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Artificial Intelligence-Based Optimal PID Controller Design for BLDC Motor with Phase Advance

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ABSTRACT

This paper proposes the artificial intelligence (AI)-based optimal PID controller design optimization of brushless direct current (BLDC) motor speed control with phase advance approach. The proposed control system allows the speed adjustment of the BLDC motor by phase advance technique. In this paper, two selected AI algorithms, i.e., the adaptive tabu search (ATS) and the intensified current search (ICS) are conducted as the optimizer for the PID controller design. The proposed control system is simulated by MATLAB/SIMULINK. Results obtained by the ATS and ICS will be compared with those obtained by the Ziegler-Nichols (ZN) tuning rule and the genetic algorithm (GA). It shows that the speed response of the BLDC motor by phase advance with the PID controller optimized by the ICS outperforms better than the ZN, GA and ATS.

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1. INTRODUCTION

The brushless direct current (BLDC) motor is a kind of synchronous motor having permanent magnets on the rotor and stator winding. It has been broadly utilized in automotive, hard disk, robotics, vehicle, aerospace, home appliance and instrumentation. The BLDC motor has many advantages over the induction motor including simple structure, low size, excellent efficiency, less maintenance, low noise and wide speed range [1] -[3]. In the future, motor controllers need to be improved for application targets through simple and economical design.

The BLDC motor can be expanded to operation speed range more than base speed by phase advance [4]. This allows the utilization of BLDC motor in various applications for high speed range. So, it is necessary to have a controller that can improve performance for developing three phases of the BLDC motor drive. The PID controller is extensively used in the BLDC motor drive because of the effectiveness and simple structure [5], [6]. The parameters of PID controller are very essential for the performance of motor control system, particularly in motor device with nonlinearity and large inert [7]. From the previous researches [4], [8]-[11], the BLDC motor system with phase advance is regulated by conventional control methods. It is found that the performance of motor has steady state error and slow speed response. Therefore, the speed response of the

BLDC motor system with phase advance can be done effectively by optimizing the values of PID controller parameter using artificial intelligence (AI) algorithms. Furthermore, the applications of AI algorithms for PID controller of the BLDC motor system with phase advance have not been presented in the previous researches [4], [8]-[11]. The AI algorithms have been extensively accepted for the controller design in many industrial applications [12]. For example, designing of BLDC rotor speed by fuzzy logic [13], genetic algorithm (GA) for controller design [14], self-turning the PID controller using GA [15], controller design using adaptive tabu search (ATS) [16], aircraft electric control by ATS [17] and control synthesis using current search (CS) [18],

[19]. Hence, this paper presents the use of AI algorithms for tuning the PID parameters (K_P, K_i and K_d) for controlling the BLDC motor with phase advance.

In this paper, there are divided six sections. Firstly, the introduction is described. Secondary, the details of the modeling of BLDC motor and phase advance technique are presented. Thirdly, the details of AI algorithms are demonstrated. Fourthly, the application of selected AI algorithms is tuned the PID parameters for the BLDC motor system. Fifthly, the simulation results are illustrated. Finally, the conclusions are described.

2.   MODELING OF BLDC MOTOR AND PHASE ADVANCE TECHNIQUE
2.1. Modeling of BLDC motor
The equivalent circuit model of the BLDC motor is illustrated as shown in Figure 1. The modeling of BLDC motor can be performed in equation (1) [1], [2].
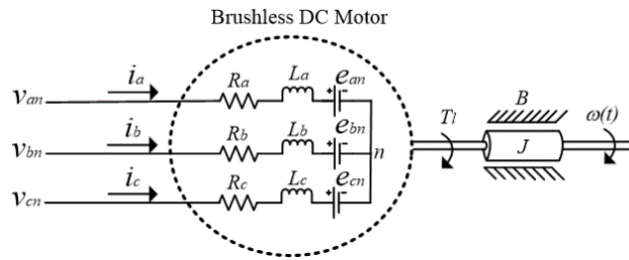

Figure 1. Equivalent circuit model

In Figure 1, it consists of inductance, back emf and resistance, where v_{an}, v_{bn} and v_{cn} are the output phase voltages, i_a, i_b and i_c represent the phase currents, L_a, L_b and L_c are the phase inductances, e_{an}, e_{bn} and e_{cn} are phase back emfs, R_a, R_b and R_c are the phase resistances of rotor.

$$\left. \begin{array}{l} v_{an} = R_a i_a + L_a \dfrac{di_a}{dt} + e_{an} \\[2mm] v_{bn} = R_b i_b + L_b \dfrac{di_b}{dt} + e_{bn} \\[2mm] v_{cn} = R_c i_c + L_c \dfrac{di_c}{dt} + e_{cn} \end{array} \right\} \tag{1}$$

The trapezoidal back emfs in equation (2) are related to a function of rotor position, where θ_e and K_w are the electrical rotor angle and the back emf constant of each phase, ω_r denotes the motor angular velocity in rad/s and f_a, f_b and f_c represent the function of rotor position.

$$\left. \begin{array}{l} e_{an} = K_w \omega_r f_a(\theta_e) \\ e_{bn} = K_w \omega_r f_b(\theta_e - 2\pi/3) \\ e_{cn} = K_w \omega_r f_c(\theta_e - 4\pi/3) \end{array} \right\} \tag{2}$$

The electromagnetic torque is a simple equation of phase current and phase back emf as expressed in equation (3), where T_e is electromagnetic torque and T_{ea}, T_{eb} and T_{ec} represent phase electric torque. The relation between the speed and the torque are stated in equation (4), where T_l is an indicative of load torque in N.m, J denotes the moment of inertia in kg-m^2 and B is the static friction in N.m-s/rad.

$$T_e = T_{ea} + T_{eb} + T_{ec} = \frac{\left[e_{an} i_a + e_{bn} i_b + e_{cn} i_c \right]}{\omega_r} \tag{3}$$

$$T_e = J\frac{d\omega}{dt} + B\omega + T_l \tag{4}$$

2.2. Phase advance
The phase advance technique is a common control of the phase current to lead the phase back emf. It can increase the speed of BLDC motor over the base speed. Figure 2 shows the phase currents shifted by the angle of α_{adv} to phase back emf. The phase currents can be varied from 0° to 60°, electrical degree [8]-[10].
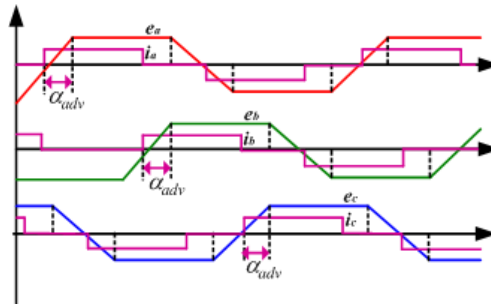
Figure 2. Waveforms of phase current and phase back emf

