



Hybrid controller for performance enhancement of direct torque control IM drives

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Abstract

In industries induction Motor drives are more popular due to their brushless structure, low cost, low maintenance and robust performance. Over the decade various types of control methods are proposed for induction motor drives. Among them the Direct Torque Control (DTC) has gained more importance due to its fast dynamic response and simple control structure. Hybridization is nowadays recognized to be an essential aspect of high performing algorithms. To enhance the performance of the DTC drives the paper proposes two types of hybrid controllers. In the first method the PI is tuned using fuzzy logic based controller and in the second method the PI tuned fuzzy logic is optimized through Ant colony. The simulation is carried out using MATLAB and the obtained result shows the comparison in performance between proportional integral, fuzzy logic tuned speed controller and fuzzy tuned through Ant colony optimization.

Keywords: Ant Colony Algorithm (ACO), Direct Torque Control drive (DTC), Fuzzy Logic Control (FLC), Induction Motor (IM), Proportional Integral (PI), field oriented control (FOC)

1. Introduction

AC Induction Motor drives have advantages due to their simplicity, reliability, and low cost. The above advantages are outmoded due to control problems in induction motor (IM) drives used in industry where high performance is needed [1-2]. The features of AC drives depend on the applied control strategy. The control strategy and estimation of stator resistance of AC induction motor drives are more complex, and this complexity affects substantially at the time of high performance. The main goal of chosen the control method is to provide the best possible performance of drive. Additionally, a very important requirement regarding control method is its simplicity (simple algorithm, simple tuning and operation with small controller dimension leads to low price of final product). The control methods can be divided into two groups: scalar control and vector control.

Two high performance control techniques for IM drives are field oriented control (FOC) [3] and Direct Torque Control (DTC) [4]. DTC have the advantages of absence of coordinate transformation and minimum torque response time. In spite of the above advantages it has some disadvantages like high torque ripple during starting, requirement of torque and flux estimator, change in stator resistance and high torque and flux ripples. In conventional DTC, the hysteresis controllers are used, in which flux error and torque error are given as input and the output of these controllers selects the voltages from the switching table. In the proposed method the hysteresis controllers are replaced by proportional integral controllers. The speed is controlled using closed loop PI controller. Another Artificial Technique (AI) technique, Ant colony and fuzzy logic are implemented to tune this PI controller. In this paper two hybrid controllers are proposed. In first method PI is tuned using FL and in second method this fuzzy tuned PI is

optimized with the Ant colony.

This paper has been organized in five sections. DTC principle and modified DTC is presented in the following section. Proposed FL scheme is given in section III. In section III Ant colony optimization technique is also explained and implemented to the PI controller. In section IV simulation results are described and finally conclusion is presented in section V.

2. Modified DTC Drive

In middle of 1980's Takahashi [5] and M. Depenbrock [6] investigated DTC system for ac motor. It is a high performance technology which is developed after the Vector Control. The schematic of a classical torque controlled induction motor drive is shown in fig. 1, where the IM is supplied for voltage source inverter. The stator flux and electromagnetic torque errors are used together with the position of stator flux linkage space vector directly to select the optimum switching vectors. The stator **q** and **d** axis flux linkages ψ_{ds} and ψ_{qs} can be as in equ. (1) and (2)

$$\psi_{ds} = \int (V_{ds} - i_{ds}R_s) dt \quad (1)$$

$$\psi_{qs} = \int (V_{qs} - i_{qs}R_s) dt \quad (2)$$

and flux linkage phasor magnitude is

$$\psi_s = \sqrt{(\psi_{qs}^2 + \psi_{ds}^2)} \quad (3)$$

and torque of drive is given by

$$T_s = (3/2)(P/2)(i_{qs}\psi_{ds} - i_{ds}\psi_{qs}) \quad (4)$$

where, V_{ds} and V_{qs} : d-q axis stator voltage, i_{ds} and i_{qs} : d-q axis stator current, ψ_{ds} and ψ_{qs} : d-q axis stator flux linkage, R_s is stator resistance, P is no. of pole.

