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RESEARCH ARTICLE

Optimal Speed Controller Design of Commercial BLDC Motor by Adaptive Tabu Search Algorithm

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ABSTRACT Brushless direct current motors are widely used in many industries because of their high efficiency and long-life. This paper presents the application of the adaptive Tabu Search algorithm for system identification and PID speed controller design to provide the best speed output performance compared with those designed using the well-known tuning method, the Ziegler–Nichols approach. The proposed design technique shows that the adaptive Tabu Search algorithm includes the control signal consideration in the design process. As a result, the resulting controller parameters can be implemented without the limitations of the real devices, while the Ziegler–Nichols method cannot provide as good a response as expected. The results are validated by simulation and experiment in which the output responses from the proposed design method are evidently better than those from the conventional method. Moreover, other artificial intelligence techniques such as the genetic algorithm, particle swarm optimization etc. can also be applied for the optimal design process following the concept in this paper in which the characteristics of the control signal are considered for real devices.

INDEX TERMS Optimal controller design, speed control, brushless direct current motor, parameter identification, adaptive tabu search.

ABBREVIATIONS

The following abbreviations are used in this paper.

DF	Decreasing factor.
d_x	commutation sequence for PWM generator.
$G(s)$	Plant model of the considered system.
H1, H2 and H3	Hall sensors.
K_P	Proportional gain of PID controller.
K_I	Integral gain of PID controller.
K_D	Derivative gain of PID controller.
L	Delay time.
n	The amount of data in the ATS process.
$radius_{new}$	New radius value.
$radius_{old}$	Old radius value.
$round_{\max}$	Amount of maximum iteration for ATS process.
S_0	Initial value of ATS process.
S_1	Best neighbor of ATS process.
$S(R)$	Solution set of ATS process.
T	Time constant.
V_{dc}	Input voltage (V).
$V_{in,dc}$	Analog input voltage for commercial driver board.
ω	Motor speed in time domain.
$\omega_{experiment}$	Experiment motor speed in time domain.
ω_{model}	Simulated motor speed in time domain.
ε	Speed error between experiment and simulation responses.
$\Omega(s)$	Motor speed in complex frequency domain.
θ_e	Electrical angle of BLDC rotor.

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I. INTRODUCTION

In recent times, BLDC motors are being widely used in many applications such as in electric vehicles, submarines,

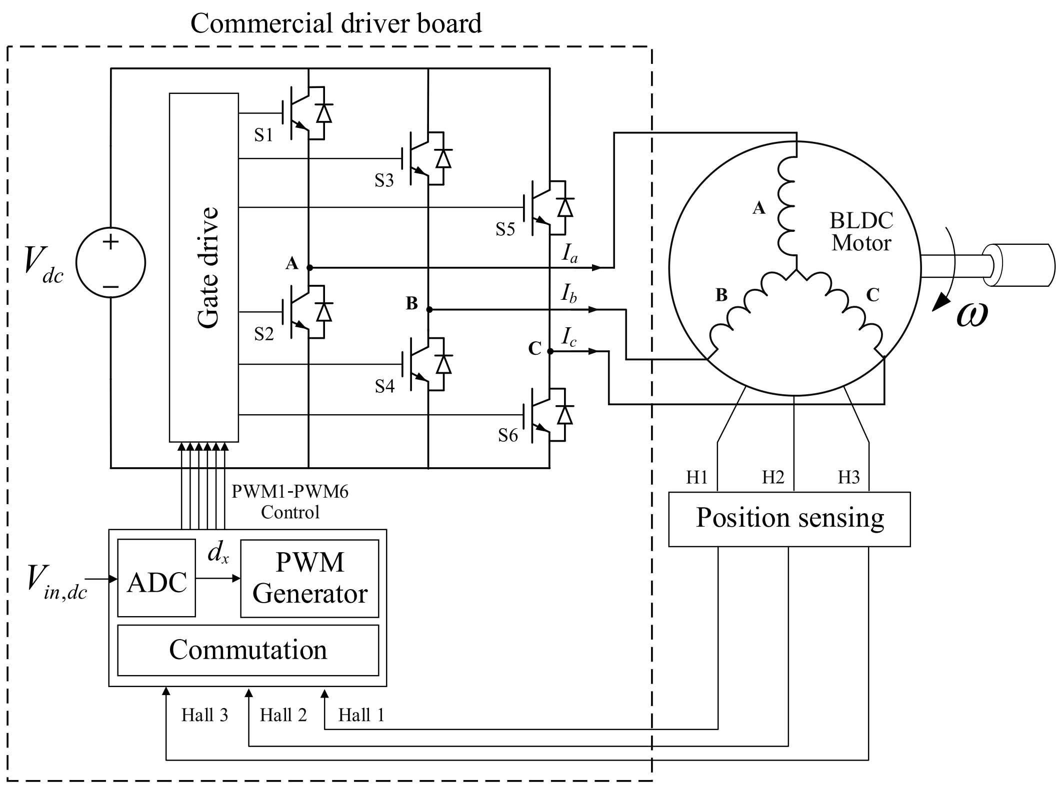

FIGURE 1. BLDC motor with a commercial driver board.

and aircraft because of their high efficiency, low cost of maintenance, and long-life [1], [2]. Generally, a commercial BLDC motor is sold with its driver board. Users can vary the motor speed via the driver board. However, if automatic speed control is required, feedback control must be added to the commercial board.

The dynamic model of the BLDC motor is very important for the design of closed-loop control. The mathematical model of a BLDC motor is very complicated. The commercial BLDC motor consists of Hall sensors to measure the rotor position and a driver board to supply the power from a DC or AC source via an integrated IGBT switch. Therefore, it is very difficult to develop the dynamic model [3] of the commercial BLDC motor for controller design using basic control theory.

In this paper, the adaptive Tabu Search (ATS) algorithm [4], [5], [6] is used for the controller design process. System identification via the ATS is the first step, which is to develop a black-box model representing the input–output relationship. After obtaining the black-box transfer function, the ATS is applied again, in the second step, to design the PID controller. With this 2-step approach using the ATS, a far better speed output performance can be obtained compared to the conventional design approach. In this study, the Ziegler–Nichols method has been selected as the benchmark conventional design method for comparison purposes. This method can be used to design a PID controller without the need for a transfer function. The open-loop response of the Ziegler–Nichols method can be determined by testing.