The phase advance is described in equation (5), where L_s is an indicative of phase inductance, α_{adv} is the angle of phase advance, V_{dc} is an indicative of voltage source, n is rotor speed and I_{ph} denotes the phase current.

$$\alpha_{adv} = \omega_r \frac{L_s I_{ph}}{V_{dc}}, \quad \omega_r = 2pn\pi \qquad (5)$$

In Figure 3, it shows the three phase inverter for BLDC motor drive. In this work, the proposed drive system composes of three phase inverter, switch control signals, Hall effect sensors, BLDC motor and DC voltage source. The switching states of three phase inverter based on Hall effect signals are visualized in Figure 4.
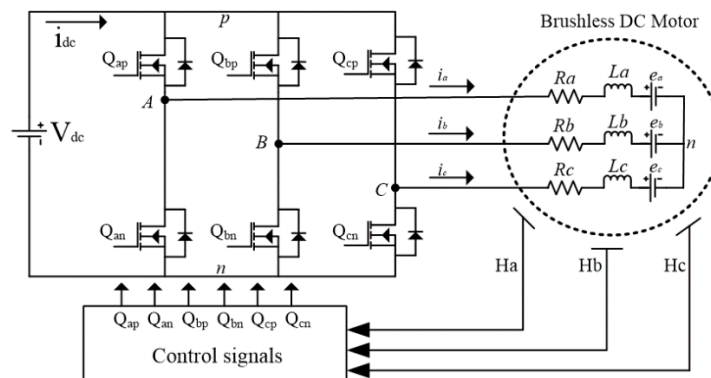

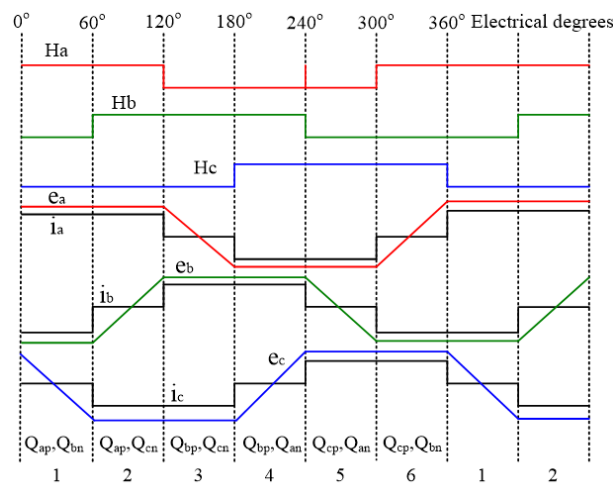Figure 3. Three phase inverter of BLDC motor drive

Figure 4. Hall effect signals, switching states and back emfs

Table 1 shows the switching states for the BLDC motor drive. Each step has an interval of 60° ,electrical degree.

Table 1. Switching states

Step	Interval	Switch	Phase A	Phase B	Phase C
1	0° - 60°	Q_{ap}, Q_{bn}	+	-	0
2	60° - 120°	Q_{ap}, Q_{cn}	+	0	-
3	120° - 180°	Q_{bp}, Q_{cn}	0	+	-
4	180° - 240°	Q_{bp}, Q_{an}	-	+	0
5	240° - 300°	Q_{cp}, Q_{an}	-	0	+
6	300° - 360°	Q_{cp}, Q_{bn}	0	-	+

Figure 5 shows Hall effect signals which effect the switching states of three phase inverter. The phase advance adjusts the Hall effect signals (Ha*, Hb* and Hc*) leading the previous Hall effect signals (Ha, Hb and Hc).
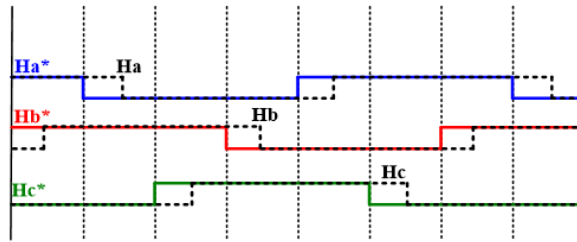

Figure 5. Waveforms of Hall effect signal

3. ARTIFICIAL INTELLIGENCE

Recently, AI algorithms have been broadly utilized to solve combinatorial and engineering problems. In this section, the AI algorithms consisting of the intensified current search (ICS) and the ATS are briefly reviewed.

3.1. ICS algorithm

The CS is one of the AI algorithms based on the current divider of the electric circuits and network systems [18], [19]. Theoretically, the CS only composed the memory list (ML). For solving the computational problems, the ICS algorithm has been modified version by adding the adaptive radius (AR) and the adaptive neighborhood (AN). In order to find the optimal solution, the ICS is able not only to escape the local entrapment but also to speed up the search process in the search space. The movement of the ICS over search space is illustrated in Figure 6. The pseudo code of the ICS is described in Figure 7 [20], [21].
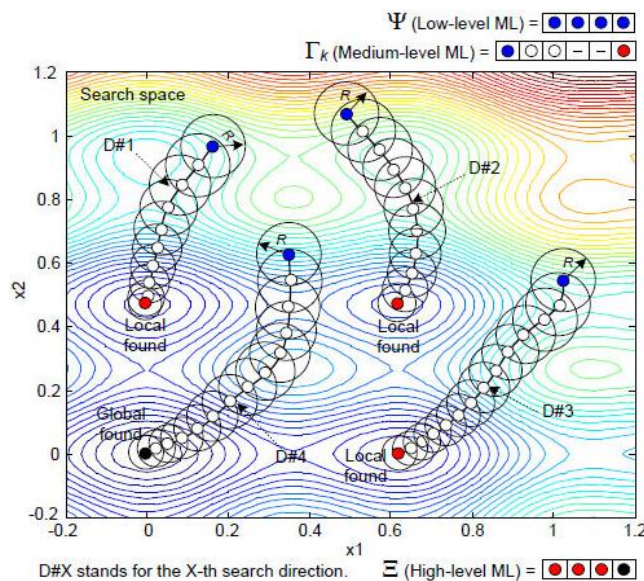

