



A novel optimal firefly algorithm based gain scheduling proportional integral derivative controller for rotor spinning machine speed control

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Abstract

In advanced yarn production, the rotor spinning machine plays a significant role due to its low power consumption and high speed of yarn delivery. Nevertheless, if the speed of the machine exceeds from its desired level, the yarn output will go worsen. Therefore, in this paper, a novel optimal firefly algorithm based gain scheduling proportional-integral-derivative controller is proposed to regulate the speed of linear parameter varying based rotor spinning machine at the desired level. Here, the OFA is added to the GSPID controller for tuning the controller parameters. Consequently, Spline piecewise interpolation is newly developed to regulate the gain tuning parameters in high desired rate. The stability of the projected controller is synthesized by the combination of linear matrix variations with H_∞ control. Moreover, the error percentage and the accuracy of the proposed system are optimized using OFA. The implementation of this projected work was done in the MATLAB R2018b platform. Furthermore, the simulation result of the developed control strategy is compared with other traditional control approaches and its efficiency measure has proved by gaining less computational time as 10 s, error rate as 0.0982%, and high accuracy as 92%.

Keywords Proportional-integral-derivative controller · Gain scheduling · Linear parameter varying system · Spline piecewise interpolation · Rotor spinning machine · Firefly algorithm

1 Introduction

In modern advanced industrial technologies, the control system plays a very important role. Because, the advancement of control process design method might incorporate in production system manufacturing to improve the production measure [1]. In machinery applications, the control system is the group of elements to control the machine working system to attain better results [2]. Moreover, the chief process of controller is regulation, which means it regulates the key parameters like position, voltage, current, temperature and so on [3]. Besides, in control process the linear parameter varying (LPV) control method is an interesting area for researchers because, in control system the gains of the

controller are adjusted based on parameter scheduling [4]. Henceforth, the outcome of parameter scheduling illustrates the particular working state of each controller parametric function. In some situations where the dynamics of the system varied beneath dissimilar working states, then the gain scheduling based controller can be executed [5]. Moreover, the resultant terminologies of controller maintain the engineering works of LPV systems [6, 7]. In addition, the very developed controllers have been designed with the help of H_∞ study.

Usually, the gain scheduling scheme is processed in three chief frames [8]. In that, the first frame includes the operation parameter specification of each subspace [9]. In second phase, the controllers are designed for each parameterized model [10]. To attain a good stability range, an interpolation approach is merged in the gain scheduling paradigm. Furthermore, the LPV model is processed based on bounded time duration varying process [11]. Often closed control loop system is applied in industrial applications. From that, the calculated signal is compared with the desired value and the difference between the values is termed as an error [12]. Moreover, in the foremost industries such as textile

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industries, chemical industries, and aerospace work, the gain scheduling based control method plays a significant part [13]. In textile industries, the rotor spinning machine works as a significant role in the yarn production. Panda et al. termed the rotor spinning machine as open spinning machine [14].

Due to the nonlinear qualities of rotor spinning machine such as the sudden speed variation, and temperature, the system became more challenging. In order to maintain the rotor speed, the high-speed rotor may escort to fiber worsening. Also, tearing out of fiber bunches might reduce the rotor speed that tends to cause fiber lapping [15]. Hence, the performance of the spinning machine must be improved by the proper controller to achieve the desired values of constraints.

Therefore, the proportional expansion has described the quantitative relation of the error signal outcome. Afterward, the control input is given to the actuator which can work up to reduce the error rate [16]. The reason of using PID type controller is for attaining accurate control performance and stability range [17]. Beside these, to improve the controller performance optimization framework is introduced in gain scheduling module. Even though, these methods have some limitations and this is the motivation potency of the heuristic [18] rules capability to the controller. So, in this proposed work, the application as rotor spinning machine is adopted, the performance of the system response has improved the sensitivities of control under the external disturbances using a novel optimized hybrid method of controller [19].

The rest of the paper is sketched out as follows. Section 2 explains the related work of this research. In Sect. 3, the modeling and problem of rotor spinning machine are described. In Sect. 4, the proposed design of the controller and its stability, as well as robustness is described. Section 5 covers the simulation outcomes of the proposed control and comparison. Finally, the paper is concluding in Sect. 6.

2 Related work

Some of the current works connected to the GSPID controllers are explained as follows.

The demand of electric vehicle is increasing because of increased emission pollution. For this reason, Yonathan Weiss et al. [20] projected a fresh Yaw Stability Controller (YSC) method in driven electric vehicle. In addition, the LPV system of the vehicle design, longitudinal run estimation, and tire cornering firmness strength are used as control parameters. However, the error in the controller is increased.

The wind turbine efficiency is increased even during variable speeds. However, the high speed of wind tends to break the blade of the wings. Therefore, Bektachea and Boukhezzarb [21] proposed a nonlinear predictive controller, which enhanced the power capture optimization

and load reduction. Consequently, the nonlinear model is measured for both the aero turbine and the Doubly-Fed Induction Generator (DFIG). Moreover, vector control with PID controller is estimated to control the nonlinear model. Here, the action of controller is not validated under disturbances or varying its input.

In nonlinear system, the heat control is a necessary method to avoid more accidents in industrial technologies. Therefore, Trudgen and Javad [22] proposed an LPV based control method for modeling and regulating of rapid thermal processing (RTP) arrangements. The RTP execution based upon the employ of light commencing heating lamps to make available a heat flux. Sequentially, this nonlinear function is appropriate to the reason of radioactive heat conversion also substance characteristics. Therefore, the principal component analysis (PCA) technique is utilized to diminish the quantity of LPV representation of training parameters. However, the accurate control is not possible by this approach because the reduction of scheduling variables tends to diminish the gain of the controllers.

Moreover, magnetic levitation (ML) is used in various industrial and textile applications. For this reason, a non-parametric PID control approach is introduced by Samia and Boiko [23] for an ML system. Furthermore, a two relay controller validation method is developed which gives the recognition of frequencies higher than the progression phase cross over frequency. Using the outcomes of the validation, the PID controller parameters are evaluated. Nevertheless, this control method is only applicable for the frequency domain not for time based domain.

Nowadays unmanned aerial vehicles (UAVs) are utilized essentially in the military for surveillance applications. However, under the operational condition, the dynamic nonlinear UAVs are flight forward; this tends to complex the design of control methods in such vehicles. To resolve these issues, a new fuzzy GSPID control method is introduced by Khaled et al. [24]. Moreover, the numerous method of particle swarm optimization (PSO) is developed to integrate the fuzzy GSPID for UAV performance improvement. The developed PSO is categorized as PSO with Constriction feature (PSO-Co), PSO with the changeable inertia load (PSO-In), and PSO with the finest global particle (PSO-gbest).

In the power system network, the multilevel inverter is mainly utilized for AC motor, renewable energy integration, and others. However, the reliability of the converter is the main problem due to the noise created by the electromagnetic interface. To overcome these drawbacks, Yilmaz et al. [25] projected Iterative Reduction-based Heuristic Algorithms (IRHA) for the GSPID controller in Z-Source Inverter (ZSI). Moreover, the H_∞ norm depends optimization strategy is also developed to enhance the scheduling algorithm. The voltage fluctuation of the system is maintained constant

by this method. However, this method is considered fewer values for operational conditions.

The main contribution of this work is summarized below.

- In this paper, a novel OFA-GSPID control method is proposed to control the speed of rotor spinning machine effectively. Also, the proposed method in the rotor spinning machine estimates the dynamics of nonlinear system and regulates the speed of machine under the different parameter changes, disturbances, and uncertainties.
- Moreover, the chattering influences of the system are controlled by the proposed controller. Furthermore, the Spline piecewise interpolation strategies are used for gain, poles, and zeros progression in the OFA-GSPID controller.
- More significantly, the control technique stability guarantee is developed based on the LMV- H_∞ approaches, which undertaking the stability of the system.
- The parameters of the GSPID controller are tuned by OFA method also, the error percentage and accuracy is optimized and has attained better results in terms of speed control while compared with other existing control approaches.

3 Modeling of rotor spinning machine

Rotor spinning machine is utilized in spin-pile fabrics, apparel, industrial and technical applications for yarn manufacturing processes. It is the high speed, well-organized self-draining kind of open-end spinning machine and has an impurities liberation mechanism. Moreover, it is an excellent recycling device as the spinning mill-waste is used.

schematic diagram of the rotor spinning machine is illustrated in Fig. 1.

