# An Improved Fuzzy Logic Controller for Speed Optimization of Harry-Ward Type Motor

Zairan LI [1, 2], Kai SHI[2,*], and Tongzhan CUI[2]

[1] Tianjin Key Laboratory of Process Measurement and Control, *School of Electrical Engineering and Automation, Tianjin* University, Tianjin, 300072, P.R. China
[2] Wenzhou Vocational & Technical College, Wenzhou, 325035, P.R. China
* Corresponding author: shikai@wzvtc.cn

***Abstract*** **- Harry-Ward control system is a widely used speed control system of DC motors. In this paper, we propose a fuzzy logic based speed control system further optimized by considering state variables and transfer functions. The simulation is performed using the tool Simulink in Matlab. The fuzzy control method is improved to detect errors of input signals, filter the whole process and change the error signals. The simulation shows that the fuzzy logic controller algorithm gives better performance compared with conventional control, largely reduces the error in speed, and continuously adapts to give a more robust approach to the motor speed control system. Several experiments are performed and we conclude that the proposed algorithm gives higher efficiency of the speed control in motor.**

***Keywords - Harry Ward Motor, Speed Optimization, Fuzzy Logic Control***

## I. INTRODUCTION

Motor control is an essential part of the industries and in 1891 Harry Ward introduced a new method for controlling the speed of DC motor. There have varieties of applications for motors being utilized in a way that requires both the speed control and robust control. DC motors' exemplary application are in electric cranes, conveyers and rollers etc. The earliest method evolved in controlling the speed of the DC motor was the voltage control devised by Harry Ward[1].

With the development of modern science and physics including the semi-conductors, the properties for motor control and dynamics had changed immensely. The introduction of thyristor as voltage controlling device greatly enhances the technique of motor control. Together with thyristor, modern physics introduces semi-conductors components such MOSFET, IGBT and Transistors[2], which make the controlling being much more improved, and it also allows fast switching of the voltage and power in DC motors.

In order to control the speed of the motor, there are various methods in previous studies, and in this paper, we focuses on the optimization of the speed control based on the principles of Harry Ward Leonard using fuzzy logic. The optimization algorithm is formulated based on many simulations of the speed of the motor. The simulation is performed on the mathematical model formulated in the motor model section, and the control of speed of a DC motor goes through a dreary task involving complex mathematical calculations thus a need to override the complexities and execute a better control, it is therefore becomes a necessity to involve several other techniques such as fuzzy logic to incorporate and cope with the difficulty in applying intricate mathematics. The application of fuzzy logic in motor speed control system is incorporated early in 1987 in Japan in metro system project [3].

The conditions that are used in the simulation consist of both loaded and unloaded. The simulation is collective study of the motor model selected and further analysis is completed using the mathematical equations and concepts. Moreover, the simulation is performed on MATLAB using its Simulink technology. In order to conclude a better performance aspect of the algorithm, the design system is put under a simulation using the fuzzy logic controller system. In the study, the utilization of the system in Ward Leonard motor speed control system is made on chopper circuits. The comparison is also made with respect to the PI model as well with speed set constant as well as monitors speeds at different load conditions. The Simulink models presented in the paper implement the algorithms to optimize the speed of motor by enforcing the three stage process including preprocess, fuzziness and de-fuzziness.

## II. MOTOR MODEL

The system that has been put under test is the Harry Ward Leonard motor speed control system. The system was widely used in early 1900s in both war and commercially [4]. The methodology implemented behind the motor control system is high-power amplifier.

### *A. Principle of the system*

The system consists of a motor and generator coupled through a shaft resulting in an electrical amplified output. The motor is either supplied an altering current source or a direct current source. However, the generator can get its power from direct source. The field windings on the generator are supplied with the input, and the output electricity is delivered from the armature winding. The output collected at the armature winding is transferred to the motor connected that in turn drives the load. The change in the field winding current generates a larger current in the armature winding due to magnetic excitation in the generator thus producing large amount of current at the output and providing a smooth control of the amplification (Shown in Figure 1).

The connection in this manner allows large changes by altering small input current thus the control of the motor is energy efficient.

*B. System Analysis*

However, considering the following functional scheme shown in Figure 2 can imagine the implementation of the Harry Ward Leonard system. The scheme can be formulated in an electrical circuit by replacing magnetic actions as inductors and resistive actions as resistors. The circuit form of the winder is shown in Figure 3.

