An R-OPID controller for speed control of Brushless DC motors for energy conservation of electrical machines

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Abstract: Brushless Direct Current (BLDC) motors owing to their high reliability, low maintenance, high efficiency, along with numerous other benefits are extensively utilized in servo-robotic positioning fans, actuators, traction, together with blowers. In numerous industrial processes, one amongst the important aspects would be the BLDC motor's Speed Control (SC). But still, the effectual SC in addition to current control of BLDC motor is hard. Thus to enhance the SC performance, numerous schemes were introduced for energy conservation of electrical machines, but all in vain, they are not suitable for producing better outcomes. To trounce such drawbacks, this work proposed an R-OPID controller for BLDC motors' SC. In the proposed methodology, the BLDC motor's mathematical model is explained. After that, the R-OPID controller takes care of the SC. And the AEHO algorithm optimizes the PID controller parameters. Finally, the proposed work's performance is contrasted to the existing system in experimental analysis. The proposed system gave a better performance than the existing methodologies.

Key words: *Rule based optimized proportional integral Derivative (R-OPID) controller, Adaptive Elephant Herding Optimization (AHEO) algorithm, Brushless DC motor and speed control.*

1. INTRODUCTION

In the precedent years, to improve the flexibility along with the constancy of manufacturing, a selection of control methods was employed, for instance, controlling the equipment's speed, varying the gear ratios or pulleys, in addition, utilizing hydraulic drives [1]. Electric motors encompass broad applications in fields like business, industry, public service, and household electrical appliances, powering several equipment including water pumps, wind blowers, compressors in addition to machine tools [2] and BLDC comes under them. The electric motors consume a considerable amount of complete national power consumption in industrially developing and developed nations [3]. In order to enhance life's quality, electrical energy consumption is globally increasing [4].

Electrical motor drives stand as a key aspect for attaining the energy consumption objective. Furthermore, scalar control can be regarded as a legitimate solution since several applications don't need high performance for the handling of such electrical drives [5-7]. The industrial area has utilized around thirty-seven percent of the earth's entire delivered energy, which is more compared to any other sector. A disparate group of the industrial sector such as agriculture, manufacturing, mining, as well as construction consumes energy for processing, assembly, lighting, and space conditioning [8].

For disparate industries like the iron-steel industry, petroleum industry, textile industry, small and medium scale industries, cement industry, and manufacturing industry, a lot of analytical studies were done on energy auditing or conservation. Along with these, more studies have emphasized on using energy conservation techniques to enhance energy efficiency [9]. Thus, from the studies, it can be understood that the utilization of rigid and efficient types of drives could save a significant quantity of energy [10]. The speed controllers such as Variable Speed Drives and Variable Frequency Drives (VFDs) allow the electric motor's speed to be changed.

The paper is planned as Section 2 surveys the associated work regarding the proposed technique. Section 3 shows a concise discussion concerning the proposed work. Section 4 analyses the investigational results. Section 5 surmises the paper.

2. RELATED WORK

Krishanu Nath *et al.* [11] attempted to attain the SC for an independently excited DC motor centered on the field along with armature control methods at the maximum efficiency condition. Artificial Neural Network (ANN) was selected for the preferred task since any non-linear data could well be fit in it. This work is executed in the MATLAB platform. After that, an independently excited DC motor was joined with the neural network in which some simulated outcomes were taken for the verification of the task. The simulation was done in Simulink. In addition, for disparate load torques in addition to reference speeds, the output curves were attained.

Ramesh S *et al.* [12] presented an energy conservation strategy in which a VFD was retrofitted in the motor drive of the hydraulic clamp system for varied the motor's speed at disparate load conditions and lessens the power consumption. The VFD centred hydraulic pumping system was contrasted to the existing circuit with respect to flow characteristics along with electric power consumption; in addition, the outcomes were provided. Subsequent to VFD implementation, it was established that the hydraulic pumping system functioned at a lower follow rate and also consumed less power contrasted with an existent hydraulic clamping system.

