A PLC-based modified-fuzzy controller for PWM-driven induction motor drive with constant V/Hz ratio control

Nordin Saad *, M. Arrofiq

Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS, Bandar Sri Iskandar, 31750 Tronoh, Perak, Malaysia

1. Introduction

Motor drives are used in a very wide power range. In adjustable-speed drive applications the ranges of speed achievable is very important in applications such as controlling of a boiler feed-water pump. In all drives where the speed and position are controlled, a power electronic converter is needed as an interface between the input power and the motor. A controller is also needed to make the motor, through the power electronic converter, meet the drive requirements. Notably, the extensive automation in modern industries demand several strategies that have high reliability and robust to be introduced and one of the main requirements is the control technique used. The controller used in this work is a programmable logic controller (PLC) that proves to be very efficient and reliable in applications involving sequential control and the synchronization of processes and auxiliary elements in the manufacturing, chemical and process industries [1]. The availability of PLC with basic features like arithmetic operations and the improvement of graphical user interface (GUI) in programming and communication, promises the means to utilize the advantages of PLC in adjustable speed application [2].

Successful examples of utilizing PLCs in control as main controller are related in [3–9], while as an assistant device control is related in [10].

In this paper, a method to develop and design a fuzzy-hybrid control on an industrial controller to control speed of an induction motor and implementing a constant V/Hz ratio control is presented. Detailed discussions on the controller for a PWM-driven induction motor drive system, the system identification for the model transfer function, and the analysis on output responses and the associated manipulated variables are presented. The control objective is to provide an effective control action to sudden changes in reference speed and/or load torque. A switching type controller consisting of two control modes are devised: a PID-type fuzzy controller consisting of a PI-type and a PD-type fuzzy controller, and a conventional PID. At the early phase of the control action, the control task is handled by the PID-type fuzzy controller. At a later phase when the absolute of error is less than a threshold value, the input of integrator at the output side is no longer given by fuzzy action but fed by the incremental PID action. In term of control action, this is an enhanced proportional and derivative action when the actual value is closed to reference. Detailed evaluations of the controller’s performance based on pre-defined performance indices under several conditions are presented. The findings demonstrate the ability of the control approach to provide a viable control solution in response to the different operating conditions and requirements.
can be seen as a PI, PD or PID controller in which the decision would be made by fuzzy algorithm. Hence, most of the improvement works are on tuning the parameters of the $P$, $I$ or $D$ either individually or simultaneously. Several previous work on improving the fuzzy logic controllers can be found in [8,19–25]. Li et al. [10] considered the problem of developing the input–output gain scheduling to improve the control resolution. An alternative way to increase the resolution of fuzzy controller on PLC has been conducted. Chung et al. [19] attempted to tune all three scaling factors using a single input fuzzy controller. There are quite a number of reports on tuning the change of error input gain and output gain based on peak observer, mathematical function driven by error and rate of error, respectively. These include Karasakal et al. [8], Qiao and Mizumoto [24] and Woo et al. [25].

There are quite a number of reports on the hybrid fuzzy-PID controller. These includes Mudi and Pal [22,23] and Guzelkaya et al. [20]. More specifically, Mudi and Pal [22,23] developed an approach to tune a PI and PD-type fuzzy controllers to output gain. In the design, an extra fuzzy logic controller performs as a controller to tune the output gain. A second fuzzy controller, with quite complex rules, is used to tune the output scaling factor and utilized the same input as main fuzzy controller i.e. error and change in error values. The proposed rules of the fuzzy parameter tuner were also able to provide self-tuning and anti-windup mechanism. Karasakal et al. [21], proposed a self-tuning for PID-fuzzy controller. A second fuzzy controller is employed to perform the self-tuning, and was based on the information of error and relative rate of error. A relative rate observer was utilized to indicate whether the system response was fast or slow. Based on that condition, the developed rules determined the scaling factor for the change in error input gain and PI-fuzzy output gain. Basically the proposed method tries to tune the fuzzy parameters keeping proportional parameter fixed, but it provides a gain to change the proportional parameter as well.

In addition to the above, there were a few reported works on attempting to improving fuzzy controller using PLC. For example, [8,21] discussed the implementation of gain scheduling and tuning with relative rate observer. A comparative analysis of PI and Fuzzy controllers was presented in [26]. It was a comprehensive comparison in a different situation including sudden change in reference and load. It was accounted that in some conditions fuzzy logic has better performance than PI, and vice versa. It was shown that for a large change in reference, fuzzy controlled gives faster response than a conventional controlled. In relation to insufficient resolution of fuzzy inference, the theoretical study shows that an inferior performance of fuzzy controlled process around a reference point is expected [10]. In real implementation, it can be caused by either the truncating process, rounding process or less word length.

Notably, there is substantial literature on control using hybrid-fuzzy controllers: however, there is only a few literature on induction motor speed control fed by variable-voltage variable-frequency (VVVF) using hybrid-fuzzy controller, examples in [12,13,27]. This work is similar to [12,13], but unique in terms of the controller used, i.e., a hybrid fuzzy-PID, and the control technique approached, i.e., VVVF with constant V/Hz ratio.

This paper’s contribution is as follows: a design of a fuzzy control algorithm for a PLC-based fuzzy controller for an induction motor speed control (adjustable speed drive) at constant V/Hz ratio with the PLC-based fuzzy controller interfaced to the motor via a pulse-width-modulation (PWM) inverter.

The paper is organized as follows: Section 2 discusses the system layout of PLC-based fuzzy controller for PWM-driven induction motor drive. Section 3 summarizes the design of the proposed modified-fuzzy controller. Illustrative example on the system identification for the model transfer function is presented in Section 4. Section 5 discusses on the controller design and the implementation in PLC. The experimental results are presented in Section 6, while Section 7 gives the conclusion of this paper.

2. The system layout of PLC-based fuzzy controller

The plant consists of a PWM inverter, an induction motor and a load. The PWM inverter functions as an interface between the PLC and the induction motor. The personal computer (PC) acts as a terminal for developing and downloading the program including the fuzzy logic routines to PLC and human–machine-interface (HMI) design to HMI. The connection between PC and PLC is established via Ethernet TCP/IP. The system also has a forward/reverse contactor to accommodate bidirectional rotation for the motor. The physical system layout and the related electrical connection of the test rig is illustrated in Fig. 1.