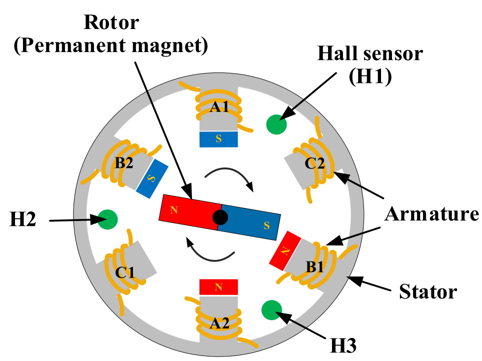

FIGURE 2. Structure of a BLDC motor.

Simulation and experimental results show that the proposed design technique using the ATS algorithm provides better speed response than the Ziegler–Nichols method. From the literature reviews [7], [8], [9], [10], [11], many artificial intelligence techniques were applied to design the optimal controllers. However, the control signal limitation has not been concerned in which it may be saturation when the optimal controller gains are achieved [12]. Therefore, during the design process in this paper, the control signal from the PID controller can be observed when the ATS is used for the design process, while the control signal cannot be considered for the Ziegler–Nichols method. For this reason, PID controller design using the proposed ATS technique can

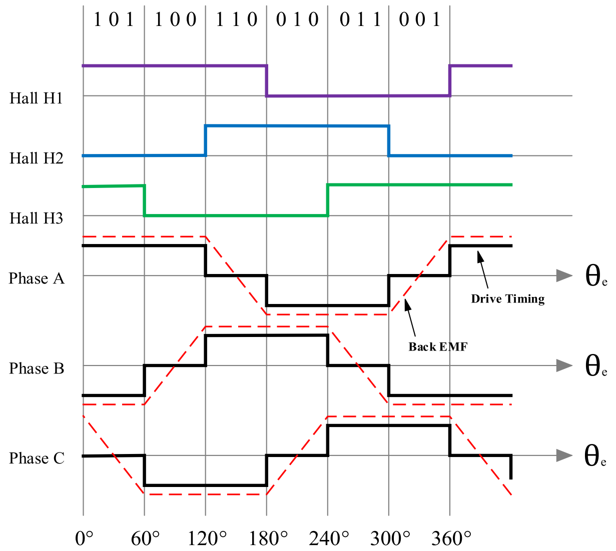

FIGURE 3. Rotating communication sequence.

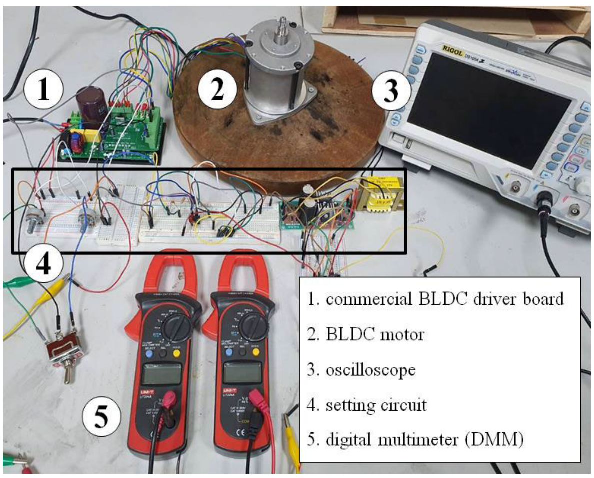

FIGURE 4. Test setup.

guarantee that the resulting PID controller can be implemented with real devices, while the control signal cannot be observed for the Ziegler–Nichols approach. As a result, the Ziegler–Nichols cannot provide as good a practical response as expected.

The proposed design process using the ATS has following main advantages:

1) The ATS algorithm can be efficiently used for both system identification and optimal PID controller design of the commercial BLDC motor with its driver.

2) The resulting PID controller can provide a better response compared to that designed using the conventional Ziegler–Nichols method.

3) The ATS technique considers the control signal during the design process. Therefore, the resulting PID controller can be implemented without any limitations on the control signal. The speed response will be good as expected; however,

TABLE 1. Commercial driver board details.

Power supply voltage	275 V_{rms} (AC) 390 V_{rms} (DC)
Three-Phase Peak Output Current	9.3 A (Peak)
Max controller Motor Speed	50000 rpm
Hall Sensor Reference Voltage Output current	20 mA
Hall Input Voltage range	5.5 V
Speed Frequency Feedback digital Output	1 Hz/10 rpm

TABLE 2. BLDC motor specifications.

Maximum Output Power	471 W
Nominal Voltage	220 V
Rotor/Bearing Rated Speed	23000 rpm
Number of Poles	2

the conventional method cannot achieve the expected speed response.

4) Other artificial intelligent algorithms, such as the genetic algorithm and the particle swarm, can also be applied to obtain an optimal design by following the concept in this paper.

The manuscript is organized as follows. Section I is the introduction. The system considered is explained in Section II. The method for deriving the model of the system considered is presented in Section III. The controller design using both conventional and ATS techniques is described in Section IV. Experimental results are provided in Section V. Finally, the conclusions are addressed in Section VI.

II. SYSTEM CONFIGURATION

In this paper, the system considered is the BLDC motor driven by a commercial driver board, as shown in Figs. 1.

A BLDC motor is developed from a brushed DC motor [13], [14] as the internal structures of the motors are similar. Three sets of coils provide magnetic induction. A brush is not required as in the case of a synchronous three-phase AC motor. That is why a BLDC motor requires a power converter circuit [15]. The structure of a BLDC motor can be shown in Fig. 2.

As shown in Figs. 2, a BLDC motor has three important parts. The first part is a stationary part known as the "stator," which has an armature winding connected to the AC/DC converter. The second is a rotating part, also known as the "rotor," which is a permanent magnet [16]. The operation of the BLDC is based on the simple principle of force interaction (attraction and repulsion) between the permanent magnet (rotor) and the electromagnet (stator), similar to a synchronous AC motor [15]. The third part consists of the position detectors or Hall effect sensors to measure the rotor position. A logic control signal, an electronic switching sequence, is sent to the driver board to control the BLDC motor. The rotating communication sequence is shown in Fig. 3 [17].