In the spinning machine, the rotor diameter is in the range between 32.5 and 56 mm and in rotor, the pivots are at really high speed over 140,000 rpm. During the operation, the rotor twists the unit of silver fibers then it turn into yarn. If the yarn in the twisting sector is weak, it requires a very high twist to allow the spinning. The yarn tail in the spinning machine is pressed next to the rotor channel and navel by the centrifugal force, which is mainly caused by the revolving of rotor. The speed of the rotor is enhanced by increasing the centrifugal force inside the rotor on the yarn tail which is expressed using Eq. (1),

$$\text{Centrifugal force} = dN^2R_r^2 \quad (1)$$

where, d is the linear density of yarn (tex), N is the speed of the rotor (rpm) and R_r is the radius of rotor channel (m). Moreover, the spinning tension in Eq. (2) and peeling tension in Eq. (3) are calculated as,

$$\bar{F}(cN) = \beta_1 R_r^2 N^2 d \quad (2)$$

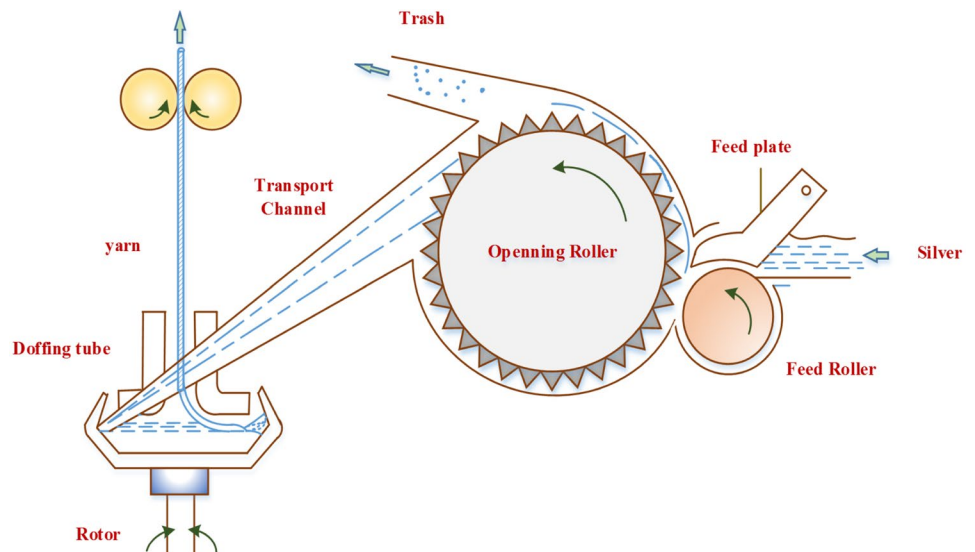
$$P = \beta_2 \times \text{Centrifugal force} \quad (3)$$

where β_1 and β_2 are the positive constant, P is the peeling tension. Furthermore, if the strength of the yarn in cN is specified by \hat{S} then $\frac{\hat{S}}{p} > 1$. The spinning tension is evaluated based on the Grosberg using Eq. (4),

$$\bar{F} = 0.6d\omega'^2 R_r^2 \quad (4)$$

where ω' is the rotor angular velocity. Besides, depends upon the amount of fibers in yarn radius, yarn cross-section, twist factor, and rotor speed only the yarn fiber will form

Fig. 1 The schematic diagram of the rotor spinning machine



by torque. The expression of torque in spinning machine is evaluated in Eq. (5),

$$T = YR_y t_f \tag{5}$$

$$T < \eta l^{1/2} R_r \omega'^2. \tag{6}$$

Nevertheless, at the time of low tension in yarn manufacturing the required torque will reduce for twisting in Eq. (6). Where the tension of yarn at the position of yarn production is Y , t_f is the twist factor and R_y is the radius of yarn, η is the friction coefficient between rotor wall and fiber ring and l is the average fiber length, respectively. The twisting of rotor spinning machine is expressed using Eq. (7),

$$T' = \frac{N_{yarn}}{S_d} = \frac{1}{\eta \pi R_r} + \frac{\omega'}{S_d} \tag{7}$$

where S_d is the speed of the delivery. Moreover, the twisting and speed of the rotor spinning machine relationship are expressed by Eq. (8),

$$T' = \frac{\omega'}{S_d} + \frac{1000}{\pi R_r} + Y_m \frac{1000}{\pi R_r} \tag{8}$$

where Y_m is termed as the movement of yarn constant. The state space depiction of the motor is shown in Eqs. (9) and (10) [26],

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} = \begin{bmatrix} -\frac{\omega'}{S_d} & \frac{1}{\eta \pi R_r} & 0 \\ \frac{1}{\pi R_r} & -\frac{\omega'}{S_d} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} Y_m \\ 0 \\ 0 \end{bmatrix} \hat{u} \tag{9}$$

$$\hat{y} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} \tag{10}$$

where the state variable is denoted as \hat{x} , \hat{y} is the output vectors and \hat{u} is the input constraints. The explicit constraints is represented as R_r . The nonlinear system is converted in the linear parameter dependent system by the LPV. The state-space representation of the LPV based dynamic model is articulated in Eq. (11),

$$\begin{cases} \hat{x}(t') = \hat{P}\hat{x}(t') + \hat{Q}\hat{u}(t') + \alpha(\hat{x}, \hat{u}, t') \\ \hat{y}(t') = \hat{R}\hat{x}(t') + \hat{S}\hat{u}(t') \end{cases} \tag{11}$$

where $\hat{u}(t') = -\hat{K}\hat{y}(t') + g(t')$, $\hat{x}(t')$ is the state vector, $g(t')$ is the set point input, $\hat{u}(t')$ is the input vector, α is the disturbances, the state matrix is referred as \hat{P} , input matrix is denoted as \hat{Q} , output matrix is \hat{R} and the feed forward matrix is denoted as \hat{S} .

3.1 Problem statement

In high speed of rotor, the centrifugal forces will be higher which gives more pressure to yarn on navel, which can cause the superior false twist by the frictional resistance increment. The rotor spinning machine is frequently working in a vibrant condition hence, it is firm to regulate the speed of the rotor spinning machine. Therefore, the speed of the rotor must be control as per the desired level.

4 Proposed OFA-GSPID approach

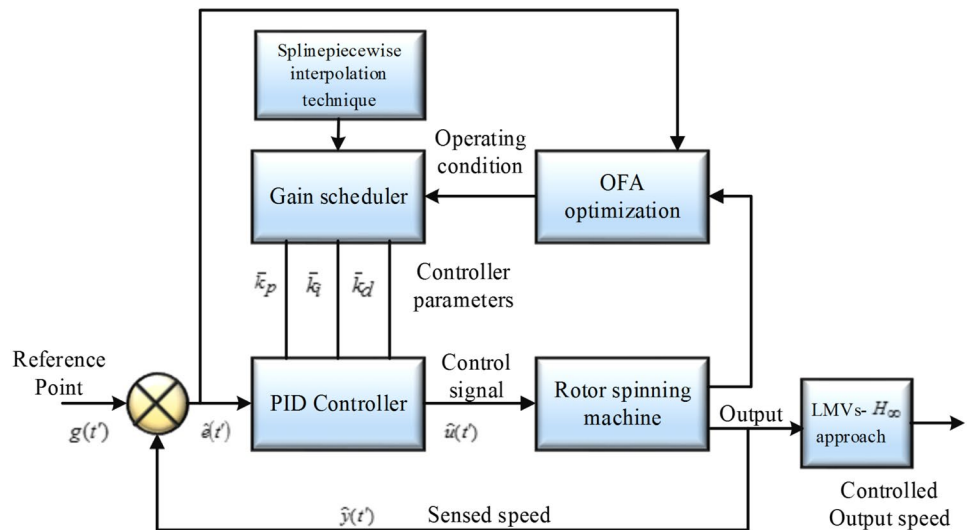
The proposed method is a basis on implementing an OFA based GSPID controller for LPV based rotor spinning machine speed systems. The block diagram for the proposed OFA-GSPID control methodology is illustrated in Fig. 2. Hence, the application as rotor spinning machine is taken to verify the efficiency of the proposed OFA-GSPID controller. In other words, the purpose of using optimal firefly procedure in controller approach is to attain better optimized results in terms of proper speed regulation in rotor spinning machine. Here, GSPID controller, LMVs, H_∞ approach, OFA method, and Spline piecewise interpolation technique are investigated.

The integration of gain scheduling in PID controllers has achieved foremost preferential controller because of its straightforward arrangement and uncomplicated to execute in nonlinear dynamic system. The LPV system based plant used in this research is the open-end spinning machine, which is also referred to as rotor spinning machine.