Figure 6. Movement of the ICS algorithm [20], [21]

```
Start
Step 1: The objective function, the search space, the number of initial solution and
        the number the neighborhood members are initial as f(x),x=(x₁, x₂,...xₐ), Ω,
        N and n respectively.
Step 2: The memory list, ML(Ψ, Γₖ, Ξ) = ∅, the search radius R, k=j=1,
        xᵢ is random within Ω.
Step 3: The number of maximum allowance of solution cycling jₘₐₓ is initial,
        x₀ = xₖ as initial solution.
Step 4: The Xglobal = Xlocal = x₀ is evaluated by the objective function f(xᵢ) and then
        the solution xᵢ is set in the Ψ.
Step 5: while( k ≤ N or termination criteria (TC) )
                Let x₀=xₖ be initial solution
                for j to jₘₐₓ
                        xᵢ is random around x₀ in the R.
                        f(x) is evaluated then x* is defined as the best solution
                        if f(x*)<f(x₀)
                                x₀ is save to Γₖ, update x₀=x* and set j = 1
                            else
                                x* is save to Γₖ, and update j=j+1
                        end if
                        Activate AR by R=ρR,0<ρ<1
                        Invoke AN by n=αn,0<α<1
                end for
                The Xbest = x₀ is set and Xglobal is save to Ξ
                if f(Xlocal)=f(Xglobal) then  Xglobal= Xlocal
                end if
                Then k=k+1, j=1 and x₀ = xₖ as initial solution
        end while
Step 6: Best solution found.
Stop
```

Figure 7. Pseudo code of ICS [20], [21]

3.2. ATS algorithm

The ATS was firstly launched in 2002 [22], [23] as one of the AI algorithms. It has been modified version of the TS [24], [25] and based on an interactive neighborhood search approach for solving combinatorial and nonlinear problems. The mechanisms of ATS have the adaptive radius (AR) and back tracking (BT). To speed up the search process of ATS, AR mechanism is utilized to intensity. Moreover, the BT mechanism is able to conduct to escape the local entrapments. The movement of ATS over search space can be illustrated in Figure 8. The pseudo code of the ATS is shown in Figure 9 [22], [23].

Figure 8. Movement of the ATS algorithm [22], [23]

Start
Step 1: The objective function, the search space, Tabu list, search radius and termination
      criteria are initial as $f(s), s = (s_1, s_2, ..., s_2), \Omega$, TL, R and TC, respectively.
Step 2: The solution, N is generated randomly around s_0 within Ω and the occurred local
      entrapment L_{flag}
Step 3: The objective function, $f(s_0)$ is evaluated.
Step 4: **while**(TC);
        The neighborhood solution s' is generated randomly.
        Evaluate $f(s')$ via given the objective function.
        The best neighborhood solution $s*$ is discovered.
        if $f(s*) < f(s_0)$
            Save s_0 to TL and $s_0 = s*$
         else
            Save $s*$ to TL
        end if
        if L_{flag}==true
            Activate the backtracking mechanism.
        end if
        if $s_0 \rightarrow$ local minimum
            Invoke the adaptive radius mechanism to reduce R by adjusting
            $R = \mu R, 0 < \mu < 1$
        end if
      end while
Step 5: Best solution found.
Stop

Figure 9. Pseudo code of ATS [22], [23]

4.   PID CONTROLLER OF BLDC MOTOR

The PID controller was firstly conducted to industrial applications in 1939 [26]. It has been extensively used in the industrial control systems because of its simple structure and effectiveness. Figure 10 shows the conventional control loop of PID controller, where $R(s)$ is reference input signal, $E(s)$ is an error signal, $U(s)$ is control signal, $D(s)$ is disturbance signal and $C(s)$ is output response, respectively. $G_c(s)$ is the PID controller model and $G_P(s)$ is the BLDC motor model. Referring to Figure 10, $G_c(s)$ will receive $E(s)$ different between $R(s)$ and $C(s)$) and generate $U(s)$ for controlling $G_P(s)$ to provide desired $C(s)$ according to $R(s)$, whereas regulating $D(s)$, simultaneously. The liner transfer function of the BLDC motor plant can be stated in equation (6) [27], where τ_A is the driver time constant, K_A is the driver gain and K_t is the torque constant.
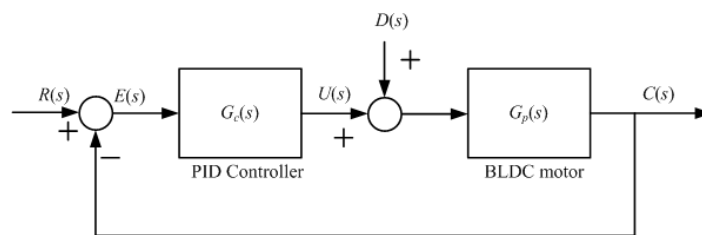
Figure 10. PID conventional control loop

$$G_P(s) = \left(\frac{K_A}{\tau_A s + 1} \right) \left(\frac{K_t}{(L_a J) s^2 + (R_a J + L_a B) s + (R_a B + K_t K_w)} \right) \qquad (6)$$

The PID controller model in the s-domain transfer function is stated in equation (7). Therefore, the PID controller can be written in the form of closed loop as shown in equation (8).

$$G_C(s) = K_P + \frac{K_i}{s} + K_d s \qquad (7)$$

$$\frac{C(s)}{R(s)} = \frac{(K_P + \frac{K_i}{s} + K_d s) G_P(s)}{1 + (K_P + \frac{K_i}{s} + K_d s) G_P(s)} \qquad (8)$$

