Imperialist Competitive Algorithm: A Novel Approach for Speed Control of Induction Motor Supplied by Wind Turbine

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Abstract- This paper proposes the design of a Proportional Integral (PI) controller using Imperialist Competitive Algorithm (ICA) to control the speed of an Induction Motor (IM) fed from wind turbine. The wind turbine plays as a prime mover to a connected DC generator. Pulse Width Modulation (PWM) is used to get three phase AC voltage from the output of DC generator. The proposed design problem of speed controller is established as an optimization problem. ICA is adopted to search for optimal controller parameters by minimizing the time domain objective function. The behaviour of the proposed ICA has been estimated with the behaviour of the conventional Zeigler-Nichols (ZN) and Genetic Algorithm (GA) in order to prove the superior efficiency of the proposed ICA in tuning PI controller. Also, the behaviour of the proposed controller has been estimated with respect to the change of speed wind turbine and load torque. Simulation results confirm on the better performance of the optimized PI controller based on ICA in compare to optimized PI controller based on GA and conventional one over a wide range of operating conditions.

Key-Words: Genetic Algorithm, Imperialist Competitive Algorithm, Induction Motor, Integral Time Absolute Error, Speed Control, Wind Turbine.

Nomenclature

R_s, L_{ls}	Stator resistance and leakage inductance,
R'_r, L'_{lr}	Rotor resistance and leakage inductance,
L_m	Magnetizing inductance,
L_S, L'_r	Total stator and rotor inductances,
V_{qs}, i_{qs}	q axis stator voltage and current,
V'_{qr}, I'_{qr}	q axis rotor voltage and current,
V_{ds}, i_{ds}	d axis stator voltage and current,
V'_{dr}, I'_{dr}	d axis rotor voltage and current,
$\varphi_{qs}, \varphi_{ds}$	Stator q and d axis fluxes,
$\varphi'_{qr}, \varphi'_{dr}$	Rotor q and d axis fluxes,
ω_m	Angular velocity of the rotor,
θ_m	Rotor angular position,
P	Number of pole pairs,
ω_r	Electrical angular velocity (ω_m . P) ,
θ_r	Electrical rotor angular position (θ_m .P),
T_e	Electromagnetic torque,
T_L	Shaft mechanical torque,
J_c	Combined rotor and load inertia coefficient,
B	Combined rotor and load viscous friction coefficient,
R	The wind turbine rotor radius,
V_ω	The wind speed,
ω_t	The mechanical angular rotor speed of the wind turbine,
P_t	Wind power (hp),
p	Air density (kg/m^3),
V	Wind speed (m/s),
R_A	The area of turbine blades (m^2),
C_P	Wind power coefficient,
i_a , V_a	The armature generator current and terminal voltage,
i_f, V_f	The field generator current and voltage,
R_a, L_a	The armature resistance and inductance,
R_f, L_f	The field resistance and inductance,
R_L, L_L	The load resistance and inductance,
R_t	$R_a + R_L$,
L_t	$L_a + L_L$,
M_{af}	The mutual inductance between stator and rotor,
ω_r	The input angular speed.

1. Introduction

The induction motor (IM) is the object of several research works because of its robustness, relatively low cost, reliability and efficiency. However, its control presents difficulties because of its high non-linearity and its highly coupled structure [1-2]. Many intelligent approaches are used for speed control of IM such as Artificial Neural Network (ANN) [3-4]. The ANN approach has its own advantages and disadvantages. The performance of the system is improved by ANN based controller but, the main problem of this controller is the long training time, the selecting number of layers and the number of neurons in each layer. Another artificial intelligence approach likes Fuzzy Logic Control (FLC) for designing adaptive speed control of IM is introduced in [5-7] but it requires more fine tuning and simulation before operational.

