Wasit Journal of Computer and Mathematics Science
Journal Homepage: https://wjcm.uowasit.edu.iq/index.php/WJCM
e-ISSN: 2788-5879 p-ISSN: 2788-5879

A concepts and techniques related to the DC motor speed control system design: Systematic Review

Muhammad Hilal Mthboob[1,*], **Haider TH. Salim ALRikabi**[2] **and Ibtisam A. Aljazaery**[2]

[1]Electrical Engineering Department, College of Engineering, Wasit University, Wasit, Iraq
[2]Babylon University, Babylon, Iraq

*Corresponding Author: Muhammad Hilal Mthboob

DOI: https://doi.org/10.31185/wjcm.121
Received: December 2022; Accepted: February 2023; Available online: March 2023

ABSTRACT: The first sources of direct current (DC) were invented, DC machines were one of the first types of electro-mechanical machines used. DC machines are more advantageous over AC machines as regards to Speed regulation and versatility. A DC motor is an electrical actuator with a lot of control that is used in a lot of applications, like robotic manipulators, guided vehicles, steel rolling mills, cutting tools, overhead cranes, electrical traction, and other applications. Due to their speed-torque characteristics and ease of control, DC motors are utilized extensively in industries for demanding variable speed applications. In terms of controller design and implementation, the process control industry has seen numerous advancements over the past two decades. In the industry, there is a great demand for automatic controllers that can respond quickly and accurately to perform precise tasks. The feedback loop is an essential component of system control that must be utilized in order to achieve the desired performance in the majority of systems. Numerous control strategies have been developed for various feedback control systems in order to achieve rapid system dynamic response. Controls in a drive system are crucial if the reference speed is to be accurately and quickly tracked, with little or no steady-state error and as little overshoot as possible. This paper presents the Systematic literature review that was conducted as covers pertinent established concepts and techniques related to the DC motor speed control system design, for applications that require actuators with accurate speed characteristics. Simulation and real time implementation results employed for DC motor speed control systems in various literature are analysed and discussed.

Keywords: DC Motor, Speed, Controller, PWM

1. INTRODUCTION

For many decades, the Brushed DC machine has been the automatic choice where speed torque control was very necessary [1–3]. Figure 1 shows a schematic of a brushed DC motor showing all its important part consisting of the Commutator, Brushes, Armature conductor, and the Field windings. The applications of a DC motor range from steel rolling mills, electric traction, center winders to a very wide range of industrial drives, robotics printers and precision servos. The range of power outputs is wide, which varies from several mega-watts to a few watts of power as mentioned in [4]. Also, the speed of DC machines can be easily varied and controlled which makes them very suitable for precision industrial activities. Their speed-torque characteristics also makes them very useful in various applications. A few major components of a DC motor are described in turn. These parts provide a major contribution in the operation of a DC machine. They are also used to determine the kind of DC machine in use as mentioned in [5].

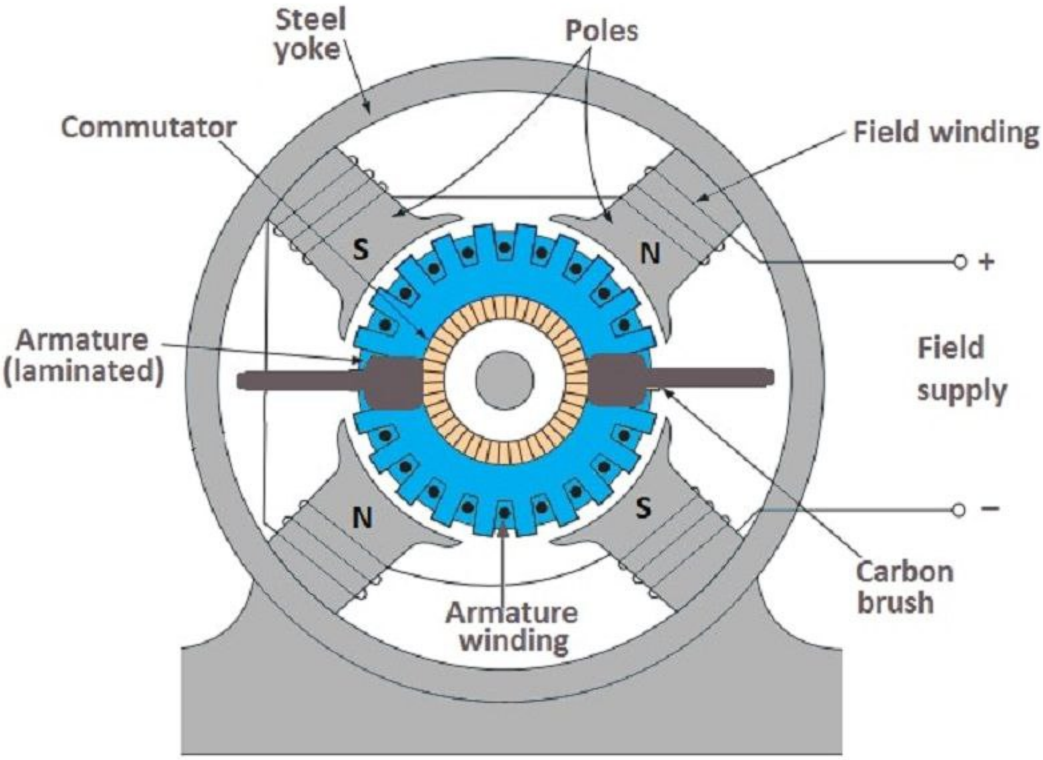

FIGURE 1. **Conventional Brushed DC Motor [5].**

1.1 THE PARTS OF A DC MACHINE

1. COMMUTATOR: A ring on a motor shaft designed to maintain a current flow pattern such that positive pole current is against the positive magnetic pole and the direction of the negative current against the negative magnetic pole, connecting with all motor

2. BRUSHES: The brushes are made of carbon, used to supply electric current to motor parts, while in generators they are used to extract current to the external circuit.

3. ARMATURE CONDUCTORS: This consist of copper conductors wound on a laminated former. Current flowing through the armature windings when interact the magnetic field in the air gap of motor

4. FIELD WINDINGS: The field windings are responsible for developing magnetic flux during motor operation as mentioned in [6]. Field windings configuration are divided to group dc machines into two types namely, separately excited dc machine and self-excited dc machine, then there is PMDC machine. Self-excited machines develop their field magnetic flux from the current applied to the motor terminals i.e. the field and armature windings are excited from the same source, separately excited machines rely on an external voltage source for production of magnetic flux. PMDC machines rely on magnets for production of field magnetic flux. The type of DC motors can be divided as below:

The connection between the field winding and the armature distinguishes the three varieties of self-excited DC machines that are the subject of the subsequent discussion.

A. Shunt-wound motor a shunt-wound motor has parallel connections between the armature and field windings. The armature current and the current that runs through the shunt field windings are not the same thing. The shunt field windings are constructed with a large number of high-resistance wire turns to generate the required MMF. This suggests that the shunt field is smaller than the armature current.

B. A series of motor injuries: This kind of motor has armature and field windings connected in series. The armature current is carried by the series field windings.

C. A motor with a compound wound design a motor with a compound wound design has both a series and a shunt field winding, or one winding in series and one winding in parallel with the armature circuit. The series field windings must be designed with significantly fewer turns for the same MMF due to the identical magnitude of the armature current passing through the shunt field windings. The series field winding will have a low resistance due to its relatively small number of thick wires as mentioned in [7]. When the shunt field winding is connected directly across the armature terminals, this is called a "short shunt connection." Otherwise, when the shunt windings are connected in such a way that they shunt the series connection between the armature and the series field, a long shunt connection is made. The shunt field windings of the compound motor generate significantly more flux than the series field windings. In recent times, the need for accurate speed control in industries as led to the demand for highly controllable actuators. DC machines are versatile and robust machines used extensively in industries as actuators for a wide range of operations as mentioned in [8]. Torque-speed characteristics of DC machines is highly demanded in most industrial applications. This has led to extensive research interest in the fabrication of robust control systems for DC machines for carrying out more precision tasks in industries

2. CONTROL SPEED D.C MOTOR

2.1 DIRECT CURRENT SPEED CONTROL METHODS

A DC motor speed control that utilizes both Field and Armature control simultaneously has been proposed by researchers in [9]. It was discovered that the field circuit resistance of the windings should be varied in order to increase the speed of a Shunt DC motor. As the resistance rises, the current flow in the field circuit decreases. As a result of this action, the flux produced by the field windings decreases, resulting in an increase in motor speed. Additionally, in order to reduce the motor's speed, the resistance of the armature winding must be increased while the resistance of the field winding must be maintained at a minimum. The armature experiences a large voltage drop as a result of this action. We are able to deal with a variety of motor speeds using this method because the supply voltage is constant, and equation 2.1 can be used to analyses the system.

