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Power Turbines Control, Part III: Wind Turbine Speed Control using PD-PI, PI-PD and 2DOF-3 Controllers Compared with a PI Controller

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Abstract:

This paper is the third in a series of research papers presenting the control of power turbines using controllers from the second generation of PID controllers. It handles the control of wind turbines speed using PD-PI, PI-PD and 2DOF-3 controllers with comparison with the use of a PI controller from the first generation of PID controllers. The MATLAB optimization toolbox is used to tune the four controllers an ITAE performance index. The step time response of the control system using the three proposed controllers is presented and compared with using a PI controller to control the same wind turbine and the time-based characteristics are compared. The comparison reveals the best controller among the four controllers depending on a quantitative comparison study for both reference and disturbance inputs.

Keywords — Power turbines control, wind turbine speed control, PD-PI controller, PI-PD controller, 2DOF-3 controller, PI controller, controllers tuning.
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I. INTRODUCTION

Wind turbines are of the important renewable machines used in electric energy production. We start by taking an idea about some historical literature about the use of wind turbines along the human history and some of the research work regarding modeling and control of wind turbines-generators systems:

It was reported that a wind-driven wheel was used to power a machine by Heron of Alexandria (Greek Engineer) in the first century AC [1]. It was reported also that the first use of wind wheels for grain mills was during the rule of the second Caliph of the Islamic state, 'Omar Ibn Alkhattab' in 644 AC [2]. The first use of wind wheels in electricity generation started in 1883 by the Austrian 'Josef Friedlander at Vienna Electrical Exhibition [3]. In USA, the first constructed wind turbine for electricity generation was in 1887-1888 for 12 kW electricity generation by Charles Brush [3].

Leith and Leithhead (1997) studied the implementation of three genetic issues to develop controllers for constant speed wind turbines. They presented stability analysis of controller start-up and proposed an anti-wind-up method based on the start-up strategy they presented. They considered controller realization using a 300 kW turbine [4]. Wright and Fingersh (2008) handled control development for wind turbines covering control objectives, controller design, controller testing, field implementation and field testing. They outlined that classical control design techniques such as PID control for pitch regulation are used to design the controls for wind turbines. They outlined also that MIMO control design method can be used to meet multiple control objectives and use the available actuators and control inputs in a single control loop [5]. Ostergaard, Stousrup and Brath

(2009) presented the design of linear parameter varying (LPV) controller for wind turbines for the purpose of obtaining multi variables control law covering the entire operating trajectory. They proposed a controller construction algorithm used to design a LPV controller for wind turbines with comparison with controller designed using classical techniques[6]. Pintea, Popescu and Borne (2010) stated that wind turbines have proven to be the cheapest and most reliable solution for energy production. They used a polynomial control method to control the wind turbine. They derived 5th order transfer function models for a wind turbine and applied their proposed controller to control it [7].

Singh and Santoso (2011) presented an introduction to wind turbine modeling considering a fixed-speed wind turbine as a machine having four elements: prime mover (turbine and blade assembly), shaft and gearbox unit, generator and control unit. The presented a block diagram for a fixed-speed wind turbine between the wind velocity and generator electrical output. They derived the mathematical model of the four units and presented the power curve of the wind turbine generator system in MW for wind speed from 0 to 20 m/s. They investigated the modeling of variable-slip wind turbine generator with rotor resistance control for power output control using a PI controller. They presented two-loop PI controller for output power and rotor current, the step time response of the pitch angle for wind speed change from 11 to 15 m/s [8]. Mahdi, Tang and Wu (2011) derived a complete transfer function of a variable speed wind turbine generator system using a reduced order model method verified experimentally. They concluded that the simulation results of the reduced model order were reliable and very close to simulation using full order model and experimental results [9]. Pintea, Christov, Borne and Popescu (2011) discussed the application of a robust multivariable control system designed for a variable speed wind turbine. They designed a H∞ controller based on a linear model. They used an H∞ theory to design the controller for robust performance and stability and discussed the performance of the dynamic system dynamics through using the proposed controller and presented by MATLAB simulation [10].

