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Robust speed control of induction motor drive for electric traction application

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Abstract: The proposed system focuses on improving the speed performance of traction drive by implementing the robust fuzzy logic controller-based inverter fed parallel connected induction motors. Fuzzy controller is compared with a conventional controller. The performance of modified induction motor drive for traction is analysed and improved under parameter variations to achieve the robust speed control. The simulation and hardware results are realised for the proposed system and compared with conventional system.

Keywords: asynchronous motor; robust speed control; PI controller; fuzzy controller; parameter variations; traction drive.

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1 Introduction

An induction motor has numerous advantages, mainly with a clear structure, substantiated operation, and the limited capacity of definite power. In the conventional electric traction, sensor based parallel connected induction motors required inverter set up for every motor (Badr et al., 2010). The implementation of induction motor in traction drive is not very efficient since it holds numerous disadvantages in terms of high maintenance cost due to shaft mounted speed encoder, speed digression, control methods and higher torque ripple. The standard traction drives include boost converter, one voltage source inverter for one induction motor, and combined rectifiers have faded eventually (Uddin et al., 2002; Nehrir, 1975).

To achieve the energy efficient traction drive, the complexity and the cost of the conventional method are reduced by the proposed set up of single inverter fed poly phase induction motors in parallel. The poly phase has several advantages over three phase machines. Initially, scalar control methods were used to control the induction motors, but the technique was complicated as a result of computations. Speed of the motor was sensed using tacho-generators, and the speed deviation of the feedback system was verified by Lyapunov formula. The system requires better control performance, precision, and quicker torque response (Holtz, 2006; Dabbeti and Varalakshmi, 2013).

Analysing the characteristics of machine and the designing of controllers, the accurate modelling of induction motor is necessary. Any parameter of the system like speed, torque or flux is dependent on the design of a controller. The different types of mathematical modelling are first principle method, system identification methods, finite element method, equivalent magnetic circuit approach and by using ordinary differential equation, linear/nonlinear differential equation, model with lumped parameter and distorted parameter, static and dynamic modelling (Terng, 2002; Talukder et al., 2012)

The mathematical model described by differential equations is used in the theory of electrical machines. To describe the magnetic field, temperature distribution and other particular quantities of electrical machines, partial differential equations can be used as they describe more completely. However, the drawback while using partial differential equations is that they are considerably complicated for investigation purpose (Xu et al., 2013; Matsuse et al., 2004).

For industry and academia, the simulation and dynamic modelling of induction motor carries much importance. Its value increases more because of the widespread presence of induction motor drives in dissimilar construction settings and also for sensor-less control of induction motor drive. Therefore, this work presents a detailed discussion of dynamic modelling of an asynchronous motor. Dynamic induction models based on Simulink are available in several books and research papers. Some of these texts have recommended the use of purpose for approaching the model data but they are not feasible as they do not use the Simulink in full power and capacity. The stator fault of induction motor is reviewed using different control techniques (Gunabalan and Subbiah, 2014; Yoshinaga et al., 2008). In industries, the most common type of motor used is induction motor because of its reliability, robustness, and low cost.

DC motor was used initially as it offers controlled speed and torque. But due to the existence of a commutator, it requires frequent maintenance and this problem was overcome by using an induction motor (Li et al., 2015). The elimination of commutator in induction motor lowers in cost and widens its application. However, the problem with induction motor was its speed control which was a difficult task to accomplish. This problem was soon rectified by advancements in power electronic converters. The different speed control methods using Proportional Integral (PI) controller are discussed (Ben-Brahim et al., 1999; Khader et al., 2016) Separate PI controller can also be dropped out this way since this can be interspersed into the neural network based adaptive device. The fuzzy logic controller has the probability of using divergent types of speed adjustable signals. Some of these selections offer high precision and are correspondingly vigorous to parameter modification (Dementyev et al., 2015; Usha and Chinnamuthu, 2017).

The dynamic modelling comprises all the mechanical equation including the speed – torque characteristics. The differential voltages, flux linkages, currents between the moving rotor as well as stationary stator can also be modelled by dynamic modelling. Generally, an AC motor is driven by the DC to AC converter equipped with a speed sensor, but this speed sensor may tend to lower the system's reliability and increase the investment cost. Also, its implementation is difficult (Usha, 2017; Liu et al., 2018; Zalhaf et al., 2019).

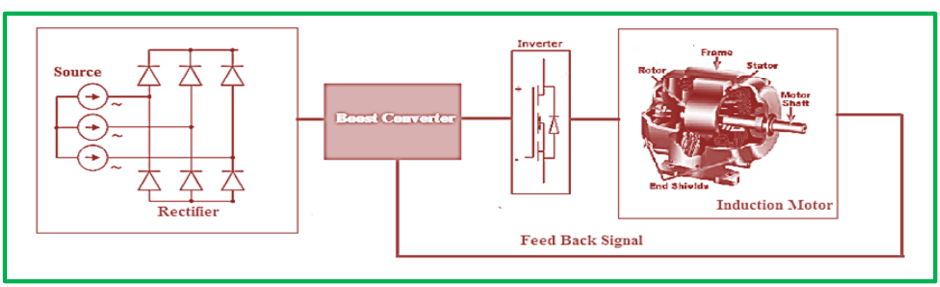
The attractive transform is linking with stationary frame three phase variables to synchronise the rotating frame of two-phase quantities. In case where the objective is to create a rotating space, vector describing a circle, poly phase sinusoidal currents are not necessary. For circle to be described in space, the two coordinates, namely *d* and *q* analytical geometry is required. Two coils are placed perpendicular by varying the fact and sinusoidal current is supplied to them which are displaced by an angle of 90 degree. The two coils are called the direct coil and the quadrature coil. In the rotating frame of reference, with regard to phase *a*, *d* axis is considered and the other axis is considered as *q* axis (Zalhaf et al., 2019).

In this paper, Section 2 describes the design and modelling of the proposed system. The simulation and hardware results of the induction motor drive with fuzzy controller are explained in Section 3. The proposed work is concluded in Section 4.

2 Design and modelling of proposed system

In this traction field, variable frequency drive (VFD) is commonly used to make connection between induction motor and power supply. However, the usage of VSD's tends to introduce harmonics in the current supply signal that makes it difficult to identify the fault. The different harmonics of the stator currents were obtained by using discrete wavelet transform. DWT offers the advantage of local representation of the current signal for both typical and defective modules. Also, by changing the value of KP and Ki, the usage of PI controller provides variable data. Out of all the above-mentioned techniques, fast Fourier transform is the easiest to implement. The only disadvantage of this technique is that transient signals using the time frequency representation cannot be analysed by it. On the other hand, short time Fourier transform (STFT) is useful for analysing short-lived signals using time frequency description but its drawback is that it can only examine the signal with all frequencies for stable size window. This marshal to imperfect frequency solution of this technique is that, transient signal using the time frequency. However, a powerful tool that helps in detecting and analysing the fault of induction motor by using a variable sized window is Wavelet Transform. The various software techniques and for fault diagnosis are MATLAB, Lab VIEW, Pscad, Neutral Net, etc. Artificial neural network, fuzzy logic, space vector modulation are some of the intelligent techniques developed to detect the faults. The proposed system is depicted in Figure 1.