4.1 Proposed GSPID controller design

In this paper, the GSPID controller is proposed to control the constraints of the LPV based rotor spinning machine. In the nonlinear dynamic system used PID controller parameters are changing by observing the operating conditions of the method. This design is referred to as a GSPID controller. The gains of the controller are varied based upon the function time, system parameters, and operating conditions. In the proposed controller design are continuously estimate the error and the time taken for the system to reach stability based upon PID terms. In gain scheduled controller the constant scheduling parameter variable is denoted as m , which is replaced by the considered variable in terms as $m(t')$. The GSPID control can tune itself as per the variations in the dynamics of the rotor spinning machine. Then the LPV system from Eq. (11) is rewritten for control purposes based on the scheduling variables in Eq. (12),

Fig. 2 Block diagram for the proposed OFA-GSPID control approach



$$\Lambda(m_i): \begin{cases} \hat{x}(t') = \hat{P}(m_i(t'))\hat{x}(t') + \hat{Q}(m_i(t'))\hat{u}(t') \\ \hat{y}(t') = \hat{R}(m_i(t'))\hat{x}(t') + \hat{S}(m_i(t'))\hat{u}(t') \end{cases} \quad (12) \quad \bar{k}_d(m_i|t') = \bar{k}_{d0} + \sum_{i=1}^p \bar{k}_{d,m_i}(t'). \quad (16)$$

Considering the gain scheduler and interpolation of $\Lambda(m_i)$, $m_i \in \Theta^i$ in controller scheduling the controller design should be linearized and gives a steady control value producing zero error. Here, Θ^i is the set variance or open set. The speed of the rotor spinning machine is given as the input of proposed controller. Consequently, the system performance based on the parameters of the controller is changed using gain scheduling in terms as $\bar{k}_p(m_i)$, $\bar{k}_i(m_i)$, and $\bar{k}_d(m_i)$, which attains the finest performance of the system than the operating range m_i values. The GSPID control law is described in Eq. (13) as follows,

$$\hat{u}(t') = \bar{k}_p(m_i|t')\hat{e}(t') + \bar{k}_i(m_i|t') \int_0^{t'} \hat{e}(\tau')d\tau' + \bar{k}_d(m_i|t') \frac{d\hat{e}(t')}{dt'} \quad (13)$$

where the proportional gain is represented as \bar{k}_p , the integral gain is expressed as \bar{k}_i , the derivative gain is represented as \bar{k}_d and the error is expressed as $\hat{e}(t') = \hat{y}(t') - g(t')$, respectively, here, $g(t')$ is the set point speed and $\hat{y}(t')$ is the sensed speed value. The error signal is providing to the developed GSPID controller and the error signal is computed by the controller integral and derivative gain. The gain matrix indexes of GSPID controller are in the form of Eqs. (14)–(16), where, p is the symmetric matrices.

$$\bar{k}_p(m_i|t') = \bar{k}_{p0} + \sum_{i=1}^p \bar{k}_{p,m_i}(t') \quad (14)$$

$$\bar{k}_i(m_i|t') = \bar{k}_{i0} + \sum_{i=1}^p \bar{k}_{i,m_i}(t') \quad (15)$$

In the gain matrices of the controller only it takes two-mode because another one is uncertainty, which is equal to zero. For this reason, the set point $g(t')$ does not manipulate the stability of the closed-loop system. Suppose the set point $g(t') = 0$, and then the control law can be estimated in Eq. (17). Here, $\hat{y}(t') - \hat{y}(t' - 1)$ is the continuous sampling time framework, thus it is equal to derivative error and applied this in Eq. (13),

$$\hat{u}(t') = \bar{k}_p(m_i|t')\hat{y}(t') + \bar{k}_i(m_i|t') \sum_{i=0}^k \hat{y}(i) + \bar{k}_d(m_i|t')(\hat{y}(t') - \hat{y}(t' - 1)). \quad (17)$$

In gain scheduling, the state space description of PID can be derived by the two-state variables, which are expressed in Eq. (18),

$$\hat{z}(t') = [\hat{z}_1^T(t') \hat{z}_2^T(t')]^T \quad (18)$$

where $\hat{z}_1(t') = \sum_{i=0}^{k-2} \hat{y}(i)$ and $\hat{z}_2(t') = \sum_{i=0}^{k-1} \hat{y}(i)$. Consequently, substitute $\hat{y}(t' - 1) = \hat{z}_2(t') - \hat{z}_1(t')$ in Eq. (17). Then, the control law obtained from Eq. (19),

$$\hat{u}(t') = (\bar{k}_p(m_i|t') + \bar{k}_i(m_i|t') + \bar{k}_d(m_i|t'))\hat{y}(t') + \bar{k}_i(m_i|t')\hat{z}_2(t') - \bar{k}_d(m_i|t')(\hat{z}_2(t') - \hat{z}_1(t')) \quad (19)$$

The extensive measurement output vector is $y' = [\hat{y}(t'), \hat{z}_1(t'), \hat{z}_2(t')]^T$ and the matrix form transformation of the control law is expressed in Eq. (20),

$$\hat{u}(t') = K(m_i|t')y'(t') \quad (20)$$

where the expression

$$K(m_i|t')^T = \begin{bmatrix} \bar{k}_p(m_i|t') + \bar{k}_i(m_i|t') + \bar{k}_d(m_i|t') \\ \bar{k}_d(m_i|t') \\ \bar{k}_i(m_i|t') - \bar{k}_d(m_i|t') \end{bmatrix}$$

is substitute

in Eq. (20). Furthermore, the proposed GSPID control law is applied to the LPV based rotor spinning machine speed system. The control signal $\hat{u}(t')$ is given to the rotor spinning machine, the gain which is equal to \bar{k}_p at the instant of the magnitude of error. The gain \bar{k}_i at the instant of integral error and gain \bar{k}_d at the instant of derivative error. Consequently, $\hat{u}(t')$ is move to the spinning machine and attained better controlled speed output. In common, the GSPID controller is scheduled using the progress range of the scheduling changeable to interpolate the coefficients of the controller. Moreover, in the GSPID controller scheduling the corresponding model of the linear controller is linearizes and the control value provides zero error. The transfer function of the proposed GSPID in speed control mechanism is specified in Eq. (21),

$$G_c(s) = \bar{k}_p(m_i) + \frac{\bar{k}_i(m_i)}{s} + \bar{k}_d(m_i)s. \tag{21}$$

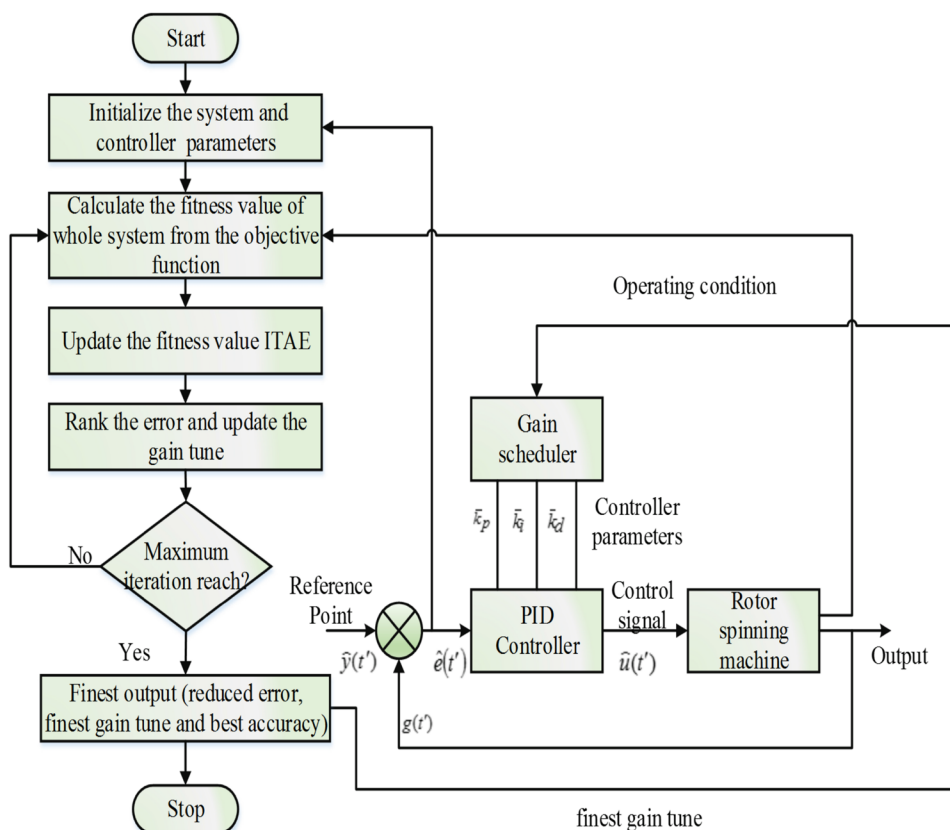
The speed of the rotor spinning machine is regulated by the controller gain constraints are \bar{k}_p , \bar{k}_i , and \bar{k}_d at a constant $g(t')$ with the meeting rate of regulation error under the control law for the initial speed.

4.2 Design of proposed OFA in GSPID controller

The OFA is a nature-inspired based heuristic algorithm that is receiving stronger in resolving the current global optimization harms, mainly on the description of multifaceted non-linear optimization problems. The OFA works based upon the performance of the fireflies flashing light characteristics. The working of OFA-GSPID in rotor spinning machine is shown in Fig. 3. The structure of OFA-GSPID controller enclosed the $\hat{u}(t')$ of control signal from the controller, $g(t')$ is the set speed of the machine, $\hat{y}(t')$ is the sensed speed of the spinning machine and $\hat{e}(t') = \hat{y}(t') - g(t')$ is the error speed of the rotor.