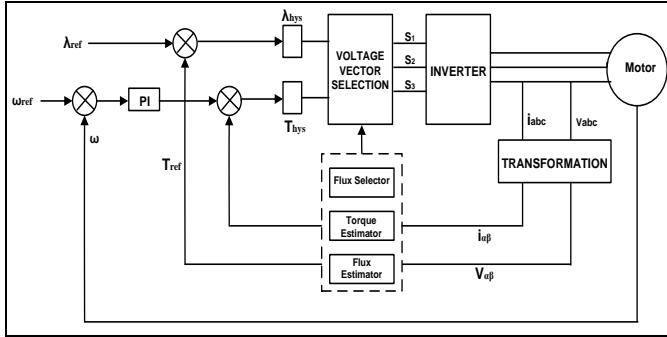


Fig 1: Classical Direct Torque Control

In the paper the DTC [7-8] is modified [9-10] with the application of PI controllers in place of torque and flux hysteresis controllers. The error in speed is the input to PI speed controller which gives the reference torque T_s^* as output. This T_s^* is compared with the calculated torque T_s . The error of torque and flux (error between ref. flux and calculated flux) is used for the pulse generation to inverter. The modified DTC is shown in fig. 2.

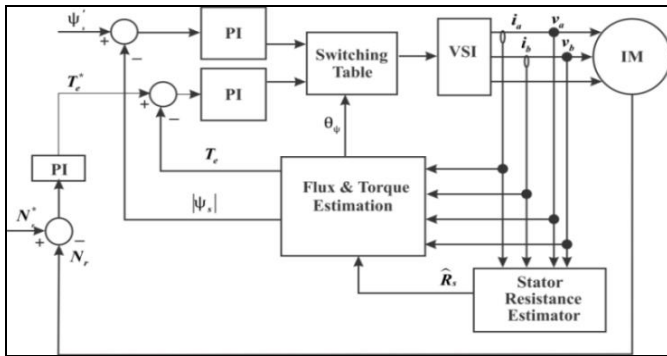


Fig 2: Block diagram of Modified DTC

3. The Hybrid Integrated Speed Controller

3.1 Fuzzy Logic

Fuzzy controller converts a set of linguistic rules, based on expert knowledge, into an automatic control strategy. Three steps involves in fuzzy logic system are [11]:

(i) fuzzification, (ii) rule base design, and (iii) defuzzification. Fuzzification involves mapping input crisp values to Fuzzy variables. Fuzzy inference consists of Fuzzy rules and decision is made based on these Fuzzy rules. These Fuzzy rules are applied to the fuzzified input values and Fuzzy outputs are calculated. In the last step, a defuzzifier converts the fuzzy outputs back to the crisp values. In the system presented in this work Mamdani type of fuzzy logic is used for speed controller [12-14], which consists of two inputs e and Δe

and one output Δu .

One FL is implemented on the error in reference speed and actual speed. Other FL is applied on the change in error in speed. The output of these controllers tune the k_p and k_i of the speed controller. The range of control, which is the universe of discourse is -0.75 to 0.75 for speed error, -0.75 to 0.75 for change in speed error and 0 to 1 for output respectively. The rule base for fuzzy input is 49 (7x7) rules. The membership distribution functions designed are shown in Figs. 3, 4 and 5.

