



ENHANCING THE OPERATIONAL AVAILABILITY OF CNC MACHINE USING FUZZY LOGIC CONTROLLER

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ABSTRACT

In the environment of automation and emergence of the *Mechatronics* field in an industrial sector especially in Computer Numeric Controlled (CNC) machines, use of Artificial Intelligence (AI) techniques is emerged as novel scheme to control the process more effectively. This further enhances the operational availability of CNC machines to help improve the productivity of the organization.

This paper presents a rule-based fuzzy logic controller applied to a closed loop control of an Induction Motor (IM) with slip regulation. The IM has modeled in terms of dq windings, with synchronous frame associated with the frequency ω_s of the stator excitation. This Induction motor has installed in Makino A77 CNC machine at Mahindra and Mahindra Limited, Nagpur, India. The results obtained are interesting, considering the power failure at 0.5 seconds and the power and machine operational recovery at 1 second. The fuzzy logic used in the program is taking care of the actual environment prior to the occurrence of power failure.

KEYWORDS – *Fuzzy logic controller (FLC), Induction motor (IM)*

1. INTRODUCTION

Mechatronics is the synergetic integration of mechanical engineering with Electrical Engineering and/or Electronics and possibly with other disciplines too for the purpose of design, manufacture, operation and maintenance of a product. It include production systems, synergy drives, planetary exploration rovers, automotive subsystems autofocus cameras, video, hard disks, CD-players, washing machines. The major application areas includes, Automation, and in the area of robotics and CNCs, Servo-mechanics, Sensing and control systems, Automotive engineering, in the design of subsystems such as anti-lock braking systems, Computer engineering, in the design of mechanisms such as computer drives etc.

In the environment of automation and emergence of the *Mechatronics* field in an Industrial sector, fuzzy logic has met a growing interest in many motor control applications due to its non-linearities handling

features and independence of the plant modeling.

The fuzzy controller (FLC) operates in a knowledge-based way, and its knowledge relies on a set of linguistic if-then rules, like a human operator.

The transcase of each tractor is drilled , bored & finishes inside the CNC machines The CNC is used mainly for drilling, boring, finishing, aligning etc. The main problem that motivate to this study is the problem in spindle operation of CNC machine during power failure/fault condition, it has to relocate at its actual position. The machine has to reset by adjusting the instruction to the nearest execution of operation and then the operation starts.

The procedures and the machine resetting were needs some time. The time may vary from few minutes to an hour, which affects the production further hampered company's productivity.

The primary aim of this research is to develop an intelligent scheme to control this CNC machine under breakdown condition. The present work comprises to develop and program of a fuzzy controller for a closed loop speed control where the manipulated variable is the speed relation and, therefore, the slip value. For such applications, the proposed Fuzzy knowledge based controller



(FKBC) is a suitable way to provide the necessary frequency variation command signal. The frequency command also generates the voltage command through a volts/Hz function generator, with the low frequency stator drop compensation.

After this introduction, section 2 provides an overview of electrical drives and control including application of AI techniques. Section 3 provides motivation of study of the present work related to drives and control including CNC machine and more particularly Induction Motor. Section 4 provides the basic approach in designing Fuzzy Knowledge based Controller for the problem under consideration. Section 5 briefs the modeling of an Induction Machine. In section 6, Fuzzy Logic Controller design scheme has implemented and results have discussed. Finally, we conclude the results.

2. ELECTRICAL DRIVES AND CONTROL: AN OVERVIEW

Electrical drives play an important part as electromechanical energy converters in transportation, materials handling and most production processes. About 50 percents of electrical energy produced has used in electric drives today. Today still about 75 percent of all electric drives run at constant speed because there is not much need for speed control except for starting, stopping and protection. However, there is a still smaller 25 percent group of applications, with very fast annual expansion rate where the torque and speed must be varied to match the mechanical load. A typical variable speed electric drive contains, in addition, a power electronic converter to produce energy conservation (in pumps, fans etc.) through fast, robust and precise mechanical motion control as required by the application like machine tools, robots, computer - disk drives, transportation means etc.

