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DUAL FUZZY LOGIC PID CONTROLLER BASED REGULATING OF DC MOTOR SPEED CONTROL WITH OPTIMIZATION USING HARMONY SEARCH ALGORITHM

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This paper discusses the implementation of a Proportional-Integral-Derivative (PID) controller for regulating the speed of a closed loop four quadrant chopper fed DC motor. The PID controller is combined with a Dual Fuzzy Logic Controller to form a DFPID controller for enhancing the performance of speed control of the DC motor. The DFLC is optimized using a metaheuristic algorithm known as Harmony Search Algorithm (HSA). The major aim of this research is to gain an effective control over the speed of the motor in the closed loop environment. For achieving this, the parameters for the DFPID are selected through time domain analysis which aims to satisfy the requisites such as settling time and peak overshoot. Initially, the fuzzy logic controller in the DFPID controls the coefficients of the PID achievement gain an effective control over the system error and rate of error change. Further, the DFPID is improved by the HAS for obtaining a precise correction. The solutions obtained by tuning the DFPID controller are evaluated from simulation analysis conducted on a MATLAB/SIMULINK platform. The closed loop performance is analyzed in both time and frequency domain analysis and the performance of DFPID is optimized using the HSA algorithm to obtain precise value of the control process. As observed from the Simulation analysis, the DFPID-HSA generates optimized control signals to the DC motor for controlling the speed. The performance of the intended speed control approach is analyzed in terms of different evaluation metrics such as motor speed, torque and armature current. Experimental outcomes show that the proposed approach achieves better control performance and faster speed of DC motor compared to conventional PID controllers and SMC controllers

Keywords: PID controller, dc motor, dual fuzzy logic controller, sliding mode control, optimization

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1. Introduction

Direct current or DC motors are successfully implemented in different applications such as locomotives [1, 2], elevators [3], air compressors and other industrial applications [4]. The increased adaptability of DC motors is in view of its advantages such as high-power density, simple control, reliability, and effective speed regulation [5]. Although DC motors are characterized by their implementation in broader applications, it is difficult to control the speed of the motor. With the increasing significance of speed control for DC motors, the problems associated with controlling mechanisms also increases. Several researchers have used different intelligent control techniques for achieving better control performance of DC motors [6–8]. Most commonly used control strategies for DC motors are feedback linearization technique-based model controller [9], adaptive control strategy [10], Sliding mode control (SMC) technique [11] and Proportional, Integral, and Derivative (PID) controller. Different combinations of PID controllers such as PI, PD, and PID controllers are extensively utilized to control the speed response of DC motors [12, 13]. Although conventional PID controllers are advantageous in terms of controlling the speed and position of the DC motors, there are certain limitations such as inadaptability to nonlinear systems, and presence of non-deterministic parameters which can affect the stability of the system. In addition, PID controllers fail to achieve desired performance of nonlinear systems due to the uncertainty of system parameters. Hence, there is a need to modify the parameters of traditional PID systems in order to enhance their performance such as the application of auto tuned PID controllers [14], Fuzzy logic based PID controller [15]. Fuzzy based PID controllers are considered to be a potential alternative to traditional PID controllers since it provides a simple yet effective performance in terms of speed control and analyze system characteristics without requiring any mathematical model. It also provides better results for nonlinear and dynamic systems. However, the problem of parameter tuning affects the performance of fuzzy based PID controllers. Hence, it requires efficient techniques for tuning the parameters of the controllers and reducing the output error and augmenting the performance. With the emergence of swarm intelligence based metaheuristic algorithms, several researchers have utilized various optimization algorithms for tuning the parameters of fuzzy based PID controllers such as particle swarm optimization (PSO) [16], genetic algorithm (GA) [17], and ant colony optimization (ACO) [18] and harmony search algorithm (HSA) [19] for optimizing the DFPID controller.

As a consequence, studies devoted to DFPID-HSA to regulate DC motor speed control are scientifically relevant. Traditional PID controllers and FLCs often fail to achieve effective speed control for DC motors that are operating in dynamic and uncertain environments. These control techniques may lead to overshoot, long settling times, and steady-state errors, which can hinder the optimal functioning of industrial processes. Besides, the optimization of controller parameters, especially in FLCs, can be intricate and time-consuming. Optimizing these parameters to achieve desired performance in varying operational scenarios poses a significant challenge.