Vidyanandan and Seroy (2013) discussed the application of reduced order dynamic models of deloaded wind turbine generator for frequency regulation studies. At constant wind speed, they linearized the nonlinear model to obtain first-order transfer function models relating the system frequency and generator output power. They displayed the first-order transfer function of the wind turbine generator system against wind speed from 9 to 12 m/s [11]. Rosyadi et al. (2015) presented simplified models for wind farm composed of variable speed wind turbines with two types of generators for dynamic simulation study. They performed simulation analysis in time domain for steady-state and transient nature to check the accuracy of the proposed models and presented comparison analysis between the proposed simplified and the detailed models showing sufficient accuracy for the simplified models for steady-state and transient conditions. They presented a ½ transfer function for a steam turbine between power and speed change [12]. Toft, Poulsen, Christiansen and Knudsen (2016) proposed a linear analysis method for wind turbine blade fatigue testing. Their objective was to make the turbine blade oscillated with controlled amplitude. They designed a linear controller (integral) regulating the input amplitude of the blade vibration. They derived a nonlinear model for the blade and linearized it to suit the linear analytical control system design. The gain of the controller was determined using pole placement and the controller achieved robustness and actuation energy reduction [13].

Menezes, Aranjo and Silvia (2018) stated that the control of wind turbines plays a key role in wind energy applications ensuring high efficiency and cost effectiveness. They presented a literature review for wind turbine control and assigned the objectives of their work to form detailed background for new researchers on wind turbines. They discussed the most recent control developments for wind turbine control [14]. Bouderbala et al. (2018) presented modeling and power control of wind energy conversion systems based on doubly fed induction generator by using PI regulators. They derived the model of the wind energy conversion system and applied the PI regulator. They presented the results using MATLAB/simulink [15]. Rodaideh, Bodoor and Al-Quraan (2021) proposed an optimal gain scheduling for linear quadratic regulator to control the performance of wind turbines and doubly fed induction generator. They used an active and reactive power decoupling to simplify the generator nonlinearities and derive a compact linear model. They used the whale optimization algorithm to optimize the liner quadratic regulator. They integrated the control framework with the effect of pitch angle control mechanism for active power improvement and reactive power support. They compared the performance of the proposed control with a conventional PI controller [16].

Liu (2022) proposed a wind power grid-connected model based on permanent magnetic synchronous governor. He used a PI controller to control the pitch angle of the wind turbine and the waveform of the grid-side current. He presented simulation results revealed final output current frequency and phase meeting the requirements of grid- connection. He presented the time response of the pitch angle and the rectified-side DC generator voltage [17]. Ramzan et al. (2024) proposed a pitch control scheme based on using PI controller design. They proposed a flow chart for the proposed control methodology between wind speed, rotor speed and blades pitch angle. They did not present any dynamic model relating the input and output variables of the control system [18].

II. THE CONTROLLED WIND TURBINE GENERATOR AS A PROCESS

Mahdi, Tang and Wu derived transfer function models in reduced and full forms for a wind turbine generator dynamic system [9]. The experimental step time response of a wind turbine generator unit for wind speed from 4 to 8 m/s is shown in Fig.1 [9]. The y-axis of te plot is adjusted to start from zero change of speed at zero time of step application.

The experimental step time response of the wind turbine generator unit was far from the analytical one using both full and reduced models derived by the authors. Therefore, a reasonable transfer model for the experimental data in Fig.1 was identified by the author.

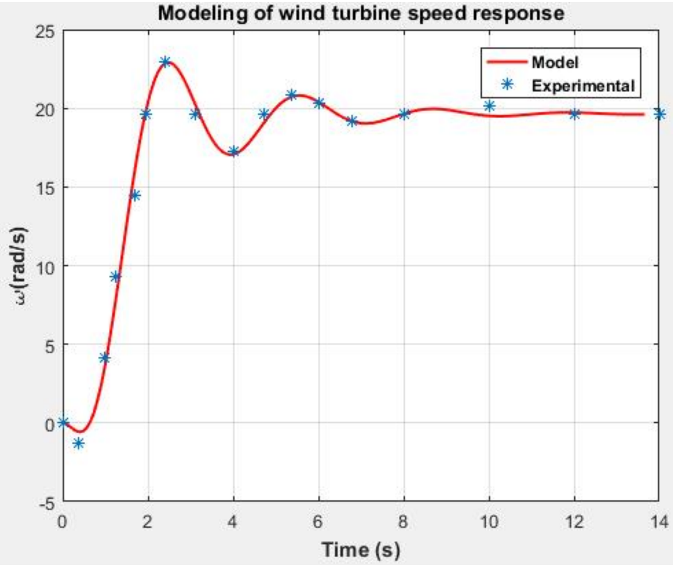

Fig.1 Wind turbine generator step time response.