Muhammad R. A. R. Santabudi *et al.* [13] presented the execution of the Sliding Mode Control (SMC): ‘2’-Steps (Linear Matrix Inequalities) LMI Approach on a BLDC motor. ‘2’-Steps LMI approach was a technique to model an SMC controller thus it was guaranteed that the constancy of the closed-loop system in the Lyapunov sense. For solving the entire LMIs, the approach utilized the MATLAB LMI Solver Toolbox. The simulation that operated on MATLAB was stable yet still encompassed steady-state error. The system’s stability was proved by the implementation result although it still encompassed chattering issues on account of high-speed frequency switching nature in SMC.

Mirela Dobra *et al.* [14] presented a quick as well as effectual means of reaching a functional setup of BLDC Permanent Magnets (PM) motor velocity SMC. A concise discussion was prepared on the BLDC-PM motor mathematically. The SC loop aimed at the electric drive with BLDC-PM was tested in respects to load torque variation which was presumed as the additive uncertainty. The TMS320F28335 micro-controller, which encompasses special processing, was used by the loop control functioning for electric drive signals. The last objective was to authenticate a quick process to set-up the speed/position control loop with a simple preliminary SMC algorithm. Test outcomes utilized the disparate valued parameters of the SMC that supported the swift prototyping procedure.

Surabhi Agrawal and Vivek Shrivastava [15] elaborated on the Particle swarm optimization (PSO) technique along with a fuzzy controller that enhanced the electric vehicle BLDC motor’s speed with the decline in a gain of PI Controller. The PI Controller’s parameters were tuned by the PSO. In MATLAB/Simulink, the system was modeled and simulated. Compared the Fuzzy Logic Controller (FLC) controlled electric vehicle motor with PI controller and PSO Optimizes electric vehicle motor with the fuzzy controller. Motor’s speed was negative as well as the error was extremely high in the absence of FLC. But, contrary to the preceding one the motor’s speed was enhanced and error was reduced for the FLC and PSO optimized PI Controller.

3. PROPOSED METHODOLOGY

In a lot of industrial applications, the chief reason for the employment of BLDC motor will be the ease of control along with high power density. Generally, the Power Semiconductor Bridge controls the BLDC motors. BLDC motor will be the best choice in case of high power, high reliability in addition to high-efficiency applications. This paper proposed an R-OPID controller for SC of BLDC motors for the energy conservation of electrical machines. Here, the mathematical description of the BLDC motor is explained. Next, the R-OPID controller controls the speed. In the R-OPID controller, the AEHO algorithm optimizes the PID parameters. The proposed methodology's block diagram is exhibited in Figure 1,