From the beginning of this century, electric drives have been replacing fluid power actuators and IC machines in both high performance and general purpose applications. The growth of electric drives applications being determined by the current level of technology. High reliability, long lifetime, relatively low maintenance and short startup times of electric drives are in consort with their ecological compatibility: low emission of pollutants. The quality of electric drives has

extended by a high efficiency, low no-load losses, high overload capability, fast dynamic response, the possibility of recuperation, and immediate readiness for the full-featured operation after the drive startup. Electric drives are available in a wide range of rated speeds, torques and power, they allow for a continuous speed regulation, reversal capability, and they easily adapt to different environment conditions such as the explosive atmosphere or clean room requirements. Unlike the IC engines, electric motors provide for a ripple-free, continuous torque and secure a smooth drive operation.

During the past two decades, the evolution of powerful digital microcontrollers allowed for a full-digital control of the electromechanical conversion processes taking place in an electrical drives. The process automation made significant progress in the fifties, thanks to the introduction of Numerical Control (NC). Although not flexible and fully programmable, NC systems replaced relays and mechanical timers common on the factory floor in the first half of the century. As the first reliable and commercially available microcontrollers were made in the sixties, they were advantageously used for the purpose of a flexible control of electric drives in production machines. As from then, the hydraulic and pneumatic actuators gradually disappear and give space to DC and AC electric motors.

Although more robust and easier to produce than the DC motors, the AC electric motors were mostly used in constant speed applications and it supplied from the mains until the technological breakthroughs in the early seventies. It took the development of transistorized three phase inverters with digital PWM to provide for a variable frequency supply of induction motors. The invention of IGBT transistors and high speed digital controllers made the variable speed AC drives reliable and acceptable for the drive market. For their increased reliability, low maintenance, and better characteristics, the frequency controlled induction motors gradually replaced DC drives in many of their traditional fields of application. At this level, the reign of DC drives reduced to high speed servo applications.

In early eighties, the frequency controlled AC drives are widely accepted, but their prices still level those of DC drives. The cost of an AC drive package has a 30 percent motor plus 70 percent power converter structure, while in the case of a DC drive the motor is worth 70 percent of the package cost. The prices of power- and signal- semiconductors will presumably decline, while the cost of electric motors will remain tied to the copper and iron prices. For that reason, the AC drives have the perspective of decreasing the package cost,



evermore cheaper than their DC counterparts. Further technological improvements are likely to make the frequency controlled AC drives the cheapest actuators ever. At present, in an industrialized country the AC drives substitute DC motors at a pace of 15% per year. More than 20% of the drives are frequency controlled, while the remaining 80% operate at a constant speed.

In most of high volume applications of digitally controlled electric motors, microcontroller executes both the drive control functions and the application specific functions such as the handling of the washing, rinsing and drying in the case of modern dishwashers and washing machines. Compact digital controllers emulates the functions traditionally implemented in the analog form and allows the execution of nonlinear and complex functions that could not have been completed by analog circuitry (ANN, nonlinear estimators, spectrum estimation and others). Recently the vector control concept empowered the AC machines to conquer the high performance drives market.

2.1. Applications of AI Techniques in Electrical Drives and Control

Recently Artificial Intelligence based techniques (i.e. fuzzy logic, neural networks, fuzzy-neural networks, genetic algorithms, etc.) have gained a wide attention in control applications. There are numerous AI applications to electrical machines and drives. The drives are D.C. drives, induction motor drives, synchronous motor drives, switched reluctance motor drives and sensorless drives etc. For most drives, high accuracy is not usually imperative, however, in high performance drive applications, a desirable control performance in both transient and steady states must be provided even when the parameters and load of the motor are varying during the motion. Controllers with fixed parameters cannot provide these requirements unless unrealistically high gains are used. Thus, the conventional constant gain controllers used in the high performance variable speed drives become poor when the uncertainties of the plant exist, such as load disturbance, mechanical parameter variations and un-modelled dynamics in practical applications. Therefore, control strategy of high performance electrical drives must be adaptive and robust. As a result, interest in

