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Development of a Fuzzy Logic Controller for Industrial Conveyor Systems

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Abstract: In many industrial operations, it is essential and desirable that the speed of two or more movable members be synchronized. In this paper, the design of a fuzzy logic controller (FLC) to control the speed of a conveyor belt system of the Champion Breweries Bottling plant is presented. The need to control the conveyor speed is borne out of the necessity to synchronize the conveyor lines speed with the speed of action of all the process machines within the production network. The traditional Proportional Integral Derivative (PID) controllers have some shortcomings that may be eliminated by the use of the more robust fuzzy logic control strategy. However, an accurate mathematical model of the conveyor system was first developed before the development and deployment of the PID controller and the fuzzy logic controller. Comparing the performance indices of both controllers, it was seen that the fuzzy Logic Controller performed better on the conveyor system than the PID controller.

Keywords: Conveyor, Fuzzy Logic Controller, Membership Function, Rule Base, Modelling

1. Introduction

Fuzzy logic controllers are widely used in various and varied control schemes. In most instances it is positioned in the forward path of a feedback control system. The control output is compared with a reference, and if there is an offset, the controller takes action to minimize the error to a value as low as practicable. [1]. Fuzzy Logic differs in concept and content from the traditional multivalued system. Fuzzy logic systems make use of linguistic variables instead of numbers hence it is actually a computing methodology that employs words rather than numbers [2]. Besides, computing with words harnesses the tolerance of most systems to imprecision and thereby lowers the cost of an intended solution. The development of the fuzzy logic controller involves preprocessing, fuzzification, fuzzy inference system development, rule base formulation, defuzzification and post processing [3].

A conveyor is mechanical systems that is used to move either bulk materials or unit items through the manufacturing process, and are available in various types of industrial plants [4]. Conveyor systems may benefit from the precision capability of fuzzy logic controllers. Conveyor applications involve an elementary speed control strategy in which the drive simply regulates the operating speed at a set point that may be adjusted from time to time. The speed set point might be set manually by an operator or automatically by a controller [5].

2. Methodology

2.1. Design Procedure

The following steps were followed for modelling the fuzzy logic controller:

- The control objectives and criteria were defined. This essentially involved determining what to control, what to do to control the system and the kind of response expected.
- The input and output relationships were determined and a minimum number of variables chosen for input to the fuzzy logic engine (typically error and rate-of-change-of-error).
- The control problem was broken down into a series of IF X AND Y THEN Z using the rule-based structure of fuzzy logic. These rules defined the desired system output response for given system input conditions. The

number and complexity of rules depended on the number of input parameters that were to be processed and the number of fuzzy variables associated with each parameter.

- Fuzzy logic membership functions were created which helped to define the values of input/output terms used in the rules.
- Following the construction of the fuzzy control system, the simulation of the system was carried out.
- The system was tested, the results evaluated, the rules and membership functions tuned and re-tested until satisfactory results were obtained.

2.1.1. Design and Modelling of Fuzzy Logic Controller

Typically, a fuzzy logic controller has at least two inputs and one output. A fuzzy inference system (FIS) maps given inputs to outputs using fuzzy logic membership functions. A membership function (MF) is a shape that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse which needs to be specified by the designer. There are two styles of FIS used in fuzzy logic controller and these are Mamdani and Sugeno styles. Mamdani's fuzzy inference method is the most commonly used methodology and can make do with different membership functions in its inputs and outputs [6]. For this design, the input and output is defined as follows: since FLC requires at least two inputs and one output, the first input will be the speed error(E)while the second is the change in error of the speed(ΔE) and the DC motor shaft rotational speed is the output(ω), and the equations relating these are written in equations 1, 2 and 3.

$$E(t) = \omega_{ref}(t) - \omega_{ac}(t) \tag{1}$$

$$\Delta E = E(t) - E(t-1) \tag{2}$$

$$\omega(t) = \omega(t) - \omega(t-1) \tag{3}$$

Where:

t is the time factor,

$\omega_{ac} = 1414\, rpm$ is the actual speed achieved by the motor,

$\omega_{ref} = 1450$ is the desired speed required by the system for synchronisation

2.1.2. Membership Function Definition and Rules Formulation

However, one needs to define all the linguistic terms that would be used for specifying our membership functions - MF. These terms formed the sets of antecedents and consequents in the fuzzy rule-based table which are employed in quantifying the input and output values or degree of membership in the fuzzy sets [7]. Table 1 shows the linguistic term for MF.