Global optimization techniques have caught the attention in the field of controller parameter optimization [8]. Genetic Algorithm (GA) is illustrated in [9-13] for optimal design of conventional stabilizer and speed control of IM. Despite this optimization technique requires a very long run time that may be several minutes or even several hours depending on the size of the system under study. Another heuristic technique like Tabu Search (TS) is discussed in [14-15] to design a robust controller for IM and stabilizers. However, it appears to be effective for the design problem, the efficiency is reduced by the use of highly epistatic objective functions, and the large number of parameters to be optimized. Simulated Annealing (SA) is introduced in [16, 17] for optimal tuning of controller but this technique might fail by getting trapped in one of the local optimal. Swarming strategies in fish schooling are used in the Particle Swarm Optimization (PSO) and presented in [18] for optimal design of multiply stabilizers and speed control of IM and DC permanent magnet motor [19–23]. However, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction [24, 25]. Also, the algorithm pains from slow convergence in refined search stage, weak local search ability and algorithm may lead to possible entrapment in local minimum solutions. A relatively newer evolutionary computation algorithm, called Bacteria Foraging (BF) scheme has been presented by [26–28] and further established recently by [29–33]. The BF algorithm depends on random search directions which may lead to delay in reaching the global solution. In order to solve the these drawbacks, this paper introduces a new evolutionary algorithm known as Imperialist Competitive Algorithm (ICA) to design a robust speed controller for IM. ICA is recently addressed [34] that is inspired by the imperialistic competitive. ICA has shown good performance in solving optimization problems in different areas such as linear IM design [35] and Power System Stabilizer (PSS) design [36]. The ICA is a meta-heuristic optimization method that is based on modelling of the attempts of countries to command other courtiers [37].

This paper proposes the ICA for optimal designing of PI controller for speed control of IM supplied by wind turbine, which has a simple structure and robust performance in a wide range of operating conditions. The design problem of the proposed controller is formulated as an optimization problem and ICA is employed to search for optimal controller parameters. By minimizing the time domain objective function, in which the deviations in error between the reference and actual speed is involved; speed control of IM is improved. Simulations results validate the effectiveness of the proposed controller in providing good speed control over a wide range of load torque and speed turbine. Also, these results assure the superiority of the proposed ICA method in tuning controller compared with GA and conventional method.

2. System under Study

The system under study consists of wind turbine plays as a prime mover to a connected DC generator. The DC output voltage is converted to three phase voltage through a Pulse Width Modulation (PWM). The three phase output voltage of PWM is supplied to the three phase IM. The proposed controller based on ICA is used to control the speed of IM. The schematic block diagram is shown in Fig. 1.

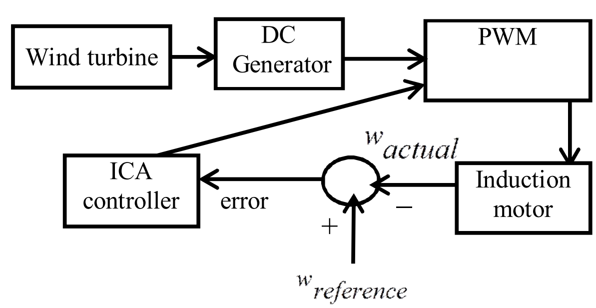

Fig. 1. The schematic block diagram of system under study.

2.1. IM Model

The electrical part of IM is represented by a fourth-order model and the mechanical part by a second-order model. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs (') in the machine equation given below. All stator and rotor quantities are in the arbitrary two-axis reference frame (q-d frame) [40-42].

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega\varphi_{ds}, \quad V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega\varphi_{qs} \tag{1}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt}\varphi'_{qr} + (\omega - \omega_r)\varphi'_{dr}, \quad V'_{dr} = R'_r i'_{dr} + \frac{d}{dt}\varphi'_{dr} - (\omega - \omega_r)\varphi'_{qr} \tag{2}$$

$$T_e = 1.5P(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \tag{3}$$

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}, \quad \varphi_{ds} = L_s i_{ds} + L_m i'_{dr} \tag{4}$$

$$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs}, \ \varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds} \tag{5}$$

$$L_s = L_{ls} + L_m, \ L'_r = L'_{lr} + L_m \tag{6}$$

$$\frac{d}{dt}\omega_m = \frac{1}{J_c}(T_e - B\omega_m - T_L) \tag{7}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{8}$$

2.2. Dynamic Modelling of the Wind Turbine

The wind turbine is characterized by no dimensional curves of the power coefficient (C_p) as a function of both the tip speed ratio (λ) and the blade pitch angle (β). In order to fully utilize the available wind energy, the value of (λ) should be maintained at its optimum value. Therefore, the power coefficient corresponding to that value will become maximum.