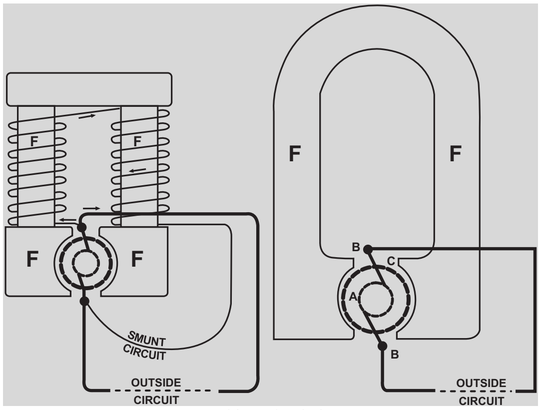


Figure 1. Self-excited shunt DC motor

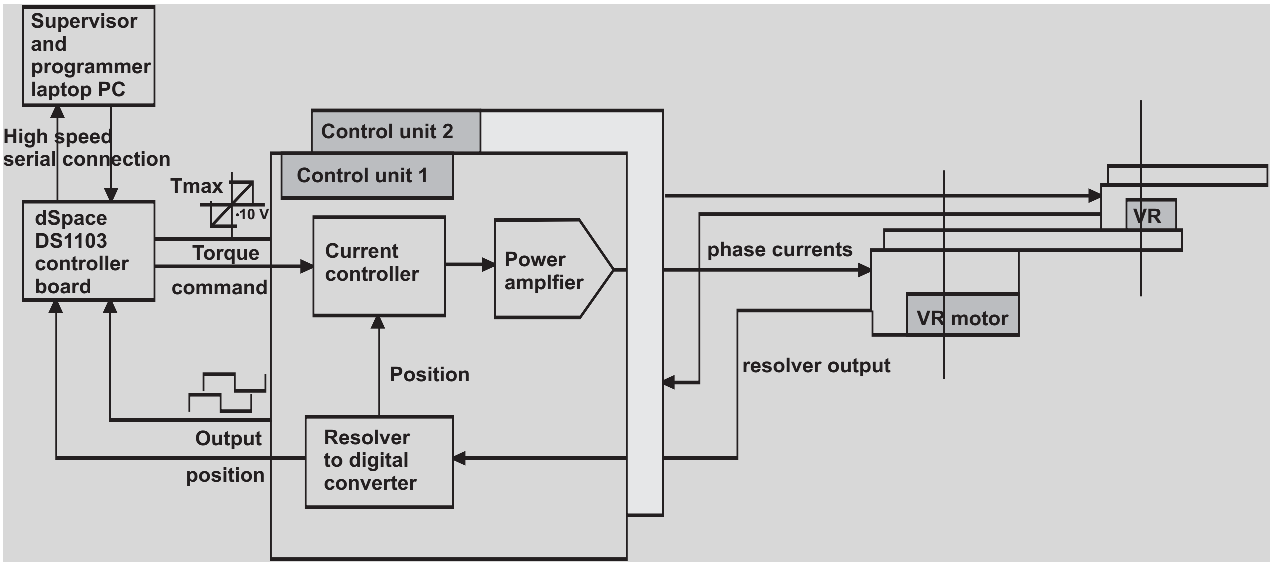


Figure 2. The function process.