Researchers in [10] described a method for controlling the speed of a DC motor by altering the machine's terminal voltage. The terminal voltage, not the armature voltage, is the most common method for controlling the speed of a DC motor. This effect can be described using the equation IA = VT EA RA. It can be deduced from the equation that an increase or decrease in the DC motor's terminal voltage causes an increase or decrease in the armature current. Taking into account an increase in the armature voltage, which corresponds to an increase in the armature current, will result in an increase in the torque that is generated, as shown by the equation Tind = KIA. The armature current will decrease as a result of the increased torque, which will further reduce the torque induced. The speed of the motor shaft increases as a result of the increased torque at constant load . The speed increases the inside produced EMF (EA), also known as back EMF (EA = K). The induced torque is reduced until it reaches the equivalent of the load torque. The motor will accelerate and enter a steady state at this point as mentioned in [11].

Researchers in [12] described the speed control of a DC motor by changing the armature resistance which will lead to a corresponding change in the armature current. Since increasing the armature current leads to the increasing in speed. Hence, it is evident that increasing the resistance of the armature leads to low armature which leads to decrease in speed of the DC motor. This method can be used to decrease the speed of a motor below its base speed. The problem faced by this method is that the increase in resistance will increase power losses. This method can be used if the motor runs at the base speed most of the time and only for a short time slow speed is required.

2.2 PULSE WIDTH MODULATION (PWM) METHOD

Researchers in [13] proposed a DC motor fixed speed control with high precision and dependability. An LCD display was used to actually monitor the motor's performance, and the ATmega128 microcontroller was used for the implementation. The motor rotates at a predetermined speed when it receives manual input. Contactless infrared sensors are used to monitor the speed of the motor. PWM signals are used by the microcontroller to control a MOSFET transistor in the DC motor's drive circuit, which supplies voltage directly to the motor. The PWM signal from the microcontroller will cause the motor to rotate at a predetermined speed. The operation of pulse width modulation (PWM) entails creating a square wave with a variable on-off ratio. The average percentage of pulses that arrive on time can range from 0% to 100%. Because of this effect, the load receives varying amounts of power. The primary advantage of a PWM circuit over a resistive circuit is its efficiency; At a 50% level, the PWM will transfer nearly all of the power to the load and consume approximately 50% of the full power as mentioned in [14]. A resistive controller can use up to 71% of its full power to heat the series resistor and 50% to the load at 50% load power. It was discovered that the design with fixed speed control and PWM for DC motor control was reliable and fairly accurate.

Researchers in [15] has proposed a method of speed control of a DC motor using analogy PWM technique. In this method an analogy PWM is developed, that drives the DC motor by switching four H-bridge connected MOSFETs. The H-bridge configuration results in the realization of a bidirectional full bridge circuit capable of operating in four quadrant of the I-V graph. For effectively controlling the motor, a systematic approach was laid for determining the switching frequency of the PWM pulses, as the switching frequency has a direct effect on the motor current ripples due to the fact that a dc motor works like a low pass filter and has a bandwidth of allowable frequencies. A method of choosing the PWM frequency based on the motor characteristics was presented. It works by setting an allowable percent for the current ripples, then the minimum frequency to attain that goal is worked out mathematically. Firstly, the average power of the motor during switching is determined using equation 1.

$$P = 2I^2R \tag{1}$$

The DC motor current response to a PWM pulse at 50% duty cycle is shown in figure 2

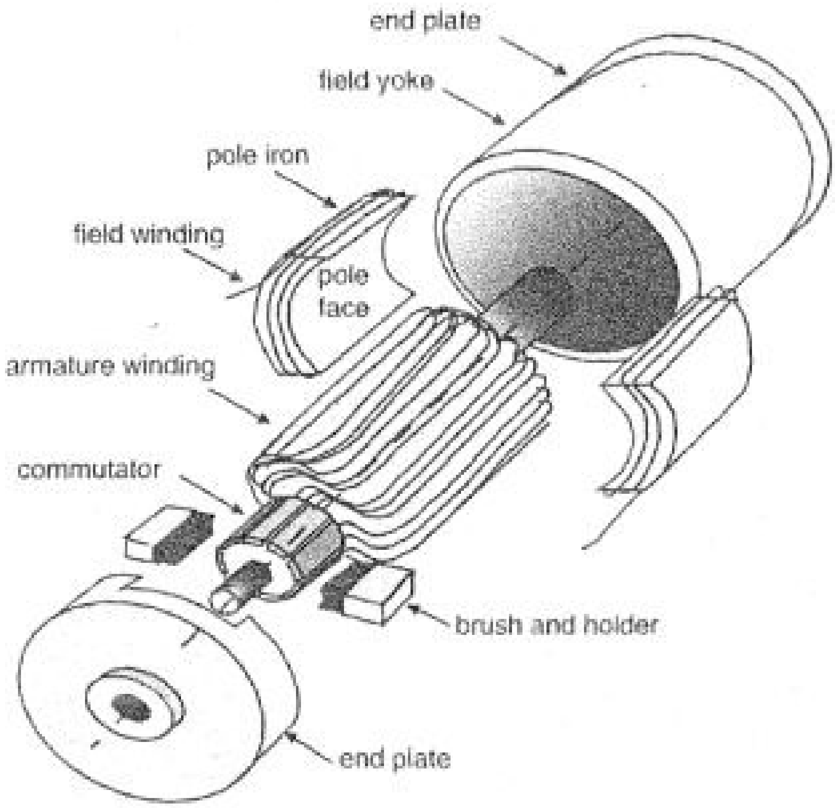

FIGURE 2. DC motor basic constructive elements and fixtures [15].

T is given as the switching period of the pulses. Figure 2 shows the motor at stall condition which is the highest operating current in the DC motor i.e. the worst case scenario. These formulas were used to prove that the optimal frequency for the PWM pulse is not the highest possible frequency, but somewhere between high and low in the KHZ range.

2.3 CONTROL SCHEMES

2.3.1. Single loop feedback control

A control system with a feedback mechanism maintains a prescriptive relationship by continuously comparing the process output and the set point utilising the error signal as a means of control. Feedback control is the most straightforward closed loop control strategy. A feedback control system can be used for many commonplace tasks, such as regulating an air conditioner's temperature or an automobile's speed as mentioned in [16]. By exploiting the difference between the actual speed and the intended temperature, these systems modify the controlled variable. When the output is utilised to regulate the output, the system is said to be closed-loop. The block diagram in Figure 3 shows a simple feedback control system. Different variation of a feedback loop is used in the design of speed control of DC motor, due to its simple and robust structure

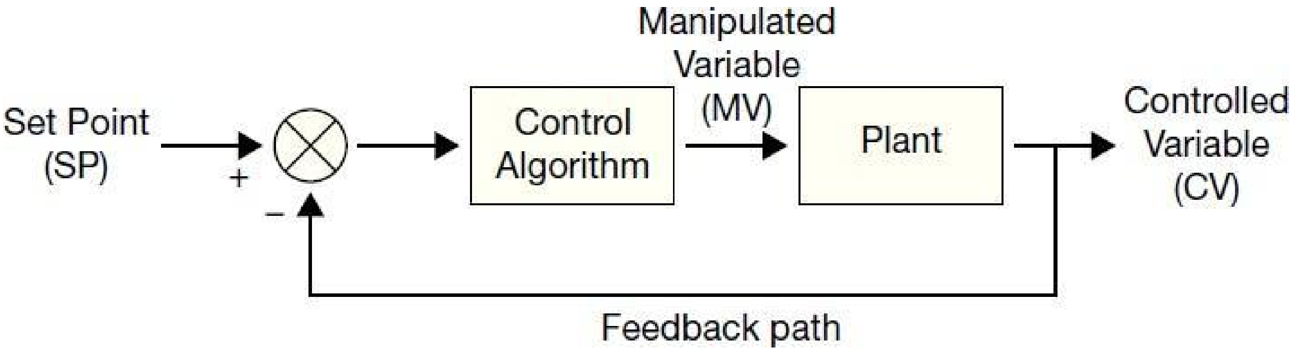

FIGURE 3. **Feedback Control System [16].**

2.3.2. Cascade feedback control

This type is most frequently used in the steam process industry and speed control drives. A cascade control consists of an inner loop and an outer loop. A cascade control method performs at its best when the inner loop has a faster dynamic than the outer loop. The structure of a cascade scheme is seen in examples 2 and 3. The inner loop regulates the secondary process, such as the voltage at the armature terminal of a DC motor. The outer loop regulates the primary process, such as the angular displacement of a DC motor as mentioned in [17]. The exterior circle regulator is first left in manual mode while the internal circle is tweaked first. The inner loop can be adjusted using the direct synthesis, Ziegler-Nichols, RA, and metaheuristic approaches (IWO, GA, etc.). The outside tuning completes the tuning process.

