Real-Time Implementation of BLDC Motor-Based Intelligent Tracking Control Fed from PV-Array for E-Bike Applications

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Abstract: - The essential goal of this research is designing and modeling a speed and position tracking system for driving an electric bike (e-bike) motordrive. This motor is a brushless DC (BLDC) motor as a high-performance drive. It is supplied from twin electric sources to drive it and charge the storage elements (i.e., batteries, super-capacitors, etc.). The first one is a renewable, neat, and clean source photovoltaic (PV) module and the second one is a pedal generator driven by the rider. The submitted design of the controllers is optimized to improve the system's dynamic stability. The artificial bee colony (ABC) as an artificial intelligent (AI) algorithm is suggested for searching the optimal gains of the proposed proportional-integral-derivative (PID) controllers by reducing the error of its fitness function. The system behavior is studied with that controller when directly feeding from the PV array with and without batteries. The response of the proposed technique - against dynamic troubles and PV oscillations such as irradiance- is also verified. Other evolutionary computational techniques - such as ant colony optimization (ACO) and genetic algorithm (GA)- have been compared with the behavior of the proposed controller to ensure high efficiency in optimized tuning of PID gains. Then, the proposed controller that gives a high performance will be executed in real-time by using OPAL-RT 4510 RT-simulator and rapid control prototyping.

Key-Words: - Artificial Bee colony (ABC), Brushless DC motor (BLDC), Electric Bicycle (E-bike), Intelligent Control, Photo-Voltaic (PV).

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1 Introduction

The interest in various different types of vehicles has grown over the last two decades, with the aim of reducing environmental pollution, achieving a smooth flow of traffic, and reducing the transportation cost. Electric powertrains and trams are environmentally friendly but are not economical for long driving distances compared with fossil-fuel engines. Despite the advantages of electric hybrid vehicles, which overcome the environmental problems, they cause traffic jams. Vehicles with small size, which do not occupy a large space, are preferably used to overcome the traffic congestion. In recent years, people have returned once again to the bicycle – especially electric bikes – as light electric vehicles in most places for all countries, [1], [2].

E-bikes are human-powered and require some level of physical traction effort. The market of e-bikes are rapidly growing, [3]. The electric bike has many advantages such as: getting fit, saving money and time, going faster, and further, having fun, and being environmentally friendly, [4]. But, up to now, in our Country (Egypt), there are some constraints for e-bikes to be the first local transportation. Such constraints are: high cost, limited speed, storage-element charging, control techniques, etc., [5].

Several types of research are introduced to develop the production of those bikes and reduce the cost. Some researchers try to make them as smart and intelligent as, [6], [7], [8]. Also, there are several efforts to develop the charging processes for the batteries. Some proposed wired charging as in, [9], [10]. In addition, wireless or inductive power transfer (IPT) for battery charging is introduced as a more comfortable and safer method as in, [11], [12], [13]. Others suggested a renewable and green energy resource for the charging process such as, [12], [14]. Other researchers are interested in regenerative braking as in, [15]. But, on the other hand, several efforts from researchers went hand in hand with the most important part of the system which is the electric-motor drive. A review of the electric-bike driving systems concluded that the following motors can be used such as: permanent-magnet synchronous (brushless DC and AC), and switched reluctance motors (3 or 4- phases), [16], [17], [18], [19], [20], [21].

Among all, the Brushless DC (BLDC) motor is suitable because it has many features. Its performance is high, more durable, and energy-saving with high torque, [22]. So, many researchers are introduced to optimize all variables of that host drive by proposing several control techniques such as in, [23], [24].

The gains of the classical PID controllers can be designed by means of classical methods such as the Ziegler-Nichols (ZN) formula, Root locus method, pole placement technique, and Routh- Hurwitz criterion. Most of these techniques failed to optimize the performance of this drive. So, intelligent control techniques are suitable for achieving optimality.

Now, artificial intelligence (AI) algorithms such as genetic algorithm (GA), Particle Swarm Optimization (PSO), or germ of intelligence (as bacteria foraging (BF) and ant colony optimization (ACO)) algorithms have been considered new techniques for optimizing PID-controller gains, [25], [26], [27]. Another artificial intelligence technique was proposed in 2005, known as the Artificial Bee Colony (ABC), [28].

So, this research proposes an ABC algorithm to compute the PID controllers' gains for optimization. This proposed controller is called ABC-PID. As a result of repeated incidents of children riding electric bicycles by themselves, this robust controller will be proposed in a tracking system for a bike-like robot and unmanned e-bike. This auto-bike is driven by a BLDC motor fed from PV as a neat renewable energy source and controlled by using this proposed intelligent controller.

A multi-input single output DC/DC converter is proposed for power management to the drive. Three DC sources are saved to the motor: PV, DC human-pedal generator, and storage elements (i.e., batteries and/or supercapacitor).

The proposed system is modeled and simulated with the help of the Matlab/Simulink and m-functions are written as m-files for the ABC algorithm. Simulation results are demonstrated with the proposed rig for studying the behavior of the system. Furthermore, several pre-scribed reference-speed paths are selected for the robustness test of that controller against dynamic fluctuation and PV-irradiance variation. A comparison study is implemented among other intelligent controllers such as genetic and ACO algorithms. Then, the optimal controller will be executed in real-time with the help of the OPAL-RT 4510 simulator and rapid control prototyping (RCP).

This manuscript is planned as: Section 1 includes an introduction and Section 2 introduces the overall proposed system. Section 3 and Section 4 elaborate on the proposed intelligent algorithm with the simulation results. The RT-implementation is shown in section 5 followed by the final conclusions with recommendations in the end through section 6.

2 The System under Study

Figure 1 demonstrates the system under study. It implies: a solar supply, converter for power maximization, inverter, BLDC-host motor with the controller, and e-bike – with the hybrid human pedal.