Table 1. *Membership Function Terms.*

MF Terms	Description
NL	Negative Large
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PL	Positive Large

In theory, the choice of MF in FLC design does not cause much attention. Designers simply use isosceles triangles for defining membership functions of the FLC structures within the specified universe of discourse. This particular MF has a paramount advantage of easing difficulties encountered in FLC structure analysis [8]. It is absolutely important to mention that in real-time modelling of FLC and depending on application, a non-equal span of membership function is always adopted to deal with real control problems [9]. Besides, the function itself can be an arbitrary curve whose shape one can define as a function that suits one from the point of view of simplicity, convenience, speed, and efficiency [10].

There were two MF used for modelling the FLC, and these include the triangular and the trapezoidal. The membership functions types used for the DC motor has universe of discourse of E, ΔE and ω as $+/-36$, $+/-3.6$ and $0 - 225.63$ respectively. The range of the rotational speed of the DC motor was chosen in such a way that it would not damage the motor when the FLC is implemented, and this is the reason why expert knowledge of the system is really essential in FLC design.

The 49 formulated rules, as carried out in MATLAB, are shown in the Table 2 and the shapes of the membership functions used are presented in Figure 1.

Table 2. *Rules Table.*

		NL	NM	NS	Z	PS	PM	PL
	NL	*NL*	*NL*	*NL*	*NL*	*NM*	*NS*	*Z*
Speed	NM	*NL*	*NL*	*NL*	*NM*	*NS*	*Z*	*PS*
Error	NS	*NL*	*NL*	*NM*	*NS*	*Z*	*PS*	*PM*
Change	Z	*NL*	*NM*	*NS*	*Z*	*PS*	*PM*	*PL*
(ΔE)	PS	*NM*	*NS*	*Z*	*PS*	*PM*	*PL*	*PL*
	PM	*NS*	*Z*	*PS*	*PM*	*PL*	*PL*	*PL*
	PL	*Z*	*PS*	*PM*	*PL*	*PL*	*PL*	*PL*

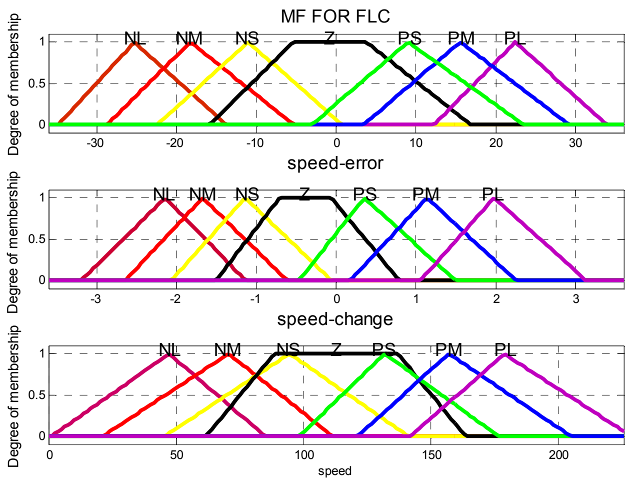

Figure 1. *Initial Membership Functions for the FLC.*

The triangular and trapezoidal membership functions are often used because these curves make it flexible and easy to represent the proposed ideas and facts of the model, and with less computational time requirement. Then in order to obtain the output of the FLC, the rotational speed of the motor, output fuzzy set is defuzzified into crisp value using the centre of gravity method.

Moreover, FIS mapped given inputs to outputs using fuzzy logic rules via the membership functions. The typical mapping of the two-input one-output fuzzy controller is depicted in a 3-D plot of Figure 2.