developing adaptive control methods for electrical drives has increased considerably with in the last two decades and several adaptive control methods based on linear model have developed for induction motor drives. In the past decade, fuzzy logic and neural network control techniques have applied to electrical drives to deal with nonlinearities and uncertainties of the control system. Fuzzy control has the ability of implementing expert human knowledge and experience expressed in the form of linguistic rules. It is easy to understand the structure of the fuzzy controller and to modify the control laws. Hence, fuzzy logic control introduces a good tool to deal with the complicated, nonlinear and ill-defined systems, which cannot be described by precise mathematical models. However, fuzzy controllers have difficulties in determining suitable fuzzy control laws and tuning the parameter of the membership functions for system changes. The major advantageous features of neural network are their learning and generalization capability and fault tolerance. It can adapt itself to changing control environment using the system input and output and it does not require complicated control theories and exact knowledge of the system. However, neural network has some problems in training: the sensitivity of the controlled system, which is difficult to obtain for unknown and nonlinear systems are required and the local minimum of the performance index can be trapped. Besides, it is difficult for the user to decide the structure of the neural network for the desired control. Fuzzy-Neural Network (FNN) approach incorporates the fuzzy logic controller into the neural network structure. Neural network provides connectionist structure and learning abilities to the fuzzy logic controller. In recent years, FNN control has applied to induction motors and used to update the control gain of the sliding mode position controller for an induction motor drive. Fuzzy-neural network controller has augmented with an PI controller, PD controller and an adaptive controller.

3. MOTIVATION OF STUDY

The work on related study has reviewed as a background of the present work but with no intention to cover all the published work. [1] It describes the industrial applications increasingly require electric drives with good position command tracking and load regulation responses. These can be achieved by adaptive-type control because of the loading conditions, inertias and system parameters all change during the motion. This paper developed an Adaptive Speed Controller for AC drives with a very low computational algorithm. [2] presents a



closed-loop control strategy to operate an off-the-shelf single-phase induction motor (IM) as an unsymmetrical two-phase motor. The scheme is capable of making the two-phase unsymmetrical IM behave like a symmetrical two-phase motor.

Fuzzy logic controller has employed in feed forward path of the control scheme. The control scheme achieves reduction in the inherent torque oscillations, rendering its behavior and achieve cost-effectiveness in both initial and running costs. [3] proposes simulators to employ computer-generated images as part of the training process over CNC milling machine. Paper describe a VR-based Training System (VRTS) for the trainees to acquire the set of skills necessary to perform basic milling operations. [4] it explains an intelligent robust position controller for permanent-magnet synchronous motor (PMSM) servo drives. A systematic mathematical procedure is derived to find the parameters of the 2DOF I-PD position controller [5] presents an improved direct torque control based on fuzzy logic technique. The fuzzy proposed controller be able to reduced the torque and flux ripples and to improve performance DTC especially at low speed. [6] presents a novel design of a control scheme for speed control of Induction motor. A new type of Rough-Fuzzy controller is proposed to control the speed of Induction motor which is compared with conventional PID controller. [7] presents a hybrid system controller, incorporating fuzzy controller with vector-control method for induction motors. [8] Variable speed drives are growing and varying. Drives expanse depend on progress in different part of science like power system, microelectronic, control methods, and so on. Artificial intelligent contains hard computation and soft computation. [9] presents a simple method for estimating rotor resistance in an indirect vector-controlled induction motor drive. A rotor resistance estimator using fuzzy logic technique is used to demonstrate the effectiveness of the proposed estimator. [10] Open-architecture technology is ushering in new advances in the world of computer numerically controlled (CNC) machines. This framework supports component-based technology by specifying a control class hierarchy, plug-and-play components and a design framework. [11] presents Flexible Manufacturing Systems and controllers in agreement with the CNC technology of the

correspondent machine tool manufacturer. [12] presents a fuzzy logic based speed controller and its design for vector controlled induction motor drive. It has been implemented on a 3 phase, 415V, 0.75kW squirrel cage induction motor. [13] presents a rule-based fuzzy logic controller applied to a scalar closed loop Volts/Hz induction motor (IM) control with slip regulation and also compared with those of a PI controller. [14] A conventional PI controller is compared practically to fuzzy logic controller using a simple cassy card. The results obtained experimentally with fuzzy logic controller are compared with classical PI controller. [15] Several methods have been proposed and published for control of induction motors. The objective of this work is to develop a fuzzy controller with reduced rule base. [16] presents two approach intelligent techniques of improvement of Direct Torque Control (DTC) of Induction motor such as fuzzy logic (FL) and artificial neural network (ANN), applied in switching select voltage vector. [17] presents design and implements a voltage source inverter type space vector pulse width modulation (SVPWM) for control a speed of induction motor. The fuzzy logic controller is also introduced to the system for keeping the motor speed to be constant when the load varies.