2.1 PV-Array Mathematical Model

The mathematical model of the PV-array can be computed from those equations, [29], [30].

$$I_A = N_p I_{irr} - I_o \left[e^{\left(\frac{q\left(V_A + I_A \frac{N_s}{N_p} R_s \right)}{N_s n k T} \right)} - 1 \right] \frac{V_A + I_A (\frac{N_s}{N_p}) R_s}{\frac{N_s}{N_p} R_p} \quad (1)$$

The current module will be obtained as:

$$I_M = I_{irr} - I_o \left[e^{\left(\frac{q(V_M + I_M N_s R_s)}{N_s n k T} \right)} - 1 \right] - \frac{V_M + I_M N_s R_s}{N_s R_p} \quad (2)$$

The cell current can be determined as:

$$I = I_{irr} - I_o \left[e^{\left(\frac{q(V + I R_s)}{n k T} \right)} - 1 \right] - \frac{V + I R_s}{R_p} \quad (3)$$

Where,

I_{irr} irradiance current (A), I_o the saturation current of the diode (A), V, V_M, V_A is the voltage of the cell, module, and array voltages (V), $q = 1.6 \times 10^{-19}$ (C), $K = Boltizmann\ constant$=1.3806503$\times 10^{-23}$ (J/K), R_s, R_p the resistance of series and parallel paths (Ω) $N_s N_p$ are series and parallel cell numbers, and T is the temperature of the cell (ºK).

2.3 The Host-BLDC Motor Mathematical Model

The state-space equation is used to represent the mathematical model of the host BLDC-motor as, [31]:

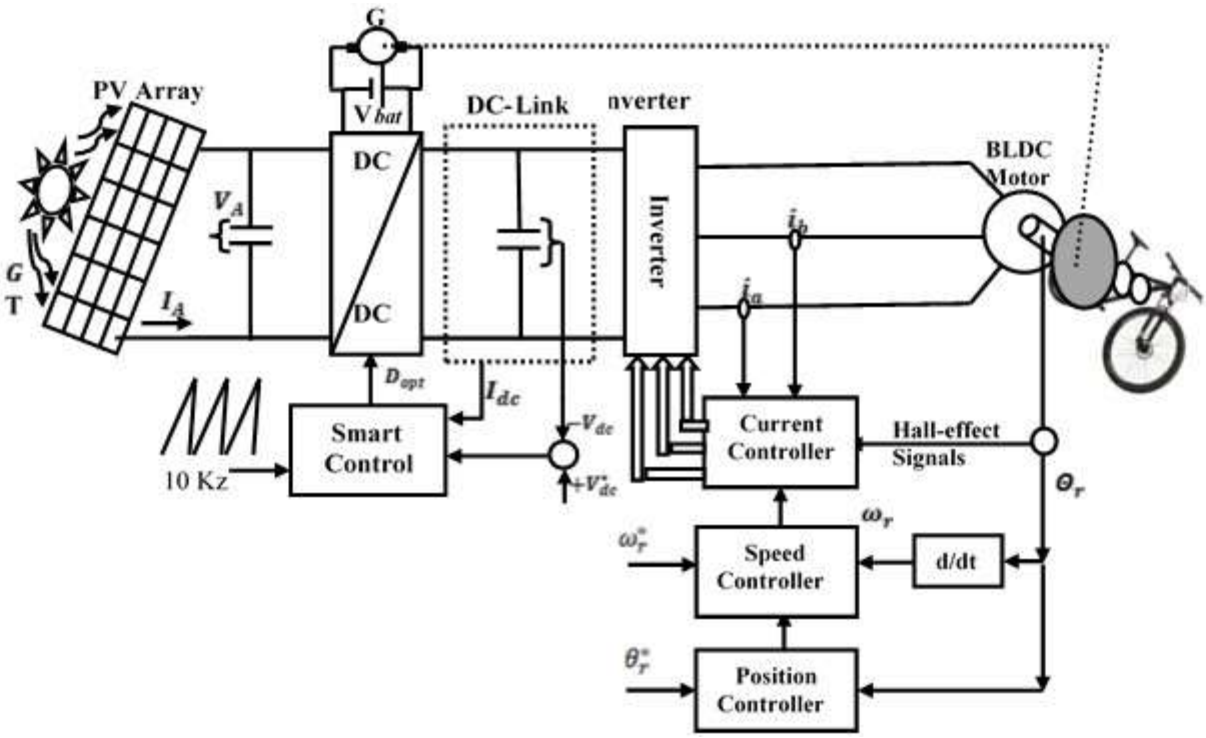


Fig. 1: The proposed system

$$p\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1/(L-M) & 0 & 0 \\ 0 & 1/(L-M) & 0 \\ 0 & 0 & 1/(L-M) \end{bmatrix} . \left[\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right] \quad (4)$$

The motor's internal torque is determined as:

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_r \quad (5)$$

The motion dynamic equation is given by:

$$p\omega_r = (T_e - T_L - B\omega_r)/J \quad (6)$$

Where, e_a, e_b, e_c are back emf's in (V), L is self-inductance (H), v_a, v_b, v_c are phase voltages (V), i_a, i_b, i_c are phase currents (A), T_L is the load torque in (N.m), J is the motor inertia (Kg.m^2), B is the friction coefficient (N.m.sec), and ω_r The motor speed (rad/sec).

2.3 Multi-input single-output Boost Converter

This research uses the boost converter with 3-voltage supplies: battery and /or supercapacitor, solar PV, and the DC-pedal generator, [32]:

$$V_o = V_i\left(\frac{1}{1-D_{opt}}\right) \quad (7)$$

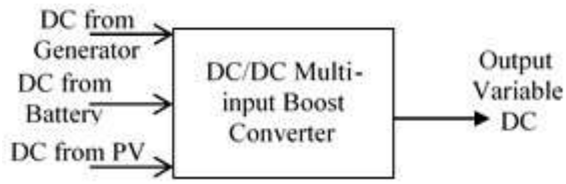


Fig. 2: Multi-input single output boost converter

Where, V_i , V_o are the converter input and output respectively, D_{opt} are the duty cycle that maximizes the output power of the PV generator. The Multi-input single-output boost converter is presented in Figure 2.