Initially, the controller and system parameters are initialized in the OFA method. The OFA has attracted the finest gain and less error from one another without considering the value because all the parameters are regarded as identical. Consequently, in irregular sampling time, the normal (initial) gain moves towards the finest gain and if there is no finest gain has attained then it shifts arbitrarily. Hence, the attractiveness of the gain is relative to their error. Moreover, if both high error and reduce gain tends to attain low performance. The gains are straightly changes by the objective function. Furthermore, the gain and the values of the objective function are proportional under the minimization and maximization issue. The gain function $\chi(q)$ of a controller is expressed in Eq. (22),

Fig. 3 Working of proposed OFA-GSPID controller in rotor spinning machine



$$\chi(q) = \chi_0 e^{-\lambda q^n} \quad (n \geq 1) \tag{22}$$

where the initial value is referred as λ . Using, Cartesian distance method in Eq. (23) the distance between two gain parameters is estimated.

$$q_{a,b} = \|y_a - y_b\| = \sqrt{(y_a - y_b)^2 - (z_a - z_b)^2} \tag{23}$$

The Integral Time Absolute Error (ITAE) is estimated as the objective function for evaluating the performance index using Eq. (24).

$$ITAE = \int_0^T t^* |e^*(t^*)| dt^* \tag{24}$$

The attractive of a gain of controller to the finest b gain and its tuning is estimated by Eq. (25),

$$y_a = y_a + \chi_0 e^{-\lambda q_{a,b}^2} (y_b - y_a) + \sigma \left(rand - 1/2 \right) \tag{25}$$

where the parameter of randomization is denoted as $\sigma = ITAE$. The first term expressed the current location of controller gain, the second term expressed the gain and error of the controller also the third term is used for the arbitrary tuning of gain parameters. In addition, arbitrary tuning means tuning the random time delay. In the OFA, the parameter λ is an essential element, because the convergence speed and the behavior of OFA are estimating by this parameter. In this implementation, the OFA is tuning the controller gains to attain the finest control performance at insignificant operating conditions. The OFA is used to tune the gain parameters of GSPID controller such as \bar{k}_p, \bar{k}_i and \bar{k}_d using the system model. A fine set of GSPID controller state constraints can produce a fine response of system and outcome of performance index minimization. When the criteria satisfied, the process stops until it starts initialization again. In addition, by designing an OFA tool kit, it is effectively applied in real time applications.

4.3 Spline piecewise interpolation

Considering the interpolation technique $\Lambda(m_i)$ in OFA based GSPID controller, where m_i represents the scheduling variable. The Spline piecewise interpolation technique is introduced in this paper to enhance the scheduling variables of proposed controller. It is a method to place the near data gain point and assign the same gain point. The stability condition for the controller $\Lambda(m_i)$ is based on the interpolation technique, $m \in [m_i, m_{i+1}]$ with respect to $\sum N(m)$. Here, the controller state constraints are incorporates with interpolation techniques to attain better stability range. The spline function f on $[u, v]$ are considered to the points

$u = m_0 < m_1 < \dots < m_n = v$. The function of spline interpolation has some properties such as,

1. The function value $p_i(m_i) = f_i(m)$ for $i = 0, 1, \dots, n$
2. $f_i(m_{i+1}), f'(m_{i+1}), f''(m_{i+1}) \dots f'''(m_{n+1})$ Continuous on $[m_0, m_n]$.

Spline piecewise interpolation employs as low-degree polynomials in each of the intervals, which is in the form expressed in Eq. (26),

$$p_i(m) = \begin{cases} f_0(m) & m \in [m, m_1] \\ f_1(m) & m \in [m_1, m_2] \\ \vdots & \vdots \\ f_{n+1}(m) & m \in [m_{n+2}, m_n] \end{cases} \tag{26}$$

where $p_i(m)$ is the polynomial of degree mainly at n . Moreover, the Spline piecewise data to the linear OFA-GSPID controller is given as $(m_0, n_0), (m_1, n_1) \dots, (m_{n-1}, n_{n-1}), (m_n, n_n)$, such that the data point can be assumed as $(m_i, f(m_i))$. Hence, the linear Spline piecewise is given as $f(m) = f_i(m)$, $m \in [m_i, m_{i+1}]$ with respect to the polynomial $f_i(m)$ is estimated by Eq. (27),

$$f_i(m) = f(m_i) + \frac{f(m_{i+1}) - f(m_i)}{f_{i+1} - f_i} (m - m_i), \quad m \in [m_i, m_{i+1}] \tag{27}$$

The properties of this function $f_i(m)$ is satisfying under the minimizing of integral $\int_{m_0}^{m_n} |f_i(m)|^2 dm$ is does not alter rapidly for the first derivative. It turns out there is only one of its kind solution. It gives high degree polynomial to Spline piecewise interpolation which gets the process in smooth and simple. Moreover, this approach is a multivariate interpolation accepted neighbor interpolation and its expression is evaluated in Eq. (28),

$$\Lambda(m) = \sum_{i=1}^n s_i(m) f_i(m) \tag{28}$$

where the estimate is denoted as $\Lambda(m)$ at m , s_i is the weights and $f_i(m)$ are the known statistics. The smooth non-oscillatory interpolation can occur in the Spline piecewise polynomial interpolation process. Based on the covering conditions of the stability only the interpolation design for $\Lambda(m_i)$, $m_i \in \Theta^i$ with respect to $\sum(m)$, $m \in \Theta$. The covering conditions of the stability demands the continuation of OFA-GSPID controller $\Lambda(m_i)$, $m_i \in \Theta^i$ that stabilizes $\sum(m)$.

Moreover, if $m \in \bigcup_{m_i \in \Theta^i} F_{m_i}$ where $F_{m_i} \subset \Theta$ an untiie neighborhood gain value including $m_i \in \Theta^i$. From that $\Lambda(m_i)$ of scheduling variable range stabilizes $\sum(m)$ for all $m \in F_{m_i}$ consequently, the OFA based GSPID controller local set

$\Lambda(m_i), m_i \in \Theta^i$ is stability enclosing for $\sum(m), m \in \Theta$. This is sufficient condition on the gain parameter value Θ^i selection for the OFA based GSPID controller $\Lambda(m_i), m_i \in \Theta^i$ are designed.

4.4 LMVs- H_∞ stabilization

The calculated output \hat{y} is obtainable for producing \hat{u} , and then the feedback control law of output is in the form $\hat{u}(t') = K(m_i|t')y'(t')$ can be predicted. Thus, the constant feedback output of the control law is $\hat{u}(t') = K(m_i|t')y'(t')$. This assessed method is called as gain scheduled controller. Consider the LMVs bounded-real lemma for the LPV based rotor spinning system, which is expressed in Eq. (29), when the $K > 0$,

$$K > 0, \begin{bmatrix} \hat{P}^T(m_i)L + L\hat{P}(m_i) + \hat{R}^T(m_i)\hat{R} & L\hat{Q}(m_i) + \hat{R}^T(m_i)\hat{S} \\ \hat{Q}^T(m_i)L + \hat{S}^T(m_i)\hat{R}(m_i) & \hat{S}^T(m_i)\hat{S} - I \end{bmatrix} \leq 0 \tag{29}$$

where $\hat{P}(m_i) \in \bar{R}^{n \times n}$, $\hat{Q}(m_i) \in \bar{R}^{n \times p}$, $\hat{S}(m_i) \in \bar{R}^{p \times n}$, and $\hat{R}(m_i) \in \bar{R}^{p \times p}$ are specified and the variable of the matrix is specified as $K = K^T \in \bar{R}^{m \times n}$. In the LPV based approach, the system became stable at the time of zero disturbances which means $\alpha(t') = 0$. The interpolated LPV based rotor spinning system has controlled output $\hat{y}(t')$ that gratifies under the initial zero condition, where $(\hat{x}(t'_0) = 0, t'_0 = 0)$, the LMV is sufficient to the LPV based rotor spinning system, which is expressed in Eq. (30),

$$\int_0^T \hat{y}(t')^T \hat{y}(t') dt' \leq \int_0^T \hat{u}(t')^T \hat{u}(t') dt'. \tag{30}$$

The state of this Eq. (30) can consider as transfer matrix \tilde{H} . The transfer matrix of the LPV system is evaluated in Eq. (31),

$$\tilde{H}(s) \triangleq \hat{R}(m_i)(sI - \hat{P}(m_i))^{-1}\hat{Q}(m_i) + \hat{S}(m_i). \tag{31}$$

The bounded real conditions are satisfying in the corresponding based rotor spinning system is to \tilde{H} in Eq. (32),

$$\tilde{H}(s)^* \tilde{H}(s) \leq I \text{ For all } \bar{R}es > 0. \tag{32}$$

Equation (32) can be expressed in H_∞ function as $\|\tilde{H}\|_\infty \leq 1$. The H_∞ norm of \tilde{H} is referred as,

$$\|\tilde{H}\|_\infty \triangleq \sup \{ \hat{R}(m_i)(sI - \hat{P}(m_i))^{-1}\hat{Q}(m_i) + \hat{S}(m_i) \mid Res > 0 \}. \tag{33}$$

Substitute Eq. (31) H_∞ condition in the $\|\hat{R}(m_i)(sI - \hat{P}(m_i))^{-1}\hat{Q}(m_i) + \hat{S}(m_i)\|_\infty \leq 1$. The system became exponentially stable only if the condition of the matrix exists at $K = K^T > 0$ such that $\hat{P}^T(m_i)K + K\hat{P}(m_i) < 0$. The system became exponentially

stable with $\|\hat{R}(m_i)(sI - \hat{P}(m_i))^{-1}\hat{Q}(m_i) + \hat{S}(m_i)\|_\infty < \gamma$ and $\hat{P}(m_i)$ stable with $\tilde{H}(s)$ in Eq. (34). If the matrix exists at $K = K^T > 0$ such that,

$$\begin{bmatrix} K\hat{P}(m_i) + \hat{P}^T(m_i)K & K\hat{Q}(m_i) & \hat{R}^T(m_i) \\ \hat{Q}^T(m_i)K & -\gamma I & \hat{S}^T(m_i) \\ \hat{R}(m_i) & \hat{S}(m_i) & -\gamma I \end{bmatrix} < 0. \tag{34}$$

The condition of this Eq. (34) satisfies the system under stabilization and $\gamma = 1$. By applying the association of LMVs and H_∞ norm approach synthesizes the proposed OFA based GSPID controller stability. The performance of the controller is enhancing by this control law approach of stabilization.