The AI search techniques are applied to the PID controller design for the BLDC motor system as depicted in Figure 11. The objective function (f_{obj}), sum absolute-error (SAE) between $R(s)$ and $C(s)$ as stated in equation (9) will be fed back to the AI tuning block (ATS or ICS). The f_{obj} will be minimized by ATS or ICS to find the optimal PID parameters (K_p, K_i and K_d) to satisfy the inequality constrainted functions as stated in equation (10), where e_{ss} is steady-state error, e_{ss_max} is maximum allowance of e_{ss}, t_r is rise time, t_{r_max} is maximum allowance of t_r, M_p is maximum percent overshoot, M_{p_max} is maximum allowance of M_p, t_s is settling time, t_{s_max} is maximum allowance of t_s, K_{p_min} and K_{p_max} are the search space of the K_p, K_{i_min} and K_{i_max} are the search space of the K_i and K_{d_min} and K_{d_max} are the search space of the K_d. Flowcharts of ATS and ICS algorithms for the PID controller design optimization for the BLDC motor system are shown in Figure 12 and Figure 13, respectively.
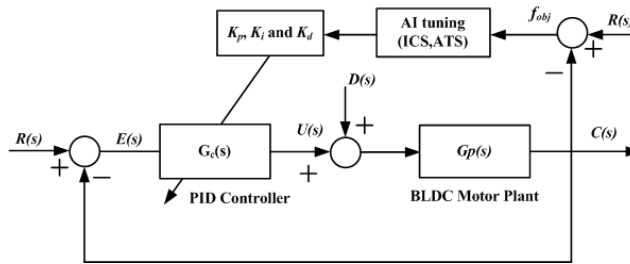
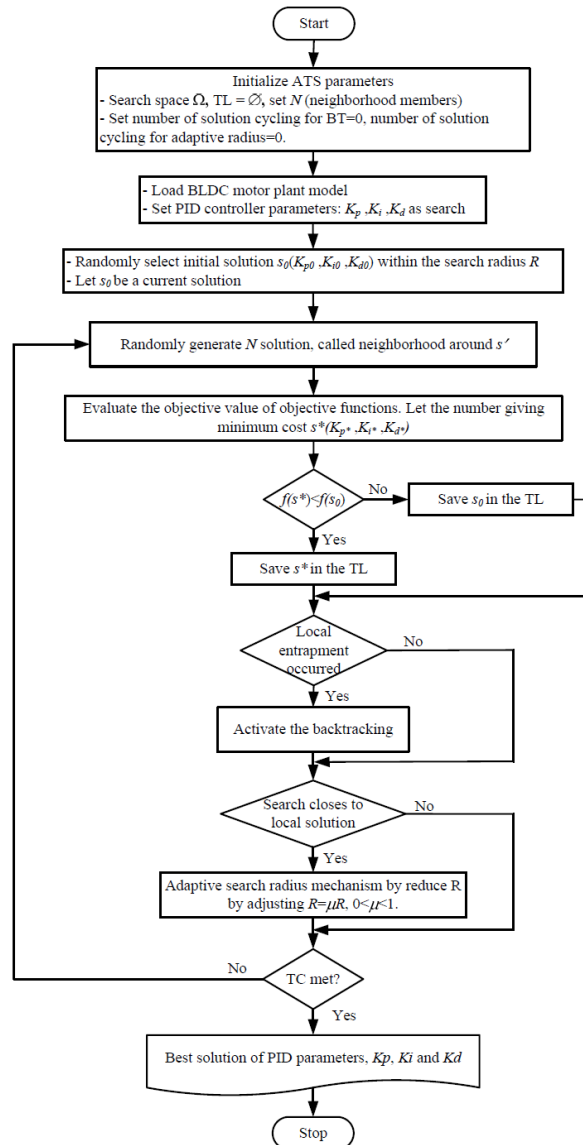Figure 11. AI-based PID controller design.

Figure 12. Flowchart of the ATS algorithm for PID controller design

Minimize:

$$f_{obj}(K_p, K_i, K_d) = \sum_i^N \left[R(i) - C(i) \right]^2 \tag{9}$$

Subject to:

$$\left. \begin{array}{l} e_{ss} \leq e_{ss\_max}, \\[4pt] t_r \leq t_{r\_max}, \\[4pt] M_p \leq M_{p\_max}, \\[4pt] t_s \leq t_{s\_max}, \\[4pt] K_{p\_min} \leq K_p \leq K_{p\_max}, \\[4pt] K_{i\_min} \leq K_i \leq K_{i\_max}, \\[4pt] K_{d\_min} \leq K_d \leq K_{d\_max} \end{array} \right\} \tag{10}$$
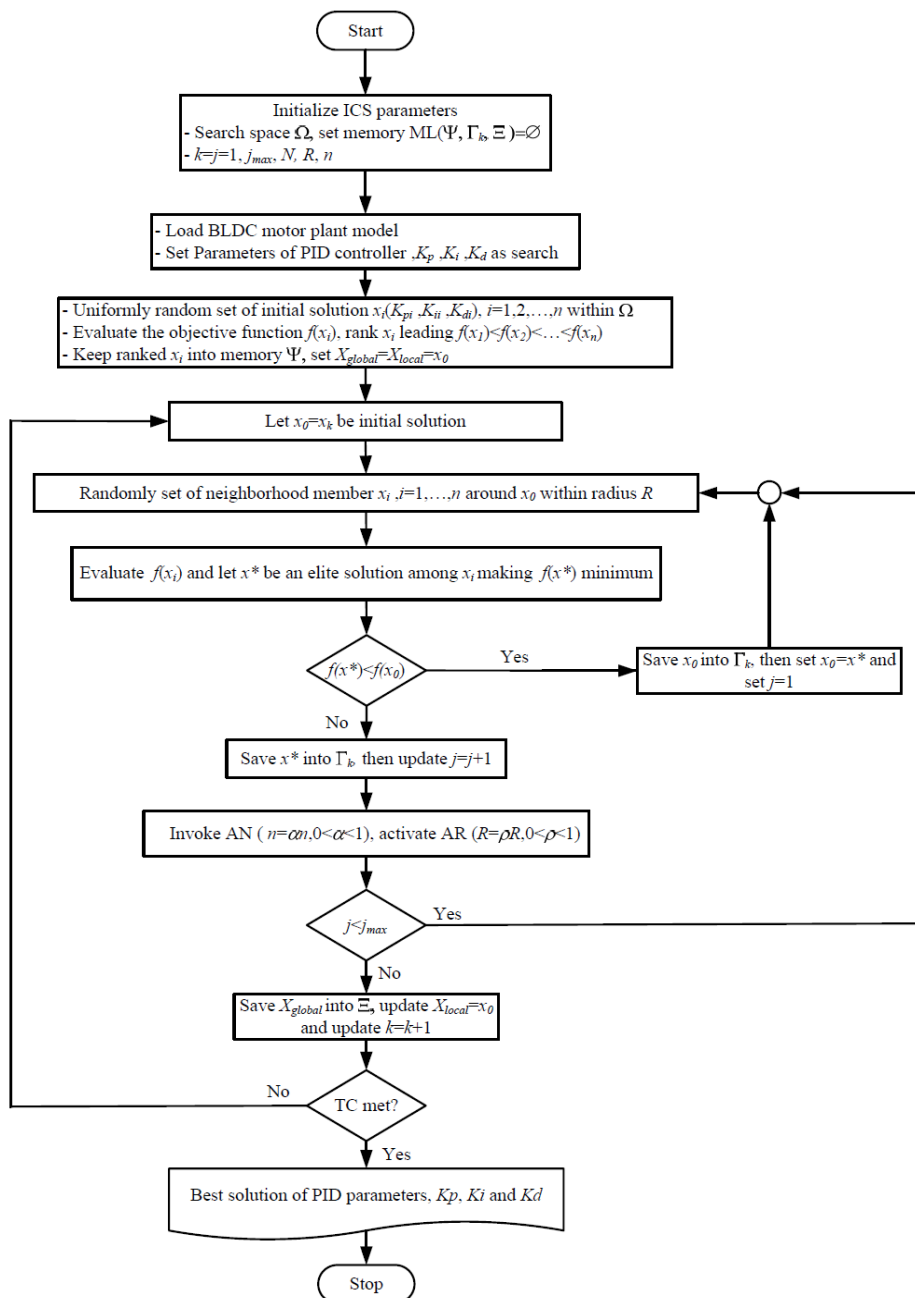
Figure 13. Flowchart of the ICS algorithm for PID controller design