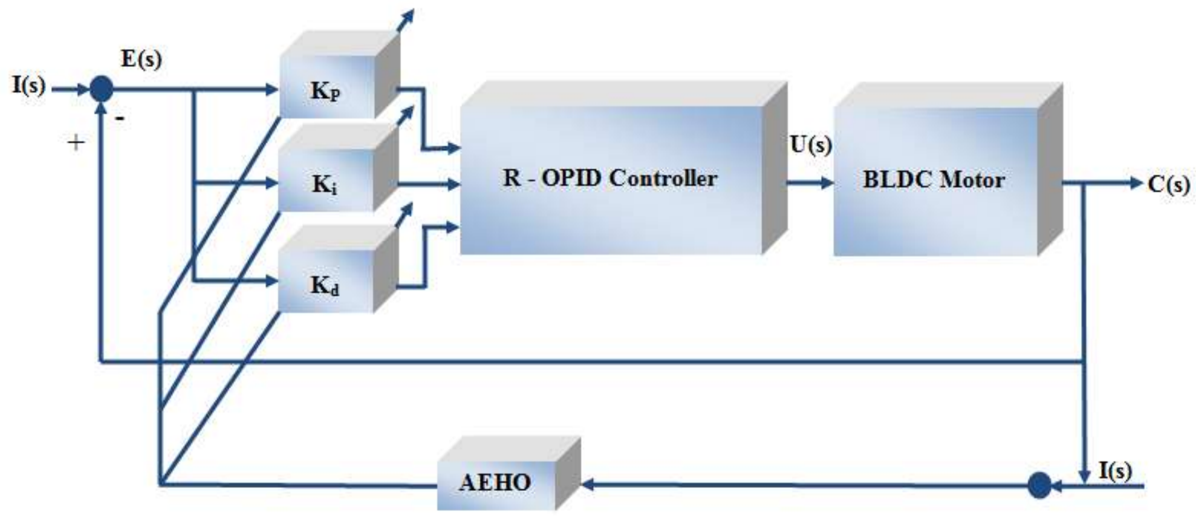

Figure 1: Block diagram for the proposed methodology

In Figure 1, the term $I(s)$ denotes the reference input, $E(s)$ represents the controller receives error signals, $U(s)$ produces the control signal and $C(s)$ signifies the controller output.

3.2 Brushless DC Motor

For attaining the commutation aimed at brushed DC motors, Mechanical rotors along with brushes are utilized commonly. With disparate parts of the commutator that is rotating, the stationary brushes will meet. The electrical-power flows via the armature coil that is nearer to the stationary stator (PM) since the commutator along with the brush system forms a collection of electrical switches. In BLDC motors, PM rotate and also the armature stays static whereas the electromagnets remain stationary. Hall Effect sensors are employed as non-contact position sensors rather than a mechanical commutation system centred on brushes for

BLDC motors. It detects the rotors' position to be the commutating signals. The motor's electric as well as mechanical part is respectively described as,

$$v_{app}(t) = S_r(c(t)) + I\frac{dc(t)}{dt} + v_{emf}(t) \quad (1)$$

$$L\frac{d\alpha(t)}{dt} = \sum \eta_i \quad (2)$$

Where, $v_{app}(t)$ implies the applied voltage, $c(t)$ indicates the current of the circuit, $v_{emf}(t)$ is the counter electromotive force, I is the stator's inductance, $\alpha(t)$ indicates the angular velocity, and S_r is the stator's resistance. Equation (2) implies that the inertial load ' L ' times the angular acceleration is equivalent to the sum of the entire torques η_i. In this BLDC motor, the Rule-based optimized Proportional Integral Derivative (R-OPID) controls the speed. By utilizing this controller, energy conservation is obtained effectively, which is explained in the below section.

3.2 Rule-based Optimized Proportional Integral Derivative (R-OPID) controller

A controller controls the speed of any system using a BLDC motor and also conserves the energy. For which, the proposed method uses the R-OPID controller. The most broadly applied controller in disparate industries is the Proportional Integral Derivative (PID) controller. This controller is simple to design. This is popular on account of the low order transfer matrices and its simplicity. A high level of knowledge is not needed by this control algorithm. It lessens the steady-state error to ameliorate the responses. The proposed method employs the rule-centred PID controller to augment the PID controller's quality. The performance of the PID controller is enhanced by the parameter selection, which is performed by the Adaptive Elephant Herding Optimization (AEHO) algorithm. By taking $\Delta\psi_i$ as the BLDC motor's output, the control vector for the traditional PID controller (Q_i) is given by:

$$Q_i = K_p\,\Delta\psi_i(t) + K_i\int_0^t \Delta\psi_i(t)dt + K_d\,\Delta\psi_i(t) \quad (3)$$

Where, K_p, K_I, and K_d represents the proportional, integral in addition to derivative parameters, respectively. The parameters K_p, K_I, and K_d are ascertained by an assortment of fuzzy rules of the form:

On the off-chance that the $\Delta\psi_i$ is A_i and $\Delta(\Delta\psi_i)$ is B_i, then

$$K_p = C_i \tag{4}$$

$$K_i = D_i \tag{5}$$

$$K_d = E_i \tag{6}$$

Where A_i, B_i, C_i, D_i and E_i signify the fuzzy sets on the equivalent supporting sets. In the proposed R-OPID controller, the Membership Function (MF) sets intended for the K_p, K_i, and K_d are stated as triangular partitions. The partitions are i) Positive Big (PB), ii) Positive Small (PS), iii) Zero (ZO), iv) Negative Big (NB) and v) Negative Small (NS). The MF sets for $\Delta\psi_i$, $\Delta(\Delta\psi_i)$ is the selfsame as MF sets. All the three parameters like K_p, K_i, and K_d are optimized by means of using the AEHO algorithm, here the trajectory error function is considered as the fitness function. The AEHO algorithm is elucidated as follows,