The tip speed ratio (λ) can be defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades [43]. It can be expressed as follows:

$$\lambda = \omega_t R / V_\omega \tag{9}$$

In addition to Eq. 9, the relation between λ and β can be found in the following relation [44]:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{10}$$

A generic equation is used to model $C_p(\lambda, \beta)$. This equation, based on the modelling turbine characteristics of [43-45], is:

$$C_p(\lambda,\beta) = C_1(C_2/\lambda_i - C_3.\beta - C_4)e\hat{\ }(-C_5/\lambda_i) + C_6.\lambda \tag{11}$$

where β is the pitch angle and the coefficients C_1 to C_6 are:

$C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$,
$C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$

The maximum value of C_P characteristics ($C_{P\max} = 0.48$) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the nominal value (λ_nom). Wind turbine is designed to have low cut-in and cut-out speed (2-3m/s: 7-9m/s). The power output equation of wind turbine can be described in equation (12):

$$P_t = \frac{1}{2}\rho\,\Pi\,C_p * V(\lambda,\beta)^3\, R_A^2 / 735 \tag{12}$$

2.3. DC Generator

The proposed system can be simulated with proper mathematic modelling. The DC generator can be written in terms of equations as follows [41-42]. These nonlinear equations can be simulated using Matlab/ Simulink in overall system.

$$V_f = R_f\, i_f + L_f \frac{di_f(t)}{dt} \tag{13}$$

$$i_f\, \omega_r\, M_{af} = R_t\, i_a + L_t \frac{di_a(t)}{dt} \tag{14}$$

$$V_a = R_L\, i_a + L_L \frac{di_a(t)}{dt} \tag{15}$$

3. Optimization Process

The main objective of an optimization problem is to minimize the objective function derived for the system considering a particular performance index of the system. A performance index can be defined by the Integral of Time multiply Absolute Error (ITAE) of the error between reference and actual speed of IM. Accordingly, the objective function J is set to be:

$$J = \int_0^\infty t|e(t)|dt \tag{16}$$

where $e = w_{reference} - w_{actual}$

Based on this objective function optimization problem can be stated as: Minimize J subjected to:

$$K_p^{\min} \le K_P \le K_p^{max}, K_i^{\min} \le K_i \le K_i^{max} \qquad (17)$$

This paper focuses on optimal tuning of PI controller for speed tracking of IM using ICA algorithm. The aim of the optimization is to search for the optimum controller parameters setting that minimize the difference between reference speed and actual one.

4. Overview of ICA and GA Optimization Technique

4.1 Imperialist Competitive Algorithm (ICA)

ICA is an algorithm for optimization inspired by the imperialistic competition. Like other evolutionary ones, the proposed algorithm begins with an initial population. Population individuals called country are in two types: colonies and imperialists that all together shape some empires. Imperialistic competition among these empires forms the basis of the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition hopefully converges to a state in which there exists only one empire and its colonies are in the same position and have the same cost as the imperialist [34-36].

After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist country. This movement is a simple model of assimilation policy that was perused by some imperialist states [37]. Figure 2 shows the movement of a colony towards the imperialist. In this movement, α and x are random numbers with uniform distribution and d is the distance between colony and the imperialist [38-39].

$$x \sim U(0, \alpha \times d) \qquad (18)$$

$$\alpha \sim U(-\gamma, \gamma) \qquad (19)$$

In (18, 19) α and γ are arbitrary numbers that modify the area that colonies randomly search around the imperialist. The total power of an empire depends on both the power of the imperialist country and the power of its colonies. In this algorithm, this fact is modelled by defining the total power of an empire by the power of imperialist state plus a percentage of the mean power of its colonies. Any empire that is not able to succeed in imperialist competition and cannot increase its power will be eliminated. The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones. Weak empires will lose their power and they will collapse. The movement of colonies toward their relevant imperialists along with competition among empires and also collapse mechanism will cause all the countries to converge to a state in which there exist just one empire in the world and all the other countries are its colonies. In this ideal new world colonies have the same position and power as the imperialist. In this paper, the ICA is used to tune the parameters of PI controller. Fig. 3 shows the flow chart of the proposed algorithm.