4. FUZZY KNOWLEDGE BASED CONTROLLER

Fuzzy logic has met a growing interest in many motor control applications due to its non-linearity's handling features and independence of the plant modeling. The fuzzy controller operates in a knowledge-based way, and its knowledge relies on a set of linguistic if-then rules, like a human operator.

4.1 Fuzzy Architecture

The controller architecture includes some rules which describe the casual relationship between two normalized input voltages and an output one. These are:

- Error (e), that is the speed error,
- Change-of-error (Δe), that is the derivative of speed error, and
- Output, defined as the change-of-control ($\Delta \omega$), that added to the motor speed (ω) is the input (ω) to the converter. These error inputs are processed by linguistic variables, which require to be defined by membership functions (Ouiguini et al, 1997).

Fig.1 shows an IM control structure with fuzzy knowledge based controller (FKBC). The FKBC includes four major blocks: First, one that computes the error into two input variables, second, a fuzzification block, third, an inference mechanism, and the last one is defuzzification. The speed reference control is ω_m^*

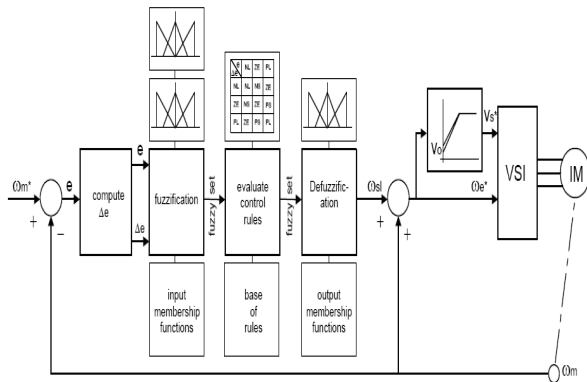


Fig. 1: Induction Motor Control with FKBC scheme

4.2 Fuzzy Knowledge Base Proposed

4.3

Fig. 2 shows the triangle-shaped membership functions of error (e) and change-of-error (Δe). The fuzzy sets are designated by the labels:

- NL (negative large); NM (negative medium);
- NS (negative small); ZE (zero);
- PS (positive small); PM (positive medium), and
- PL (positive large).

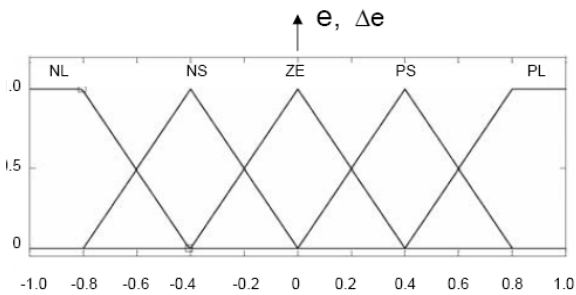


Fig. 2. Triangular membership functions for input variables e and Δe

Fig. 3 and Table 1 show the proposed membership functions for output variable and the control rules. The inference strategy used in this system is the Mamdani algorithm, and

the center-of-area/gravity method is used as the defuzzification strategy.

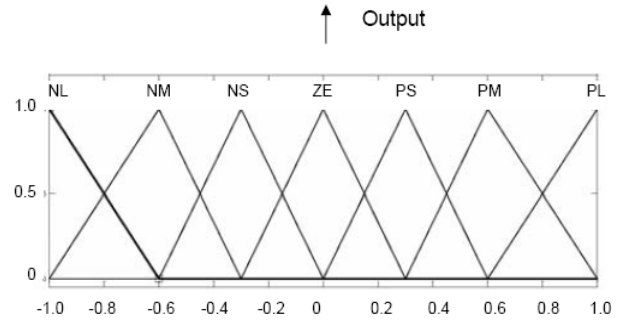


Fig. 3. Triangular membership functions for output variable

Table 1: Linguistic Rule Table

$\Delta e \backslash e$	NL	NS	ZE	PS	PL
NL	NL	NL	NM	NS	ZE
NS	NL	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PL
PL	ZE	PS	PM	PL	PL

The command signal is obtained from twenty-five rules with all have the same weight of one, as shown in appendix.