The PLC is equipped with a digital input–output and an analog input–output module. The rated input voltage of the digital input is 24 V DC while for the digital output is 12–24 V DC. To control the low voltage forward/reverse relay contactors running at low voltage (24 V) that drive the magnetic contactors two digital output points are used. One channel of analog input and two channels of analog output are used where the input channel is to measure the analog voltage that represents the actual speed while one of the two analog outputs is to send the manipulated variable (u) to the variable speed drive and the other is to specify the load applied to the induction motor.

The PWM inverter constitutes the main component of a variable speed drive (VSD). The VSD requires a three-phase supply on its line side and produces sequences of three-phase PWM on its output side, and this is arranged to drive the 3-phase squirrel cage 240/115, 50 Hz, 175 W and 1395 rpm induction motor. The VSD is rated at 0.75 kw, 415 V line-to-line on its output load side and its frequency is controlled by a 0–10 V analog signal coming from the analog output module of the PLC. There is a linear relation between 0 and 10 V of analog signal to the PWM inverter and 0–50 Hz analog output from PWM inverter to the three phase induction motor. The modulation implemented on the PWM inverter is a sine pulse-width-modulation (PWM) that runs on
a carrier frequency of 7.5 kHz and operates on a constant V/Hz ratio control. The PLC-based controller, as being interfaced to an induction motor via the PWM inverter provides a signal to the PWM inverter that depends on the inter-related variables i.e., the error and the rate of change in the error of the actual speed and the desired speed, the fuzzy rules, and the speed and torque requirements. Since, the PWM inverter operates on a constant V/Hz ratio control, the output of the PWM inverter in the form of voltage and frequency supplied to the induction-motor stator, depends on the controller's output signal to the PWM inverter and the V/Hz ratio relationship.

The programmable terminal (PT) consisting of a liquid crystal display (LCD) and a touch panel provides user friendly HMI interfacing between system and operator. In order to acquire a particular mechanical load, an analog control voltage is adjusted to provide a voltage that is proportional to the speed as to be provided by a dynamometer. The dynamometer consists of a permanent-magnet direct current (DC) machine that operates as a generator and is mechanically coupled to the motor by a timing belt. The analog voltage is related to the speed at 500 rpm/V, and the voltage is then fed to the PLC as the measured process variable.

3. Modified PID-type fuzzy controller

A common PID-type fuzzy controller is depicted in Fig. 3. The analysis of a linear PID-type fuzzy controller was presented in [24]. The controller is a combination of PI-type and PD-type controllers. The PI-type is recognized to reduce steady-state error but yields penalized rise time and settling time. The PD-type leads to fast rise time and minimum peak overshoot but does not improve steady-state error. As illustrated in Fig. 2, the output \( u \) is fed by integrator output \( u_1 \) and gain \( u_2 \). The integrator output represents the PI-type fuzzy controller and gain \( u_2 \) provides PD-type fuzzy controller. Eqs. (1) and (2) represent the corresponding PI-type and PD-type fuzzy controller output equations, respectively. The combination of Eqs. (1) and (2) forms the PID-type fuzzy controller output as in Eq. (3). In Eqs. (1), (2) and (3), \( A, P \) and \( D \) are the fuzzy parameters that relate to the input–output membership functions while \( \alpha, \beta \) are the output gains. \( K_1 \) and \( K_2 \) are the error input and change in error input gains, respectively.

\[
\begin{align*}
    u_1 &= \alpha A + \alpha PK_1 e + \alpha DK_2 \dot{e} \\
    u_2 &= \beta A + \beta K_2 D e + \beta K_1 P \int e dt \\
    u_c &= u_1 + u_2 = \alpha A + \beta A + (\alpha K_1 P + \beta K_2 D) e + \beta K_1 P \int e dt + \alpha DK_2 \dot{e}
\end{align*}
\]

where

\[
\begin{align*}
    P &= \frac{u_{i+1}y - u_i}{e_{i+1} - e_i} \\
    D &= \frac{u_{i+1}e - u_i e}{e_{i+1} - e_i} \\
    A &= u_{ij} - Pe_{ij} - De_{ij} \\
    i,j &= \text{fuzzy subset} \\
    u &= \text{rule output}
\end{align*}
\]

The proposed controller is simply the combination of the two controllers: PID-fuzzy and the conventional PID. This concept is investigated in this work by developing a switching type controller for a drive system, where a PID-type fuzzy is executed first and then switched to an incremental PID. The expression of the incremental output for conventional PID is as Eq. (4). Here \( \Delta t, T_i \) and \( T_d \) are the sampling period, integral time and derivative time, respectively. The improvement is realized by replacing the accumulator of the PLC with the incremental PID and this happens at the time \( n=k \), where \( |e(n)| < \text{threshold error} (e_{th}) \), that corresponds to 50 rpm. The structure of the proposed method is shown in Fig. 3. When the condition is satisfied, the controller derives the command signal to the PWM that is represented mathematically as Eq. (5). If it is not satisfied then the controller output is represented mathematically as Eq. (3). The flowchart of the decision process develop towards control action is illustrated.
in Fig. 4.

\[
\Delta u_c(n) = K_p \left[ e(n) \left( 1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t} \right) - e(n-1) \left( 1 + 2 \frac{T_d}{\Delta t} \right) + e(n-2) \frac{T_d}{\Delta t} \right]
\]

(4)

The proposed controller has the proportional and derivative values higher than a PID-type fuzzy controller. It is expected that the system would be able to reach the steady state faster because of the higher proportional action, and also to minimize the steady state error due to the contribution of the integral and derivative actions. For clarity, the proposed controller that consists of the hybrid of a conventional PID and a PID-type fuzzy controllers will be referred to as ‘modified FLC’, while the PID-type fuzzy controller will be designated as ‘FLC’.

4. Model structures

The process considered here is an integration of a PWM inverter, an induction motor and a dynamometer that form a VSD, as shown in Fig. 5. The process has two inputs and one output. The voltage to the PWM inverter, \(v_i\), is a signal that controls the frequency, \(f\), and voltage output, \(v\), while the input voltage to the dynamometer is the signal, \(v_d\), that specifies the load applied to the induction motor. The process output is the motor speed, \(n\).

The procedures as outlined in [28–30] were used to develop the model from experimental input–output data i.e. input output data, choice of model structure, estimation of the model parameter and validation.

4.1. Input output data

An open loop experiment is conducted on the integrated VSD system consisting of PWM inverter, induction motor and dynamometer (or load) to determine the minimum and maximum VSD input data. The minimum and maximum VSD input data is the data that correspond to minimum and maximum speed as specified in the operating point. The minimum and maximum input values are 700 and 1900 steps, and following the V/Hz constant rate, this corresponds to PWM inverter output frequency of 17.5 and 47.5 Hz, respectively.