Elephants naturally are social animals encompassing some intricate structures consisting of females and calves. Several clans of elephants form a group with matriarch leadership. These clans mostly comprise one female, its calves and sometimes certain related females. Mostly, the groups are formed by female elephants since they prefer to live with their family whereas the male tends to leave the group once they are all grown up and live alone. However, these Male Elephants (ME) stay in touch with their families by low-frequency vibrations. In Elephant Herding Optimization (EHO) algorithm, the Genetic Algorithm (GA) which is known as AEHO takes care of the position updation. AEHO considers the under-mentioned presumptions.

- The elephants are grouped into clans containing a fixed number of elephants.
- A fixed number of ME live alone by leaving their clan.
- Each clan follows the matriarch leadership.

In the herd, the position of the matriarch encompasses the best solution whereas that of the ME encompasses the worst solutions. The updating procedure of EHO has been shown below.

The entire population (elephant) is grouped into j clans. As per matriarch, each member n of clan m moves, where matriarch is the elephant c_m that encompasses the best fitness value in generation, which is exhibited in equation (7).

$$o_{new,c_m,n} = o_{e_m,n} + o\left(o_{best,c_m} - o_{c_m,v}\right) \times r \quad (7)$$

Here, $o_{new,c_m,n}$ represents the elephant n's new position in clan m, $o_{c_m,n}$ is the old position, o_{best,c_m} implies the best solution of clan c_m, $o \in [0,1]$ is algorithm's parameter which determines the influence of the matriarch and r is the random number utilized to ameliorate the diversity of the populace in the upcoming stages of the algorithm.

The best elephant's Position in clan o_{best,c_m} is updated by using the equation (8).

$$o_{new,c_m} = \delta \times o_{center,c_m} \quad (8)$$

Here, $\delta \in [0,1]$ implies the second parameter of the algorithm that controls the effect of the o_{center,c_m}, which is defined as given by the equation (9).

$$o_{center,c_m,d} = \frac{1}{n_{e_m}} \times \sum_{j=1}^{n_{c_m}} b_{c_m,j,d} \quad (9)$$

Here, $1 \le d \le D$ is d^{th} dimension and D is total dimension of the space and n_{c_m} indicates the total elephants in clan m.

Elephants that leave the clan are employed to model exploration. In every clan z, some elephants that have the worst values (objective function) are shifted to new positions as per the equation (10).

$$o_{worst,e_m} = o_{\min} + \left(o_{\max} - o_{\min} + 1\right) \times rand \quad (10)$$

Here $o_{\min}$ and $o_{\max}$ are lower as well as upper bound of the search space respectively. Parameter $rand \in [0,1]$ is random number chosen from uniform distribution.

Crossover and mutation operations are executed in order to make more effectual optimization after the elephants' positions are calculated. There are disparate types of crossovers wherein two-point crossovers are selected, where dual points are picked from the parent chromosomes. The genes in-between the two points are interchanged within the parent chromosomes which in turn bring about children chromosomes. The crossover points are ascertained as follows,

$$x_1 = \frac{|o_{new,c_m}|}{3} \tag{11}$$

$$x_2 = x_1 + \frac{|o_{new,e_m}|}{2} \tag{12}$$

Where, x_1 and x_2 denotes the '2'-crossover points. After that, some genes as of every chromosome are replaced with new ones, which are randomly generated ones that does not form any repetition within that chromosome and this is termed as the mutation. Until better solutions are obtained, this process recurs. The AEHO algorithm's Pseudo code is exhibited in Figure 2,

