A Review on Hybrid Controller Using Soft Computing Algorithms

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Abstract Aadaptability and self-organization of a system is two key factors, when it comes to how well the system is surviving for the changes to the environment and how these work within the plant. Different tuning methods and soft computing techniques improve these two factors in controllers. Considering the increasing complexity of dynamic systems along with their need for feedback controls, using more complicated controls has become necessary and these techniques can be a suitable response to this necessity. This paper briefly describes a review on different techniques used for PID tuning as well as soft computing algorithm for hybrid controllers. This paper provides a comprehensive reference source for people working with hybrid controllers.

Keywords: *PI Controller, PID Controller, FLC, Neuro-fuzzy system, Tuning, ANFIS*

1. Introduction

Conventional proportional-integral-derivative (PID) controllers are extensively used for industrial automation and process control. PID controllers are simple, easy to understand and implement in hardware and software and do not require a process model for operation [1]. Many nonlinear processes can be satisfactorily controlled using PID controller parameters provided that controller parameters are tuned well. According to a survey in 1989, 90% of process industries use them. This widespread use of PID in industry can be attributed to their simplicity and ease of re-tuning on-line [2].

The PID controller is so named because its output sum of three terms, proportional, integral and derivative term.
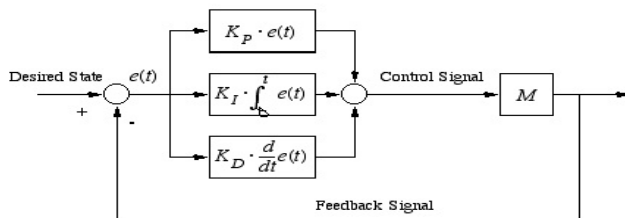

Figure 1. Block diagram of PID controller

Each of these terms is dependent on the error value e(t) between the input and the output,

$$output = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \qquad (1)$$

Where K_P, K_I and K_D are the P, I and D parameters respectively. By tuning these constants in PID algorithm, the controller provides control action designed for specific requirements [3].

The Fuzzy Logic is closer as to human reasoning and in language than conventional logical systems [3]. Fuzzy hardware systems have been developed, including fuzzy rules, fuzzy interface systems and optical fuzzy inference systems [3]. Fuzzy logic is successful applications for control engineering field and can be used for various parameters control of the real time systems. The main problem to overcome in applications is the uncertainty in fuzzy modeling of the linguistic structure for process [3].
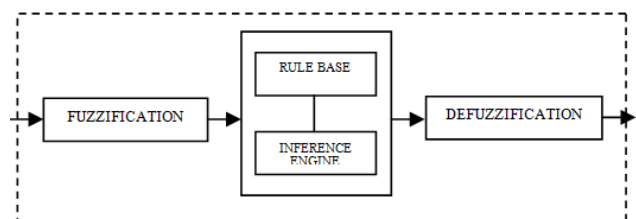

Figure 2. Block diagram of Fuzzy logic controller

While Artificial Neural Networks are mathematical models inspired from biological nervous system [4]. They can get large number of inputs and learn solely from training samples [4]. As mathematical models for biological nervous system, artificial neural networks are useful in establishing relationships between input and output of the system [4]. Neural network is collection of artificial neuron. Neural network can learn from data. However, the knowledge learned by neural networks has been difficult to understand while Fuzzy models are easy

to understand due to use linguistic terms and the structure of IF-THEN rules.

However, fuzzy logic by itself cannot learn. Since neural networks can learn.

Neuro-fuzzy system is the combination of artificial neural network and fuzzy logic [4]. Fuzzy system provide a framework to represent imprecise information and to reason with this kind of information, while neural networks enhance fuzzy systems with the capability of learning capability of input-output samples, learning is used to adapt parameters of the fuzzy system as a membership function or rule [4]. By these two methodologies, improve the performance of the system and get advantage of the each methodology and at the same time overcome the limitations of individual techniques [4].
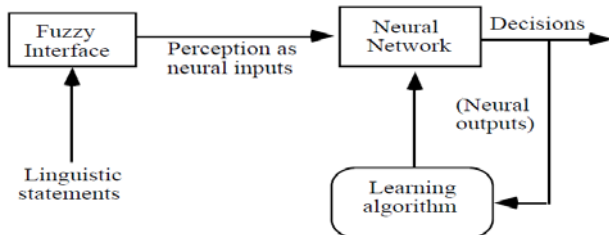

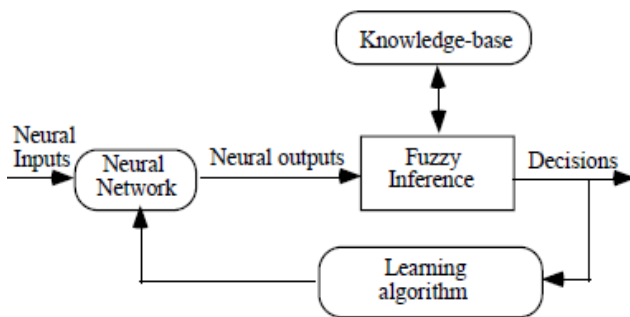**Figure 3.** First model of fuzzy neural system

Figure 4. Second model of fuzzy neural system

2. Literature Review

The literature survey carried out related to impact in the study of Fuzzy system, neural network, Neuro-Fuzzy system and PID controller.

Amit Kr. Singh et al.[4] described the Self Tuning Fuzzy PID controller developed to improve the performance of the plants having 2nd order, 3rd order and 5th order system. Firstly, maintained the modeling for the higher order plant and designed the adaptive fuzzy-PID controller and simulated using MATLAB/Simulink. The response of the plants (i.e.2nd, 3rd and 5th order) using adaptive fuzzy-PID controller has improved significantly as compared to conventional PID controller.

Figure 5 shows the comparative result of PID Controller and Adaptive Fuzzy PID Controller for 5th order plant. A simulation result shows that the response of Adaptive Fuzzy PID Controller is superior in comparison to conventional PID Controller.

Y.M.Zho et al. [5] investigate performance-based parameter tuning method of model-driven Two-Degree-of- Freedom PID (MD TDOF PID) control system to enhance the control performances of a process. Tuning

methods for the MD TDOF PID are based on internal model control (IMC) method instead of optimizing the performance indices. In this paper, an Integral of Time Absolute Error (ITAE) zero-position-error optimal tuning and noise effect minimizing method is proposed for tuning two parameters in MD TDOF PID control system to achieve the desired regulating and disturbance rejection performance.
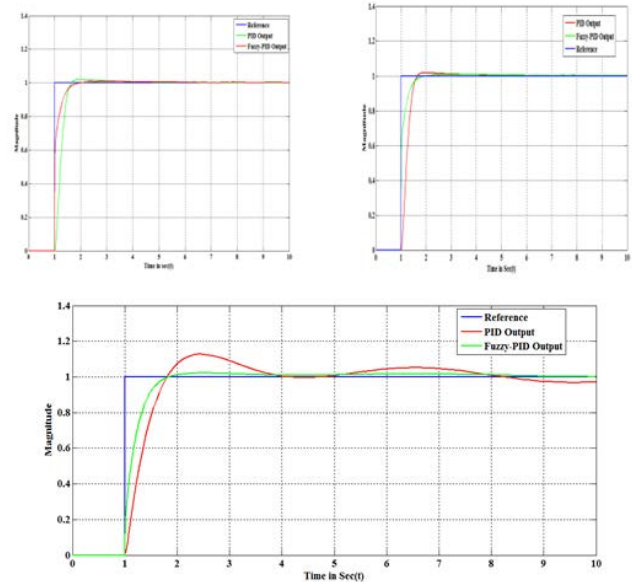

Figure 5. Comparative result of 2nd , 3rd and 5th order plant
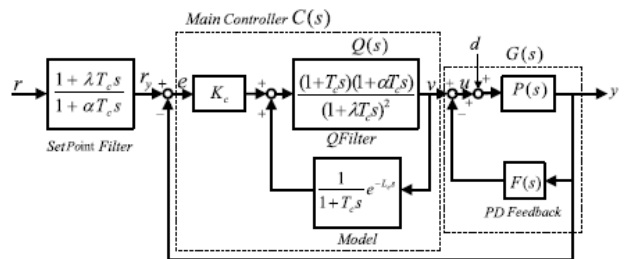

Figure 6. MD TDOF PID control system

In this paper, the function of each block of MDTDOFPID is analyzed. Two performance decisive factors – variance control and variance tracking – are used to design the tuning method. The variance tracking is the ability for output to follow the input signal and the variance control consists in keeping the output of the system at a set point while recovering as quickly as possible from disturbances.