5. SIMULATION RESULTS

The parameters of the BLDC motor plant were conducted as follows: $R_a = 11.8183$ Ω, $L_a = 0.027$ H, $J = 0.0001$ kg-m^2, $B = 0.0003$ N.m-s/rad, $K_t = 0.2526$ N.m/A, $K_w = 0.1319$ V/rpm, $K_A = 10.7615$ and $\tau_A = 0.0015$ s. Thus, the BLDC motor plant in equation (6) can be written in equation (11).

$$G_p(s) = \frac{2.718}{4.05 \times 10^{-9} s^3 + 4.485 \times 10^{-6} s^2 + 1.245 \times 10^{-3} s + 0.0368} \quad (11)$$

Referring to Figure 11, the AI algorithms were simulated via MATLAB/ SIMULINK run on CPU Core i5, 2.5 GHz and 6 Gbytes DDR-RAM computer. The optimal gains using AI techniques are setup. The design optimization by the ATS and ICS are performed as shown in Table 2 and Table 3, respectively. In addition, results obtained from the ATS and ICS will be compared with Ziegler-Nichols (ZN) tuning rule [28],[29] and GA [30]. The ZN tuning rule is the analytical design method, while the GA is one of the most popular metahueristic optimization techniques. However, both ZN and GA are not new anymore. Then, details of ZN and GA are omitted in this paper. Readers can find their details from the given references. The parameters of the GA are shown in Table 4. For design the PID controller, the search spaces of PID parameters in equation (10) are specified in Table 5.

Table 2. Parameters of ATS

Parameters	Values
Number of iterations	100
Search radius	0.5
Number of neighborhood	10
Solution cycling	10
Back tracking	5
Adaptive radius: $f_{obj} < 0.5$, $f_{obj} < 0.1$, $f_{obj} < 0.01$	0.25, 0.1, 0.01

Table 3. Parameters of ICS

Parameters	Values
Number of iterations	100
Number of neighborhood	10
Number of search direction	10
Search radius	0.5
Solution cycling	10
Adaptive radius: $f_{obj} < 0.5$, $f_{obj} < 0.1$, $f_{obj} < 0.01$	0.25, 0.1, 0.01
Adaptive neighborhood: $f_{obj} < 0.5$, $f_{obj} < 0.1$, $f_{obj} < 0.01$	15, 20, 25

Table 4. Parameters of GA

Parameters	Values
Number of iterations	100
Number of population	10
Crossover rate	95 %
Mutation rate	5%
Generation	100

Table 5. The search spaces of PID parameters

Parameters	Search space
K_p	0 - 10
K_i	50 - 100
K_d	0 - 1
t_{r_max}	0.20 s
M_{p_max}	10 %
t_{s_max}	0.30 s
e_{ss_max}	0.01%

The convergent rates of the proposed objective function in equation (9) and its corresponding inequality constrained functions in equation (10) proceeded by GA, ATS and ICS are depicted in Figure 14. The PID parameters of the BLDC motor system obtained by ZN tuning rule and optimized by GA, ATS and ICS are expressed in (12), (13), (14) and (15), respectively. The system responses of the BLDC motor without controller and with PID controllers are plotted in Figure 15 and summarized in Table 6.