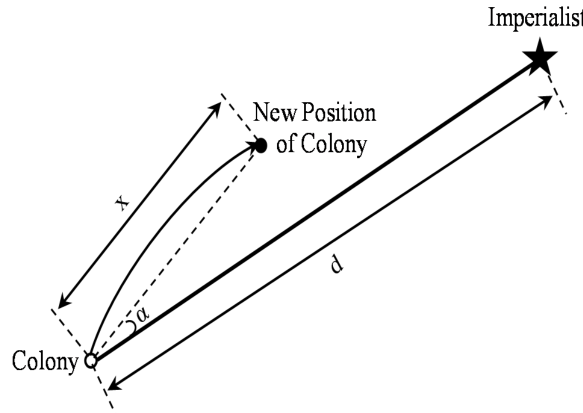

Fig. 2. Motion of colonies toward their relevant imperialist.

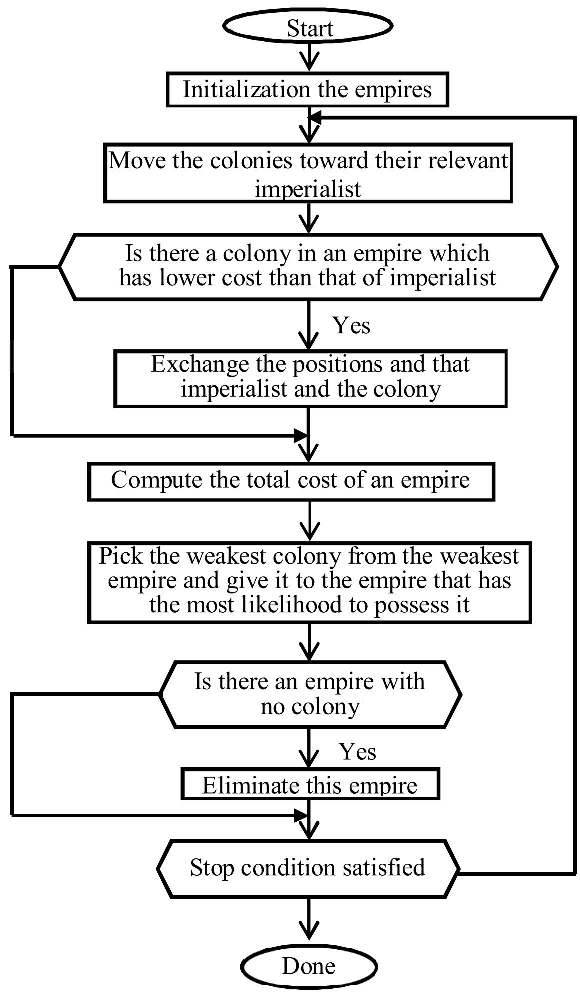

Fig. 3. Flow chart of the Imperialist Competitive algorithm.

4.2. Genetic Algorithm (GA)

In the animal kingdom, animals evolve and generate according to the role of "survival of the fittest". In nature, animals fight constantly for food, shelter and mates. Thus, only the fittest will survive and the weak will perish. This mechanism of weeding out the useless has worked perfectly for centuries and it is a good method for optimization. GA is such an optimization method. It is based on the mechanics of natural selection and natural genetics. The search process is very similar to the natural evolution of biological creature in which successive generations of organisms are given birth and raised until they are able to breed. Just like in animal kingdom, only the fittest will survive to produce while the weakest will be eliminated [46].

Four main parameters affect the performance of GAs: population size, number of generations, crossover rate, and mutation rate. Larger population size and large number of generations increase the likelihood of obtaining a near-global optimum solution, but substantially increase processing time. Crossover among parent chromosomes (solution vectors) is a common natural process and traditionally is given a rate that ranges from 0.6 to 1.0. In crossover, the exchange of parents' information produces an offspring. As opposed to crossover, mutation is a rare process that resembles a sudden change to an offspring. This can be done by randomly selecting one chromosome from the population and then arbitrarily changing some of its information. The benefit of mutation is that it randomly introduces new genetic material to the evolutionary process, perhaps thereby avoiding stagnation around local minima. A small mutation rate less than 0.1 is usually used [47]. A flowchart for the GA algorithm is shown in Fig. 4.