Input: K_p, K_i, and K_d
Output: optimized parameters

Begin
  Initialization Set generation counter $t = 1$,
    Set Maximum Generation M_G
    Population $X_i = \{X_1, X_2, ..., X_n\}$
  While $t < M_G$ **do**
    Sort all the elephants according to their fitness
    for all clans c_m in the population **do**
      for all elephants j in the clan c_m **do**
        Update $o_{c_m,j}$ and generate $o_{new,c_m,j}$ by using,
        $o_{new,c_m,j} = o_{c_m,j} + \alpha(o_{best,c_m} - o_{c_m,j}) \times r$
        if $o_{c_m,j} = o_{best,c_m}$ **then**
          Update $o_{c_m,j}$ and generate $o_{new,c_m,j}$ by using,
          $o_{new,c_m} = \delta \times o_{center,c_m}$
        end if
      end for
    end for
    for all clans c_m in the population **do**
      Perform crossover and mutation
      Replace the worst elephant in clan c_m by using
      $o_{worst,c_m} = o_{min} + (o_{max} - o_{min} + 1) \times rand$
    end for
    Evaluate population by the newly updated positions.
    $t = t + 1$
  end while
  return the best solution among all population
End

Figure 2: Pseudo code for AEHO

4. SIMULATION RESULTS

Here, the proposed system's performance is analyzed. The proposed SC of BLDC motors for energy conservation of electrical machines based R-OPID controller is functioned in the working platform of MATLAB Simulink. The change of speed is given as the input to the R-OPID controller, which can be computed by comparing the reference speed with actual speed. The optimized data is selected by the AEHO algorithm. Thus, it can control the BLDC motor's speed and conserve energy. The simulation outcomes are performed to evaluate the performance of BLDC motor in respects to stator current, torque, etc. The proposed system's simulation circuit is exhibited in Figure 3,