2. Literature review and problem statement

Several optimization strategies have been developed to optimize the coefficients of PID based controllers. The authors in [20, 21] optimized PID controllers using neural networks. Neural networks can either be trained online or offline and are characterized by their slow response and high computational complexity. [22, 23] used the PSO algorithm for optimizing the coefficients of PID controllers. The PSO algorithm improved the control performance significantly. However, it is highly challenging for the PSO algorithm to reach optimal solutions with a lesser number of iterations. Another metaheuristic algorithm called Genetic algorithm is used for optimizing the gain of PID controller is proposed in [24]. It can be inferred from the study that it is difficult to evaluate the initial population in the algorithm. In general, FLC models do not require any fixed system model and can be performed using only calculations, knowledge base, and rules. Hence, optimization techniques for FLCs have a strict control effect on the performance compared to other algorithms [25]. For instance, a novel fuzzy based self-tuned PID optimal controller is proposed in [26]. The controller is used for controlling the output which is used to turn ON the switching devices. Here, a MOSFET is used as a switch whose operation is controlled by varying the duty ratio of the pulse width modulation (PWM) control signal. The speed of the brushless DC motor is controlled through the control signals. An adaptive PI control technique along with fuzzy parameters is used for regulating the speed of the DC motor in [27]. Simulation analysis shows that the proposed control strategy has a robust control over the speed and the stability and reliability can ensure smooth motor operation under different speed conditions. Although the effectiveness of the optimization techniques for FLC is proven in several cases, its drawbacks cannot be ignored. Since there is no fixed definition of the knowledge rule base in FLCs, it is challenging to calibrate PID parameters and hence FLCs should be optimized. An Adaptive Network based Fuzzy Inference System (ANFIS) controller with fuzzy PID is employed in [28] for realizing the speed control of DC motors which exhibit better performance under different driving conditions. However, the performance varies when tested under steady state. The work presented in [29–31] discussed the implementation of genetic algorithm, PSO, and Bat algorithm for calibrating the parameters of the fuzzy PID controller. These algorithms are used for optimizing the scaling factor of the output variables of the controller. The work presented in [29] applied an improved GA to regulate the optimal parameters of the FLC in order to maximize the convergence speed and accuracy. Although the proposed approach achieved an improved efficiency, the performance optimization in terms of hardware consumption needs to be addressed. The tuning problem of the controller parameter was studied in [30]. A PSO algorithm with a linear-quadratic-regulator (LQR) method was employed for designing an effective strategy for parameter tuning. A BAT optimization algorithm was adopted in [31] for optimizing the fuzzy based PD controller in a brushless DC motor. The proposed approach exhibited excellent results in terms of mitigating uncertainties and effect of nonlinearities in real-time scenarios. However, the performance can be improved in terms of achieving an effective closed loop performance. In [32] the genetic algorithm is adopted to optimize the membership function of the fuzzy PID by employing a rule base. The above discussed algorithms achieve a better controller performance compared to classic fuzzy PID control technique and also suffer from the drawbacks as discussed previously. In [33] a global optimal adaptive HAS is employed to optimize the performance of the neural network and thereby enhance the training efficiency of the model. Results show that the adaptive HAS enhanced the accuracy of the neural network. The effectiveness of the HAS and differential evolution (DE) algorithm is validated in [34] in terms of optimizing the parameters of the network model. The work mentioned in [35] states that the speed of the controller can be controlled effectively using HSA. Results show that the proposed approach achieved an excellent controlling performance. It can be inferred from the existing works that the HSA exhibits superior performance compared to other optimization algorithms. To overcome the limitations of these algorithms, HSA is used as a new global search algorithm which is extensively used in various optimization processes [34] such as problem solving in continuous optimization tasks, resolving unconstrained issues, and in electrical applications such as DC motors [35]. It can be inferred from the existing works that the HSA exhibits superior performance assessed to other optimization algorithms.

As observed from the previous works, it is highly challenging to obtain a precise and efficient speed control of the DC motors and traditional PID-based control techniques suffer from the limitations such as nonlinearities, uncertainties, and disturbances which are inherent to industrial processes. In addition, it also difficult to tune the coefficients of the PID controller to accommodate varying operating conditions. Although, intelligent control strategies, such as FLC exhibit excellent performance in terms of handling the nonlinearities, it is complex to optimize the coefficients of the controller. Conventional optimization algorithms such as PSO, GA, and ACO exhibit a slower convergence rate, generation of suboptimal solutions, increased computational complexity, premature convergence, and high parameter sensitivity. Hence, it is important to address these limitations by selecting an appropriate optimization algorithms.

All this allows to assert that it is expedient to conduct a study on the proposed DFPID-HSA to regulate the DC motor by providing an optimum control signal for speed regulation.