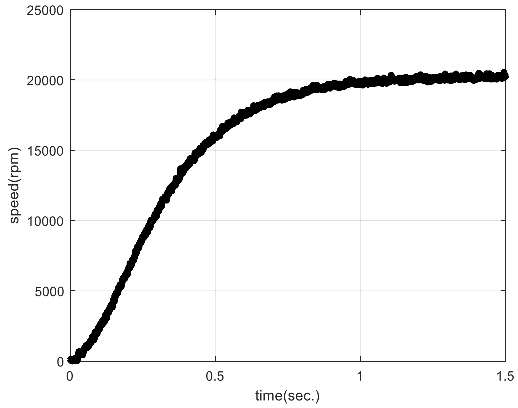

FIGURE 5. Speed response of the BLDC motor.

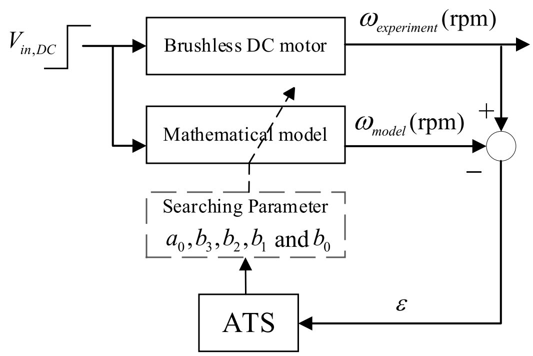

FIGURE 6. The ATS algorithm for the system identification of the BLDC motor and commercial driver board.

In Fig. 1, the input to the PWM generator is a speed control signal d_x which is adjusted by the analog voltage $V_{in,dc}$ applied to the driver board. Therefore, the driver board behaves as an actuator for the open-loop speed control of the BLDC. The connection of the BLDC with the driver board is shown in Fig. 4.

The commercial driver board driving the BLDC for this research as shown in No.1 of Fig.4 is the BLMD-4CTV39-B1P-TSM4 model from Beijing Electechnic Co., LTD. The summarized details from datasheet that is sufficient for the design process are given in Table 1.

As shown in Fig. 4, the setting circuit used in the test system is depicted in No. 4. This circuit consists of a signal conditioner circuit to adjust the signal and a frequency to voltage (F/V) converter. The F/V converter was used to change the variation frequency signal to the analog voltage. As for the BLDC motor, the motor specifications are given in Table 2.

Although the rated speed of the motor is 23000 rpm, this paper will consider 20000 rpm as the rated speed because of the presence of safety of devices. The speed response test results of the BLDC motor at 20000 rpm (rated speed) tested as per Fig. 4 are shown in Fig. 5. $V_{in,dc}$ is set to 3.7 V to match the commercial driver board rating.

TABLE 3. Coefficients obtained by the ATS method.

Coefficient	Value
a_0	0.2059 x 10^8
b_3	0.0597
b_2	31.2477
b_1	364.4712
b_0	1069.9862

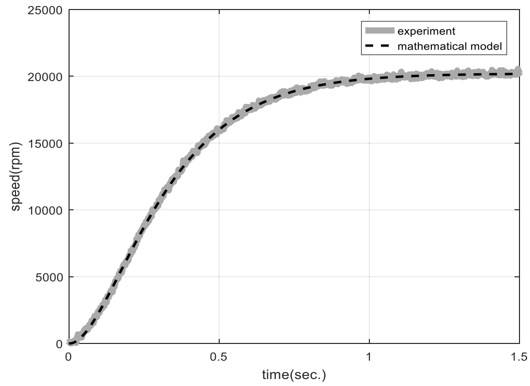

FIGURE 7. Model validation.

The speed response in Fig. 5 will be used with the ATS algorithm to develop the dynamic model of the BLDC motor and commercial driver board. Then the dynamic model will be used to design the speed controller of the proposed BLDC motor.

III. DYNAMIC MODEL DERIVATION

There are two ways to develop the dynamic model of a physical system. One is by exact topology analysis in which basic electrical circuit and machine theories are directly applied to generate a dynamic model. The second is the black-box transfer function approach in which the model parameters are unknown terms in the polynomial equation used to describe the dynamic behavior of the system. For the proposed BLDC motor and commercial driver board considered in this paper, deriving the model directly using basic engineering theories is a very complex approach. Moreover, the system parameters are difficult to measure. Therefore, this paper will present the black-box model using a 3rd degree polynomial equation as the transfer function of the system [3]. The proposed model is a simple transfer function in terms of speed output $\Omega(s)$ and dc input voltage $V_{in,dc}(s)$ as given in (1).

$$G(s) = \frac{\Omega(s)}{V_{in,dc}(s)} = \frac{a_0}{b_3 s^3 + b_2 s^2 + b_1 s + b_0} \quad (1)$$

In equation (1), there are five unknowns which can be determined by the ATS algorithm. The set of parameters to be determined for the system identification is $[a_o, b_o, b_1, \ldots, b_3]$. The details of the ATS algorithm are given in the Appendix. The ATS parameters obtained through the system identification process by trial and error are as follows: radius equal

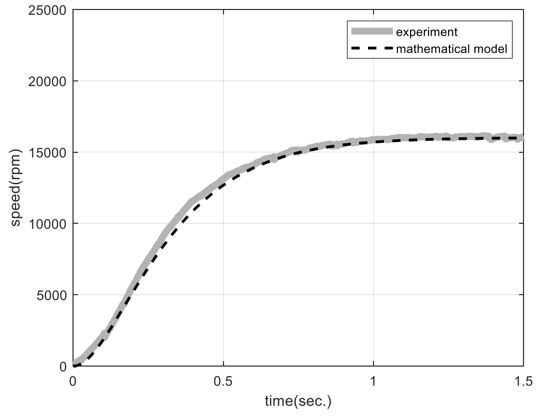

FIGURE 8. Comparison of motor speed response at 16000 rpm.

