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Power Turbines Control, Part II: Banu Musa Axial Turbine Power Control using PD-PI, PI-PD and 2DOF-3 Controllers Compared with a PI Controller

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Abstract:
This paper investigates the tuning of PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers when used to control the power of an axial flow turbine invented by Banu Musa bin Shaker in the 9th century AC. The controllers are tuned using MATLAB optimization toolbox and the ITAE performance indices. The tuning results are presented and applied to generate the unit step time response for both reference and disturbance inputs. The disturbance rejection associated with the proposed controllers is improved through a special technique used by the author. The characteristics of the step time responses are compared with those of a PI conventional controller from the first generation of PID controllers. The best controller for both reference and disturbance inputs is assigned.
Keywords — **Banu Musa bin Shaker, Banu Musa axial turbine, PD-PI controller, PI-PD controller, 2DOF-3 controller, PI controller, controller tuning.**

I. INTRODUCTION

Axial flow turbines were first invented in medieval centuries by three Arabic scientists, Banu Musa bin Shakir from the era of some of the Abbasid Caliphs from Al-Mamun (died 833) to Al-Mutawakkil (died 861) in Baghdad of Iraq [1]. Banu Musa (three brothers) were pioneers in mathematics, astronomy and applied mechanical engineering. They wrote number of books and articles, the most famous of them is the 'book of ingenious devices' comprising the design and construction of 100 mechanical devices including the axial flow wheel (turbine) [2]. Their axial flow turbine was used to drive a dynamic fountain with two changing water shapes emerging from the fountain as shown in Fig.1 [3]. The water strikes the turbine blades through flow in parallel tubes (f) from a water source (k) at an angle with the turbine blades (m). This is exactly what is used nowadays in the modern design of axial turbines where variable-angle vanes adjust the input flow to the axial turbine. Unfortunately, this turbine in the west is referred to the Austrian mechanical engineer Viktor Kaplan who registered his patents about the axial turbine in 1912/1913, i.e. after Banu Musa with more than 1000 years [4]. During the whole course of this paper I will call the axial turbine as '*Banu Musa turbine*' and not '*Kaplan turbine*' because they were the real inventors of it.

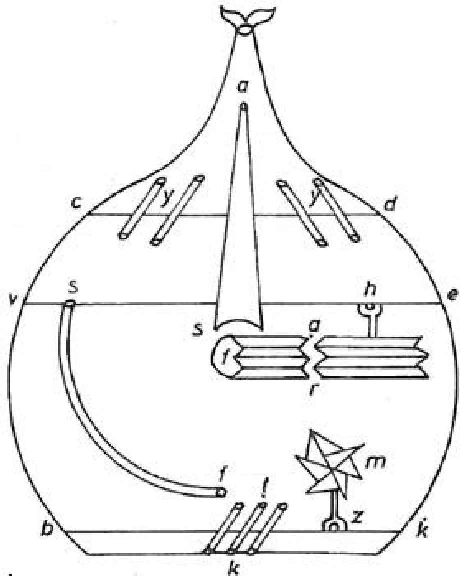

Fig.1 Automatic dynamic fountain of Banu Musa [3]

Here are some of the research efforts regarding modeling and control of the axial turbine:

Vinatoru, Iacu, Maican and Canureci (2008) presented the modeling and simulation of hydraulic power plants with the analysis of different control strategies and algorithms. They presented also the block diagram of a hydraulic turbine control system with adaptive control, turbine flow control, group power control, group speed control, runner and guide vanes position, hydraulic local servomechanism for runner and guide vanes. They showed that the water time constant is function of the flow rate through the turbine and the water level in the reservoir. They used a PI controller to control the speed and power of the hydraulic power unit [5]. Naghizadeh, Jazebi and Vahidi (2012) presented an educational procedure for modeling, simulation and governor tuning of hydro-power plants. They reviewed existing dynamic models of hydro-plant components and presented a procedure for calculating model parameters from used data. They studied appropriate methods for tuning different types of hydro-governors including PID governors. They presented a simplified 1/1 linear model for plant power related to gate opening. They used Ziegler-Nichols method to tune the proposed PID controller [6]. Koritarov et al. (2013) presented a nomogram for the hydraulic turbine application ranges in terms of water head and turbine-generator output in kW and another nomogram for selecting hydraulic reaction turbines. They presented the linear 1/1 penstock/turbine transfer function in terms of the water column time constant with mechanical power change as output and gate position change as input. They presented also block diagrams for turbine-generator-penstock dynamics [7].