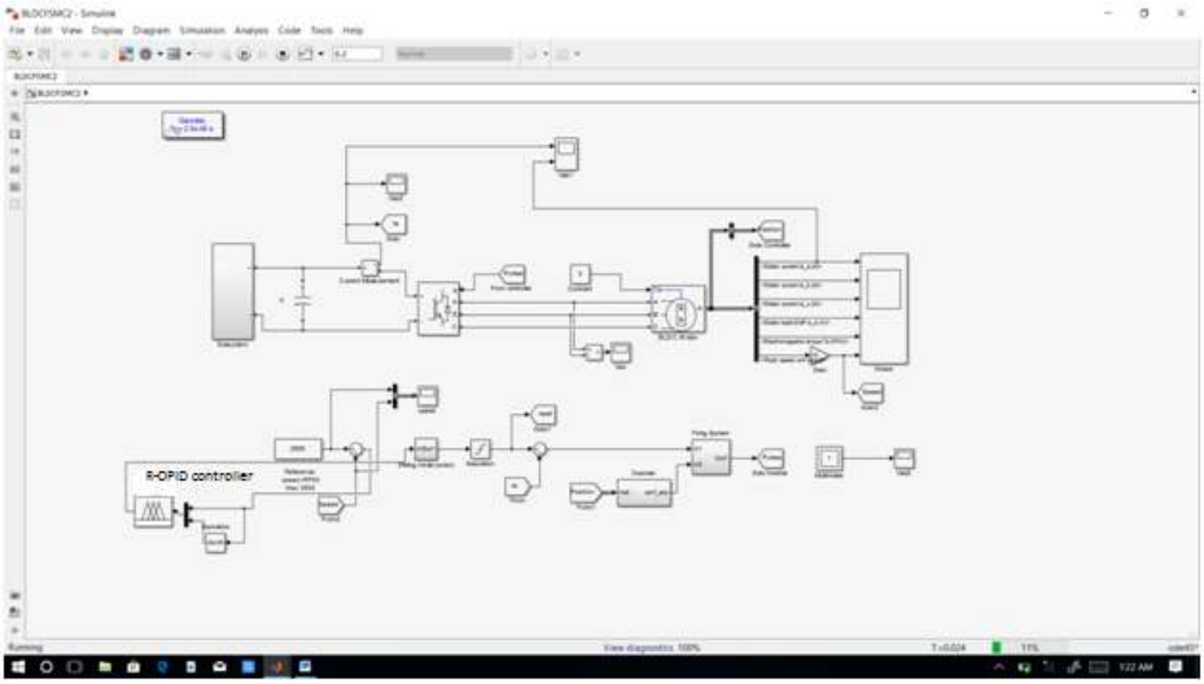

Figure 3: Matlab simulation of BLDC motor control using R-OPID Controller

The DC voltage and stator current of the BLDC motor is exhibited in Figure 4,

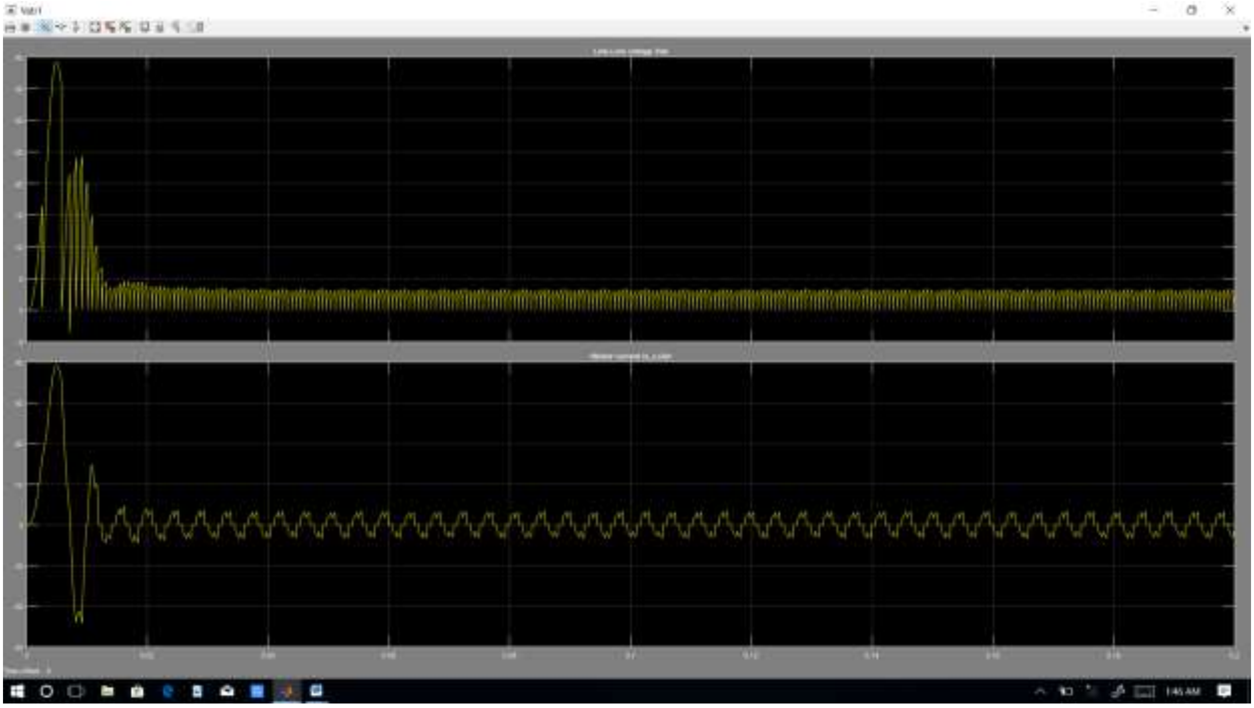

Figure 4: DC voltage and stator current of BLDC motor

Next, the reference speed of the BLDC motor is compared with actual speed is depicted in Figure 5.