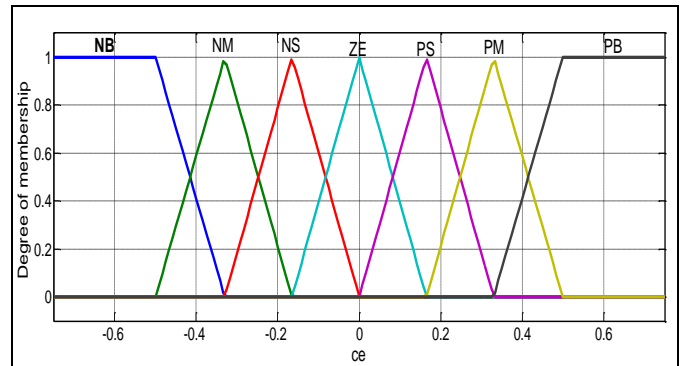


Fig 3: Membership function of change in error

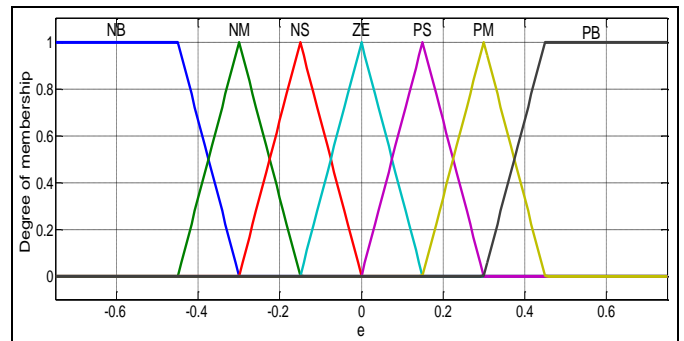


Fig 4: Membership function of error

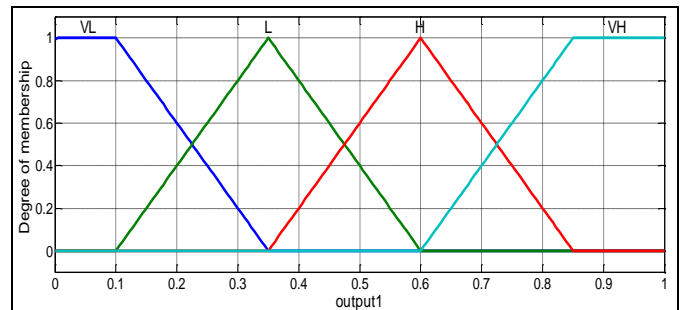


Fig 5: Membership function of output

3.2. Implementation of Hybrid Fuzzy-PI Controller

Hybridization is nowadays recognized to be an essential aspect of high performing algorithms. To tune the PI speed controller of IM DTC drive fuzzy logic implementation [15] is shown in Fig. 6 & 7. The expression of the PI speed controller is according to equation (5)

$$T_s^*(k) = k_p(k) + k_i T \sum_{j=1}^k e(j) \tag{5}$$

where T : Sampling period, $e(k)$: Speed error signal, k_p : Proportional coefficient, k_i : Integral coefficient, $T_s^*(k)$: value of torque output.

By adjusting the k_p and k_i at different speeds $T_s^*(k)$ can be obtained by equation (5). In FL controller, two inputs are speed error e and its derivative de/dt and $\Delta k_p, \Delta k_i$ as output variables. Input and output scaling factors affect the fuzzy controller sensitivity and system stability respectively.

In this paper, the scaling factors of input variable k_{e1} and k_{e2} are 1/8000 and 1000 respectively. The scaling factors of output variable k_{u1}, k_{u2} are 5 and 0.6 respectively. The fuzzy inference is a system with two-inputs and two- outputs.

The output variables Δk_p and Δk_i are corrected value based on a set of rules. Then the k_p and k_i can be obtained by the following formula:

$$k_p = k_{p0} + \Delta k_p \tag{6}$$

$$k_i = k_{i0} + \Delta k_i \tag{7}$$

where, k_{p0} and k_{i0} are the reference values which are already obtained by the PI.

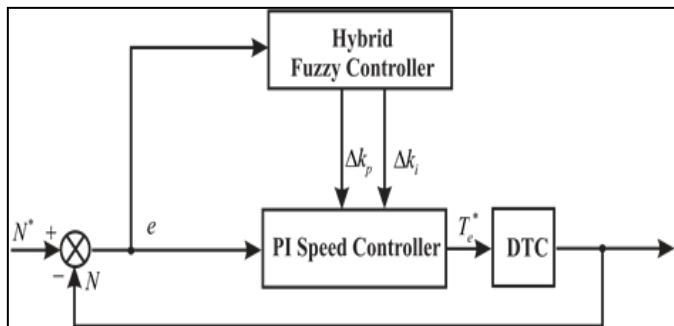


Fig 6: Block Diagram of Fuzzy-PI Speed controller

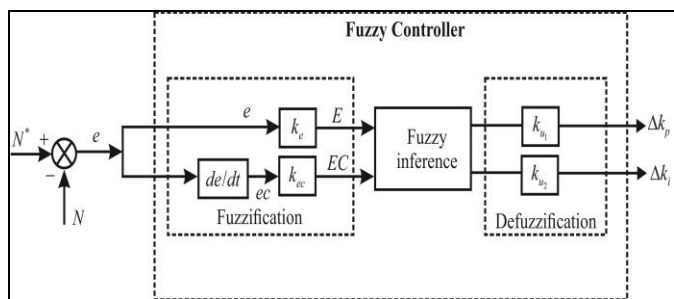


Fig 7: Block Diagram of Inner control of Hybrid Fuzzy-PI controller

3.3. Hybrid FL tuned with Ant Colony

Now a days, FL (Fuzzy Logic) has been widely used in control system. PI parameters on-line tuning ability, hybrid FLPI controller (FL-PI) is implemented to improve the

performance. At the same time ACA (Ant Colony Algorithm) applies to optimize FLPI to the DTC drive. This implemented PI controller is named as ACFL-PI controller, shown in fig. 8. In solving different optimization problems ACA is an excellent optimization methodology and a promising approach because ACA can be able to generate a high-quality solution within shorter calculation time and stable convergence characteristic than other stochastic methods.