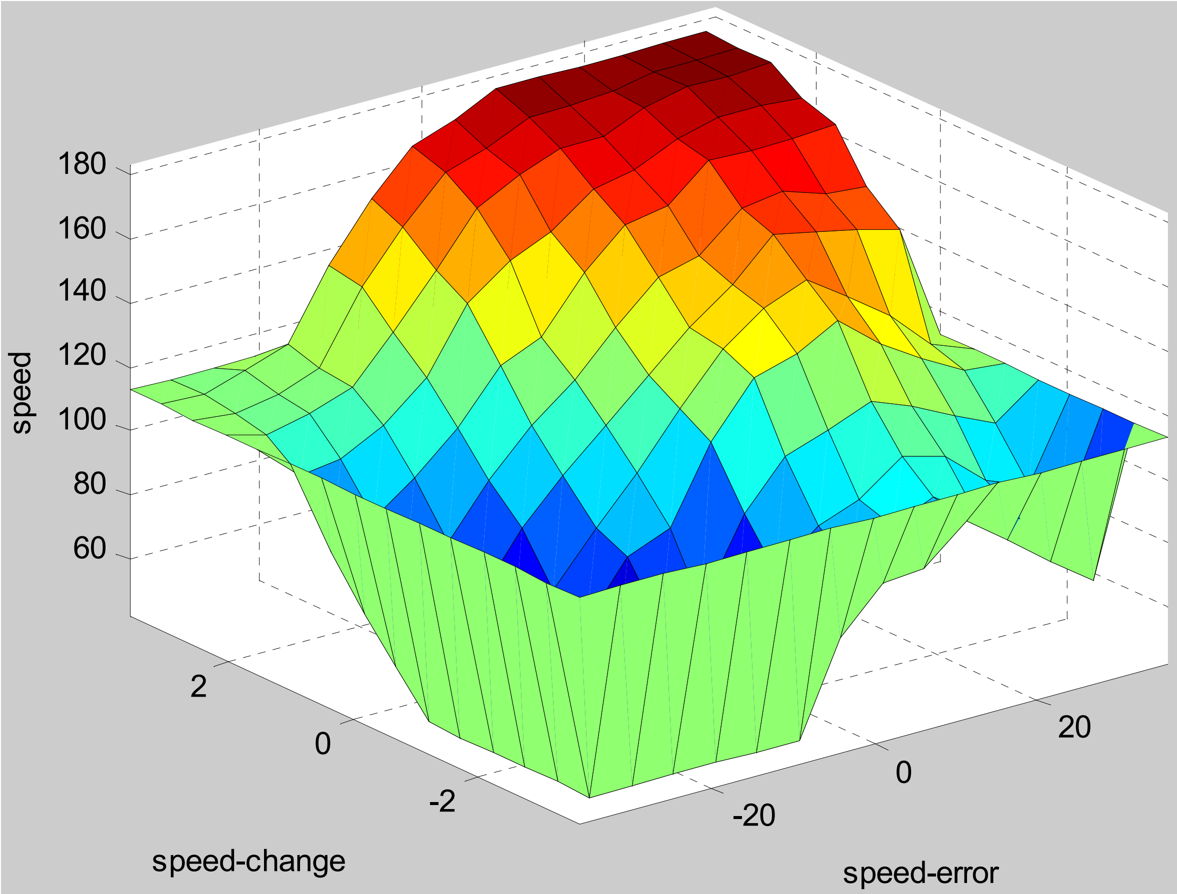

Figure 2. *Nonlinear 3-D Fuzzy Control Surface.*

The plot is often referred to as the control surface plot, and in this case, it is nonlinear. The 3-D nonlinear control surface has higher control action gain near the positive extreme of the E and CE and this helps to reduce the error more quickly when the error is small. When the error is large, the controller becomes less aggressive so that control action is limited to avoid possible saturation.

2.2. Speed Response of the DC Motor with the Fuzzy Logic Controller

The Simulink model of the FLC used for synchronisation of the conveyor lines with the EBI and FBI Machines is shown in Figure 3. This FLC-DC motor conveyor model is simulated for a period of 1 sec and speed response is shown in Figure 4.