MDTDOFPID control system functionally having three parts: PD feedback mechanism, main controller and set point. Main controller further decomposed into gain block, Q filter block and first order model with time delay. PD feedback is used to stabilizing the plant and make a transfer function of the process including PD feedback itself to first order system with time delay. Main controller is designed by adjusting the parameters of Q filter to meet design specifications and improves the speed response ability of the system as well as also helps in rejecting noise from entering system in low frequency. Set point filter is used to cancel one zero and one pole in the system and reduce the order of the system from second order to first one.

After tuning the both parameters of Q filter, there be two cases in this paper: for unstable first order plus time delay process and for pure integrating process plus time delay process. By simulation, the results have been compared with ITMDTDOFPID, PTMDOFPID and TDOFCSMSP. The results show, by tuning of parameters of PD feedback compensator, most of many processes can be converted to a first order with dead time process which makes it easy to design MDTDOFPID. The main controller improves the set point tracking and disturbance rejection properties of control system. Set point filter helps system reduce oscillations and make system more stable.

Mohamed S. Zaky [6] presented a self tuning PI controller for the speed control of electrical motor drives. The performance of the proposed self tuning PI controller using field oriented control of hybrid stepper motor is simulated and compared with conventional PI controller under tracking performance, parameters variation and load torque disturbances. Firstly maintained the dynamic modeling of hybrid stepper motor with d-q model using Park transformation and apply field oriented control principles in which direct current i_d set zero for simplify the control and then design the self tuning PI controller in which gains are varied over a pre-determined range for varying operating condition. Proportional term (K_p) is responsible for improving overshoots, rise time response while integral term (K_i) reduces steady state error. For large speed error, high value proportional gain is required for speed up the transient response and small integral gain is used to eliminate the undesirable oscillations and overshoot while for small seed error, high value of integral gain is required to overcome steady state error and minimum value of proportional gain is used to eliminate overshoots and oscillations. So that two gains are varied online as a function of speed error e(t). Hence in proposed self tuning PI controller using Root Locus Method gives better performance for highly under damped system in comparison to other control.

Dao Thanh Liem et al. [7] Presented a new method for estimating the load torque of a DC motor shaft by using a novel modelling method based on an adaptive control technique, named as online tuning grey fuzzy PID (OTGFPID). A test rig using a DC motor is setup to investigate the torque behavior as well as to evaluate the developed estimator. Firstly, mathematical model is developed for the motor. Secondly, the experimental speed-torque data and the optimized motor model is used to optimize the torque estimator. Then the optimized estimator is used to estimate accurately the load torque. This paper proposes to separate the actual speed of the DC motor ω into two distinct parts for estimating load torque: speed due to the armature current (ω_n) and speed variation (ω_e) due to the current generated from the unknown load torque which needs to be estimated. Therefore, it is necessary to estimate the ideal speed ω_n and subsequently, to determine the speed difference ω_e caused by the load torque. A control algorithm is then proposed to drive the second DC motor model to track this speed different. If the controller is able to make the model track the desired speed, ω_e, then the load torque can be precisely estimated.

Firstly physical model of DC motor is developed and optimized through an identification process using least square algorithm and iterative procedure. OTGFPID

model having three main blocks: the online tuning fuzzy PID controller, the optimized motor model and the Fuzzy Grey Predictor (FGP). The OTFPID controller is to produce the control input for the optimized model which is also the estimated load torque. Then model creates a speed corresponding to the voltage and the estimated torque. For actual working condition, a noise source is added to the model output. By subtracting to the ideal speed, the estimated value of the speed difference is achieved. At the same time, the input and output MFs of the fuzzy structure inside the OTFPID are optimized online with respect to the control error minimization by using the learning mechanism while the PID gains are updated through the robust checking conditions, consequently, improving the control quality. To improve the control quality, the FGP predictor with online tuning ability of its prediction step size is designed to estimate the motor speed difference in a near future. This estimated speed is finally fed-back to the controller to create the control input and subsequently, performs the close-loop control system.
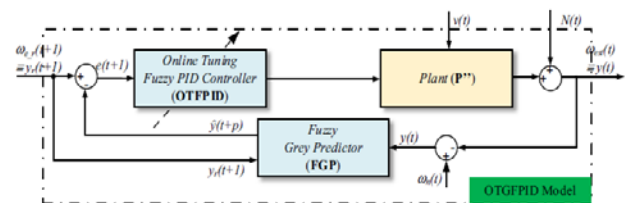

Figure 7. Structure of the OTGFPID model

Hence, the proposed method using FPID-based estimator investigates the effectiveness of the purpose estimation technique. The OTGFPID was successfully design as the combination of online tuning fuzzy PID controller and fuzzy gray predictor. Here, OTFPID controller based on PID algorithm is to estimate the motor torque from motor speed. Learning mechanism with robust checking conditions was implemented into the OTFPID in order to optimize online its parameters with respect to control error minimization. Meanwhile, the FGP predictor techniques takes part in estimating the system output in near future to optimize the controller parameters in advance and consequently, improve estimation performance.

Juing-Shian Chiou et al. [8] presents a novel approach to determining the parameters of fuzzy PID controller using practical swarm optimization (PSO) reinforcement evolutionary algorithm. PSO with Q- learning developed an adaptive fuzzy PID controller scheme for automotive active suspension system.
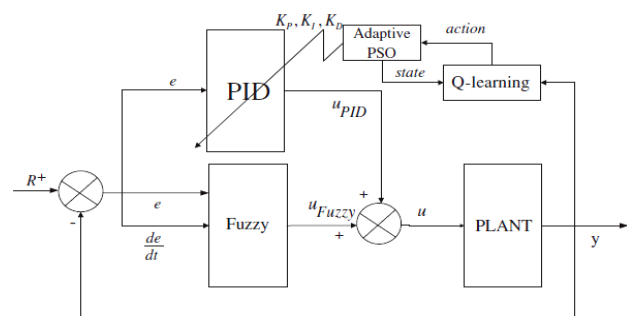

Figure 8. Hybrid structure of fuzzy-PID controller

For improving the efficiency and accuracy, PSO reinforcement evolutionary algorithm is employed to adjust the swarm of Q-learning to obtain global optimum solution. By this scheme, reduces the suspension deflection, spring mass acceleration and beating distance between the tire and the ground relative and also improves ride comfort and vehicle stability.

Rajani K. Mudi et al. [9] investigate an improved auto tuning scheme for PI controller which proposes an augmented Zieglar Nichols PI controller (AZNPIC). This proposed controller is tested with several high order linear and non-linear dead time processes under both set point change and load disturbance. It shows better performance, if compared with ZNPIC and RZNPIC (Refined Zieglar Nichols PI controller).
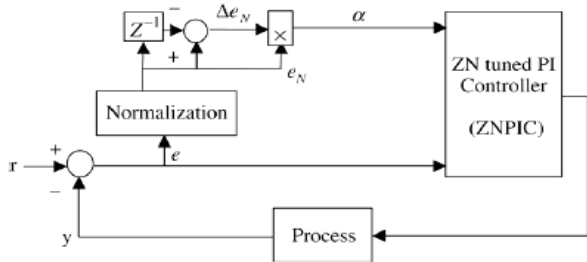
Figure 9. Block diagram of proposed AZNPIC

AZNPIC introduce an online gain updating factor which continuously modifies its proportional and integral gains based only on recent process trend.

Transfer function of the second-order linear process is

$$G_p(s) = \frac{e^{-Ls}}{(1+s)^2} \qquad (2)$$

Response characteristics for the process in (2) with L = 0.2 s and L= 0.3 s under ZNPIC, RZNPIC, and AZNPIC are as under
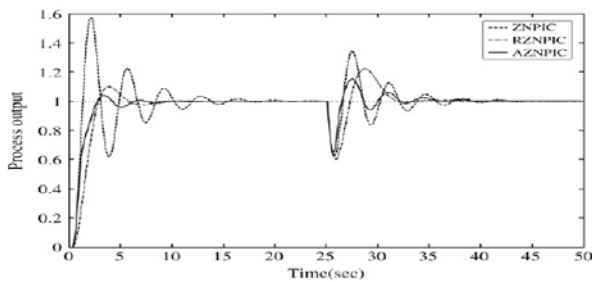
Figure 10. Response of the second order linear process with L=0.2 s
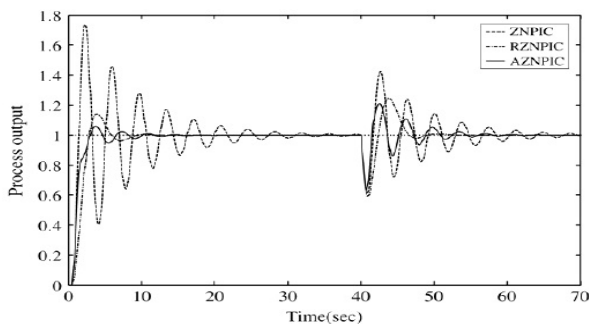
Figure 11. Response of the second order linear process with L=0.3 s

Figure 10 indicates that the performance of AZNPIC is better than that of RZNPIC. To study the robustness of the proposed scheme a 50% higher value of dead time i.e., L=0.3 sec is considered with same controller setting as that of L=0.2 sec and the corresponding responses are shown in Fig 11also shows that AZNPIC is superior over RZNPIC and ZNPIC.

