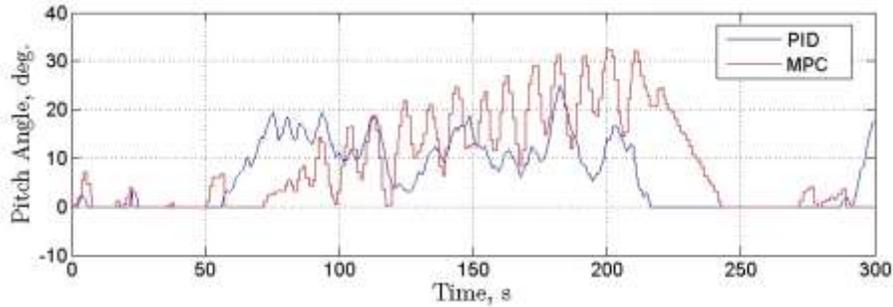
Figure 11 shows a duplicate outcome key for an operation that consists of a full load. It is important in examining the strength of the suggested MPC against uncertainties in the parametric. The power production when using the MPC leads to a more even and decreased fluctuation levels in the power output. The value of the decrease on the fluctuation of power production is enabled and enhanced based on the speed variations in the generator when compared to the PID control method as shown in Fig. 11. Since the speed of wind is up to the first 50 seconds, it is below the rated wind speed 10m/s as shown in Figure 11(a). The pitch angle is forced to level zero while the devolved torque is manipulated. In addition, from time 50 to 218 seconds, the angle pitch control is introduced to get the maximum power above the rated wind speed as in Fig. 11(d). Compared to the PID controller that forces the pitch angle to zero at early time of 218 seconds, this enhances the wind power exploitation.



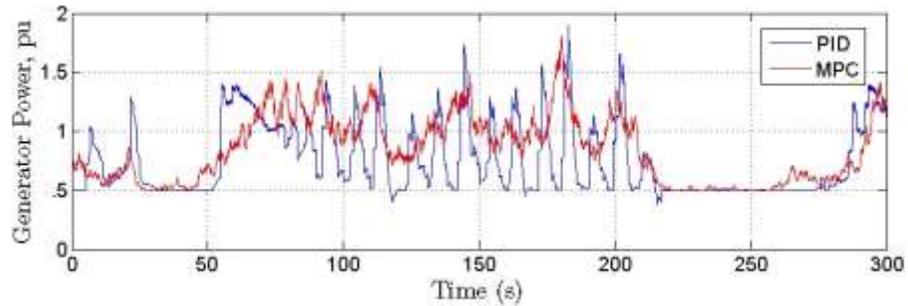
(a) Wind speed, m/s



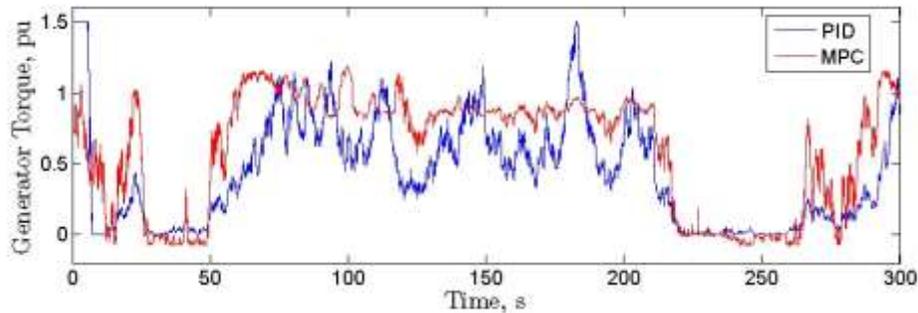
(b) Angular speed, pu.



(c) Pitch angle, deg.



(d) Generator power, pu.



(e) Generator torque, pu.

Fig.11. Full load operation

Table 1 shows the evaluation of performance in the two systems and this arises because of the sustainable differences in the w_g^* which follows the MPT. However, the scales of these fluctuations reduce with the utilization of the MPC regulation approach. When the MPC is compared with other methods based on performance, the MPC is vital for either strong or mild wind speeds. Table 1 illustrates average speed in the generator, the average energy, as well as the highest pitch motion. The outcomes from Table 1 indicate captured power shut by union at the mild or strong wind speeds. Nevertheless, the highest level of the pitch angle was reduced by the MPC regulator as compared to the PID. The requested method proved most valuable as compared to other methods based on the level of performance.

Table 1. Output parameters for MPC, and PID controllers

Parameters	Mild wind velocity		Strong wind velocity	
	MPC	PID	MPC	PID
Power output, pu.	0.97	0.73	0.94	0.87
Pitch angle, deg.	26	13	34	26
Generator speed, pu	0.89	0.81	0.89	0.78

6. Conclusion

The main objective of the paper was to examine the variable speed as well as the pitch turbine regulatory designs. This was to be carried out with the goal of deriving full wind energy and enhancing the progress between the two methods of wind turbines; the full load and partial load. The paper has also illustrated how the MPC controller regulates the wind turbine. It introduces a system which is dynamic based on its speed, pitch wind turbine as well as limitations in the of the rotation and pitch angle regulator. The analysis indicates that the MPC which is made of both linear and soft actions is stable when it comes to the progression of the wind turbine. Its stability is in terms energy usage and energy limitations of the rotation regulation when used at partial load regime and at the pitch of the blade. The regulation must be used at full load regime. The wind turbine performs best when there is better utilization and satisfactory drive train transient loads. There must also be efficient application which is simple when compared to the PID regulator approaches where a controller has to be designed. The replication outcome from the exercise revealed that the MPC regulator was steady when compared to the parameter perturbation of the approach. The MPC was also seen to have better performance outcome as compared to the PID regulation design.

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Appendix:

Studied system parameters:

Equivalent mass tower = 15×10^4 Kg, Blade mass = 9.6×10^3 Kg, Blade length = 38.5 m, Rotor diameter = 80m.

Rotor, blade, and generator moment of inertia = 6×10^6 Kg.m²/sec, 2×10^6 Kg.m², and 245 Kg.m² respectively.

Tower stiffness = 1.18×10^6 N/m, Blade stiffness = 72×10^6 Nm/rad, Rotor damping = 1.25×10^6 N/m/sec,

Density of air = 1.25 Kg/m³, gearbox ratio = 62, and pitch time constant = 0.1 sec.

Nominal, cut-in, and cut-out wind speed = 10, 4, and 25 m/sec respectively.

Rated power = 1.5MW, nominal generator speed = 120 rad/sec, and generator time constant = 0.5 sec.

MPC Predicted horizon = 10, and MPC Control horizon = 2.

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