2.4 Position, Speed, and Current Controller

The position of the rotor for the drive can be detected by using a position-shaft encoder or can be estimated by using a sensor-less algorithm and the position will be differentiated to give the angular speed of the rotor (ω_r). The block diagrams for both speed and current controllers are demonstrated in Figure 3 and Figure 4, respectively. The hall-effect current sensors are used to sense the motor currents, [33]. The error signals of the stator currents are used as an input to the proposed optimal controller. Then, a hysteresis-band current controller is used to generate the IGBT switching patterns. This is clearly shown in Figure 4.

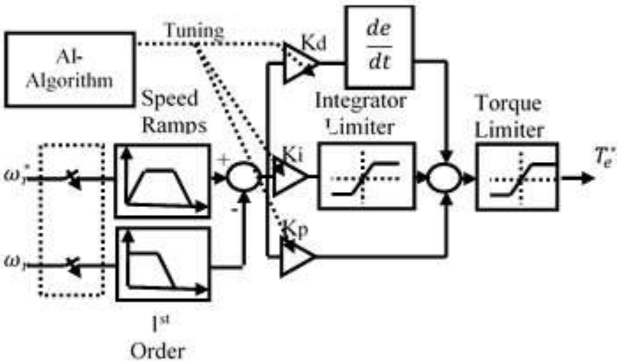


Fig. 3: The proposed speed PID-controller

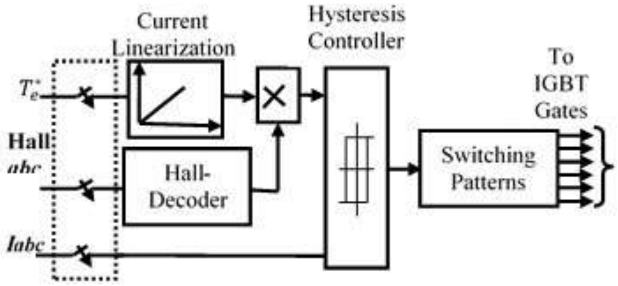


Fig. 4: Hysteresis current controller of motor

3 ABC-PI Proposed Controller

For proper tracking control, the BLDC motor should follow the preselected reference speed trajectory. So, a suitable and robust controller should be used. The artificial bee colony (ABC) algorithm is used to optimize the PID-controller gains. This controller is called ABC-PID. Integral time absolute error (ITAE) for the speed is used as an objective function for optimization, where:

$$J = ITAE = \int_0^{\infty} (t^* |e(t)|) dt \quad (8)$$

$$e = \omega_r^* - \omega_r \quad (9)$$

Where, ω_r^*, ω_r are the reference and actual speed. Minimize J: Subject to the constraint: $\phi_{\min} \le \phi \le \phi_{\max}$. As, ϕ represents $K_p, K_i K_d$.

3.1 ABC-Optimization Algorithm

The ABC optimization algorithm is an evolutionary computation that was proposed by, [34], [35]. It depends on three groups for bees: employed, onlookers, and scouts. All contribute towards randomly searching for food sources with higher amounts of nectars.

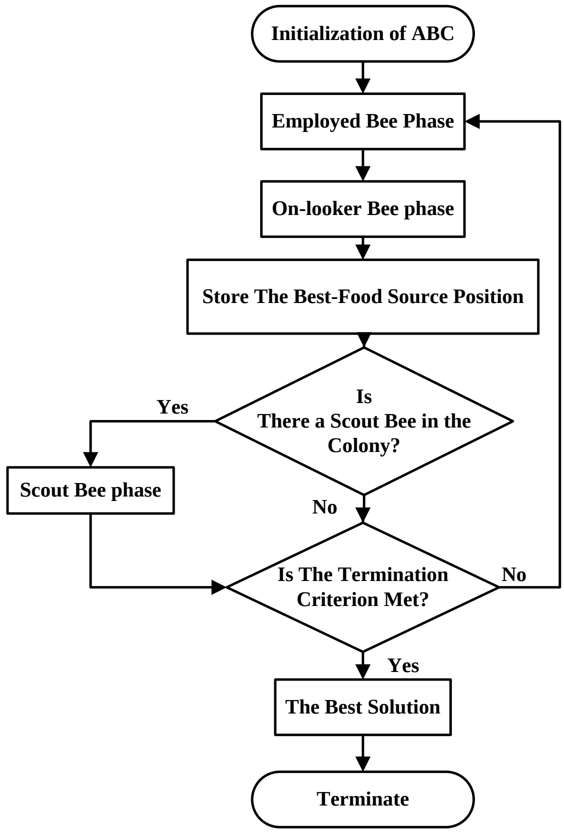


Fig. 5: ABC-algorithm flowchart, [39], [40]

The flowchart for the ABC algorithm is shown in Figure 5.

Through initialization, the size number of population SN and no. of food sources FS are randomly selected. $X_i, i = 1,2,....FS$ is the solution vector with C-dimension. Where, $C = [K_p \ K_i \ K_d]$. However, the following equation computes the food source position *i* for each cycle of one iteration: $X_i = (X_{i1}, X_{i2}, X_{i3},...)$. According to the probability value P_i, the onlooker group moves towards the food source X_i, where:

$P_i = \frac{fit_i}{\sum_{k=1}^{FS} fit_K}$, and the fitness value fit_i can be computed as: $fit_i = \frac{1}{1 + f(X_i)}$, the value $f(X_i)$ equal to J where J is the objective function of the system. In this work, J=ITAE can be computed from Eqns. (8) and (9). The best food source can be found by the onlooker in the region of X_i,

where:

$$X^j_{inew} = X^j_{min} + rand(0,1) * (X^j_{inew} - X^j_{min})$$

If the new position achieves a fitness value better than that obtained so far, the onlooker moves to it, other, it stays on the old one. This process is repeated according to the maximum number of iterations. Finally, the optimization is achieved.