The performance of the proposed auto-tuner is tested for different nonlinear processes which is described by

$$\frac{d^2 y}{dt^2} + \frac{dy}{dt} + 0.2y^2 = u(t - L) \qquad (3)$$

Response characteristics for the nonlinear process in (3) with L = 0.2 s and L= 0.3 s under ZNPIC, RZNPIC, and AZNPIC are as under
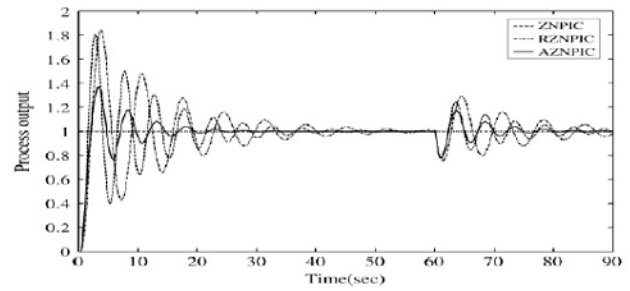

Figure 12. Response of the second order nonlinear process with L=0.2 s
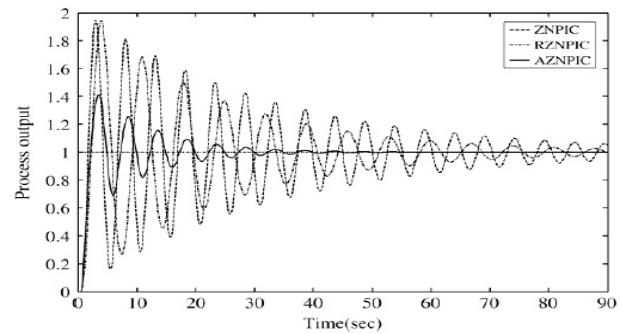

Figure 13. Response of the second order nonlinear process with L=0.3 s

From Figure 12 and Figure13, it is seen that in case of AZNPIC, % overshoot is considerably reduced, and steady state is reached faster, which reveal that unlike ZNPIC and RZNPIC.

Transfer function of the second-order marginally stable process is

$$G_p(s) = \frac{e^{-Ls}}{s(s+1)} \qquad (4)$$

Response characteristics for the integrating process in (4) with L = 0.2 s and L= 0.3 s under ZNPIC, RZNPIC, and AZNPIC are as under
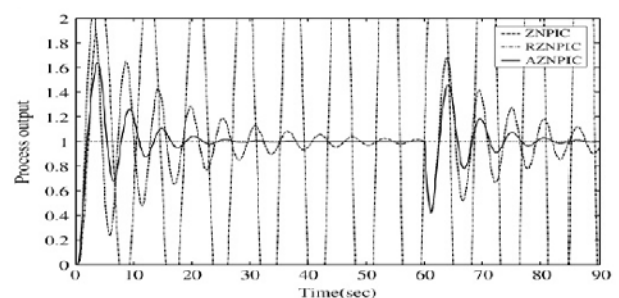

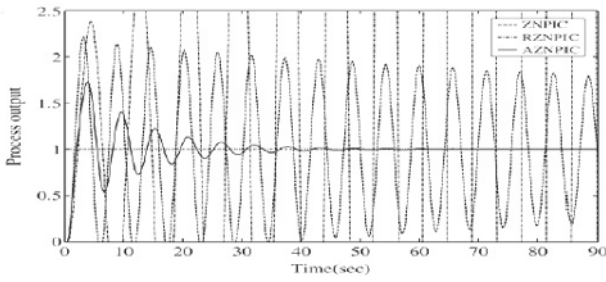**Figure 14.** Response of the marginally stable process with L=0.2 s

Figure 15. Response of the marginally stable process with L=0.3 s

ZNPIC provides a very poor performance due to excessively large overshoot and oscillation. The %OS of ZNPIDC is also very large (about 80%). Whereas, AZNPIC is found to reduce the %OS and t_s by about 40% and 60%, respectively compared to ZNPIC. When the process dead-time is increased from 0.2 to 0.3 s without changing the controller parameters, the system goes to the verge of instability under ZNPIC. However, AZNPIC still provides a highly stable performance. In both cases (L = 0.2 s and 0.3 s) the integrating process in (4) becomes completely unstable under RZNPIC.

In this study third-order linear as well as nonlinear process models are also tested to justify the effectiveness of the proposed scheme. Such a linear system is expressed by the following transfer function

$$G_p(s) = \frac{e^{-Ls}}{s^3 + s^2 + s + 0.2} \qquad (5)$$

Response characteristics for the process in (2) with L = 0.4 s and L= 0.5 s under ZNPIC, RZNPIC, and AZNPIC are as under
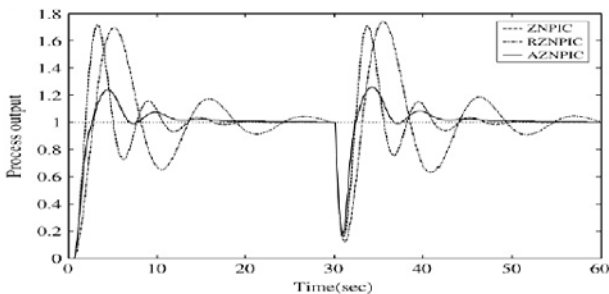
Figure 16. Response of the third order linear process with L=0.4 s
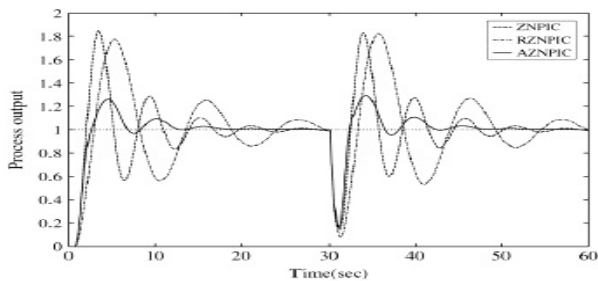
Figure 17. Response of the third order linear process with L=0.5 s

Figure 16 and Figure 17 indicate that the performance of AZNPIC is better than that of RZNPIC and ZNPIC.

Third order non-linear process is considered as:

$$\frac{d^3 y}{dt^3} + \frac{d^2 y}{dt^2} + \frac{dy}{dt} + 0.5y = u(t - L) \qquad (6)$$

Response characteristics for the nonlinear process in (3) with L = 0.3 s and L= 0.4 s under ZNPIC, RZNPIC, and AZNPIC are as under:
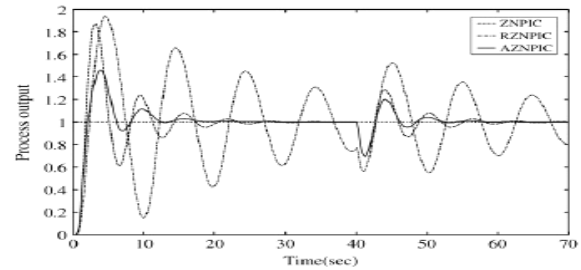
Figure 18. Response of the third order nonlinear process with L=0.3 s
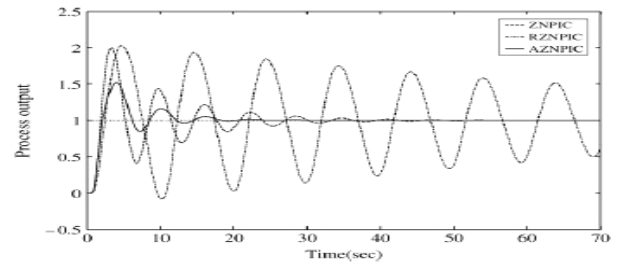

Figure 19. Response of the third order nonlinear process with L=0.4 s

The proposed controller (AZNPIC) exhibits better performance compared to ZNPIC for nonlinear process in (6). Also, RZNPIC shows a very poor performance.

The performance of AZNPIC is also evaluated for practical process, pH neutralization. For this process both ZNPIC and RZNPIC are not suitable.

From above results for various processes it is evident that the proposed AZNPIC shows consistently improved performance over ZNPIC and RZNPIC.