Figure 1 Speed control of induction motor (see online version for colours)



The simulation and dynamic modelling of induction motor is vital to both industries and academics due to the epidemic usage of electric drive system mostly induction motor drives in diverse industrial environment. Since dynamic and steady state analysis is difficult to compute for an induction motor, mathematical modelling is prepared to carry out the analysis. Induction machine modelling has been constantly attracting researches as these machines have various model of operations and are used in large numbers. The theory of reference frame has been efficiently analysed as a potent approach, in order to determine the mathematical model of the three-phase induction motor.

2.1 Dynamic modelling of induction motor

In α and β axis stator voltage is given by equations (1) and (3)

$$V_{S\alpha} = R_S * I_{S\alpha} + \frac{d\left(L_s * I_{s\beta} + L_m * I_{r\beta}\right)}{dt} - \omega_s \left(L_s * I_{s\beta} + L_m * I_{r\beta}\right) \quad (1)$$

$\omega_S = 0$ at stationary point

$$V_{S\alpha} = R_S * I_{S\alpha} + L_s * \frac{dI_{s\alpha}}{dt} + L_m * \frac{dI_{r\alpha}}{dt} \quad (2)$$

$$V_{S\beta} = R_S * I_{S\beta} + \frac{d\left(\phi_{s\beta}\right)}{dt} - \omega_S * \varphi_{s\alpha} \quad (3)$$

$$V_{S\beta} = R_S * I_{S\beta} + \frac{d\left(L_s * I_{s\beta} + L_m * I_{r\beta}\right)}{dt} + \omega_S \left(L_s * I_{s\alpha} + L_m * I_{r\alpha}\right) \quad (4)$$

$\omega_S = 0$ at stationary point

$$V_{S\beta} = R_S * I_{S\beta} + L_s * \frac{dI_{s\beta}}{dt} + L_m * \frac{dI_{r\beta}}{dt} \quad (5)$$

In α and β axis rotor voltage is given by equations (6)–(10)

$$V_{r\alpha} = R_r * I_{r\alpha} + \frac{d\phi_{r\alpha}}{dt} - \left(\omega_S - \omega_r\right) * \phi_{r\beta} \quad (6)$$

$$V_{r\alpha} = R_r * I_{S\alpha} + L_s * \frac{dI_{r\alpha}}{dt} + L_m * \frac{dI_{s\alpha}}{dt} + \omega_r * L_r * I_{r\beta} + \omega_r * L_m * I_{S\beta} \quad (7)$$

$$V_{r\beta} = R_r * I_{r\beta} + \frac{d\phi_{r\beta}}{dt} + \left(\omega_S - \omega_r\right) * \phi_{r\alpha} \quad (8)$$

$$V_{r\beta} = R_r * I_{r\beta} + \frac{d\left(L_{sr} * I_{r\beta} + L_m * I_{s\beta}\right)}{dt} + \left(\omega_S - \omega_r\right)(L_{sr} * I_{r\alpha} + L_m * I_{S\alpha}) \quad (9)$$

at stationary, $\omega_S = 0$

$$V_{r\beta} = R_r * I_{r\beta} + L_r \frac{dI_{r\beta}}{dt} + L_m \frac{dI_{s\beta}}{dt} - \omega_r * L_m * I_{r\alpha} - \omega_r * L_m * I_{S\alpha} \quad (10)$$

The induction motor has been modelled dynamically based on the above equations in MATLAB platform to reduce the complexity of the three-phase time varying differential equations.

2.2 *Proposed fuzzy controller*

The fuzzy logic controller is appropriate with nonlinearity as given in Figure 2. The fuzzy logic membership function is shown in Figure 3. The rules are illustrated in Table 1.The above-mentioned rules are implemented in the inverter fed induction motor in parallel for speed control under parameter variation.

Figure 2 Proposed fuzzy controller (see online version for colours)

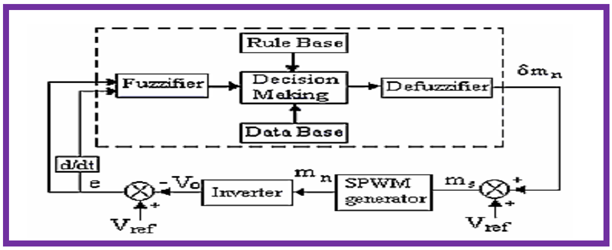


Figure 3 Triangular membership occupation (see online version for colours)

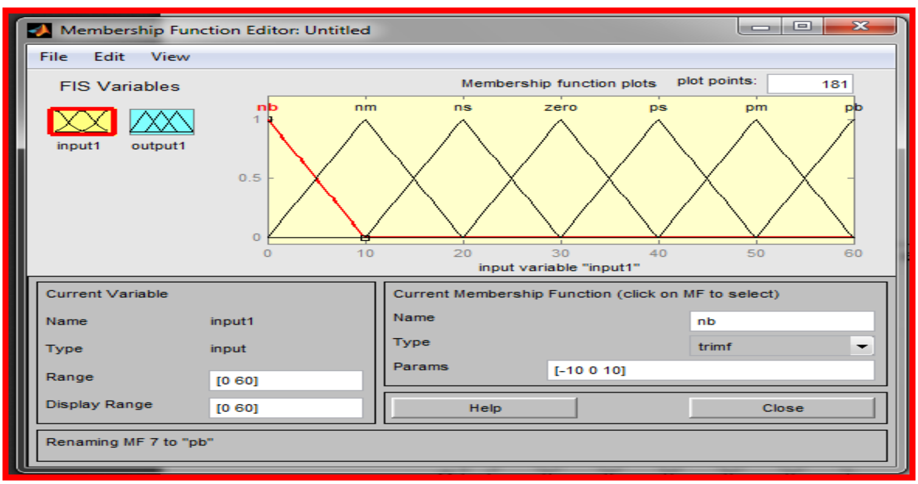


Table 1 Fuzzy logic rubrics for the modified system

	CE						
E	*Negbig*	*Negmed*	*Negsma*	*Zero*	*Possma*	*Posmed*	*Posbig*
Negbig	Negbig	Negbig	Negbig	Negmed	Negmed	Negsma	Zero
Negmed	Negbig	Negbig	Negmed	Negmed	Negsma	Zero	Possma
Negsma	Negbig	Negmed	Negmed	Negsma	Zero	Possma	Posmed
Zero	Negmed	Negmed	Negsma	Zero	Possma	Posmed	Posmed
Possma	Negmed	Negsma	Zero	Possma	Posmed	Posmed	Posbig
Posmed	Negsma	Zero	Possma	Posmed	Posmed	Posbig	Posbig
Posbig	Zero	Possma	Posmed	Posmed	Posbig	Posbig	Posbig