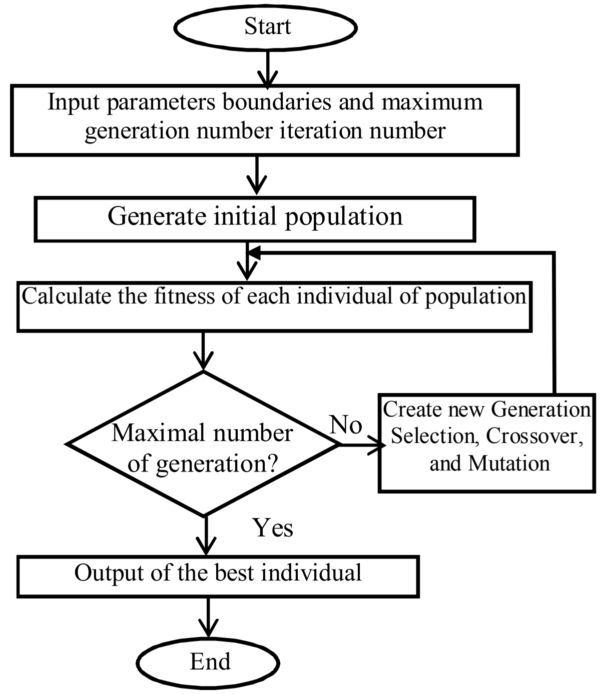

Fig. 4. Flow chart of GA algorithm.

Table. 1. The characteristics of time response for all controllers.

	K_P	K_i	Settling time	Percentage Overshoot
ICA	0.1664	0.6543	0.78	12.4
GA	0.1258	0.4659	0.97	13.1
ZN	0.0135	0.7848	2.74	48.8

5. Simulation and Results

In this section, the superiority of the proposed ICA algorithm over GA and conventional ZN in designing PI controller for speed control of IM is illustrated. The proposed ICA methodology and GA are programmed in MATLAB 7.1 and run on an Intel(R) Core(TM) I5 CPU 2.53 GHz and 4.00 GB of RAM. Table 1. shows the parameters of PI controller and the time domain characteristics for all algorithms. It is clear that, the values of settling time and percentage overshoot with the proposed ICA are smaller than conventional controller and GA. This demonstrates that oscillations are greatly reduced by applying the proposed ICA [48].

5.1 Response under variable wind turbine speed

As the first test case, the system responses under variation of the wind turbine speed are obtained. Fig. 5. shows the variation of the speed wind turbine as an input disturbance while the load torque is constant at full load torque (11.8 N. m). Fig. 6 shows the output power of the wind turbine. The output power is variable due to the change in wind speed. Fig. 7.a illustrates the output phase voltage of PWM inverter by using the proposed controller while Fig 7.b illustrates the zoom for phase voltage. Figs. 8-9, show a comparison between the ICA, GA and conventional controller on the control output signal and speed response of IM respectively. It is clear, the steady state and dynamic operation of IM in terms of overshoot and settling time has been enhanced. Moreover, the proposed controller is indeed more efficient in improving speed control of IM compared with GA and ZN based controller.

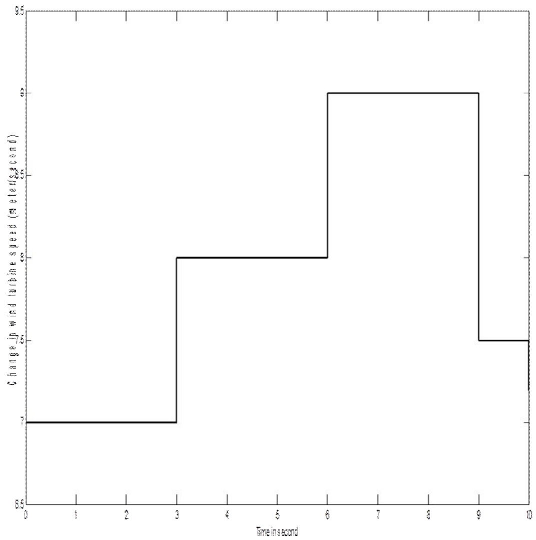

Fig. 5. The change of speed wind turbine.

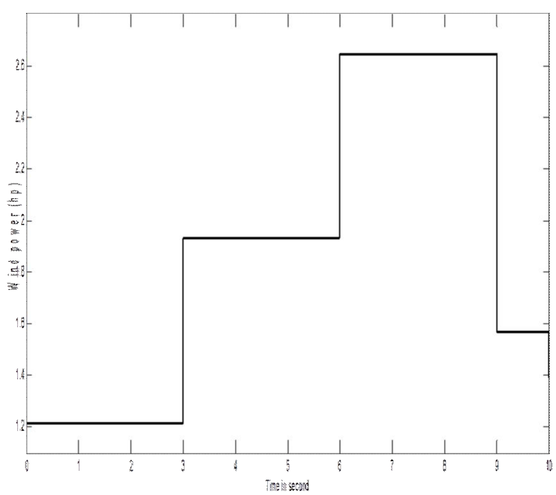

Fig. 6. The output power of wind turbine.