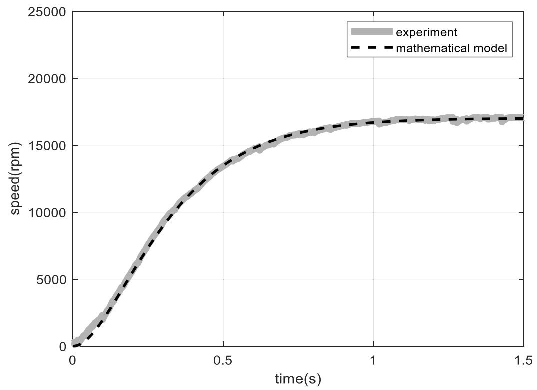

FIGURE 9. Comparison of motor speed response at 17000 rpm.

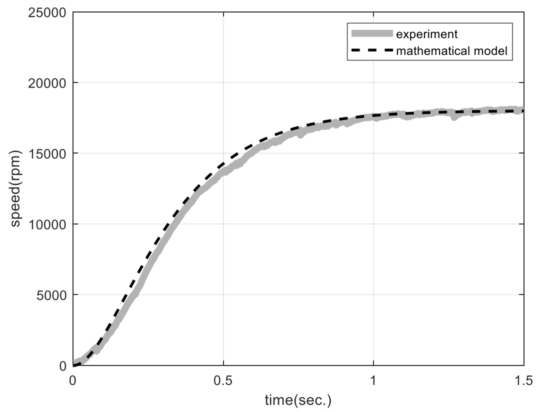

FIGURE 10. Comparison of motor speed response at 18000 rpm.

to 30, decreasing factor (DF) equal to 1.08, initial number of neighbors equal to 150, and number of neighbors equal to 250. The application of the ATS algorithm to identify the dynamic model of the proposed driven BLDC motor is shown in Fig. 6.

As shown in Fig. 6, the process of system identification using the ATS starts with the speed response of the real BLDC motor. In this paper, the real speed response obtained from the experiment and shown in Fig. 5 was used and set as $\omega_{experiment}$

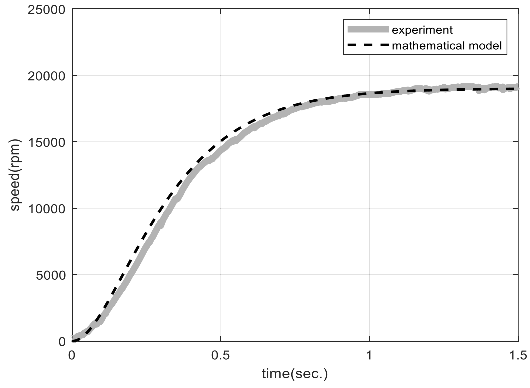

FIGURE 11. Comparison of motor speed response at 19000 rpm.

in Fig.6. Then, using the same step input $V_{in,dc}$ as for the dynamic model given in (1), the speed response obtained from the ATS model is ω_{model}, as shown in Fig. 6. During the parameter search process, the ATS tunes the system parameters a_o, b_o, b_1, b_2, *and* b_3 until the error between $\omega_{experiment}$ and ω_{model} is minimized. If this error (ε), calculated as per equation (2), is less than 0.01, the search process is stopped. This means that the transfer function, as given by (1) with the system parameter values obtained from the ATS search, can describe the behavior of the proposed BLDC motor system accurately. The speed responses of the real system and the model for the same input $V_{in,dc}$ are nearly the same with only a small difference ε. The objective of the ATS algorithm is to minimize the error in the speed response as calculated by (2).

$$\varepsilon = \sqrt{\frac{\Sigma error^2}{n}} = \sqrt{\frac{\Sigma \left(\left|\omega_{experiment} - \omega_{model}\right|\right)^2}{n}} \tag{2}$$

The search results are shown in Table 3. The transfer function of the proposed BLDC motor and commercial driver board is given by (3). To validate the resulting model given by (3), the speed response for 20000 rpm was compared with the experimental result, as illustrated in Fig. 7.

As shown in Fig.7, the resulting dynamic model with the parameters obtained from the ATS algorithm can provide the same speed response as obtained from the experiment. Fig.7 shows the results only at the rated speed of 20000 rpm, which was used in the search process. To ensure that the resulting model can be used for other operating points also, the comparison results at 16000, 17000, 18000, and 19000 rpm are shown in Figs. 8 to 11, respectively.

$$G(s) = \frac{0.2059 \times 10^8}{0.0597s^3 + 31.2477s^2 + 364.4712s + 1069.9862} \tag{3}$$

Fig. 7 shows that the speed values of the model match the experimental values in both the transient and steady states. Although the motor response at different speeds was used to confirm the performance as shown in Fig. 8 to 11, different speed values were not used for the parameter identification

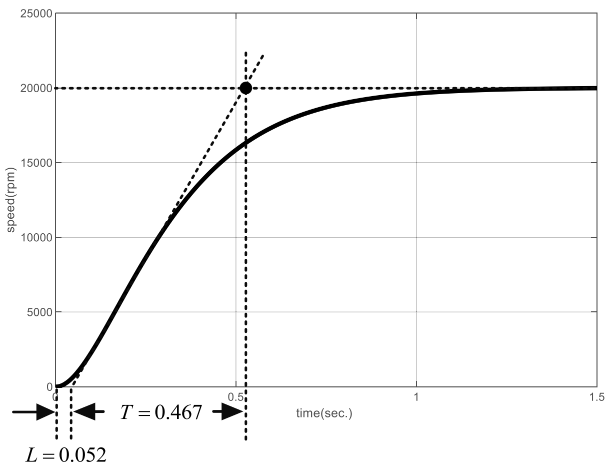

FIGURE 12. Obtaining L and T values for Method 1 of the Ziegler–Nichols approach.

