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The Optimal Indirect Vector Controller Design via an Adaptive Tabu Search Algorithm

P. Sawatnatee, S. Udomsuk, K-N. Areerak, K-L. Areerak, A. Srikaew

Abstract**—**The paper presents how to design the indirect vector control of three-phase induction motor drive systems using the artificial intelligence technique called the adaptive tabu search. The results from the simulation and the experiment show that the drive system with the controller designed from the proposed method can provide the best output speed response compared with those of the conventional method. The controller design using the proposed technique can be used to create the software package for engineers to achieve the optimal controller design of the induction motor speed control based on the indirect vector concept.

Keywords**—**Indirect Vector Control, Induction Motor, Adaptive Tabu Search, Control Design, Artificial Intelligence.

I. Introduction

THE induction motor is widely used in industries because it is simple, easy to use, low maintenance, and high efficiency. There are two mains control techniques of the induction motor. The first is the scalar method called v/f constant, while another technique is the vector control. This paper focuses on the vector control techniques because these techniques can directly control torque of the motor. Therefore, the better speed performance can be achieved compared with those of v/f constant method. As for the vector control method, it consists of two types, namely direct and indirect vector control. The direct vector control uses the rotor flux measurement inside the control process [1], [2]. Hence, the control system becomes more complex. To solve the measurement problem, the indirect vector control [3], [4] is applied to the induction motor drive system, in which the rotor flux can be approximated by using motor parameters.

In addition, it is well known that the artificial intelligence (AI) techniques have widely been applied to many works of engineering such as the system identification using an adaptive tabu search (ATS) [5]-[9], the protection design of the relay via the ATS [10], the active power filter design using a genetic algorithm (GA) [11], power loss minimization using a particle swarm optimization (PSO) and an artificial bee colony (ABC) [12], reactive power optimization for distribution systems based on an ant colony optimization (ACO) [13]. From the literature reviews, the ATS algorithm has the mathematical proof to confirm that the algorithm can escape the local solutions [7]. Hence, in the paper, the ATS algorithm is selected to design the controller of the indirect vector control of the machine. The expected result is that the best performance in the speed response of the motor will be achieved.

The paper is structured as follows. In Section II, considered power system is firstly explained. In Section III, the controller design using the conventional method is illustrated. The review of ATS algorithm is also addressed in Section IV. The indirect vector controller design using the ATS method is then explained in Section V. The simulation results are fully given in Section VI. Moreover, the experimental result is shown in Section VII to confirm that the proposed design technique can improve speed response compared with the conventional method. Finally, Section VIII concludes and discusses the advantages of the proposed technique for the optimal controller design of the drive systems.

II. System Considered

The considered power system is depicted in Fig. 1 as a standard motor drive indirect vector control of an induction motor (IM) [14]. The motor is vector-controlled in a rotating dq frame aligned with the rotor flux [14], [15]. For q-axis, there are two PI controllers for the speed loop control (outer loop) and the current loop control (inner loop), while only one PI current loop control is used for the d-axis. Both current loop controllers for dq-axis are identical. The flux of the IM can be controlled via the d-axis. In addition, motor torque and speed can be controlled via the q-axis. The more details of indirect vector control can be found in [14], [15].

This paper presents the application of AI techniques called ATS algorithm to design the controllers for the indirect vector control of Fig. 1. These controllers can provide the better speed performance compared with those using the controller designed from the conventional method. The IM parameters are used for the controller design via the conventional method. These parameters can be determined from the testing. The IM parameters of the machine for the work of this paper are shown in Table I.

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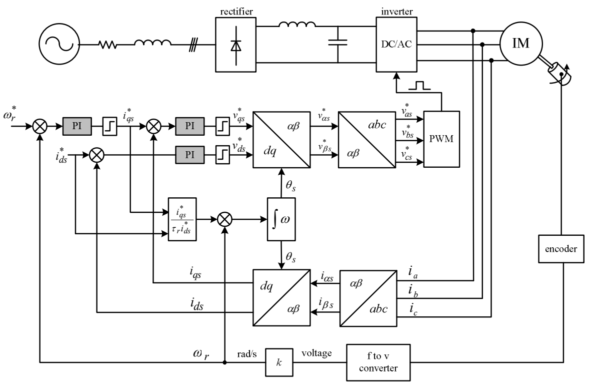

Fig. 1 System considered

TABLE I
THE IM PARAMETERS

IM Parameters	Value
R_s	25.13 Ω
L_{ls}	0.0866 H
L'_{lr}	0.0866 H
L_M	0.9672 H
R'_r	20.79 Ω
J	0.0072 Kg.m^2

III. CONVENTIONAL METHOD

The details how to design the indirect vector controllers using conventional method are as follow:

The schematic of the current loop control of the system in Fig. 1 is shown in Fig. 2.