Using multilevel periodic perturbation signal as the input to generate the output data, similar to the method as proposed in [31], seven sets of pseudo-random data were generated. The input data repetition rate is 3 s and the number of sequence is 15, with the period of input data equals 45 s. The experimental output data for each input consists of 4500 sampled data.

The input i.e., speed and load requirement, are sent to PWM inverter and load, respectively, and the induction motor speed is recorded. The similar experiment is conducted using different data sets to ensure that if it can give the best overall fit value for the different data sets, the model will be a good representation of the system.

Example of the open loop experiment results (speed in rpm) for the VSD model under multilevel periodic perturbation signals is shown as in the lower plot of Fig. 6.

4.2. Selection of model structure

The candidates for the model structure are the process model, state space (N4S2), Box–Jenkins (BJ), ARMA, ARMAX and Output Error (OE). The evaluation of model structure is based on the fit value that indicates the percentage of the output variation between the model output (simulated) and the measured output [32].
The detail of fit value equation is expressed in Eq. (6) where $y$, $\hat{y}$ and $\bar{y}$ are the experimental output data, simulated model output data and mean of experimental output data, respectively. The higher fit value implies that the difference of simulated model data as compared to experimental data is small. The maximum fit value is 100%.

$$
\text{Fit} = \frac{1 - \text{norm}(y - \hat{y})}{\text{norm}(y - \bar{y})} \times 100\%.
$$

The first four different input–output data sets named as identification I, II, III and IV are used to produce a basic model structure that will later be refined. Table 1 summarizes the combination of data to be identified.

The process model has been named as follows. The first parameter is $P$ that indicates pole. The number of pole or poles is indicated by the number after $P$. The second parameter is delay ($D$). The existence of integration, if any, is indicated by the letter $I$ as a third parameter. The fourth parameter indicates zero ($Z$). The last parameter ‘U’ to indicate the process is under-damped, if any.

### 4.3. Estimation of model parameter

The selected model structure, P3DZ, has three poles and a single zero with dead time process model. The model expression is as in Eq. (7) and the parameters given by identification process are summarized in Table 2.

$$
Y(s) = G_1(s) + G_2(s)
$$

where

$$
G_1(s) = \frac{1 + Tz s}{(1 + Tp_1 s)(1 + Tp_2 s)(1 + Tp_3 s)} e^{-Td s}
$$

$$
G_2(s) = \frac{1 + Tz s}{(1 + Tp_1 s)(1 + Tp_2 s)(1 + Tp_3 s)} e^{-Td s}
$$

It is clearly shown in Fig. 7 that the simulated model output has an offset error as indicated in the plot for Model P3DZ. Hence, an offset is introduced in the model’s transfer function to increase the fit value, by shifting the simulated output data so as to reduce the offset error, see plot for Model P3DZ + offset. A single value offset is required in the final model. The averaging process in determining the offset is selected to represent the required offset to the final model.

The model in continuous time is expressed as in Eq. (8).

$$
Y(s) = G_1(s) + G_2(s) + \text{offset}
$$

where

$$
G_1(s) = 0.72527 \times \frac{1 + 351.21 s}{(1 + 326.38 s)(1 + 0.090062 s)(1 + 0.10037 s)} e^{-0.069926 s}
$$

$$
G_2(s) = 0.12728 \times \frac{1 + 13.363 s}{(1 + 13.85 s)(1 + 0.03672 s)(1 + 0.03817 s)} e^{-0.025044 s}
$$

offset = -53.86.

### Table 1

<table>
<thead>
<tr>
<th>(a) Identification I</th>
<th>(b) Identification II</th>
</tr>
</thead>
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<tr>
<td>Model</td>
<td>Fit (%)</td>
</tr>
<tr>
<td>P3DZU</td>
<td>90.64</td>
</tr>
<tr>
<td>P3DZ</td>
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<tr>
<td>P1DZ</td>
<td>88.45</td>
</tr>
<tr>
<td>N4S2</td>
<td>88.23</td>
</tr>
<tr>
<td>BJ</td>
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<tr>
<td>OE221</td>
<td>88.15</td>
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</table>

### Table 2

<table>
<thead>
<tr>
<th>Parameters of P3DZ model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>$G_1(s)$</td>
</tr>
<tr>
<td>$G_2(s)$</td>
</tr>
</tbody>
</table>

### Fig. 7

Plots for P3DZ, comparisons between the experiment, P3DZ model without offset, and P3DZ with offset.
Consequently, the model in discrete-time representation can be written as in Eq. (9).
\[ Y(z) = G_{-1}(z) + G_{-2}(z) + \text{offset} \]  
where
\[ G_{-1}(z) = \frac{2.357e^{-7}z^3 + 0.004082z^2 - 0.003965z - 0.003695}{z^4 - 2.8z^3 + 2.81z^2 - 0.81z} \]
\[ G_{-2}(z) = \frac{-0.009853z^3 + 0.004062z^2 + 0.004328z + 0.0007145}{z^4 - 2.53z^3 + 2.116z^2 - 0.5857z} \]
offset = −53.86.

More detailed discussion on the system identification to obtain the model’s transfer function can be found in [33,35].

4.4. Model validation

Simulations were conducted to observe the effect of increasing and decreasing the input speed requirements on the output speed. The results show that the output follows the input with some delay, which is as expected. Simulations were also made to observe the effect of applying and releasing load on the speed of the induction motor. It shows that applying load to the system reduces the speed and vice versa. The results of the validation exercise are comparable to the available knowledge about the actual system.

5. Controller design

As to ascertain the correctness of the controller parameter values during real-time implementation on the test prototype, a simulation model of the system consisting of the PWM inverter, induction motor and dynamometer is built in MATLAB/Simulink using empirical data via system identification technique. Detail analyses of several realistic situations are simulated and the results, i.e., control parameters can then be used on the test prototype. The model developed in Section 4 is used in the controller analysis to obtain a proper setting of the controller parameter. As depicted in Fig. 8, the system consists of a fuzzy controller block, an incremental PID-control block, a low pass filter block and the process model block. The first three blocks constitute the components that represent the PLC. Thus during simulation run, the system would simulate the functions as in the PLC. The implementation of fuzzy logic in the PLC does not use any dedicated fuzzy module. By implementing using basic arithmetic and logic unit, and having the mathematical operations on integer numbers the computation task time and the usage of memory would be reduced. In a similar way, the variable speed drive also receives integer input number.

