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Optimal tuning of PID controller for speed control of DC motor using equilibrium optimizer

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ABSTRACT

The efficient and smooth operation of direct current (DC) motors is of high significance in various industrial applications. This study proposed a recent optimization technique, named equilibrium optimizer (EO) for optimal tuning of the parameters of proportional integral derivative (PID) controller to provide accurate and robust control in DC motors. Mathematical modelling of the motor was carried out in Simulink environment using basic electric machine theory. Conventional Ziegler-Nichols (ZN) technique is initially designed to tune the PID controller parameters, an optimization model based on the minimization of integrated absolute error and named EO-PID is formulated and subsequently implemented to optimize the tuned parameters obtained using the ZN-PID controller. Simulation results showed that there is a significant reduction in terms of rise time, settling time, overshoot and mean square error using the proposed EO-PID tuning model as compared to the ZN-PID technique. The result also showed that the proposed EO-PID model gives a better dynamic performance as it eliminates the oscillatory response common with most conventional control techniques. The results of this study have established EO as an effective optimization technique for optimal tuning of PID controller parameters, and can therefore be used by machine operators for various industrial applications.

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1. INTRODUCTION

Direct current (DC) motors find wide applications where there is need for efficient operation. These types of motors are less complex when compared to alternating current (AC) motor and they are usually less expensive for low horsepower ratings [1]. DC motors are servo motor which are made of low power rating and are usually used as an actuator to drive a load connected to it. Some of the many characteristics of this type of motor is its high ration of starting torque to inertia and faster dynamic response. Other advantages of using a DC motor include higher reliability, flexibility and low cost. All these attributes make them suitable for use in many industrial applications such as robot manipulators and home appliances where the need for smooth machine operation is of high significance. In the past 100 years, DC motors are the most common machine used majorly as an adjustable speed drives; they are usually required when the speed of an electrical drive operating over a wide speed range is to be controlled [2]. The design of high-performance motor drives has received an extensive research in the last two decades, nevertheless industrial applications are continuously demanding motors with greater reliability and performance [3].

In order to meet industrial standards, a high performing motor must be able to maintain dynamic speed, command tracking and have the ability to regulate the load connected to it. DC motors provide excellent speed control for acceleration and braking as compared to other type of motor available in the market. DC motors are ideal for drive applications because its field windings are energized directly; thus allowing for accurate control of voltage and speed, which in turn make them suitable for torque and speed control [4]. They are commonly classified as single-input, single-output (SISO) systems with a relatively small speed-torque range that can be used with different mechanical loads [5]. Generally, DC motors are classified under three main catergories as depicted in Figure 1. However, for the purpose of this study, we are more concern with the speed control of a of a separately excited DC motor.

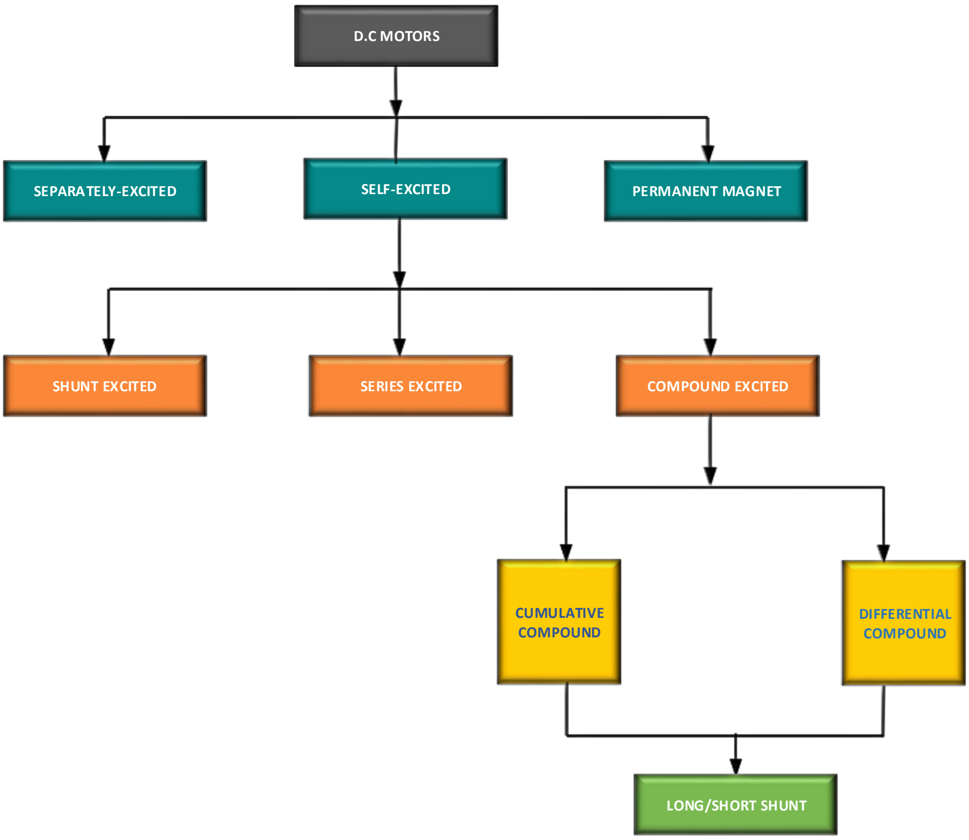

Figure 1. Classification of DC motors [5]

In addition to their ability to control speeds over a broad range, DC motors also offer an excellent voltage adjustment pattern. These characteristics make them an excellent alternative when considering complex control algorithms for efficient speed control [6]. By utilizing a converter, a separately excited DC motor can be controlled from its minimum speed, up to its rated speed. Therefore, DC motor speed control is defined as the deliberate alteration of the drive speed to match the required speed to complete a given task. In contrast to speed regulation, where the speed changes naturally owing to a load change on the shaft, speed control can either be provided manually or automatically [1], [6].