Pourbeik et al. (2013) studied the dynamic models for steam, gas and hydraulic turbines. They presented simple models for hydraulic turbines for gate/speed governor and power/gate dynamics. They presented also block diagrams for mechanical hydraulic governor, PID governor, double generative governor, lead-lag governor. One of the presented models for the water column-turbine was a general form of 1/1 transfer function having seven parameters [8]. Zhao et al. (2015) presented dynamic models for a Kaplan turbine regulating system for: governor system model, blade control system model, water diversion and turbine model. They presented block diagrams for the turbine regulating system, PID governor model, vane control system and blade control system [9]. Ur Rahman and Khan (2018) presented the modeling and simulation of a micro-Kaplan turbine for power generation with low head. They investigated the dependence of the output power on various parameters of the Kaplan turbine. They outlined that the head and discharge are the major parameters affecting the output power. The models were in the static form without dynamic models for the studied turbines [10].

Acevedo (2021) presented the dynamic model of a Kaplan turbine coupled to a DC generator. He designed a robust controller using H∞ mixed sensitivity and quantitative feedback theory techniques. He analyzed the controller robustness using te indicators: parameters uncertainty, transient response and robustness against disturbances. He derived the dynamic model of the control system in the state-space form with speed, armature current and turbine discharge as state variables. He presented experimental time responses for runner speed for reference input tracking and disturbance [11].

Iovanel (2022) in his Ph.D. thesis presented a numerical analysis for the flow developed inside a Kaplan turbine model and prototype. His models could be used in industries to test, diagnose and optimize the exploitation of axial turbines. He validated the numerical simulations against experimental data and presented the frequency of the pressure fluctuations on the runner blades compared with experimental values. He investigated the sensitivity of the numerical models to the runner blades clearance value [12]. Geneni et al. (2024) explored the practical viability of repurposing aging Kaplan turbines into variable speed propellers by exploring full-size frequency converters. By conducting experiments on a reduced scale model, they found that Kaplan turbines repurposed as variable speed propeller exhibit simple dynamic response characteristics compared to standard Kaplan turbine operation. They claimed that the ability to control the turbine speed increased the hydraulic efficiency for certain operating points [13].

II. THE CONTROLLED PROCESS

The controlled process is a penstock-axial flow turbine dynamic system modelled by a number of researchers relating turbine mechanical power change and gate position change [7], [8], [9]. The simplified model of the turbine, $G_t(s)$ has the form:

$$G_t(s) = (1-T_w s) / (1+ 0.5T_w s) \quad (1)$$

Where T_w is the time constant of the water flow in the penstock-axial turbine. It is function of: penstock area, penstock length, flow rate of water in the turbine and operating head at turbine inlet [8]. Zhao et al. assigned T_w for a specific axial turbine as 1.8 s [9].

To take an idea about the dynamics of the controlled process its step time response is generated using MATLAB '*step*' command using the process model in Eq.1 [14]. It is shown in Fig.2.

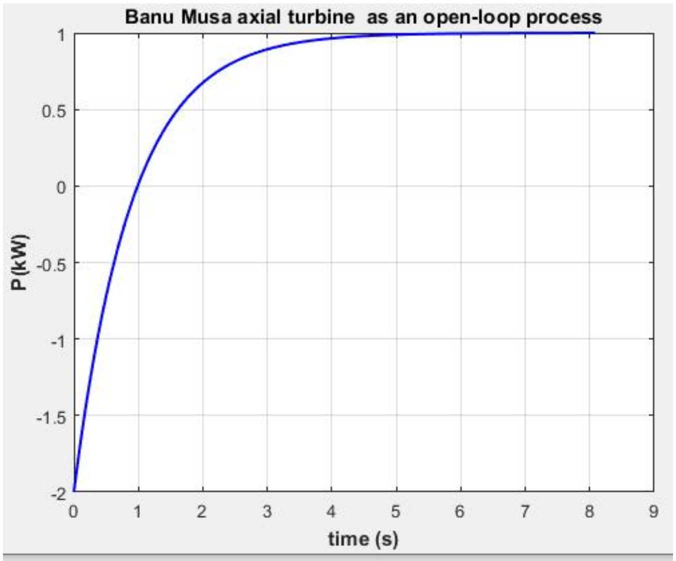

Fig.2 Step time response of an axial turbine.