For more details about ABC, please refer to, [36], [37], [38], [39], [40].

4 Simulation Results

The MATLAB Software package with both SIMULINK and M-function are used in simulating the overall proposed system, [41]. The PV array consists of two series modules $N_s = 2$, and a parallel one $N_p = 1$ for producing this power at 48 V-rated voltage and rated current 5.3 A. The PV array supplies 500-W to the BLDC by using Suntech STP270S-24_S. The overall characteristics and specifications are illustrated in, [42]. Also, the main parameters for the e-bike host BLDC motor are obtained from [43], and they are given in Table 1:

MATLAB/M-file was written to optimize the gains of the proposed controller that can be defined as:

$$\theta(FS,C) = \begin{vmatrix} K_p^1 & K_i^1 & K_d^1 \\ K_p^2 & K_i^2 & K_d^2 \\ .. & .. & .. \\ K_p^S & K_i^S & K_d^S \end{vmatrix} \quad (10)$$

Where C and FS are the numbers of parameters optimized and food sources. In this study, D and S are selected equal to 3 and 10 respectively. Other ABC- variables are tabulated in Table 2 (Appendix). Also, the gain parameters for the proposed algorithm are limited by these values:

$$\{0, K_{p\max}\}, \{0, K_{i\max}\}, \{0, K_{d\max}\}$$

And,

$$0 \le K_p \le 300, 0 \le K_i \le 50, 0 \le K_d \le 1.0$$

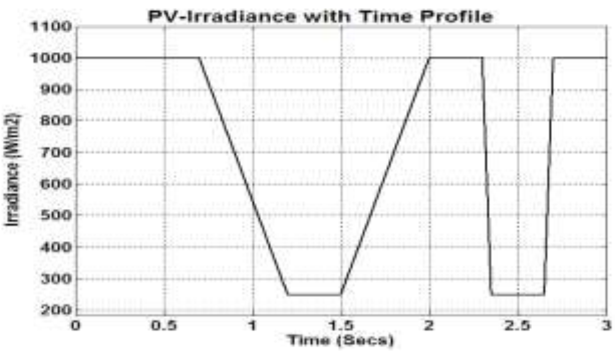
The value of the load torque is considered as (T_L = 5 N.m) and the bike is supposed to move forward, backward, hill-climbing with regeneration, and in special tracks. So, the motor rotates in four-quadrant operation and should be a high-performance drive with robustness. To test the controller robustness against the dynamic and PV disturbances, more position and speed tracks (sinusoidal, step-stairs, etc.) are selected. In addition, the irradiance of the PV array is randomly selected and its value ranges from 200 to 1000 (W/m²). The simulation results are firstly obtained when the motor is directly fed from a solar supply via a converter and then it is supplied only from the storage battery.

Table 1. Nameplate data of the BLDC-Motor, [43]

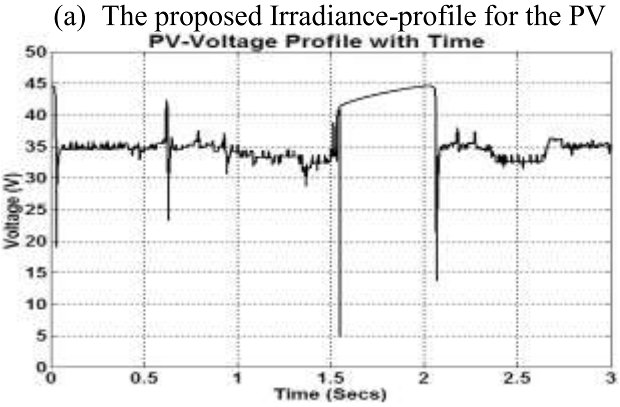
Parameters of Motor	Nominal values
Motor Nominal Power (Watts)	485
Machine Poles	2
DC-Rated Voltage (V)	300
Motor Nominal (rpm)	1500
Constant of the Torque V/(rad/sec))	0.4
Resistance of one Phase (Ω)	0.4
Self-inductance (mH)	13

Figure 6 shows the PV- PV-insolation profile with time, the PV output voltage, power generated from the PV array, and finally the change of duty cycle for the converter when insolation is changed from 1000 to 200. Also, to show the movement of the bees towards optimization in 3-D for PID gains, Figure 7 is illustrated.

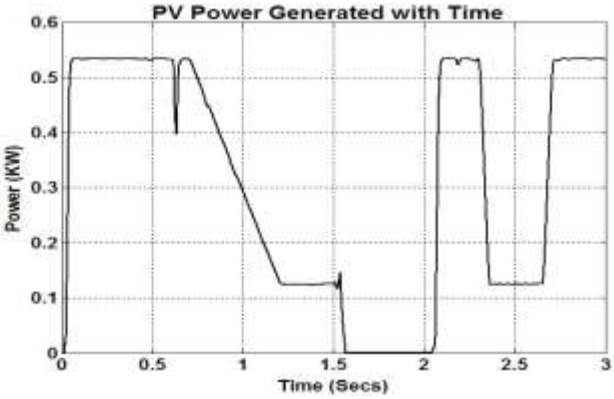
The robustness is tested and observed by tracking several speed trajectories. Figure 8 demonstrates the real and locus speed (a) and torque (b) for the trapezoidal two-quadrant speed track.