$$G_C(S)\big|_{PID\_ZN} = 4.527 + \frac{66.473}{s} + 0.425s \tag{12}$$

$$G_C(S)\big|_{PID\_GA} = 3.326 + \frac{71.210}{s} + 0.035s \tag{13}$$

$$G_C(S)\big|_{PID\_ATS} = 3.853 + \frac{67.542}{s} + 0.023s \tag{14}$$

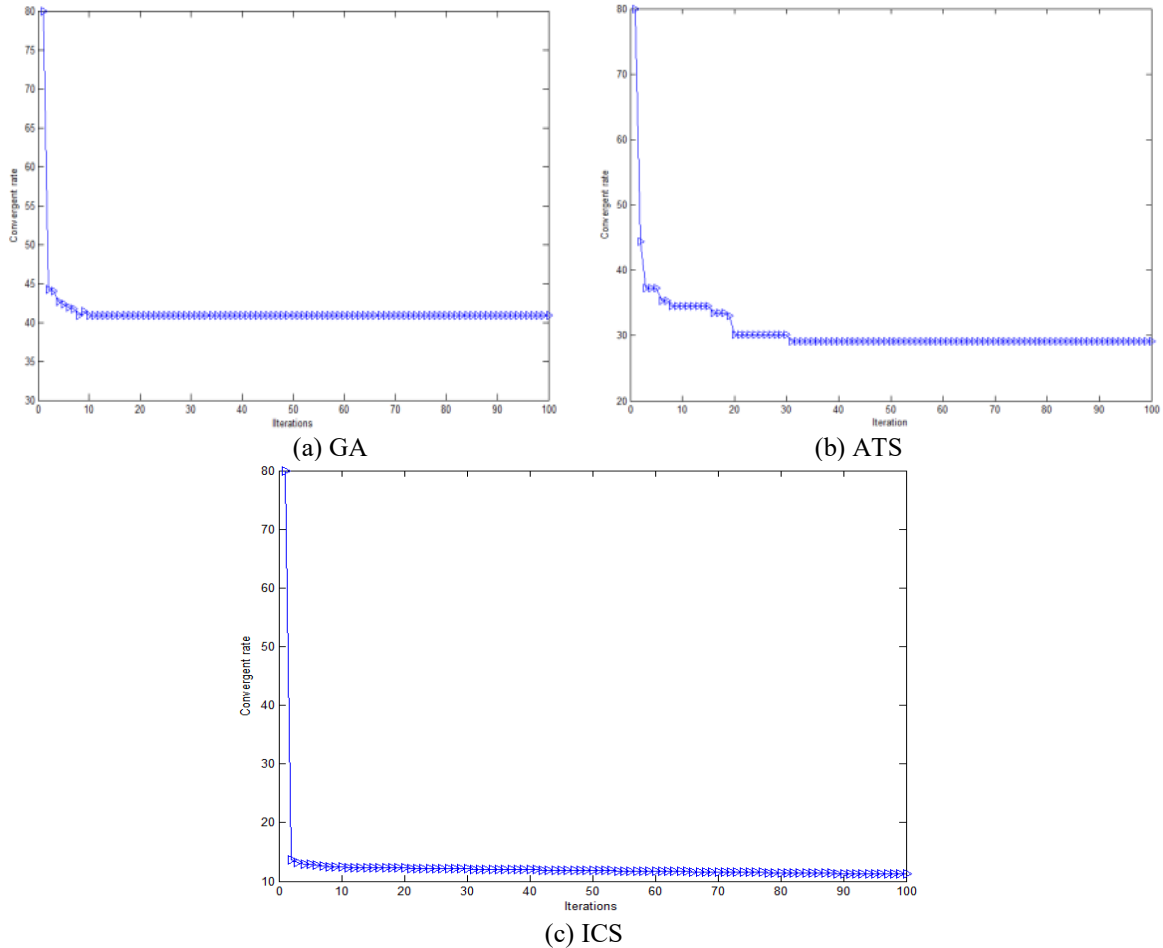$$G_C(S)\big|_{PID\_ICS} = 4.135 + \frac{64.261}{s} + 0.021s \tag{15}$$

(a) GA   (b) ATS
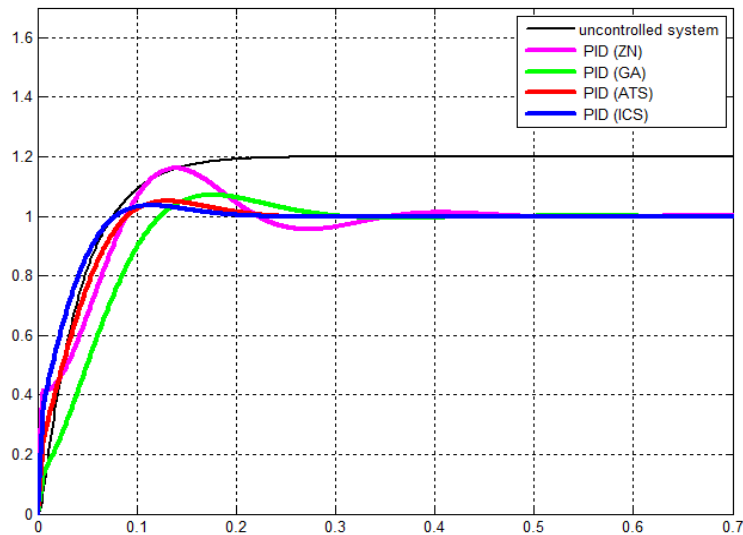

(c) ICS

Figure 14. Convergent rates of objective function

Figure 15. System responses of PID controller

Table 6. Performance of PID controller

Algorithms	Responses				Search time (s)
	t_r(s)	M_p(%)	t_s(s)	e_{ss}(%)	
ZN	0.0861	16.75	0.4761	0.00	-
GA	0.136	6.38	0.3150	0.00	27.253
ATS	0.0854	3.75	0.2083	0.00	18.582
ICS	0.0670	3.46	0.1538	0.00	14.427

From to Figure 15 and Table 6, the performance with the PID controller optimized by the GA gives the slowest response. The system response with the PID controller obtained by the ZN tuning rule provides faster response but greater overshoot than that by the GA. The system response with the PID controller optimized by the ATS performs faster response and smaller overshoot than that by the GA and ZN tuning rule. However, the system response with the PID controller optimized by the ICS outperforms that by ZN tuning rule, GA and ATS with the fastest response and smallest overshoot according to inequality constrained functions in equation (10).