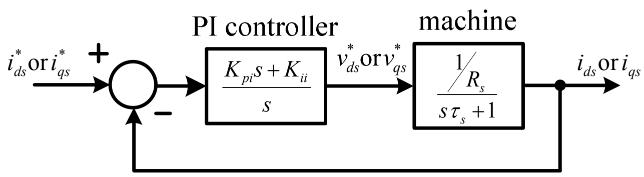

Fig. 2 Block diagram for a current loop

A. Current Loop Control

In Fig. 2, the K_{pi} and K_{ii} are the PI parameters of current loop control for both d- and q- axis, while R_s and τ_s are the IM parameters as given in Table I. Closed loop transfer function of the current loop is given by (1).

$$\frac{i_{ds}}{i^*_{ds}} = \frac{i_{qs}}{i^*_{qs}} = \frac{\left(K_{pi}s + K_{ii}\right)/R_s\tau_s}{s^2 + \left(\left(R_s + K_{pi}\right)s/R_s\tau_s\right) + \left(K_{ii}/R_s\tau_s\right)} \quad (1)$$

The closed loop denominator has roots with $\omega_{ni}$and ζ. The standard second order form is

$$D(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (2)$$

Hence, the current loop controller can be designed by comparing between the denominator of (1) and (2) to yield:

$$\left.\begin{aligned} K_{pi} &= 2\zeta\omega_{ni} \times R_s\tau_s - R_s \\ K_{ii} &= \omega_{ni}^2 \times R_s\tau_s \end{aligned}\right\} \quad (3)$$

where τ_s is equal to $\frac{(L_{ls}+L_M)}{R_s} - \frac{L_M^2}{R_s(L_{ls}+L_M)}$.

B. Speed Loop Control

The schematic of the speed loop control of the system in Fig. 1 is shown in Fig. 3.

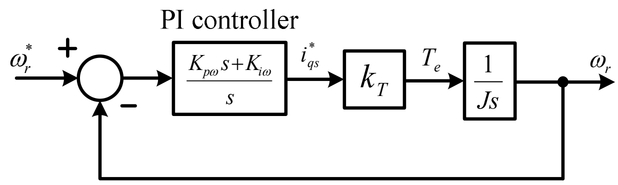

Fig. 3 Block diagram for a current loop

In Fig. 3, the $K_{p\omega}$ and $K_{i\omega}$ are the PI parameters of speed loop control, while k_T and J are the IM parameters. Closed loop transfer function of the speed loop is given by:

$$\frac{\omega_r}{\omega_r^*} = \frac{k_T\left(K_{p\omega}s + K_{i\omega}\right)/J}{s^2 + \left(k_T K_{p\omega}s/J\right) + \left(k_T K_{i\omega}/J\right)} \quad (4)$$

Therefore, the speed loop controller can be also designed by comparing between the denominator of (4) and (2) to yield:

$$\left.\begin{aligned} K_{p\omega} &= 2\zeta\omega_{ns} \times J/k_T \\ K_{i\omega} &= \omega_{ns}^2 \times J/k_T \end{aligned}\right\} \quad (5)$$

where $k_T = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_M^2}{L'_{lr}}\right)$

It can be seen in (3) and (5) that the PI controller parameters depends on the IM parameters, in which these parameters used in the paper were determined from the experiment as depicted in Table I.

IV. ATS ALGORITHM

The ATS algorithm is improved from the Tabu Search (TS) method by adding two mechanisms namely back-tracking and adaptive search radius. The modified version of the TS method has been named the adaptive tabu search of ATS. The ATS algorithm can be outlined as follows:

Step I: Initialize the tabu list *TL*, and *Count* (a number of search round) = 0.

