ENHANCEMENT OF STATIC & DYNAMIC RESPONSE OF
THE THREE PHASE INDUCTION MOTOR UNDER THE
EFFECT OF THE EXTERNAL DISTURBANCES AND
NOISE BY USING HYBRID FUZZY-PID CONTROLLER

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ABSTRACT

For electrical drives good dynamic performance is mandatory so as to respond to the changes
in command speed and torques, so various speed control techniques are being used for real time
applications. The speed of a Three Phase Induction Motor can be controlled using various controllers
like PID Controller, Fuzzy Logic Controller, Genetic Algorithm (GA) controller and Hybrid Fuzzy-
PID Controller. a Ziegler-Nichols (Z-N) based PID plus fuzzy logic control (FLC) scheme is
proposed for speed control of a direct field-oriented induction motor (DFOIM). The Z-N PID is
adopted because its parameter values can be chosen using a simple and useful rule of thumb. The
paper describes application of Hybrid Fuzzy-PID Controller in an enhancement of Static & Dynamic
Response of the Three Phase Induction Motor under the effect of the external disturbances and noise
that uses the Fuzzy-PID Controller for enhancement of Static & Dynamic Response of the Three
Phase Induction Motor under the effect of the external disturbances and noise is implemented in
MATLAB/SIMULINK. The simulation study indicates the superiority Hybrid Fuzzy-PID Controller
over the PID controller separately. This control seems to have a lot of promise in the applications of
power electronics. The speed of the Three Phases Induction Motor Drives can be adjusted to a great
extent so as to provide easy control and high performance. There are several conventional and
numeric types of controllers intended for controlling the Three Phase Induction Motor speed and
executing various tasks: PID Controller, Fuzzy Logic Controller; or the combination between them:
Fuzzy-Swarm, Fuzzy-Neural Networks, Fuzzy-Genetic Algorithm, Fuzzy-Ants Colony. We describe in this paper the use of Hybrid Fuzzy-PID Controller for enhancement of Static & Dynamic Response of the Three Phases Induction Motor Drives under the effect of the external disturbances. In this case, the obtained results were simulated on SIMULINK/MATLAB environment.

**Keywords:** A Ziegler-Nichols (Z-N), Fuzzy Logic Controller (FLC), Proportional Integral Derivative Controller (PID), Hybrid Fuzzy-PID Controller (FLC-PID)

**I. INTRODUCTION**

The variable speed systems took a great importance in the industry and in the research and require multidisciplinary knowledge in the field of the electric genius [1]. The induction motor is considered since its discovery as actuator privileged in the applications of constant speed, and it has many advantages, such as low cost, high efficiency, good self starting, its simplicity of design, the absence of the collector brooms system, and a small inertia [1-3]. However, induction motor has disadvantages, such as complex, nonlinear, and multivariable of mathematical model of induction motor, and the induction motor is not inherently capable of providing variable speed operation [3-4]. These limitations can be solved through the use of smart motor controllers and adjustable speed controllers, such as scalar and vector control drive [5]. The controllers of the speed that are conceived for goal to control the speed of Three phase Induction Motor to execute one variety of tasks, is of several conventional and numeric controller types, the controllers can be: PID Controller, Fuzzy Logic Controller; or the combination between them Fuzzy-Genetic Algorithm, Fuzzy-Neural Networks, Fuzzy-Ants Colony, Fuzzy-Swarm (Swarm). Fuzzy theory was first proposed and investigated by Prof. Zadeh in 1965.

