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Speech Control Optimization for Electric Vehicle Based on PI Controller

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Abstract

With technological advancement and increased concern for controlling pollution, electric vehicles are becoming influential in the transport field. The Brushless Direct Current (BLDC) Motor is employed in electric vehicles converting electrical power into mechanical energy. Due to its low maintenance and compact structure, BLDC Motor technologies are widely used for global industrial applications, and variable speed drives in electric vehicles. This project aims to design the PI controller for speed control of BLDCM (Brushless DC Motor) used in electric vehicles and by using motor parameters monitored and controlled. The control parameters of the PI controller are Proportional Gain (KP) and Integral Gain (Ki), which are found in PI tuning. Simulation is carried out on different optimized algorithms showing the dynamic response for rapid tuning results of the proposed modified PI controller. The best-fitted optimized algorithm with smaller overshoot, less setting time, and rising time for the design of the controller is proposed, which can help control the motor's speed and maintain constant speed during load changes.

Keywords: Pollution Electric Vehicles; Brushless Direct Current (BLDC) Motor; PI Controller.

1. Introduction

Of the growing need for technological developments, sustainable energy utilization, and stringent rules and regulation for environmental safety, Electric Vehicles (EVs) are persistently acquiring significance in the automotive sectors (Khooban et al., 2017). EVs have a vast number of advantages, including smooth and quiet operation as well as high proficiency (Huang et al., 2009). Among the most used actuators in the construction of electric vehicles, Brushless DC Motos (BLDCM) are widely used (Has et al., 2017). The BLDCM includes various pretty properties, such as smooth speed control and better torque versus speed attributes, and is proposed for multiple applications due to its simple structure, high speed, minimal size, robustness, high efficiency, and reliable performance (Saravanan et al., 2020). Control of the DC motor's speed is generally done by adjusting the input voltage on DC motors. To control the speed of DC motors, various control techniques have been designed and applied in previous studies (Huang et al., 2009; Khatun et al., 2003].

From studies, the most widely used control technique for DC motors speed control is Proportional Integral Derivative (PID) technique due to its simplicity and effectiveness in control (Kalangadan et al., 2015). The execution of a regulator for speed control application is the main aim of this study. The conventional strategies are used to fix control parameters; Proportional Gain (Kp) and Integral Gain (Ki) found from PI tuning.

Numerous algorithms have been established to design the controller, especially swarms' behavior like GA (Ibrahim et al., 2019); BAT algorithm (Premkumar et al., 2015); cuckoo search algorithm (Murali et al., 2018), particle swarm optimization (Awadallah et al., 2009) flower pollination algorithm (Awadallah et al., 2009) and GOA (Potnuru et al., 2018) are used for BLDCM speed control. This work comprises of simulation of different algorithms showing the dynamic response for rapid tuning results of the proposed modified PI controller. Harris Hawks Optimization Algorithm (HHO) is the best fitted optimized algorithm with smaller overshoot, less settling time, and rising time for the design of the controller, which can help control the motor's speed and to maintain constant speed during load changes. HHO is a popular swarm-based, gradient-free optimization algorithm with several active and time-varying exploration and exploitation phases.

The main inspiration of HHO is the cooperative behavior, and chasing style of Harris' hawks in nature called surprise pounce. In this intelligent strategy, several hawks cooperatively pounce prey from different directions in an attempt to surprise it. Harris hawks can reveal a variety of chasing patterns based on the dynamic nature of scenarios and escaping patterns of the prey (Heidari et al., 2019). This work mathematically mimics such dynamic patterns and behaviors to develop an optimization algorithm. The

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effectiveness of the proposed HHO optimizer is checked through a comparison with other nature-inspired techniques. The statistical results and comparisons show that the HHO algorithm provides very promising and occasionally competitive results. A basic flowchart about the operation of the complete system with the HHO algorithm is given in figure 1.

This study aims to design the PI controller for speed control of BLDCM used in an electric vehicle. The control parameters of PI are found from PI tuning. The system is modeled by state equations and transfer functions. Simulation for conventional PI and different Optimized algorithms are carried out, showing the dynamic response for rapid tuning results of the proposed modified PI controller. The best fitted optimized algorithm with smaller overshoot, less settling time, and rising time for the design of the controller is proposed to control the speed of BLDCM.