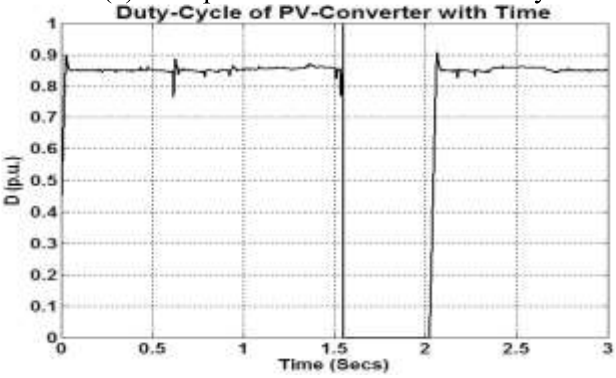
(a) The proposed Irradiance-profile for the PV



(b) Voltage profile of PV- output

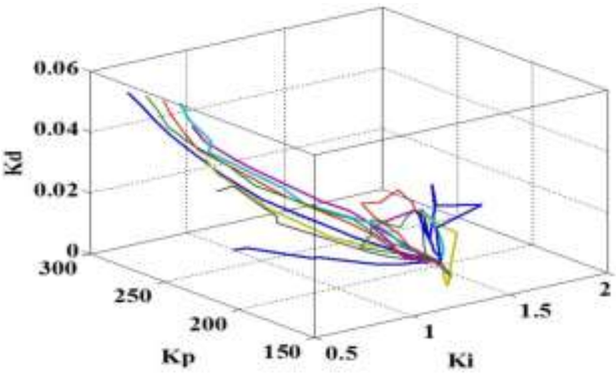


(c) The power emitted from PV arrays

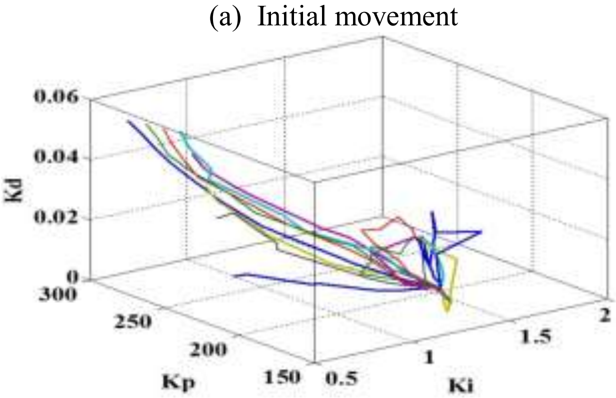


(d) Converter duty-ratio

Fig. 6: PV- variables (insolation, voltage, power, and duty ratio)

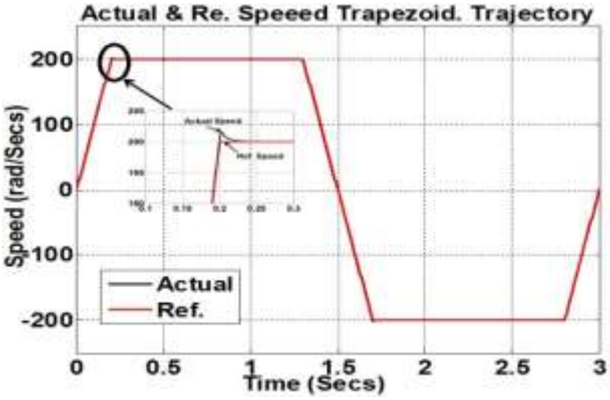


(a) Initial movement

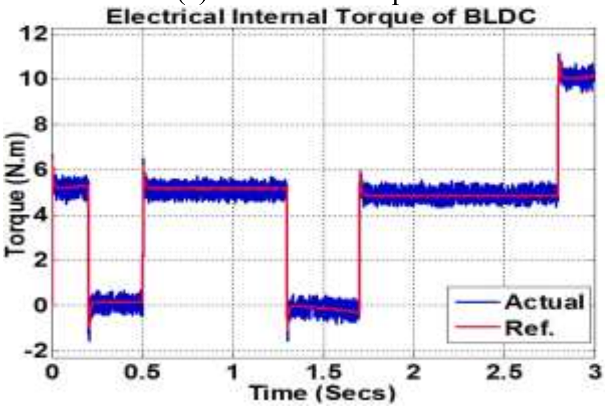


(b) Through tuning

Fig. 7: PID-Tuning process with ABC



(a) Ref. & actual speed



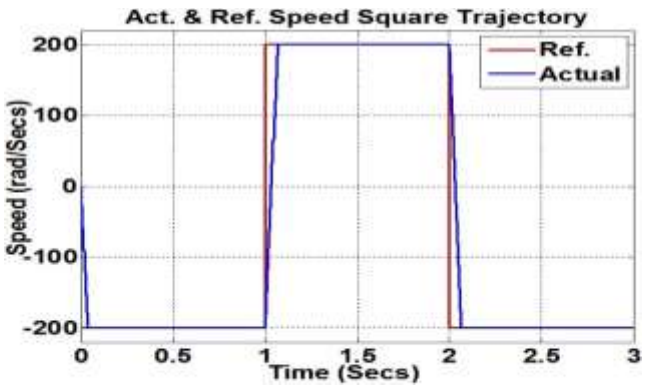
(b) Ref. & actual torque

Fig. 8: Trapezoidal Track (Speed & Torque)

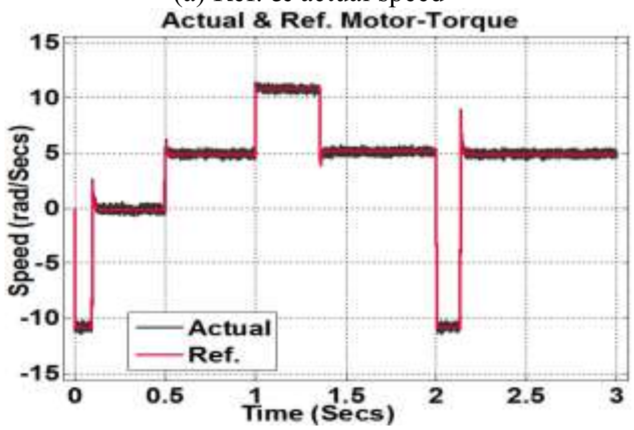
The speed trajectories or both actual and ref. are approximately identical although the insolation profile of the PV-array is changed from 1000 to 200 W/m².