5. MODELLING OF AN INDUCTION MOTOR

The induction motor is modelled with three phase sinusoidal symmetrical excitation and is in vectorized form in conformity with state vector formulation. Synchronous frame is used where,

- $\omega_k = \omega_m$ and $\theta_{tk} = \omega t$ and where:
- $\omega =$ base frequency;
- $\omega_m =$ rotor frame frequency;
- $\omega_k = dq$ frame
- $\text{freq } \omega_s =$ synchronous frame frequency (rad/sec)
- $\lambda_s =$ stator flux, $\lambda_r =$ rotor flux (pu)
- $R_s ; R_r =$ stator and rotor resistance (pu)
- $v_s ; v_r =$ stator and rotor voltage (pu)
- $i_s ; i_r =$ stator and rotor current (pu)
- $L_s ; L_r =$ stator and rotor inductance (pu)
- $L_m =$ magnetizing inductance (pu)
- $L_{sl} =$ stator leakage inductance (pu)
- $L_{rl} =$ rotor leakage inductance (pu)
- $T_e =$ electromagnetic torque (pu)
- $T_L =$ load torque (pu)



- Bm = viscous friction coefficient. (pu)
- d, q=direct and quadrature axis
- p =number of poles
- H= inertia constant (s)

Operators: \square =cross product; \bullet =dot product

5.1 Equations of Electrical System

According to [18] the equation giving a PI-like FKBC is

$$\Delta \omega_{sl} = k_p \Delta e + k_l \Delta e \quad (1)$$

The fuzzy if-then statements are symbolically expressed with the form,

If e is (...) and e Δ is (...) then sl ω is (...)

The output control is, then

$$\omega_e^* = \omega_m + \omega_{sl} \quad (2)$$

Refereeing to [19-22], the Induction Motor equations in per unit (pu) are:

$$\bar{v}_s = R_s \bar{i}_s + \frac{1}{\omega_o} \left(\frac{d \bar{\lambda}_s}{dt} \right) + \omega_k M(pi/2) \bar{\lambda}_s \quad (3)$$

$$\bar{v}_r = R_r \bar{i}_r + \frac{1}{\omega_o} \left(\frac{d \bar{\lambda}_r}{dt} \right) + (\omega_k - \omega_m) M(pi/2) \bar{\lambda}_r \quad (4)$$

where respective i, v, the space vector λ and the rotational operator M are defined as

$$\bar{\lambda} = \begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix}; \bar{i} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \quad M_{(pi/2)} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

5.2 Flux Linkage-Current Relations

On d axis:

$$\bar{\lambda}_{sd} = L_s \bar{i}_{sd} + L_m \bar{i}_{rd} \quad (5)$$

$$\bar{\lambda}_{rd} = L_m \bar{i}_{sd} + L_r \bar{i}_{rd} \quad (6)$$

Where

$$L_s = L_m + L_{si} \quad (7)$$

$$L_r = L_m + L_{ri} \quad (8)$$

On Q axis

$$\bar{\lambda}_{sq} = L_s \bar{i}_{sq} + L_m \bar{i}_{rq} \quad (9)$$

$$\bar{\lambda}_{rq} = L_m \bar{i}_{sq} + L_r \bar{i}_{rq} \quad (10)$$

5.3 Equations of Mechanical System

$$T_e = 2H \frac{d \omega_{mec}}{dt} + B_m \omega_{mec} + T_L \quad (11)$$

Where

$$T_e = \bar{\lambda}_s \otimes \bar{i}_s = M_{(pi/2)} \bar{\lambda}_s \bullet \bar{i}_s \quad (12)$$

$$\text{and } \omega_{mec} = \frac{2}{p} \omega_m \quad (13)$$

6. FUZZY KNOWLEDGE BASE CONTROLLER: RESULTS AND DISCUSSION

The problem associated with the spindle of Makino A77 CNC machine installed at Mahindra & Mahindra Limited, Nagpur, India is formulated using a Fuzzy logic has been investigated with the Matlab7.1 programming. The parameters describing the electrical and electromechanical system are expressed in per unit,pu.