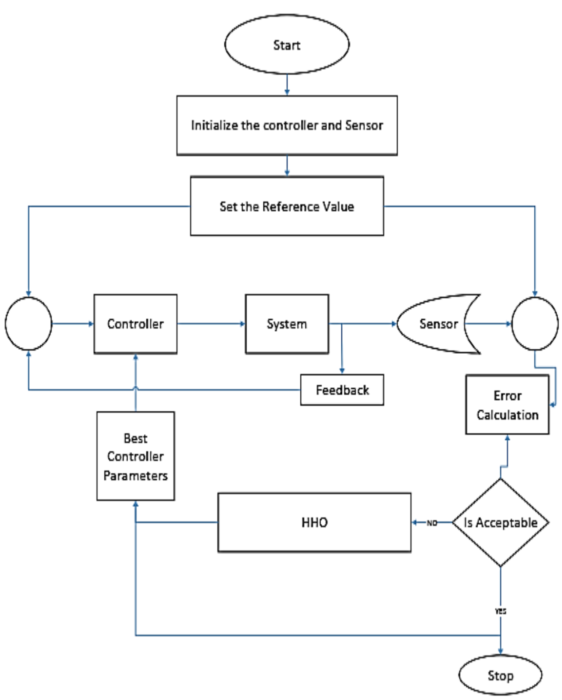

Fig. 1. Flow Chart of HHO

2. Objectives

The goal of this study is to meet the following objectives:

- To model the system with the interference of PI(Proportional Integral) controller.
- To optimize PI controller parameters for speed control of EV(Electric Vehicle) motor.
- To compare the proposed optimized result with the existing method.

3. Scope and Limitations

This design problem focuses on designing a controller to regulate the motor's speed rather than the motor's internal architecture. The system will be designed based on simulations, but due to time constraints, a prototype may not be produced to test the validity of simulation-based results and the controller's practicality. Even if a prototype is designed, then it might not be tested in EV due to its unavailability. Sensors will be inserted into the motor to measure its parameters; these sensors are based on electronics and have a thermal disadvantage.

4. Literature Review

In 2009, Huang et al. modeled the DC motor of an electric vehicle. A controller is designed with a differential geometric approach and linear quadratic regulator techniques to guarantee optimal performance. Ibrahim et al. (2019) produced an optimally designed controller of Brushless DC motor speed control depending on the genetic algorithm (GA). The result showed that the genetic algorithm designed PID has the finest relations to the rise time, settling time, and percentage overshoot than the conventional technique. Studies by Heidari et al. (2019) prove that HHO was capable of finding excellent solutions compared to other well-regarded optimizers.

Further, in 2020 Saravanan et al. designed a PI controller using a different algorithm and also debated with Grasshopper Optimization Algorithm (GOA) and Harris Hawks Optimization Algorithm (HHO). The motor parameters were monitored and controlled around the globe with the establishment of the Internet of Things (IoT). The results of the work show that the HHO controller yields the least error compared with other algorithms.

Author & Year	Objective	Result
Saravanan et al. 2020 [1902-1915]	Design PI controller using a different algorithm and also debated with Grasshopper Optimization Algorithm (GOA), Harris Hawks Optimization Algorithm (HHO). The motor parameters are monitored and controlled around the globe with the establishment of the Internet of Things (IoT).	• The BLDC motor model with the controller is developed in MATLAB. • Simulated results show HHO controller yields the least error.
Huang et al., (2009) [437-444]	An electric vehicle driven by a DC motor is modeled. A controller is designed with a differential geometric approach and linear quadratic regulator techniques to guarantee optimal performance.	• The performance of the designed controllers is compared with that of PID controllers. • The controller designed here demonstrates much better performance than that of the regular PID controller under test.
Ibrahim et al. (2019) [8694]	This article produces an optimally designed controller of Brushless DC motor speed control depending on the genetic algorithm (GA).	• The proposed controller has much better time response characteristics. • The genetic algorithm designed PID has the finest relations to the rise time, settling time, and percentage overshoot than the conventional technique
Premkumar & Manikandan, 2016 [818-840]	The design of fuzzy proportional derivative controller and fuzzy proportional derivative integral controller for speed control of brushless direct current drive has been presented using nature-inspired optimization algorithms such as particle swarm, cuckoo search, and bat algorithms.	• An optimized fuzzy proportional derivative controller has superior performance than the other controllers considered.