Other speed trajectories are tested such as square, sinusoidal, ramp, and up-down stairs as shown in Figure 9, Figure 10, Figure 11, and Figure 12 (a for speed and b for motor internal torque). We noticed that most tracks for both speed and torque are approximately in phase (actual and reference) with a very fast response to any disturbance. This ensures the robustness of the system drive with that proposed ABC-PI controller. All previous results are obtained when the BLDC motor is directly supplied from the solar arrays. The proposed controller is also used when the motor is fed from the battery. The voltage for the converter DC-link (both actual and reference) is shown in Figure 13. The response for the step-change is so high with a very fast time. When the motor is fed directly from the battery, the performance is improved.

Also, it should compare the proposed intelligent controller with others such as (GA), (ACO), and also with the traditional controller (PID).

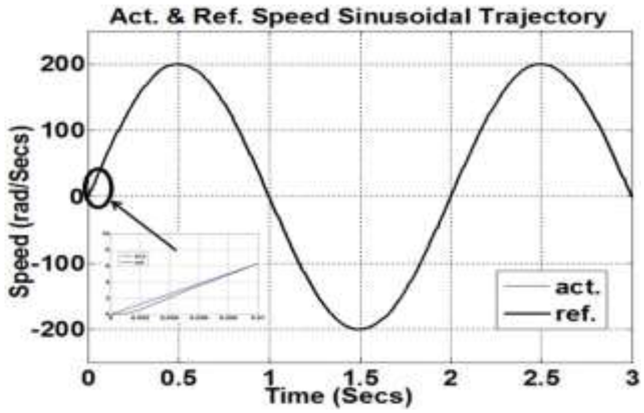


(a) Ref. & actual speed

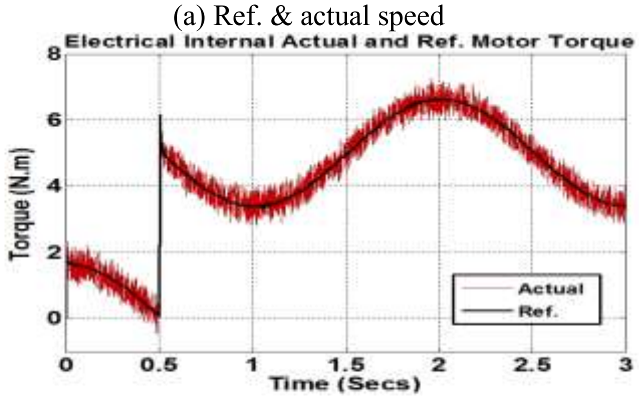


(b) Ref. & actual torque

Fig. 9: Square Track (Speed & Torque)

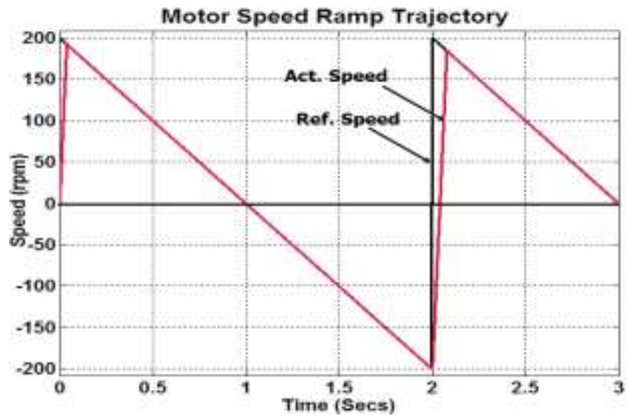


(a) Ref. & actual speed



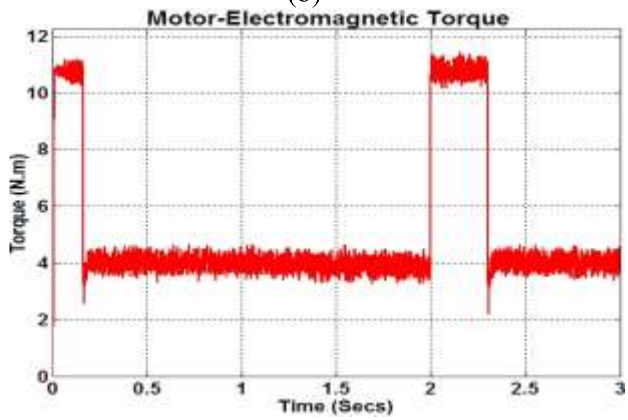
(b) Ref. & actual torque

Fig. 10: Sin Track (Speed & Torque)



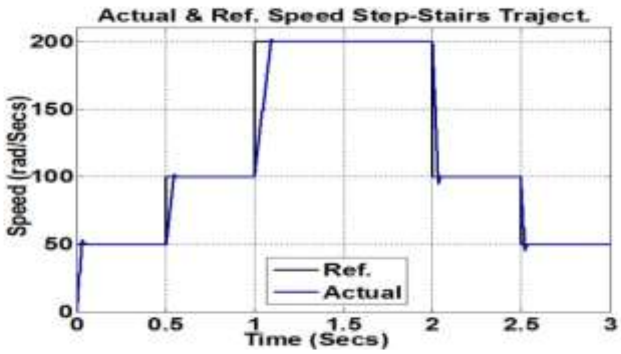
(a) Ref. & actual speed

(b)