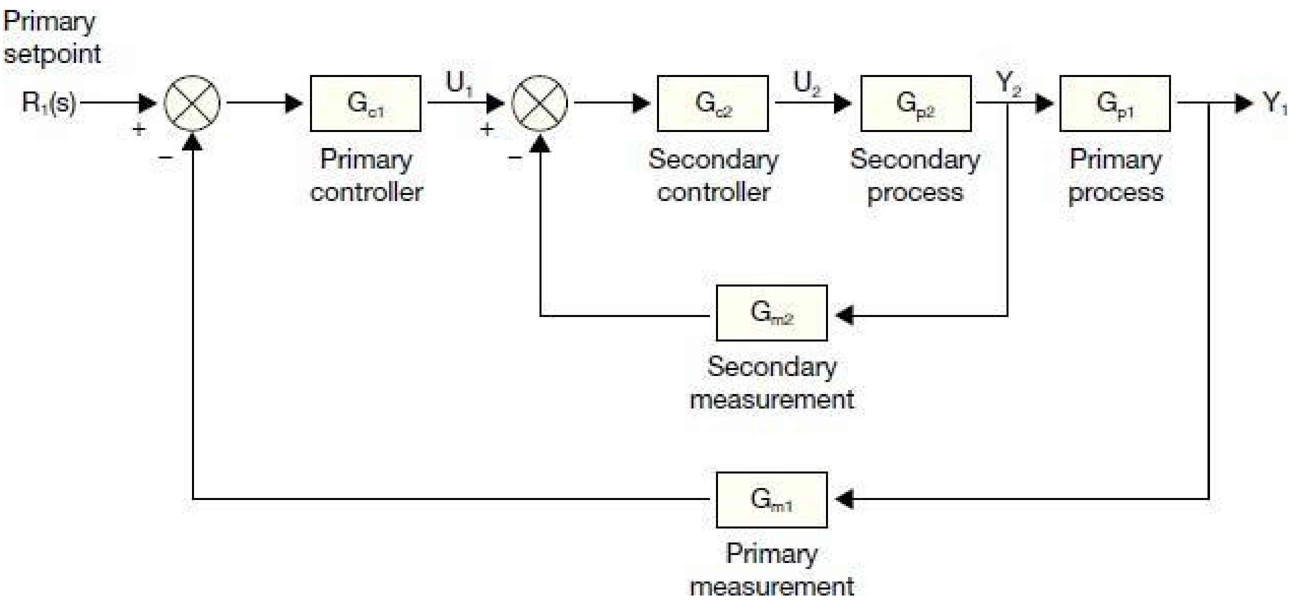

FIGURE 4. **Cascade Control System [17].**

Most literature investigate the speed control of a DC motor as a feedback control loop otherwise known as a closed loop control system. The research activities carried out on these areas shows the need for continuous improvements on the simple feedback loop in controlling the speed of industrial actuators (DC motors). Literature based on various kinds of controllers used for DC motor speed control are presented and discussed.

3. GRNN ALGORITHM

The GRNN algorithm is by far the most frequently used control algorithm. The majority of feedback loops are handled by this algorithm or one of its minor variants. A GRNN regulator's design is depicted in Figure 5. It is possible to put it into action in a number of different ways, such as a stand-alone controller in a PC, PLC, DCS, or microcontroller, as part of a Direct Digital Control (DDC) package, or as part of a hierarchical distributed process control system. The GRNN algorithm can be approached in a variety of ways. It can be approached analytically or as a tool that can be utilized with a few general rules. The "textbook" version of the GRNN algorithm is given in equation 2. In the following section, researchers in [12] discuss the various components of a GRNN algorithm and how they affect the performance of the control system:

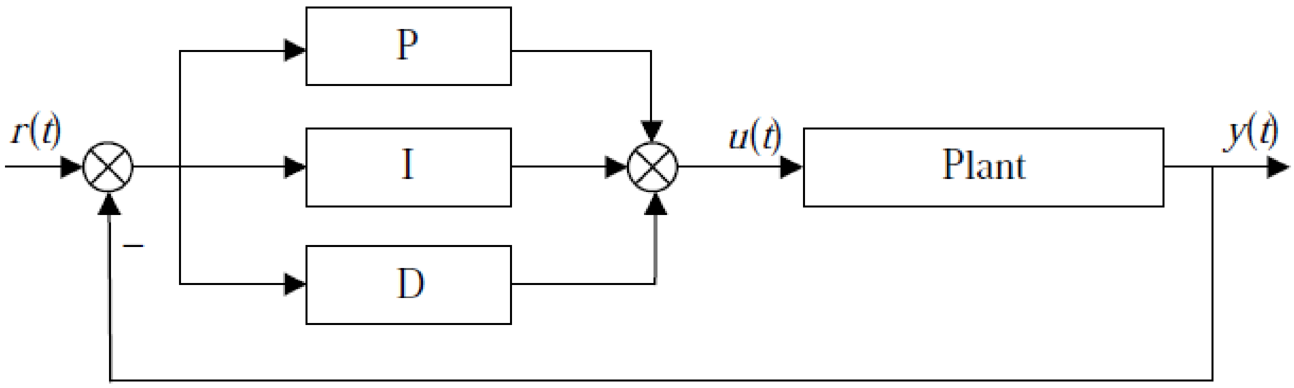

FIGURE 5. **Diagram of a GRNN Control System**

Where "u" is the control variable and e is the control error (e = ysp – y) where ysp is the Set- point and y is the Feedback control signal. The control variable is thus a sum of three terms: The P-term (which is the proportional to the error), the I-term (which is proportional to the integral of the error), and the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain K, integral time Ti and the derivative time Td. The GRNN parameters are further discussed in [18].

The proportional action considers the present state error only. The proportional signal is a measure of difference between the present value (PV) and set point (SP). The magnitude of the proportional signal increases with this difference. When the PV approached the SP, the error becomes so small so that the controller cannot trigger the PV to meet up with the SP. This implies that there is always a steady state error, which is an offset value form the set point in the system. This effect leads to the choice of higher value for the gain of the proportional term. This higher value, however, makes the system unstable with oscillations and overshoots, which makes the behavior like that of an on-off controller as mentioned in [19]. It can be concluded that the P-term cannot sufficiently satisfy accurate system control especially in higher order systems with more than one energy storage elements. The P-term is usually in conjunction with the Integral or Derivative term. The Mathematical equation of the output of a P-controller is given by the equation 2.

$$(t) = K_p(t) \tag{2}$$

The integral action of a GRNN algorithm is proportional to the integral of the control error. In terms of equation. It turns out that the integral action and the control errors past and present values are linked. Due to the presence of a pole at the complex plane's origin, the steady-state error can be reduced to zero when a step load disturbance or step reference signal is applied. Because the integral action is able to set the term up to the appropriate value on its own, this indicates that there is no steady state error. The integral term is utilized when the controller must correct for any steady state offset from a constant reference signal value. Integral control overcomes the drawback of proportional control by eliminating offset and limiting controller gain as mentioned in [20]. The rate of change of control error serves as the foundation for the derivative action. The derivative action has a great potential for improving control performance because it can anticipate an incorrect trend of the control error and compensate for it. Because the controller is able to take the rate of change of an error signal as an input, this adds a layer of prediction to the control action. In contrast to P and I control, care is required when using subsidiary control. The majority of applications prohibit the use of pure derivative control due to the possibility of measurement noise amplification. However, derivative control is still required for some real-world control applications, such as DC motor control tacho generator feedback.