4.5 Robustness of the proposed OFA-GSPID controller

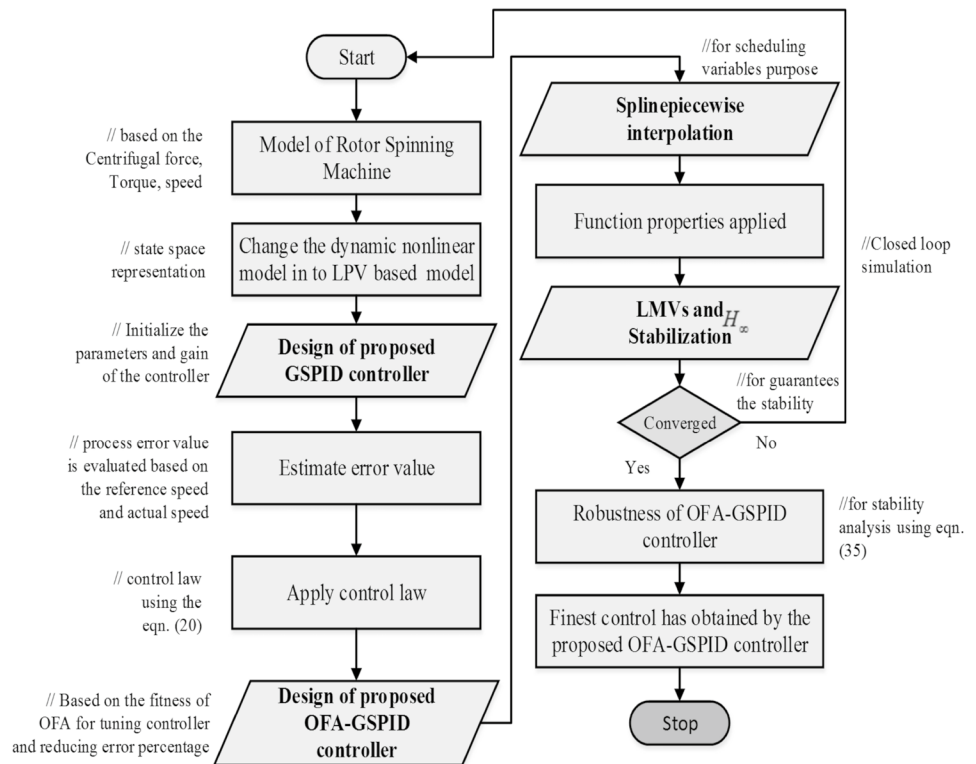
In this paper, the purpose of gain in feedback condition for a control law $\hat{u}(t' + m_i/t') = \hat{K}\hat{y}(t' + m_i/t')$ that stabilizes the LPV based rotor spinning system and better performance is obtained while fulfilling the parameters of input and output. The optimization problem is solved and the control input $\hat{u}(t') = K(m_i|t')y'(t')$ is implemented to the process. The state $\hat{P}^T(m_i)K + K\hat{P}(m_i)$ is a strictly diminishing the condition and the closed-loop LPV system is robustly stabilized by the gain of feedback condition. By this gain any condition of Eq. (20) can be stabilized. Thus the corresponding OFA based GSPID control law in Eq. (12) assures robust controlling to the LPV based rotor spinning machine. Consequently, robust stabilization of the controller performance is validate by the $\|\hat{R}(m_i)(sI - \hat{P}(m_i))^{-1}\hat{Q}(m_i) + \hat{S}(m_i)\|_\infty \leq 1$. The external bounded perturbation robust performance of the system is expressed by Eq. (35),

$$\|\tilde{H}(j\omega)\|_\infty = \max_\omega \left\| \frac{G(j\omega)G_c(j\omega)}{1 + G(j\omega)G_c(j\omega)} \right\|_\infty \leq 1. \tag{35}$$

The overall work flow of the proposed OFA based GSPID control process in rotor spinning machine is illustrated in Fig. 4.

Thus, the design performance of the proposed OFA-GSPID controller has been achieved the finest control strategy in rotor spinning machine in terms of reduced error and high gains. In addition, the input of the control system is managed by the signal of feedback. Usually, the closed loop system utilized the signal of feedback to produce the output of closed loop system. In some cases, the closed loop system might causes error and that error is corrected by feedback loop. Hence, the purposed of using feedback loop system is for error auto correction in the control system frame. However, the original system is stable in some critical cases the stability rage became reduced because of complicated

Fig. 4 Overall work flow of the proposed OFA-GSPID control in spinning machine



designs real time systems, in that case the feedback loop guarantee for system stability.

To structure a control frame feedback loop is a powerful tool. The chief usage of this feedback loop is to adjust the system performance to attain the desired output.

5 Result and discussion

The proposed method of OFA based GSPID controller in the rotor spinning machine is executed in a numerical and restrictive programming language of MATLAB 2018b environment, which was created by the Math Works in windows 7, Intel processor with 4 GB RAM. The parameters of this projected method are simulated and executed also compared with different existing control approaches.

5.1 Case study on rotor spinning machine system

Rotor spinning machine is an extremely nonlinear method also has been an industrial problem terms as speed over the few years. For efficient yarn production, the speed of the rotor spinning machine is regulated by the controller gains. The GSPID controller for the rotor spinning machine speed control has been done by the optimization algorithm such as OFA. In OFA based on the objective function design, the best output can optimize, hence objective function plays an essential part in this process.

Consider, the rotor spinning machine speed as 6000 rpm, 9000 rpm, and 11,000 rpm in this case study. The nominal rates of the method parameters and constraints incorporated with the rotor spinning machine with respect to the constant working state, which is illustrated in Table 1.

Initially, consider that $\hat{y}(t')$ is set to be 6000 rpm. The error between the set speed 6000 rpm and the real speed 5999.98 rpm is about 0.12 rpm low percentage. The transfer function of rotor machine is in Eq. (36),

$$G(s) = \frac{1}{s^2 + 6s + 5} \tag{36}$$

The performance enhancement of the system by the controller synthesize, which is considered as the LMVs and H_∞ arrangement. It is validated by the expression in

Eq. (34), where $\hat{P} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -5 & -1 \end{bmatrix}$, $\hat{R} = [0 \ 0 \ 1]$, $\hat{Q} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$,

and $\hat{S} = [1]$ are the system value from the transfer function of the system. The voltage and current response of the spinning machine is shown in Figs. 5 and 6. The graph in Fig. 6 shows that the voltage of the rotor machine is maintained as per level and the current of the machine is regulated on the nominal rating.

The produced torque in the rotor spinning machine is shown in Fig. 7. The torque is based on the twisting force of the rotor also the speed of the machine depends upon the torque produced in the rotor spinning machine.