In addition, the BLDC motor speed control system with phase advance technique and the PID controllers obtained by the ZN tuning rule and optimized by the GA, ATS and ICS is simulated by MATLAB/SIMULINK as depicted in Figure 16. The BLDC motor in the simulink block diagram is a three phase motor rated 3,000 rpm. The effectiveness of the obtained PID controllers is analyzed under different operating conditions and compared with the conventional control of phase advance. Figure 17(a) depicts the responses of BLDC motor when speed changed from 0 to 2,800 rpm with no load condition without phase advance. From the Figure 17(a), the responses of speed control are very satisfactory. Figure 17(b) shows the relation between the phase current (i_a) and the back emf (e_a). It was found that i_a and e_a are in phase.
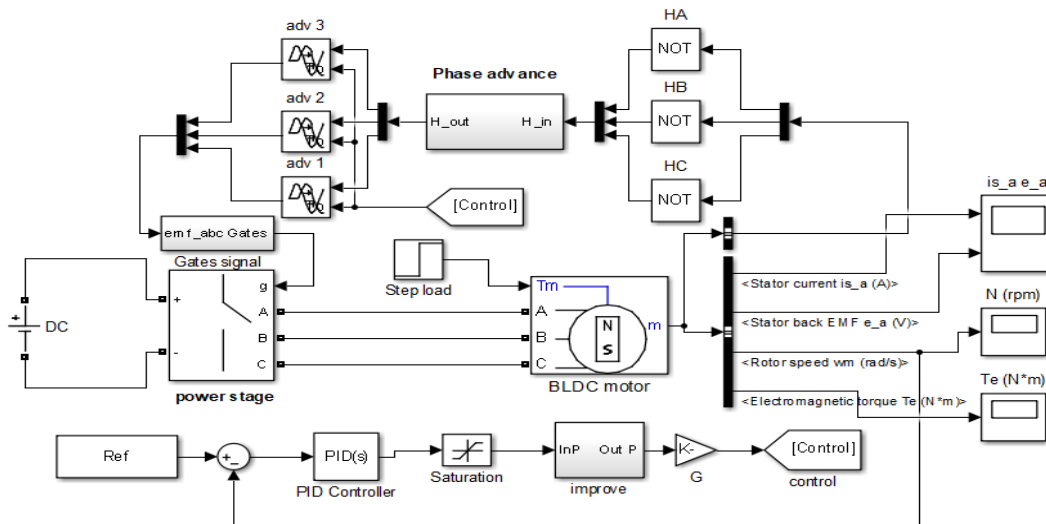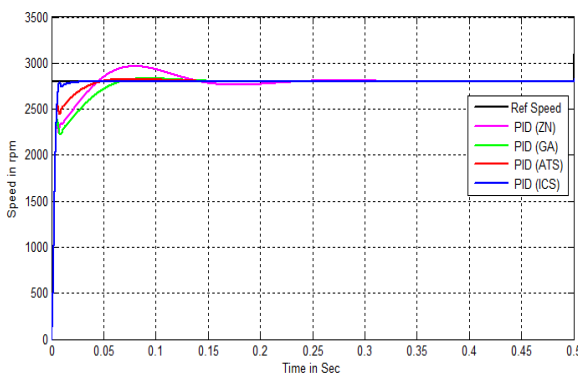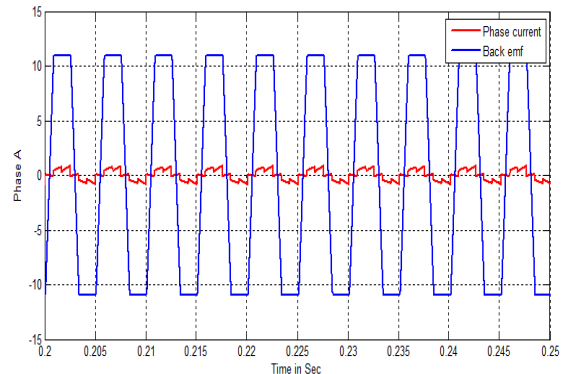
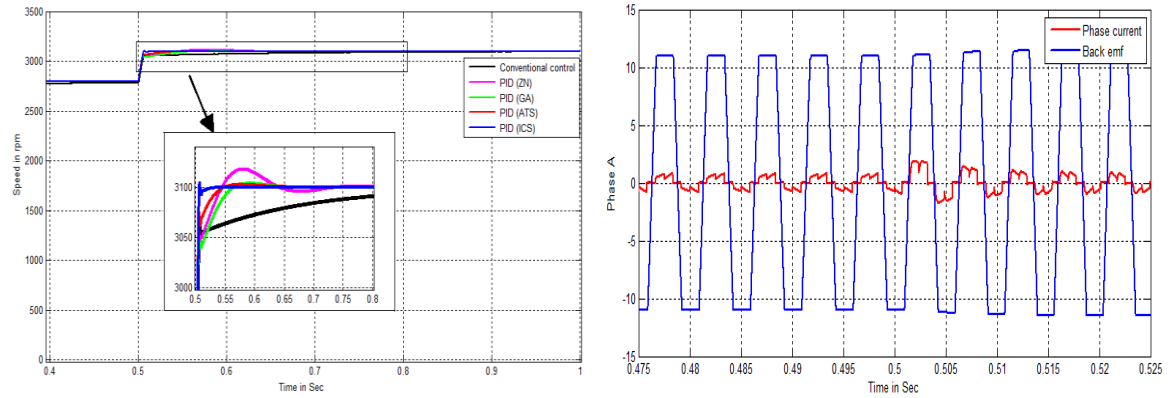

Figure 16. Simulink block diagram

(a) Step change from 0 to 2,800 rpm
(b) Comparison between i_a and e_a

Figure 17. Responses of BLDC motor speed control system without phase advance (no load)

Figure 18(a) depicts the responses of BLDC motor speed control system when speed changed from 2,800 to 3,100 rpm with no load condition with phase advance. From the figure18(a), the BLDC motor system can extend the speed range over the 3,000 rpm. The speed response with the PID controller optimized by the ICS outperforms other controllers. Figure 18(b) depicts the relation between i_a and e_a, it was found that i_a leads e_a at 0.5 s.
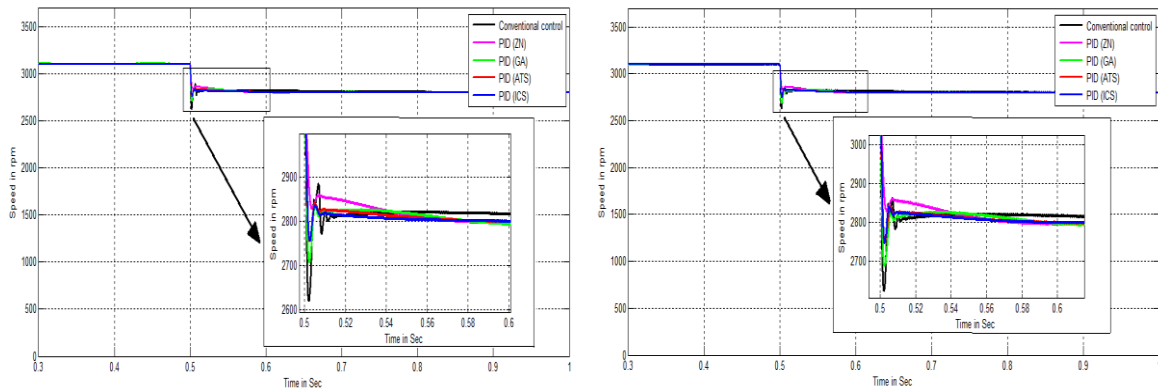
| (a) Step change from 2,800 to 3,100 rpm | (b) Comparison between i_a and e_a |