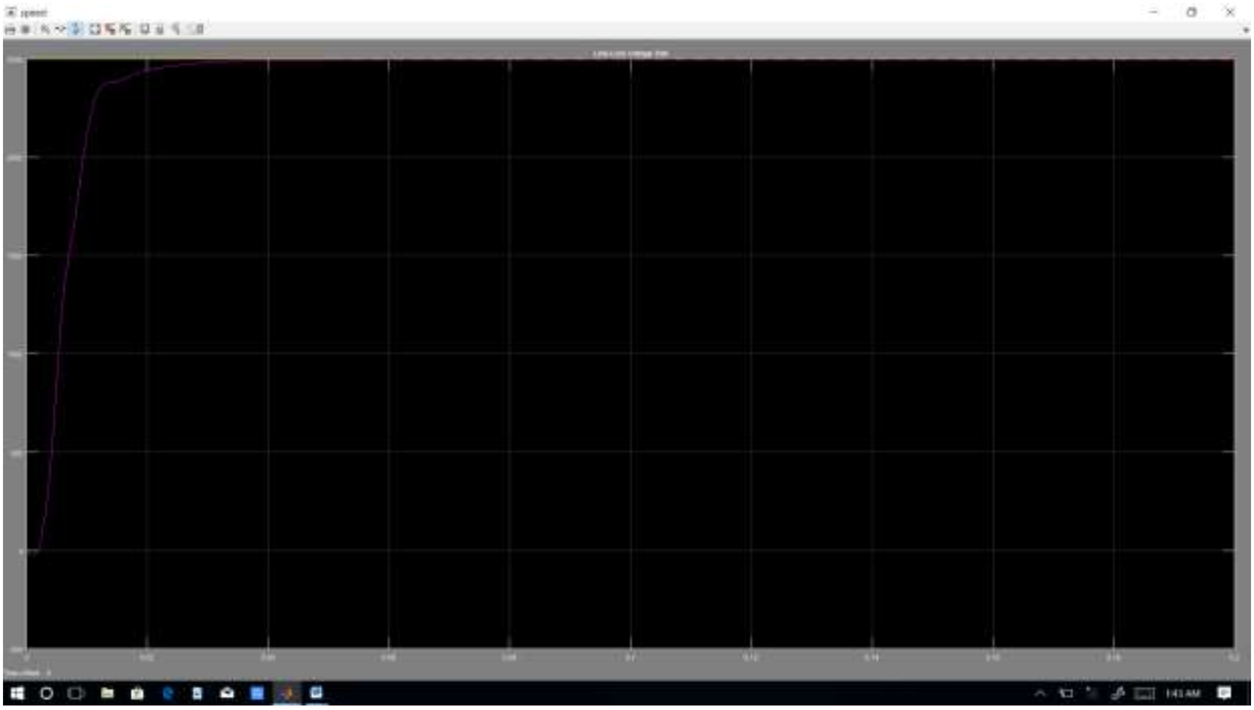

Figure 5: Reference speed Vs actual speed attainment of BLDC motor using fuzzy logic controller

Figure 6shows the line to line voltage of BLDC motor and Figure 7 shows the line to line voltage at the inverter of BLDC motor respectively.