Fig.2 reveals the following dynamic characteristics of the controlled Banu Musa axial turbine:

- Maximum overshoot: zero
- Maximum undershoot: -2 kW
- Settling time: 3.33 s
- Steady-state error: zero

This is another example of bad processes that has to be controlled to overcome its bad dynamics of very large maximum undershoot at the starting time of the step input. Any proposed controller has to overcome this challenges and provide step response with better settling time.

III. BANU MUSA TURBINE CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation of PID controllers. The author used PD-PI control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [15], integrating plus time delay process [16], delayed double integrating process [17], overdamped second-order processes [18], fourth-order blending process [19], coupled dual tanks [20], internal humidity of a greenhouse [21], rocket pitch angle [22], liquefied natural gas tank pressure [23], liquefied natural gas tank level [24], boiler temperature [25], boiler drum water level [26], furnace temperature [27], electro-hydraulic drive [28], rolling strip thickness [29], injection molding mold temperature [23], IMM barrel temperature [31], IMM cavity gate pressure [32], IMM mold packing pressure [33], IMM ram velocity [34], full-electric IMM [35] and Al-Jazari turbine [36].
- The two elements of the PD-PI controller (PD and PI control modes) are set in cascade in the forward path of the block diagram of the barrel temperature control system just after the error detector.
- The transfer function of the PD-PI controller is given by [21]:

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

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 = integral gain of the PI-control mode

- The controller has four gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, c(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, controller transfer function in Eq.2, process

transfer function in Eq.1 and the '*step*' command of MATLAB [14].

- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index [37] is minimised using the MATLAB optimization toolbox [38].
- Minimizing the error function ITAE reveals the optimal gain parameters of the PD-PI controller as:

$K_{pc1} = 0.0401252$; $K_d = 0.2132158$

$K_{pc2} = -0.4188746$; $K_i = 0.6093039$ (3)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PD-PI controller tuned gain parameters in Eq.3 and its transfer functions is shown in Fig.3.

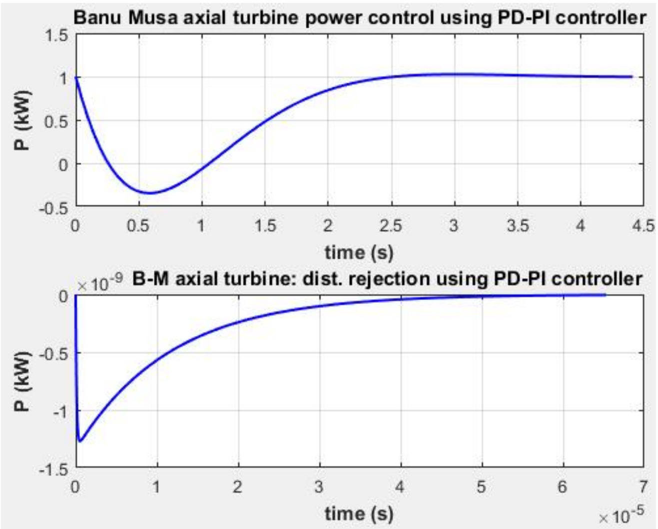

Fig.3 Step time response of the PD-PI controlled Al-Jazari turbine.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 2.9 %
  - Maximum undershoot: -0.347 kW
  - Settling time: 2.415 s
- For disturbance rejection using the tuned PD-PI controller (with second order high pass filter receiving the disturbance input):
  - Maximum step time response: zero
  - Minimum step time response: -1.348×10^{-8} kW
  - Approximate settling time to zero: 0.6 ms

IV. BANU MUSA AXIAL TURBINE CONTROL USING A PI-PD CONTROLLER

- The PI-PD 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 PI-PD control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [39], third-order process [40], greenhouse humidity [21], fourth-order blending process [19], boost-glide rocket engine [41], BLDC motor [42], boiler drum water level [31], electro-hydraulic drive [28], rolling strip thickness [29], IMM barrel temperature [31], IMM cavity gate pressure [32], IMM packing pressure [33] and IMM ram velocity [34].
- The block diagram of a control system incorporating a PI-PD controller controlling the full-electric IMM is shown in Fig.4 [28].
- The PI-PD controller is composed of two elements: PI-control-mode in the forward path receiving its input from the error detector of the control system and a PD-control-mode in the feedback path of an internal loop with the controlled process.