Heidari et al., 2019 [849-872]	In this paper, HHO technique is proposed to compete with other optimizers. For this purpose, a new mathematical model is developed in this paper.	• HHO was capable of finding excellent solutions compared to other well-regarded optimizers

Table 1. Reviewed literature summary: Optimization for Electric Vehicle based on PI Controller using different algorithms.

The review of literature hence validates the Optimization for Electric vehicles based on PI Controller using different algorithms. Results show that Brushless DC motors are one of the most used actuators in the construction of electric vehicles, with PID being one of the main used controllers. Different Techniques are employed for the designing of the controller of Brushless DC motors. Harris Hawks Optimization Algorithm gives the best-predicted outcome.

5. Methods, Observations and Calculations

The brushes in conventional DC motors wear out over time. Thus, the brushed DC motor cannot be used for operations that demand long life and reliability. To solve this problem, a brushless DC motor is used. The rotor of the BLDCM is a permanent magnet. The coil arrangement in the stator, when energized, will form an electromagnet. The operation of a BLDCM is based on the force interaction between the permanent magnet and the electromagnet.

A BLDC almost acts as a flipped version of a brushed motor because the permanent magnets become the rotor. Whereas the coil windings become the stator. There are motors with different magnet arrangements. Where the stator may have a different number of windings, and the rotor may have multiple pole pairs.

Dynamic Model

The phase voltages consist of voltage drop, resistance voltage drop, rate of flux linkages and the induced emf in the phase winding.

Van *= R.s ia + L.s dia/dt + ea* *(i)*

Vbn *= R.s ib + L.s dib/dt + be* *(ii)*

Vcn *= R.s ic + L.s dic/dt + ec* *(iii)*

Where ea, eb, ec are the induced EMFs in each phase. Van, Vbn, and Vcn are the phase voltages. R is the resistance per phase and L is the inductance per phase. These equations are represented in the matrix form:

$$\begin{bmatrix} van \\ vbn \\ vcn \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} Ia \\ Ia \\ Ia \end{bmatrix} + \begin{bmatrix} dia / dt \\ dib / dt \\ dic / dt \end{bmatrix} + \begin{bmatrix} e & a \\ e & b \\ e & c \end{bmatrix}$$

Transfer Function

The transfer function is the ratio of the Laplace Transform of output to the Laplace Transform of input when all the initial conditions are assumed to be zero. The transfer function of a system has an important part in determining the response of a system. Consider the load torque on the system equal to zero. If a certain armature voltage is supplied, a speed (ws) is attained.

Figure 2. shows the block diagram between voltage and speed. Block diagram reduction techniques are used to develop the transfer function for the BLDCM (Xia, 2012).

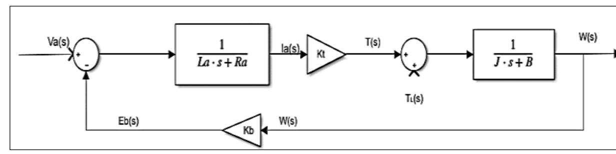

Fig. 2. Transfer Function of the BLDC Motor

$$\frac{\omega(S)}{v(S)} = \frac{k}{(La \cdot S + R_a) + (J_S + B) + K_2}$$

***Back* EMF**

Motors act as a generator when they are rotating. This means that a back-EMF voltage is induced in the stators, which opposes the driving voltage of the motor. Back EMF is an important characteristic of a motor as by looking at its shape; it can be determined what type of motor is in use. And it also indicates the type of control algorithm that is needed to be used to control the motor. BLDCs have a trapezoidal shape and are commonly controlled by trapezoidal control (Pimentel et al., 2013). An easy way to observe the back-EMF shape is to use simulation. A one-pole pair BLDC motor is simulated with open-circuit terminals.

Inner Configuration of BLDC

There are six possible ways of energizing coil pairs. By commutating two phases at a time, the stator magnetic field is made to rotate, which will cause the rotor to turn. The rotor angle is measured concerning the horizontal axis with six different rotor alignments. If the correct phases every 60 degrees are commutated, it will make the motor spin. This is called six-step commutation or trapezoidal control (Xia, 2012). It is observed that with more pairs of poles, the commutation occurs more frequently. To properly commutate the motor at the right times with the correct phases, the rotor position is needed to be known. Which is usually measured by using hall sensors. The poles of the same kind repel each other, making the rotor turn counterclockwise. At the same time, the opposite poles attract each other, and the rotor keeps on turning in the same direction. Once it completes 60 degrees (for single pole pair) of rotation, the next commutation occurs. The commutation occurs in such a way that the rotor never aligns with the stator magnetic field, but it is always chasing it. Two things can explain this behavior.