Manually, the speed of a DC motor can be control by either of the two popular methods-armature control and field control. In armature control method, the speed control of a DC motor is achieved through the variation of the applied armature voltage in the constant torque region. The applied armature voltage must be applied when the motor is operating below its base speed, while the field flux remains constant. An increase in the applied armature voltage will lead to an equivalent increase in the speed of the motor. However, if the applied voltage is beyond its rated value, there will be no further increase in speed of the motor and the field flux is usually introduced to obtain speed at this point. In the case of field control method, the operation of the motor at a constant power region will lead to a corresponding reduction in the field flux in such that the motor is continually operated above its rated speed. Nevertheless, keeping the armature voltage constant at its rated value will lead to a reduction in the field flux which in turn increases the speed of the motor [7]-[9].

One of the simplest and most effective method used to provide automatic control to the speed of a motor in most engineering applications is by employing a device or software which is capable of managing, commanding or directing the flow of data between two entities. In general, the two most popular types of controllers used for this purpose are the passive controller and adaptive controller. Typical examples of a passive controllers include relay control, hysteresis and sliding mode control. On the other hand, proportional integral (PI), proportional integral derivative (PID) and Fuzz logic controllers fall under the adaptive type of controllers [10].

Over the years, the PID control scheme. The PID control scheme has proven to be the most efficient solution when considering the control of most electric motors; this is mainly due to their ease of design, ease of implementation and the simplicity in their structure. One major challenge peculiar to the PID control scheme is the difficulty experience when tuning their parameters for optimal control [4]. Hence, the development of tuning methods for Adaptive controllers is the most researched area in providing automatic control in DC motors. This type of controller find wide application in most industrial settings due to the amplification in the feedback measurement produced by the derivate part. In addition to that, the derivate mode of this type of controllers helps stabilize and improves the speed response of a DC motor without extreme oscillation [11], [12].

Proportional integral derivative is a type of speed control with the ability to produce feedback. The controller has the optimum control dynamics and impressive properties due to its simplicity, clear functionality, reliability and applicability to a linear system, reduced steady-state error, fast response, ease of implementation, no oscillations, higher stability and robust performance. They are mostly used in more than 95% of industrial process control applications [13], [14]. The three main parameters involved are proportional (P) which accounts for the anticipated set point and controls the controller output; integral (I) is needed to eliminate any kind of steady-state error present in the control system and subsequently improve the steady-state response; and derivative (D) is necessary to enhance the transient response of the system [13], [15]. The set-up of the PID control system showing the various parameters is depicted in Figure 2.

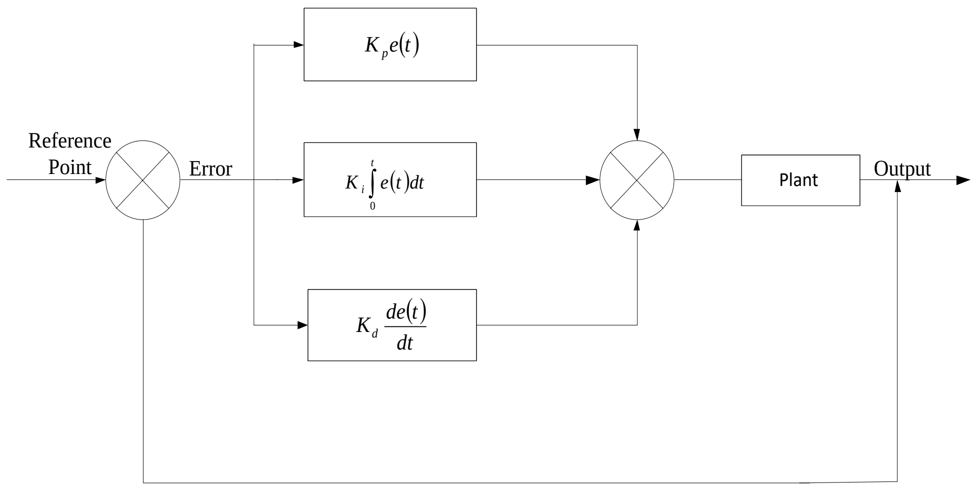

Figure 2. Block diagram of conventional PID controller [13]

The variable $e(t)$ is used to describe an error which measures the difference between the desired input value and the generated output. K_p, K_i, K_d are the proportional gain constant, the proportional-integral gain and the derivative gain respectively. Therefore, in order to determine the proper combination among the gains K_P, K_i and K_d of the PID controller, an appropriate tuning procedure is imperative. A slight variation in the proportional gain K_P could result in system error and cause severe disturbances to the system. Moreover, the integral gain K_i helps to decrease the steady-state error; however, it is responsible for the increase in overshoot and the decrease in system stability. The derivative gain K_d stabilizes the system and also slows down the response [5]. It is obvious that these three parameters determine the efficient operation of the PID controller and hence, it is important to get right balance among the three meters using appropriate tuning techniques [9], [16], [17].