3.1 MOTOR SPEED CONTROL USING GRNN ALGORITHM

Because a DC motor requires precise speed control, precise control strategies are required. Because of their heartiness and exactness with regards to accomplishing accuracy speed control, GRNN regulators are presently quite possibly of the most broadly involved control in ventures. A GRNN algorithm's performance is significantly affected by the gain parameters for the proportional, integral, and derivative terms. We will examine and discuss a variety of newly developed tuning strategies in this section. Due to the difficulty of the tuning process, research into ways to make GRNN Algorithm even more accurate and user-friendly has required a significant amount of time and effort as mentioned in [21].

The DC drive consists of a Power Electronic Modulator (PEM) that converts electrical energy from the source into a form suitable for the motor, an input and output filter that performs signal processing functions to remove unwanted frequency components from the signal, and a controller that controls the power modulator. Researchers discussed the DC motor drive and controller for speed control under varying load conditions in [12]. The various controllers that were looked at were P (proportional), PI (proportional integral), and GRNN (proportional integral and derivative). Because it has a smaller amplitude and phase margin, faster dynamics, and a lower steady state error, the proportional controller is only suitable for first-order systems. It was discovered that the PI controller performed poorly when the plant controller was highly non-linear. It is only used when there are significant noise and disturbances during the process and the system cannot respond quickly. When the K_d is low, the GRNN algorithm's rise time, settling time, steady state, and stability were found to be more suitable for controlling the PEM. A closed loop speed control scheme for the entire system consists of an outer speed loop and an inner current loop. The inward current circle lessens the converters and engine's force and current underneath as far as possible. Additionally, it helps to lessen the impact of any converter-motor system non-linearity on drive performance. The Simulink simulation result demonstrates that the motor speed only slows by approximately 270 rpm (9%) in 980 milliseconds under full load. The motor is also hunting at approximately 200 rpm (6.66 percent) in 900 milliseconds when it is in the unloading condition.

A researcher in [22] suggested a separately exited DC motor drive for the speed control application due to its high reliability, controllable torque, simplicity, and accurate speed control. Using the derived dynamic model of the separately exited DC motor, a transfer function was created for the relationship between the applied voltage and angular position. In order to achieve the desired speed and armature current response in the system's control loop, a GRNN algorithm was utilized. Utilizing MATLAB/SIMULINK programming, the framework's block outline was made and recreated with and without the GRNN regulator. The first step was to compare the system's step response with and without the GRNN algorithm. The system was evaluated both with and without a GRNN algorithm under full load (load disturbance) conditions. The rise time was greatly reduced by the GRNN algorithm by approximately 20%, and the settling time was also improved by 20%. It was noticed that the speed did not reach the desired level when there was no GRNN algorithm. The recent concern of controlling pace under load was settled by using the GRNN regulator. The first parameter tuning step of the GRNN algorithm was carried out using the Ziegler-Nichols tuning technique. Under no load, this approach eliminates steady-state error as well as the issue of overshooting between reference speed and actual speed as mentioned in [23]. The loading effect's issue with motor speed undershoot was fixed in the following step through manual tuning. The GRNN algorithm supplies a voltage to the armature terminals of the DC motor. The final parameters of the gain values were discovered and simulated. The family of controllers labelled P, PI, PD, and GRNN that make up a GRNN algorithm can be seen in Figure 6 of the selection flowchart. The flowchart provides a guide for choosing the best controller strategy for a variety of applications that require precise

3.2 GRNN TUNNING METHODS

The second step in setting up the GRNN algorithm is to tune or select numerical values for the GRNN coefficients after selecting the control process's GRNN design, as shown in Figure 2-6. Tuning is the process of adjusting control parameters to achieve the best possible response from the system. For various control systems, stability is a crucial requirement as mentioned in [24]. However, the behaviour of various systems and the requirements of various applications may conflict with one another. GRNN tuning is troublesome issue, even though there are just three boundaries which is easy to portray on a fundamental level. This is since parameters must fulfil intricate criteria within the confines of GRNN control. There are several different kinds of GRNN tuning strategies, some of which include:

Classical Techniques:

1. Manual Tuning method
2. Ziegler-Nichols method
3. Internal Model control (Model-based)
4. Pole-Placement method

Heuristic Algorithms:

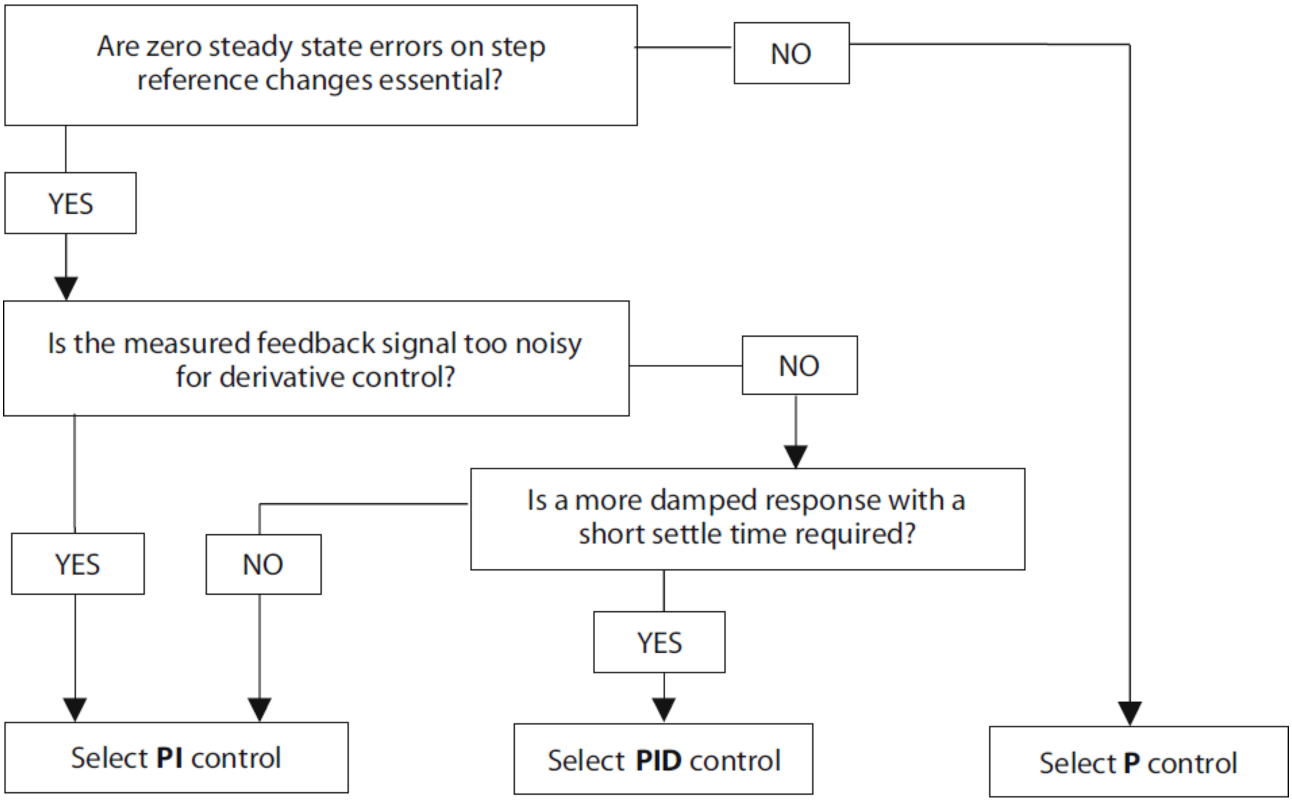

FIGURE 6. GRNN Term Selection Flowchart.

1. Genetic Algorithm (GA)
2. Invasive Weed Optimization (IWO)
3. Simulated Annealing

3.2.1. Mannual tunning method

The manual tuning method entails changing the system's parameters and monitoring the results. The parameters (KP, Ki, and Kd) are adjusted until the system behaves as expected. Despite how easy it is to use, only trained professionals should employ this technique. Researchers in [25] discussed a manual tuning procedure in which the parameters Ki and Kd are initially set to zero. Kp is then increased until an oscillation is seen in the loop's output. The appropriate Kp value should be set to around half of that for a "quarter amplitude decay" response. Then, unless any offset is corrected in time for the process, the Ki is raised. However, too much Ki will cause instability. After a load disturbance, the Kd parameter is increased until the loop returns to its reference table 1.