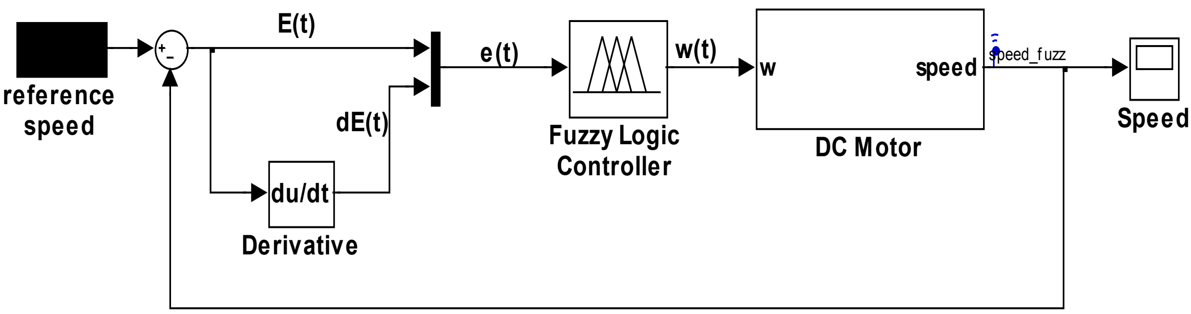

Figure 3. *Simulink Model of FLC and DC Motor Conveyor.*

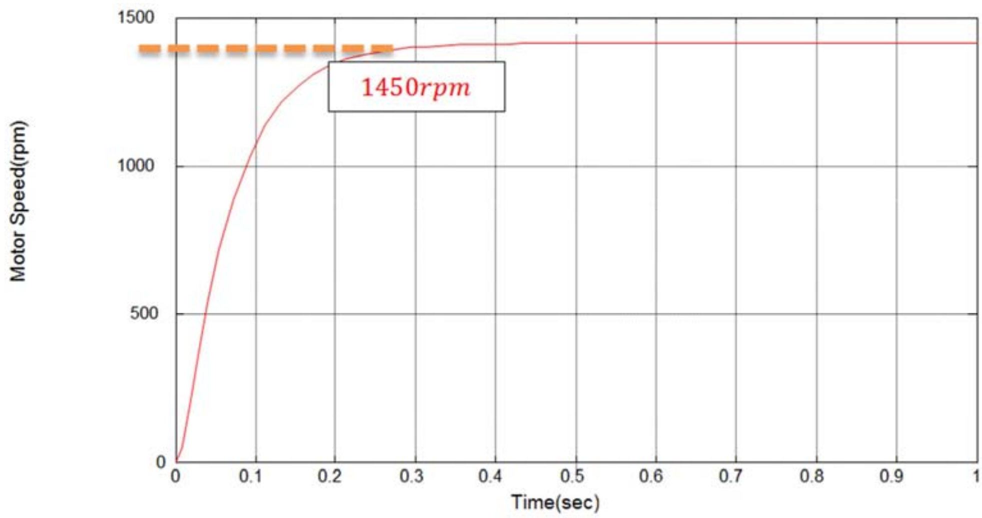

Figure 4. *Speed Response of DC Motor Conveyor System with FLC.*

The speed response indicated that the FLC controller is able to issue a control action which finally corrected motor speed to the required optimum speed of $1450\ rpm$ in 0.3 seconds which coincides with the 0.3 seconds duty time cycle specified to synchronise the conveyor with the EBI and FBI machines.

3. Research Analysis And Results

3.1. Simulation of the DC Motor Conveyor System and Fuzzy Logic Controller

The final transfer function representing the composite of the electrical system, mechanical system and the belt conveyor torque as obtained from is presented in equation 4 [7].

$$\frac{V_b(s)}{V_{app}(s)} = \frac{0.1181s-41.74}{s^3+29.63s^2+1.217s-2.362} \quad (4)$$

The model was simulated for period of 20 seconds and the DC motor speed and angular position responses are depicted in Figures 5 and 6.

The speed response showed that the motor attained an actual maximum speed of ω_{ac} = 1414 rpm in 6 seconds. This speed ω_{ac} = 1414 rpm is lower than the optimum speed (ω_{op} = 1450rpm) needed to synchronise the system.

Therefore, it would be necessary to model a controller to enable the optimal speed for the motor to be achieved. Also, Figure 6 illustrates the angular position of the motor shaft in radians which is directly tied to the rotational speed of the motor.