A good model for the data in Fig.1 was a delayed second-order transfer function model for the speed of the wind turbine generator unit in rad/s and a step input of wind velocity having 4 m/s magnitude producing a process transfer function, $G_p(s)$ having the form:

$$G_p(s) = K\,\omega^2 \exp(-T_d s) \,/\, (s^2 + 2\zeta\omega_n s + \omega^2) \quad (1)$$

Where:

K = wind turbine generator gain = 19.65

ω_n = wind turbine generator natural frequency = 1.1 rad/s

ζ = wind turbine generator damping ratio = 0.9

T_d = wind turbine generator time delay = 0.5 s

To simplify the analysis of the dynamic system with time delays, Pade approximation is used to replace the exponential term with a rational form of polynomials of various orders. A first order approximation for the exponential term is [19]:

$$\exp(-T_d s) \approx (2 - T_d s) \,/\, (2 + T_d s) \qquad (2)$$

Combining Eqs.1 and 2 gives the wind turbine generator transfer function as:

$$G_p(s) = \frac{-KT_d\,\omega_n^2 s + 2K\,\omega_n^2}{T_d s^3 + (2\zeta\omega_n T_d + 2)s^2 + (T_d\,\omega_n^2 + 2\zeta\omega_n)s + 2\,\omega_n^2} \qquad (3)$$

- The wind turbine generator unit as an open-loop dynamic system has the dynamic characteristics (using Fig.1):
  - ➢ Maximum overshoot: 16.81 %
  - ➢ Maximum undershoot: -0.572 rad/s

- Settling time: 7.533 s
- Steady-state error: -18.614 rad/s

- This process dynamically has bad dynamics because of its high maximum overshoot and high steady-state error.

III. CONTROLLING THE WIND TURBINE GENERATOR USING A PD-PI CONTROLLER

The PD-PI controller was introduced by the author in 2014 as one of the good controllers of the second generation of the PID controllers. The author tested the performance of the PD-PI controller through its use in controlling first-order delayed processes [20], highly oscillating second-order process [21], integrating plus time-delay process [22], delayed double integrating process [23], third-order process [24], boost-glide rocket engine [25], rocket pitch angle [26], LNG tank pressure [27], boiler temperature [28] boiler-drum water level [29], greenhouse internal humidity [30], coupled dual liquid tanks [31], BLDC motor [32], furnace temperature [33], electro-hydraulic drive [34], barrel temperature [35], mold packing pressure [36], IMM ram velocity [37], full-electric IMM [38], Al-Jazari hydraulic turbine [39] and Banu Musa axial turbine power control [40].

The block diagram of the control system incorporating a PD-PI controller comprises a PD-control and PI-control modes in series after the error detector feeding its output directly to the controlled process.

The PD-PI controller has a transfer function, $G_{PDPI}(s)$ given by [30]:

$$G_{PDPI}(s) = [K_d K_{pc2} s^2 + (K_d K_i + K_{pc1} K_{pc2})s + K_{pc1} K_i]/s \quad (4)$$

Where:

K_{pc1} = proportional gain of the PD-control mode.

K_d = derivative gain of the PD-control mode

K_{pc2} = proportional gain of the PI-control mode.

K_i = derivative gain of the PI-control mode

The PD-PI controller has four gain parameters to be tuned to optimal performance for the control system.