The Mamdani fuzzy inference system was presented to control a steam engine and boiler combination by linguistic rules [6, 10]. Fuzzy logic is expressed by means of if-then rules with the human language. In the design of a fuzzy logic controller, the mathematical model is not necessary. Thus, the fuzzy logic controller owns good robustness. Fuzzy controller has been widely used in industry for its easy realization. However, the rules and the membership functions of a fuzzy logic controller are constructed by expert experience or knowledge database. Much work has been done on the analysis of fuzzy control rules and membership function parameters [6]. In recent years, field-oriented induction machine (FOIM) drives [7] have been increasingly utilized in motion control applications due to easy implementation and low cost. Besides, they have the advantage of decoupling the torque and flux control, which makes high servo quality achievable. However, the decoupling control feature can be adversely affected by load disturbances and parameter variations in the motor so that the variable-speed tracking performance of an IM is degraded. In general, both conventional PI and PID controllers have the difficulty in making the motor closely follow a reference speed trajectory under torque disturbances. In this regard, an effective and robust speed controller design is needed. In [8]-[14], fuzzy-logic-based intelligent controllers have been proposed for speed control of FOIM drives. Those intelligent controllers are associated with adaptive gains due to fuzzy inference and knowledge base. As a result, they can improve trial-and-error PI or PID controllers. Nonetheless, no performance advantages of intelligent controllers in combination with a PI or PID controller are investigated in [8]-[14]. Motivated by the successful development and application in [8]-[14], we propose a hybrid Fuzzy-PID controller consisting of a PID controller and a fuzzy logic controller (FLC) in a serial arrangement for speed control of FOIM drives, more specifically, direct field-oriented IM (DFOIM) drives. The Ziegler-Nichols (Z-N) method in [15] is adopted for designing a PID controller (denoted as “the Z-N PID”) because its design rule is simple and systematic. We next design a FLC carrying out fuzzy tuning of the output of the Z-N PID controller to issue adequate torque commands. This paper is organized as follows. Mathematical
modeling of the three-phase induction motor is given in Sec. II. Fuzzy logic controller and PID controller are given in Sec. III and IV. The Proposed Hybrid Fuzzy-PID Controller is given in Sec V. Design requirements for the system are given in VI. Simulations and conclusion are demonstrated in Sec. VII and VIII.

II. MATHEMATICAL MODELING OF THE THREE-PHASE INDUCTION MOTOR

Fig. 1 shows that d-q axis equivalent circuit at synchronously rotating reference frame.

Fig. 1: Equivalent Circuit at Synchronously Rotating Reference Frame

Fig. 2 shows a schematic diagram of a 3-phase induction motor with the d-q axes.

Fig. 2: d-q Axes Superimposed onto a Three-Phase Induction Motor

The dynamic model of the induction motor is derived by transforming the three-phase quantities into two phase direct and quadrature axes quantities. The equivalence between the three-phase and two-phase machine models is derived from the concept of power invariance. Induction motor model in the synchronous reference frame is shown in equation (1) and subscript e. denotes this reference frame, the models is discussed in more details in [16].
The mechanical equation of induction motor is equal below that:

\[
T_r = J \frac{d\omega_m}{dt} + B \omega_m + T_l
\]  
(2)

\[
\omega_r = \frac{P}{2} \omega_m
\]  
(3)

\[T_e = J \frac{d\omega_m}{dt} + B \omega_m + T_l
\]

\[
T_e = \frac{3P}{2} \frac{L_m}{2} (i_q^s i_d^r - i_d^s i_q^r)
\]  
(4)

Where

\[\omega_d = \omega_s - \omega_r\]  
slip angular speed

\[\omega_s\]  
Synchronous speed,

\[\omega_r\]  
Electrical speed (rotor speed)

\[P\]  
Number poles of IM,

\[T_e\]  
Electromagnetic torque,

\[L_m\]  
Mutual inductance,

\[L_s\]  
Stator leakage inductance

\[L_r\]  
Rotor leakage inductance

\[R_s\]  
Stator, resistance,

\[R_r\]  
Rotor resistance

\[i_q^s\]  
Stator current in synchronous frame on q - axis,

\[i_d^s\]  
Stator current in synchronous frame on d - axis,

\[i_q^r\]  
Rotor current in synchronous frame on q - axis,

\[i_d^r\]  
Rotor current in synchronous frame on d - axis,

\[V_q^s\]  
Stator voltage in synchronous frame on q - axis,

\[V_d^s\]  
Stator voltage in synchronous frame on d - axis,

\[V_q^r\]  
Rotor voltage in synchronous frame on q - axis,

\[V_d^r\]  
Rotor voltage in synchronous frame on d - axis.
The dynamic equations of the induction motor in synchronous reference frames can be represented by using flux linkages as variables. This involves the reduction of number of variables in dynamic equations, which greatly facilitates their solution. The flux-linkages representation is used in motor drives to highlight the process of the decoupling of the flux and torque channels in the induction machine. The stator and rotor flux linkages in the synchronous reference frames are defined as in:

\[
\begin{align*}
\lambda_{ds} &= L_s i_{ds} + L_m i_{dm} \\
\lambda_{qs} &= L_s i_{qs} + L_m i_{qm} \\
\lambda_{dr} &= L_r i_{dr} + L_m i_{dm} \\
\lambda_{qr} &= L_r i_{qr} + L_m i_{qm} \\
\lambda_{qm} &= L_m (i_{qs}^* + i_{qs}^c) \\
\lambda_{qm} &= L_m (i_{qs}^* + i_{qs}^c)
\end{align*}
\]