That is the research seeks to explore the feasibility and effectiveness of a Dual Fuzzy Logic PID controller for regulating DC motor speed, with the goal of achieving enhanced control precision, reduced settling time, and improved steady-state performance through systematic parameter optimization.

3. The aim and objectives of the study

The aim of this study is to development of a dual Fuzzy Logic PID controller for regulating the speed response of a DC motor.

To achieve this aim, the following research objectives are accomplished.

- get the Sliding Mode Controller's performance analysis;
- stability study for all controllers;
- fuzzy lead-lag controller's performance analysis;
- optimize the performance of the DFLC using a meta-heuristic-based Harmony Search Algorithm (HSA) optimization algorithm which generates optimized control signals to the DC motor for controlling the speed.

4. Materials and methods of research

4. 1. Object and hypothesis of the study

This research paper introduces a new approach for speed control of DC motors using a dual fuzzy logic PID (DFPID) controller. The optimization of the DFPID controller is conducted by utilizing a metaheuristic optimization algorithm called the harmony search algorithm (HSA). The HSA algorithm utilizes an enhanced dynamic adjustment mode and a triple selection process to achieve an optimized global search process, thereby facilitating the attainment of optimal global harmony. The proposed DFPID-HSA effectively controls the DC motor through the provision of an optimal control signal for regulating the speed.

As an initial step, the DC motor is modeled and the closed loop transfer function is obtained. The proposed DFPID controller consists of a conventional PID controller with a FLC to perform adaptive switching based on the speed error. A dual fuzzy logic consists of two separate FLCs in order to achieve better performance in terms of controlling and regulating the dynamic system. The rules of the two distinct FLCs are incorporated in the design to capture the complex relationships between the variables of the system and generate control actions which is not feasible using a conventional PID controller. In the second stage, the DFPID is optimized using a HAS for obtaining an optimal control signal for controlling the speed of the DC motor.

4. 2. Modeling of direct current motor

The speed of the DC motor can be controlled and maintained above or below the reference speed. This can be achieved by using an armature control method and a field control method also known as a flux weakening method, which maintains the speed below and above the reference speed respectively. In the proposed approach, the armature control of a separately excited DC motor is used to regulate the speed above the reference speed. In this approach the voltage across the armature is varied consistently by maintaining a constant field value and in this way, different speed values are obtained. A basic DC motor is illustrated in Fig. 1 and the parameters used to model the DC motor are tabulated in Table 1.

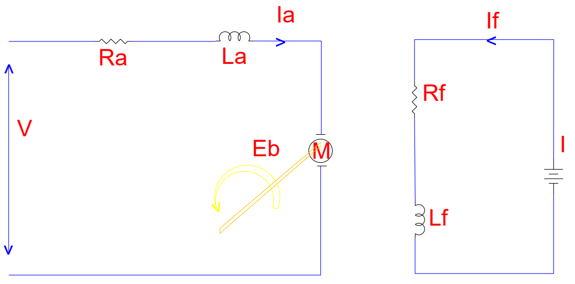

Fig. 1. Schematic of the Direct Current motor

Table 1

DC motor parameters

Parameters	Values	Units
Terminal Resistance (R)	4.67	Ohm
Terminal Inductance (L)	170×10^{-3}	H
Motor Inertia (J)	42.6×10^{-6}	$Kg{\cdot}m^2$
Viscous friction coefficient (b)	47.6×10^{-6}	Nms/rad
Torque constant (kt)	14.7×10^{-3}	Nm/Amp
Back EMF (ke)	14.7×10^{-3}	V-sec/rad

The mathematical equations that define the modeling of DC motors are defined using the below given equations:

$$V-E_b=L\frac{di}{dt}+i_aR_a, \tag{1}$$

$$T_d=J\frac{d\omega}{dt}+B\omega+T_L, \tag{2}$$

$$\tau(s)=K_t\,Ia(s), \tag{3}$$

$$E_b(s)=Kb\,\omega(s), \tag{4}$$

where ω is the angular velocity of the rotor in rpm, R_a is the armature resistance, L is the armature inductance, K_b is the back emf constant, τ is the electromagnetic torque, K_t is the torque constant, E_b is the back emf, T_L is the load torque, V is the armature terminal voltage, B is the friction of the DC motor, J is the inertia of the motor, Ia is the armature current.