Various researchers have applied different conventional techniques such as Ziegler-Nichols (ZN) method, Cohen-Coon method and Chien-Hrones-Reswick s in tuning the parameter of a PID controller. A method for the control of speed in DC motors based on an analog controller is presented by [18]. The performance of the fuzzy controller for a comprehensive analysis and speed control design methods of the motor was demonstrated. The motor was modeled in Simulink to obtain its speed response characteristics. Kushwah and Patra [19] applied the weighted tuning approach in tuning the PID controller for speed control of DC motors. The model of the DC motor is developed in MATLAB and the conventional Ziegler-Nichols tuning formula and modified Ziegler-Nichol PID tuning formula was applied to tune the PID parameters. The two methods were compared based on output response, minimum settling time and minimum overshoot. The speed control of a DC motor based on the tuning of PID parameter using traditional ZN is presented by Sharma and Patra [20]. Speed control analysis of the DC shunt motor was carried out to minimize the transient response specifications chosen for better speed response of the motor. Mathematical models of the motor are developed using Simulink environment in MATLAB. Simulation was done to determine the speed reponse of the machine and the result compared with another traditional method.

Furthermore, Dursun and Durdu [6] investigated the speed control of DC machines based on sliding mode control (SMC) approach. The machine was subject to various loading condition and its reponse is compared with a commonly used PID control approach. A series multi-cell chopped based on proportional integral (PI) and Petri nets controllers for controlling the speed of a DC motor was described by [21]. The Petri nets controller was used to regulate the armature current and simultaneously maintain the capacitor voltage of the multi-cell converter to its reference value. In addition, the Petri nets controller was also used to generate the binary control switches to determine the switch response of the motor. The system is simulated using MATLAB sim power. The result of simulation showed that the series multi-cell chopper and the system controller have a better performance and low disturbance under loading condition.

Nevertheless, the speed response of many of these conventional techniques have failed to produce satisfactory results in the control of the motor. This is as a result of their inability to permit the introduction of constraints to the basic design parameters such as settling time, overshoot, among others [6]. Furthermore, many of the conventional techniques suffer from issues of high computational time and high mathematical complexity. It should also bed noted that the design of any classical PID becomes a complex combinatorial problem, which can be solved using optimization techniques only in order to achieve the desired result [16].

In the last decade, artificial intelligence (AI) based optimization methods such as particle swarm optimization (PSO), bacteria foraging algorithm (BFA), genetic algorithm (GA), ant colony optimization (ACO), among others have been extensively applied to many optimization problems including the tuning of PID parameters, and their solutions have been very positive. Habib *et al*. [22] appled an improved whale optimization algorithm (IWOA) to tune the parameters of PID controller. The proposed algorithm was applied to determine the appropriate parameters values of the controller to improve the transient response of the machine. Comparative analysis was conducted with other meta-heuristic techniques to demonstrate the effectiveness of the proposed approach. The speed control of a DC motor based on the application of soft computing techniques such as fuzzy logic controller and PSO for PID controller parameter tuning is examined by Tharani *et al*. [23]. The motor was modelled in MATLAB using the various manufacturer specifications and the proposed model was applied to eliminate manual tuning and to obtain the speed response output of the motor. Simulation results showed that there is minimal overshoot and settling time, and the motor has a satisfactory performance.

Devi and Biate [15] presented a new displacement based particle swarm optimization (DPSO) algorithm optimized PI controller for speed control of a DC Motor. Two sets of velocities of the particles based on the previous and current values were considered to determine the position of the particles. The PI controller parameters were optimized using the proposed DPSO and simulated in laboratory virtual instrument engineering (LabVIEW). A comparative analysis was carried out with standard PSO to determine the efficiency of the proposed method. Simulation results showed that the proposed method is very robust and effective in tuning of the parameters for speed control as compared to the standard PSO. Suman *et al*. [24] investigated and implemented a PID controller based on GA for speed control of DC motor. The GA optimization technique is used to tune the PID controller parameters before it was applied to the motor. The results of the GA technique were compared with traditional tuning strategies. The results showed that GA-PID controller gives better results than the traditional strategies.

Sankardoss and Geethanjali [4] estimated the parameters of a permanent magnet direct current (PMDC) motor using GA and compared the speed control of a PMDC motor using PI, PID and the state feedback controller. The speed controllers were designed from the estimated parameters of the PMDC motor in MATLAB/Simulink. The performance of PI, PID and state feedback speed controllers were compared. The results showed that performance of the state feedback controller is much efficient as compared to the PI and PID controllers. Sultan and Jarjes [25] proposed an optimal fuzzy PID controller design based on conventional PID control and nonlinear factors using the GA. Fuzzy logic controllers act as one individual in the initial population of GA and significantly enhance the efficiency of the algorithm.

The main traits common among many of the AI techniques is their ability for an exhaustive search, fast convergence speed, high computational time and the ability to converge to global optimum [26]. This study therefore, focused on the design of an optimum PID controller usin equilibrium optimizer (EO). The EO optimization technique is one of the recently developed optimization algorithms; since its introduction, the algorithm has shown outstanding performances when applied to different optimization problems. The main strengths of the algorithm is its ease of implementation and the balance it provides between exploitation and exploration phases [27].