Table 1. Effect of changing control parameters

Parameter	Rise Time	Overshoot	Settling Time	Steady State Error
K_P	Decrease	Increase	Minor Change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_d	Minor Change	Decrease	Decrease	Minor Change

Manual tuning can also be done using the MATLAB software GRNN tuner which allows to tune the response of the system according to the desired transient response and loop stability criteria. A method for tuning the gains of a GRNN algorithm optimally using MATLAB Simulation Software. The design criteria were first set be Rise time <3seconds, Settling time <10 seconds, Overshoot of <5% and a steady state error <1%. The plant to be controlled was a temperature controlling system, which could be used in a furnace, industrial chemical process etc. A first order model and a second order model approximation were derived for the system. For the first order system, a Proportional controller with gain of 12 satisfied the desired performance criteria. Unlike the first order system, a proportional controller was not sufficient for achieving the set criteria. Hence gains of K_p = 110, K_i = 10, K_d = 100 was found satisfying all the control requirements. Manual tuning using the root locus approach was also presented which makes used of the MATLAB tool Graphic User Interface (GUI) and enables tuning of the GRNN algorithm by viewing the root locus of the system. The step response of the system is also observed in the GUI until the desired response is achieved. The GRNN algorithm achieved on MATLAB can be integrated with Arduino or any other type of microcontroller. The controller can then be used for generating PWM pulses through its digital pin, which intern can be used to effectively control the plant.

3.2.2. Ziegler-Nichols tunning method

The numerical values of the GRNN coefficients are determined by the Ziegler-Nichols methods through an online process experiment that is based on rules. This frequency domain approach is based on the experimentally determined point at which the system becomes marginally stable. A researcher came up with the Ziegler-Nichols closed loop method and the Ziegler-Nichols open loop method in 2015 to adjust the parameters of a GRNN algorithm. The definition of acceptable stability serves as the foundation for the Ziegler-Nichols method's controller tuning rules. The belief that the step response's 14 decay ratio indicates poor control loop stability is widespread as mentioned in [26]. This is because a disturbance or step change in the control loop's set point results in the ratio of the amplitudes of subsequent peaks in the same direction. The first step in improving the system is to lower the KP value if the control loop's stability becomes too low. The tuning procedure is as follows:

I. Bring the process as close as possible to the specified operating point of the control system to ensure that the controller is "experiencing" representative process dynamics and to lessen the likelihood of tuning variables reaching limits. The process variable is manually adjusted until it is approximately equal to the set-point when the controller is in manual mode to bring the process to the operating point.

II. The gain KP is initially set to "0" when Ti = and Td = are set to make the GRNN algorithm a P controller. Switch the controller to automatic mode to end the control loop.

III. Raise KP after the system has been excited until there are long-lasting oscillations in the control system signals, like in the process measurement. When the system continues to oscillate, it has reached its stability limit. The value of Kp at this point is the ultimate (or critical) gain, or Kpu. The excitation can take the form of a step at the set-point. This step should be relatively small—say, 5% of the highest set-point range—so that the cycle doesn't get too far from the place where the unique properties of the interaction might be. In addition, the step shouldn't be too small because, without it, the measurement noise that is bound to occur could make it hard to see the oscillations.

Researchers in [26] proposed the modified Ziegler Nichols tuning method as well as the traditional Ziegler Nichols tuning method. The step response of the various kinds of plants that the Traditional Ziegler Nichols tuning method is applied to is depicted in Figure 7. A common reaction of a first request framework with a transportation delay is the reaction. There are two parameters that define these systems' response: the time delay (L) and the constant time (T). By tracing a tangent to the step response at its inflection point and locating its intersections with the time axis and steady state value, these points can be derived...

When the step response of the system is derived, the output signal can be noted as shown in figure 2.7, from this figure the parameters k, L, T can be extracted by the straight forward approach shown in Figure 2.6. With these parameters and the Ziegler Nichols formula shown in Table 2, the controller parameters of the system can be derived.

Table 2. Ziegler-Nichols tuning first method.

Controller	K_P	T_i	T_d
P	T/L	N/A	N/A
PI	0.9T/L	L/0.3	N/A
GRNN	1.2T/L	2L	0.5L

The Modified Ziegler-Nichols tuning method proposed by [27] uses Chien Hrones Reswick (CHR) tuning algorithm which emphasizes on set-point regulation. The modified Ziegler Nichols Tuning method unlink the Traditional method, uses the Time constant T of the plant explicitly. The controller tuning formulas are given in Table 2-3

Table 3. Modified Ziegler Nichols tuning method

Controller	K_P	T_i	T_d
P	0.7/a	N/A	N/A
PI	0.6/a	T	N/A
GRNN	0.95/a	1.4T	0.47T

The transfer function used to model the dc motor is derived from the values of Kp, Ki, and Kd in the table. The

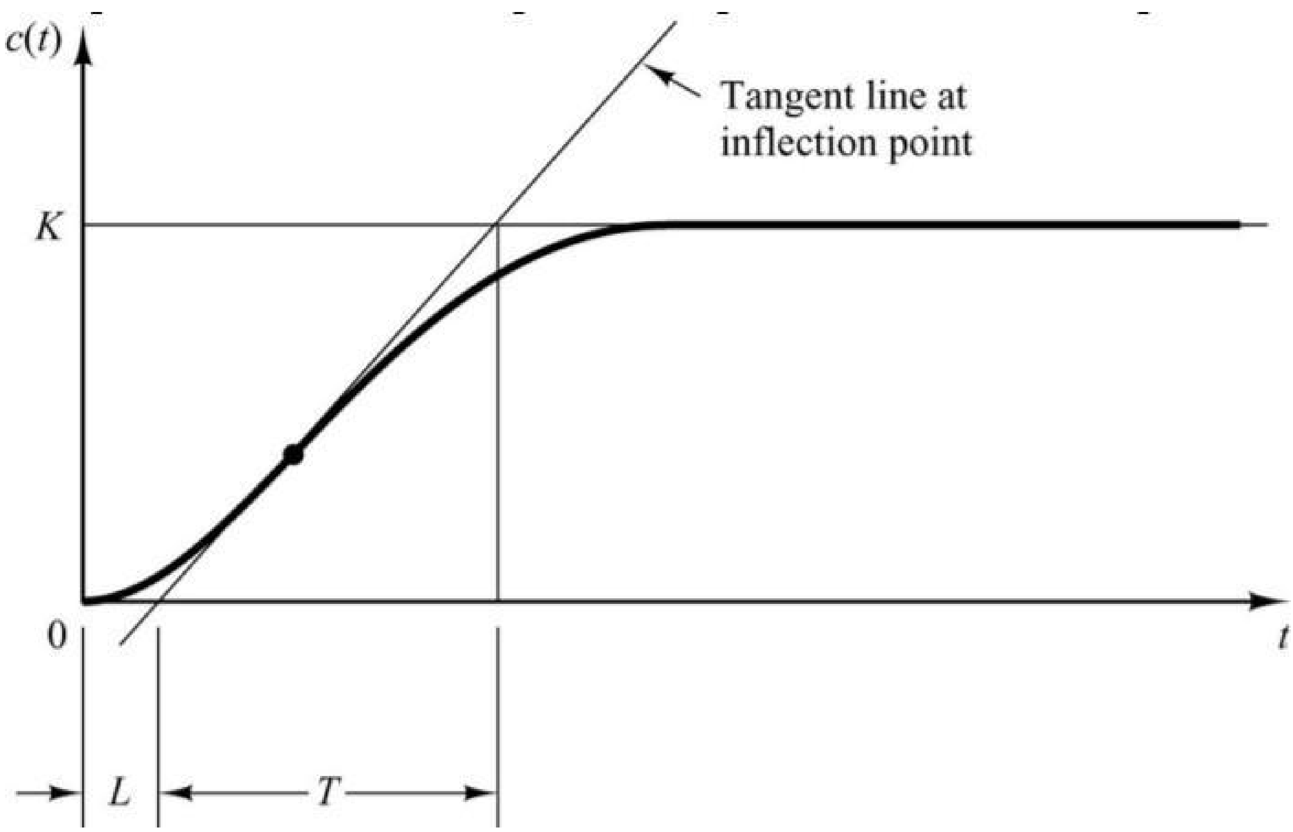

FIGURE 7. **Response Curve for Ziegler Nichols Method**

response curve is used to calculate the parameters K, L, and T. According to the findings of a computer simulation that was carried out in MATLAB Simulink, the Modified Ziegler-Nichols tuned GRNN algorithm performs better than the conventional Ziegler-Nichols tuning method for the control objectives of minimum rise time, minimum overshoot, and minimum settling time.