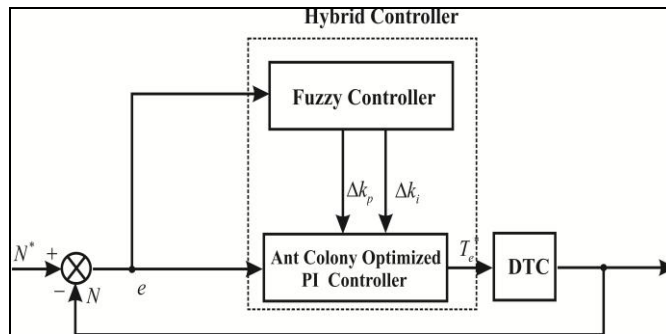


Fig 8: ACFL-PI speed controller (change it with Ant colony)

3.4 Ant colony optimization

Ant system (AS) was the first ACO algorithm to be proposed in [16-17]. Ant colony optimization [18] (ACO) is a population-based metaheuristic that can be used to find approximate solutions to difficult optimization problems.

ACO technique was introduced by M. Dorigo in early 1900s as a novel nature inspired metaheuristic for the solution of combinatorial optimization problem. This algorithm is based on the real ant behaviour in searching the source of food. It is evident that the shortest path has large pheromone concentrations, so that more ants tend to choose it to travel. There are three major phases in the Ant Colony Algorithm:

- Initialization
- Constructing ant solution
- Updating pheromone

The global updating rule is implemented in the ant system where all ants start their tours and pheromone is deposited and updated on all edges based on:

$$\tau_{ij} \leftarrow (1 - \rho) \cdot \tau_{ij}(t) + \sum_{k \in \text{colony that used edge (i,j)}} \frac{Q}{L_k} \tag{8}$$

Where ρ_{ij} is the probability between the town i and j , Q is constant, L_k is the length of the tour performed by K_{th} ant, ρ is the evaporative rate.

In this study, the number of ants= 20, pheromone (τ)=0.5, evaporation rate (ρ) = 0.7 and the number of iterations= 50. The flow chart of the Ant Colony Optimization is shown in Fig. 9. In this work, design of PI controllers as a multi objective optimization problem taking in consideration the ACO algorithm.

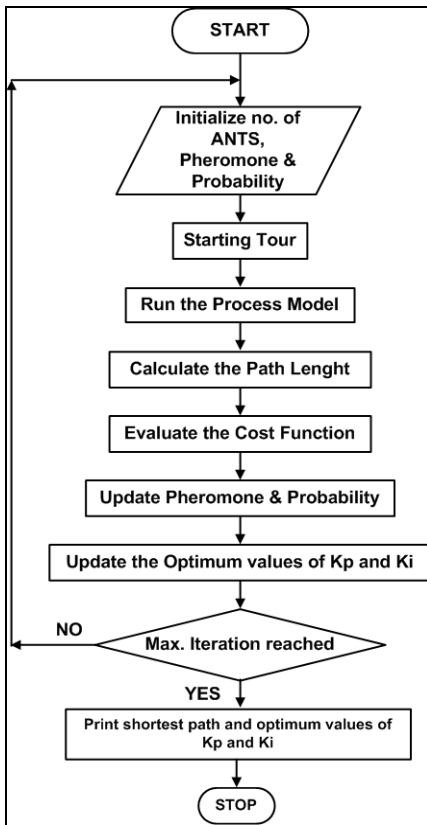


Fig 9: Flow chart for tuning PI controller using ACO

4. Results and Discussions:

DTC with hybrid controllers is simulated in MATLAB/simulink and performance is summarised. In this section, the proposed ACFL-PI is performed the DTC drive system and examine the performance of induction motor with two different operating conditions. The figures and tables show the comparative study of DTC with PI, Hybrid PI and ACFL-PI controller. In the proposed DTC model k_p and k_i

of speed controller are optimized with Hybrid PI with ant colony. The effectiveness of speed PI controller, Mamdani type fuzzy logic controller and ACFL-PI controller can be seen. Three different control techniques are implemented in speed controller which is tested for step change in speed and variable speed or speed reversal of induction motor drive. Under these operating conditions the performance analysis of the proposed ACFL-PI controller and Hybrid PI with fuzzy logic is made with reference to settling time and improvement in % overshoot in different cases shown in table 1 and table 2.