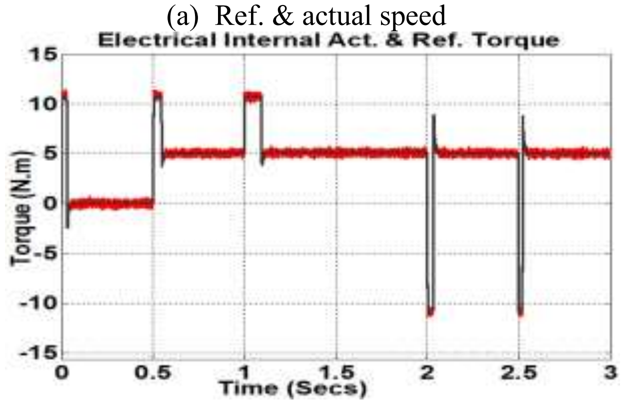


(b) Ref. & actual torque

Fig. 11: Ramp Track (Speed & Torque)



(a) Ref. & actual speed



(b) Ref. & actual torque

Fig. 12: Up-down stairs Track (Speed & Torque)

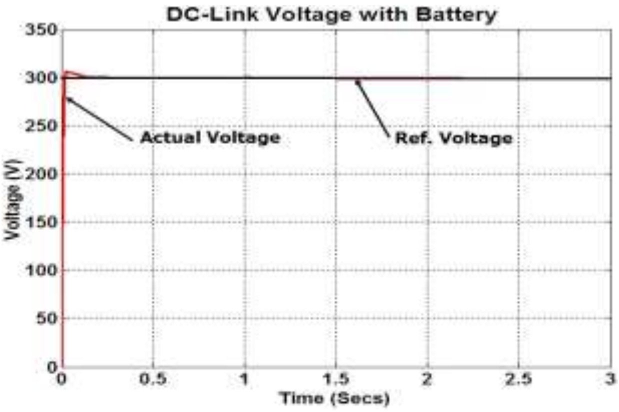


Fig. 13: The converter DC-link voltage (act. & ref.)

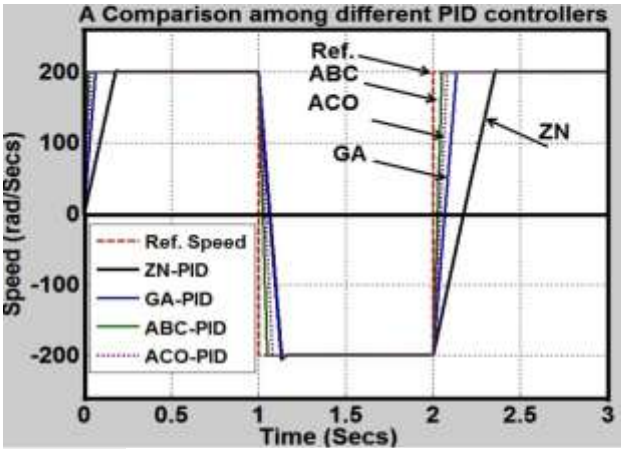


Fig. 14: A comparison among ABC, ACO, GA, and ZN-PID Controllers

The GA-PID controller algorithm data is obtained from [44], and the overall algorithm parameters are given in Table 3 (Appendix). Also, the ACO-PID controller algorithm is designed, modeled, and simulated with the help of, [5], and the main ACO algorithm parameters are given in Table 4 (Appendix). In addition, the comparison includes the traditional ZN-PID controller and Ziegler-Nichols criteria had the following gains:

$$K_p = 30.1,\ K_i = 13.22, K_d = 0.02$$

As shown in Figure 14, the comparison among all is verified only for square reference prescribed speed trajectory only as a sample, wherever, this is considered as a sharp and step-change complex test.

So, it can be easily noticed that both ABC-PID and ACO-PID controllers follow this sharp speed trajectory with fast response and minimum overshoot. But, ABC-PI is the best one. On the other hand, the GA-PID and traditional PID controllers take more time to reach a steady state.

Because the ABC-PID controller contributed towards improving and enhancing the tracking control of the BLDC motor with an e-bike, it will be implemented in real time.

5 Real-Time Implementation

The proposed system is implemented in real time to ensure its ability to be constructed as a physical system. The OPAL OP4510v is a digital real-time hardware simulator, [45]. This platform is used with the help of the HIL controller and data acquisition OP8660 set, [46], – in the ERI lab. – to test the proposed system in real time. The overall experimental rig is shown in Figure 15. All the real input/ output signals can be checked and recorded by using a digital oscilloscope. The interface language – used as compiler and interpreter – between Matlab/ Simulink and OP4510 RT-simulator is the RT-LAB software package. All signals can be output on the analog ports as real. Because the maximum output for these analog ports is 16V, all signals should be scaled to reduce their value to be seen on the oscilloscope. The RT results will be recorded only for the proposed ABC-PID controller. The square-wave speed trajectory is tested to be tracked because this trajectory includes both positive and negative speeds in both directions. Also, in this trajectory, the speed is sharply step-changed from zero to 200 rad/sec in a very short time. Figure 16 (Ch. A) describes the proposed insolation profile for the PV- array used to supply the motor. In the Simulink model, the irradiance was scaled by 200. So, as shown in Figure 16, the oscilloscope is set to 200 mV/ div, and 2.5 divisions means 1000 W/m². Figure 17 shows the proposed reference and actual speed tracks. As shown, the motor response is fast and takes a few milliseconds to reach its steady state reference value with minimum overshoot. Dependently, Figure 18 describes both reference and real motor torque. As shown, both actual and reference signals are in phase and approximately identical with some harmonics, ripples, or noise.