1. When the rotor and stator magnetic fields align perfectly, the motor creates zero torque. It is not to be aligned.
2. Maximum torque occurs when the fields are at 90 degrees to each other. The desired outcome is to bring this angle close to 90 degrees. In BLDC motor, 90 degrees can never be achieved with six-step commutation. But the angle fluctuates within some

range. This is due to the simple nature of trapezoidal control.

Six-Step Commutation Logic (HALL Sensor)

The selected Brushless DC motor has three coil windings in the stator and a single pole pair in the rotor. Two phases are energized simultaneously: positive DC (north pole) and negative DC (south pole). This occurrence leads to simultaneous attraction and repulsion between the stator and rotor. In the simulation, the hall effect sensor wmodeledled based on relational operator and AND gates to select the sector based on the relations. In order to choose a switching pattern logic based on sector, a multiport switch has been used in the simulation. The selected sector number is used as the first input to the multiport switch to tell which sector's logic pattern is required for proper commutation for continuous rotor rotation.

Pulse Width Modulation

The desired outcome is to make the motor spin at different speeds. A constant DC voltage is used at the input to the inverter, which leads to constant speed. The voltage can be adjusted by closing the loop with a suitable controller; based on the difference between the desired and measured speed, the controller will adjust the voltage to bring the motor speed close to the desired value. An ideal voltage source is used to generate different DC voltage levels commanded by the controller. But in reality, the DC voltage supplies a fixed voltage which is needed to be modulated using a technique called PWM before providing it to the three-phase inverter. PWM is a square wave signal that repeats itself at a certain frequency. The longer the duty cycle the higher the voltage. PWM control has an averaging effect on the output voltage that is sensed by the motor. Frequency of PWM must be selected very carefully. If the frequency is too low, instead of observing an averaged voltage the model will observe a voltage that tries to follow the square wave shape, this will lead to poor tracking of the reference speed and the motor will keep speeding up and slowing down. However, if the frequency is increased to certain reasonable value the voltage will be averaged out, which will improve the speed control performance. The ripples will occur due to the switching nature of PWM. The frequencies normally are on the order of a few kilohertz and need to be selected to be much higher than the reciprocal of the motor time constant.

Practical Motor Selection

The Brushless DC motor has multiple applications, however, the main focus in this system is BLDCM used in electric vehicle. The Brushless DC motor is mainly used in small EVs like e-bikes and e-cycle. It was observed while researching that 250W BLDC motors are being used frequently to power e-bikes ("Top 20 Cheapest Electric Scooters, n.d.) therefore, a 250W BLDC motor manufactured by Maxon company (maxon EC 45) was selected for this system. The parameters of the system were taken from ("EC 45 Ø45 mm, March 2021).

Nominal speed (rpm)	4300
Nominal torque (mN.m)	331
Max. efficiency	85 %
Phase-Phase resistance	0.43 Ohm
Ph-ph inductance	0.17 Mh
Torque constant (mNm/A)	45.5
Speed constant (rpm/V)	210
Rotor inertia gcm2	209
Damping Factor (Nm/rad/s)	0.000735

Table 2. Motor Parameters

Proportional Integral Controller

For speed control, a discrete PI controller is used. The PI controller is responsible for generating the necessary voltage that will cause the motor to run at the desired speed; if the tuning parameters are selected correctly, then the motor will be able to respond quickly with minimum overshoot and high stability. There are multiple methods to tune PI parameters (kp and ki) for optimal rise time and overshoot. Model based tuning method in MATLAB was used to determine the constants for the controller. Manual methods like pole placement and loop shaping in which the position of poles and zeros of the PI-controller in an s-plane can be used to vary response and gains. However, this method was found to be less accurate; therefore automatic MATLAB based tuning method was used for determining controller constants, in which gains are automatically calculated with respect to the selected system's response characteristics. After inserting the tuned constants in the PI block, the system's response to varying loads was fast and accurate.

Model-based tuning can also be done on the model's transfer function estimated through MATLAB's system identification toolbox or linear analysis tool. However, the complex control of the BLDC motor resulted in inaccurate transfer functions. As a result, automatic tuning was directly used on Simscape blocks of the system for accurate observations.