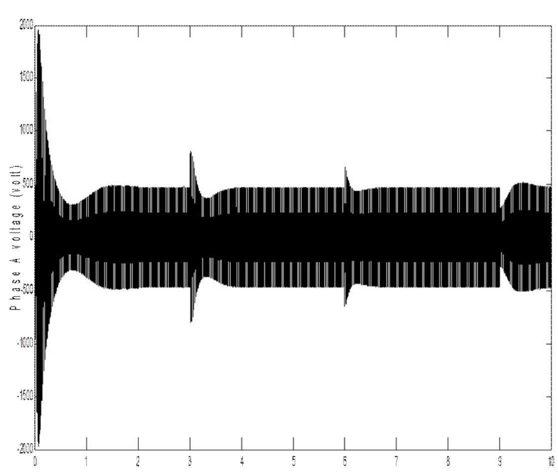

Fig. 7.a. The output phase voltage of PWM inverter.

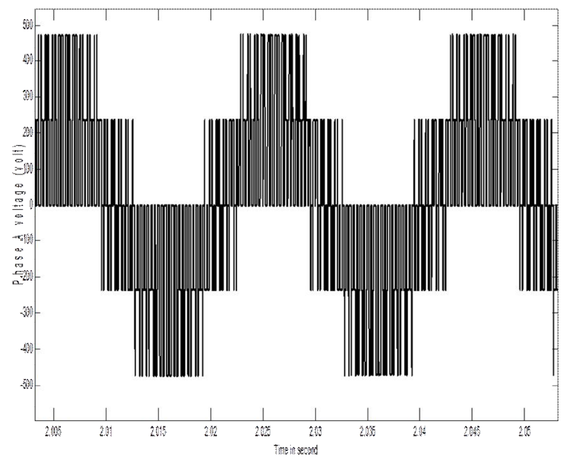

Fig. 7.b. The zoom for output phase voltage of PWM inverter.

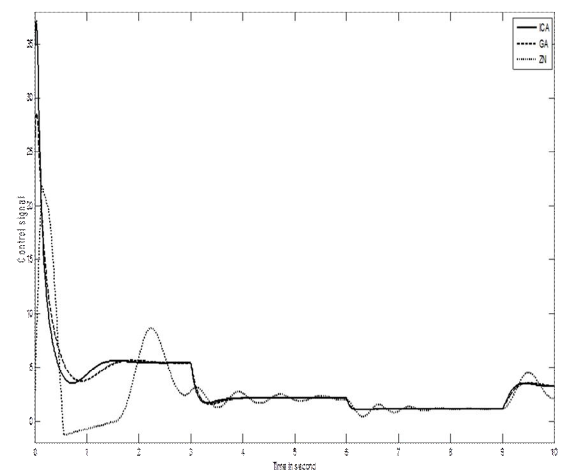

Fig. 8. The output controller signal for all controllers.

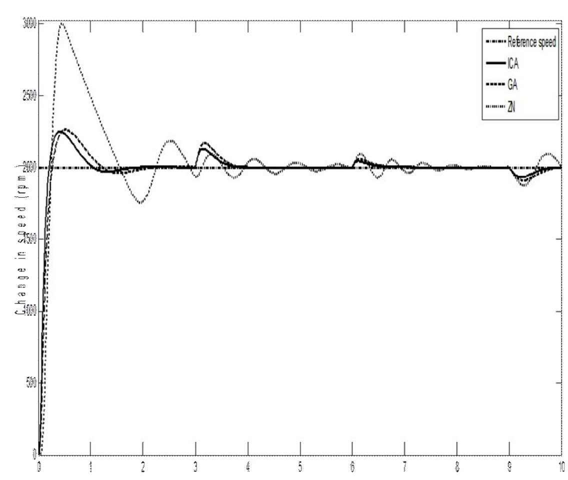

Fig. 9. The response of IM speed under different controllers.