Chanchal Dey and Rajani K Mudi [10] investigate an improved auto tuning scheme for PID controller which proposes an augmented Zieglar Nichols PID controller (AZNPIDC) through an online gain updating factor which continuously modifies its proportional, integral and derivative gains based only on recent process trend and compared with ZNPIDC and RZNPIDC, gives better performance.
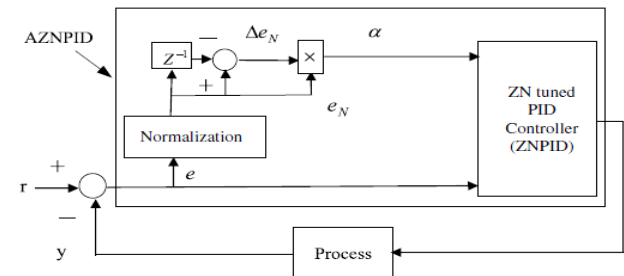

Figure 20. Block diagram of proposed AZNPID

For various processes (linear process and nonlinear process) it is evident that the proposed AZNPIDC shows consistently improved performance over ZNPIDC and RZNPIDC.

Muguo Li and Da Liu [11] proposed recurrent wavelet neural network PID controller [RWNNPID] for PMSM speed servo drive system to adjust the parameters online to be adaptive to the parameters variety and load disturbance.
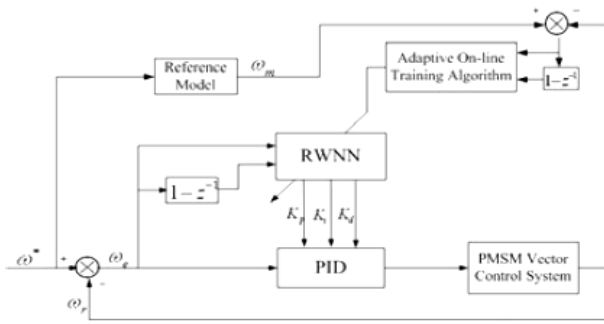
Figure 21. Recurrent wavelet neural network PID control system

The algorithm uses WNN to turn PID parameters adaptively. The recurrent nodes in addition to the network increase the network response speed and ensure the network has stable outputs. Network algorithm is working online for obtaining optimal parameters to realize an adaptive system with strong learning ability and good robustness.

From Figure 22 and Figure 23, results show that proposed controller gives improve performance if compared with conventional PID controller for PMSM speed regulation.
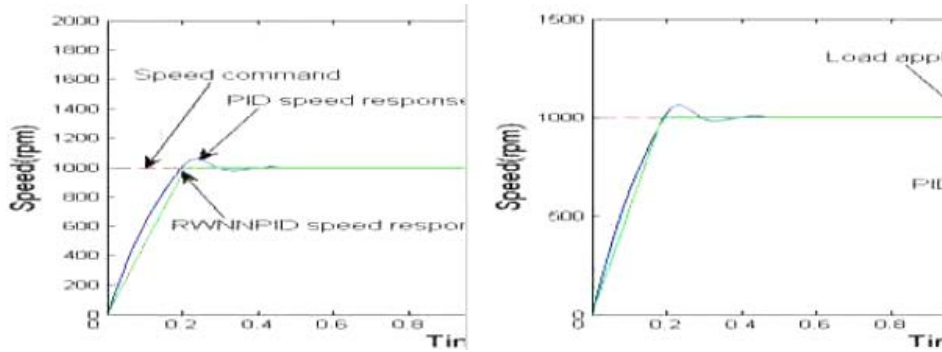
Figure 22 (a). Simulation investigation of conventional PID and RWNNPID speed response on condition that step speed command is changed; (b): Simulation investigation of conventional PID and RWNNPID speed response on condition that load is applied
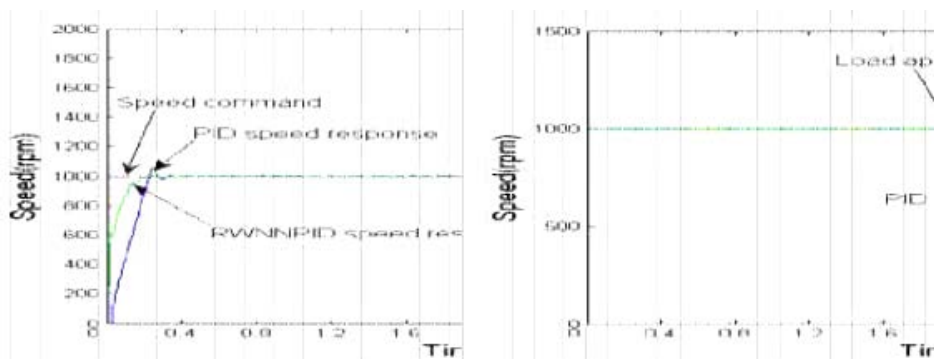
Figure 23. (a): Experimental results of conventional PID and RWNNPID speed response on condition that step speed command is changed; (b): Experimental results of conventional PID and RWNNPID speed response on condition that load is applied

Muawia A. Magzoub et al. [12] investigate the efficiency improvement of induction motor variable speed drive using a hybrid fuzzy-fuzzy controller to overcome drawback of field oriented method. There are two fuzzy controller used as fuzzy frequency controller during accelerate-decelerate stage and fuzzy stator current magnitude controller for steady state stage.
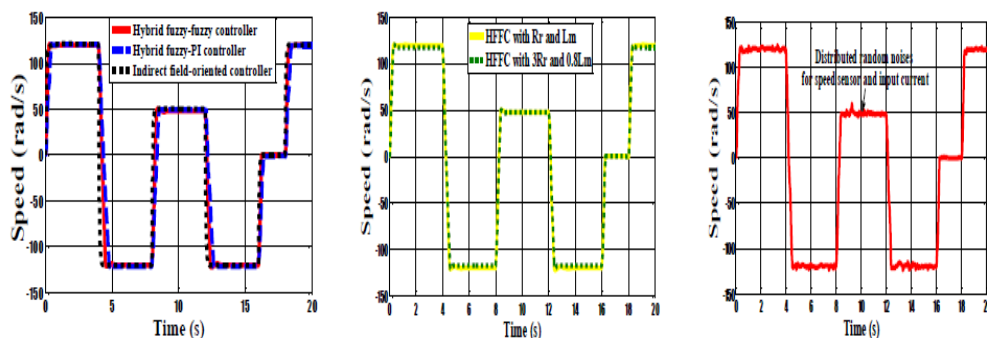
Figure 24. (a): Speed response of HFFC; (b): With parameters variation; (c): With noise

After simulation, compared with FOC results faster speed and the large changes can be accommodated in load torque. The minimization of current losses which contribute to energy efficiency system and efficiency is improved by HFFC. Henceforth, from the exploitation of the two features of field-oriented control, the fuzzy fuzzy controller has been found to be more efficient than scalar controller.
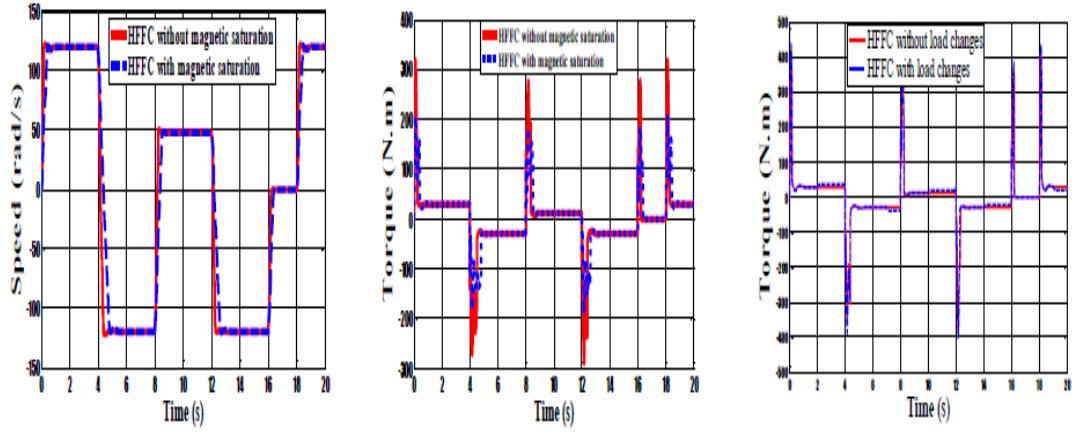
Figure 25. (a): With the effect of magnetic saturation; (b): Torque with the effect of magnetic saturation; (c): With load changes