Transfer Function based auto tuning	**Kp**	**Ki**
0.05	**0.0**	

Table 2. Controller Values

On the above grounds, we conclude that the transfer function of a system has an important part in determining the response of a system. Motors act as a generator when they are rotating. This means that a back-EMF voltage is induced in the stators, which opposes the driving voltage of the motor. BLDC motors has a Trapezoidal back EMF. There are six possible ways of energizing coil pairs. The stator magnetic field is made to rotate by commutating two phases at a time. Which will cause the rotor to turn The desired outcome is to make the motor spin at different speeds. A constant DC voltage is used at the input to the inverter, leading to constant speed. The buck converter is used to adjust the DC source voltage to different voltage levels in order to be able to control the BLDCM at varying speeds discrete PI controller is used. The PI controller is responsible for generating the necessary voltage that will cause the motor to run at the desired speed. The system must have a greater response time and less peak time, overshoot, and settling time. The behavior of a transfer function in the transient response is determined by calculating the rise time, peak time, settling time, and overshoot (Fadali & Visioli, 2012; Bolton, 2021). These values determine if the system is overdamped, underdamped, critically damped, or undamped.

Harris Hawks Algorithm

A novel population based meta heuristic algorithm with new nature inspired technique. The main idea behind HHO is inspired by the cooperative behaviors of one of the most intelligent birds called Harris hawks and its behavior of hunting prey. Meta-heuristic algorithms have been designed and utilized for tackling many problems as competitive alternative solvers because of their simplicity. The main inspiration of the HHO algorithm is the Harris hawks team's behaviors of hunting and chasing patterns for the capture of prey in nature. This algorithm has been implemented to determine the optimal values of PI tuned parameters kp and, ki. The different phases of the HHO algorithm can be seen in figure 3 below (Heidari et al., 2019).

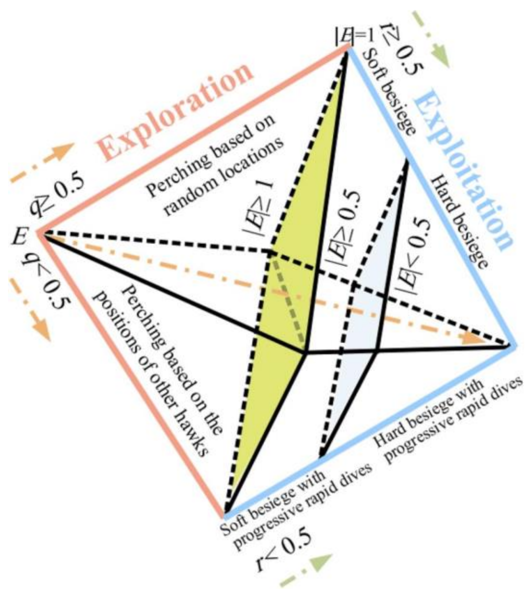

Fig. 3. Phases of Harris Hawks Algorithm

6. Results

The system was modeled in two ways to observe the effects of speed control optimization in a Brushless DC motor.

- Manual control
- Auto-control with PI controller

The obtained results are discussed below. Furthermore, a comparative analysis has been done between the results of both systems.

Manual Control

In this system, Brushless DC motor, 3-phase inverter, and its rotational logic were modeled without PI controller and PWM generator. The only way to control the motor's speed is by manually controlling the DC voltage supply.

The higher the DC voltage supply greater will be the motor's speed as observed in fig. 4. When the DC supply was 24V, the measured speed of motor was around 210 RPM. Similarly, when supply was 50V, the measured speed was around 430 RPM. This method is not practical since manual control would require 24/7 monitoring of the motor's desired speed. The modeled system is shown in fig 4. This drawback necessitates the use of a PI controller for automated speed controlling of the BLDC motor.