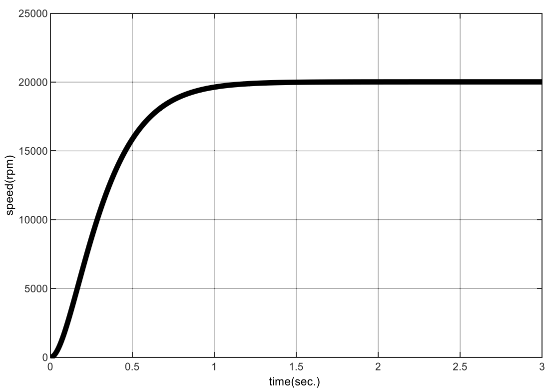

FIGURE 13. Motor speed response obtained by simulation for the PID controller designed using the Ziegler–Nichols approach when the command speed equals 20000 rpm.

process; however, the accuracy is still within acceptable limits. These results confirm that the ATS method can be used to identify the model of a BLDC motor and its commercial driver board. The model is accurate and suitable for the controller design in the next step. Note that the BLDC model normally is nonlinear. As for the controller design, the model in the form of linear (transfer function) around the operating point, here is the rated speed 20000 rpm is required. If other speed responses far away from the 20000 rpm are used, the unique transfer function with a good accuracy cannot be obtained. This is why 16000 17000 18000 19000 rpm responses were used for the model validation as depicted in Fig. 8 to 11. Using resulting transfer function model for the controller design, the good speed responses can be achieved.

IV. PID CONTROLLER DESIGN

After the open-loop characterization of the BLDC motor and its commercial driver board based on the black-box model, a 3rd-order transfer function was identified in Section III.

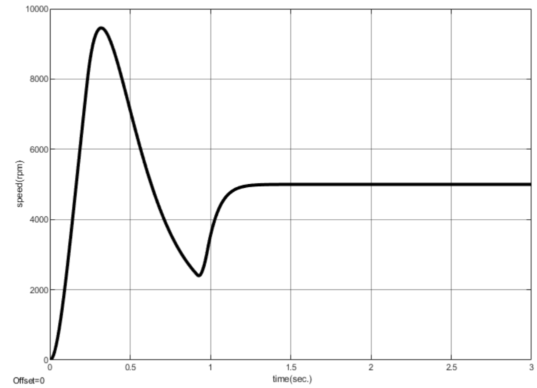

FIGURE 14. Speed control response obtained by simulation using the PID controller derived using the Ziegler–Nichols approach at 5000 rpm.

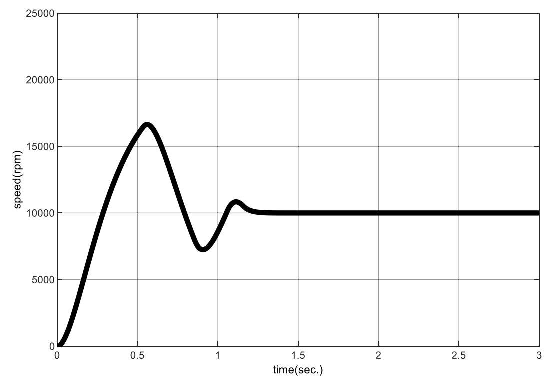

FIGURE 15. Speed control response obtained by simulation using the PID controller derived using the Ziegler–Nichols approach at 10000 rpm.

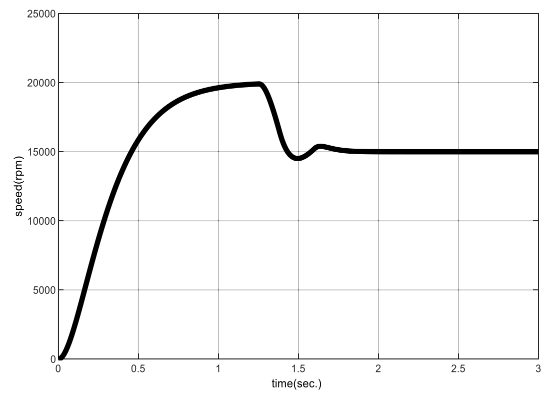

FIGURE 16. Speed control response obtained by simulation using the PID controller derived using the Ziegler–Nichols approach at 15000 rpm.

In this section, the design of a PID controller for BLDC motor speed regulation is illustrated. Two approaches to designing a PID controller will be discussed in this paper: the Ziegler–Nichols approach is presented as the conventional method and the artificial intelligence approach using the ATS approach is the proposed method to improve the speed response performance.

A. ZIEGLER–NICHOLS APPROACH

The Ziegler–Nichols approach is widely used for designing PID controllers [18]. It includes two methods. For Method 1

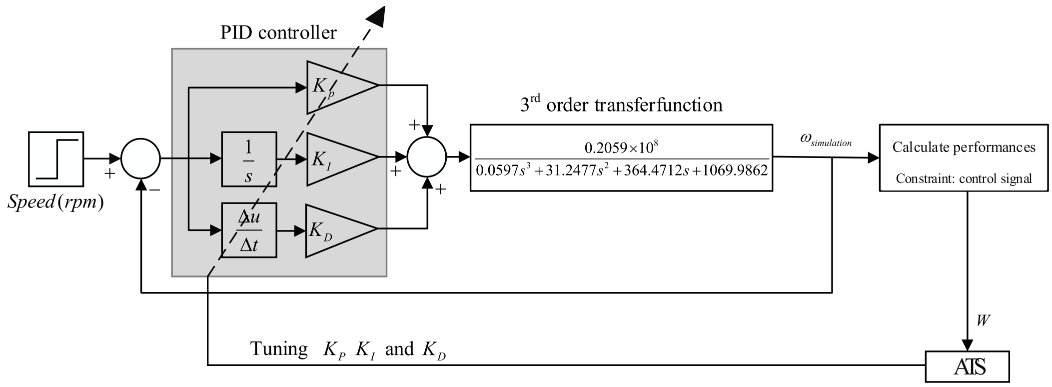

FIGURE 17. PID controller design diagram.