Sakuntala Mahapatra et al. [13] developed a prototype model using PSO-ANFIS (Particle Swarm Optimization-Adaptive Neuro-Fuzzy Inference System) hybrid technique to control the speed of an induction motor. The speed of an Induction Motor drive is controlled by the hybrid of PSO- ANFIS algorithms.
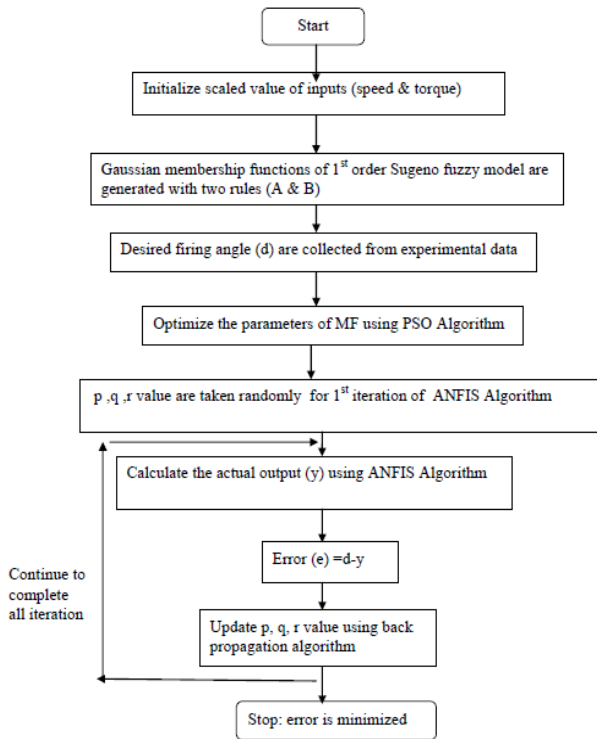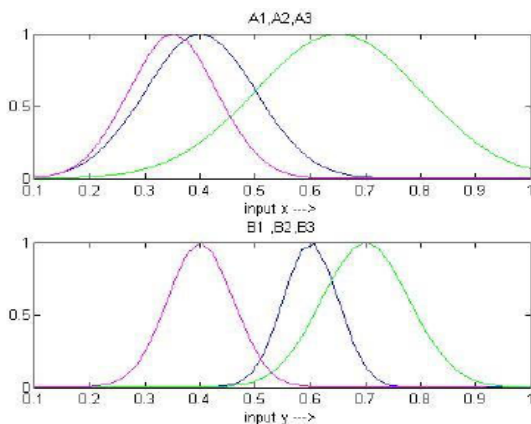

Figure 26. Flowchart of proposed model

Figure 27. Plot of membership function using 2 inputs 3 rules
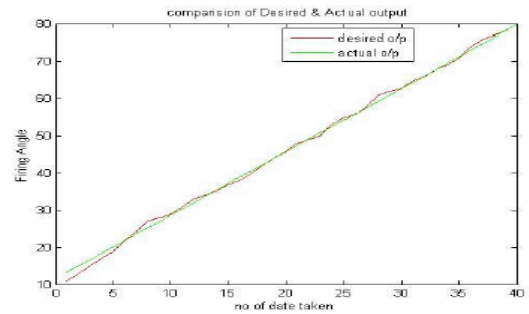
Figure 28. Comparison of actual and desired output plot
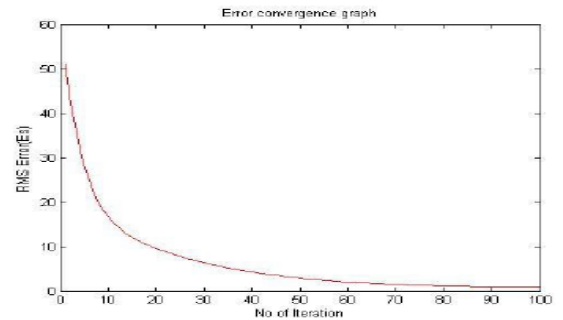
Figure 29. Error convergence plot for ANFIS
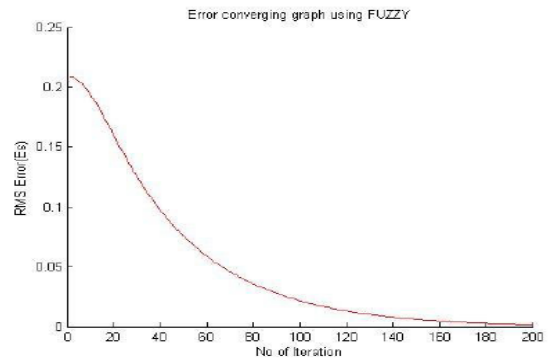
Figure 30. Error convergence plot of fuzzy back propagation

According to MATLAB simulation, the Adaptive Neuro Fuzzy (ANFIS) controller efficiently is better than the traditional FLC. The ANFIS-PSO is the best controller which presented satisfactory performances. Therefore, chose with the use of the Neural Networks and Particle Swarm Optimization for the optimization of this controller in order to control Induction motor speed. Finally, the proposed controller (PSO-ANFIS) gives a very good

result. The ANFIS-PSO is the best controller which presented satisfactory performances.
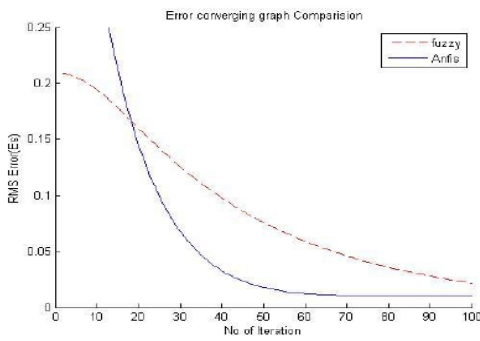

Figure 31. Error convergence comparison between ANFIS and fuzzy back propagation

Sharda Patwa [14] investigated the fuzzy logic controller for controlling induction motor parameters such as starting current, flux, torque, and speed. The results of FLC are also compared the controlling of induction motor same parameters with PI controller. The results showed that FLC has given the better performance than PI controller for controlling the induction motor parameters with improved rise time with less starting current.

P.M.Menghal and A.Jaya Laxmi [15] proposed an adaptive Neuro-fuzzy controller based dynamic performance of induction motor to overcome the problems developed in conventional fuzzy controllers. The main problem with conventional FLC is that the parameters associated with the membership functions and rules depend on intuition of the experts.
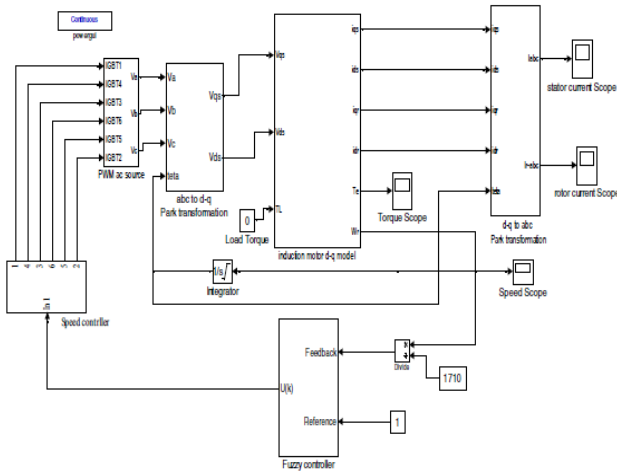
Figure 32. Adaptive neuro-fuzzy controller simulation model
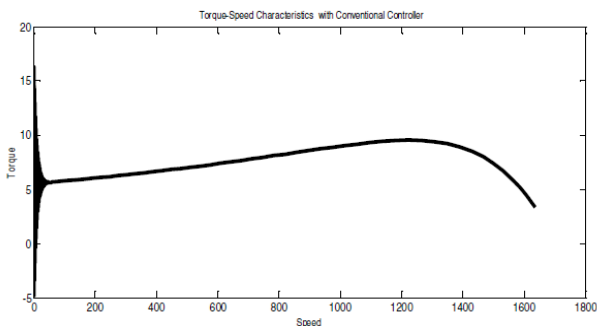
Figure 33. (a): Torque-speed characteristics with Conventional Controller
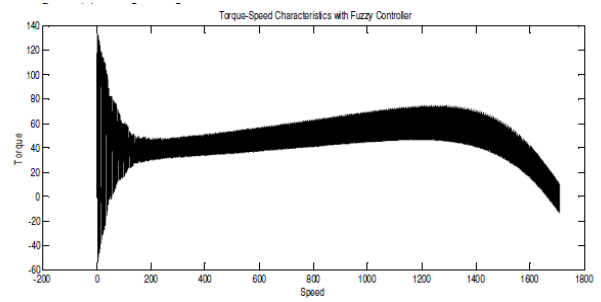