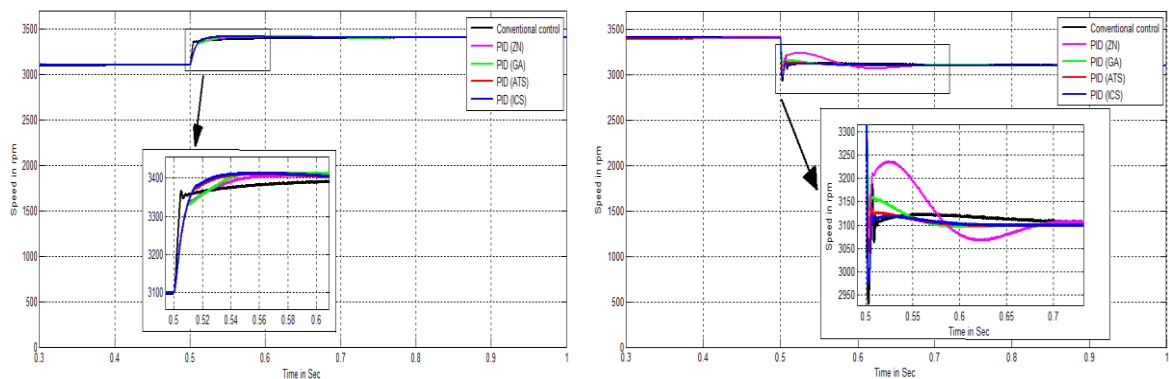Figure 18. Responses of BLDC motor speed control system with phase advance (no load)

Figure 19 depicts the responses of BLDC motor speed control system when speed changed from 3,100 to 2,800 rpm at 0.5 s with no load in Figure 19(a) and with load of 2 N.m in Figure 19(b). From Figure 19, the speed response with the PID controller optimized by the ICS also provides better response than other controllers with the least settling time of both no load and load.

| (a) No load | (b) Load of 2 N.m |

Figure 19. Responses of BLDC motor speed control system with no load and on load of 2 N.m

| (a) Step change from 3,100 to 3,400 rpm | (b) Step change from 3,400 to 3,100 rpm |

Figure 20. Responses of BLDC motor speed control system with phase advance at constant load of 2 N.m

Figure 20(a) depicts the responses of BLDC motor speed control system with phase advance when speed changed from 3,100 to 3,400 rpm with constant load of 2 N.m. Figure 20(b) depicts the speed responses of BLDC motor speed control system with phase advance when speed changed from 3,400 to 3,100 rpm. From Figure 20, the speed response with the PID controller optimized by the ICS can yield better response than other controllers with the least settling time.

Figure 21 depicts the regulating responses of BLDC motor speed control system with phase advance at constant speed of 3,100 rpm with load of 2 N.m at 0.4 s and no load at 0.7 s. From Figure 21, it was found that the speed responses once load applied and load released can be successfully controlled by the optimal PID controllers for load regulation purpose. For overall system performance, the PID controller optimized by the ICS for BLDC motor speed control system with phase advance outperforms other controllers.
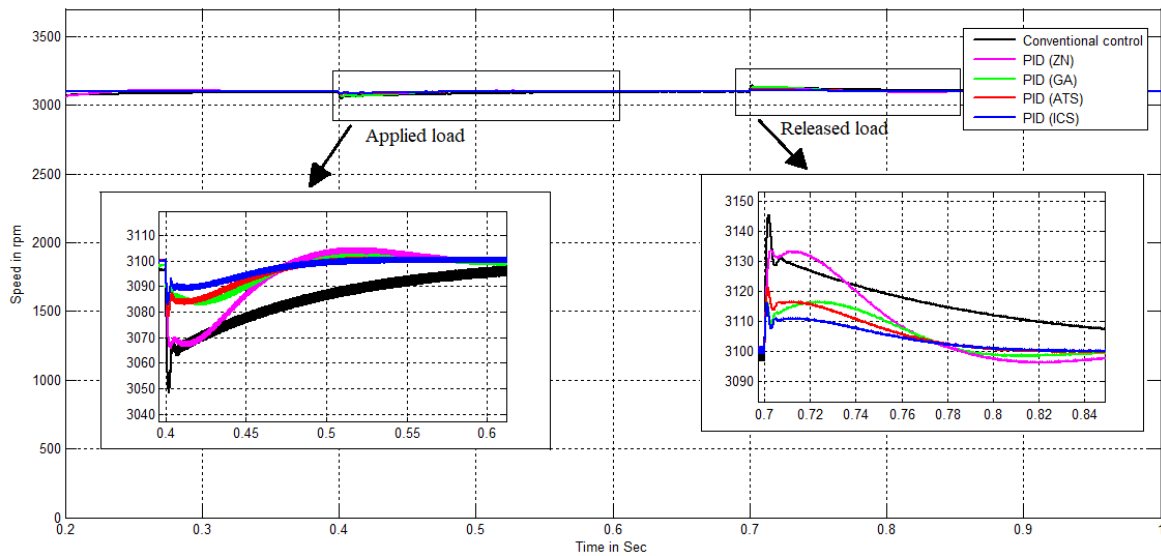

Figure 21. Responses of load regulation of BLDC speed control system

6. CONCLUSION

The AI-based optimal PID controller design optimization for BLDC motor speed control with phase advance has been presented in this paper. Two selected AI algorithms, i.e., the ATS and ICS, have been applied as the optimized to the PID controller design. In this paper, the mathematical model of the BLDC motor and the phase advance technique have been provided. Algorithms of the ATS and ICS have been clearly reviewed. The proposed design approach has been conducted by using MATLAB/SIMULINK. The PID controllers optimized by the ATS and ICS have been compared with the ZN tuning rule and the GA. As results, the ATS and ICS could successfully give optimal PID controllers. The simulation results shown that the responses of the BLDC motor speed control by phase advance with the PID controller designed by the ICS outperform that obtained by the ZN, GA and ATS, respectively. Moreover, the proposed ICS algorithm for PID controller design can be improved the system response effectively.

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