- The transfer function of the control system comprising the PD-PI controller and the controlled process is derived using the block diagram of the control system and Eqs.3 and 4.
- The performance index to me minimized by the optimization technique was selected as the ITAE [41].
- The MATLAB optimization toolbox [42] is selected to perform the minimization of the ITAE and provide the optimal gain parameters of the PD-PI controller.
- The tuned parameters of the PD-PI controller are as follows:

$$K_{pc1} = 0.0854732 \quad , \quad K_d = -0.0392258$$
$$K_{pc2} = 0.1374682 \quad , \quad K_i = 0.2260196 \quad (5)$$

- Using the closed-loop transfer function of the closed-loop control system and the PD-PI controller gains in Eq.5 with reference input and zero disturbance input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response is generated using the MATLAB command '*step*' [43] and shown in Fig.2.

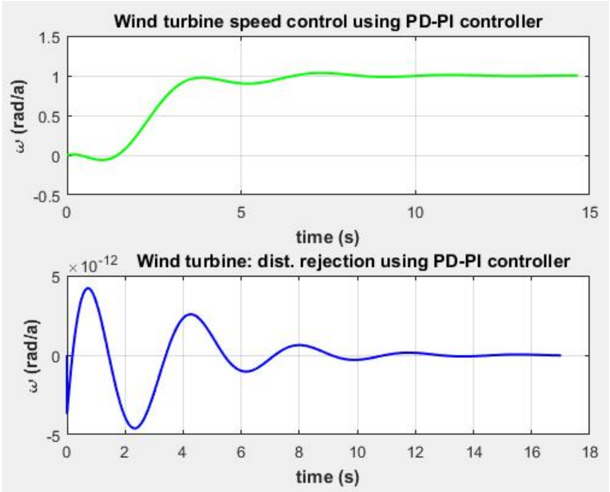

Fig.2 Wind turbine speed control using a PD-PI controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - Maximum percentage overshoot: 3.41 %

- Maximum undershoot: -0.0608 rad/s
- Settling time: 7.90 s

- Control system characteristics for disturbance rejection (with second-order high pass filter):
  - Maximum time response: 4.208×10^{-12} rad/s
  - Minimum time response: -4.601×10^{-12} rad/s
  - Approximate settling time to zero: 16 s

IV. CONTROLLING THE WIND TURBINE SPEED USING A PI-PD CONTROLLER

The PI-PD controller was introduced by the author in 2014 as one of the controllers of the second generation of the PID controllers. The author tested the performance of the PI-PD controller through its use in controlling a highly oscillating second-order process [44], second-order processes [45], delayed double integrating process [46], third-order process [47], boost-glide rocket engine [25], LNG tank pressure [27], boiler-drum water level [29], greenhouse internal humidity [30], coupled dual liquid tanks [31], BLDC motor [32], electro-hydraulic drive [34], barrel temperature [35], mold packing pressure [36], IMM ram velocity [37], full-electric IMM [38], Al-Jazary hydraulic turbine [39], Banu-Musa axial turbine power [40].

The block diagram of the control system incorporated the PI-PD controller is shown in Fig.3 [48]. It is composed of a forward element which is a PI control mode and a feedback element in an internal loop about the process which is a PD control mode.

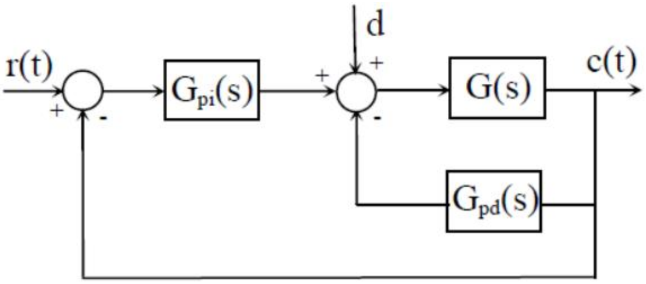

Fig.3 Structure of the PI-PD controller [48].

The PI-PD controller elements have the transfer functions:

$$G_{PI}(s) = K_{pc1} + (K_i/s)$$

$$G_{PD}(s) = K_{pc2} + K_d s \qquad (6)$$

Where:

K_{pc1} = proportional gain of the PI-control mode.

K_i = integral gain of the PI-control mode

K_{pc2} = proportional gain of the PD-control mode.

K_d = derivative gain of the PD-control mode

The PI-PD controller has four gain parameters to be tuned to provide the optimal performance of the control system. The tuning technique is the same as that used in the PD-PI controller in the previous section.