5.1. Fuzzy logic controller membership functions

The fuzzy controller used is a crisp type fuzzy controller and the inference method implemented is the product-sum. The fuzzy controller parameters are expressed in input–output membership function as shown in Fig. 13(a), i.e. negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB). In principle, any membership function forms could be implemented in PLC, but the constraint would be on the memory space. In this work, the membership function forms utilized are triangle and trapezoid. This selection is based on the desire to have simplicity in computation.

Designing the membership functions for the change in error is another important task. The data to be used in the design is obtained experimentally. A series of experiments were conducted to analyze when a step input is applied to the system, subjected to different speed and load requirements. The response provides an important value on the range of the speed and the respective values of the change in error can then be determined. Figs. 9 and 10 depict the step response of the system at 600 and 1200 rpm simultaneously, at no load and 2 Nm load.

When the reference speed is 600 rpm, the minimum change of error at no load and at 2 Nm load are −30 and −23 rpm, while for 1200 rpm, these are −45 and −30 rpm. Considering the values that can be applicable to both speeds, −30 is chosen as for the change in error. The value is determined by analyzing the trend of current speed. If the current speed is increasing, the change in error is negative and vice versa.

Another set of experiments were conducted to observe the response when applying and releasing a load. Figs. 11 and 12 depict the change in error value when load of 1 and 2 Nm is applied and released at 600 and 1200 rpm, simultaneously. The load is applied at 3 s then released at 6 s. From Figs. 11 and 12 the minimum and maximum of change in error for 600 rpm is −25
and 20 rpm while for 1200 rpm — 20 and 20 simultaneously. The value of 20 is chosen for the change in error since it is relevant for both speeds.

Similar experiments were conducted to obtain the change in error values and these produce five membership functions as follows: negative big (NB), negative small (NS), zero (NS), positive small (PS) and positive big (PB) and it is illustrated in Fig. 14. The values for the change in error of the membership functions are illustrated in Fig. 13(b).

The membership function of the fuzzy output depends on the control action scenario in determining the error membership function. For this particular case, the output membership function...
This is illustrated in Fig. 13(c). Using singleton membership positive small (PS), positive medium (PM) and positive big (PB). (NB), negative medium (NM), negative small (NS), zero (ZE), consists of seven members in singleton form namely negative big \( (\text{negative big}) \). The fuzzy rules rises and sudden falls in speed with step input speed of 1200 rpm and 2 Nm load.

Fig. 11. Simulation of the dynamic motor speed and change in error for sudden rises and sudden falls in speed with step input speed of 600 rpm and 2 Nm load.

Simulation of the dynamic motor speed and change in error for sudden rises and sudden falls in speed with step input speed of 600 rpm and 2 Nm load.

5.2. A linearization analysis at small error

Woo et al. [25] suggested a linearized PID-type FLC as in Eq. (3). The threshold value is set at 50 rpm where this value is chosen since it gives a better steady state error compared to other values, and also it is higher than the 2% tolerance bands at all operating points. Interestingly, when the absolute of error is less than 50 rpm, the control is by the incremental PID controller together with the PD-type FLC, while the PI-type FLC does not involve.

Taking for example when the \( e = 0 \), \( \dot{e} = 0 \), \( \delta e = + \) and \( \delta \dot{e} = + \), the analysis of the linearized output is explained as follows. In this situation, the \( e_i \)–ZE subset, \( e_{i+1} \)–PS subset, \( e_{i+2} \)–ZE subset and \( e_{i+3} \)–PS subset and the fuzzy rule is depicted in Fig. 15.

The fuzzy output gain, \( x \) and \( \beta \), are specified as 0.75 and 3, respectively, while the input gains, \( K_I \) and \( K_P \) are set to 1. The setting of the incremental PID controller is tuned using the Ziegler–Nichols frequency response. The sampling period of the controller is 10 ms, while the system speed range is specified as 600–1200 rpm, with the maximum load applied at 2 Nm.

The output frequency as shown in Fig. 13(c) defines the particular frequency in Hz to be applied onto the PWM inverter, as the outcome of the fuzzy rule as inferred in Table 3.

\[ f_{\text{output}} = \frac{K_P (e_i + \frac{1}{T} \dot{e}_i) + K_I e_i}{250} \]

for the input gain \( K_P \) (with respect to change in error input) = 1/30. The output frequency as shown in Fig. 13(c) defines the particular frequency in Hz to be applied onto the PWM inverter, as the outcome of the fuzzy rule as inferred in Table 3.

Fig. 14 shows the system responses to guide in generating the fuzzy rules. It is based on the situation of the actual values as compared to reference. At the lower part of Fig. 14, a table indicates the sign of error and change in error. The fuzzy rules are determined based on the sign and value of error and change in error. For example, at the initial time when the system is about to start, the system is at standstill and consequently, the error is positive big (PB) and the change in error is zero (ZE). The action should be taken to increase the output to more PB. The rule for this situation is expressed in Table 3 in the seventh column and third row. The rule for other situations can be generated following similar reasoning and with the respective value of error and change in error.

Because the number of error and the change in error are 7 and 5, simultaneously, the maximum number of fuzzy rules is 35. The complete rules for the PI- and PD-type fuzzy controllers are summarized in Table 3. It is clearly seen that even though the fuzzy rule is simple but it requires a systematic way on how to generate these rules and the step conducted here is following a graphical approach. The surface area of PI- and PD-type fuzzy is illustrated in Fig. 15.

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Taking for example when the \( e = 0 \), \( \dot{e} = 0 \), \( \delta e = + \) and \( \delta \dot{e} = + \), the analysis of the linearized output is explained as follows. In this situation, the \( e_i \)–ZE subset, \( e_{i+1} \)–PS subset, \( e_{i+2} \)–ZE subset and \( e_{i+3} \)–PS subset and the fuzzy rule is depicted in Fig. 15.

Substitution the values to the PD-type fuzzy parameters would produce the following:

\[ P = \frac{u_{ii+1} - u_i}{e_{i+1} - e_i} = \frac{\text{PS–ZE}}{250-0} = 20-0 = 0.08 \]

\[ D = \frac{u_{ii+1} - u_i}{e_{i+1} - e_i} = \frac{\text{PS–ZE}}{20-0} = 20-0 = 1 \]

\[ A = u_i - Pe_{i+1} = 0-0.08e_{i+1} = 0 \]

\[ u = A + Pe + D\dot{e} \]

\[ u = 0.08e + \dot{e} \]

This gives a linear relation to the output. It consists of \( K_P = 0.08 \) and \( K_D = 1 \). For other values of \( \delta e \) and \( \delta \dot{e} \), the linearization analysis gives the similar output form. This output combines with the incremental PID controller when the absolute error is less than a threshold value. Thus, the proportional and derivative actions have a higher gain than the normal fuzzy controller. This gives faster response and a smaller steady state error.