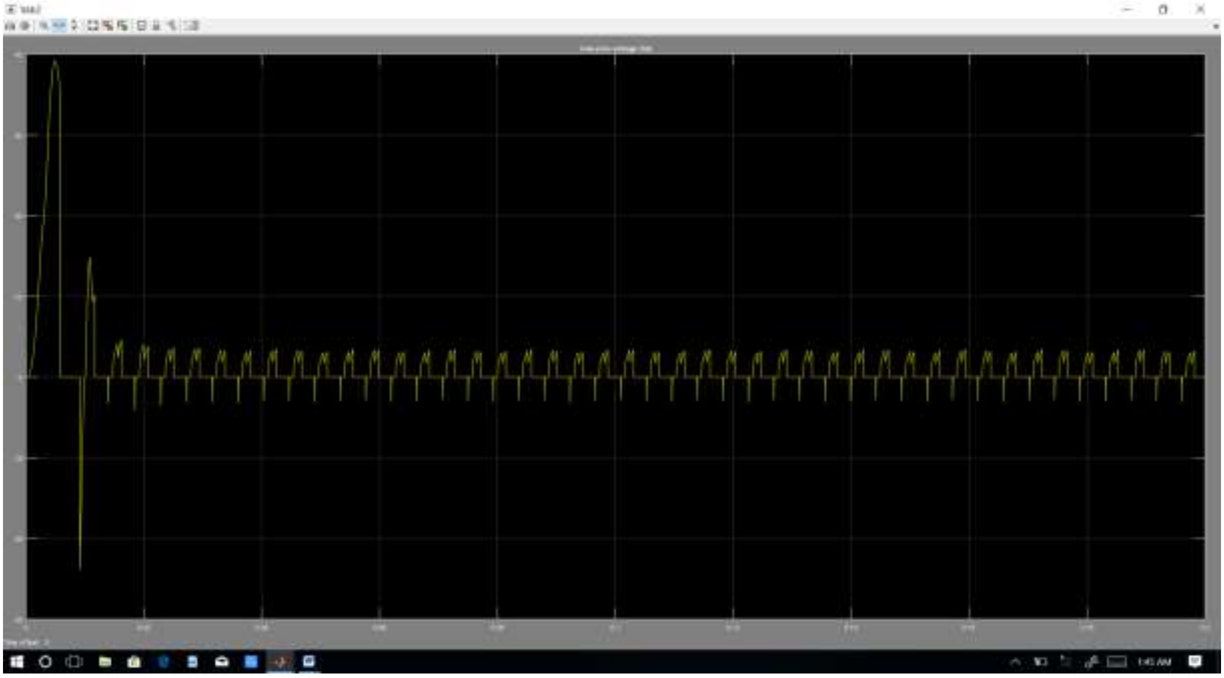

Figure 6: Line to line voltage of BLDC motor

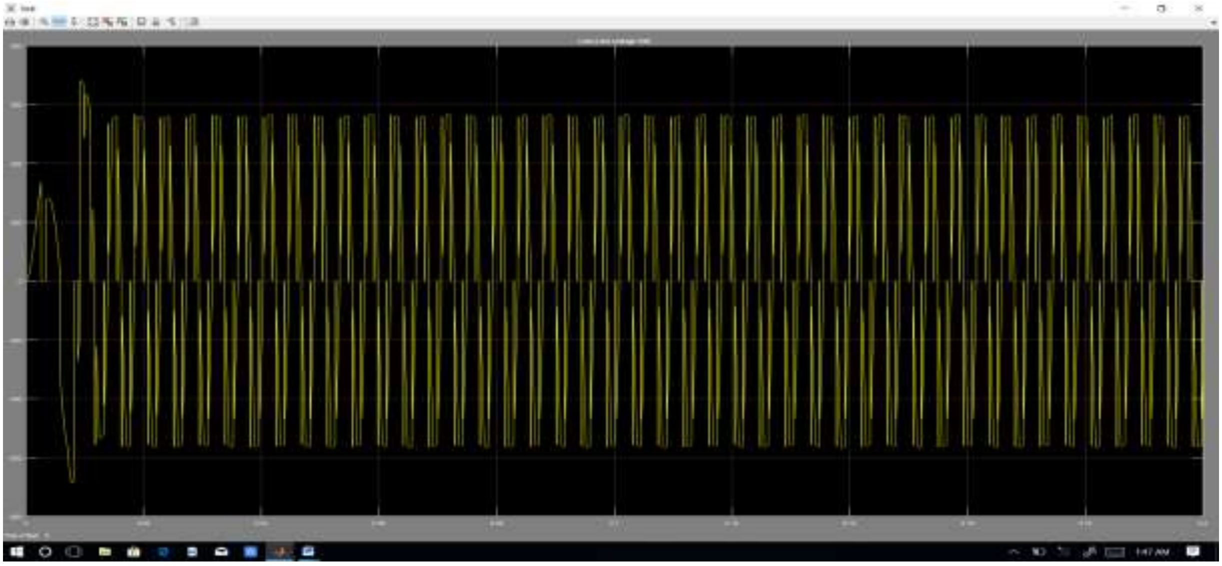

Figure 7: Line to line voltage inverter side of BLDC motor

5. CONCLUSION

One type of permanent synchronous motor, that is being applied in numerous industrial and commercial applications is the BLDC motor, which is because of its extensive pros including energy saving. The PID among various controllers is the best druthers for SC of BLDC motor. In this paper, the R-OPID controller is presented for SC of BLDC motors. Along with it, optimal input data are selected by applying the AEHO algorithm. The overall experimental system is simulated in MATLAB Simulink. From the simulation results, the performance of the motor was analyzed in terms of stator current, torque, and line to line voltage.

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