Table 1 Nominal rates of the rotor spinning machine parameters

System constraints	Nominal rate
Linear density of yarn (d)	30 tex
The speed of the rotor (N)	6000 rpm, 9000 rpm and 11,000 rpm
Radius of rotor channel (R_r)	16 mm
Rotor angular velocity (ω')	50,000 m/min
Twist factor (t_f)	950
Radius of yarn (R_y)	30 mm
Friction coefficient between rotor wall and fiber ring (η)	14
The speed of the delivery (S_d)	Up to 350 m/min
The movement of yarn constant (Y_m)	7000 r/min

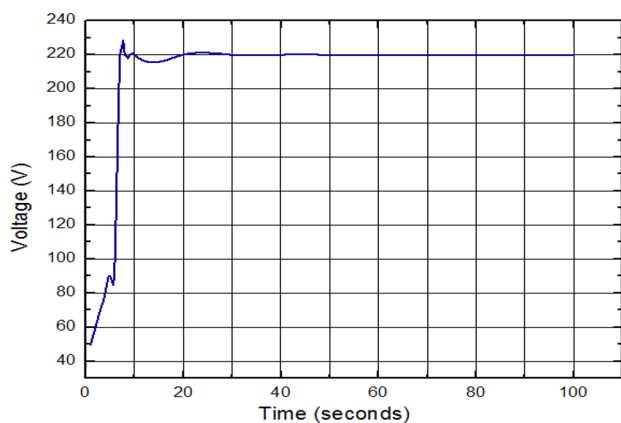


Fig. 5 The voltage source of the rotor spinning machine

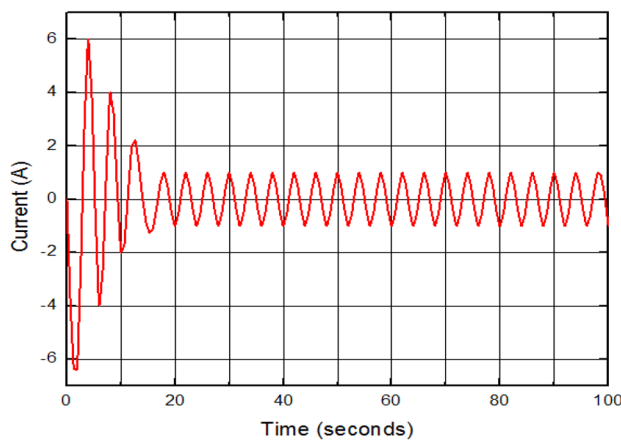


Fig. 6 The current source of the rotor spinning machine

In the set point variation, the speed of the rotor spinning machine to set point and the speed of the rotor obtained nearly identical to the set speed. The disturbances in the system are cancelled using the OFA based GSPID

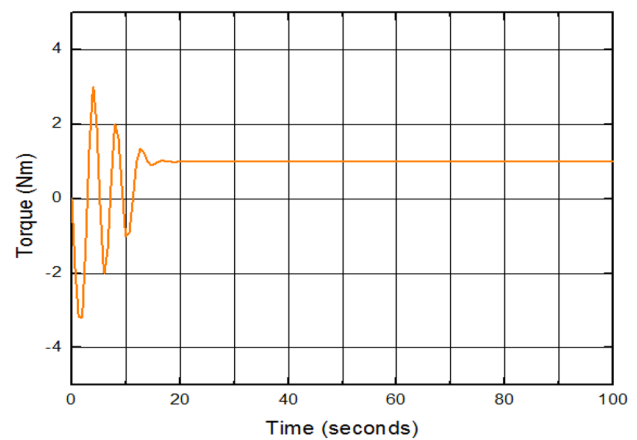


Fig. 7 The torque produces in the rotor

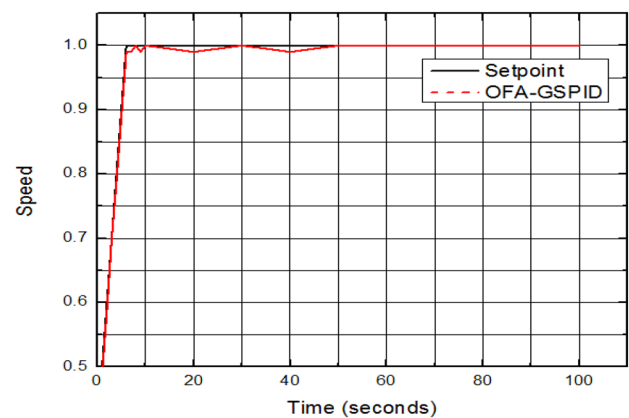


Fig. 8 The speed control of the rotor

controller approach. The OFA based GSPID control approach for the speed control of the rotor spinning system based on step tracking is shown in Fig. 8. The OFA based GSPID controller tuning process has validated their fineness in providing better outcomes by enhancing the performance indices and characteristics of the steady-state. The simulation outcome shows that the OFA based GSPID controller achieved better performance and robustness.

The tuning value of OFA optimization algorithm is known as $\bar{k}_p = 6.937$, $\bar{k}_i = 5.356$, and $\bar{k}_d = 0.0029$. The fitness value attained from the OFA function is as 6.3221. The step response tracking of the OFA based GSPID controller design in rotor spinning machine is illustrated in Fig. 9.

If the process of rotor spinning machine is initiated then it does not attain the stable range immediately. Hence, it takes some time to reach the stability that time period is determined as 50 s. Also, when the rotor machine is switch on it slowly increases the speed, thus it required some time to reach the stability range. In addition, if any application

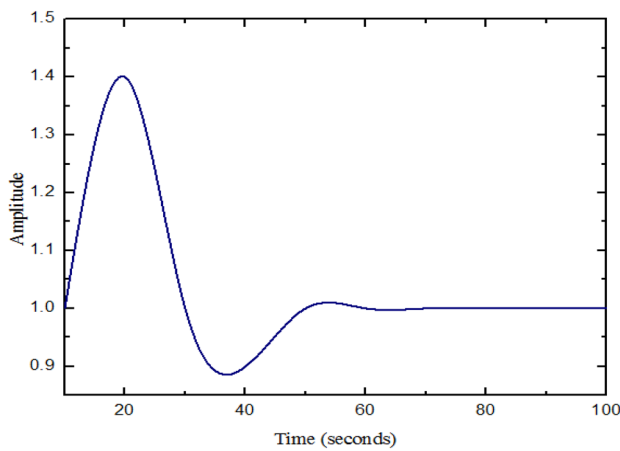


Fig. 9 The step response tracking of the OFA based GSPID controller for the rotor spinning machine system

Table 2 Parameters used in OFA

Parameters	Description	Value
N	Population size	21
n^a	Explore space element of a firefly	5
χ_0^b	Attraction coefficient base value	2
λ	Absorption coefficient	1
σ	Randomization	0.2
I_{\max}	Number of iterations	50

^aThe attractiveness function limit is greater than or equal to one

^bThe attractiveness, at q equal to zero

suddenly increases the speed when the switch is on then it might damage the controller and application system performance. So that, 50 s time taken for an application (rotor machine) resilience, which tends to attain good performance.

In this paper, ITAE is taken as an objective function, which is implemented for the spinning machine speed regulation using OFA. The parameters used in the OFA are given in Table 2.

In the time domain, the last form of controller adapted fitness function of ITAE in Eq. (37) is,

Table 3 Performance of the OFA based GSPID controller

Objective function	Speed	\bar{k}_p	\bar{k}_i	\bar{k}_d	Rising time ^a (s)	Settling time ^b (s)	Over-shoot ³ (%)	Function value
ITAE	6000	6.937	5.356	0.0029	0.00185	0.0932	1	6.937
	9000	6.937	5.356	0.0029	0.00175	0.0988	1	7.493
	11,000	6.937	5.356	0.0029	0.00194	0.0930	1	3.0763

^aRise time is defined as the time taken for the rise of 10–90% for the steady state condition

^bSettling time is defined as the time taken for the control signal to be enclosed to in a deviation $\hat{x}\%$ of the steady state response

^cOvershoot is defined as (max. value-final value)/final value $\times 100$

$$G_c(s) = 6.937 + \frac{5.356}{s} + 0.0029s. \tag{37}$$

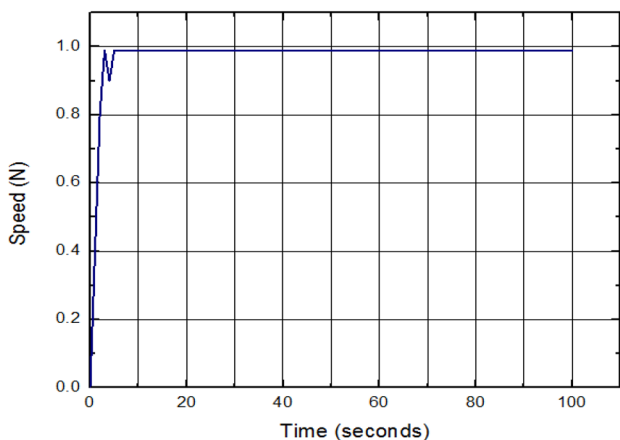
Based on the simulation outcome analysis shows the proposed OFA based GSPID control approach is able to control the speed of the rotor spinning machine in smoothly under the 0.00185 s and the high proportional gain at 6.937 is to reduce the steady-state error 0.0982, this leads to the one percentage of overshoot. Consequently, the performance of the OFA based GSPID controller is demonstrated in Table 3. The initiating process of rotor machine controller is detailed in Fig. 6. In addition, the overall performance of rotor spinning machine is detailed in Table 2. Here, after starting the rotor machining time taken for rising speed is 20 s and rising speed duration is 0.00185 s. Also, the time taken for settling rotor machine speed is 60 s and settling time duration 0.0932 s.