The transfer function (TF) of the armature controlled separately excited DC motor is formulated as shown in below equation:

$$\frac{\omega(\xi)}{V(\xi)}=\frac{k}{(J_\xi+B')(L_\xi+R')+k^2}, \tag{5}$$

where ξ is the damping factor, considering $Kb=Kt=K$, the state space model of the separately excited DC motor is given as results:

$$\begin{bmatrix}\omega'\\ t\end{bmatrix}=\begin{bmatrix}\frac{-B}{J} & \frac{K}{L_a}\\ \frac{-K}{L_a} & \frac{-R_a}{L_a}\end{bmatrix}\begin{bmatrix}\omega\\ t\end{bmatrix}+\begin{bmatrix}0\\ 1/E_a\end{bmatrix}V, \tag{6}$$

$$y=[10]\begin{bmatrix}\omega\\ t\end{bmatrix}. \tag{7}$$

By obtaining the parameters of the DC motor from (5), the *TF* of the proposed plant is given as shown in (8):

$$TF = \frac{2030}{S^2 + 28.58s + 60.34}. \tag{8}$$

Here, as per the TF function the optimal value of $k=2030$.

4. 3. Proposed dual fuzzy proportional integral derivate – harmony search algorithm (DFPID-HSA) controller

To solve the problem of speed control in DC motors, this research employs a HSA which optimizes the dual fuzzy logic system based PID controller (DFPID-HSA). A PID controller is a closed loop model with a feedback control system, which compares the output with a set point (desired state) and estimates the error $e(t)$. Based on the error generated, the controller adjusts the output of the system generated by the control unit 'M'. The process is repeated until the error becomes zero or negligible. Fuzzy logic controllers with a self-tuning PID controller are used for parameter tuning of the DC motor. Fuzzy-based PID controllers increase stability and provide efficient speed control. FLC is applied for the DC motor, for maintaining constant speed irrespective of uncertainties such as time varying parameters and external disturbances.

In the initial stage, the fuzzy logic system in the DFPID-HSA couples the coefficients of the PID controller namely; proportional (K_{P1}), integral ($K_{\mathrm{I}1}$), and derivative (K_{D1}). These coefficients can be evaluated on the basis of the system error (e) and rate of change of error (ec). Further, the precise values of the coefficients $k_{p'}$, $k_{i'}$, $k_{d'}$ of K_{P1}, $K_{\mathrm{I}1}$, and K_{D1} can be obtained by the fuzzy logic system optimized using the HSA algorithm. For obtaining an optimal value for the global harmony, the PAR and BW in the optimization algorithm employs an enhanced dynamic control mode and a triple selection technique is employed in the composition harmony section for realizing the optimal global search value. Lastly, the proposed DFPID-HSA generated an optimal control signal $u(t)$ to the DC motor for achieving better speed control.

As per the system functioning, the error of the plant output (e) is given as; $e=y-r$ and the rate of change of error (ec) is given as; $ec=de/dt$ and the control signal $u(t)$ is given as follows:

$$U(t) = K_p e + K_I \int edt + K_D \frac{de}{dt}. \tag{9}$$

Where, K_p, K_I, and K_D in the system are evaluated by determining the output parameters K_{P1}, K_{I1}, and K_{D1} of the fuzzy logic systems in the DFPID-HSA, and the output coefficients $k_{p'}$, $k_{i'}$, $k_{d'}$ of the HSA optimized DFPID-HSA is given as follows:

$$K_P = K_{P1} + k_p,$$

$$K_I = K_{I1} + k_i,$$

$$K_D = K_D 1 + k'_d. \tag{10}$$

The optimal output parameters obtained from equation (10) are combined with the FLC to create a unified control signal that optimally regulates the system. The synthesis of control signals from both paths is achieved through techniques such as FLC.

4. 3. 1. Fuzzy logic control

The basic structure of the FLC is designed using four parts namely; fuzzification, knowledge base, fuzzy inference engine, and clarification.

During fuzzification, the input quantity of the system is transformed into a fuzzification quantity. The input consists of output of the DC motor, output state, and external reference input. The knowledge base incorporates the knowledge related to the target application (here, speed control of the DC motor) and the control objectives. The knowledge base consists of two components namely; a database, and fuzzy control rule bases. The fuzzy inference engine is an integral part of the fuzzy logic system, which has the ability of analyzing the system parameters based on the fuzzy concepts. The inference rules are applied to design a specific fuzzy logic. Lastly, the objective of the clarification stage is to transform the control quantities obtained by the fuzzy inference engine, into an accurate quantity of the control system.