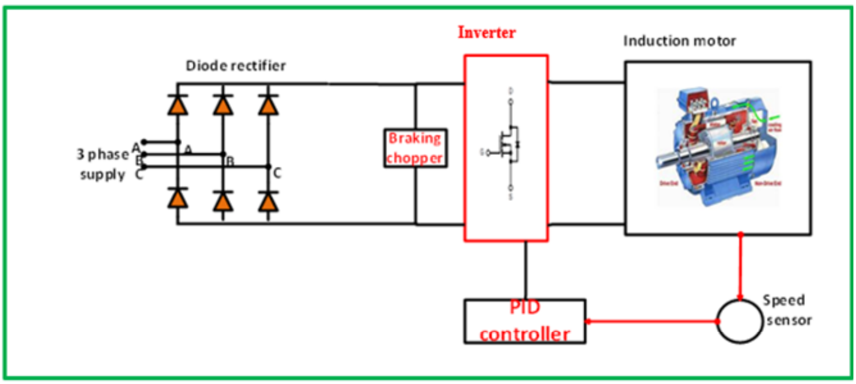
2.3 PID controller for proposed system

This method of speed control using PID controller is implemented as it has many advantages such as zero steady state error, no oscillations, higher rate of response and providing more stability to the system. This controller is used as it helps in eliminating the overshoot and the oscillations occurring in the system's output.

The output in a PID controller is the sum of proportional gain, integral gain and derivative gain as illustrated in Figure 4.

$$\text{Output} = Kpe(t) + Ki\int_0^t e(t)\mathrm{d}t + Kd * d / dt(e(t)) \tag{11}$$

Figure 4 Speed control of single asynchronous motor with PID controller (see online version for colours)



3 Result and discussion

The inverter fed with single induction motor in parallel using PID controller is analysed as illustrated in Figures 4 and 5. The speed of the motor is 1475 rpm. From this waveform that various parameters are found to compare with our proposed controller. The settling time of this waveform is 1.05 s, rise time is 0.33 s, peak time is 0.38 s and the delay time is 0.2 s as depicted in Figure 6. Then performance of speed is analysed. Further in proposed controller the perfomance parameter values are reduced to get efficient speed control waveform.

The act of the proposed system is analysed for different speed region. The speed control performance of the inverter fed with single induction motor in parallel is analysed by varying the stator resistance. The performance is compared by different parameters. The settling time is reduced slightly to 1 s, rise time is 0.37 s, peak time is 0.38 s and the delay time is 0.2 s and the noise variation is 19–20. These parameters are analysed to get a better performance. This is not the improved waveform, thus the improved controller is used to enhance the performance and to get a efficient output waveform as depicted in Figure 7.

Figure 5 Speed of inverter-fed asynchronous motor with PID controller (see online version for colours)

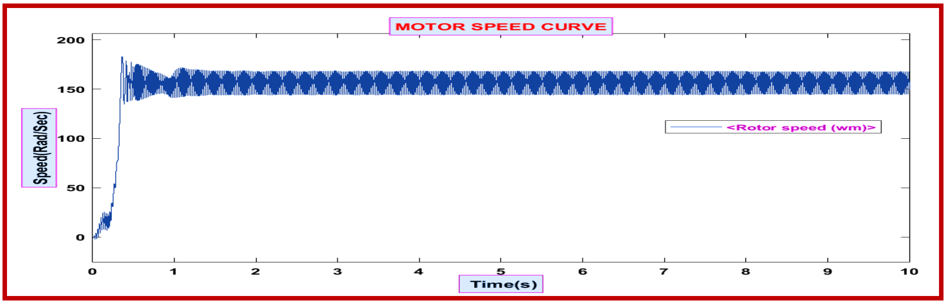


Figure 6 Speed of inverter-fed asynchronous motor by variation of rotor resistance with PID controller (see online version for colours)

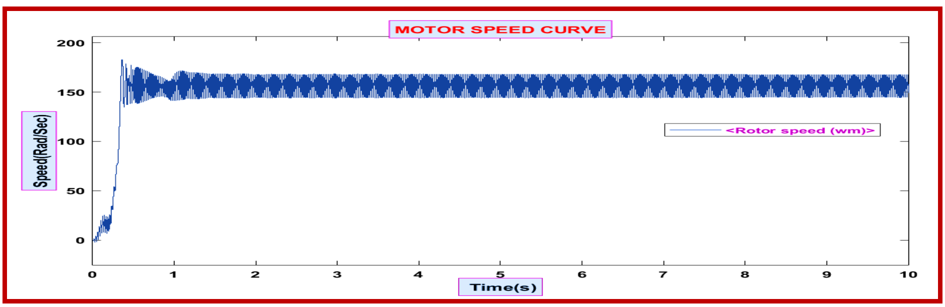
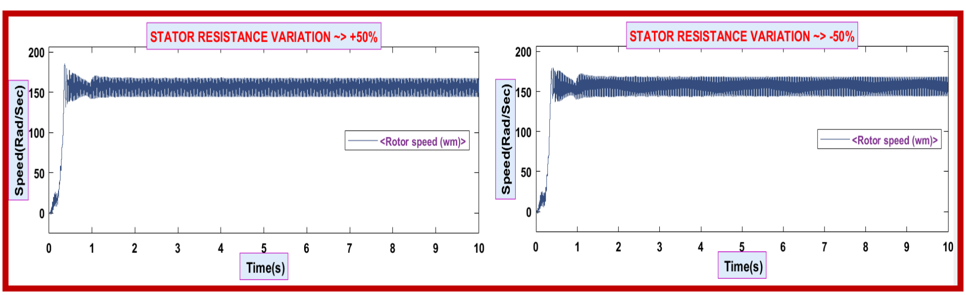
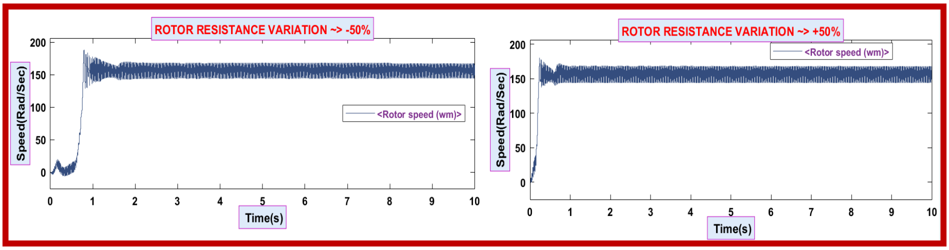


Figure 7 Speed curve of inverter-fed asynchronous motor by variation of stator resistance with PID controller (see online version for colours)



Analysis of speed control of inverter fed induction motor in parallel is done using PID controller by varying rotor resistance 50% increase and decrease. The efficiency and speed of the motor are computed by different parameters. This waveform shows the settling time 0.7–1.6 s, the rise time varies from 0.2 s to 0.75 s and peak time ranges from 0.22 s to 0.8 s and delay time decrease varies from 0.1 s to 0.6 s. These values can be reduced by introducing the proposed controller. This will lead to get better efficient speed control output waveform as shown in Figure 8.