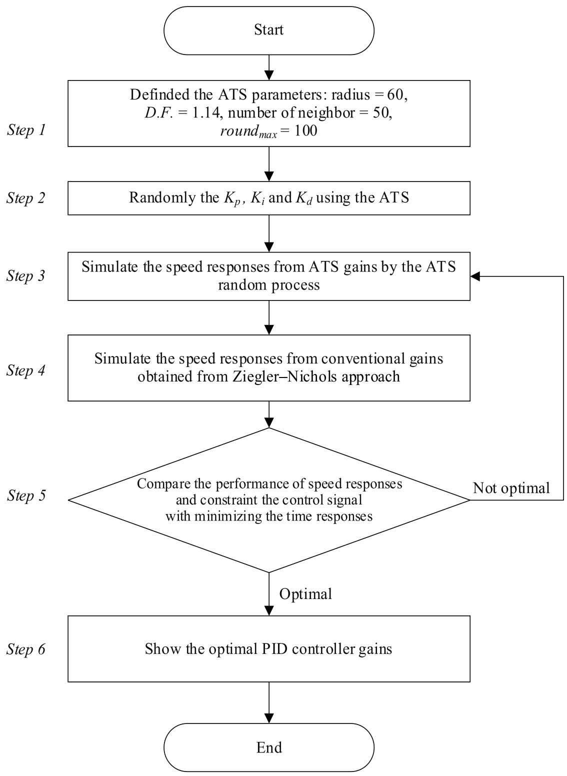

FIGURE 18. ATS procedure for PID controller design.

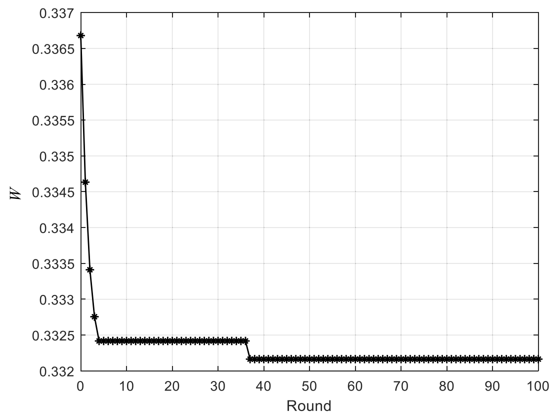

FIGURE 19. Convergence result of PID controller design using ATS.

to be used, the response of the system to a unit step input must be s-shaped. This solution applies to systems with actuators, and is known as an open-loop control system. If the unit step response is not s-shaped, Method 2, which is applicable to a closed-loop system, is used to obtain the gain at which the system starts to oscillate. The open-loop speed response of the BLDC motor with the commercial driver board to a unit step input, as shown in Fig. 5, was an s-shaped response. Therefore, the design of the PID controller relies on Method 1. The necessary information for applying Method 1 is shown in Fig. 12.

The values of L and T are obtained from Fig. 12. These L and T values will be used to design the PID controller using the Ziegler–Nichols approach [18]. The resulting values of the PID controller are $K_P = 10.7769$ $K_I = 103.6240$, and $K_D = 0.2802$. As the control signal is normally not considered during the design process, the response of the resulting controller may not be as good as expected due to the limitation of the control signal. For example, if an op-amp is used for the PWM, the control signal is limited to ∼15V. Therefore, for performance validation, the simulation on MATLAB is carried out by including the control signal limitation. Also, the input voltage $V_{in,dc}$ is limited to 1.28V to 3.83V as specified in the datasheet. Fig. 13 shows the speed response of the PID controller, designed with the conventional approach, when the command speed is equal to 20000 rpm.

To confirm that the PID controller designed using the Ziegler–Nichols approach can control the speed of the BLDC motor and the commercial driver board for various speeds, the responses at 5000, 10000, and 15000 rpm were compared, as shown in Figs. 14 to 16, respectively.

As shown in Figs. 13, the speed response from the simulation is able to control the speed of the BLDC motor. However, the responses at other operating points, as shown in

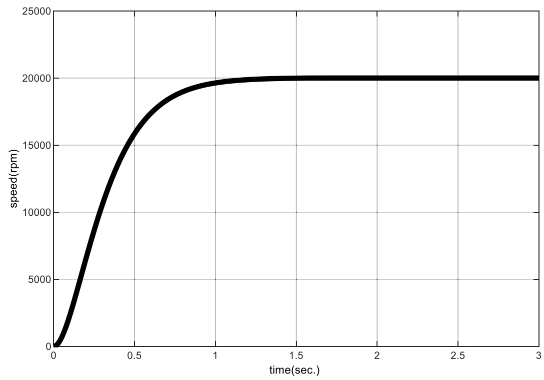

FIGURE 20. Simulated speed response of the PID controller designed using the ATS approach at 20000 rpm.

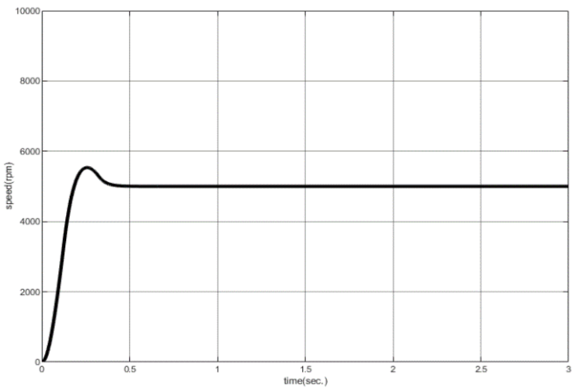

FIGURE 21. Simulated speed response of the PID controller designed using the ATS approach at 5000 rpm.

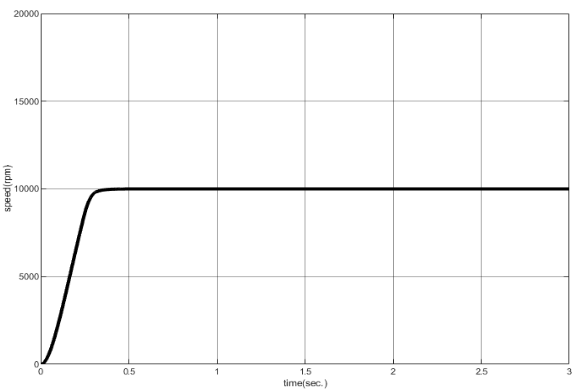

FIGURE 22. Simulated speed response of the PID controller designed using the ATS approach at 10000 rpm.