5.2 Effect of measurement noise and disturbances

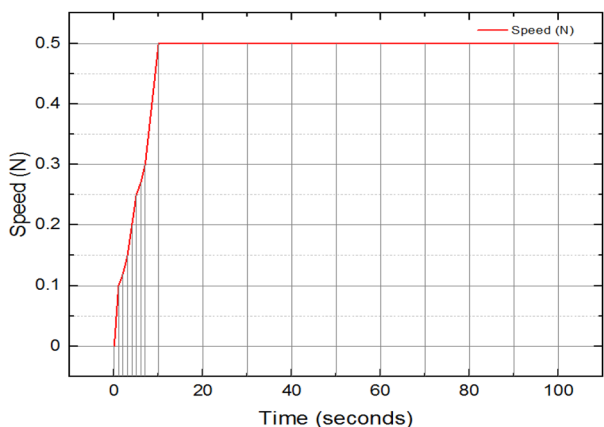
The proposed OFA-GSPID controller performance has been examined by the external injection of Noise to Ratio (NSR) is 0.014 in the simulation. Control approach for the speed control of the rotor spinning system (a) without noise, (b) with noise is illustrated in Fig. 10. From the graph observed that the control method attain finest tracking function but fewer less oscillations of amplitude are attained in the overall process because of the measurement noise occurrence. Moreover, the essential regulation is achieved in that still the particular values are bounded in its nominal values.

5.3 Stability analysis of the proposed system

The combination of LMVs- H_∞ control enhanced the stability and flexibility of the proposed controller. The LMVs bounded-real lemma for the LPV system is applied by Eq. (29). The bounded real conditions are satisfied in the system using Eq. (32). Bode plot for proposed controller stability analysis (a) with feedback controller without noise, (b) without feedback (c) with feedback controller and noise are illustrated in Fig. 11. Consequently, with feedback (proposed) controller means, the condition from Eq. (34) has



(a)



(b)

Fig. 10 Control approach for the speed control of the rotor spinning system **a** without noise, **b** with noise

been satisfied and system attained finest stability. Based upon the frequency and gain bode plot of the proposed controller is adopted. In bode plot graph illustrates that the magnitude’s transfer function is pointed against the frequency process. Consequently, the phase transfer function is drawn individually against frequency (Table 4).

5.4 Performance over method model mismatch

The consequence of measurement and disturbance noise is validated to prove the proficient measure of the proposed model. Hereafter, the robustness score of the developed closed loop system against mismatch process is calculated. That is defined as measuring the robust performance of the proposed scheme while process model is diverse from actual process.

The proposed controller response of the rotor spinning machine process in the occurrence of model mismatch (a) process output N (b) essential control input T(Nm) is

demonstrated in Fig. 12. Therefore, it can be ended that the projected methods shown robust control performance.

5.5 Performance comparison of controllers

The implementation of OFA based GSPID controller tuning is greatly easier than other conventional methods, for the reason that does not require any derivative information. The OFA based GSPID performance is compared with other controllers such as the Conventional PID controller [21], Fuzzy based GSPID [23] and IRHA based GSPID [24], which is shown in Fig. 13. The proposed OFA based GSPID controller performance is simple to employ and it does not require skilled person for tuning compare to other controllers.

In this paper exhibited a fewer steady-state error as 0.0982. Therefore, this leads to the proposed OFA based GSPID controller has obtained tremendous stability and finest accuracy than existing controllers. The optimized steady-state error percentage of the proposed OFA based GSPID controller is compared with the conventional PID controller [27], Fuzzy based GSPID [24] and IRHA based GSPID [25] are shown in Fig. 14.

In the objective function of the conventional controller got a high value of steady-state error while compared to the OFA based GSPID controller as 0.0982%. The performance of the controller is validated using this strategy of process. Moreover, the performance efficiency of the OFA based GSPID controller for the rotor spinning machine is evaluated using Eq. (38),

$$Accuracy = \frac{(T\hat{N} + T\hat{P})}{(T\hat{N} + T\hat{P} + F\hat{N} + F\hat{P})} \tag{38}$$

where $T\hat{N}$ a true is negative, $T\hat{P}$ is truly positive, $F\hat{N}$ is false negative and $F\hat{P}$ is false positive. Based on the accurate estimation of the proposed method with the rotor spinning machine speed control is obtained as 92%, which is calculated using Eq. (38). The better accuracy is obtained by the high population size and high number. The comparison of proposed OFA based GSPID controller accuracy with existing techniques is represented in Fig. 15. The overall comparison of proposed OFA based GSPID controller with other controllers in terms of gain parameters, rise time, settling time, overshoot, and settling time is demonstrated in Table 5. From the comparison table shows that the error percentage of proposed system is reduced considerably and enhanced the accuracy.

In interpolation controller, the stability of the system is managed in interpolation phase. Also, in all application the stability function is not guaranteed. For that interpolating frame is implemented in gain schedule paradigm. Hereafter, the stability of the closed loop frame is analyzed.

Fig. 11 Bode plot for proposed controller stability analysis **a** with feedback controller without noise, **b** without feedback controller, **c** with feedback controller and noise

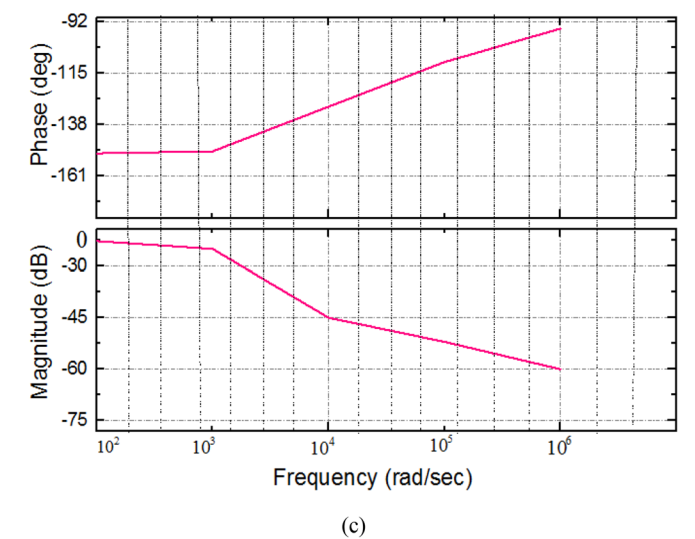
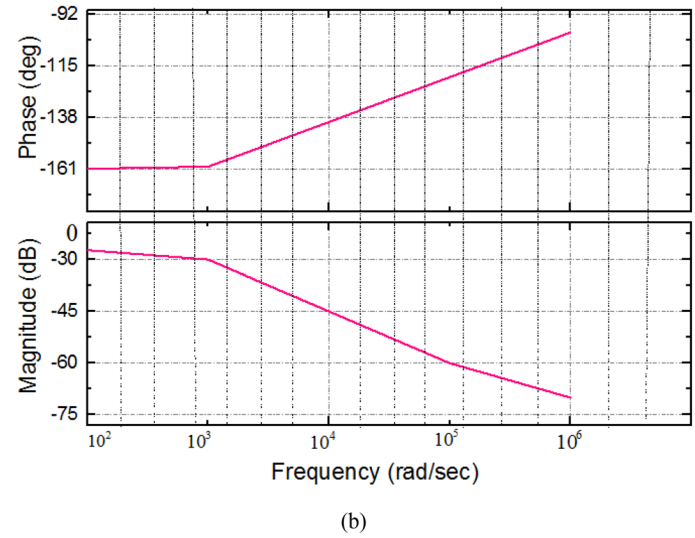
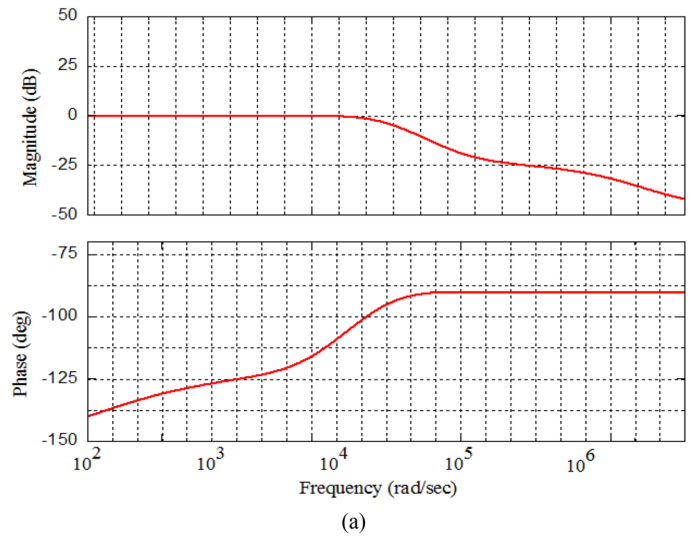
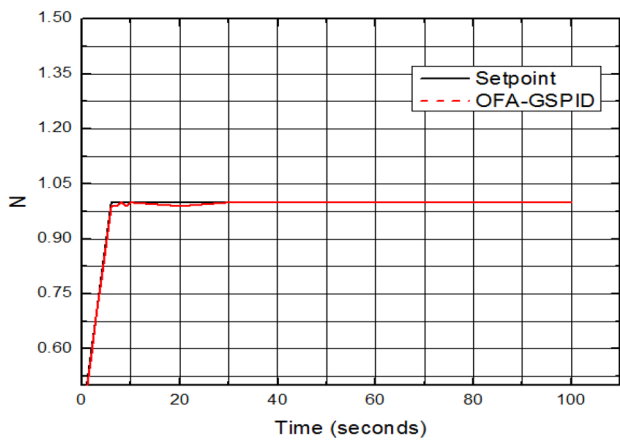
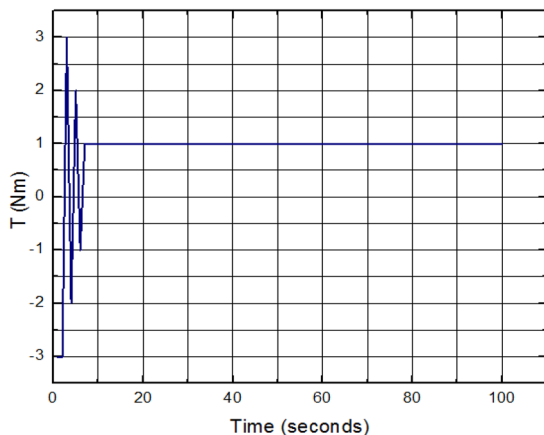