Figure 8 Speed curve of inverter-fed asynchronous motor by variation of rotor resistance with PID controller (see online version for colours)



Speed control of two induction motors in parallel with PID controller is shown in Figure 9. In this waveform the speed is 1475 rpm. The speed curve is analysed by different parameters like settling time of 1.2 s, rise time of 1 s, peak time of 1.05 s and delay time is 0.5 s. This waveform has been plotted without any variation. The analysis of this inverter fed induction motor is done by using PID controller. To get better output waveform the values of these parameter are reduced by using the proposed controller as illutrated in Figure 10.

Figure 9 Speed control of two induction motors in parallel with PID controller (see online version for colours)

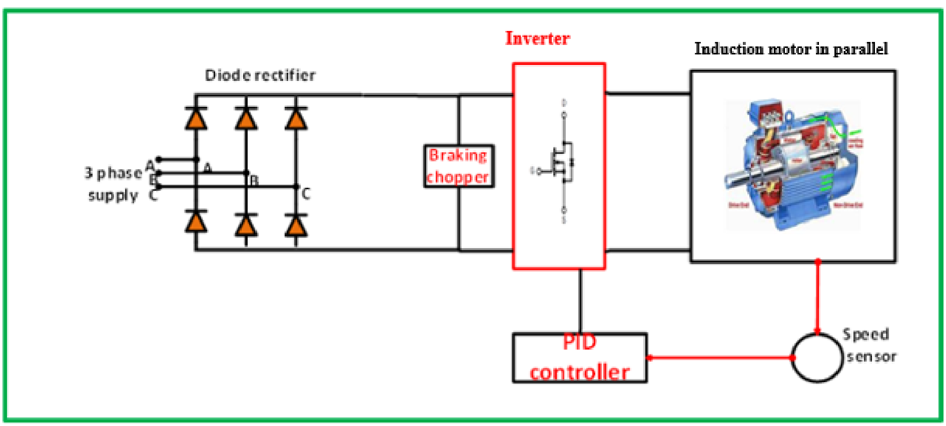
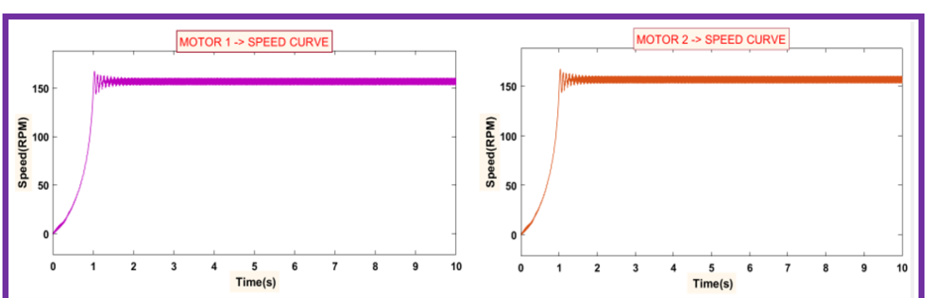
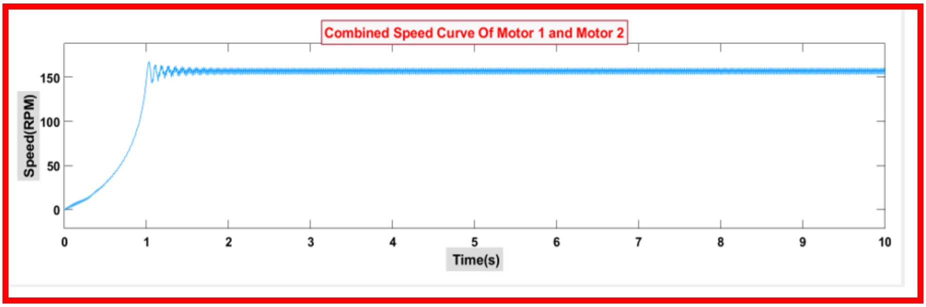


Figure 10 Speed curve of inverter-fed double asynchronous motor with PID controller (see online version for colours)



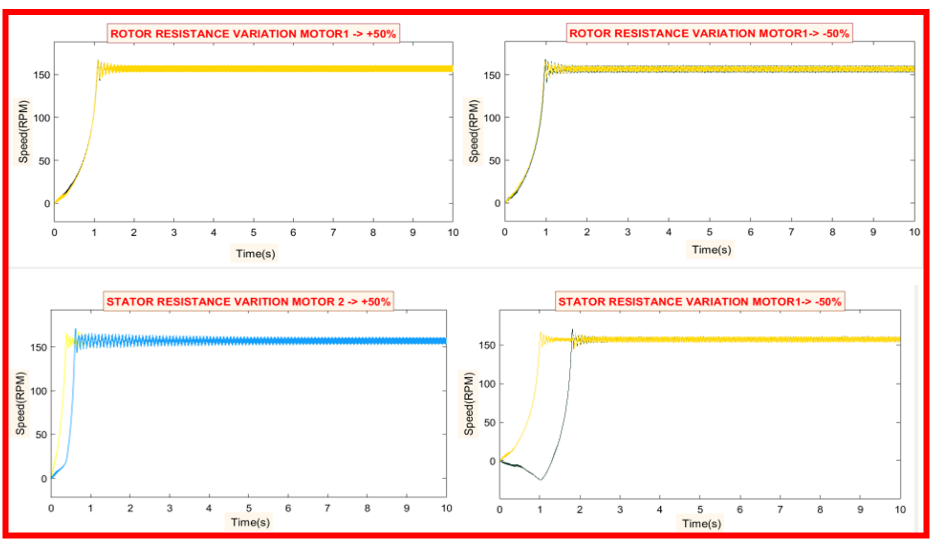
This is the combined speed curve of inverter fed two induction motors connected in parallel using PID controller. This waveform is also analysed by different parameters like settling time, rise time, peak time and delay time. But the speed is same for both the curves is 1475 rpm as given in Figure 11.

Figure 11 Combined speed curve of inverter-fed double asynchronous motor with PID controller (see online version for colours)



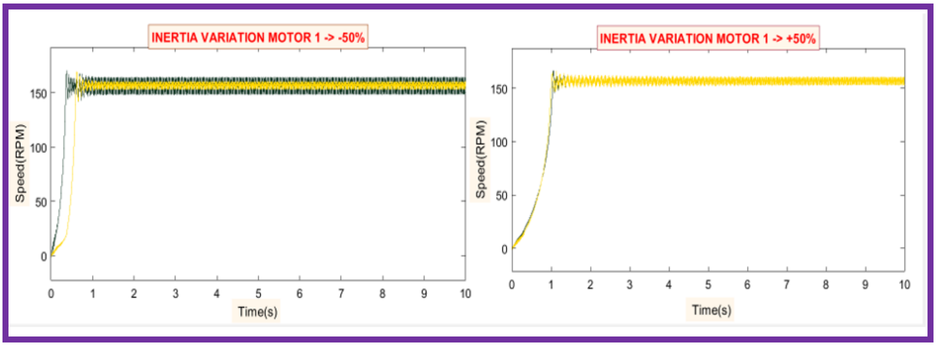
This output waveform shows the speed curve by varying rotor resistance and stator resistance by 50% increase and decrease of the magnitude. This is the waveform of inverter fed induction motor connected in parallel using PID controller. The variations in this waveform are settling time of 1.2 s, rise time of 1 s, peak time of 1.05 s and the delay time of 0.5 s. This variation of parameters is helpful in comparing and thus for better output waveform the proposed controller is introduced later as depicted in Figure 12.