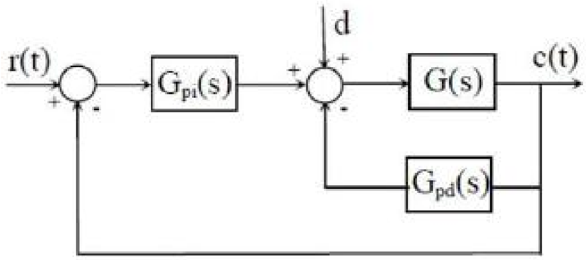

Fig.4 Block diagram of a PI-PD controlled process [28].

- The PI-PD controller elements have the transfer functions:

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

And $G_{PD}(s) = K_{pc2} + K_d s$ (4)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.

- The transfer functions of the closed-loop control system in Fig.4 are derived from the block diagram using Eqs.1 for the process and 4 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, p(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 [14].
- The parameters of the PI-PD controller are tuned in a way similar to that used with the PD-PI controller where the following optimal parameters are obtained:

$K_{pc1} = 0.363635; K_i = 0.3822866$

$K_{pc2} = -0.035399; K_d = -0.0363117$ (5)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PI-PD controller tuned gain parameters in Eq.5 and shown in Fig.5.

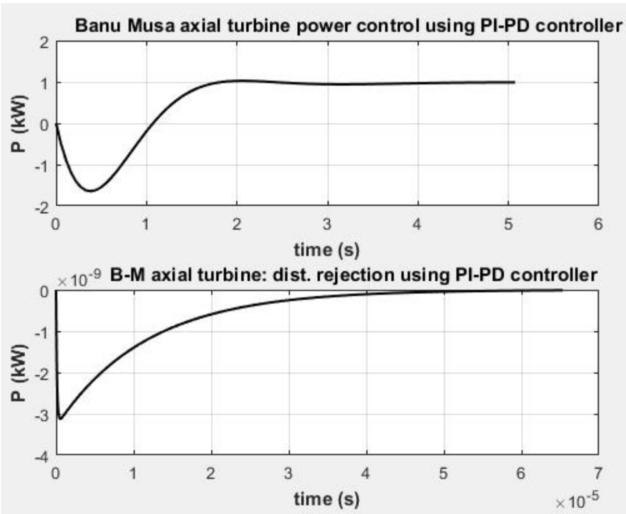

Fig.5 Step time response of the PI-PD controlled Banu Musa Axial turbine.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 3.55 %
  - Maximum undershoot: -1.645 kW
  - Settling time: 4.392 s
- For disturbance rejection using the tuned PI-PD controller:
  - Maximum step time response: zero
  - Minimum step time response: -3.317×10^{-8} kW
  - Settling time (with filter): 0.6 ms

V. BANU MUSA AXIAL TURBINE CONTROL 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 gas tank pressure control [23], liquefied natural gas level control [24], boost-glide rocket engine [41], BLDC motor control [42], highly oscillating second-order process [43], delayed double integrating processes [44], coupled dual tanks [20], furnace temperature [27], gas turbine speed [45], greenhouse temperature control [46], boiler temperature [25], boiler drum water level [26], electro-hydraulic drive [28], rolling strip thickness [29], IMM mold temperature [30], IMM cavity gate pressure [32], IMM packing pressure [33], IMM ram velocity [34], IMM barrel temperature [31], IMM full-electric machine [35] and Al-Jazari turbine [36].
- The block diagram of a control system incorporating a 2DOF-structure 3 controller (denoted as 2DOF-3) proposed to control Banu Musa axial turbine power is shown in Fig.6 [34].