4.1 Case I: Variable speed

Simulation is carried out at variable speed, the value of Proportional and integral gain obtained through Ziegler-Nichols method are $k_p=2.14$ and $k_i=15.2$. The values of k_p and k_i with different optimization techniques are given in table 1.

In this case the speed of the drive is changed in steps from 200 to 900 rpm. Initially it starts with 200 rpm till 2 s, and then the speed increases at 2 sec. from 200 to 500 rpm. After that at 5 sec. further speed steps up to 700 rpm till 7 s. At 7 sec. again speed step up to 900 rpm. As shown in Fig. 10, the drive tracks the speed in different steps. In case of PI the speed overshoots at every step of change in speed, whereas in case of hybrid PI it is nominally reduced. After that in the proposed hybrid ACFL-PI overshoot and speed settles down very fast at every step. The reduction in settling time at every step is reduced and summarized in table 1. Similarly the peak overshoot is also recorded at every step with different optimization techniques, which are also mentioned in table 1. Different optimization technique results are also compared with graph for settling time as well as for peak overshoot in Fig. 11 and Fig. 12 respectively. In the graph green line shows the performance ACFL-PI controller, whereas red shows hybrid PI and blue conventional PI controller.



Fig 10: Tracking of speed for step change in speed at constant load torque

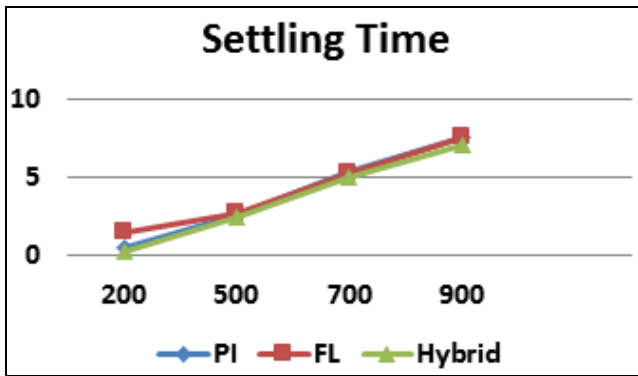


Fig 11: Graph of Settling Time of speed for different optimization Technique

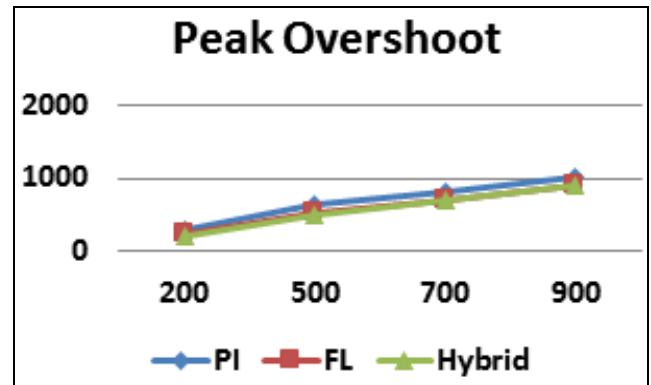


Fig 12: Graph of Peak over shoot of speed for different optimization Technique

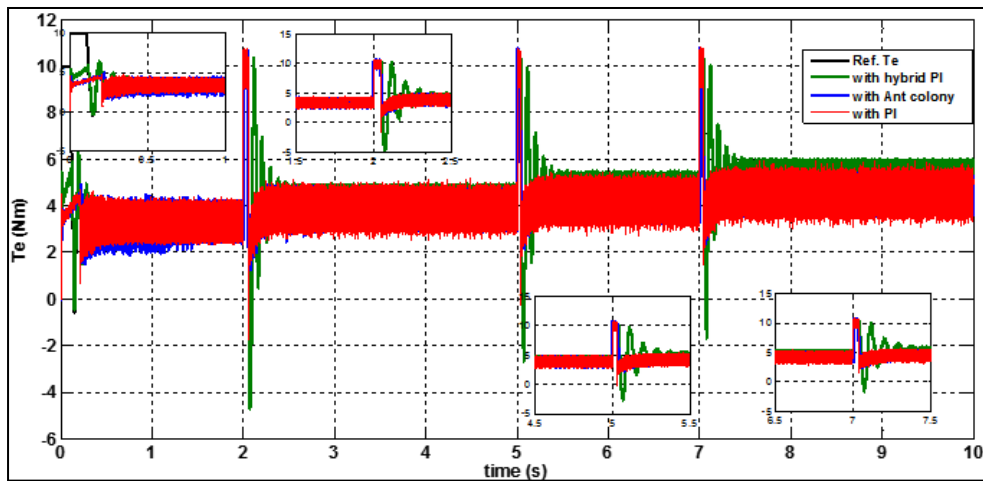


Fig 13: Electromagnetic Torque T_e with step change in speed and constant load torque