2. EQUILIBRIUM OPTIMIZER

The equilibrium optimizer (EO) is one of the most recently developed optimization algorithm based on some set of physics principle used in solving continuous optimization problems. It is inspired from the conservation of the mass that flows in and out of a definite volume. The relationship between the concentration of the non-reactive constituent in a control volume and its various source and sink mechanism is usually described using the mass balance equation [27]. This equation is used in physics to govern the conservation of the mass flowing in and out of a control volume [28].

One of the main strength of the EO algorithm is its ability to alter the optimal solution positively using its high exploration and exploitation phases. The particles, as well as their concentrations in the EO algorithm are akin to the particles and position used in PSO algorithm. These particles usually identified as the search agents in the algorithm; the concentration of the particles in the volume are updated based on the quality of the solution obtained so far and identified as equilibrium candidate. The identified candidates are used to finally attain the equilibrium state, representing the optimal solution [29], [30]. Since the algorithm is inspired based on the mass balance equation used in physics and chemistry, a first-order ordinary differential equation is mathematically used to describe a general mass balance equation. This equation is usually defined as a change in mass over time can be equated as the difference between the mass flowing into the system and the mass flowing out of the system, in addition to the internally generated volume [27], [31]. This is mathematically modelled as in (1) to (4) according to [27].

$$V\frac{dC}{dt} = QC_{eq} - QC + G \tag{1}$$

Where V and C is used to describe the control volume and the concentration of particles respectively, $V\frac{dC}{dt}$ describes the rate of change in V , while Q is used to describe the volumetric flow rate into and out of the control volume, C_{eq} is used to measure the concentration of particles inside the control volume at an equilibrium state without any internal generation, G describes the mass generation rate inside the control volume. It should however be noted that at $V\frac{dC}{dt} = 0$, a steady equilibrium state is attained. Hence, rearranging (1) at this state results in (17) as given by [27].

$$\frac{dC}{\lambda C_{eq} - \lambda C + \frac{G}{V}} = dt \tag{2}$$

Where: $\lambda = \frac{Q}{V}$ represents the turnover rate and $\frac{Q}{V}$ is the inverse of the residual time.

Integrating the expression in (2) with respect to time:

$$\int_{C_0}^{C} \frac{dC}{\lambda C_{eq} - \lambda C + \frac{G}{V}} = \int_{t_0}^{t} dt \tag{3}$$

$$C = C_{eq} + \left(C_0 - C_{eq}\right)F + \frac{G}{\lambda V}(1 - F) \tag{4}$$

the variable F can be evaluated using expression (5):

$$F = exp[-\lambda(t - t_0)] \tag{5}$$

where t_0 and C_0 represents the initial start time and concentration-dependent respectively. Generally, expression (4) is the basic framework used in developing the EO algorithm. It can be observed from equation (4) that there are three terms which are used in searching and updating the optimal solution pattern of the algorithm [27].

The optimal solution of the EO algorithm is usually obtained when the particles are at the equilibrium state which represents the final convergence state of the algorithm. At this state, a vector of equilibrium pool is constructed, this pool is used to determine the particles which keeps other particles in the equilibrium state and represents the optimal solution [28]. A total of five candidate particles which are usually determined via experiments are present in this pool, four of these particles are identified as the optimal particles, while the fifth particle represents the average of the four particles [29], [30]. The main advantage of selecting four optimal particles in the pool is to help in the exploration phase when search for an optimal solution, while the estimated average is helpful during exploitation phase. The vector of equilibrium pool is described using (6) as given by [27].

$$\vec{C}_{eq} = \left[\vec{C}_{eq}(1), \vec{C}_{eq}(2), \vec{C}_{eq}(3), \vec{C}_{eq}(4), \vec{C}_{eq}(avg)\right] \tag{6}$$

It should be noted that each particle in the concentration is updated randomly; and therefore, the updating time for each candidate representing an optimal solution remains constant [28], [29]. Another important parameter of the EO algorithm is the exponential term, (F). This parameter is crucial when there is need to provide the basic balance needed between exploration and exploitation phases. It mathematically expressed using (7) as given by [28].

$$\vec{F} = e^{-\vec{\lambda}(t-t_0)} \tag{7}$$

where λ describes random vector in the range of [0, 1], and t represents an iterative function which is proportional to the number of iterations as shown in expression (8), while t_0 is estimated using expression (9) [27], [28].

$$t = \left(1 - \frac{Iter}{Max\_Iter}\right)^{a_2 \frac{Iter}{Max\_Iter}} \tag{8}$$

$$\vec{t}_0 = \frac{1}{\vec{\lambda}} ln\left(-a_1 sig(\vec{r} - 0.5)\left[1 - e^{-\vec{\lambda}t}\right]\right) + t \tag{9}$$

Unlike the exponential term (F), a_1 and a_2 are constant used in controlling the exploration and exploitation proficiencies. A high value of a_1 will result in stronger exploration ability and weak exploitation ability and vice versa. The term $(\vec{r} - 0.5)$ is an expression used in tracking the direction of the particles during exploration and exploitation phases. Therefore expression (7) can then be re-written according to [27] as;

$$\vec{F} = a_1 sig(\vec{r} - 0.5)\left[e^{-\vec{\lambda}t} - 1\right] \tag{10}$$