- The tuned parameters of the PI-PD controller are as follows:

$$K_{pc1} = 0.002447 \quad , \quad K_i = 0.023952$$

$$K_{pc2} = 0.004452 \quad , \quad K_d = 0.004840 \qquad (7)$$

- Using the closed-loop transfer function of the closed-loop control system and the PI-PD controller (using the block diagram in Fig.3 with zero disturbance signal) and the controller gains in Eq.7 with reference input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response of the control system incorporating the PI-PD controller is shown in Fig.4.

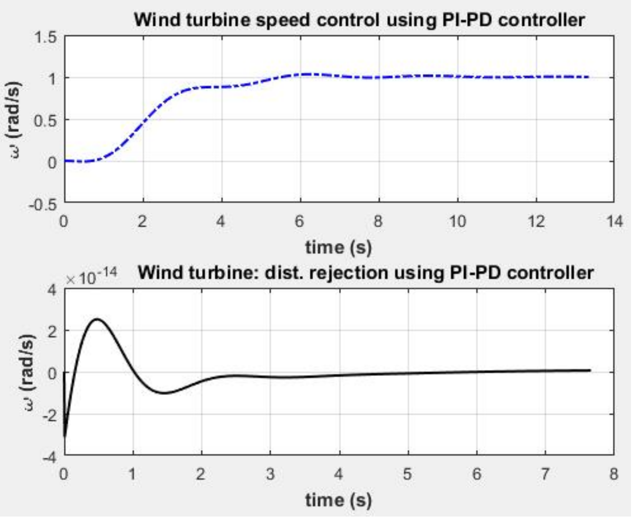

Fig.4 Wind turbine speed control using a PI-PD controller.

COMMENTS:

- Control system characteristics for reference input tracking:
    - Maximum percentage overshoot: 3.254 %
    - Maximum undershoot: -0.0075 rad/s
    - Settling time: 6.76 s
- Control system characteristics for disturbance rejection (with second-order high pass filter):
    - Maximum time response: 2.498×10^{-14} rad/s
    - Minimum time response: -3.111×10^{-14} rad/s
    - Approximate settling time to zero: 6.0 s

V. CONTROLLING THE WIND TURBINE SPEED USING A 2DOF-3 CONTROLLER

The 2DOF controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used different structures of 2DOF control to control a variety of industrial processes with bad dynamics such as: liquefied natural tank level [50], liquefied natural gas pressure [27], boost-glide rocket engine [25], BLDC motor [32], delayed double integrating process [46], boiler drum water level [29], furnace temperature [33], boiler temperature [28], an electro-hydraulic drive [34], cavity gate pressure [51], IMM barrel temperature [35], IMM mold packing pressure [36], IMM ram velocity [37], full-electrical IMM [38], Al-Jazary turbine [39], Banu Musa axial turbine power [40] and second-order like processes [49].

The block diagram of a control system incorporating a 2DOF, structure 3 and the controlled process is shown in Fig.5 [37].

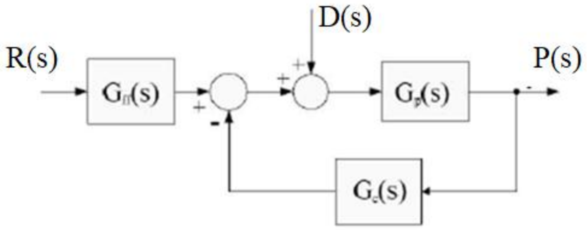

Fig.5 Wind turbine speed control system using 2DOF-3 controller [37].