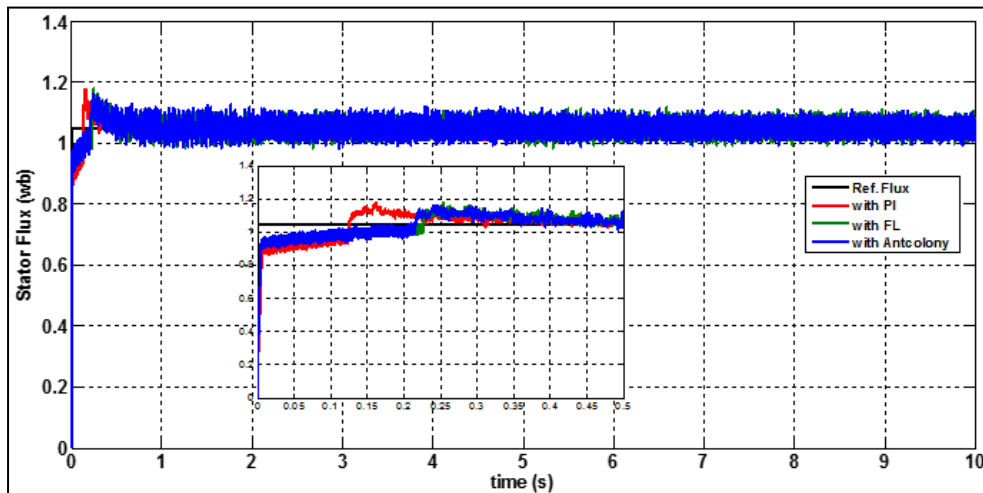


Fig 14: Stator Flux with step change in speed and constant load torque

Table 1: Performance comparison of Three Algorithms at Various Operating Points in Case I

AI Technologies	Kp	Ki	Settling Time (s) at different speed (s)				Peak overshoot at different speed (rpm)			
			200	500	700	900	200	500	700	900
PI	2.15	15.2	0.55	2.55	5.45	7.53	295	640	810	1006.6
Hybrid PI	0.09	1.01	1.5	2.7	5.24	7.6	226.2	516.27	708.45	908.7
Hybrid PI with Ant colony	2.015	0.451	0.21	2.4	5.04	7.04	200.95	500.32	701.08	900.78
% Reduction as compared with Hybrid PI and Hybrid Ant controller			72%	11.1%	3.81%	7.36%	11.16%	3.08%	1.04%	0.87%

As shown in Fig. 13, the torque ripples are less with the ACFL-PI controller. Also at every step of change in speed the torque ripples settles down fast with ACFL-PI. In Fig. 14 stator flux is shown, through the zoomed view it is clear that the peak of flux is less in the proposed system and also settling time is less.

4.2 Case II: Speed Reversal

Simulation is carried in case of speed reversal, the value of Proportional and integral gain obtained through Ziegler-Nichols method are $k_p=2.15$ and $k_i=15.2$. The values of k_p and k_i with different optimization techniques are given in table 2. First the drive operates at constant speed i.e. from 0-2 sec at 400 rpm and then speed is increased linearly from 400 to 1000 rpm and it tracks the reference speed. Then it runs at constant speed of 1000 rpm till 6 sec. at load torque of 3 Nm. Thereafter drive operates in the reverse direction starting from 6 sec and the speed decreases linearly from 1000 to -400 rpm from 6 sec. After that it runs at constant speed of -400 rpm till 10 sec. In all the conditions it is observed and shown in Fig. 15 that drive tracks the reference speed smoothly. In case of speed reversal, where the actual speed tracks the reference

speed and settles down at 0.59 s with conventional PI; but it takes 2 s to settle down in case of hybrid PI and only 1.78 s with ACFL-PI which is 11% less in comparison to hybrid PI. Similarly at different operating points the settling time is less with ACFL-PI. Here the settling time of Hybrid PI is more in comparison to conventional PI but peak overshoot is very less. With the ACFL-PI controller the settling time and peak overshoot both are less and compared in table 2. The graph for settling time and peak overshoot is also plotted in fig. 16 and fig. 17 in which it is observed that the performance of proposed controller is good.