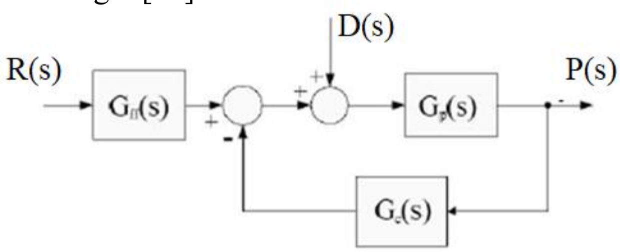

Fig.6 Block diagram of 2DOF-3 controlled process [34].

- 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 $G_c(s) = K_{pc2} + K_{d2}s$ (6)

- 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.6 are derived from the block diagram using Eqs.1 for the process and 6 for the 2DOF-3 controller for both inputs R(s) and D(s).
- The unit step time response of the control system, c(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 [14].
- 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 – c(t) for a control system with unit feedback elements.
- The ITAE performance index is minimised using the MATLAB optimization toolbox [38].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the 2DOF-3 controller:

$K_{pc1} = 0.836331$; $K_{d1} = 0.0013398$

$K_{pc2} = -0.163669$; $K_{d2} = -0.0551231$ (7)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' using the 2DOF-3 controller tuned gain parameters in Eq.7 and shown in Fig.7.

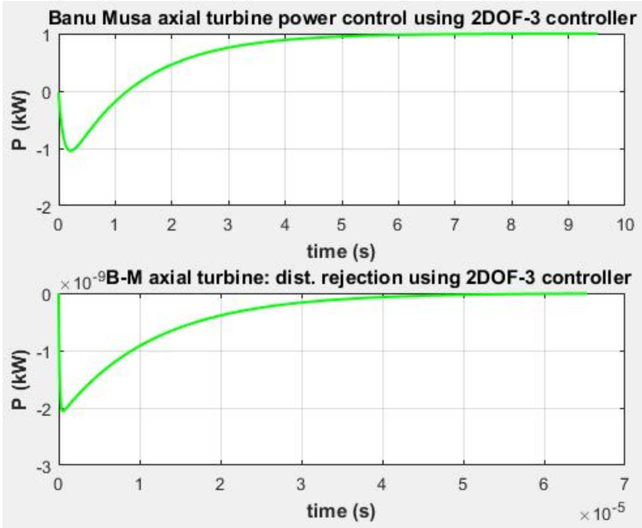

Fig.7 Step time response of the 2DOF-3 controlled Banu Musa turbine power.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Maximum undershoot: -1.04 kW
  - Settling time: 6.2 s
- For disturbance rejection using the tuned 2DOF-3 controller with second-order high pass filter:
  - Maximum step time response: zero
  - Minimum step time response: -2.185×10^{-8} kW
  - Approximate settling time to zero: 0.6 ms

VI. BANU MUSA AXIAL TURBINE CONTROL USING A PI CONTROLLER

PI controller is one of the controllers of the PID first generation controllers. It still finds interest to control a large number of industrial processes [47], [48], [49].

- The transfer function of the PI controller, $G_{PI}(s)$ is given by:

$G_{PI}(s) = K_{pc} + (K_i/s)$ (8)

Where:

K_{pc} = proportional gain of the controller

K_d = derivative gain of the controller

- The controller has two gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, p(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, controller transfer function in Eq.8, process transfer function in Eq.1 and the '*step*' command of MATLAB [14].
- The PI controller parameters are tuned using the same procedure used to tune the PD-PI, PI-PD and 2DOF-3 controllers. The optimal gain parameters of the PI controller are obtained as:

$$K_{pc} = 0.3484433\ ;\ \ K_i = 0.3982141 \qquad (9)$$

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PI controller tuned gain parameters in Eq.9 and its transfer functions is shown in Fig.8.