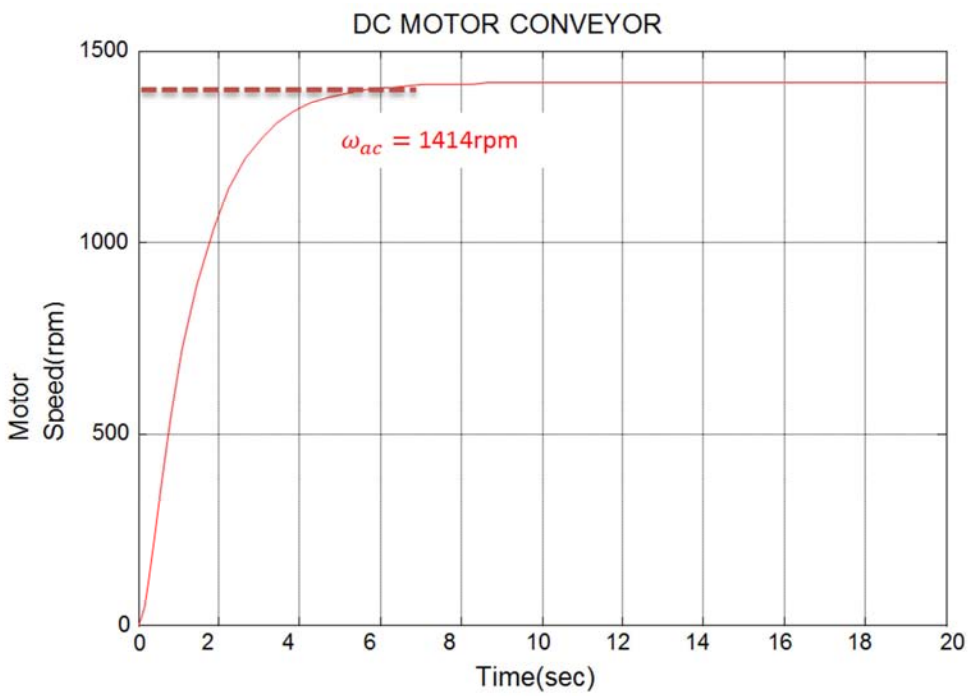

Figure 5. *Speed Response of DC Motor Conveyor System.*

From Figure 6, it can be seen that the angular position increases linearly with time.

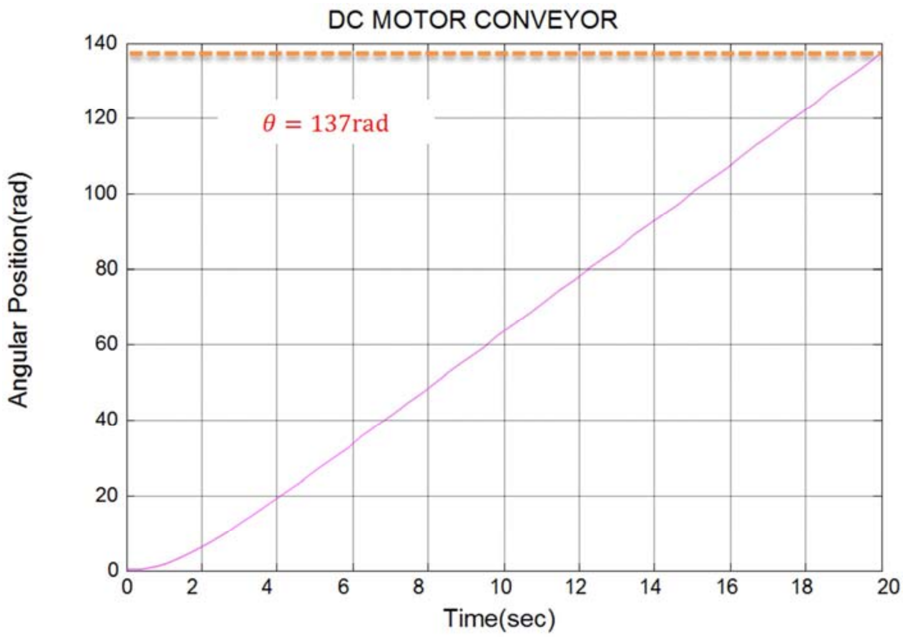

Figure 6. *Angular Position Response of DC Motor Conveyor System.*

3.2. Model Evaluation Criteria

There are many performance indices used in control engineering design for evaluating how well a designed system would perform in practice. In this work, only time domain response indices are used. Figure 7 examines the response of the system to a step input.