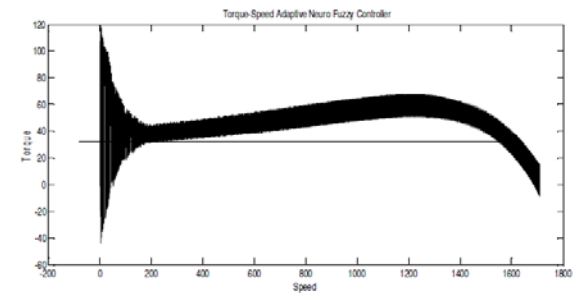**Figure 33**(b). Torque-speed characteristics with Fuzzy controller

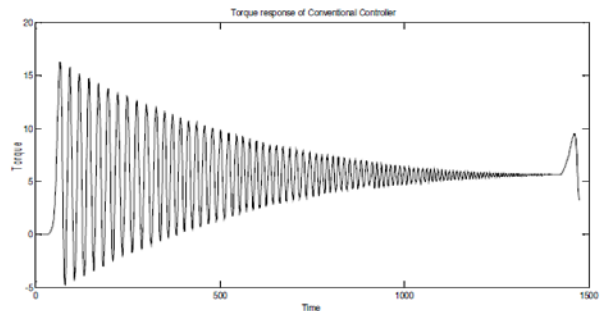**Figure 33.** (c): Torque-speed characteristics with Adaptive Neuro Fuzzy controller

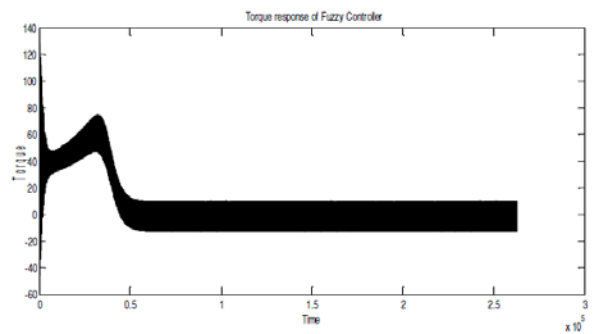**Figure 34.** (a): Torque response of Conventional Controller

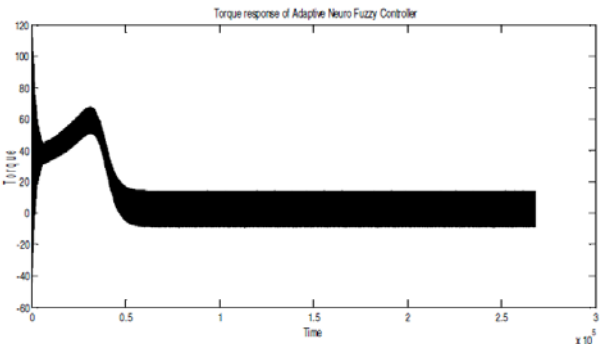**Figure 34.** (b): Torque response of Fuzzy Controller

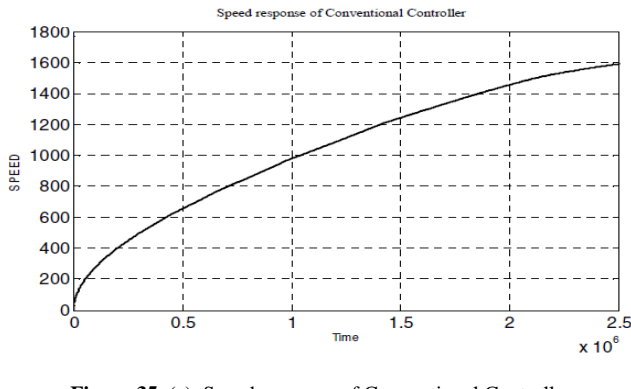**Figure 34**(c). Torque response of Adaptive Neuro Fuzzy Controller
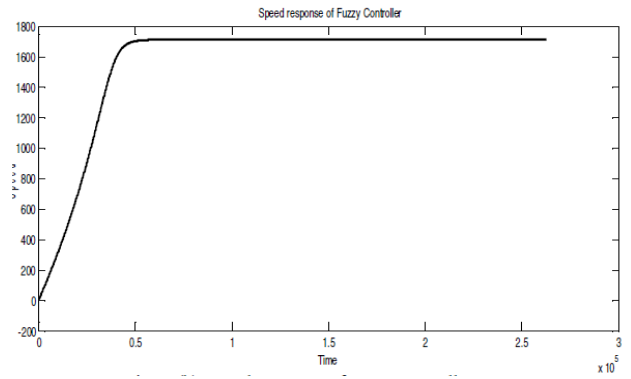
Figure 35. (a): Speed response of Conventional Controller

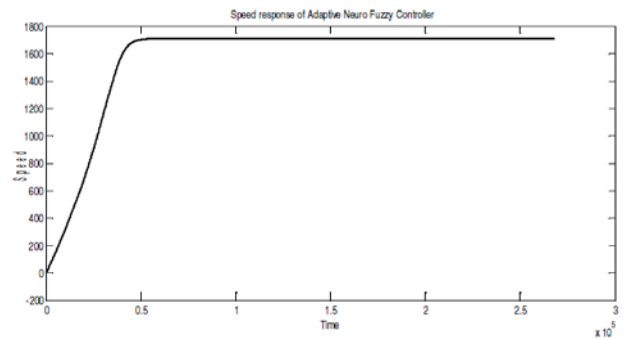**Figure 35.** (b): Speed response of Fuzzy Controller

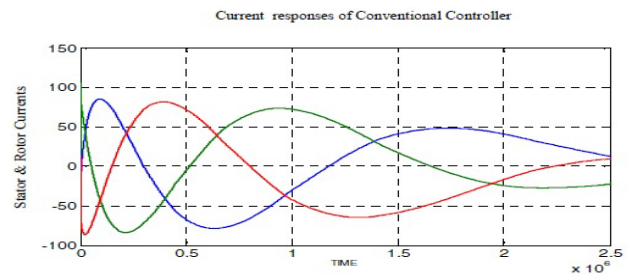**Figure 35.** (c): Speed response of Adaptive Neuro Fuzzy Controller

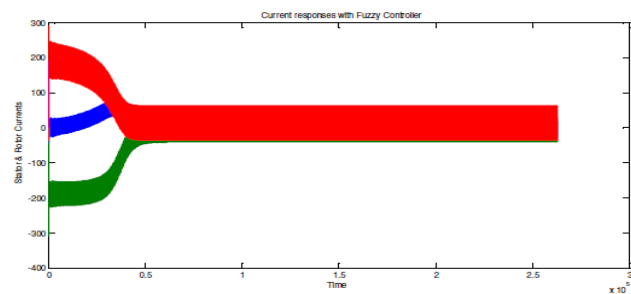**Figure 36.** (a): Stator & Rotor Currents of Conventional Controller

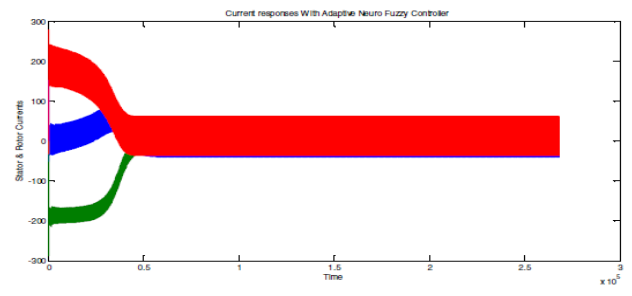**Figure 36.** (b): Stator & Rotor Currents of Fuzzy Controller

Figure 36. (c): Stator & Rotor Currents of Adaptive Neuro Fuzzy controller

The proposed adaptive neuro-fuzzy controller simulation model is designed and simulated in MATLAB/Simulation and compare with conventional and fuzzy controller. Results show that proposed adaptive neuro-fuzzy controller give better performance like speed-torque characteristics, torque response, speed response, rotor and stator currents compared to conventional and fuzzy controller.

P.M.Menghal et al. [16] present dynamic simulation of induction motor drive using neuro controller and the performance of fuzzy logic and artificial neural network based controller's are compared with that of the conventional proportional integral controller. The most popular supervised learning algorithm (i.e. back propagation) is used. On comparing neuro controller with FLC model, by adding learning algorithm to the control system will decrease rise time more than expectation and it proves neuro controller has better dynamic performance as compared to FLC and conventional controller.