Where

\[
\begin{align*}
\lambda_{ds} & : \text{Mutual flux on } d - \text{axis,} \\
\lambda_{qs} & : \text{Mutual flux on } q - \text{axis,} \\
\lambda_{dr} & : \text{Stator flux on } d - \text{axis,} \\
\lambda_{qr} & : \text{Rotor flux on } d - \text{axis,} \\
\lambda_{qs} & : \text{Stator flux on } q - \text{axis,} \\
\lambda_{qr} & : \text{Rotor flux on } q - \text{axis,}
\end{align*}
\]

The stator and rotor flux-linkage phasors are the resultant stator and rotor flux linkages and are found by taking the vector sum of the respective \(d\) and \(q\) components of the flux linkages. Note that the flux-linkage phasor describes its spatial distribution. Instead of using two axes such as the \(d\) and \(q\) for a balanced polyphase machine, the flux-linkage phasors can be thought of as being produced by equivalent single-phase stator and rotor windings, as space phasor model that has many advantages [17-21]:

- The system equations could be compact and be reduced from four to two;
- The system reduces to a two-windings system like the DC machine, hence the apparent similarity of them in control to obtain a decoupled independent flux and torque control as in the DC machine;
- Easier analytical solution of dynamic transients of the key machine variables, involving only the solution of two differential equations with complex coefficients. Such an analytical solution improves the understanding of the machine behavior in terms of machine parameters, leading to the formulation of the machine design requirements for variable-speed applications.

The space phasor model of the induction motors can be presented in state space equations from previous equation, so it can be expressed in the synchronously rotating \(d-q\) reference frame as follows [22-23]:
III. FUZZY LOGIC CONTROLLER

The concept of fuzzy logic was developed by Lotfi Zadeh in 1964 to address uncertainty and imprecision which widely exist in engineering problems. Fuzzy modeling is the method of describing the characteristics of a system using fuzzy inference rules. The method has a distinguishing feature in that it can express linguistically complex nonlinear systems. It is however, very hard to identify the rules and tune the membership functions of the fuzzy reasoning. Fuzzy controllers are normally built with the use of fuzzy rules. These fuzzy rules are obtained either from domain experts or by observing the people who are currently doing the control. The membership functions for the fuzzy sets will be derived from the information available from the domain experts and/or observed control actions.

The building of such rules and membership functions require tuning. That is, performance of the controller must be measured and the membership functions and rules adjusted based upon the performance. This process will be time consuming. The basic configuration of Fuzzy Logic Controller (FLC) consists of four main parts (i) Fuzzification where values of input variables are
measured and a scale mapping that transforms the range of values of input variables into corresponding universe of discourse is performed then performs the function of fuzzification that converts input into suitable linguistic values, which may be, viewed labels of fuzzy sets. (ii) Knowledge Base consists of database and linguistic control rule base. The database provides necessary definitions, which are used to define linguistic control rules and fuzzy data, manipulation in an FLC. The rule base characterizes the control goals and control policy of the domain experts by means of set of linguistic control rules. (iii) The Decision Making Logic, it has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. (iv) The Defuzzification a scale mapping which converts the range of values of input variables into corresponding universe of discourse [24-28].

In view to make the controller insensitive to system parameters change, fuzzy logic theory is also implemented by researchers extensively. Indulkar et. al [20] initially designed a controller using fuzzy logic for automatic generation control and responses were compared with classical integral controller. Chang et. al. [21] presented a new approach to study the FLC problem using fuzzy gain scheduling of proportional-integral controllers and proposed scheme has been designed for a four area interconnected power system with control deadbands and generation rate constraints. Ha [22] applied the robust sliding mode technique to FLC problem where, control signal consists of an equivalent control, a switching control and fuzzy control with generation rate constraints and governor’s backlash on the other hand the fuzzy controller designed by Chown et. al [23] when implemented not only grid was controlled better but also more economically.

Talaq et. al [24] in their research proposed an adaptive controller which requires less training patterns as compared with a neural net based adaptive scheme and performance was observed better than fixed gain controller. Ha et. al [25] proposed an approach which combines the salient features of both variable structure and fuzzy systems to achieve high performance and robustness. Fuzzy logic controller, designed by El-Sherbiny. [26], is a two layered fuzzy controller with less overshoot and small settling time as compared with conventional one. Ghoshal. [27] presented a self adjusting, fast acting fuzzy gain scheduling scheme for conventional integral gain automatic generation controller for a radial and ring connected three equal power system areas. Yensil et. Al [28] proposed a self tuning fuzzy PID type controller for FLC problem and satisfactory results are found when compared with fuzzy PID type controller without self tuning.