Step II: Randomly select the initial solution S_0 from the search space. S_0 is set as a local minimum and S_0 = *best_neighbor* as shown in Fig. 4.

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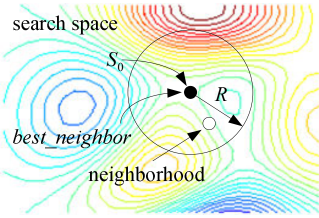


Fig. 4 Random S_0 in search space

Step III: Update *Count*, then randomly select *N* new solutions from the search space of a radius *R*. Let $S_1(r)$ be a set containing *N* solutions as shown in Fig. 5

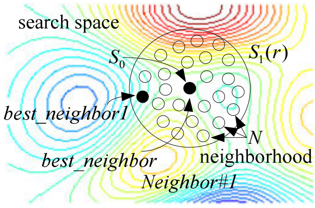


Fig. 5 Neighborhood around S_0

Step IV: Compute the cost value of each member of $S_1(r)$. Then, choose the best solution and assign it as *best_neighbor1* (see Fig. 5).

Step V: If *best_neighbor1<best_neighbor*, then keep *best_neighbor* in the *TL*, set *best_neighbor* = *best_neighbor1* (see Fig. 6), and set S_0 = *best_neighbor* (see Fig. 7). Otherwise, put *best_neighbor1* in the *TL* instead.

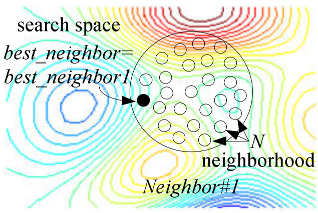


Fig. 6 Assign a new *best_neighbor*

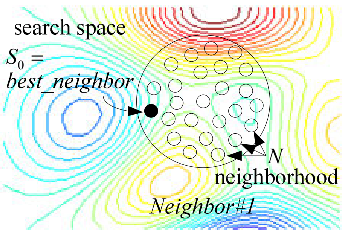


Fig. 7 Assign a new S_0

Step VI: Evaluate the termination criteria (*TC*) and the aspiration criteria (*AC*). If *Count*≥*MAX_Count* (the maximum number allowance of search round), stop the searching process. The current best solution is the overall best solution. Otherwise, go back to Step 2 and start the searching process again until all criteria is satisfied (see Fig. 8).

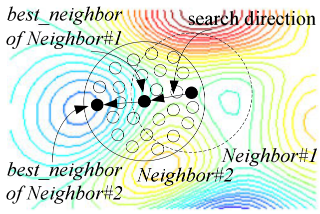


Fig. 8 Searching process in the next iteration

The back-tracking process allows the system to go back and look up the previous solutions in *TL*. The better solution is then chosen among the current and the previous solutions. Fig. 9 illustrates details of the back-tracking process.

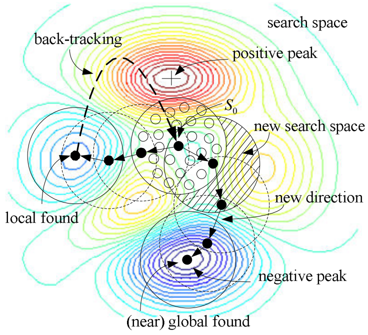


Fig. 9 Back-tracking in ATS algorithm

Given this new search space to explore, the search process is likely to have more chances of escaping from the local optimum. The back-tracking mechanism can be added into Step 5 to improve the searching performance.

The adaptive radius process as depicted in Fig. 10 decreases the search area during the searching process. The adaptive radius mechanism has been developed to adjust the radius (*R*) by using the cost of the solution. The criterion for adapting the search radius is given in (6).

$$radius_{new} = \frac{radius_{old}}{DF} \quad (6)$$

where *DF* is a decreasing factor. The adaptive search radius mechanism can be added into the end of Step 6 to improve the searching performance. The more details of ATS algorithm can be found in [7].