Ahmed J. Fattah and Ikhlas Abdel-Qader [17] investigated an improved hybrid PID fuzzy controller for performance analysis of speed control induction motor and also compare their performance with conventional PI controller. They proposed a hybrid controller with vector control to control the speed of induction motor. PI-fuzzy, PD-fuzzy and PID-fuzzy controllers are designed and simulated with MATLAB/simulink.
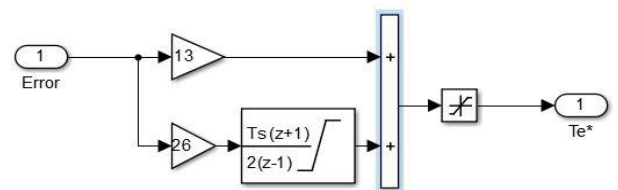

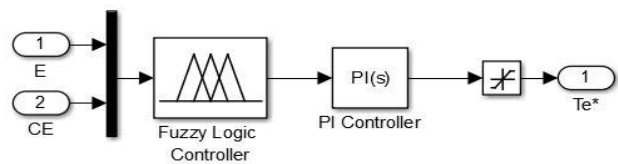**Figure 37.** The PI Controller MATLAB model

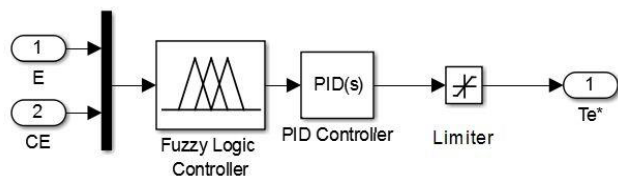**Figure 38.** The PI-Fuzzy Controller MATLAB model

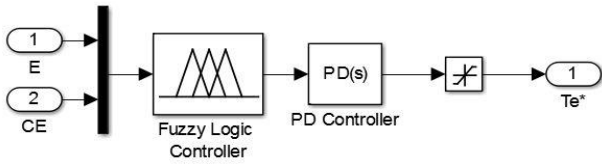**Figure 39.** The PID-Fuzzy Controller MATLAB model

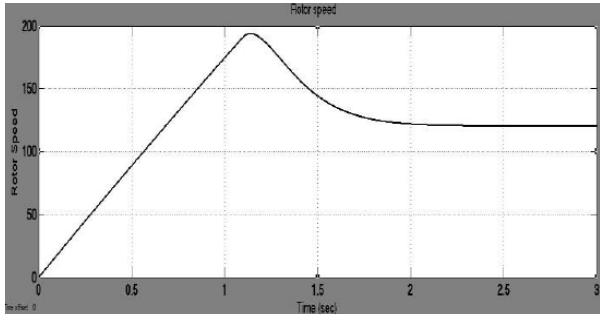**Figure 40.** The PD-Fuzzy Controller MATLAB model

Figure 41. Speed response curve of SCIM at 0 N.m load and 120 reference speed using PI Controller
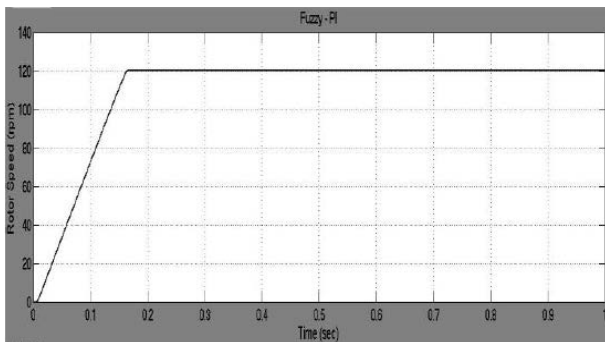

Figure 42. Speed response curve of SCIM at 200 N.m load and 120 reference speed using PI-Fuzzy Controller
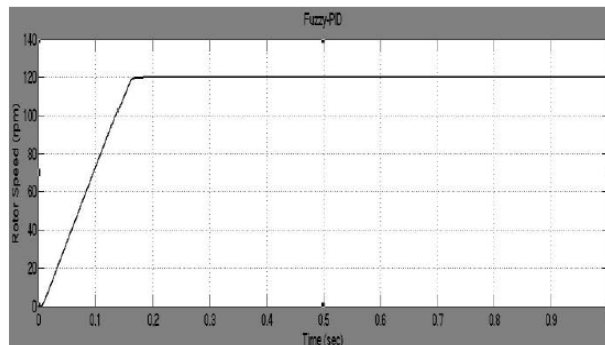

Figure 43. Speed response curve of SCIM at 200 N.m load and 120 reference speed using PID-Fuzzy Controller
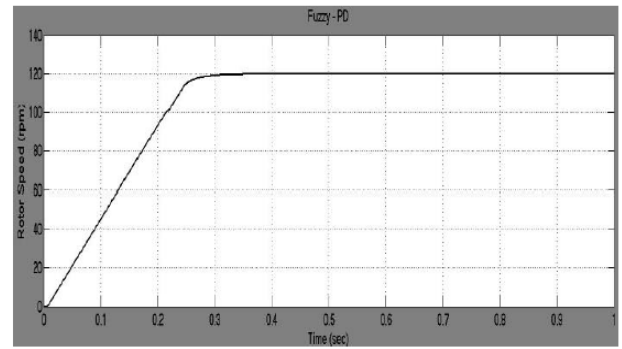

Figure 44. Speed response curve of SCIM at 200 N.m load and 120 reference speed using PD-Fuzzy Controller

Table 1. Performance analysis of different speed controllers for SCIM at different load

Load (N.m)	Controller	t_r (sec)	t_s (sec)	M_p	E_{ss}
0	PI	0.5439	1.9326	61.2028	0.015
	PD-Fuzzy	0.1649	0.2246	0	0.004
	PI-Fuzzy	0.1071	0.1386	0.1423	0.1600
	PID-Fuzzy	0.1071	0.1386	0.0763	0.005
100	PI	0.8264	2.6355	69.8537	0.005
	PD-Fuzzy	0.1815	0.2444	0	0.0570
	PI-Fuzzy	0.1146	0.1484	0.0994	0.1100
	PID-Fuzzy	0.1146	0.1484	0.0384	0.0420
150	PI	1.1171	3.3759	74.3692	0.0040
	PD-Fuzzy	0.1915	0.2563	0	0.0835
	PI-Fuzzy	0.1189	0.1539	0.0792	0.0880
	PID-Fuzzy	0.1189	0.1539	0.0200	0.0250
200	PI	1.7215	4.9398	77.3644	0.007
	PD-Fuzzy	0.2027	0.2698	0	0.1098
	PI-Fuzzy	0.1234	0.1598	0.0591	0.0650
	PID-Fuzzy	0.1234	0.1598	0.0022	0.0005

With different load conditions, comparison with conventional PI controller, the hybrid controller is increased dynamic performance such as rise time, peak overshoot, settling time and steady state error of induction motor and also to provide good stabilization.

Shamseldin and Adel A. EL-Samahy [18] presented three different controllers for speed control of BLDC motor. In which, first is conventional controller. The second controller is to use to GA technique to adjust the three cost functions. Finally, third controller hybrid fuzzy PID controller is development. All controllers are tested for speed regulation and speed tracking.

Firstly, the parameters (K_p, K_i, K_d) of PID controller is achieved by Ziegler-Nichols method and three cost function genetic algorithm techniques. Comparing among the controllers, the performance of the three cost function controller is best.
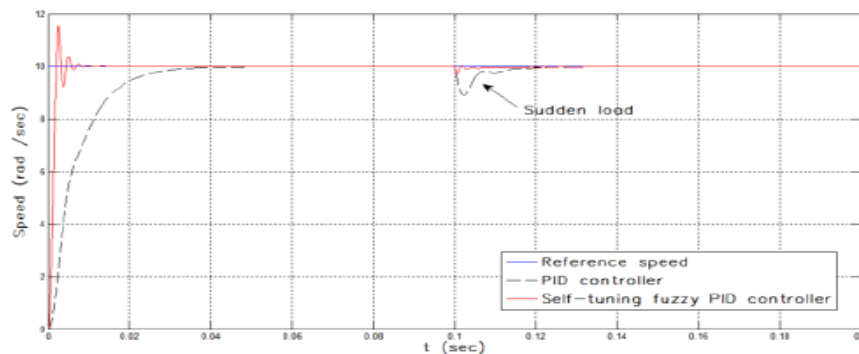

Figure 45. PID Control and Self –tuning Fuzzy-PID Controller response at sudden load

Finally, they proposed self tuning fuzzy PID controller and simulated with MATLAB/Simulink and compare with PID controller for speed regulation at sudden load, sinusoidal load, parameter variation and speed tracking of BLDC motor.
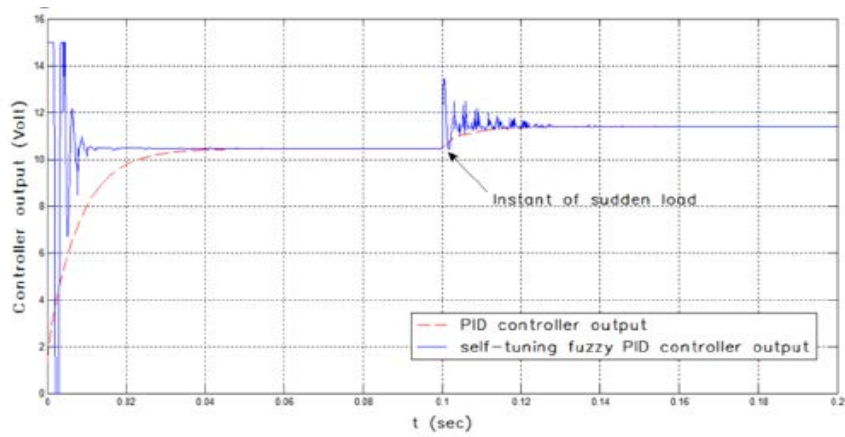