According to the researchers in [28], the Ziegler-Nichols tuning method only alters the proportional constant while maintaining the remaining two gain parameters. Kp is raised by a factor of two until the system becomes unstable. The oscillation period and gain at that point are the ultimate period and gain. Using this method, the settling time Ts and maximum overshoot Mp can be calculated. For finding the KP, TI, and Td values in a GRNN algorithm, researchers in [29] suggested using the Ziegler-Nichols method. LQR is used to best control linear plants. A method for optimal control known as model predictive control, or MPC, can be used to manage linear and nonlinear systems. Using the process model, MPC predicts how the system will react to a moving or receding horizon. The Ziegler Nicholas method is a straightforward strategy for tuning the GRNN algorithm, as the researchers discuss in [30]. The Ziegler-Nichols and Modified-Ziegler-Nichols tuning techniques are utilized for GRNN algorithm tuning for DC motor speed control. By reducing transient response parameters like rise time, settling time, and percentage overshoot, the DC motor's speed response can be improved. The Ziegler Nicholas method, according to the researchers in [31], measures speed and uses a closed loop system to provide feedback to the system. The integral and derivative parameters of the GRNN will be set to zero at initialization. The proportional term Kp gradually rises from zero until the system begins to continuously oscillate. The value of the proportional coefficients at this point is the ultimate gain (Ku), and the period of oscillation at this value is the ultimate period (Tu). The regulator's increase (Kp) has little value when the regulator is in corresponding mode, such as when the primary and subsidiary terms are set to nothing, which causes the framework to respond slowly. By increasing Kp by two, the response becomes unstable and oscillatory. Last but not least, the proportional gain is altered until the response continues to oscillate.

4. INVASIVE WEED OPTIMIZATION (IWO)

The social behaviour of swarms, such as bird flocking and fish schooling, served as the foundation for the Invasive Weed Optimization algorithm, which was developed by researchers in [32]. Each bird is referred to as a particle in this context, and in the context of a GRNN algorithm, each particle possesses the three characteristics Kp, Ki, and Kd. The social-psychological tendency of individuals to imitate the success of other individuals is the basis for the changes in position of each individual particle within the search space in IWO. Particles are used to describe the individuals who are "flynned" through the hyper-dimensional search space. To put it another way, a particle's changes in the swarm are influenced by its neighbours' experience or knowledge. The collective behaviour of finding the best locations in a high-dimensional search space is facilitated by this straightforward behaviour. The IWO algorithm keeps particles in a swarm, with each particle representing a possible solution. The d-dimensional vector xi(t), which is equivalent to (xi1, xi2, xi3, ... xid), represents the position of particle i in the search space at time step t. The swarm's position is altered by adding a velocity, vi(t), as shown in equation 3.

$$Xi(t+1) = (t) + vi(t+1) \tag{3}$$

The optimization process is driven by the velocity vector vi(t), which reflects both the experiential knowledge of the particle and the information that is socially exchanged from the particle's neighborhood. The cognitive component of a particle is its experiential knowledge, and its distance from its best position since the first time step is proportional to this distance. The social component of the velocity equation is the information that is shared socially. The neighborhood for each particle in global best IWO, also known as gbest IWO, is the entire swarm. Together, the practices form a social network resembling a star topology. The social part of the particle velocity update in this type of topology shows information from all of the swarm's particles, including the best position (collection of all of the particles). Equation 4 provides the formula for calculating particle i's velocity update.

$$v_{ij}(t+1) = v_{ij}(t) + c_1 r_1(t)\left[y_{ij}(t) - x_{ij}(t)\right] + c_2 r_2(t)\left[\hat{y}_j(t) - x_{ij}(t)\right] \tag{4}$$

c_1 and c_2 are positive acceleration constants that are used to scale the contribution of the cognitive and social components, respectively, and r_{1j} and r_{2j} are random values in the range of [0, 1] that are sampled from a uniformly distributed distribution. Where v_{ij} (t) is a vector that represents the velocity of particle i in j dimensions at time step t, x_{ij} (t) is the position of particle i in dimension j at step t. The algorithm is given a stochastic edge by these random values (r_{1j}, r_{2j}), which also cause the particles to act randomly. Particle i's best position since the first step is the personal best, or y_i. The personal best for particles in IWO will be the coordinates of the particles that minimize the fitness function f. The DC motor data was imputed to the transfer function on SIMULINK, and differential equations for the model as well as the state space representation were derived. Additionally, the open loop transfer function and closed loop system response were derived and analysed, respectively. The goal of GRNN tuning is to minimize gain values. Finally, Ziegler Nichols' GRNN tuning method was used to first tune the speed control's GRNN, and then the results—settling time, overshoot, rise time, steady, and state error—were recorded. Using the IWO algorithm, the same thing was done, and the results were recorded. Simulink was used to examine the closed loop control system's step response for both the IWO and ZN (Ziegler Nichols)-tuned controllers. The presentation of IWO calculation technique for tuning was demonstrated to be significantly better compared to conventional strategy like Ziegler - Nichols strategy as far as framework overshoot, settling time and rise time. The use of IWO in the tuning of a separately excited DC motor by a GRNN algorithm has been discussed and analysed by researchers in [32]. In order to reduce the steady state error, rise time, maximum overshoot, and settling time, the fitness function in IWO was utilized. Furthermore, the system's cost function was minimized, as shown by the integrated square error (ISE). The proposed controller demonstrated the excellent performance of the GRNN algorithm when tuned with an IWO algorithm and that an optimized speed response is always obtained when the reference input speed changes.

In tuning a GRNN algorithm for a DC motor, researchers in [33] discussed how IWO and the Genetic algorithm performed in comparison to one another. A unit step signal was used as an input reference signal for the DC motor and an output signal was obtained for tuning the GRNN algorithm based on some criteria. Using the MATLAB platform, an overshoot, a rise time, a settling time, and a steady-state error were identified, and the output signals were simultaneously analysed. The DC motor GRNN algorithm underwent the initial process of manual tuning. The GRNN was then tuned using IWO and GA. The parameters, Max overshoot, Rise Time, Settling Time, and Steady state error saw significant reductions in these algorithm's IAE, ITAE, ISE, and ITSE results. When IWO was used, the Max overshoot went from 60.9959 for the IAE index to 25.4250 for the ITAE index, which was 12.9682. Additionally, a special fitness function was obtained, and its values decreased. The exceptional wellness capability, W (k) delivered more agreeable qualities than other wellness capability as far as overshoot, immersion time, and rise time. A GRNN algorithm for DC motor speed control will be examined and implemented in this research project. Ziegler Nichols and IWO tuning can be used to get the best controller gain values.

4.1 IWO MODEL-BASED TECHNIQUE

A classical Invasive Weed Optimization (PI) tuning technique which is model based in nature and requires just the motor parameters and the cross-over frequency or bandwidth of the controller to be specified the gains of the controller are achieved by pole cancellation. Although it required lot of in depth understanding about the plant and also some pre-calculation might have to be done, it is comparatively faster to set up. This method was applied to tune a cascaded IWO algorithm for a PMDC motor. Firstly, the current loop was determined. In the case whereby the mechanical inertia of the motor is big enough, the back-EMF factor in the current loop acting as disturbance can be neglected. A simplified current loop was derived as shown in figure 8.

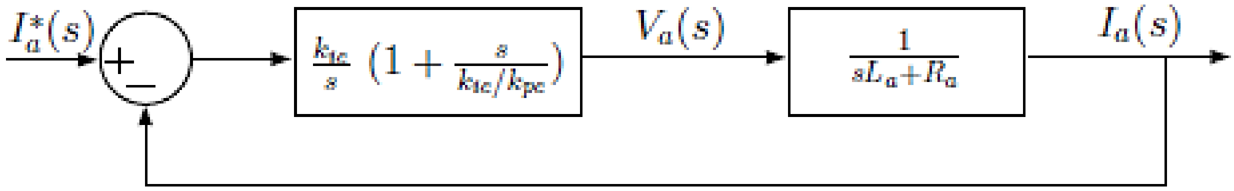

FIGURE 8. Simplified Current Loop using IWO.

Hence, the gains of the speed loop were calculated with equation choosing the cross-over frequency of the speed loop, W_{cs} to be up to 10 times of the current loop crossover frequency. Figure 9 shows the speed loop. The current loop is assumed to be ideal and equals to 1.