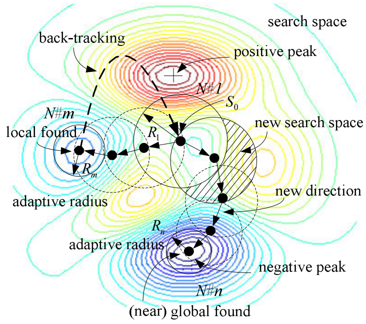


Fig. 10 ATS algorithm with adaptive search radius mechanism

V. The Optimal Controller Design Using ATS Method

In this section, the optimal PI controller design for the IM drive system via the ATS method is illustrated. The ATS algorithms are used to determine the appropriate PI controller parameters, here are K_{pi}, K_{ii}, $K_{p\omega}$, and $K_{i\omega}$ of both current loop and speed loop controls to achieve the best output performance compared with those designed from the conventional method. The block diagram to explain how to design the PI parameters using ATS algorithm is shown in Fig. 11.

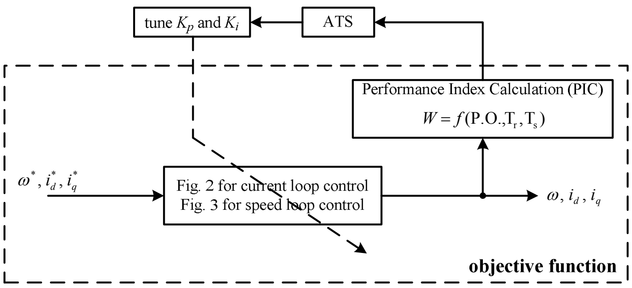


Fig. 11 The ATS algorithm for the PI controller design

In Fig. 11, the ATS algorithm will search the appropriate PI controller parameters. These parameters are used with the block diagram in Figs. 2 and 3 to simulate the system for current loop and speed loop, respectively. The output response of current loop or speed loop is then used to calculate the W value in which this value represents a performance index for each searched controller parameter determined from the ATS. The ATS will search the appropriate parameters until the minimum value of W is obtained. It means that the controller parameters from the searching process provide the best performance of the current or speed response. The W value can be defined by

$$W(T_r, T_s, P.O.) = \sigma T_r + \alpha T_s + \gamma P.O. \qquad (7)$$

and

$$\sigma + \alpha + \gamma = 1 \qquad (8)$$

where

$P.O.$ is the percent overshoot of the v_o response.

T_r is the rise time of the v_o response.

T_s is the setting time of the v_o response.

σ, α, and γ are the priority coefficients of T_r, T_s, and $P.O.$, respectively.

Note that, in this paper, the values of σ, α, and γ are set to 0.34, 0.33, and 0.33, respectively.

According to Fig. 11, the steps of searching controller parameters by using ATS can be summarized as follow:

Step 1. Determine the boundary of parameters. In this paper, the upper and lower limits of K_{pi}, K_{ii}, $K_{p\omega}$, and $K_{i\omega}$ are set to [10 300], [10000 100000], [0.1 0.5], [1 30], respectively.

Step 2. Define the initial value for each parameter by random within the search space.

Step 3. Define the radius value (R), the one of ATS parameters.

Step 4. Define the condition for ATS back tracking.

Step 5. Define the cost value, here is W calculated from (7).

Step 6. Define the maximum of searching iteration for ATS ($count_{max}$). This value is set as a stop criterion for ATS algorithm. In this paper, it is equal to 300 iterations. Note that the more details of ATS algorithm can be found in [7].

VI. Simulation Results

The system of Fig. 1 having the different controllers parameters designed from the ATS and conventional methods was simulated by using SPS^{TM} in SIMULINK. The resulting PI controller parameters with their performance index represented by the W values are given in Table II.

TABLE II
The Comparison Result between ATS and Conventional Methods

PI Controller Parameters	Design Method	
	ATS Method	Conventional Method
K_{pi}	299	150
K_{ii}	46451	69094
$W_{\text{current loop}}$	0.4	1
$K_{p\omega}$	0.5	0.5448
$K_{i\omega}$	14	42.794
$W_{\text{speed loop}}$	0.6058	1

According to Table II, the controllers designed from the ATS method provide the minimum W value compared with those of the conventional method. Fig. 12 show the speed response during start-up time to 668 rpm (ω_r^* = 668 rpm) and taking load torque 1.5 N.m. into the IM at t = 1 s.. The comparison results show that the output responses when the controllers designed by the ATS method are better than that from the conventional method in terms of percent overshoot, rise time and setting time under the changing of command input and taking load.