- Stator resistance (pu)= 0.01; Rotor resistance (pu)= 0.02; Stator leakage inductance (pu)= 0.10; Rotor leakage inductance (pu)= 0.10; Magnetizing inductance (pu)= 4.5; Base frequency (rad/s)= 2*pi*50; p=2; or ω m = ω mec; H=0.3 (s); Bm (pu)=1e-5

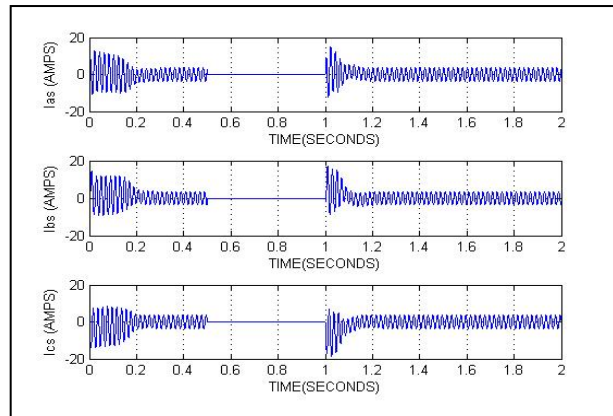


Fig 4: Results: Machine Stator Current behaviour with Fuzzy Logic Controller

The result obtained in Matlab7.1 shows the starting current taken by the motor is about five to seven times that of normal full load current. The stator currents are shown in Fig. 4. The results clearly indicate the three phase current distribution inside the three phase stator winding of an induction motor. The starting current taken by the three phase stator winding of an induction motor is shown during a time interval of 0 to 0.2 second. During this instant of time the current flowing is about five to seven times the normal running current of the motor.

The results also indicated that the normal current of about 3 A and the starting current of about 16 A.

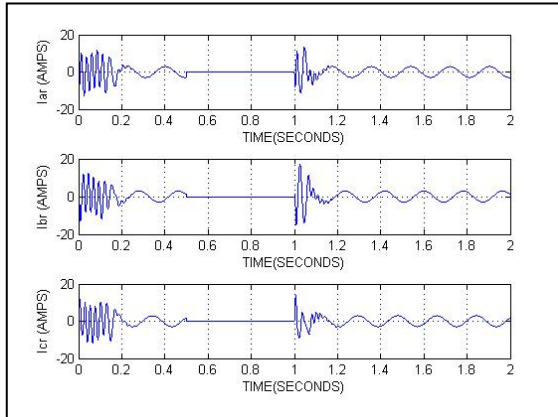


Fig 5: Machine Rotor Current behaviour with Fuzzy Logic Controller

The result shown in Fig. 5 is the variation inside the rotor of an induction motor. The rotor current flowing in the rotor of an induction motor is dependent on the value of slip. As shown in the results the initial current in the three phase rotor circuit of an induction motor is large shown in between the instant 0 to 0.2 second. This current is large due to the high value of slip at the time of starting nearly equal to 1. During normal running the current in the three phase of rotor circuit is indicating the lower value of slip between the instant 0 to 0.2 second. At the instant of 0.5 second, power failure occurs. During that instant the action taken by the fuzzy controller is shown from the instant of 0.5 seconds. The actual environment prior to the power failure is build up by the fuzzy controller. The results shown indicate the actual environment build up by the controller between the instant 0.5 second to 0.6 second. Within one second the normal operation of the motor is regain by the controller. The three phase stator current shows the value of current resumes its normal magnitude between the instant from 0.5 to 0.6 second. Also, the rotor currents are recovered within the same time. At 0.6 second and onwards shows the variation of three phase rotor current as the slip times the variation in three phase stator current of an induction motor.