The optimal solutions obtained by the algorithm can be further enhanced by enhancing the exploitation phase using the generation rate (G), which is usually expressed using a first-order decay constant as given in (11) by [27], [29].

$$\vec{G} = \vec{G}_0^{\,-\vec{k}(t-t_0)} \tag{11}$$

Where G_0 represents the initial value and k is used to describe a decay constant at $k = \lambda$ [7]. Substituting these values in (11) leads to (12) [27].

$$\vec{G} = \vec{G}_0 e^{-\overrightarrow{\lambda(t-t_0)}} = \vec{G}_0 \vec{F} \tag{12}$$

Where:

$$\vec{G}_0 = \overrightarrow{GCP}\left(\overrightarrow{C_{eq}} - \vec{\lambda}\,\vec{C}\right) \tag{13}$$

$$\overrightarrow{GCP} = \begin{cases} 0.5r_1, & r_2 \geq GP \\ 0, & r_2 < GP \end{cases} \tag{14}$$

where r_1 and r_2 describes a randomly generated numbers in the range [0, 1], GCP is used to describe the probability effect of the generation term on the updating process, and it is known as the generation rate control parameter; this parameter is used to indicate the number of particles that update their state using the generation term. The GCP is evaluated using expression (14) and GP is used to describe a constant known as the generation probability. The main role of the generation probability is to provide a good balance between exploration and exploitation phases. Lastly, the basic rule for updating the algorithm is achieved using expression (15) which according to [27] is given as;

$$\vec{C} = \vec{C}_{eq} + \left(\vec{C} - \vec{C}_{eq}\right)\vec{F} + \frac{\vec{G}}{\vec{\lambda}\vec{V}}\left(1 - \vec{F}\right) \quad (15)$$

The equilibrium concentration is described using the first term of expression (30), while the second describes the varying condition of the particles in the concentration. Moreover, the global search of the EO algorithm is achieved using the second term of expression (15), while the accuracy of the global solution is determined using the third term. Similar to some other particle-based optimization algorithm just like the PSO, the EO algorithm also makes use of a particle's memory saving mechanism which is very helpful in improving the convergence ability of the algorithm [27], [28]. The flowchart of the EO algorithm is as depicted in Figure 3.

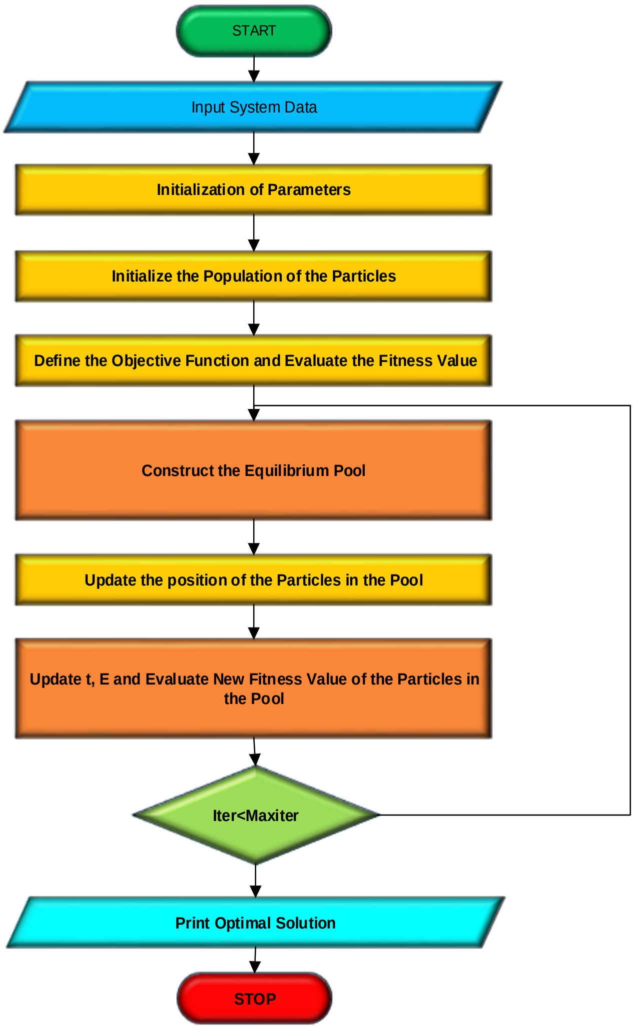

Figure 3. Flowchart of equilibrium optimizer [27]

3. MATERIALS AND METHOD

MATLAB scripts were written for the mathematical model of the separately excited DC motor presented in the work of authors [8], [9], [20], [32]-[34]. The data of DC motor used are obtained from the Electrical laboratory of Cape Peninsula University of Technlogy Bellville Campus, Capetown. Ziegler-Nichols method is primarily used to design to tune the parameter of the PID controller so as to improve its performance. The PID controller model is developed using MATLAB/Simulink. The input to this model which is known as the speed error signal is obtained from the difference between the reference speed (ω_r) and the actual speed (ω), while the output is the manipulated signal. Three terms are then summed together, the first tern is known as the integral term with gain K_i, the second is the proportional term with gain K_p and the third is the derivative term with gain K_d with an initial value of zero. The summing of the three terms gives the controller output as in expression (16).