Up to this point, a simple design of controller running on PLC implementing an FLC (the PID-type fuzzy) and a modified FLC (the hybrid of conventional PID and PID-type fuzzy controllers) has

been realized. A fuzzy controller can be seen as a conventional PID controlled, by having the configuration of the output stage determines the type of controller either in PI, PD or PID mode. Tuning the input and output gain of fuzzy controller is the same as tuning the either $P$, $I$ or $D$ parameters. Several ways to improve the fuzzy controller has been considered as modifying the parameter in response to the current state. The information used to tune can be a simple mathematical expression, peak value of overshoot, a combination between error and change of error and rate of error.

![Figure 13. Fuzzy membership functions. (a) Error input, (b) change in error input and (c) frequency output.](image)

### Table 3
The Fuzzy rule base for PI-type and PD-type FLC.

<table>
<thead>
<tr>
<th>Error</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoE</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>ZE</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

![Figure 14. Fuzzy rule-extraction using step responses.](image)

### Table 4
Simplified fuzzy rule base for PD-type FLC at small error.

<table>
<thead>
<tr>
<th>Error</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoE</td>
<td>NS</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
</tr>
<tr>
<td>ZE</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>PS</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

![Figure 15. Surface area of the PI and PD-type PLC extracted from the fuzzy rule base.](image)

The operating point for controller evaluation purpose is as illustrated in Fig. 16. Each simulation run takes 15 s to complete. At the time 5 and 10 s, a sudden change in torque and speed requirements is applied. The evaluation includes sudden change in reference speed, sudden change in load applied and both simultaneously.

### 5.3. Performance criteria

The two basic primary aims of control are to follow the reference and to reject the disturbance [16].

The following performance criterion was used for measuring the effectiveness of the controller in meeting the control
objectives [34]. Different speed and load requirements are applied to the system and the performances are taken for analysis and comparisons. The error, \( e \), the difference between reference and actual value, is commonly characterized into several quantities. The integrated absolute error (IAE) is one of the quantities to express the accumulative of the error magnitude. The IAE formula is as follows:

\[
\text{IAE} = \int_{0}^{\infty} |e(t)| \, dt
\]  

(10)

The quadratic criterion i.e. integral of squared error (ISE) gives the error quantitative in quadratic manner. The ISE accumulates the squared error. The expression of ISE is shown as follows:

\[
\text{ISE} = \int_{0}^{\infty} e^2(t) \, dt
\]  

(11)

The drawback of this criterion is that it gives large weight if the error is large, for example, a poorly damped system. Another criterion is the integral of time weighted absolute error (ITAE). The expression of ITAE is formulated in Eq. (12). Since it multiplies the absolute error with time, the ITAE gives a small weight at the initial time where the initial error is usually large. The ITAE associates the weight to the error proportionally to the time. As the consequence, for the system with large steady state error, its ITAE value would also be large.

\[
\text{ITAE} = \int_{0}^{\infty} t |e(t)| \, dt
\]  

(12)

The control objective is to minimize the error of each performance criteria. The number of test patterns is larger than that in the discussion below; however, the choice of tests pattern is sufficient to illustrate on the controllers’ performance. Each test pattern should reveal the characteristic of the responses that are important in understanding the effect of the control action on the system being analyzed. The objective here is to use the simulation model to understand how the system comprises of the PLC as the controller, the PWM inverter and the motor behave in different situations by varying the input parameters. The operating points as depicted in Fig. 16 define the speed and torque (load) and hence the operating points associated to the initial, intermediate and final states of the test.

5.4. Test model 1: varying speed at constant load

In this experiment, a sudden change in reference speed at constant load is introduced. The operating points as shown in Fig. 16 are defined as follows: at no-load points E, F, and then back to E. For the case when a load is applied, the operating points are at A, B, and then back to A for 2 Nm load, and also at points C, D and then back to C for 1 Nm load. Fig. 17 depicts the response for the sudden change in reference at 1 Nm load. Table 5 summarizes the performance analysis for no-load, at 1 Nm load and at 2 Nm load, respectively. The sudden change is applied when time is at 5 s, during a speed rise from 600 rpm to 1200 rpm, and at 10 s, during a speed fall from 1200 rpm to 600 rpm. As shown in Table 5, the settling time when speed is increased or decreased is almost the same but a little bit slower during the decrease in speed.

![Fig. 16](image-url)  

**Fig. 16.** Different operating points for the speed-load torque requirements.

![Fig. 17](image-url)  

**Fig. 17.** Simulation of the dynamic motor speed for sudden rises and sudden falls in reference speed at (a) no load, (b) 1 Nm load and (c) 2 Nm load.
A closer look at the performance criteria, ISE, IAE and ITAE, would show to exhibit smaller values. This demonstrates the action of the modified controller to successfully regulate the speed and with an improved performance.

5.5. Test model 2: varying load at constant speed

The step is an example of a change in requirement that is significantly higher or lower than the current situation. The disturbance could have originated from a change in load requirement. The operating points for speed at 600 rpm are set at points E, C, and then back to E, also at points E, A and then back to E. For the speed at 1200 rpm, the operating points are set at points F, D, and then back to F, and also at points F, B and then back to F. The sudden change in load is applied when time is at 5 and 10 s. Fig. 18 shows the speed response when a load is applied and released during a constant speed. Tables 6 and 7 summarize the performance analysis. The graphs representing the speed response, indicate that a change in load introduces an undershoot when load is released, and an overshoot when load is applied. On both situations the motor speed experiences oscillations and takes sometime before it settles at the set-point. The explanation is that the controller parameter of the proposed modified FLC approach yields a bigger value than the FLC control (PID-type fuzzy control). In other word, the increment of \( P \) and \( D \) given by the PID controller is more than that is required to avoid either the overshoot or undershoot. The steady state error for the modified FLC approach is found to be smaller than when using the FLC approach when a 2 Nm load is applied and released, and still with better performance.

5.6. Test model 3: varying reference speed and load simultaneously

It is assumed that the reference speed and the load are changing at the same time when a disturbance is introduced. The system is subjected to a sudden change in reference speed, at no-load, 1 Nm load, and at 2 Nm load. Simulation results on the effectiveness of the controller based on the performance measures.