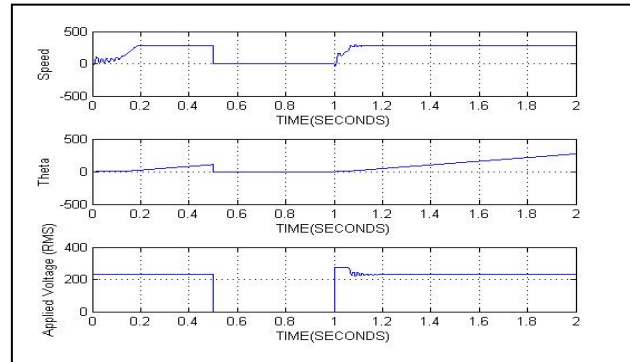


Fig 6: Results: Applied Voltage, rotor angle and speed of the Machine with Fuzzy Logic Controller

The speed of an induction motor has shown in fig. 6 the third result of Matlab7.1 program. The result clearly indicates the variation in the speed at the time of starting between instants 0 to 0.2 second. After an instant of 0.2 second, the speed attains almost a constant value. At instant 0.5 second the speed falls to zero clearly indicated in the result. The fuzzy controller takes a corrective action as shown in the results and rebuilds the speed of an induction motor between 0.5 second to 0.6 second. The normal operation of the motor is recovered. Theta is the machine rotor angle shown in the Fig.

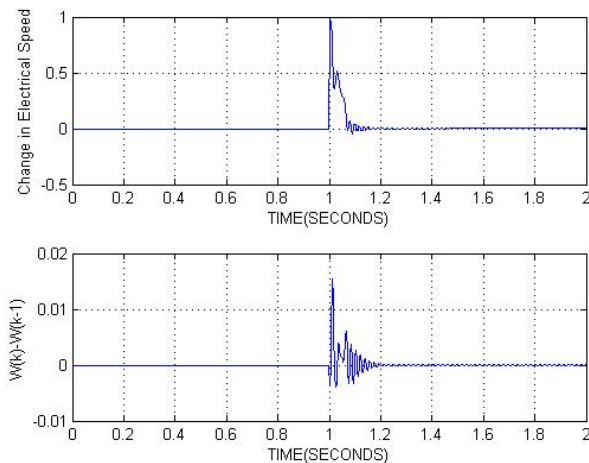


Fig 7: Results: Change in Electrical speed and $W(k)-W(k-1)$ behaviour of the Machine with Fuzzy Logic Controller

Fig. 7 shows the actual speed versus reference speed behaviour and its derivative of error has analyzed during power failure. The action has taken by fuzzy controller for smooth operation of rotor angle.



6. CONCLUSION

The FKBC improve the performance of IM speed drives has been proposed. The power failure occurs at 0.5 second can be immediately recovered by the fuzzy controller at 1 second. The actual environment is immediately build up in the Makino A77 CNC machine which minimizes breakdown. This will help in minimizing the breakdown and the minimized breakdown results in the enhancement of productivity.

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APPENDIX

The command signal has obtained from 25 rules with all have same weight of one. The if-then rules are as follow,

Rule	Fuzzy Rule Base
1	If(error is NL) and (change-error is NL) then (output is NL)
2	If(error is NS) and (change-error is NL) then (output is NL)
3	If(error is ZE) and (change-error is NL) then (output is NM)
4	If(error is PS) and (change-error is NL) then (output is NS)
5	If(error is PL) and (change-error is NL) then (output is ZE)
6	If(error is NL) and (change-error is NS) then (output is NL)
7	If(error is NS) and (change-error is NS) then (output is NM)
8	If(error is ZE) and (change-error is NS) then (output is NS)
9	If(error is PS) and (change-error is NS) then (output is ZE)
10	If(error is PL) and (change-error is NS) then (output is PS)
11	If(error is NL) and (change-error is ZE) then (output is NM)
12	If(error is NS) and (change-error is ZE) then (output is NS)
13	If(error is ZE) and (change-error is ZE) then (output is ZE)
14	If(error is PS) and (change-error is ZE) then (output is PS)
15	If(error is PL) and (change-error is ZE) then (output is PM)
16	If(error is NL) and (change-error is PS) then (output is NS)
17	If(error is NS) and (change-error is PS) then (output is ZE)
18	If(error is ZE) and (change-error is PS) then (output is PS)
19	If(error is PS) and (change-error is PS) then (output is PM)
20	If(error is PL) and (change-error is PS) then (output is PL)
21	If(error is NL) and (change-error is PL) then (output is ZE)
22	If(error is NS) and (change-error is PL) then (output is PS)
23	If(error is ZE) and (change-error is PL) then (output is PM)
24	If(error is PS) and (change-error is PL) then (output is PL)
25	If(error is PL) and (change-error is PL) then (output is PL)