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (16)$$

The variable $e(t)$ represents the tracking error which is used to describe the difference between the desired input value and the actual output. K_p, K_i, K_d are the proportional gain constant, the proportional-integral gain and the derivative gain respectively. The values of K_p, K_i, K_d obtained using ZN-PID are subsequently optimized using the EO algorithm.

3.1. Formulation of optimization problem

The most prevalent performance index used in PID tuning is the integrated absolute error (IAE) operator. The IAE is a combination of various type of errors, thus representing a number of different objectives which can only be solved using multi-objective optimization approach. Expression (17) is used to describe the IAE multi-objective operator to be optimized through the optimal tuning of the PID controller parameter using EO algorithm. The IAE multi-objective operator technique is chosen because it is simple to implement and can be easily evaluated analytically in the frequency domain:

$$min\, I\, AE = \int_0^\infty |e| \cdot \partial t \quad (17)$$

$$\int_0^\infty |e| \cdot \partial t = \beta_1\, (t_s) + \beta_2\, (t_r) + \beta_3\, (M_P) + \beta_4\, (\text{MSE}) \quad (18)$$

$$\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1 \quad (19)$$

$$MSE = \frac{1}{T} \int_0^T (e(t))^2\, \partial t \quad (20)$$

where$\beta_1, \beta_2, \beta_3$ and β_4 are co-efficients used to describe the order of importance of the individual objectives, with each of the co-efficient assigned to the setting time (t_s), rise time (t_r), maximum overshoot (M_P) and the mean squared error (MSE) respectively. The parameter, e is obtained as the difference between the reference speed and the actual speed, $e(t)$ represents the tracking error and T is a time constant.

There is no constraint in the search space of the optimal PID parameter tuning as placing constraints on the tuning parameters will limit the search space. The control parameters are proportional control, K_p, integral control, K_i and derivative control, K_d of PID controller. These control parameter values were adjusted for motor speed control.

3.2. Implementation of proposed optimization algorithm

The optimization of the PID controller parameters tuning problem described in (17) to (20) is solved using Equilibrium Optimizer algorithm. The objective function to the optimization function is encoded in each of the populations of the EO algorithm as expressed in (21).

$$X_p^i = \left(X_p^1, X_p^2, X_p^3, \ldots\ldots.. X_p^N\right) \quad (21)$$

Each of the population is assigned a fitness value based on the objectife function of (17). The vector of equilibrium pool described in expression (7) is determined experimentally from the initial population; the equilibrium pool contains five different particles with four of the particles representing a possible solution to the optimization problem. Each of the four particles is made to go through a three-dimensional search process in accordance with the parametersK_p, K_i and $K_d$that needs to be tined. The fifth particle which is the arithmetic mean of the other four particles represents the optimal solution to the optimization problem.

The generation rate "G" described in (12) is also used during the optimization process to improve the balance between the exploration and exploitation phase and to obtain the particle with the optimal solution. A script was written in MATLAB to solve the resulting optimization problem. The following are the steps involved in the EO algorithm for optimal tuning of the PID controller parameters:

- Step 1: Read the DC motor data and ZN-PID controller parameters.
- Step 2: Initialize the parameters and constants of the EO algorithm such as a_1, a_2, $GP$and set the maximum number of iterations.

- Step 3: Generate randomly 'X' number of particles as shown in expression (21), with each particle representing a possible solution to the optimization problem, and set iteration count to 1.
- Step 4: Determine the fitness function of all particles in the concentration using the mathematical expression of the objective function described in (17).
- Step 5: Identify the candidate particles in the equilibrium pool and gauge the fitness of each particle in the pool with respect to the fittest particle in the pool.
- Step 6: Check if the fitness value of the fittest particle is lower than the first particle pool in the pool, and replace the fittest particle with the first particle in the pool.
- Step 7: Update the position of fit particles relative to the fitness of the fittest particle and repear the process repeats until an equilibrium state is attained.
- Step 8: Estimate the average of the equilibrium and construct the equilibrium pool to determine the particle with the best fitness in the pool.
- Step 9: Construct$F$ GCP, G_0 G and concentration of each particle in the equilibrium pool using equations (7), (14), (13) and (12) respectively in order to achieve a good balance between the exploitation and exploration phase.
- Step 10: The iteration count is increased until it reaches the maximum iteration count is reached or convergence is achieved. If the two conditions are not met, go to step 4.
- Step 11: The fifth particle in the equilibrium pool representing the arithmetic mean of the other four particles is the optimal solution to the optimization problem.

4. RESULTS AND DISCUSSION

This section presents and discussed the results obtained after simulation. The test was conducted on the DC motor for the open-loop operation of the machine. Tests were also conducted during the closed-loop operation of the machine using the conventional Ziegler and the EO tuned optimization model. The DC motor specifications used for this study are presented in Table 1, while the Simulink model is depicted in Figure 4.