5.2 Response under variable load torque

In this case, the system responses under variation of the load torque are obtained. Fig. 10. shows the variation of the load torque as an input disturbance while the speed of wind turbine is constant at 8 m/s. Moreover, the system responses for different controllers are shown in Figs. 11-12. It is clear from these Figs., the proposed ICA outperforms and outlasts GA in controlling the speed of IM effectively and reducing settling time. Hence compared to the conventional ZN and GA based controller, PI based ICA greatly enhances the system performance.

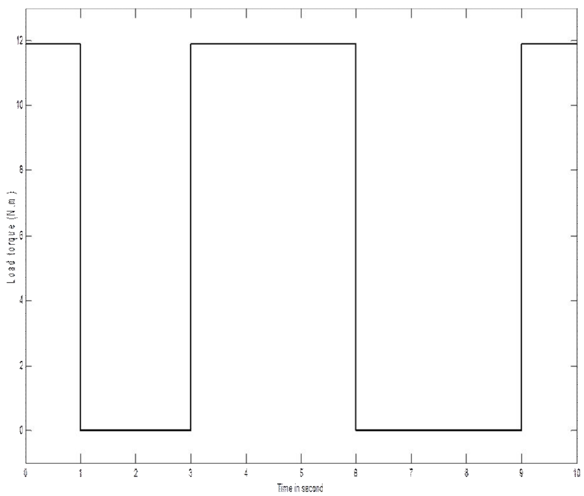

Fig. 10. The change of load torque.

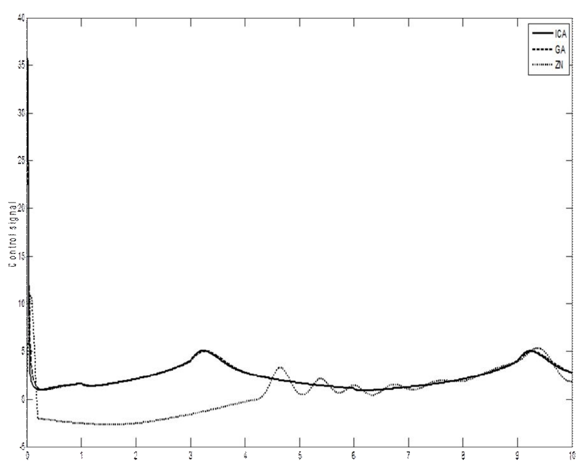

Fig. 11. The output controller signal for all controllers.

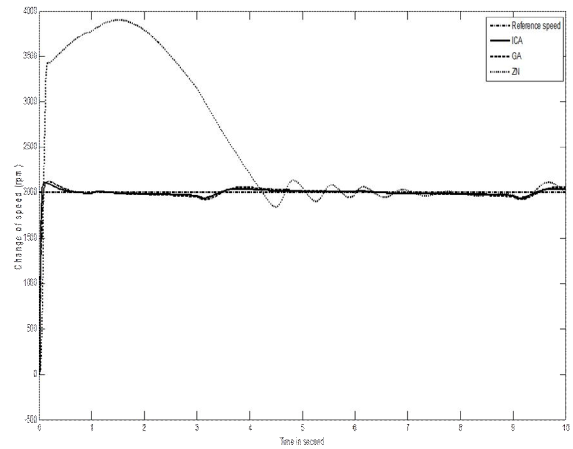

Fig. 12. Speed response of IM for different controllers.

5.3 Response under variable load torque and wind turbine speed

In this case, variations of both load torque and speed wind turbine are applied. Moreover, the system responses for both controllers are shown in Figs. 13-14. It is clear from these Figs, that the proposed ICA is more efficient in improving speed control of IM compared with GA. Also, it has a smaller settling time and system response is quickly driven with the reference speed. In addition, the superiority of the proposed ICA compared with GA for tracking every change of reference speed is shown in Fig. 14. Hence, the potential and superiority of the proposed ICA over GA and ZN is demonstrated.

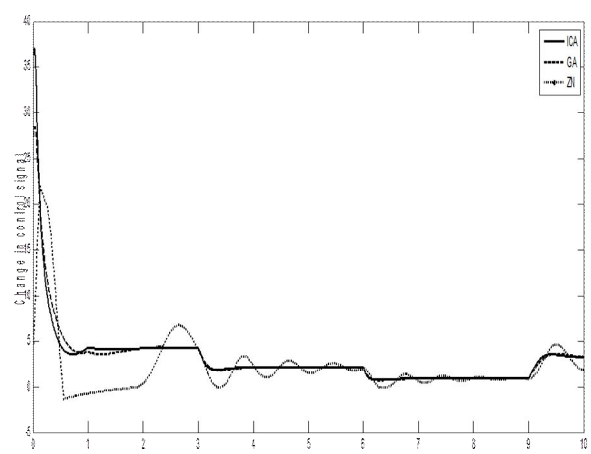

Fig. 13. The output controller signal for all controllers.