Figs. 14 to 16, are not as good as expected. This is because the Ziegler–Nichols approach does not consider the limitation. of the voltage control signal. This causes an overshoot and slight oscillation before converging to a steady state value. In this paper, the ATS approach takes into account the control signal limitation during the design process. As a result, the speed performance can be improved. The method for applying the ATS algorithm to the PID controller design will be discussed in the following sections.

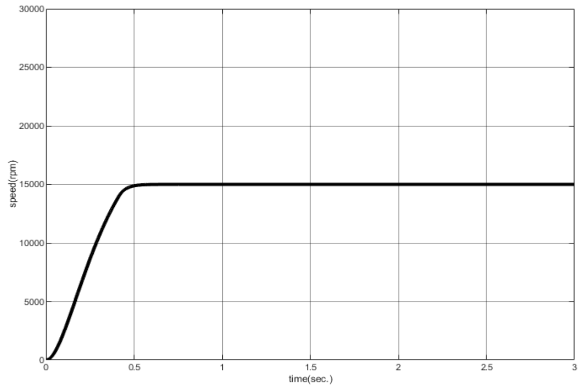

FIGURE 23. Simulated speed response of the PID controller designed using the ATS approach at 15000 rpm.

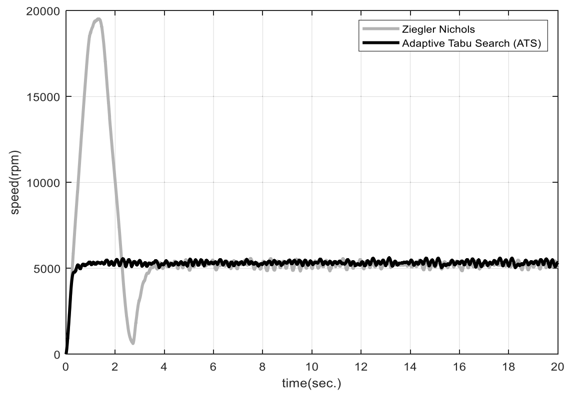

FIGURE 24. Comparison of speed response at 5000 rpm.

B. ATS APPROACH

A PID controller design using an artificial intelligence method called the ATS algorithm is presented in this section [19]. During the design process, the limitation of $V_{in,dc}$, as specified in the datasheet, can be considered in which it is equal to 3.83 V. In this paper, the main idea is to present the applications of artificial intelligent techniques for the identification and the optimal controller design. However, the ATS was selected to show the effectiveness of the AI technique. The design concept as presented in this paper shows that it is very flexible. Therefore, other AI techniques can be applied following the proposed idea. Referring to Fig.17, other AI algorithms can be used instead of ATS block for tuning K_P, K_I and K_D, while the rest blocks have remained the same. Following the concept explained in the manuscript, the better responses can be achieved compared with those from the conventional controller design process.

Using the Fig. 17 design, the proposed model from the previous section will be used to simulate the closed-loop response using Simulink blocks in the MATLAB program. The response will be calculated the performance during the ATS process to obtain the optimal PID coefficients. Moreover, in the ATS process, the control signal is also computed as a constraint. If the signal exceeds the $V_{in,dc}$ range, the cost

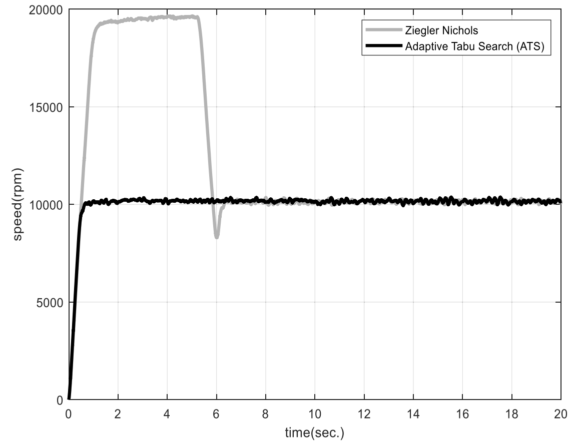

FIGURE 25. Comparison of speed response at 10000 rpm.

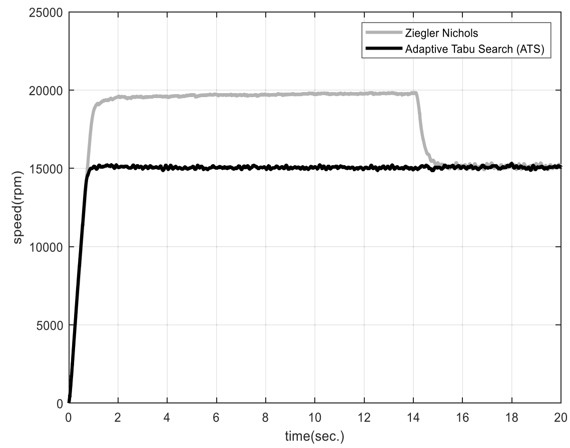

FIGURE 26. Comparison of speed response at 15000 rpm.

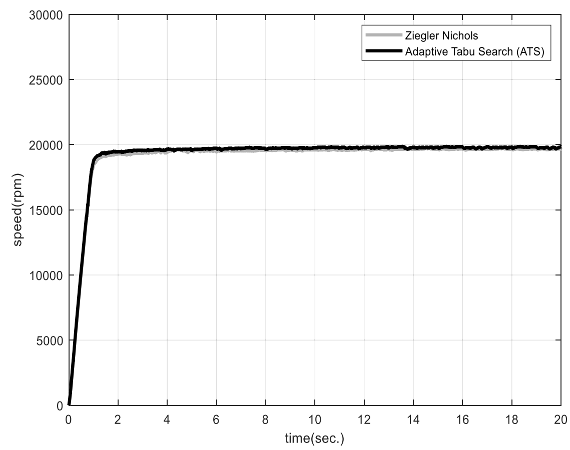

FIGURE 27. Comparison of speed response at 20000 rpm.

will be set to a huge value as a penalty. The objective function (W) of the ATS design processes is the absolute square errors between the output responses controlled by PID controller ($\omega_{simulation}$) and unit step reference. The ATS will search the controller parameters until the minimum W can be achieved.