In the proposed DFPID-HSA approach, both of the fuzzy logic systems employ dual input and output controllers. Here, fuzzification of these systems are performed in order to transform the original values of the system in terms of error (e) and rate of change of error (ec) into the respective fuzzy values based on the knowledge and membership functions. The fuzzy language set of the fuzzy systems and their input is given as {NB, NM, NS, ZO, PS, PM, PB} which also states that {«Negative big», «negative middle», «negative small», «zero», «positive small», «positive middle», «positive big»}. Correspondingly, the fuzzy language set of the fuzzy system and their output variables is given as; {VS, MS, S, M, B, MB, VB}= ={«very small», «medium small», «small», «medium», «big», «medium big», «very big»}. The fuzzy rules can be modified or altered through the simulation analysis and the important fuzzy rules are formulated as follows:

If $e=e_f$ and $ec=ec_f$, then $K_{P1}=K_{P1f}$
and $K_{I1}=K_{I1f}$ and $K_{D1}=K_{D1f}$;

If $e=e_f$ and $ec=ec_f$, then $K_{p'1}=K_{p'f}$
and $K_{i'1}=K_{i'f}$ and $K_{d'1}=K_{d'f}$,

where e_f, ec_f,K_{P1f}, K_{I1f}, K_{D1f}, $K_{p'f}$, $K_{i'f}$, and $K_{d'f}$ define the fuzzy language sets of e, ec, K_{P1}, K_{I1}, K_{D1}, $K_{p'}$,$K_{i'}$, $K_{d'}$. Considering K_{P1} as a sample illustration, the membership degree of the first fuzzy rule of K_{p1} is given as follows:

$$\mu K_p 11 = \mu NB(e) \mu NB(ec).$$

As the controller encounters various operating conditions and disturbances, the rules and membership functions of the FLCs can be fine-tuned to optimize performance and responsiveness.

4. 3. 2. Harmony search algorithm

HSA is a type of heuristic algorithm which is characterized by their ability to achieve global convergence. The HSA technique emulates the musical process of searching for a perfect state of harmony. Unlike the gradient based search process, the HSA employs a stochastic random search approach based on the harmony memory which incorporates the pitch adjusting rate. The HSA approach is used to solve various real time optimization problems which provides better performance compared to other algorithms. In this research, the parameter tuning of DFPID controller is considered as an optimization problem, which is solved to reduce the error between the actual output and the estimated output. Here, the HSA will search for optimal rules for the FLC that represent the gain of the PID controller. The steps involved in the HSA process are defined as follows:

Step 1: defining the problem and parameter values.

The issue of minimization is provided as described in (12) because the goal of this research is to minimize the problem as an objective function:

$$\min f(X), X=\{x_1, x_2, \ldots., x_n\} \cdot R_n.$$

Different parameter values considered are as follows:

a) harmony memory size (HMS);
b) harmony memory considering rate (HMCR);
c) pitch adjusting rate (PAR);
d) bandwidth (BW);
e) times of creation (Tmax).

Step 2: initialization of HMS.

The HMS harmonies are denoted as X^1, X^2, ..., X^{HMS} are formed randomly from the population space of X and are included into the HMS. As demonstrated in equation (13), The harmonics memory includes values from the external environment which avoids falling into the local optimum:

$$x_i = x_i \text{ min} + (x_i \text{ max} - x_i \text{ min}) x_r 0,$$

where r_0 is a random number in the range of [0, 1].

Step 3: generate a new harmony.

After initialization, a new harmony is generated by generating a random number r_1 between [0, 1] and is compared with the HMCR values. If r_1<HMCR, consider the random harmony variable from the HMS, else another random harmonic variable is generated from the solution space.

Step 4: update harmony memory.

Determine the value of new harmony memory value X_{new}, i. e. $f(X_{new})$. If the obtained value is higher than the value with the worst function in the harmony memory i. e., evaluate X_{new}, i. e. $f(X_{new})$. If it is better than the one with the worst function value in HM, $f(X_{new})<f(X_{worst})$, then X_{new} will replace X_{worst}; Else, no the new value is not replaced.

Step 5: Determine the stop condition.

In this research, the HSA algorithm optimizes the DFPID controller for obtaining an accurate value for $k_{p'} / k_{i'} / k_{d'}$ of the fuzzy system parameters. Since the speed control of the DC motor is correlated with the problem of error minimization, the harmony memory is given as follows $k_{p'}^{HMS}$, $k_{i'}^{HMS}$ and $k_{D'}^{HMS}$.

Once the termination or stop condition is achieved, the obtained parameters are considered to be optimal which can enhance the control performance and adaptability. These parameters help the proposed controller to formulate an intelligent control strategy for complex and dynamic systems such as DC motors.