Figure 12 Speed curve of inverter-fed double asynchronous motor with PID controller by the variation of stator and rotor resistance (see online version for colours)



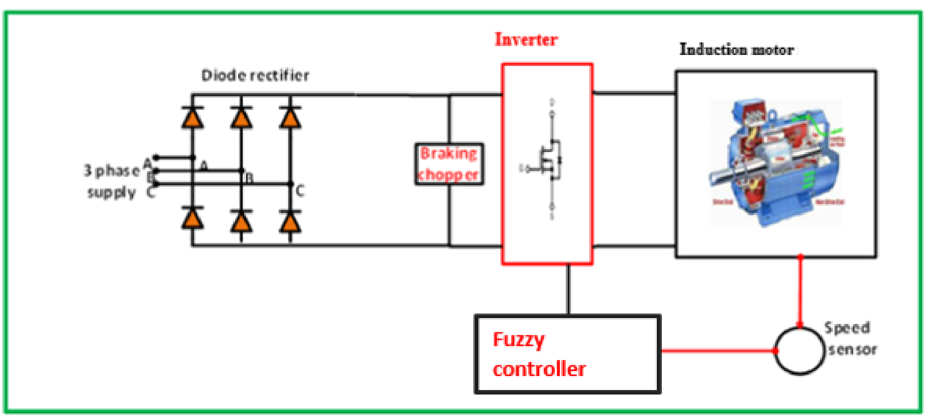
The output waveform of speed curve of inverter-fed single motor using PID controller. This waveform is analysed by varying the inertia. For better output waveform, the proposed controller is introduced by variation of same parameter as shown in Figure 13.

Figure 13 Speed curve of inverter-fed double induction motor with PID controller by the variation of inertia (see online version for colours)



Speed control of inverter-fed single induction motor with fuzzy controller are depicted in Figure 14. This is the waveform of speed of inverter fed with single induction motor in parallel. This waveform is analysed using fuzzy controller. The speed of the motor is 1475 rpm. This waveform shows the efficient result because by introducing fuzzy controller the parameter values are reduced like settling time is reduced to 0.25 s from 1.05 s, risetime is also reduced to 0.15 s, peak time is reduced to 0.18 s and delay time is decremented to 0.05 s. This shows the better speed control performance using fuzzy controller as illutrated in Figure 15.

Figure 14 Speed control of inverter-fed single asynchronous motor with fuzzy controller (see online version for colours)



This is the speed curve of inverter-fed single induction motor using fuzzy contoller. This waveform is obtained by varying the inertia. This waveform shows the better result after analysing several parametres and comapred to the conventional controller. In this waveform settling time is reduced to 0.4 s, rise time is reduced to 0.2 s, peak rime is also decremented to 0.2 s and delay time is reduced to 0.1 s. This variation of inertia by increasing and decresing by 50% represents the speed control performance of the induction motor as depicted in Figure 16.

Figure 15 Speed curve of inverter-fed single induction motor with fuzzy controller (see online version for colours)

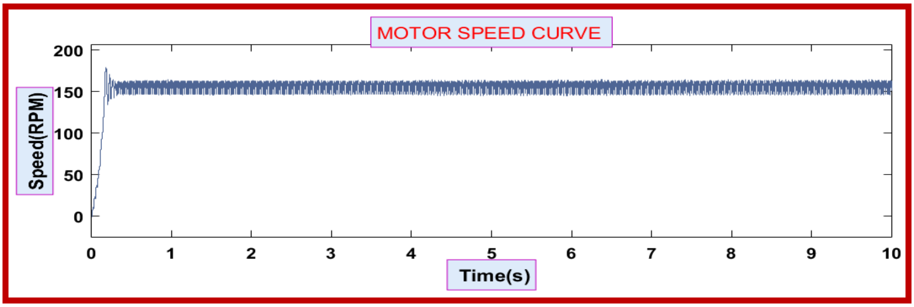
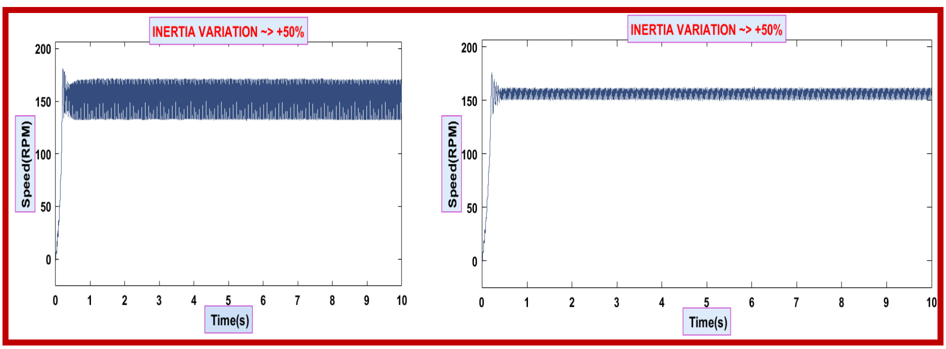


Figure 16 Speed curve of inverter-fed single induction motor with fuzzy controller by the variation of inertia (see online version for colours)



The speed control performance of inverter- fed single induction motor using fuzzy control is analysed by varying the stator and rotor resistance. This output waveform shows improved and efficient performance as compared to the conventional PID controller. This can be justified by comparing the several parameters. In case of variation of stator resitance by increasing and decreasing 50% the settling time is reduced to 0.3 s, rise time is reduced to 0.16 s, peak time is reduced to 0.19 s and delay time is reduced to 0.05 s. In the case of rotor resistance variation, the output waveform is improved by these parameters like settling time is reduce to 0.21 s, rise time is reduced to 0.11 s, peak time time is reduced 0.12 s and delay time is reduced to 0.05 s. These values are compared to analyse the waveform and the performance is enhanced using the fuzzy controller which is proved from the reduction of this parameter as shown in Figure 17.

Speed control of inverter-fed double induction motor with fuzzy controller is depicted in Figure 18. The waveform of speed curve of inverter- fed two induction motor with the parallel connection using fuzzy controller. In this waveform the speed is 1475 rpm. The result of this waveform is improved and it is analysed by several parameters like settling time is reduced to 0.6 s, rise time is also reduced to 0.45 s, peak time is reduced to 0.48 s and delayed time is also decreased to 0.2 s. This represents the efficient speed control performance as compared to the conventional controller as illustrated in Figure 19.