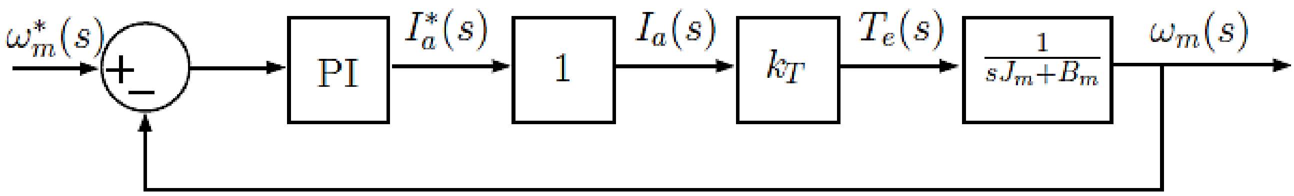

FIGURE 9. Speed Loop using IWO

5. DIRECT CURRENT TO DIRECT CURRENT (DC-DC CONVERTER

Both regulated switch-mode dc power supplies and DC motor speed drive applications frequently make use of DC-DC converters. The ideal input for DC-DC converters would be an unregulated voltage obtained by rectifying the line AC voltage, which is susceptible to fluctuation due to changes in the line voltage's magnitude. Consequently, switched-mode DC-DC power electronics are utilized to transform this unregulated dc input into a controlled dc output at the motor's desired voltage. Step-down (buck), Step-up (boost), Step-down/step-up (buck-boost), and Full-bridge converters are power electronics dc-dcc converters. Buck (step-down) converters are the foundation for full bridge converters. Figure 10 provides a summary of the switching operation used in switched-mode operation in a dc-dc converter.

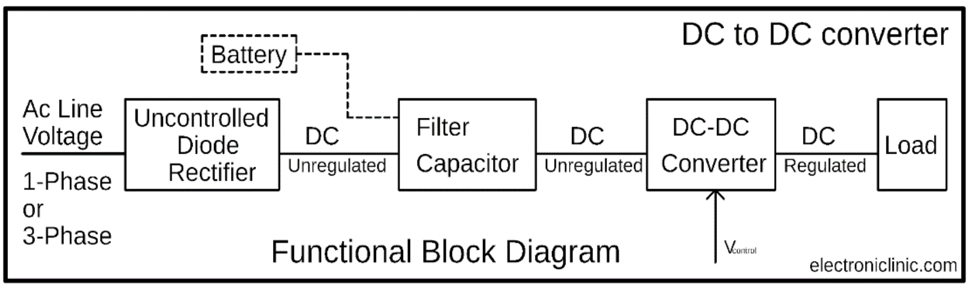

FIGURE 10. Switching Pulse Generation with comparator signal [34].

Buck converters are mainly used in dc motor speed drive applications. The basic idea of a step- down converter like a Buck converter is to produce a lower average output voltage than the dc input voltage V_d. When the associated load connected to the buck converter is an inductive load, the switch will have to be equipped with some mean of absorbing or dissipating the inductive energy during the off position of the switch or else the switch could be destroyed. Researcher in [35] has proposed a four quadrant closed loop speed control of a DC motor, which uses similar principle of operation as a buck converter. Their proposition offered a low- cost approach to high performance chopper based four quadrant closed loop speed control for a separately excited DC motor. The drive system was modelled and simulated using Scilab/XCOS. The control strategy used ensures that the output voltage of the DC-DC converter can be controlled both in magnitude and direction. The four quadrant converter consists of two switches on a leg as mentioned in [36]. The switching scheme was made to avoid turning on both switches on the same leg which would lead to shorting the source and causing damage. Also the switching of in the DC-DC converter was done using pulse width modulation PWM. A variation of PWM technique called Unipolar Switching also referred to as double PWM switching was used. This method is described in figure 10. Here a high frequency triangular waveform is compared with control voltages $+V_{control}$ and $-V_{control}$ and is used for determining the switching signals for the switches on Leg 1 and 2 on the four quadrant DC-DC converter.

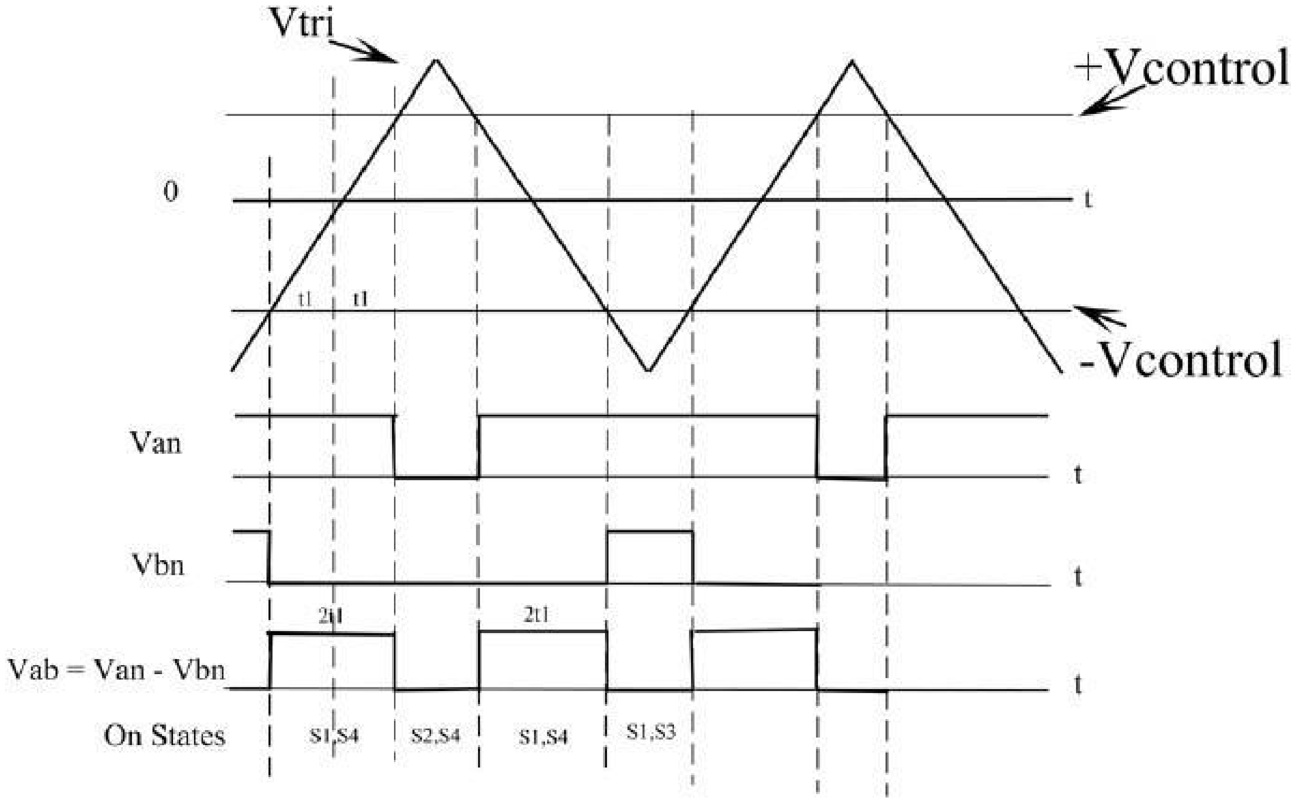

FIGURE 11. **PWM Using Unipolar Voltage Switching [36].**

The DC motor mathematical model was established using the dynamic equations of the electrical and mechanical part of the motor. A PI controller with gains of 0.25 and 0.001 for the proportional and integral respectively was derived using Trial and Error tuning method which yielded the best result. The hardware implementation consisted of a 3-phase AV supply which was to a three phase bridge rectifier and a chopper circuit. The controller circuit was realized using a L28069M Launchpad with OP-amp based level shifting circuit using a LM339. The four quadrant chopper was realized by using 4 high power IGBT transistors with two connected on each arms as mentioned in [37]. It was established that the four-quadrant dc-dc converter alongside the PI controller was robust for effectively controlling the speed of the motor in both anti- clockwise and clockwise direction.