5. Results of the dual fuzzy logic proportional-integral-derivative controller approach

5. 1. Sliding mode controller results

Fig. 2 illustrates the demonstrated efficacy of the SMC mechanism in regulating the velocity of the motor.

The performance of the SMC and PID is tested in terms of controlling the speed of the DC motor. It can be inferred from the output graph shown in Fig. 2 that the SMC provides a stable speed control in comparison to PID controller with respect to the reference speed. This is mainly due to the fact that the SMC forces the speed of the motor to slide along a defined trajectory. The speed is controlled in such a way that the state of the system remains on the sliding surface which ensures the stability and robustness against the system perturbations, which the PID controller cannot achieve.

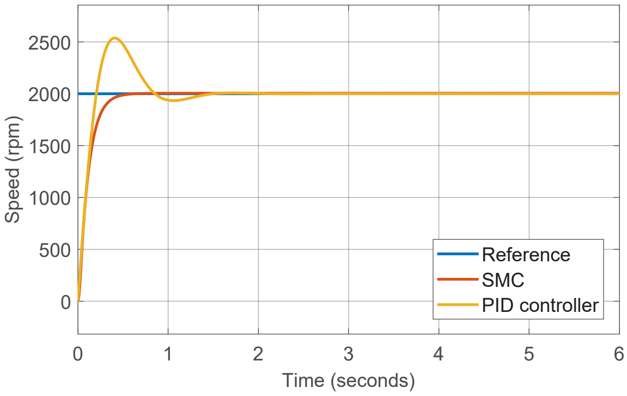

Fig. 2. Sliding mode controller for speed control of direct current motor

5. 2. Stability analysis results

The stability analysis for all controllers are analyzed using the bode plot in terms of different parameters such as gain margin, and phase margin, as shown in Fig. 3.

The Bode plot shown in Fig. 3 provides the frequency response to determine the stability of the system. The positive gain margin indicates that the system is stable and the proposed DFPID controller exhibits excellent stability characteristics compared to other techniques such as SMC, PID, and fuzzy lead-lag compensator. In addition, the proposed DFPID controller exhibits good bandwidth of control along with better stability.

The stability analysis of the SMC and PID controller is shown in Fig. 4.

The stability analysis of the SMC and PID controller shows that the SMC achieves stability after observing initial perturbations (from $t=0$ to $t=1$ sec). On the other hand, the PID controller experiences system disturbances after the initial state and this continues for a certain period of time. The PID controller achieves stability after certain state ($t=3$ sec). Results state that SMC is more stable in terms of providing better control of action without any overshoots in comparison to the PID controller.

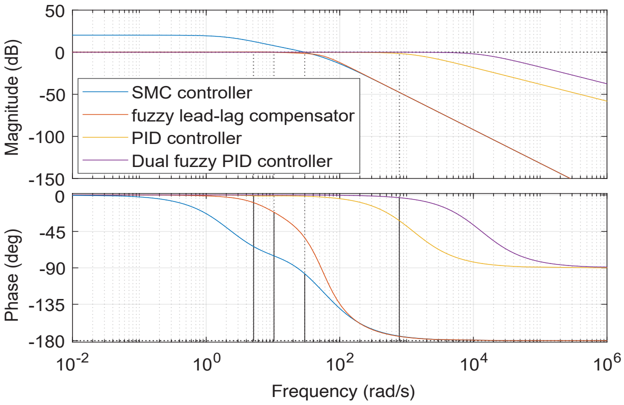

Fig. 3. Bode plot for the proposed controller

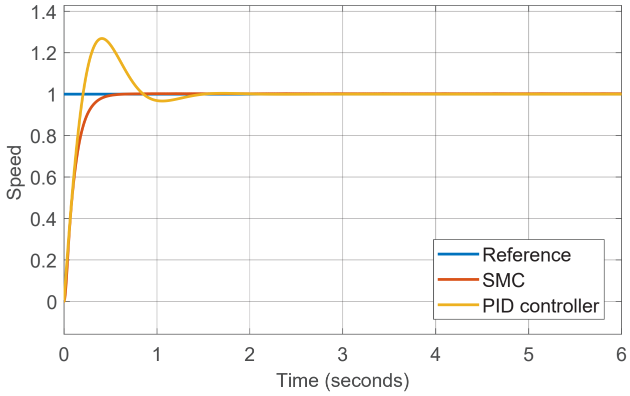

Fig. 4. Stability analysis of sliding mode control and Proportional-Integral-Derivative controller

5. 3. Fuzzy lead lag controller results

The performance of the fuzzy lead lag controller is illustrated in Fig. 5.