Table 1. Separately excited DC motor specification

D.C motor parameter	Value
Motor Rating	3 HP
Supply Voltage	220 V
Rated Current	4.3A
Armature Resistance	5 Ω
Armature Inductance	0.23kgm/A
Inertia Constant	0.01kgms2/rad
Damping Constant	0.03gms2/rad
Torque Constant	0.23Vs/rad
Back Emf Constant	0.23kgm/A
Speed	1800 rpm

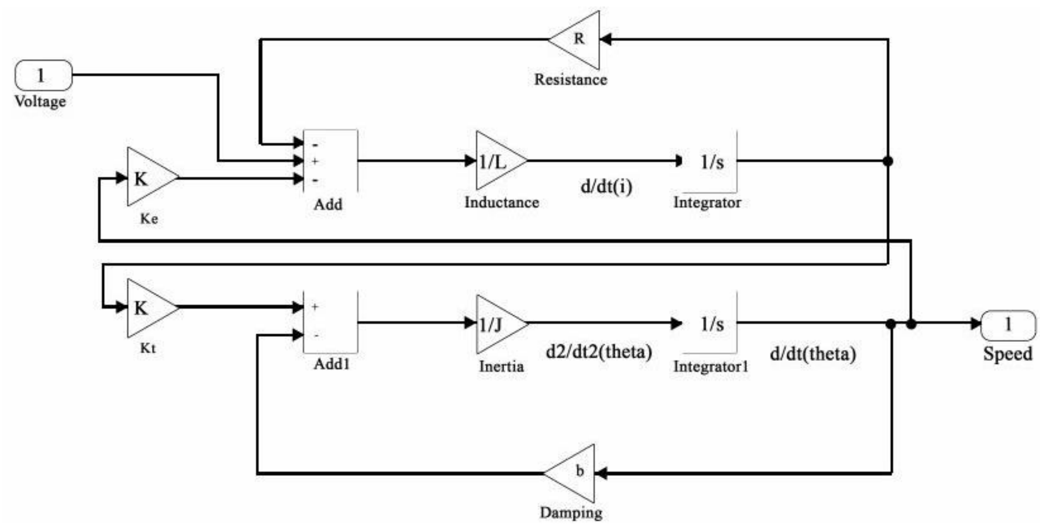

Figure 4. DC motor Simulink model

The motor speed was varied stepwise in a 20% increment. At each operating speed, ZN and EO tuned PID controllers were applied to the motor to determine the closed-loop response of the motor. One of the most operative methods of tuning the PID controllers as implied by Ziegler-Nicholas is to use the open-loop response. The open-loop response of the motor under consideration is a unit step function graph as shown in Figure 5. The conventional ZN-PID method was applied to the machine to control its speed during its closed-loop operation. The various input parameters used for the implementation of the PID controllers for the ZN tuned PID at varying speed conditions are presented in Table 2, while the time domain parameters are presented in Table 3.

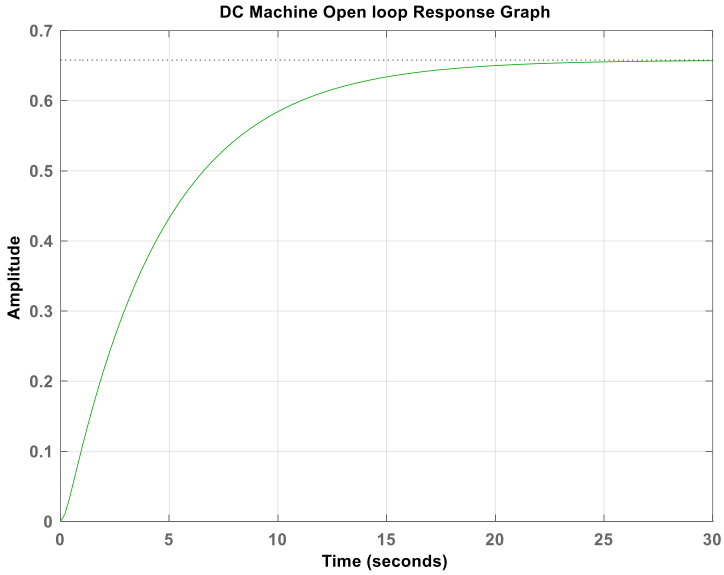

Figure 5. Open loop response of DC motor

Table 2. ZN-PID controller parameters at varying speed patterns

Ziegler Nichols Tunded PID Controller	S/N	Speed (%)	K_p	K_i	K_d
	1	20	2.808	2.1907	0.877
	2	40	2.610	2.0500	0.680
	3	60	2.504	1.9030	0.640
	4	80	2.495	1.7650	0.601
	5	100	2.487	1.7520	0.585

Table 3. ZN-PID time domain parameters at varying speed patterns

Ziegler Nichols Tunded PID Controller	S/N	Speed (%)	Tr (Rising Time)	Ts (Settling Time)	Mp (%) (Overshoots)	Mean Square Error
	1	20	0.5922	7.328	26.435	0.007182
	2	40	0.5636	7.053	25.500	0.005548
	3	60	0.5401	6.826	23.730	0.003167
	4	80	0.5300	6.205	23.010	0.001536
	5	100	0.5000	6.196	22.940	0.001415

Simulation results showed that the ZN-PID controller method presents an oscillatory response when implemented on the machine as shown in Figure 6. This indicates that the PID parameters are not optimum for direct implementation for the DC motor. Therefore, organized optimization is a must, so that better parameters can be estimated and when applied to the system, deliver near-perfect performance and robustness. The parameters obtained by Ziegler-Nichols were used as boundary limits for the EO tuned PID controller optimization populations.