Figure 17 Speed curve of inverter-fed single induction motor with fuzzy controller by the variation of stator and rotor resistance (see online version for colours)

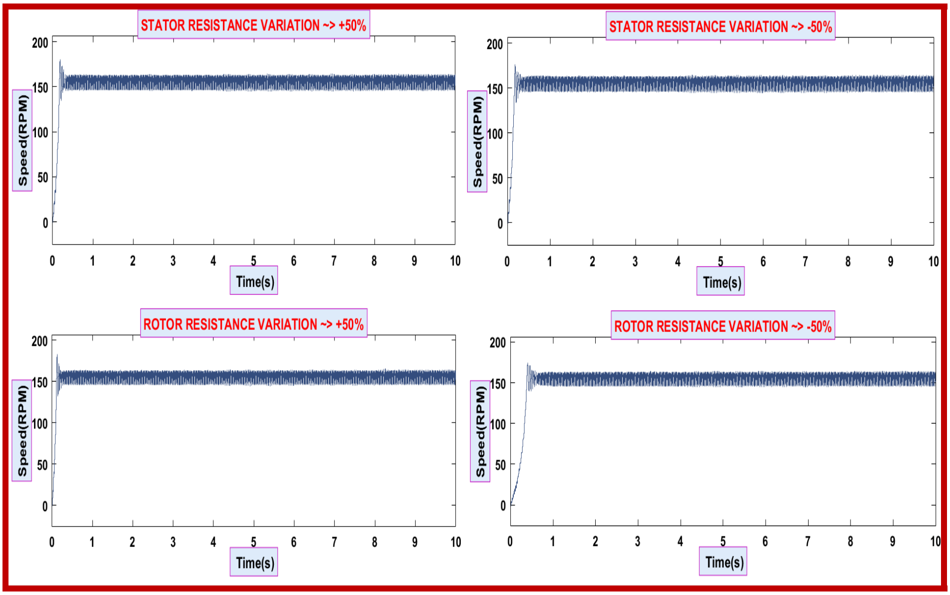


Figure 18 Speed control of inverter-fed double asynchronous motor with fuzzy controller (see online version for colours)

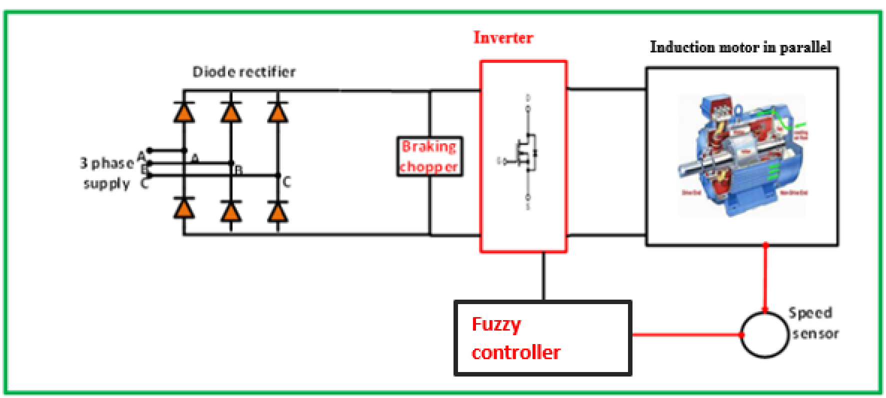
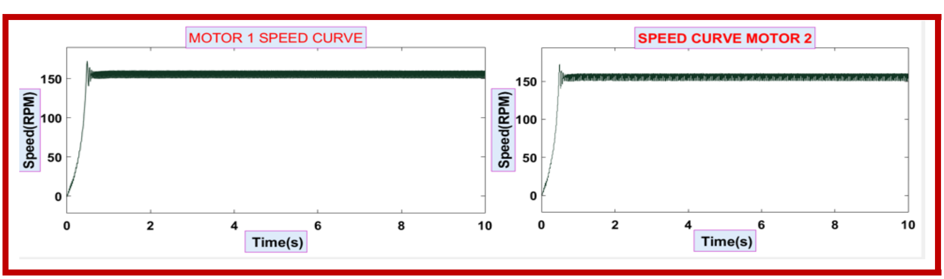
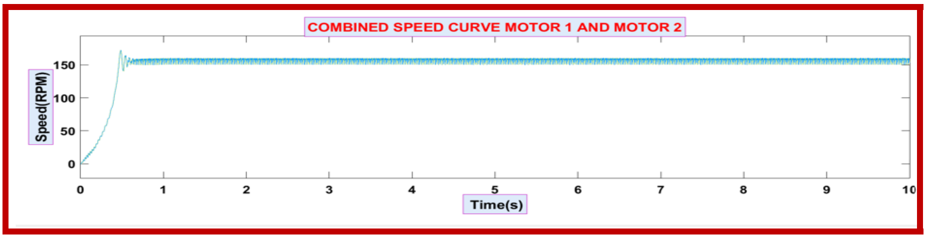


Figure 19 Speed curve of inverter-fed double induction motor with fuzzy controller (see online version for colours)



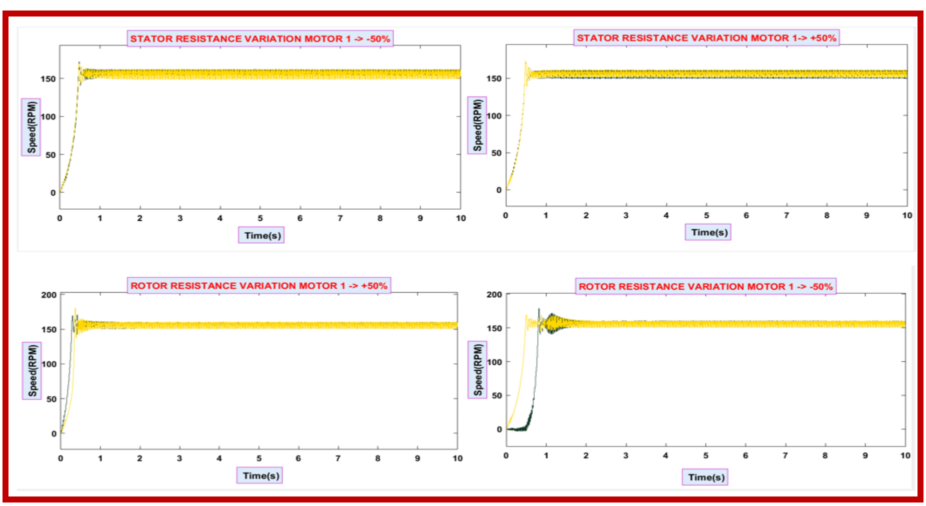
This waveform is the combination of the speed curve of both inverter-fed induction motor using fuzzy controller. This is clear explanation of the improved output waveform as shown in Figure 20.