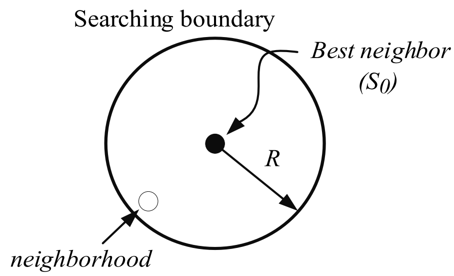

FIGURE 28. Comparison of speed response at 20000 rpm.

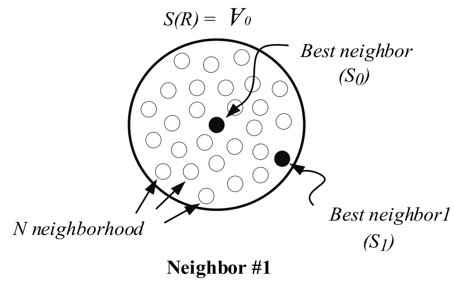

FIGURE 29. Neighborhood solutions around S_0.

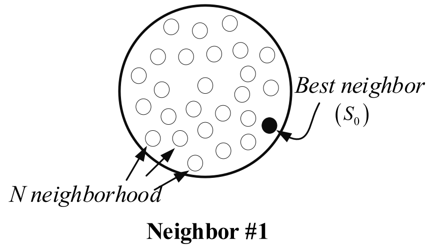

FIGURE 30. Define a new S_0.

It means that the resulting output response is very closed to the command input. As a result, the best speed response can be obtained when the controller designed by the proposed method is applied. As for the penalty condition, if the control signal is larger than 3.83 V, W will be set as a huge value ($W = 1000$).

The ATS steps based PID controller design diagram are shown in Fig. 18. After the searching process is completed, the W is minimized equal to 0.3322 in which the convergence of W is shown in Fig. 19.

The obtained parameter values of the PID controller designed using the ATS approach are $K_P = 10.7166$ $K_I = 0.0011$, and $K_D = 0.4351$. The simulated speed response at 20000 rpm is shown in Fig. 20.

To confirm that the PID controller designed using the ATS approach can control the various speeds of the BLDC motor with its the commercial driver board, the responses at 5000, 10000, and 15000 rpm are shown in Fig. 21 to 23, respectively.

Fig. 20 to 23 show that the speed responses of the PID controller designed using the ATS algorithm are better than those of that designed using the Ziegler–Nichols approach. The constraint on the control signal considered here is the value of $V_{in,dc}$, and the ATS algorithm provides a good speed response performance.

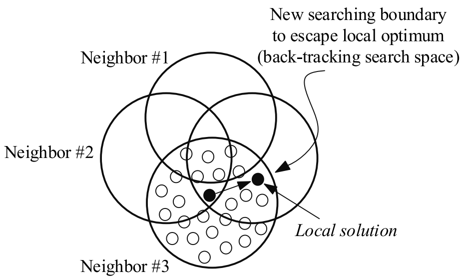

FIGURE 31. Back-tracking mechanism.

V. EXPERIMENTAL RESULT

The PID controllers designed by Ziegler–Nichols approach and the ATS approach in Section IV were implemented using the test rig shown in Fig. 4. The PID controller was built, as shown in Section IV of Fig. 4, by using the ATmega2560 microcontroller board. The responses at 5000, 10000, 15000, and 20000 rpm from the experiment are shown in Figs. 24 to 27, respectively.

As shown in Figs. 24 to 27, the speed responses of the closed-loop system of the experimental test setup using the PID controller designed using the ATS approach are better than those of that designed using the Ziegler–Nichols approach. This is because, in the ATS approach, the search for the PID controller coefficients takes into account the limitation of the control signal.

VI. CONCLUSION

This paper presents a new way to design a PID controller for a BLDC motor with a commercial driver board using the ATS algorithm. The ATS can be applied to both, the derivation of the mathematical model of the BLDC and the controller design. The results from simulation and testing show that the speed responses of the BLDC motor using the PID controller designed using the proposed ATS method are better than those of the controller designed using the conventional method. The responses are good as expected because the limitation of the control signal based on the specifications of the real component can be taken into account during the design process. Other artificial intelligence techniques, such as the genetic algorithm and particle swarm optimization, can also be applied using the approach described in this paper.

APPENDIX

The ATS algorithm is one of the most widely used artificial intelligence methods. The algorithm, developed from the Tabu Search (TS), aims to improve the efficiency of finding solutions by adding the back-tracking mechanism and adaptive boundary radius. In addition, the ATS method has also proven that it can escape the local solution and rapidly converge to the best global solution [20], [21]. The details of the ATS search process are listed as follows:

Step 1: Define the search parameters: boundary, radius, and the maximum iteration $round_{\max}$.

Step 2: Randomly set the initial value of S_0, the search boundary. The S_0 in this process will be set as the local optimal solution, as shown in Fig. 28.

Step 3: Randomly choose N new solutions around S_0 within the boundary. Let $S\,(R)$ be a solution set with N number of solutions as shown in Fig. 29.

Step 4: Evaluate each of solution member of $S\,(R)$ using the objective function. S_1 will be set as the best solution of $S\,(R)$ as shown in Fig. 29. Chose the best solution and let it be the *Best neighbor* 1 in the Tabu list (see in Fig. 29).

Step 5: If *Bestneighbor* 1 is better than *Best neighbor*, it will be defined as *Best neighbor* equal to *Best neighbor* 1 in the Tabu list, as seen in Fig. 30. However, if there is no *Best neighbor* 1, the search process will go back to step 3 until the best solution is discovered under $round_{\max}$.

Step 6: The back-tracking mechanism will be started if the solutions in each round do not escape from the local solution. This mechanism will choose the best solution from the Tabu list and it will be defined as the initial solution for the next iteration, as shown in Fig. 31.

Another mechanism added in the conventional TS is the adaptive radius. This mechanism will always decrease the radius, as expressed in (A-1).

$$radius_{new} = \frac{radius_{old}}{DF} \tag{A-1}$$

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