Table 5

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>600 → 1200</td>
<td>0</td>
<td>0.550</td>
<td>1</td>
<td>0.552</td>
<td>2</td>
<td>0.770</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.552</td>
<td>0.492</td>
<td>0.552</td>
<td>0.491</td>
<td>0.520</td>
</tr>
<tr>
<td>FLC</td>
<td>1200 → 600</td>
<td>0.593</td>
<td>0.548</td>
<td>2</td>
<td>0.770</td>
<td>0.595</td>
<td>0.560</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.595</td>
<td>0.550</td>
<td>0.595</td>
<td>0.550</td>
<td>0.568</td>
</tr>
</tbody>
</table>

Table 6

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>600</td>
<td>0 → 1</td>
<td>0.500</td>
<td>0.417</td>
<td>3.740</td>
<td>0.457</td>
<td></td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.583</td>
<td>0.527</td>
<td>0.687</td>
<td>0.633</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>1 → 0</td>
<td>0.530</td>
<td>0.437</td>
<td>2 → 0</td>
<td>0.880</td>
<td>0.472</td>
<td></td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.565</td>
<td>0.500</td>
<td>0.665</td>
<td>0.620</td>
<td></td>
</tr>
</tbody>
</table>

Table 7

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
<th>Load (Nm)</th>
<th>( t_s ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>1200</td>
<td>0 → 1</td>
<td>0.430</td>
<td>0.328</td>
<td>0.610</td>
<td>0.463</td>
<td></td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.560</td>
<td>0.225</td>
<td>0.603</td>
<td>0.562</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>1 → 0</td>
<td>0.470</td>
<td>0.355</td>
<td>2 → 0</td>
<td>0.416</td>
<td>0.385</td>
<td></td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.513</td>
<td>0.233</td>
<td>0.568</td>
<td>0.525</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 18. Simulation of the dynamic motor speed for a sudden applying and a sudden release of 2 Nm load at (a) 600 rpm and (b) 1200 rpm.
Two cases will be considered: (a) the disturbance due to two requirements, i.e., for an increase in speed and for an increase in load, and (b) the disturbance due to two of the following requirements, i.e., for an increase in speed and for a decrease in load. The responses for these cases are shown in Figs. 19 and 20, which summarize the performance analysis for cases (a) and (b). The simulation results for the two cases do not show much difference in the specified performance indicators between the proposed modified FLC and the FLC. The main findings from the simulation shows that the proposed modified-fuzzy controller yields better performance during the conditions when varying load at constant speed and also when varying speed at constant load (Tables 8 and 9).

5.7. Implementation on PLC

Only the arithmetic and logic operations instructions set available in a PLC is utilized in the implementation of the fuzzy control of the motor speed control. The rules obtained from the experiments on the speed control as discussed in Section 5, is applied to the fuzzy control algorithm. The input signals to the controller are the linguistic variable of speed error and change in

---

**Table 8**
Simulation results on the effectiveness of the controller based on the performance measures. The system is subjected to a sudden increased in speed and load, and also to a sudden reduced in speed and load.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>(t_e) (ms)</th>
<th>Load (Nm)</th>
<th>(t_e) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2%</td>
<td>5%</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>FLC</td>
<td>600 → 1200</td>
<td>0 → 1</td>
<td>0.558</td>
<td>0.508</td>
<td>0 → 2</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.560</td>
<td>0.508</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>1200 → 600</td>
<td>1 → 0</td>
<td>0.600</td>
<td>0.560</td>
<td>2 → 0</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.600</td>
<td>0.562</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IAE</td>
<td>ISE</td>
<td>ITAE</td>
<td>IAE</td>
</tr>
<tr>
<td>FLC</td>
<td>81.1e3</td>
<td>36.21e6</td>
<td>455.2e3</td>
<td>98.0e3</td>
<td>42.0e3</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td>76.3e3</td>
<td>36.04e6</td>
<td>413.9e3</td>
<td>82.4e3</td>
<td>43.2e3</td>
</tr>
</tbody>
</table>

---

Fig. 19. Simulation of the dynamic motor speed for a sudden increase in speed and load applied simultaneously at 5 s, and for a sudden decrease in speed and release of load simultaneously at 10 s, (a) 1 Nm load and (b) 2 Nm load.

Fig. 20. Simulation of the dynamic motor speed for a sudden increase in speed and load release simultaneously at 5 s, and for a sudden decrease in speed and load applied simultaneously at 10 s, (a) 1 Nm load and (b) 2 Nm load.
speed error, while the output signal is the frequency of the PWM inverter. The controller provides an output to the inverter that depends on the inter-related variables i.e., the error and the rate of change in the error of the actual speed and the desired speed, the fuzzy rules, and the speed and torque requirements. The output of the inverter, in the form of voltage and frequency supplied to the induction-motor stator, depends on the controller’s output signal to the inverter and the constant V/Hz ratio relationship. The objective of the controller is to provide stability in responses to disturbance and sudden changes in reference speed and/or load. Consider the limitation on the computation capability provided by PLC, programming and timing implementing the improvement strategy on PLC is challenging.

Fig. 21 depicts the flowchart of fuzzification, for the input error. The input has seven membership functions i.e., NB, NM, NS, ZE, PS, PM and PB. The markers Pt.6, Pt.5, Pt.4, Pt.3 and Pt.2 correspond to the minimum value of error when the degree of membership function is non-zero for PB, PM, PS, ZE, NS and NM. Seven data memory areas are required to keep the degree of membership functions. At the initial fuzzification step, all these memory areas need to be set to zero as the initial value. During the fuzzification, only two memory areas save the new data since the input data will only be under two nearest neighborhood membership functions, while the rest are kept unchanged. These seven data will be used as input data for the inference process.

The fuzzification for the second input change of error, follows the same steps as the first input except the number of required memory to save depends on the number of membership functions. As the second input has five membership functions, the total required memory to save the degree of membership function is twelve words.

As the implemented inference method is a product-sum, for a particular rule, the antecedents are multiplied and the result becomes the consequence for the rule and this is then accumulated to represent the fire of strength of a particular output. Fig. 22(a) shows the flowchart of inference process for NB output.