Figure 20 Combined speed curve of inverter-fed double induction motor with fuzzy controller (see online version for colours)



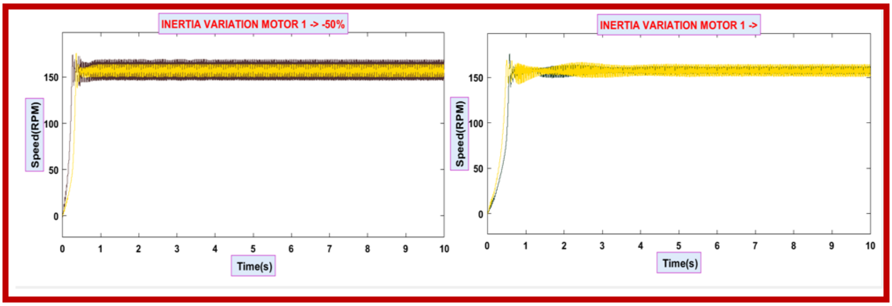
The speed control performance of inverter- fed double induction motor using fuzzy control is analysed by varying the stator and rotor resistance. This output waveform shows improved and efficient performance as compared to the conventional PID controller. This can be justified by comparing several parameters. In the case of variation of stator resitance by increasing and decreasing 50% the settling time is reduced to 0.6 s, rise time is reduced to 0.45 s, peak time is reduced to 0.5 s and delay time is reduced to 0.25 s. In the case of rotor resistance variation, the output waveform is improved by these parameters like settling time is reduce to 0.35 s, rise time is reduced to 0.8 s, peak time time is reduced 0.3 s and delay time is reduced to 0.65 s. These values are compared to analyse the waveform and the performance is enhanced using the fuzzy controller which is proved from the reduction of this parameter as illustrated in Figure 21.

Figure 21 Speed curve of inverter-fed double induction motor with fuzzy controller by the variation of stator and rotor resistance (see online version for colours)



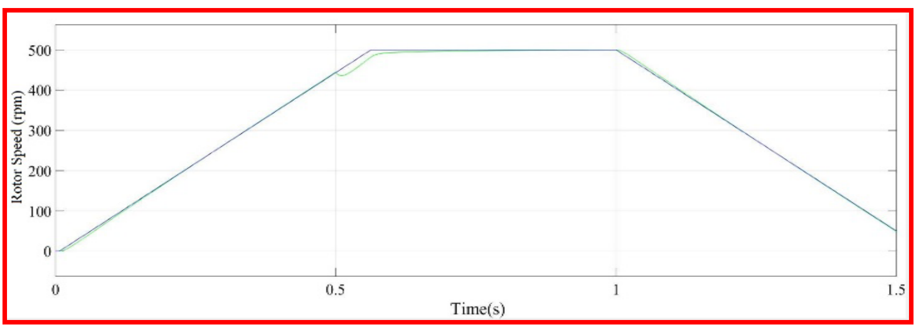
This is the speed curve of inverter-fed double induction motor using fuzzy contoller. This waveform is obtained by varying the inertia. This waveform shows the better result after analysing several parametres and comapred to the conventional controller. In this waveform settling time is reduced to 0.6 s, rise time is reduced to 0.25 s, peak rime is also decremented to 0.28 s and delay time is reduced to 0.1 s. This variation of inertia by increasing and decreasing by 50% represents the speed control performance of the induction motor as shown in Figure 22.

Figure 22 Speed curve of inverter-fed double induction motor with fuzzy controller by the variation of inertia (see online version for colours)



The speed performance on induction motor drive for traction application was analysed under different speed regions. The speed regions are starting period, running, acceleration and braking period. The improved performance has been achieved in the proposed method as shown in Figure 23.

Figure 23 Speed performance under different speed regions (see online version for colours)



This is the output result of inverter-fed single induction motor using PID controller. The parameters like settling time, rise time, peak time and delayed time are analysed to obtain the output waveform. This result is obtained without variation of parameters as depicted in Table 2.

This is output result of inverter-fed double induction motor using PID controller. The parameters like settling time, rise time, peak time and delayed time are analysed to obtain the output waveform. This result is obtained without variation of parameters as illustrated in Table 3.

From this table the speed-controlled performance of inverter-fed double induction motor using PID controller is obtained, on the basis of settling time, rise time, peak time and the delayed time the speed curve is analysed. By the variation of rotor resistance, the impact of speed control is determined as given in Table 4. The hardware setup of fuzzy based induction motor drive is depicted in Figure 24.

Table 2 Speed curve parameter of single induction motor using PID controller without any variation of parameters of motor

S. no.	*Parameters*	*No parameter variation on motor*
1	Delay-time (s)	0.2
2	Rise-time (s)	0.33
3	Peak-time (s)	0.38
4	Settling-time (s)	1.05
5	Speed (rpm)	1475
6	Noise variation	22

Table 3 Speed curve parameter of double induction motor using PID controller without any variation of parameters of motor

S. no.	*Parameters*	*No parameter variation*	*No parameter variation*
		MOTOR 1	*MOTOR 2*
1	Delay-time (s)	0.5	0.5
2	Rise-time (s)	1	1
3	Peak-time (s)	1.05	1.05
4	Settling-time (s)	1.2	1.2
5	Speed(rpm)	1475	1475
6	Noise variation	22	22

Table 4 Speed curve parameter of double induction motor using PID controller with variation of rotor resistance

S. no.	*Parameters*	*Rotor resistance variation + 50%*		*Rotor resistance variation – 50%*	
		MOTOR 1	*MOTOR 2*	*MOTOR 1*	*MOTOR 2*
1	Delay-time (s)	0.5	0.5	0.5	0.5
2	Rise-time (s)	1	1	1	1
3	Peak-time (s)	1.05	1.05	1.05	1.05
4	Settling-time (s)	1.2	1.2	1.2	1.2
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	7.5	7.5	6.5	6.5

This table shows that the speed control performance of inverter-fed single induction motor using fuzzy controller is enhanced without the variation of parameters. The speed curve becomes more efficient due to the reduction of parameters like delay time is reduced to 0.05 s, rise time is reduced to 0.15 s, peak time is reduced to 0.18 s and the settling time is reduced 0.25 s. This shows the enhancement of the output as shown in Table 5.

Figure 24 Hardware setup for inverter fed induction motors in parallel using PID- FUZZY controller (see online version for colours)

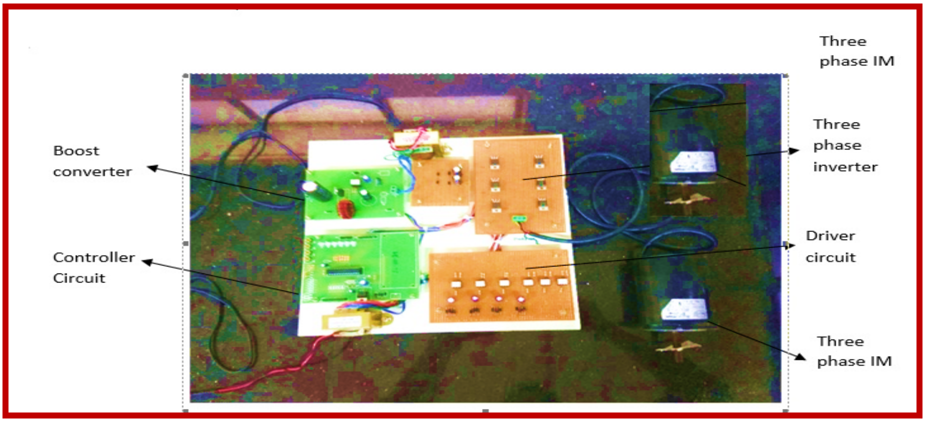


Table 5 Speed curve parameter of single induction motor using fuzzy controller without any variation of parameters of motor

S. no.	*Parameters*	*No parameter variation on motor*
1	Delay-time (s)	0.05
2	Rise-time (s)	0.15
3	Peak-time (s)	0.18
4	Settling-time (s)	0.25
5	Speed (rpm)	1475
6	Noise variation	18

This is the output result of speed curve of inverter fed induction motor using PID controller. The output waveform of speed curve is analysed by the variation of inertia.