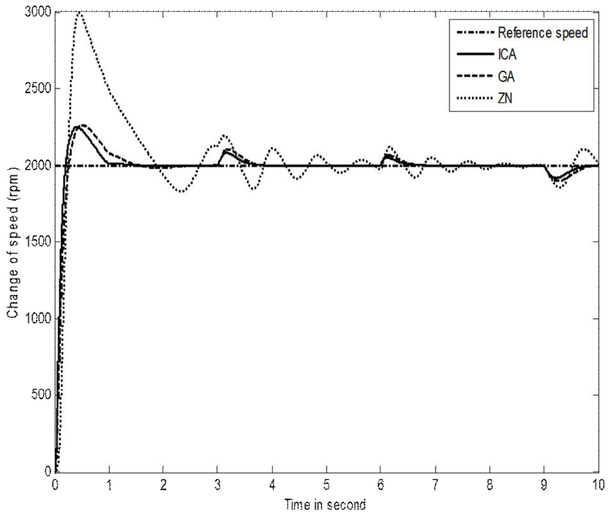

Fig. 14. The IM speed for different controllers.

5.4 Robustness and performance indices:

To demonstrate the robustness of the proposed controller, some performance indices: the Integral of Absolute value of the Error (IAE), the Integral of Square Error (ISE) and the Integral of the Time multiplied of Square Error (ITSE) are being used as:

$$IAE = \int_{0}^{t_{sim}} (|e|)dt \tag{20}$$

$$ISE = \int_{0}^{t_{sim}} e^2 dt \tag{21}$$

$$ITSE = \int_{0}^{t_{sim}} te^2 dt \tag{22}$$

where t_{sim} is the time of simulation and equals to 10 second. It is noteworthy that the lower the value of these indices is, the better the system response in terms of time domain characteristics [46]. Numerical results of performance robustness for all controllers are listed in Table (2) under large change of load torque, and parameters of wind turbine system. It can be seen that the values of these system performance with the ICA are smaller compared with those of GA and ZN. This demonstrates that the overshoot, settling time and speed deviations of all units are greatly decreased by applying the proposed ICA based tuned PI. Eventually, values of these indices are smaller than those obtained by PSO in [22].

Table. 2. The performance indices for all controllers.

	IAE	ISE	ITSE
ICA	24.94	126.38	472.4
GA	34.41	228.54	920.4
ZN	49.84	451.1	1475
PSO [22]	28.63	153.17	504.21

6. Conclusion

This paper proposes a new optimization algorithm known as ICA for optimal designing of PI controller for speed control of IM. The design problem of the proposed controller is established as an optimization problem and ICA is adopted to search for optimal controller parameters. By minimizing the time domain objective function, in which the difference between the reference and actual speed are involved; speed control of IM is enhanced. Simulation results confirm that the designed ICA tuning PI controller is robust in its operation and gives a superb behaviour for the variation in speed wind turbine and load torque compared to GA tuning PI controller and conventional one. Besides the simple architecture of the proposed controller, it is easy to implement and tune.

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Appendix

The optimization parameters are as shown below:

a) Genetic parameters: Max generation=100; Population size=50; Crossover probabilities=0.75; Mutation probabilities =0.1.

b) ICA parameters: Countries size=100, Imperialists size=10, Number of iteration=100, Revolution rate=0.2, and Assimilation coefficient=2.

c) DC generator parameters: R_f = 33.7 ohm, L_f = 1.7 H, R_a = 0.0125 ohm, L_a = 0.08 H, R_L = 0.313 ohm, L_L = 1.62 H, M_{af} = 0.8 H.

d) IM parameters: f = 60 Hz, P = 2, rated voltage =220 volt, R_s = 0.435 ohm, L_{ls} = 2 mH, B=0.001, J_c=0.356, $\mathrm{R_r}$ =0.408 ohm, $\mathrm{L_{lr}}$=2 mH, L_m =0.06934 H, T_L=11.9 N.m.