The computed parameters were implemented for the closed-loop response of the machine. Figure 7 shows the graph of the closed-loop response of the machine using the developed EO-PID model. Moreover, the speed of the machine was increased at 20% intervals for five different operating conditions to check for its response and to demonstrate the effectiveness of the EO-PID model as compared to the ZN-PID method. At each operating condition, the results were noted for comparison. Table 4 shows the results obtained for the EO-PID parameter tuning while the time domain parameter results are shown in Table 5. It is evident from the results of Tables 4 and 5 that the EO-PID solution gives the best values in rising and setting times, mean squared error, as well as overshoot. Furthermore, the closed-loop speed response of the EO-PID depicted in Figure 7 gives a less oscillatory response graph as compared to that of the ZN-PID shown in Figure 6.

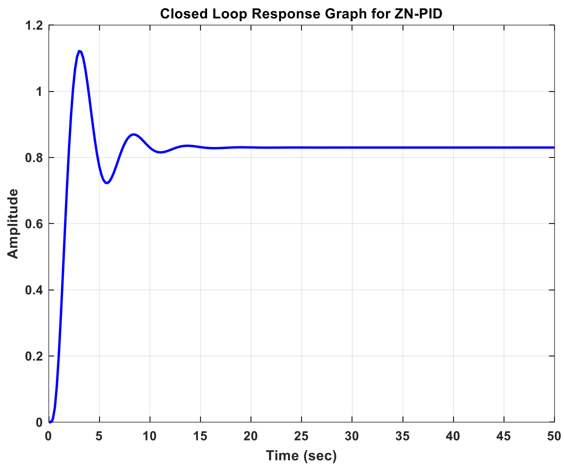

Figure 6. Closed-loop response graph of ZN-PID controller

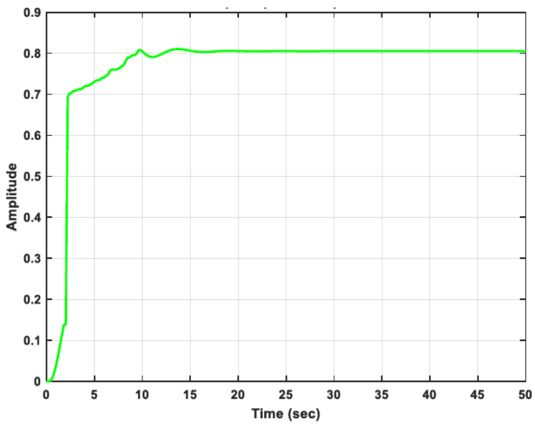

Figure 7. Closed-loop response graph of EO-PID controller

Table 4. EO-PID controller parameters at varying speed patterns

Equilibrium Optimizer Tuned PID Controller	S/N	Speed (%)	K_p	K_i	K_d
	1	20	2.765	1.64	0.41
	2	40	2.52	1.53	0.361
	3	60	2.306	1.41	0.304
	4	80	2.284	1.21	0.281
	5	100	2.280	1.18	0.277

Table 5. EO-PID time domain parameters at varying speed patterns

Equilibrium Optimizer Tuned PID Controller	S/N	Speed (%)	Tr (Rising Time)	Ts (Settling Time)	Mp (%) (Overshoots)	Mean Square Error
	1	20	0.0063	0.0120	0	0.001796
	2	40	0.0060	0.0106	0	0.001176
	3	60	0.0058	0.0097	0	0.000938
	4	80	0.0054	0.0086	0	0.000694
	5	100	0.0051	0.0081	0	0.000673

5. CONCLUSION

This study has presented an approach for optimizing the parameters of the PID controller for controlling the speed of a separated excited direct motor (DC) machine using an equilibrium optimizer (EO). The performance index considered for PID controller design is the Integrated Absolute Error (IAE). The parameters obtained by Ziegler-Nichols (ZN) method were used for the initial declaration of the parameter population, in order to achieve faster convergence. The optimization of the PID controller parameters was designed and simulated using MATLAB software tool. The control variables that were optimized are proportional control, integral control and derivative control of PID controller. The results of simulation proved that the proposed EO-PID controller has a positive effect on the transient operation of the motor as the conventional ZN-PID technique in terms of rise time, settling time, mean square error and overshoot by optimally tuning the PID controller parameters. It was also observed that the EO-based PID controller provides a more dynamic motor operation as it drastically reduces the oscillatory response common with the ZN-PID control method. Finally, sensitivity analysis was performed on the DC motor to demonstrate its reaction of the machine to speed variations. The machine speed was increased at 20% interval and the performance of the motor was noted in each increment. Simulation results showed that the application of the proposed EO-PID controller stabilize the operation of the motor against unplanned load patterns. It was also observed that the EO-PID is more robust and offer satisfactory control when compared to the conventional ZN-PID. Finally, the optimized parameters of the PID controller does not require any kind of reset regardless of the change in load variations.

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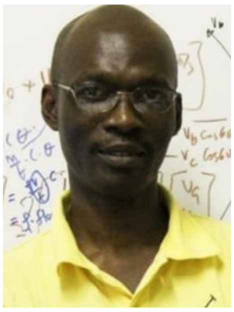

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