Table 4 Magnitude and phase: without feedback loop and noise disturbance

Fre- quency (rad/s)	Without feedback		Noise disturbance	
	Magnitude (dB)	Phase (°)	Magnitude (dB)	Phase (°)
10^2	-25	-170	-25	-170
10^3	-30	-160	-30	-160
10^4	-45	-140	-45	-140
10^5	-60	-120	-60	-120
10^6	-70	-100	-70	-100



(a)



(b)

Fig. 12 proposed controller response of the rotor spinning machine process in the occurrence of model mismatch **a** process output N , **b** essential control input $T(Nm)$

Moreover, here the OFA module controls the gain parameters to improve the controller performance.

The performance assessment of proposed controller with H_∞ controller is detailed in Fig. 16. The key metrics to

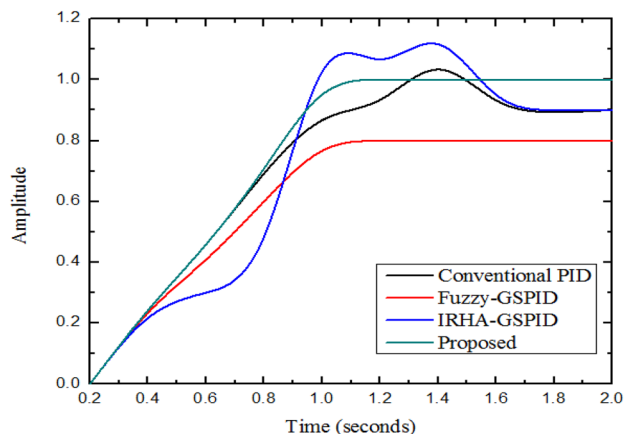


Fig. 13 Comparison analysis of the proposed controller with the existing techniques

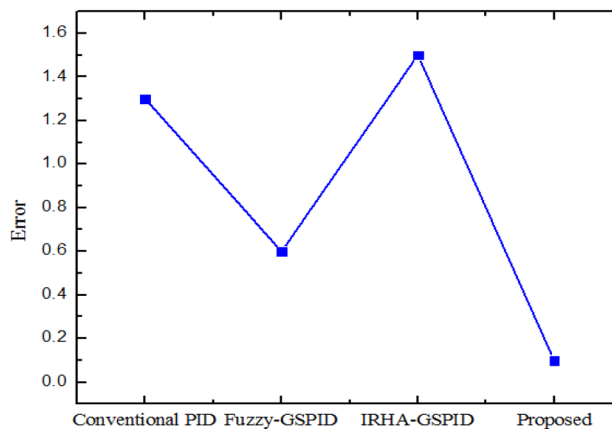


Fig. 14 Comparison of error percentage with various controllers

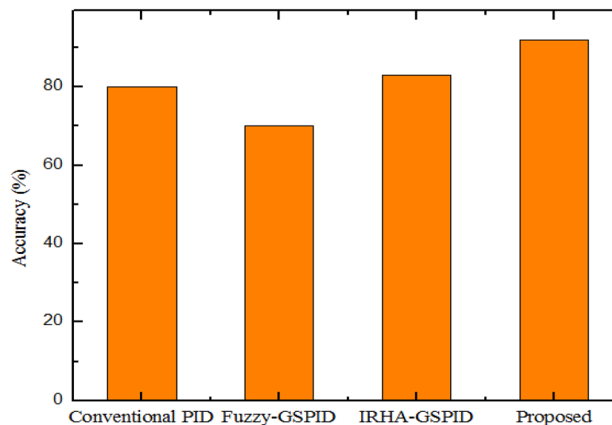


Fig. 15 The efficiency of the proposed controller with the existing controllers

Table 5 Overall comparison with existing control techniques

Methods and parameters	Conventional PID [26]	Fuzzy-GSPID [24]	IRHA-GSPID [25]	Proposed OFA-GSPID
k_p	0.758	12.97	3.84	6.937
k_i	26.74	0.316	27.96	5.356
k_d	13.06	1.853	0.456	0.0029
Rising time (s)	1.2	1	0.8	0.00185
Overshoot (%)	1.43	3.9	2.96	1
Settling time (s)	1	1.13	1.7	0.0932
ITAE	1.3	0.765	1.51	0.0982
Accuracy	80	70	83	92
Merits	Fast response	Based on condition	Reduced error	Computational time is low and reduced design complexity
Limitation	Error is high	Inaccurate result may occur	Fault can happen	–

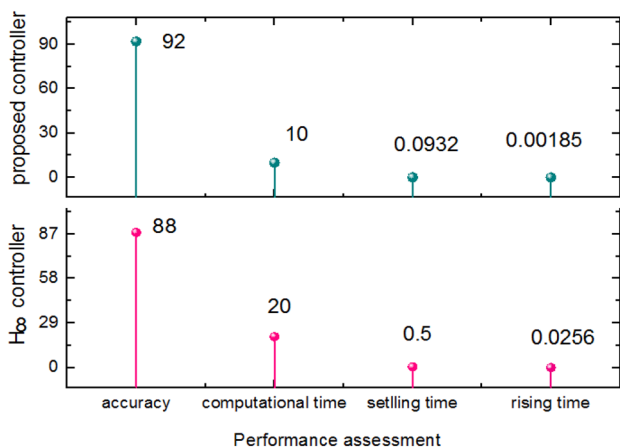


Fig. 16 Performance assessment of H_∞ controller with proposed controller

estimate the best performance of proposed scheme is computational time. Moreover, computational period is defined as the taken to execute the proposed replica simulation. Hence the comparison of the computational time is detailed in Fig. 17. Thus, the proficient measure of the projected system is verified systematically by attained less computational time as 10 s.

Thus the better performance has achieved by OFA tuning for the fitness function of ITAE in GSPID controller in terms of the low percentage of overshoot, fast rise time, and fastest settling time. The parameter of PID controller is tuned by the fitness of Firefly, thus it is determined as novel controller. Up to simulation, the developed method has attained very good performance result In addition the proposed system will applicable in real time whenever, it is broadly designed with the embedded function parameters.

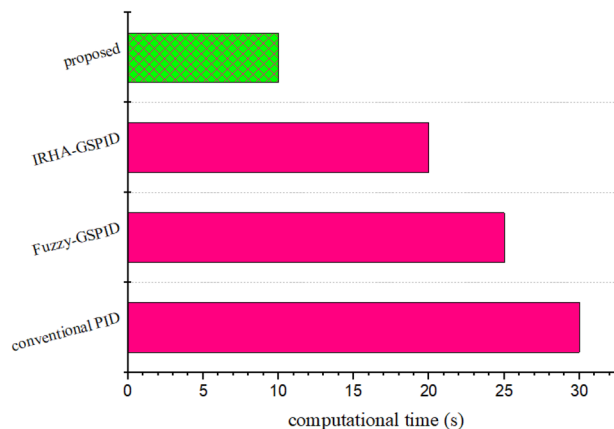


Fig. 17 Comparison of computational time

6 Conclusion

In this research, a novel OFA based GSPID controller approach is proposed to regulate the speed of the rotor spinning machine at the desired level. Moreover, the LMVs and robust H_∞ control association synthesized the stability of OFA based GSPID controller. Consequently, Spline piecewise interpolation was developed to the gain scheduling controller for resolving scheduling issues. The OFA optimization was used for tuning the controller parameters and steady-state error optimization. Moreover, there was less percentage of overshoot and the settling time was attained by this control process due to the high gain of proportional. Furthermore, the robustness of the controller was analyzed and the efficiency of the controller outcome is obtained at accuracy as 92%. Consequently, the OFA based GSPID controller was validated with other existing controllers. Thus, the comparison illustrates the effectiveness of the proposed

control approach in the speed control process in the rotor spinning machine with less error percentage and high accuracy. Furthermore, the small drawback behind in this proposed model is it taken few seconds to design the interpolation scheme. So in future, the GSPID controller with hybrid optimization can improve the stability performance and avoids the interpolation function.

Declarations

Conflict of interest The authors declare that they have no potential conflict of interest.

Ethical approval All applicable institutional and/or national guidelines for the care and use of animals were followed.

Informed consent For this type of study formal consent is not required.

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