6. CONCLUSION

When direct current (DC) power sources were first developed, DC machines were among the first electromechanical devices to be used. In terms of speed regulation and versatility, DC machines are superior to AC machines. A DC motor is a powerful electrical actuator that has a wide range of uses, including electrical traction, overhead cranes, steel rolling mills, cutting tools, robotic manipulators, and guided vehicles. DC motors are widely used in industries for difficult variable speed applications because of their speed-torque characteristics and simplicity of control. The process control industry has made many strides in the last 20 years in terms of controller design and implementation. Automatic controllers that can react quickly and accurately to complete precise tasks are in high demand in the industry. In order to get the desired performance from the majority of systems, the feedback loop, which is a crucial part of system control, must be used. To achieve a quick system dynamic response, a variety of control strategies have been developed for various feedback control systems. In order to track the reference speed quickly and accurately, with as little steady-state error and as little overshoot as possible, controls in the drive system are essential. This paper presents the results of a systematic literature review that was carried out in order to design a DC motor speed control system that is appropriate for applications that call for actuators with precise speed characteristics. Analyzed and discussed are simulation and real-time implementation results used for DC motor speed control systems in various works of literature. [38, 39]

FUNDING

None

ACKNOWLEDGEMENT

None

CONFLICTS OF INTEREST

The author declares no conflict of interest.

REFERENCES

[1] N. E. Ouanjli, S. Motahhir, A. Derouich, A. E. Ghzizal, A. Chebabhi, and M. Taoussi, "Improved DTC strategy of doubly fed induction motor using fuzzy logic controller," *Energy Rep*, vol. 5, pp. 271–279, 2019.
[2] G. Farahani and K. Rahmani, "Speed Control of a Separately Excited DC Motor Using New Proposed Fuzzy Neural Algorithm Based on FOPID Controller," *J. Control. Autom. Electr. Syst*, vol. 30, pp. 728–740, 2019.
[3] W. I. Hameed, B. A. Sawadi, and A. Muayed, "Voltage Tracking Control of DC-DC Boost Converter Using Fuzzy Neural Network," *Int. J. Power Electron. Drive Syst*, vol. 9, pp. 1657–1665, 2018.
[4] D. Bista, "Understanding and Design of an Arduino-based GRNN algorithm," 2016.
[5] S. Dani and D. Ingole, "Performance evaluation of GRNN, LQR and MPC for DC motor speed control," 2017.
[6] A. P. Engelbrecht, *Computational Intelligence. An Introduction*. South Africa: John Wiley and Sons, Ltd, 2007.
[7] I. S. Fatah, Iwo-Based, Tunning, G. A. For, Speed, Of, and Motor, "IWO-BASED TUNNING OF GRNN ALGORITHM FOR SPEED CONTROL OF DC MOTOR," 2014.
[8] T. N. G. ucin, M. B. glu, B. Fincan, and M. O. G. ulbahçe, "Tuning Cascade PI(D) Controllers in PMDC Motor Drives: A Performance," 2015.
[9] M. Gajanan, "Design of GRNN algorithm for improved performance of higher order systems," 2011.
[10] B. N. Getu, "Tuning the Parameters of the GRNN algorithm Using Matlab," *Journal of Engineering and Applied Sciences*, 2019.
[11] J. U. Liceaga-Castro, I. I. Siller-Alcalá, and R. A. Alcántara-Ramírez, "Least Square Identification using Noise Reduction Disturbance Observer," *Trans. Syst*, vol. 18, pp. 313–318, 2019.
[12] F. Wang, R. Wang, E. Liu, and W. Zhang, "Stabilization Control Mothed for Two-Axis Inertially Stabilized Platform Based on Active Disturbance Rejection Control with Noise Reduction Disturbance Observer," *IEEE Access*, vol. 7, pp. 99521–99529, 2019.
[13] T. He and Z. Wu, "Extended Disturbance Observer with Measurement Noise Reduction for Spacecraft Attitude Stabilization," *IEEE Access*, vol. 7, pp. 6137–66147, 2019.
[14] J. H. She, M. X. Fang, Y. Ohyama, H. Hashimoto, and M. Wu, "Improving disturbance-rejection performance based on an equivalent input-disturbance approach," *IEEE Trans. Ind. Electron*, vol. 1, pp. 380–389, 2008.
[15] J. H. She, X. Xin, and Y. D. Pan, "Equivalent-input-disturbance approach-Analysis and application to disturbance rejection in dual-stage feed drive control system," *IEEE/ASME Trans. Mechatronics*, vol. 16, pp. 330–340, 2011.
[16] E. Vazquez-Sanchez, J. Gomez-Gil, and J. C. Gamazo-Real, "A New Method for Sensorless Estimation of the Speed and Position in Brushed DC Motors Using Support Vector Machines," *IEEE Trans. Ind. Electron*, vol. 59, pp. 1397–1408, 2012.
[17] P. Radcliffe and D. Kumar, "Sensorless speed measurement for brushed DC motors," *IET Power Electron*, vol. 8, pp. 2223–2228, 2015.
[18] E. Vazquez-Sanchez, J. Sottile, and J. Gomez-Gil, "A Novel Method for Sensor less Speed Detection of Brushed DC Motors," *Appl. Sci*, vol. 7, pp. 14–14, 2016.
[19] M. Vidlak, P. Makys, and M. Stano, "Comparison between model based and non-model based sensorless methods of brushed DC motor," *Transp. Res. Procedia*, vol. 55, pp. 911–918, 2021.
[20] M. R. Gharib, "Comparison of robust optimal QFT controller with TFC and MFC controller in a multi-input multi-output system," *Rep. Mech. Eng*, vol. 2020, pp. 151–161.
[21] D. Bozanic, D. T. c, D. M. c, and A. M. c, "Modeling of neuro-fuzzy system as a support in decision-making processes," *Rep. Mech. Eng*, vol. 2021, pp. 222–234.
[22] B. A. Obaid, A. L. Saleh, and A. K. Kadhim, "Resolving of optimal fractional PID controller for DC motor drive based on anti-windup by invasive weed optimization technique," *Indones. J. Electr. Eng. Comput. Sci*, vol. 15, pp. 95–103, 2019.
[23] Q. Wang and F. He, "The Synchronous Control of Multi-Motor Drive Control System with Floating Compensation," in *Proceedings of the 2016 12th World Congress on Intelligent Control and Automation (WCICA)*, pp. 1940–1954, 2016.
[24] N. E. Ouanjli, M. Taoussi, A. Derouich, A. Chebabhi, A. E. Ghzizal, and B. Bossoufi, "High Performance Direct Torque Control of Doubly Fed Induction Motor using Fuzzy Logic. Gazi Univ," *J. Sci*, vol. 31, pp. 532–542, 2018.

[25] A. A. M. R. Khan, “Speed Control of a DC Motor under varying load using GRNN algorithm,” 2015.
[26] M. A. Mutalid, “Speed control of DC Motor uisng PI controller,” 2008.
[27] R. M. M. M. H. Elhag, “Speed control of a DC motor using fuzzy logic and PI controller,” *SUDAN UNIVERSITY OF SCIENCE & TECHNOLOGY*, 2016.
[28] V. S. Patil, S. Angadi, and A. B. Raju, “Four Quadrant Close Loop Speed Control of DC Motor,” 2016.
[29] N. D. Prof and P. A. Mehta, “Modeling and simulation of P, PI and GRNN algorithm for speed control of DC Motor Drive,” 2017.
[30] V. M. Rao, Pi, and Algorithm, “Performance Analysis of Speed Control of DC Motor Using P,” 2013.
[31] S. K. Singla and R. K, “Comparison among some well-known control schemes,” 2013.
[32] M. M. Sabir and J. A. Khan, “Optimal Design of GRNN algorithm for the speed control of DC motor by using Metaheuristic Techniques,” 2014.
[33] A. Senawi, N. M. Yahya, and W. A. Yusoff, “Tuning of Optimum GRNN algorithm Parameter Using Particle,” 2010.
[34] M. Walaa, Elsrogy, Naglaa, M. E. Bahgaat, and . S, “Speed contol of a DC motor using GRNN algorithm based on changed intelligent techniques,” 2018.
[35] C. Xia, *Permanent Magnet Brushless DC Motor drives and controls*. Singapore: John Wiley & Sons, 2012.
[36] G. V. Zalm, “TUNING OF GRNN-TYPE CONTROLLERS: LITERATURE OVERVIEW,” 2004.
[37] B. J. Baliga, M. S. Adler, P. R. Love, and P. V. Gray, “Zommer ND, the insulated gate transistor-a new three terminal MOS controlled bipolar power device,” *IEEE transactions Electron development*, pp. 821–829, 1984.
[38] Muniracad, “Speed control of DC Motor,” 2019. https://muniracademy.com/speed-control-of-dc-motors/.
[39] S. Shrivastava, J. Rawat, and A. &agrawal, “Controlling DC Motor using Microcontroller (PIC16F72) with PWM,” *International Journal of Engineering Research*, vol. 1, no. 2, pp. 45–47, 2012.