As observed from Fig. 5, the reference speed is maintained in the range of –1 to 1 and the reference speed also achieves better speed regulation.

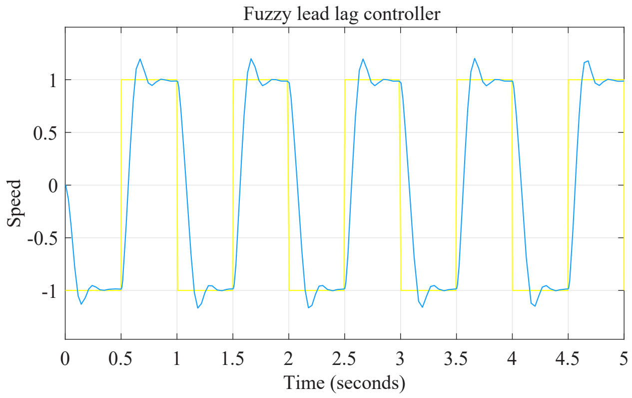

Fig. 5. Performance of the fuzzy lead lag controller

5. 4. Dual Fuzzy Proportional-Integral-Derivative controller results

A closed loop control of a four-quadrant chopper fed DC motor using a DFPID controller is analyzed experimentally. The controllers are designed and simulated using MATLAB/Simulink. The performance is analyzed in both time domain and frequency domain analysis in order to obtain better transient response in terms of fast settling time and less overshoot. The MATLAB platform is one of the highest performance-oriented simulation software which adopts a strong technical programming language for generating Simulink models. The SIMULINK model consists of an integrator, time-delay blocks, an amplifier and output blocks. The simulation model integrates computation, visualization, and programming in a systematic manner and the problems and solutions are expressed using appropriate mathematical expressions. The DC motor parameters were considered while modelling the dynamic system.

The coefficients of the DFPID controller were tuned utilizing a metaheuristic-based harmony search algorithm and the optimal signal was generated by the optimized controller for the DFPID to control the speed of the DC motor.

The performance of the Dual Fuzzy Proportional-Integral-Derivative controller is illustrated in Fig. 6.

The speed achieves the reference speed at near 0.1 sec as shown in Fig. 6 without overshooting.

The performance comparison of different controllers are illustrated in Fig. 7.

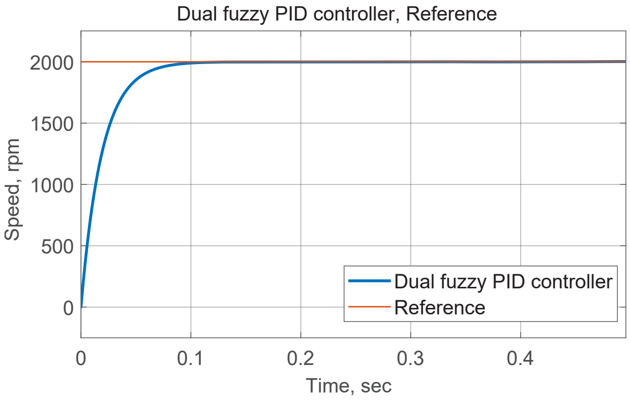

Fig. 6. Performance of the Dual Fuzzy Proportional-Integral-Derivative controller

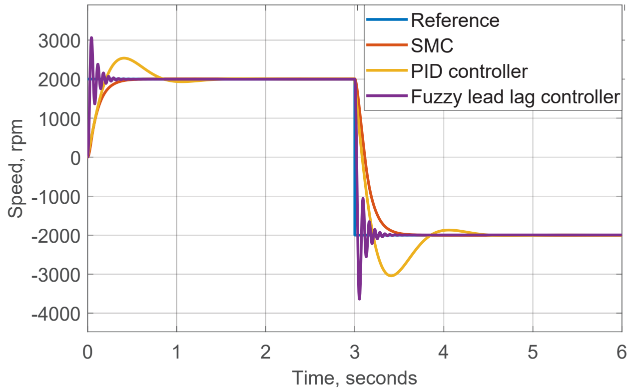

Fig. 7. Comparison of different control strategies for speed control

The performance of different controller in terms of controlling the speed is shown in Fig. 7. Among different techniques such as SMC, PID, and Fuzzy lead-lag controller, both SMC and PID achieves better speed control and the fuzzy lead-lag controller attains stability even in the presence of perturbations or system disturbances in the presence of uncertainties.

Lastly, the four-quadrant operation was implemented and the results are shown in Fig. 8.