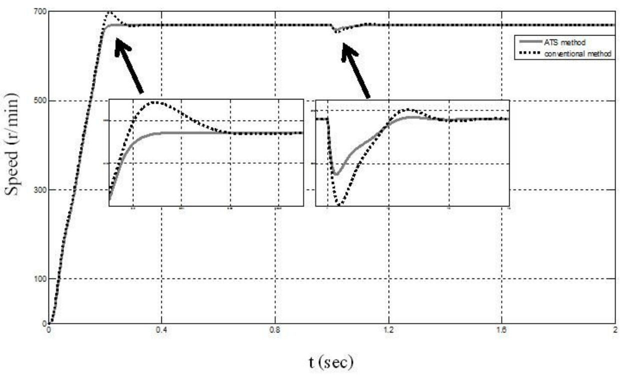
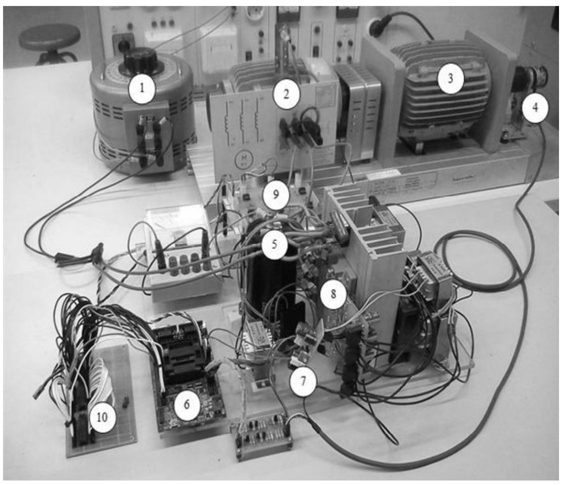


Fig. 12 The comparison results of speed responses between Conventional and ATS methods

VII. Experimental Results

The test rig of the system in Fig. 1 is shown in Fig. 13. This rig was implemented for the experimental validation.

The controller of the rig was implemented using the DSP eZdsp^{TM} F28335 as shown in the rig in number 6 of Fig. 13. The inverter has been constructed using 50A and 1200 V. The PI controller parameters as shown in Table II were coded in the DSP eZdsp^{TM} F28335. The comparison of the output speed responses between the controllers designed from the conventional and ATS methods for a step change of the speed command ω_r^* from 0 rpm to 668 rpm that occurs at t = 3 s. is given in Fig. 14.



1. Single-Phase Voltage Source	6. Indirect-Vector Control
2. Induction Motor	7. f to v Converter
3. Load	8. Inverter
4. Rotary Encoder	9. Current Sensor
5. Diode Rectifier	10. D/A Converter

Fig. 13 The testing rig of the system in Fig. 1

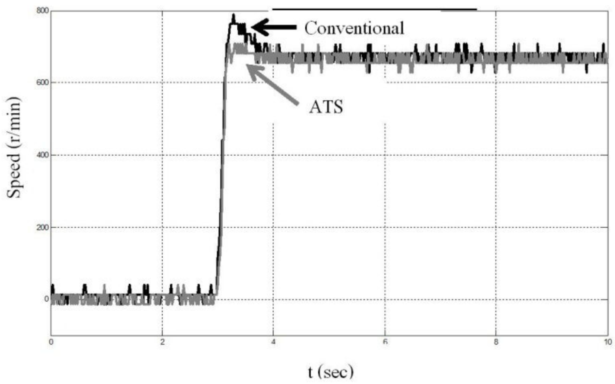


Fig. 14 The results for the experiment validation

The comparison results from the simulation and experiment show that the output speed response when the PI controllers of current and speed loops designed by the ATS method is better than that from the conventional method in terms of percent overshoot, rise time and setting time under the changing of command input and taking load.

VIII. Conclusion

The paper presents the optimal PI controller design for the indirect vector control of IM drive using the ATS algorithm. The resulting output speed responses using the ATS design is better than that of the conventional method for variations in a command input and taking load. The experimental results from the testing rig are also used to support the simulation results. The results show that the proposed design technique is very useful for engineers. The proposed method can provide the best output performance with the stable operation confirmation. Other AI algorithms can also be applied to design the PI controllers of IM drive under the same concept as described in the paper.

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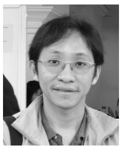

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