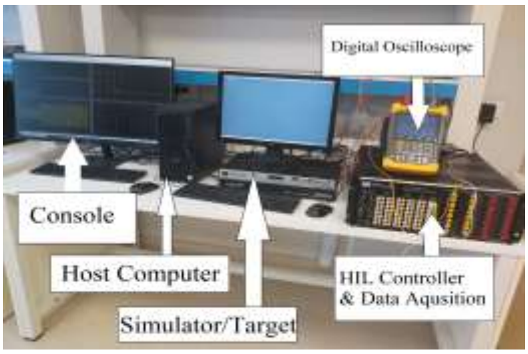


Fig. 15: Real-time simulator and its controller

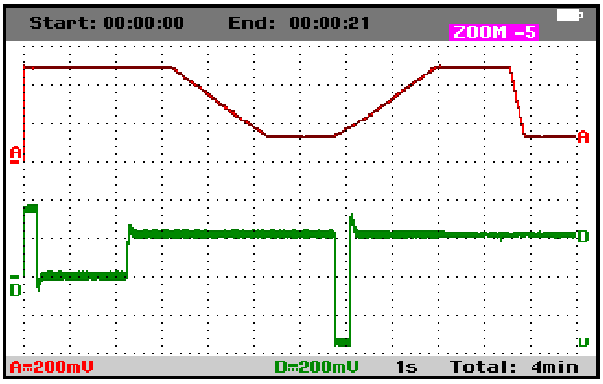


Fig. 16: PV-Irradiance with motor torque

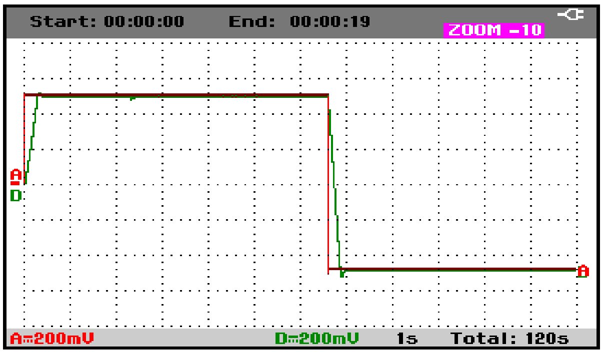


Fig. 17: RT-Speed tracks (Ref. & actual)

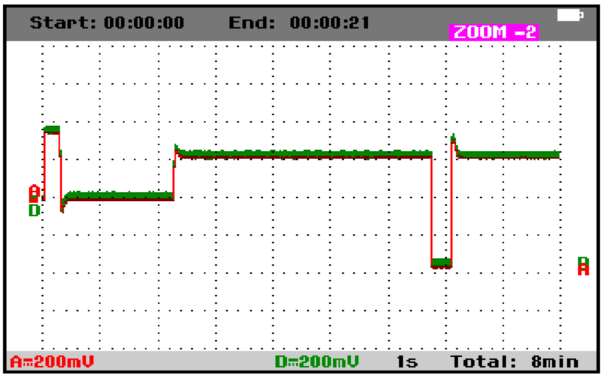


Fig. 18: RT-torque signals (actual (D) & ref. (A))

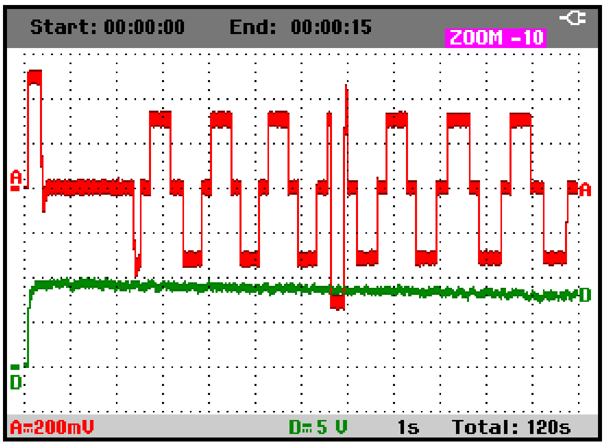


Fig. 19: RT Motor current (A), DC voltage (A)

This is due to the selection of a small sampling time, the switching rate for the IGBT switching module, and the hysteresis current controller of the proposed technique. In addition, for the same speed trajectory, the stator current of the motor is shown in Figure 19 (Ch. A) and the DC-link voltage is shown in Figure 19 (Ch. D). The current was scaled by 5 and the voltage by 200.

6 Conclusion

This paper proposed intelligent speed and position controllers for e-bikes driven by a BLDC motor. This controller depends on the ABC algorithm as an optimization technique. The main gains of that controller are optimized.

A general-purpose software package was introduced to be used in designing; modeling and simulating any BLDC drive for an e-bike with different artificial intelligence (AI) controllers using the Matlab/Simulink and M-file routines. AI controllers – that depend on evolutionary computation such as ABC, GA, and ACO - are robust and can depend on them especially, in speed and position tracking of e-bikes. Among those controllers, ABC and ACO gave good results in pre-scribed speed-tracking with fast response rather than GA and ZN-PID controllers. So, the system was implemented in real time with the ABC-PID proposed controller. The system performance and response were improved.

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APPENDIX

Table 2. ABC algorithm parameters, [39], [40]

Parameters 0f ABC	Values
Colony Size numbers =Np	20
Food Sources number (S=Np/2)	10
Cycles numbers (maximum)	50
Probability of the Threshold	0.75
Parameters Optimized number	3

Table 3. GA –algorithm parameters, [44]

GA-algorithm parameters	Values
Max. generation	100
Population size	50
Cross-over probability (CR)	0.75
Mutation rate	0.1

Table 4. ACO algorithm parameters, [5]

ACO-algorithm parameters	Values
K	5
α	0.2
β	0.6
ρ	0.3
q_o	0.5
τ_o	0.2
Max. no. of iteration	50

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