By the variation of inertia of inverter-fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced to 0.35 s, peak time is reduced to 0.2 s and the rise time is reduced to 0.2 s and delayed time is reduced to 0.1 s. this is the representation of improved output result as depicted in Table 6.

By the variation of stator resistance of inverter- fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced to 0.3 s, peak time is reduced to 0.18 s and the rise time is reduced to 0.16 s and delayed time is reduced to 0.05 s. This is the representation of improved output result as given in Table 7.

By the variation of rotor resistance of inverter- fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced to 0.21 s, peak time is reduced to 0.12 s and the rise time is reduced to 0.11 s and delayed time is reduced to 0.05 s. This is the representation of improved output result as in Table 8.

Table 6 Comparison of speed parameter of single induction motor using fuzzy and PID controller with variation of inertia

		Fuzzy controller		*PID controller*	
S. no.	*Parameters*	*Inertia variation + 50%*	*Inertia variation – 50%*	*Inertia variation + 50%*	*Inertia variation – 50%*
1	Delay-time (s)	0.1	0.1	0.2	0.1
2	Rise-time (s)	0.2	0.2	0.38	0.19
3	Peak-time (s)	0.21	0.22	0.4	0.2
4	Settling-time (s)	0.4	0.35	0.1	0.8s
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	38	11	30	20

Table 7 Comparison of speed parameter of single induction motor using fuzzy and PID controller with variation of stator resistance

		Fuzzy controller		*PID controller*	
S. no.	*Parameters*	*Stator resistance variation + 50%*	*Stator resistance variation – 50%*	*Stator resistance variation + 50%*	*Stator |resistance variation – 50%*
1	Delay-time (s)	0.05	0.05	0.2	0.2
2	Rise-time (s)	0.16	0.15	0.37	0.37
3	Peak-time (s)	0.19	0.18	0.38	0.38
4	Settling-time (s)	0.3	0.3	1	1
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	17	17	19	20

Table 8 Comparison of speed parameter of single induction motor using fuzzy and PID controller with variation of rotor resistance

		Fuzzy controller		*PID controller*	
S. no.	*Parameters*	*Rotor resistance variation + 50%*	*Rotor resistance variation – 50%*	*Rotor resistance variation + 50%*	*Rotor resistance variation – 50%*
1	Delay-time (s)	0.05	0.15	0.1	0.6
2	Rise-time (s)	0.11	0.38	0.2	0.75
3	Peak-time (s)	0.12	0.4	0.22	0.8
4	Settling-time (s)	0.21	0.6	0.7	1.6
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	9	9	21	21

From Tables 6–8, the speed-controlled performance of inverter-fed single induction motor using PID controller is obtained, on the basis of these parameters like settling time, rise time, peak time and the delayed time the speed curve is analysed with the proposed fuzzy controller. The proposed fuzzy controller has better performance than the conventional PID controller.

This table shows that the speed control performance of inverter-fed double induction motor using fuzzy controller is enhanced without the variation of parameter. The speed curve become more efficient due to the reduction of parameters like delay time is reduced to 0.2 s, rise time is reduced to 0.45 s, peak time is reduced to 0.48 s and the settling time is reduced 0.5 s. This shows the enhancement of the output as depicted in Table 9.

Table 9 Speed curve parameter of double induction motor using fuzzy controller without any variation of parameters of motor

S. no.	Parameters	*No parameter variation*	*No parameter variation*
		MOTOR 1	*MOTOR 2*
1	Delay-time (s)	0.2	0.2
2	Rise-time (s)	0.45	0.45
3	Peak-time (s)	0.48	0.48
4	Settling-time (s)	0.6	0.6
5	Speed (rpm)	1475	1475
6	Noise variation	10	10

By the variation of rotor resistance of inverter- fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced from 1.4 s to 0.45 s, peak time is reduced from 0.5 s to 0.3 s and the rise time is reduced from 0.48 s to 0.25 s and delayed time is reduced from 0.65 s to 0.1 s. This is the representation of improved output result as described in Table 10.

Table 10 Speed curve parameter of double induction motor using fuzzy controller with variation of rotor resistance

S. no.	Parameters	*Rotor resistance variation + 50% on motor1*		*Rotor resistance variation – 50% on motor1*	
		MOTOR 1	*MOTOR 2*	*MOTOR 1*	*MOTOR 2*
1	Delay-time (s)	0.1	0.2	0.65	0.2
2	Rise-time (s)	0.25	0.35	0.8	0.48
3	Peak-time (s)	0.3	0.36	0.82	0.5
4	Settling-time (s)	0.45	0.5	1.4	0.7
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	10	10	13	13

By the variation of rotor resistance of inverter- fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced to 0.6 s, peak time is reduced to 0.48 s and the rise time is reduced to 0.48 s and delayed time is reduced to 0.25 s. This is the representation of improved output result as given in Table 11.

Table 11 Speed curve parameter of double induction motor using fuzzy controller with variation of stator resistance

		Stator resistance variation + 50% on motor 1		*Stator resistance variation – 50% on motor 1*	
S. no.	*Parameters*	*MOTOR 1*	*MOTOR 2*	*MOTOR 1*	*MOTOR 2*
1	Delay-time (s)	0.25	0.2	0.2	0.2
2	Rise-time (s)	0.45	0.45	0.48	0.48
3	Peak-time (s)	0.48	0.48	0.5	0.5
4	Settling-time (s)	0.6	0.6	0.62	0.62
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	12	12	13	13

By the variation of inertia of inverter- fed induction motor using fuzzy controller, the speed control performance is analysed and it is improved due to the reduction of the value of the parameters like settling time is reduced to 0.6 s, peak time is reduced to 0.28 s and the rise time is reduced to 0.35 s and delayed time is reduced to 0.1 s. this is the representation of improved output result as depicted in Table 12.

Table 12 Speed curve parameter of double induction motor using fuzzy controller with variation of inertia

		Inertia variation + 50% on motor 1		*Inertia variation – 50% on motor 1*	
S. no.	*Parameters*	*MOTOR 1*	*MOTOR 2*	*MOTOR 1*	*MOTOR 2*
1	Delay-time (s)	0.1	0.2	0.28	0.28
2	Rise-time (s)	0.25	0.35	0.55	0.48
3	Peak-time (s)	0.28	0.38	0.58	0.5
4	Settling-time (s)	0.6	0.6	1.2	1.2
5	Speed (rpm)	1475	1475	1475	1475
6	Noise variation	20	20	19	19

4 Conclusion

The induction motor was dynamically modelled using the estimated parameters to analyse the speed performance characteristics. The proposed system focuses on improving the speed of traction drive by implementing the robust fuzzy logic controller-based inverter fed parallel connected induction motors. The controller has been compared with the conventional controller. The simulation and hardware results show that the proposed system has better performance compared with conventional system.

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