IV. PID CONTROLLER

Fundamentally, PID controllers are composed of three basic control actions given in Table 1. They are simple to implement and provide better performance. The tuning process of the gains of PID controllers can be complex because it is iterative. First, it is necessary to tune the “Proportional” mode, then the “Integral”, and then add the “Derivative” mode to stabilize the overshoot, then add more “Proportional”, and so on. The PID controller has the following form in the time domain

\[ U(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \]  

(12)

Where e(t) is the system error (difference between the reference input and the system output), u(t) the control variable, Kp the proportional gain, Ki is the integral gain, and Kd adds some special characteristics to the output response of the derivative gain. The effects of these parameters on the output response of the system are shown in Table 2 [29].
A PID controller does not “know” the correct output to bring the system to the set point. It moves the output in the direction which should move the process toward the set point and needs to have feedback (measurements) to perform. Using the Laplace Transform for equation (12) and assuming initial conditions equal to zero the transfer function of the PID can be written as

\[ G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \]  

(13)

Let’s rearrange that a little, transfer function of a PID controller, the three terms can be recognized follows:

\[ G(s) = K_p \left( \frac{T_i T_d s^2 + T_i s + 1}{T_i s} \right) \]  

(14)

Where:

- \( K_p \) is the proportional gain
- \( T_i = K_p / K_i \) is the integral time constant
- \( T_d = K_d / K_p \) is the derivative time constant

PID control is a proportional integral plus derivative controller whose transfer function is:

\[ G_{PID}(s) = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right) \]  

(15)

The selection of the Proportional Integral and Derivative (PID) controller parameters can be obtained using the Ziegler-Nichols methods. Depending on the values of as shown in fig. 3 and using the Ziegler-Nichols tables, we can find the PID parameters.
Now, using the following equations, the PID parameters can be derived:

\[ K_p = 1.2 \frac{T_p}{L_p} \]
\[ T_i = 2L_p \]
\[ T_d = 0.5L_p \]

**V. THE PROPOSED HYBRID FUZZY-PID CONTROLLER**

Hybrid intelligent Fuzzy-PID controller has been proposed for speed control of FOIM drives. This intelligent hybrid controller is associated with adaptive gains due to fuzzy inference and knowledge base. As a result, they can improve torque disturbance rejections in comparison with best trial-and-error PID controller and fuzzy logic controller. We propose a hybrid Fuzzy-PID controller consisting of a PID controller and a fuzzy logic controller (FLC) in a serial arrangement for speed control of FOIM drives, more specifically, direct field-oriented IM (DFOIM) drives. The Ziegler-Nichols (Z-N) method is adopted for designing a PID controller (denoted as “the Z-N PID”) because its design rule is simple and systematic. We next design a FLC carrying out fuzzy tuning of the output of the PID controller to issue adequate torque commands. The PID controller employed in this study is used to tune the fuzzy logic controller. The tuning approach employs the use of MATLAB M-files and functions to manipulate the fuzzy inference system and scaling gains, run simulation, check the resulting performance and continuously modify the fuzzy inference system for a number of times in search for an optimal solution. The integral of absolute error is used as a measure of the system performance since it is known to give a better all round performance indicator of a control system response where overshoot, settling time and rise time are the main considerations [30].

\[ IAE = \int_0^\infty |e(t)dt| \]  

**VI. DESIGN REQUIREMENTS FOR THE SYSTEM**

The most basic requirement of Three Phase Induction Motor is that it should be rotated at the desired speed without and under the effect of loads (external disturbances and noise) and intelligent controller is used for reducing the sensitivity of actual response as to load variations (external disturbances and noise), where the actual response variations that have been induced by such external disturbances and noise must be minimized rapidly. The steady-state error of the Three Phases Induction Motor speed should be minimized. The other performance requirement is that motor must accelerate to its steady-state speed as soon as it turns on, The three phase induction motor is driven by applied voltage. The reference input (applied voltage) (V) is simulated by unit
step input, then an actual response of Three phase induction motor should have the design requirements for the system as follows

(i) Minimize the maximum overshoot  
(ii) Minimize the rise time  
(iii) Minimize speed tracking error  
(iv) Minimize the steady state error  
(v) Minimize the settling time  
(vi) The system is controllable and observable  
(vii) All roots of characteristic equation are lying in the left half of s-plane.  
(viii) Damping ratio ($\zeta$) is between (0.5 & 0.8).