### Table 9
Simulation results on the effectiveness of the controller based on the performance measures. The system is subjected to a sudden increased in speed but a reduced load, and also to a sudden reduced in speed but an increased in load.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>$t_s$ (ms)</th>
<th>Load (Nm)</th>
<th>$t_s$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2%</td>
<td>5%</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>FLC</td>
<td>600 → 1200</td>
<td>1 → 0</td>
<td>0.563</td>
<td>2 → 0</td>
<td>0.595</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.560</td>
<td></td>
<td>0.600</td>
</tr>
<tr>
<td>FLC</td>
<td>1200 → 600</td>
<td>0 → 1</td>
<td>0.640</td>
<td>0 → 2</td>
<td>0.870</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td></td>
<td></td>
<td>0.635</td>
<td></td>
<td>0.850</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.560</td>
<td></td>
<td>0.595</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>IAE</th>
<th>ISE</th>
<th>ITAE</th>
<th>IAE</th>
<th>ISE</th>
<th>ITAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>73.7e3</td>
<td>28.20e6</td>
<td>385.4e3</td>
<td>66.4e3</td>
<td>26.02e6</td>
<td>306.7e3</td>
</tr>
<tr>
<td>Modif. FLC</td>
<td>65.6e3</td>
<td>27.76e6</td>
<td>306.8e3</td>
<td>63.2e3</td>
<td>26.12e6</td>
<td>271.5e3</td>
</tr>
</tbody>
</table>

Fig. 21. Steps for the calculation of the degree of membership functions during fuzzification.
As summarized in Table 3, there are six rules influencing the NB output. As the NB output is influenced by six rules, there are similar six multiplications of the antecedents. The inference process flow diagram for other outputs is similar to Fig. 22(a).

The last stage of the fuzzy algorithm is defuzzification that transforms the fire of strength of each output to a unique form of output. The centre-of-gravity (COG) method is utilized and the output membership function in the form of singleton is as shown in Fig. 22(b).

5.8. Implementation of modified FLC (Hybrid FLC-incremental PID) on PLC

The hybrid controller consists of two control algorithms, i.e. PID-fuzzy controller and incremental PID. The control algorithm outputs are namely $U_{FZ}$ and $dU_{PID}$ for the PID-fuzzy and the incremental PID, respectively. Fig. 23 illustrates the flow diagram of the modified FLC in PLC.

The final control output is $U(t)$ that comprises of $z$ gain output and accumulator output. The $z$ gain is multiplied with the fuzzy control output, $U_{FZ}$. The $z$ gain output represents the output of PD-type fuzzy control. The accumulator output accumulates the input signal that comes either from the incremental conventional PID output, $dU_{PID}$, or the $b$ gain output. The input signal to the accumulator is determined by the comparison between an absolute error and a defined threshold error. At the early stage of control action or when the error is larger than a defined threshold value, the accumulator input signal is given by $b$ gain output and the accumulator output represents the PI-type fuzzy controller output. When the accumulator input is fed by incremental PID control, the update of accumulator is given by the incremental PID. A sample ladder diagram of PLC program representing the hybrid control is illustrated as in Fig. 24 is generated based on the fuzzification flowchart of Fig. 21. As depicted in Fig. 24, one can implement the fuzzification flowchart into the PLC by specifying the conditions of the error for the particular membership functions to be determined. Nevertheless it is not the intention of this paper to discuss in great detail on the PLC programming and ladder diagram code generation. More detail can be found in [35].

6. Experimental results

The simulation examples presented in Sections 5.4–5.6 illustrate how the system could be performing when subjected to the various speed and load requirements. This section will now discuss the on-line implementation of the controller in regulating the speed of the motor in response to certain operating conditions. The system runs in a sample period of 10 ms that corresponds to the PLC scanned time. As in the simulation, the system is evaluated for a 15-s-duration, and the sudden change in the operating conditions is applied when the time is at the 5 and 10 s. There are various operating conditions possible, but for the purpose of illustration only the following extreme cases are presented.

6.1. Varying reference speed and load simultaneously

The response at the extreme situations i.e. during a sudden change in reference speed and load simultaneously are shown in Fig. 25. The performance analysis is summarized in Tables 10 and 11.

Interestingly, in Table 10 the modified FLC performs better than FLC in maneuvering the speed to a steady state when a load and speed is released. One may notice the quite large steady state error in Fig. 25(b). The cause for this is firstly, the fuzzy rules used are not refined enough to accommodate for the large load torque applied or released during when the speed is low, and secondly, due the slow
The slow sampling-time affects the observation of the controller to counter the disturbance and when a particular control is decided, it is not fast enough as well as capable of providing an effective control action. This is where a more precise observation of error and change in error when a load is either applied or released, especially when the speed is low and the load is at maximum should be conducted, as well as using a PLC with a faster sampling-time. More refined fuzzy rules can be formulated that would improve the overshoot and undershoot during these situations. The observation should emphasize to the value of change in error when that situation happens and determines the suitable output of the fuzzy control.

In relation to this as indicated in Table 11, for the case of FLC as the controller, it is not possible to record the settling time at 2% tolerance band when the reference speed is increased while the load is released. This relates to the inability of the controller to bring the speed to within 2% band due to slow sampling-time of the PLC, which affects the control observation and action. Fig. 26 reveals the manipulated variable \((u)\) for a sudden change in load at 1200 rpm. Here the manipulated variable of the PID controller is used as a reference for comparison with the FLC (i.e., PI and PD-types fuzzy controller) and the modified FLC (hybrid FLC + incremental PID). The modified FLC is showing to provide a better control signal to the PWM inverter as compared to the FLC, since the later could not react as fast to the change in load requirement. With reference to Fig. 26(b), the manipulated variables of the FLC and modified FLC remain at the saturated-value of 2000 when the load is applied. The manipulated variable, \(u\), for the controllers has been designed to saturate at 2000 when a load is applied. In this experiment, the value 2000 rpm is chosen as the upper bound of the VSD input, and this implies that the PI-type portion of the FLC cannot quickly reduce the integrator output after saturation.

6.2. Low reference speed with varying load

The following experiment is conducted to evaluate the output response during a low speed operation. Experimental results for output response and the manipulated variables with load 2 Nm and speed 600 rpm are depicted in Fig. 27. The introduction of a load slows down the motor but some moments later it regains speed due to the controller’s action. A similar phenomenon would also be observed at much lower speed until the operating speed is somewhere below 300 rpm that is when the motor is brought to a halt after the load of 2 Nm is applied. In terms of the controller’s actions at this low threshold speed, the controller is not able to provide the
Fig. 25. Experimental results for sudden change in reference speed and load simultaneously. (a) Load applied and released is 1 Nm, (b) load applied and released is 2 Nm, (c) load released and applied is 1 Nm and (d) load released and applied is 2 Nm.