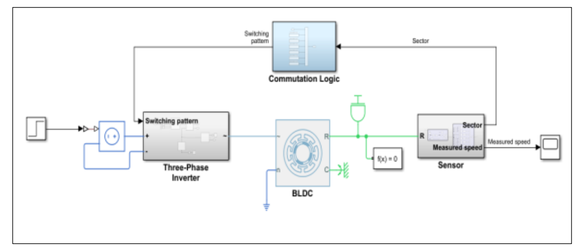

Fig. 4. BLDC Simulation on Matlab without PID

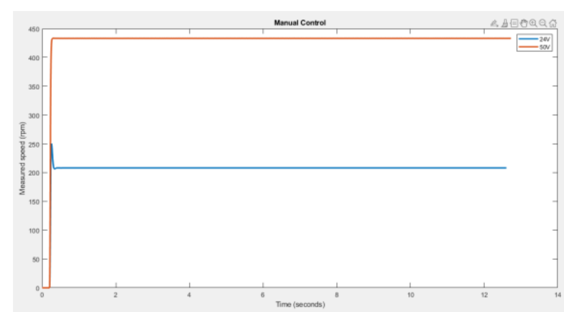

Fig. 5. Manual Control BLDC Simulation

Automatic Control With PI

PI controller was incorporated to measure the error between demanded and measured speed. This steady state error is then eliminated by supplying the required voltage (duty cycle) to the PWM generator. This model was simulated on MATLAB; motor parameters were taken according to the selected motor's data sheet. Varying demanded speed was given as input to the comparator, which compares the value of the required speed with the measured speed coming from a closed feedback loop, as seen in figure 6.

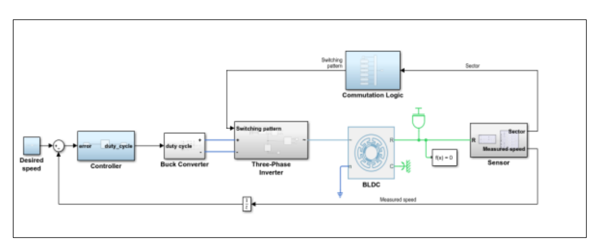

Fig. 6. BLDC Simulation on Matlab with PI Controller

Simulink's repeated sequence block was used to create a varying demanded speed scenario. It was set to be varied every 5 seconds to observe controller's response through measured speed. It was observed that the system's response time was rapid to demanded speed variations as shown in figure 7.

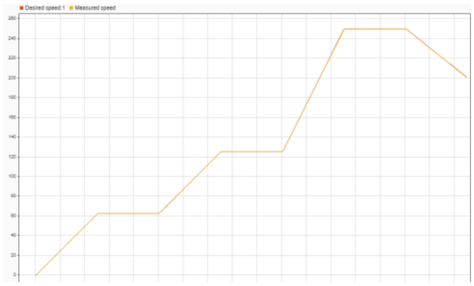

Fig. 7. Automatic Control BLDC Simulation

7. Conclusion and Future Implications

Simulink was used to successfully model and simulate the system presented in the initial proposal. A 250W BLDC motor was selected whose trapezoidal back EMF was used to sense the rotor position. Commutation logic was created using designated sectors of rotors monitored with a Hall sensor. This commutation logic was used in a 3-phase MOSFET-based inverter circuit that converted DC-AC voltage and energized two output phases at the same time to ensure proper motor rotation. The system's response was overdamped, which can only be controlled by varying supply voltage manually in case of varying loads.

Therefore, PI controller was developed for the motor's speed control. An automatic model based tuning method was applied to the PI controller to determine the controller constants. A Pulse Width Modulation (PWM) generator was used to generate different voltages for different demanded speeds through duty cycle variation to control the DC voltage supplied to the inverter. This duty cycle variation is done through PI controller, which converts the error difference into the required duty cycle to eliminate the steady state error. This modeled system was simulated successfully, resulting in a rapid system response to variable speed demands.

8. Practical Implementation

This project should be practically implemented in the future in order to verify the computed results in real time. Moreover, this project was completely based on MATLAB simulations which indicate that the results might be different if a prototype is designed in a practical world where the computed parameters will be subjected to multiple intermittent practical constraints.

Optimized Algorithm

Multiple algorithms like probabilistic, heuristic, and meta-heuristic algorithms have already been developed. Harris Hawks algorithm was just one implementation to find the tuned parameters in this project. There are multiple other algorithms that can be tested on this system in the future, like particle swarm optimization, Ant Lion Optimization algorithm, gradient descent algorithm, leader Harris Hawk's algorithm, etc. might be able to produce more optimized results than the HHO.

Fractional Order PI Controller

A fractional version of the PI controller called as FOPI controller has been designed as an advancement of PI controller. A comparative analysis of PI and FOPI controllers can be made by checking its performance on controlling a BLDC motor.

Learning can provide exceptional assistance in improving the reliability of existing power systems.

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