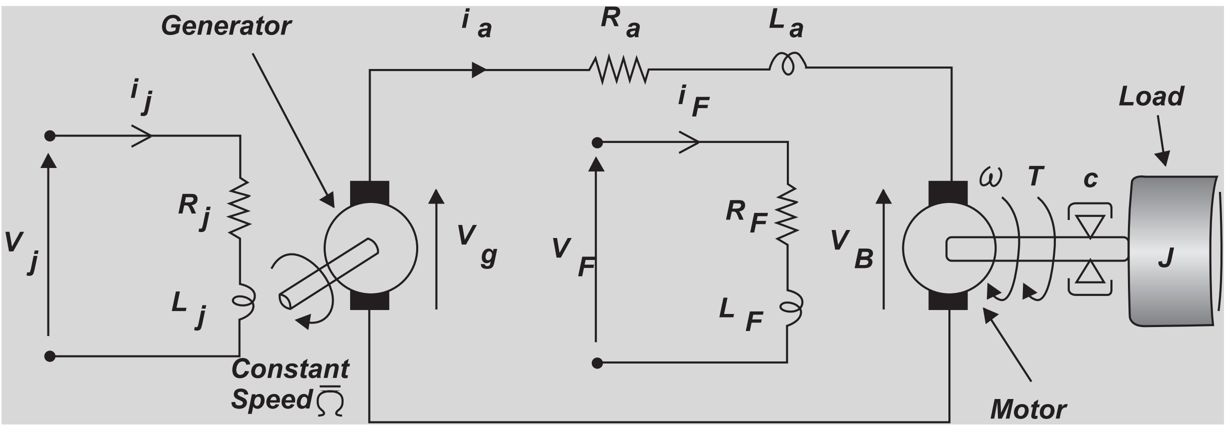


Figure 3. Ward-Leonard motor generator system

The circuit has two sections, a generator and a motor. The input is supplied on the generator end and the mechanical motorized action is resulted at the other end.

The fuzzy logic applied to the internals of the motor operation. The methodology implementing the fuzzy logic can become very complex for conventional processes. The circuit modeled for fuzzy optimization is shown in Figure 4 as below.

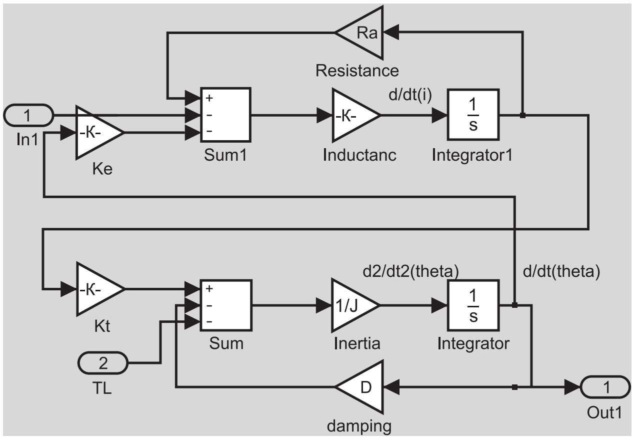



Figure 4. Converted to Ward Leonard system.

## III. SYSTEMS DERIVING MATHEMATICAL MODEL

The winder shown in Figure 5 can be modeled as a Harry Ward Leonard motor generator system, as shown in Figure 5.

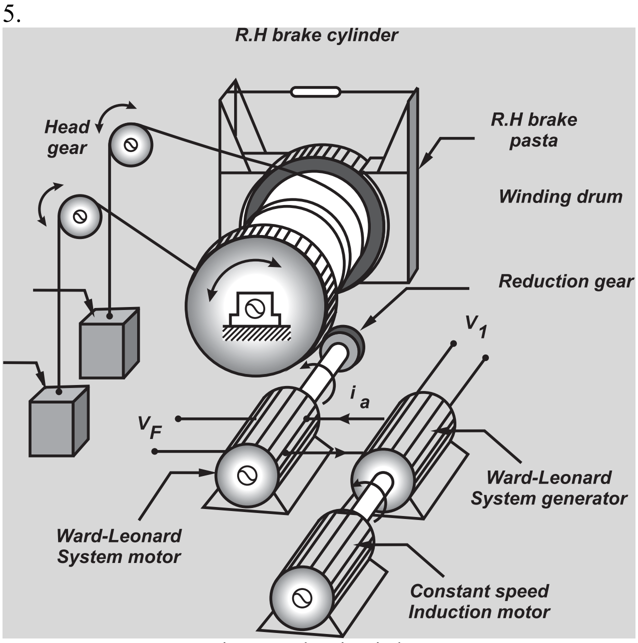



Figure 5. Electric winder.

In order to convert the Harry Ward Leonard system into a mathematical form which is to be analyzed in the simulator and several techniques are to be applied on it. The circuit must be converted to a mathematical form by applying various magnetic and electric laws.

The circuit is analyzed in two sections considering the anatomy of the circuit. It is divided into the generator section and motor section. Analyzing the first part and applying the Kirchhoff's voltage law on the generator, circuit yields the following equation,

$$L_f \frac{di_f}{dt} + R_f i_f = V_f \tag{1}$$

The torque of the motor can be calculated by the product of current in the armature and field winding,

$$T_m = C_2 \times I_a \text{ (Constant field current)} \tag{2}$$

The torque generated by the motor is proportional to the electromotive force or *emf* generated, therefore a back *emf* is also generated which can be calculated by the application of derivative on the flux, that is, conversely, can be related to the generator voltage, and can be formulated as a product of field winding current and the magnetic constant.