- The 2DOF-3 controller is composed of two elements: PD-control-mode of $G_{ff}(s)$ transfer function in a forward path receiving the reference input and another PD-control mode of $G_c(s)$ transfer function in the feedback path of the control system loop.
- The 2DOF-3 controller elements have the transfer functions:

$$G_{ff}(s) = K_{pc1} + K_{d1}s$$

And

$$G_c(s) = K_{pc2} + K_{d2}s \qquad (8)$$

- The 2DOF-3 controller has four gain parameters K_{pc1}, K_{d1}, K_{pc2} and K_{d2} to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.5 are derived from the block diagram using Eqs.3 for the process and 8 for the 2DOF-3 controller for both inputs R(s) and D(s).
- The unit step time response of the control system, ω(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [43].
- Investigating the closed loop transfer function of the control system with reference input tracking reveals a condition relating some of the 2DOF-3 controller to each other for a zero steady state error.
- In such a case, an error signal e(t) of the control system for a unit step input is assigned as: 1 – ω(t) for a control system with unit feedback elements.
- The ITAE performance index [41] is minimised using the MATLAB optimization toolbox [42].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the 2DOF-3 controller:

$$K_{pc1} = -16.59972 \quad ; K_{d1} = 0.0437321$$
$$K_{pc2} = 0.1151066 \quad ; K_{d2} = 0.1268780 \qquad (9)$$

- The closed-loop transfer functions are used to plot the unit step input step time response of the control system using the '*step*' command of MATLAB [43] as shown in Fig.6.

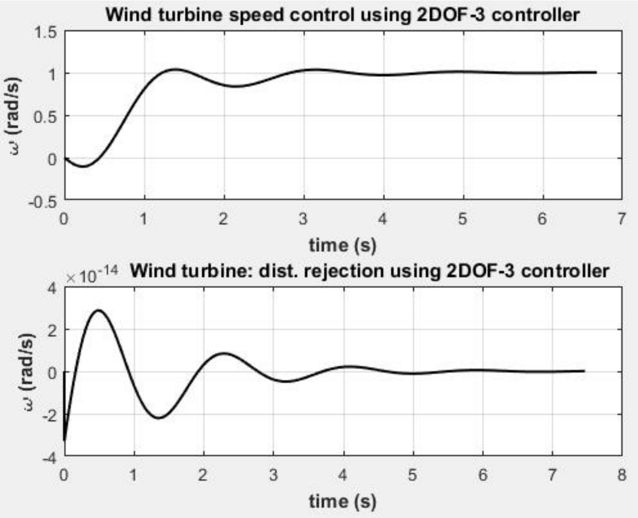

Fig.6 Wind turbine speed control using a 2DOF-3 controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: 3.666 %
  - ➢ Maximum undershoot: -0.108 rad/s
  - ➢ Settling time: 4.285 s
- Control system characteristics for disturbance rejection (using second-order high pass filter):
  - ➢ Maximum time response: 2.860×10^{-14} rad/s
  - ➢ Minimum time response: -3.285×10^{-14} rad/s
  - ➢ Settling time to zero: 7 s

VI. CONTROLLING THE WIND TURBINE SPEED USING A PI CONTROLLER

PI controller is one of the first generation of PID controllers. It has a simple design compared with the PID controller where the derivative action part of the PID is cancelled completely in the PI controller. The PI controller is still in use in many processes including the wind turbine generator unit [8, 15, 16, 17 and 18].

- The PI controller is set in the forward path of a single-loop control system incorporating a classical controller and the controlled process. It receives its input from the error detector and feeds its output to the process.
- It has the transfer function, $G_{PI}(s)$:

  $$G_{PI}(s) = K_{pc} + (K_i/s) \qquad (10)$$

Where K_{pc} is its proportional gain and K_i is its integral gain.

- The transfer functions of the closed-loop control system are derived from the block diagram using the wind turbine generator transfer function in Eq.3 and the PI controller transfer function in Eq.10 for reference and disturbance inputs.
- The transfer function of the control system using the PI controller for reference input tracking is used in the tuning process of the controller using an ITAE performance index [41] and the MATLAB optimization tool box [42]. The tuning results of the PI controller are as follows:

  $$K_{pc} = 0.0080157 \;\; ; \;\; K_i = 0.0263426 \quad (11)$$
- The closed-loop transfer functions are used to plot the unit step input step time response of the control system using the '*step*' command of MATLAB [43] as shown in Fig.7.