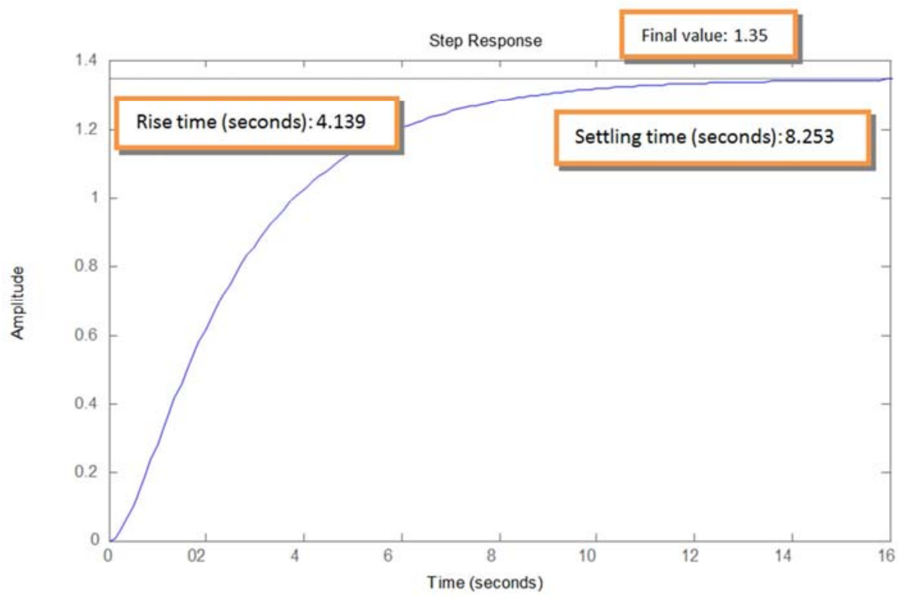

Figure 7. *Response of DC Motor Conveyor System.*

In computing the system step response, Simulink software first linearizes the nonlinear mathematical relationship in equation 4 about the input and output point of the model. The system has a rapid and smooth response to step input. The overshoot of $2.22 \times 10^{-14}\%$ indicated that the system step response is not chaotic. This is because the system has no complex poles and no zeros, a pointer to the fact that there are virtually no internal delays. Table 3 summarizes all the performance indices for the step response. The transient response disappears beyond the rise time of $4.139\ sec$ and finally gives way to the steady-state response at the settling time of $8.253\ sec$. Overshoot and the settling time represent the degree of closeness of the step response to the desired response. The final peak value of the step response occurred at an amplitude of 1.34. These low rise and peak times actually demonstrate how swift the system is to step input signals, and the optimality of the system dampness.

Table 3. *Step Response Performance Analysis DC Motor Conveyor System.*

Performance Indices	Values	Units
Peak Amplitude	≥ 1.34	rpm
Peak Time	> 16.4	Sec
Rise Time	4.139	Sec
Settling Time	8.253	Sec
Overshoot	2.22×10^{-14}	%

The steady-state error is equally low at > 0.34, and this means it is > 34 %. This can be driven low or zeroed when the FLC is introduced into the system.

A linear model is first computed from the nonlinear Simulink model of the FLC before the linear response plotted. During simulation, the software linearizes the portion of the model between specified linearization inputs and outputs, and plots the response of the linear system. The Simulink model can be continuous- or discrete-time or multi-rate and can have time delays depending on whether the design is aimed to be implemented in real-time hardware. Refer to Table 4 for a complete list of the response performance indices of the FLC.

Table 4. *Performance Indices of DC Motor Conveyor System with FLC.*

Performance Indices	Values	Units
Peak Amplitude	1450	rmp
Peak Time	1	sec
Rise Time	0.12	sec
Settling Time	0.20	sec
Overshoot	6	%

Table 5 shows the performance indices of the DC motor conveyor system with a PID controller [7].

Table 5. *Performance Indices of DC Motor Conveyor System with PID Controller.*

Performance Indices	Values	Units
Peak Amplitude	1450	rmp
Peak Time	1.02	sec
Rise Time	0.342	sec
Settling Time	0.836	sec
Overshoot	2.29	%

Finally, Table 6 shows a comparison of the performance indices of the system with no controller, with a PID controller and FLC

Table 6. *Comparison of System Performance.*

Performance Indices	Without Controller	With FLC	With PID
Peak Amplitude(rpm)	1414	1450	--
Peak Time (sec)	20	1	1.02
Rise Time (sec)	4.139	0.12	0.342
Settling Time (sec)	0.253	0.20	0.836
Overshoot	0	6	2.29

It is clear from Table 6 that there is an improvement in the performance of the DC motor conveyor system when the fuzzy logic controller is deployed over the controller-less system and the PID controller. This is because FLC is inherently robust and nonlinear with elements of uncertainties in its structure. The Peak Time, the Rise Time and the Settling time are lower with the fuzzy logic controller.

Most importantly, as earlier stated, the FLC controller is able to issue a control action which finally corrected motor speed to the required optimum speed of 1450 rpm in 3 seconds which coincides with the 3 seconds duty time cycle specified to synchronise the conveyor with the EBI and FBI machines

4. Conclusion

The results from the motor conveyor system modelled and simulated indicated that based on industry parameters, the motor attained a maximum speed of 1414 rpm. However, the developed FLC was introduced into the control loop to correct the speed of the DC motor to the required operating speed of 1450 rpm in 3 seconds duty time cycle specified to synchronise the conveyor with the EBI and FBI machines. The simulation results obtained using MATLAB/Simulink showed that the overshoot, settling time, peak time and control performance improved greatly by with the use of the fuzzy logic controller.

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