In Fig. 18 torque results are shown. At starting the torque ripples reached at 10 Nm for 0.8 s and it takes 0.5 s to settle down in case of PI controller, whereas with the hybrid PI controller it reaches to 5.2 N-m for 0.7 s and settle down in 0.3 s and with ACFL-PI it reaches to 4.9 Nm for 0.6 s and settle down at 0.25 s. The torque ripples are reduced in comparison to conventional method at the time of starting, which is a major drawback of DTC and it is improved by hybrid PI which are further reduced by ACFL-PI. In Fig. 19 stator flux is shown in which at the time of starting the flux ripples are low with the proposed controller.

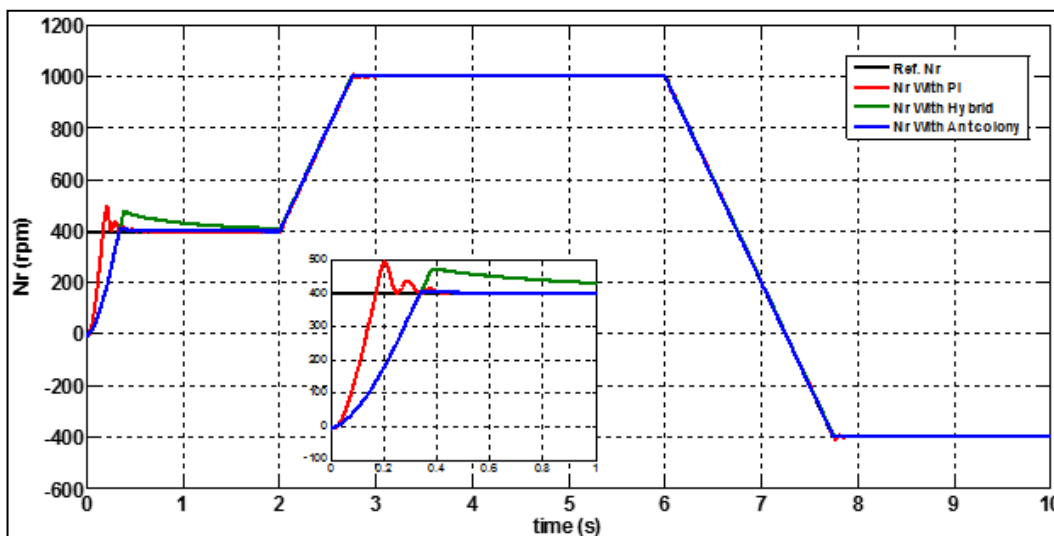


Fig 15: Tracking of speed reversal at constant load torque

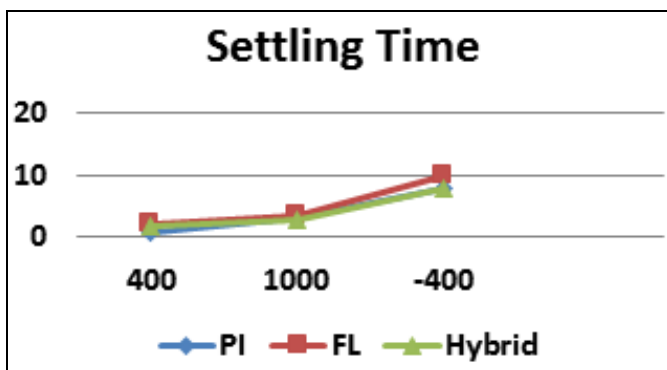


Fig 16: Graph of Settling Time of speed for different optimization Technique

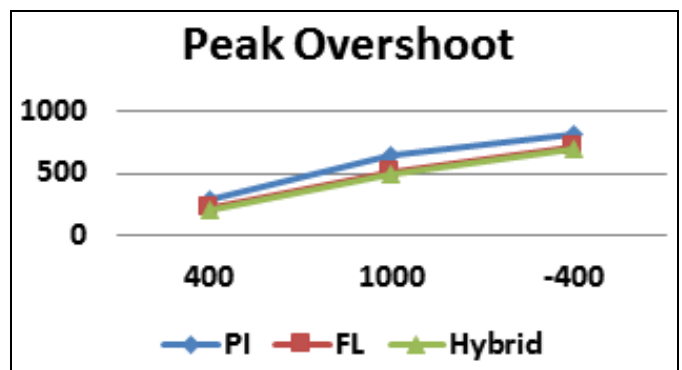


Fig 17: Graph of Peak over shoot of speed for different optimization Technique

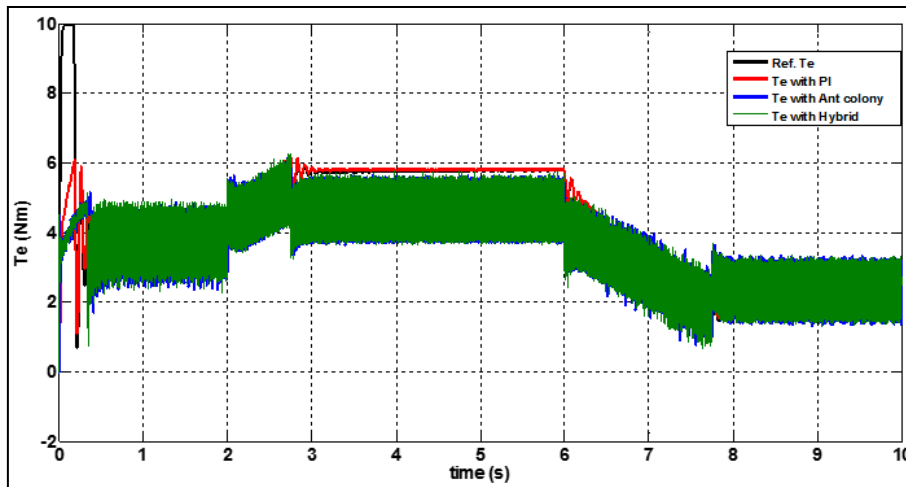


Fig 18: Electromagnetic Torque T_e with speed reversal and constant load torque

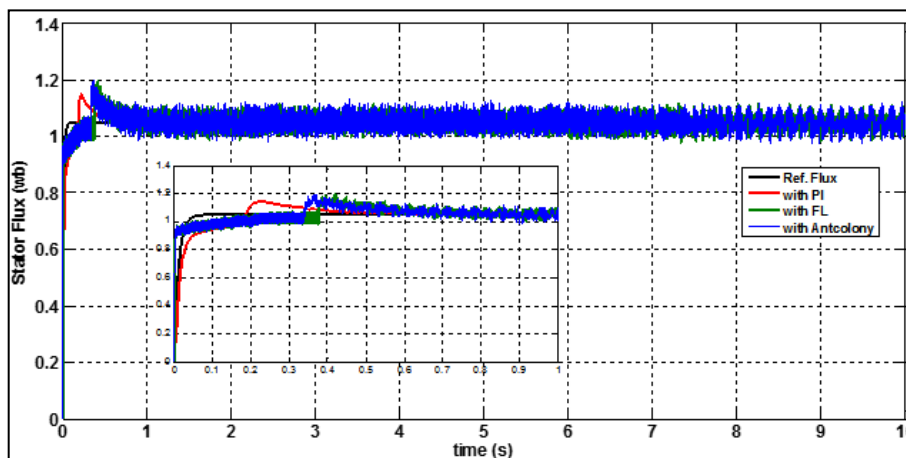


Fig 19: Stator Flux with speed reversal at constant load torque

Table 2: Performance comparison of Three Algorithms at Various Operating Points in Case-II

AI Technologies	Kp	Ki	Settling Time (s) at different speed (s)			Peak overshoot at different speed (rpm)		
			400	1000	-400	400	1000	-400