Table 10
Comparison on the effectiveness of the controller based on the performance measures. The system is subjected to a sudden increased in speed and load, and also to a sudden reduced in speed and load.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>ts (s)</th>
<th>Load (Nm)</th>
<th>ts (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>600 → 1200</td>
<td>0 → 1</td>
<td>0.913</td>
<td>0.747</td>
<td>0 → 2</td>
</tr>
<tr>
<td>Modif.–FLC</td>
<td></td>
<td></td>
<td>0.776</td>
<td>0.487</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>1200 → 600</td>
<td>1 → 0</td>
<td>1.270</td>
<td>0.877</td>
<td>2 → 0</td>
</tr>
<tr>
<td>Modif.–FLC</td>
<td></td>
<td></td>
<td>1.060</td>
<td>0.847</td>
<td></td>
</tr>
</tbody>
</table>

Table 11
Comparison on the effectiveness of the controller based on the performance measures. The system is subjected to a sudden increased in speed but a reduced load, and also to a sudden reduced in speed but an increased in load.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>ts (s)</th>
<th>Load (Nm)</th>
<th>ts (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>600 → 1200</td>
<td>1 → 0</td>
<td>–</td>
<td>0.560</td>
<td>2 → 0</td>
</tr>
<tr>
<td>Modif.–FLC</td>
<td></td>
<td></td>
<td>0.833</td>
<td>0.550</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>1200 → 600</td>
<td>0 → 1</td>
<td>–</td>
<td>0.707</td>
<td>0 → 2</td>
</tr>
<tr>
<td>Modif.–FLC</td>
<td></td>
<td></td>
<td>0.850</td>
<td>0.677</td>
<td></td>
</tr>
</tbody>
</table>

IAE | ITAE | ISE | IAE | ITAE | ISE

| FLC   | 76.59e3 | 429.30e3 | 33.14e6 | 72.88e3 | 310.16e3 | 24.98e6 |
| Modif.–FLC | 73.77e3 | 405.92e3 | 32.49e6 | 68.85e3 | 290.59e3 | 24.73e6 |
necessary manipulated variables to revive the motor. This signifies that at the much lower speed operation the constant V/Hz ratio control needs to be revised and one of the options is by introducing ‘voltage boost’ at the lower frequency to maintain the flux constant by compensating the ‘stator impedance drop’, so that the air gap flux per pole and torque become available up to zero speed. Unless to obtain an optimize value when applying the voltage boost, finding and estimating the threshold speed should not be a difficult problem since in this case, 300–350 rpm should be an acceptable value.

In another perspective, as can be seen in Fig. 27(a), the drive reaches the reference speed relatively fast when using PID as compared to the FLC (PI and PD-types fuzzy controller) and the modified FLC (hybrid FLC + incremental PID). Another observation is the drop in speed when a load applied using PID control is less as compared to the FLC.

At the lower speed operation, Table 12 suggests that the PID fares a better control action as compared to the modified FLC. Fig. 27(b) shows the manipulated variable of the three controllers anticipating the load applied and released. It is clearly shown that the manipulated variable of the modified FLC (hybrid FLC + incremental PID) has quite a similar pattern as the PID control, however, with a slightly lagged reaction. On the other hand, the modified FLC controller, which is essentially an enhancement to the FLC (PI+PD-type fuzzy controller) with the incorporation of incremental PID, is shown to respond fast to a sudden change in load as compared to the FLC (PI+PD-type fuzzy controller). In the control perspective, the controller’s action on the error is improved: in the case when the error is small. When the error is lower than the integrator switch threshold value, the input of integrator at the output side of hybrid-fuzzy controller is given by the incremental PID controller. An attractive aspect of the modified FLC (hybrid FLC + incremental PID) is that its performance resembles the PID controller.

7. Conclusion

The aim of this work has been to address the design, simulation and implementation of a PLC-based fuzzy controller PWM-driven of an induction motor drive. To achieve wide ranges of speed

Table 12

<table>
<thead>
<tr>
<th>Controller</th>
<th>Ref. (rpm)</th>
<th>Load (Nm)</th>
<th>t_s (s)</th>
<th>Load (Nm)</th>
<th>t_s (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>600</td>
<td>0 → 1</td>
<td>0.630</td>
<td>0 → 2</td>
<td>1.370</td>
</tr>
<tr>
<td>FLC</td>
<td>1540</td>
<td>1.127</td>
<td>-</td>
<td>1.144</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.650</td>
<td>0.598</td>
<td>2.610</td>
<td>1.033</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>1 → 0</td>
<td>0.610</td>
<td>2.0 → 0</td>
<td>0.900</td>
<td></td>
</tr>
<tr>
<td>FLC</td>
<td>0.700</td>
<td>0.437</td>
<td>0.750</td>
<td>0.507</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.863</td>
<td>0.390</td>
<td>0.593</td>
<td>0.520</td>
<td></td>
</tr>
<tr>
<td>IAE</td>
<td>1.18x10^3</td>
<td>4.1x10^3</td>
<td>1.18x10^3</td>
<td>13.63x10^3</td>
<td></td>
</tr>
<tr>
<td>ISE</td>
<td>3.4x10^3</td>
<td>4.1x10^3</td>
<td>1.45x10^3</td>
<td>26.26x10^3</td>
<td></td>
</tr>
<tr>
<td>ITAE</td>
<td>2.7x10^3</td>
<td>4.2x10^3</td>
<td>1.28x10^3</td>
<td>16.11x10^3</td>
<td></td>
</tr>
</tbody>
</table>
operation, requires the incorporation of two control modes, namely the PI+ PD-type fuzzy controller and the incremental PID controller, and hence a modified FLC has been proposed. The selection of the control mode depends on the phase of drive operations. The modified FLC operation has shown to give good response when the drive system is subjected to disturbances and sudden changes in reference speed and/or load. Overall, this study indicates the following outcomes: an improvement of control action, which does not need the complex mathematical model of real plant is feasible. Also the control algorithm could be easily implemented into the PLC that would perform well in industrial environment.

This work has contributed to an improved understanding of the procedure for configuring and implementing a PLC-based fuzzy controlled PWM-driven of an induction motor with constant V/Hz ratio control. The work presented here offers some promising tools in terms of hardware and software handling of a PLC system and provides avenues for other research scope to address different aspects of issues pertaining to the PLC-based fuzzy controller and promises the means to utilize the advantages of PLC in adjustable speed drives application.

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References