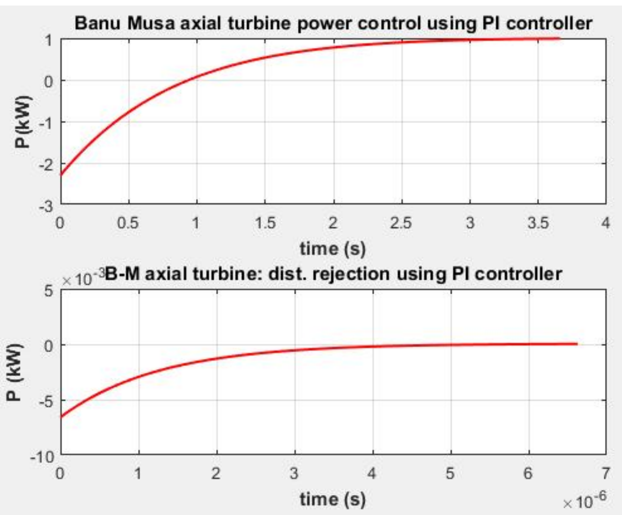

Fig.8 Step time response of the PI controlled Banu Musa turbine power.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Maximum undershoot: -2.299 kW
  - Settling time: 3.33 s
- For disturbance rejection using the tuned PI controller with second-order high pass filter:
  - Maximum step time response: zero
  - Minimum step time response: -0.0065 kW
  - Approximate settling time: 5 µs

VII. COMPARISON OF TIME BASED CHARACTERISTICS

- Graphical comparison for both reference and disturbance inputs: Presented in Figs.9 and 10.

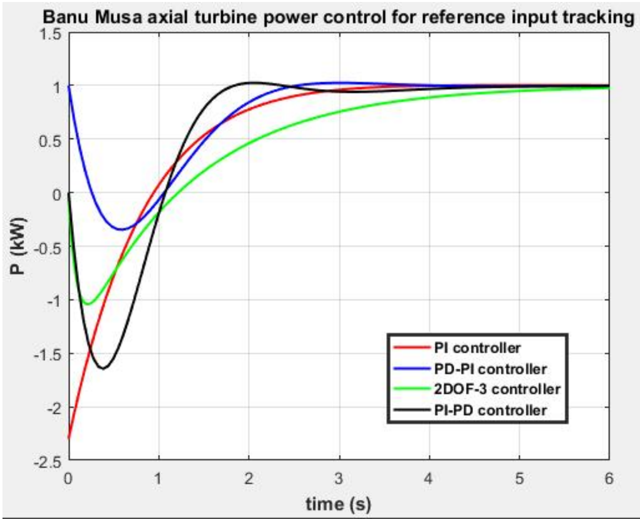

Fig.9 Comparison of the step reference input time response for Banu Musa axial turbine.

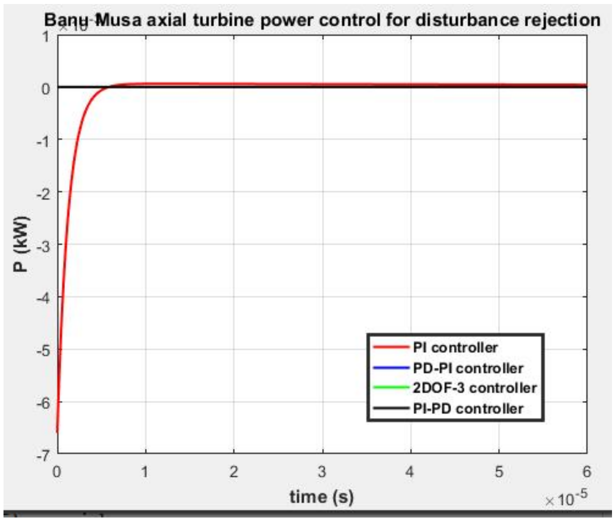

Fig.10 Step disturbance input time response comparison for Banu Musa axial turbine.

- Numerical comparison for the time-based characteristics of the step time response for reference input and disturbance input of the control system with the three proposed controllers is presented in Tables 1 and 2 with comparison with the application of a conventional PI controller used to control the same process.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF THE BANU MUSA AXIAL TURBINE POWER CONTROL

Controller	PD-PI	PI-PD	2DOF-3	PI
OS_{max} (%)	2.90	3.55	0	0
US_{max} (kW)	-0.347	-1.645	-1.040	-2.299
T_s (s)	2.415	4.392	6.200	3.330