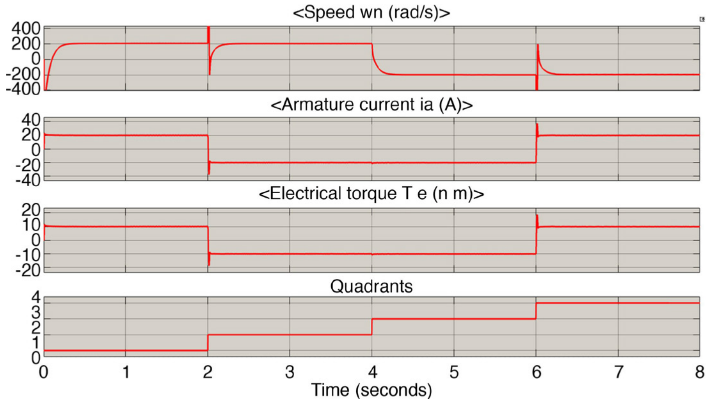

Fig. 8. Four quadrant operation

The four-quadrant operation includes different stages: Stage I quadrant is analyzed from 0 to 2 second wherein both speed and torque are in positive state. In the second stage quadrant which operates from 2 to 4 sec, the speed is negative and torque is positive. In the third stage (from 4 to 6 sec), both speed and torque go into a negative mode and in the last stage (from 6 to 8 sec) the speed is negative and the torque is positive.

6. Discussion of experimental results of the dual fuzzy logic proportional-integral-derivative controller approach

This section discusses the simulation results of the intended approach.

The performance of the intended approach is compared with the existing sliding mode control (SMC), conventional PID control and fuzzy lead-lag compensator. Sliding based controlling method is found to be effective as shown in Fig. 2 in handling the non-linear uncertainties as it is inconsiderate towards voltage variations, system uncertainties and disturbances.

The sliding mode control technique is more robust and performs better when compared to conventional sliding control. The main objective of using SMC in control systems is the sliding attribute of SMC which enables the controller to attain a predestined fixed hyperplane which is nothing but a sliding surface or slip manifold specified in the desired state space. The sliding surface after hitting the state trajectory, shifts to the sliding mode and remains there after which, the system achieves its objectives of controlling and can conceal the internal parameter perturbations and external load variations.

The proposed DFPID controller has good stability properties from the bode plot that indicate by Fig. 3 when compared to other approaches such as SMC, PID, and fuzzy lead-lag compensator. Furthermore, the suggested DFPID controller has a good control bandwidth as well as improved stability. The reference speed for SMC controllers is achieved nearby one second. As indicated by Fig. 4, there are no overshoots in the SMC controller. However, with the PID controller, the signal overshoots and reaches stability within 3 seconds.

The dual fuzzy PID controller combines the advantages of both fuzzy logic control that indicate by Fig. 5, and classical PID control. It may modify its settings based on the operating circumstances of the system, making it more resilient and adaptable in dealing with variances or uncertainties in the controlled system. The Dual Fuzzy Proportional-Integral-Derivative controller achieves an excellent speed control response as indicated by Fig. 6, also an excellent performed in four-quadrant operation as indicated by Fig. 8 with better control performance and faster speed compared to conventional PID controller, SMC, and fuzzy lead lag compensator as shown in Fig. 7. Complexity is one of the limitations of a dual fuzzy PID controller since they are more sophisticated than standard PID controllers. They necessitate the design and implementation of two different fuzzy logic systems, which can be challenging and time-consuming.

The disadvantages of the Dual fuzzy PID controllers tend to have more complex structures and it may require more computational resources, impacting real-time performance and system requirements.

The proposed model was simulated using MATLAB and results validated the superior performance of the proposed control strategy. In future, learning based strategies such as reinforcement learning can be adopted for controlling the dynamics of the system.

7. Conclusions

1. The results indicate that the SMC produces more accurate results with no overshoots in transient analysis than the PID controller.

2. The performance of the DFPID based controlling approach is compared with other control strategies such as SMC, PID, and Fuzzy lead-lag controller in terms of peak overshoot, settling time, motor speed, torque and armature current. Results show that the DFPID performs significantly better than all indicated conventional techniques.

3. The peak overshoot of the fuzzy lead-lag controller is greater than that of the conventional PID controllers.

4. The optimization algorithm assisted the DFPID control to generate optimal control signals for the DC motor and thereby gain better control over the speed of the DC motor. The proposed DFPID controller exhibited excellent results in terms of achieving better accuracy and robustness for speed control of DC motors in four quadrant operation. The DFPID technique automatically learns the nonlinearities associated with the external environment and decides the corresponding action.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data will be made available on reasonable request.

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