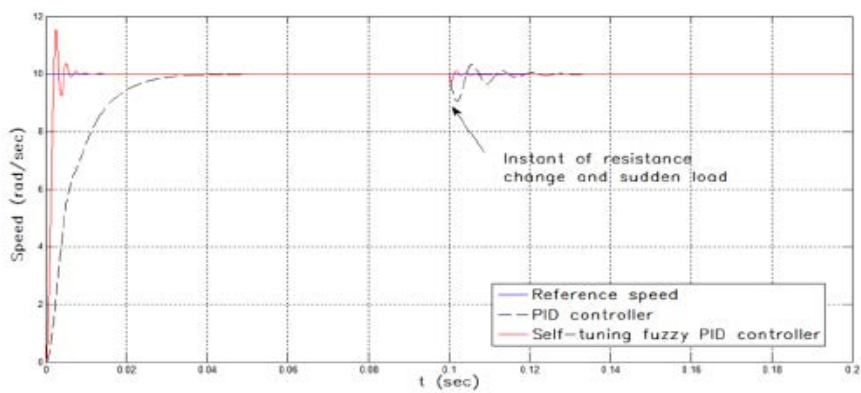**Figure 46.** PID Control and Self –tuning Fuzzy-PID Controller output at sudden load

Figure 47. PID Controller and Self –tuning Fuzzy-PID Controller response at resistance change and sudden load
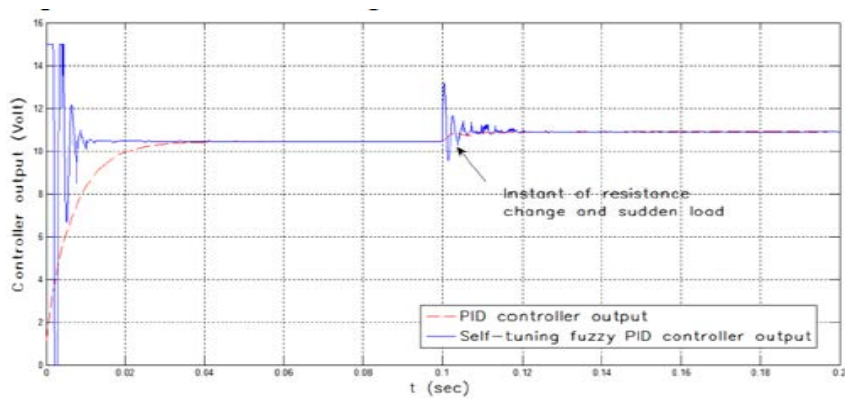

Figure 48. PID Controller and Self –tuning Fuzzy-PID Controller output at resistance change and sudden load
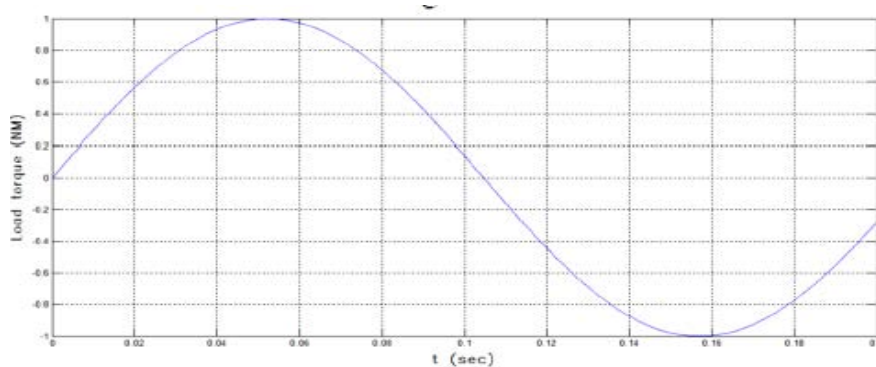

Figure 49. Sinusoidal load torque that exposed to the BLDC motor during simulation
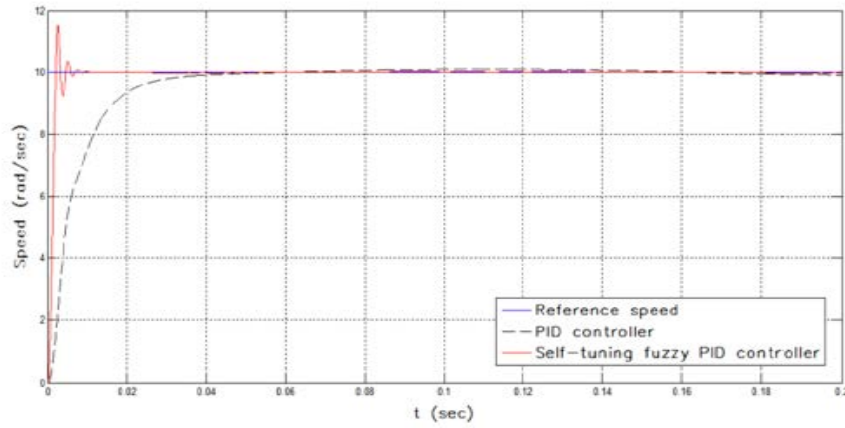
Figure 50. PID Controller and Self –tuning Fuzzy-PID Controller response at Sinusoidal load
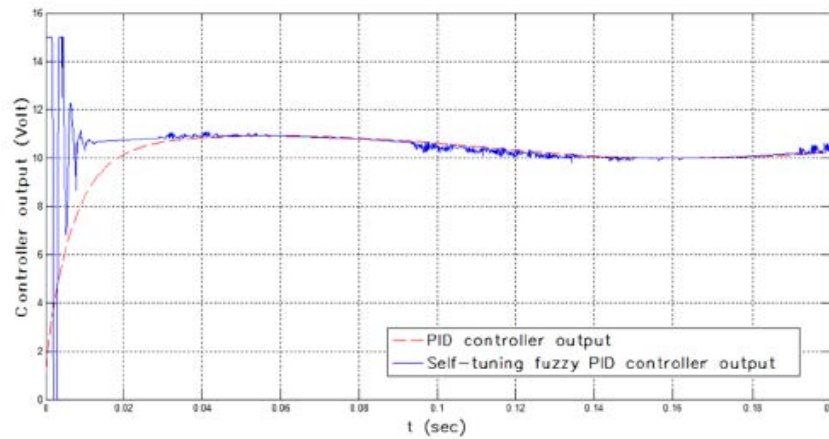

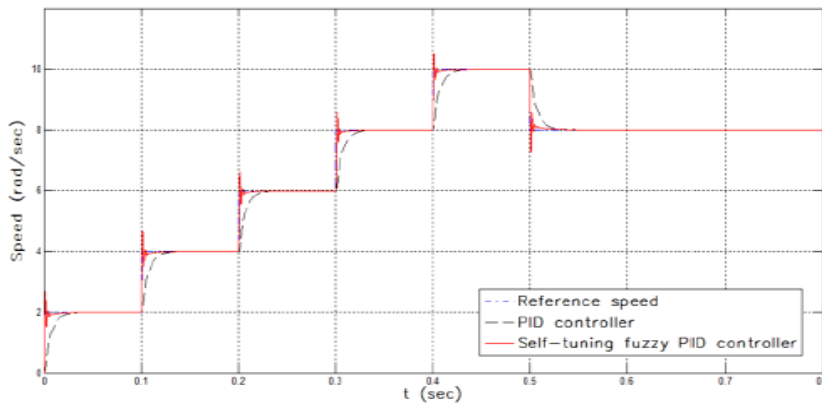**Figure 51.** PID Controller and Self –tuning Fuzzy-PID Controller output at Sinusoidal load

Figure 52. PID Controller and Self –tuning Fuzzy-PID Controller response at speed tracking

Results show that proposed self tuning fuzzy PID controller give better performance compared to other two techniques.

3. Conclusion

This review presents a overall summary on the various implementation techniques of fuzzy systems, neural network, PID-fuzzy system, neuro-fuzzy system, PID controller. This overview represents the information about Neuro-Fuzzy system and PID Controller focuses on its usability and challenges. This study suggests that the future development of Neuro-Fuzzy PID controllers using different soft computing techniques will improve its flexibility and re-usability of the controller.

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