TABLE 2
TIME-BASED CHARACTERISTICS FOR DISTURBANCE INPUT REJECTION

Controller	PD-PI	PI-PD	2DOF-3	PI
P_{Dmax} (kW)	0	0	0	0
P_{Dmin} (kW)	$-1.348\text{x}10^{-8}$	$-3.317\text{x}10^{-8}$	$-2.155\text{x}10^{-8}$	-0.0065
T_{s0} (ms)	0.6	0.6	0.6	0.005

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PD-PI, PI-PD, 2DOF-3 and PI controllers used to control Banu Musa axial turbine power.
- The paper presented three controllers from the second generation of PID controllers and one controller from the first generation.
- The controlled process was a stable one with bad dynamics of very large maximum undershoot of -2 kW to its unit reference input putting a real challenge for any proposed controller.
- The Banu Musa axial turbine as a process had an un-delayed 1/1 first-order transfer function with negative zero.
- The negative zero of the process represented a real challenge for the proposed controllers during the tuning operation.
- The four controllers were tuned using the MATLAB optimization toolbox with an ITAE performance index aiming at providing a good dynamic performance for the control system for both reference and disturbance inputs.
- Because of the high efficiency of the used tuning procedure, the conventional PI controller could produce a step time response without any overshoot, with a settling time of 3.33 s and disturbance rejection settling time better than those of the second generation controllers but with minimum response time very much greater than those of the second generation controllers.
- The PD-PI controller could generate a step time response for reference input tracking of 2.9 % maximum overshoot (compared with no overshoot for the PI controller) and 2.415 s settling time (compared with 3.33 s for the PI controller).
- The PI-PD controller could generate a step time response for reference input tracking of 3.55 % maximum overshoot (compared with no overshoot for the PI controller) and 4.392 s settling time (compared with 3.33 s for the PI controller). The 2DOF-3 controller could generate a step time response for reference input tracking of 2.9 % maximum overshoot (compared with no overshoot for the PI controller) and 2.415 s settling time (compared with 3.33 s for the PI controller).
- The PD-PI controller was selected as the best controller regarding reference input tracking if the selection criterion is the settling time and maximum undershoot. If the selection criterion is the maximum overshoot and maximum undershoot, then the 2DOF-3 controller is the best.
- Regarding disturbance rejection associated with Banu Musa axial turbine power, the PD-PI is the best selection.

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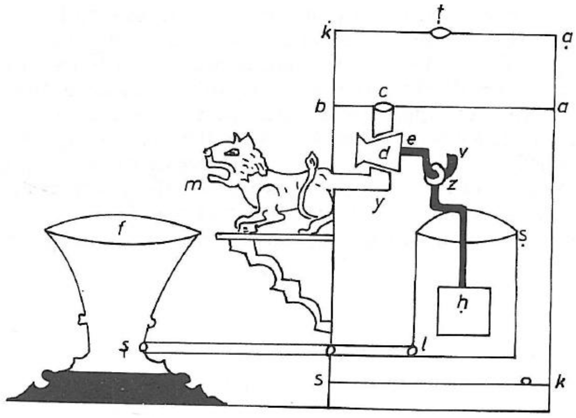
DEDICATION

Banu Musa bin Shakir



Banu Musa bin Shaker level control system [2]

- Three brothers born in Baghdad and lived and educated in the 'Wisdom House' ('Wisdom Academy') during the Abbasid Dynasty (8th/9th centuries AC).
- Were the most famous scientists of the Islamic civilization in the medieval centuries specialized in mathematics, astronomy and applied mechanics.
- Were the founders of automatic control technology through the invention of various level control systems.
- Were the founders of dynamic fountains using axial flow turbines as prime movers.
- Were the first inventers to use the crank-slider mechanism technology in their control systems.
- Presented the design and production of 100 ingenious devices in one book ('book of ingenious devices').
- Spent huge efforts and financial support to translate manuscripts of the ancient civilizations.
- Were sent by Some Abbasid Caliphs to investigate the dam of 'Ya'jooj and Ma'jooj' and the cave of 'Cave People'.
- Supervised the digging of 'Ja'fari canal' and 'Amod bin El Monajjem canal'.
- Constructed an automatic hydraulic simulator for some of the stars in the sky simulating their movements.

BIOGRAPHY

Galal Ali Hassaan

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 320 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
- Reviewer in some international journals.
- Scholars interested in the authors publications can visit:

http://scholar.cu.edu.eg/galal