PI	2.15	15.2	0.59	3.04	7.98	495.1	1009.18	-409.23
Hybrid PI	0.09	1.01	2.0	3.45	9.78	475.5	1003.36	-398.5
Hybrid PI with Ant colony	1.5433	19.270	1.78	2.82	7.75	405.3	1000.2	-400.05
% Reduction as compared with Hybrid PI and Hybrid Ant controller			11%	18.26%	20.75%	14.76%	0.31%	0.38%

5. Conclusion

The paper presents a decoupled control method for control of speed, torque and flux for Direct Torque Control of induction motor drive. A new approach for tuning the controller using ACFL-PI has been presented. From the simulation results it can be concluded that the performance of the proposed ACFL-PI tuned PI controller is better than the conventional PI and Hybrid PI controller with reference to peak overshoot and settling time in the speed response.

The performance of the DTC drive is investigated using Hybrid PI, ACFL-PI controller and from the results it is observed that the torque ripples is considerably reduced and the speed of the drive tracks the reference speed smoothly with reduced overshoot. Not only that, there is a considerable reduction in the settling time of torque as compared to the

other controllers. The overshoot and variation in flux with different operating points is also better in case of ACFL-PI tuned PI controller. It can be concluded that the decoupled based DTC drive using ACFL-PI based speed controller is a better alternative to the conventional PI controlled DTC drive.

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