Conventional control of an induction motor is difficult due to strong nonlinear magnetic saturation effects and temperature dependency of the motor’s electrical parameters. As the conventional control approaches require a complex mathematical model of the motor to develop controllers for quantities such as speed, torque, and position. Recently, to avoid the inherent undesirable characteristics of conventional control approaches, Fuzzy Logic Controller (FLC) is being developed. FLC offers a linguistic approach to develop control algorithms for any system. It maps the input-output relationship based on human expertise and hence, does not require an accurate mathematical model of the system and can handle the nonlinearities that are generally difficult to model. This consequently makes the FLC tolerant to parameter variation and more accurate and robust [31-33]. The FLC is connected to the PID controller for enhancing robust performance in both dynamic transient and steady-state periods. The FLC is developed based on the output of the PID controller.

VII. SIMULATION RESULTS

Fig. 4 shows The structure of the fuzzy controller with PID and Fig. 5-7 shows results of simulation (Matlab environment) of a Enhancement of static & dynamic response of the Three Phase induction motor without and under the effect of the external disturbances and noise by using intelligent controller (Fuzzy logic controller, FLC-PID ). The actual response of FLC-PID controller comparing with the actual response of PID controller is shown in Fig. 7. Table 3 lists the Comparison of the performances of PID and hybrid Fuzzy-PID controllers, to show the effectiveness of the proposed approach. Figure 8 and 9 shows the performance comparison of the various parameters for different types of controller.

![Figure 4: FLC with PID structure](image.png)
**Figure 5:** The block diagram of the proposed controller with DFOIM

**Figure 6:** Root Locus of the System
Figure 7: Simulation Results of the Comparison between the PID and Hybrid Fuzzy-PID Controller

Table 3: Comparison of PID Controller and Hybrid Fuzzy-PID Controller

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Strategy of control</th>
<th>PID control Method</th>
<th>Fuzzy-PID control Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ratio (ξ)</td>
<td></td>
<td>0.51021</td>
<td>0.55885</td>
</tr>
<tr>
<td>Settling Time (ts)</td>
<td></td>
<td>0.98047</td>
<td>1.0188</td>
</tr>
<tr>
<td>Maximum Overshoot (%Mp)</td>
<td></td>
<td>15.5102 %</td>
<td>12.0375 %</td>
</tr>
<tr>
<td>Steady-State Error (e_{ss})</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Peak Time (tp)</td>
<td></td>
<td>0.027 sec</td>
<td>0.035 sec</td>
</tr>
<tr>
<td>Rise Time (tr)</td>
<td></td>
<td>0.012 sec</td>
<td>0.014 sec</td>
</tr>
</tbody>
</table>

Figure 8: Comparison of Maximum Overshoot for PID Controller and Hybrid Fuzzy-PID Controller (FLC+PID)
VIII. CONCLUSION

By using Hybrid Fuzzy-PID Controller for enhancement of static & dynamic response of the Three Phase Induction Motor under the effect of the Static & Dynamic Response, the speed response for constant load torque shows the ability of the drive to instantaneously reject the perturbation. The design of controller is highly simplified by using a cascade structure for independent control of flux and torque. Excellent results added to the simplicity of the drive system, makes the Hybrid Fuzzy-PID Controller based control strategy suitable for a vast number of industrial. The sharpness of the speed output with minimum overshoot defines the precision of the proposed drive. Hence the simulation study indicates the superiority of Hybrid Fuzzy-PID Controller over PID controller separately. This control seems to have a lot of promise in the applications of power electronics. In this paper, a novel hybrid PID-FLC-based speed control of a DFOIM has been presented. The proposed controller has exhibited the combined advantages of a PID controller and a FLC. Specifically, it can improve the stability, the transient response and load disturbance rejection of speed control of a DFOIM. PID plus fuzzy logic control (FLC) scheme is proposed for speed control of a direct field-oriented induction motor (DFOIM). The PID is adopted because its parameter values can be chosen using a simple and useful rule of thumb. The FLC is connected to the PID controller for enhancing robust performance in both dynamic transient and steady-state periods. The FLC is developed based on the output of the PID controller.

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