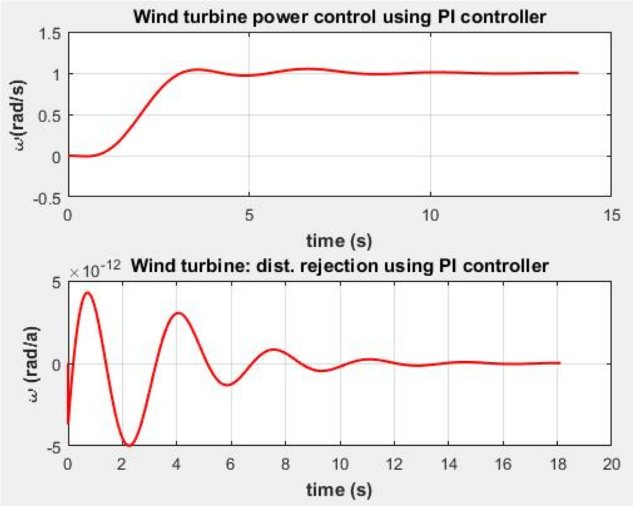

Fig.7 Wind turbine speed control using a PI controller.

COMMENTS:

- Control system characteristics for reference input tracking:

  - ➤ Maximum percentage overshoot: 5.035 %
  - ➤ Maximum undershoot: -0.0079 rad/s
  - ➤ Settling time: 7.50 s
- Control system characteristics for disturbance rejection (using second-order high pass filter):
  - ➤ Maximum time response: 4.284×10^{-12} rad/s
  - ➤ Minimum time response: -4.988×10^{-12} rad/s
  - ➤ Settling time to zero: 18 s

VII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controllers, the step time response for reference input is compared with that using a PI controller tuned using the same procedure for tuning the three proposed controllers from the second generation of PID controllers.
- A quantitative comparison for the time-based characteristics of the control systems proposed to control the wind turbine generator unit is given in Table 1 for a reference step input and table 2 for disturbance rejection.

TABLE 1
TIME-BASED CHARACTERISTICS OF THE WIND TURBINE GENERATOR SPEED CONTROL SYSTEM FOR REFERENCE INPUT TRACKING

Controller	**PD-PI**	**PI-PD**	**2DOF-3**	**PI**
Maximum overshoot (%)	3.410	3.254	3.666	5.035
Maximum undershoot (rad/s)	-0.0608	-0.0075	-0.1080	-0.0079
Settling time (s)	7.900	6.760	4.285	7.500

TABLE 2
TIME-BASED CHARACTERISTICS OF THE DISTURBANCE STEP TIME RESPONSE OF THE WIND TURBINE GENERATOR UNIT SPEED

Controller	**10^{14} Maximum time response (rad/s)**	**10^{14} Minimum time response (rad/s)**	**Settling time to zero (s)**
PD-PI	420.8	-460.1	16
PI-PD	2.498	-3.111	6
2DOF-3	2.860	-3.285	7
PI	428.4	-498.8	18

VIII. CONCLUSIONS

- This research paper investigated the use of PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers to control the wind turbine generator of a power generation system.
- The process under control wind turbine generator speed) is an example of processes with bad dynamics because of its maximum overshoot and steady-state characteristics.
- The performance of the proposed controllers was compared with that of a PI controller from the first generation of PID controllers.
- The maximum overshoot of the control system was 3.41, 3.666 3.254 and 5.035 % for PD-PI, PI-PD, 2DOF-3 and PI controllers for reference input tracking.
- The settling time of the step input tracking was 7.9, 4.285, 6.76 and 7.5 s when PD-PI, PI-PD, 2DOF-3 and PI controllers were proposed to control the wind turbine generator speed.
- If the selection criterion for the best controller is the maximum percentage overshoot, then the PI-PD controller will be the best one to control the wind turbine generator unit.
- If the selection criterion for the best controller is the settling time, then the 2DOF-3 controller will be the best one to control the wind turbine generator unit.
- Regarding the disturbance rejection, the four proposed controllers provided very low maximum time response, minimum time response. The settling time to zero with using a proper second-order high-pass filter with the disturbance input was in the range 6 to 18 s. The best controller for disturbance rejection is the PI-PD controller providing minimum maximum time response, minimum minimum time response and minimum settling time.

- In general, the PI-PD controller has proven to be the most suitable controller for the application of wind turbines in electrical power generation.

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