$$V_g = C_1 \times i_f \tag{3}$$

The overall torque calculated for the whole motor drive system is as follows,

$$J \frac{d\varpi}{dt} + B\varpi = T_m = C_2 \times I_a \tag{4}$$

In order to execute several simulations and optimize the system, it must be necessary to select state variables. The parameters independent are the field winding current that is $I_f$ and the flux. The transfer function obtained by resolving for the relation is as follows,

$$\frac{di_f}{dt} = \frac{E}{L_f} - \frac{R_f}{L_f} i_f \tag{5}$$

Transforming it into the state variable form results in the following equation,

$$\dot{X}_1 = -\frac{R_f}{L_f} X_1 + \frac{u}{L_f} \tag{6}$$

Substituting the equation into the main torque equation yields a large equation,

$$J\frac{d\varpi}{dt}+B\varpi=C_2+I_a$$
$$=C_2(\frac{V_g-E_m}{R_a})$$
$$=C_2(\frac{C_1 i_f-C_3\varpi}{R_a})$$
$$=\frac{C_2}{R_a}(C_1 i_f-C_3\varpi)$$
$$\frac{d\varpi}{dt}=\frac{C_2}{JR_a}(i_f-(C_3+B)\varpi) \quad (7)$$

Transforming it into state variable yields, we have that,

$$\dot{X}_2=\frac{C_2}{JR_a}(C_1 i_f-(C_3+B)X_2) \quad (8)$$

Converting the equations into a matrix form gives the square matrix,

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\end{bmatrix}=\begin{bmatrix}-\frac{R_f}{L_f} & 0\\ \frac{C_2C_1}{JR_a} & \frac{-C_2(C_3+B)}{JR_a}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix}+\begin{bmatrix}\frac{1}{y}\\ 0\end{bmatrix}u \quad (9)$$

Thus the output equation is as follow,

$$y=\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix} \quad (10)$$

The equation (10) yields the speed of the motor and depends on the two state variables chosen. The simulations are to be run against this equation with involving the techniques of fuzzy logic and Bayesian network discussed in detail in the following section.

## IV. EXPERIMENT RESULT ANALYSIS

The optimization of motor speed is formulated based on the analysis conducted above. The mathematical model created is put to the test by simulating various aspects of the final equation, that is, the state variables. One of the first inclusions in the optimization algorithm is the effects created by the fuzzy logic. All the simulation data and finding from the results are explored in this section.

### *A. Fuzzy logic optimization*

Fuzzy logic is an approximation logic that cannot be justified in an exact manner. In comparison to the closest counterpart, the binary operations, fuzzy logic deals with the approximation of the true value to the degree between zero value and the highest value 1 [5].

Zadeh has introduced the theory of fuzzy set theory in 1965 to define the process of the fuzzy logic implementation [6]. The relation between the fuzzy logic and fuzzy set theory is very much similar to the popular Boolean logic and the classic theory. However the classic control has their dependencies on the fixed and accurate parameters. The fuzzy logic controller, on the other hand, processing the information based on the experiences is rather than depending purely on the system designing parameters. In other words, the fuzzy logic controller uses the approximation methods and located the nearness and estimate the output based on the input provided. A basic simple structure for fuzzy logic controller is shown Figure 6 illustrating various operational blocks that are to be used in the controller. It can be formulated by the design of the controller and the nature of the fuzzy logic that the knowledge of system model is not necessary. However in contrast to the extensibility of the controller, it cannot work properly and provide disrupted results if the process control is not well defined [7].

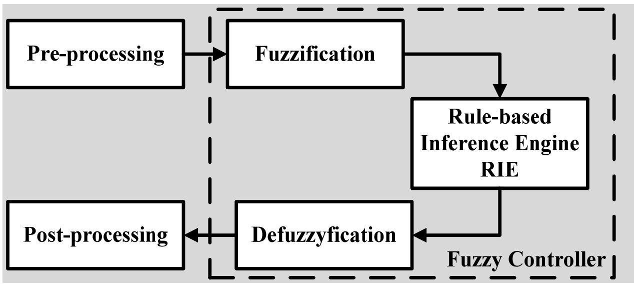



Figure 6. Block diagram of fuzzy logical control.

Most of the complex system tends to identify the impressions and estimation while keeping a value of uncertainty in the equation. An expression to what fuzzy logic can deliver upon the scenario presented can be classified as the nearest possible justification mostly in the format of “appropriate”, “higher”, “little high” and “too high” etc. These indicators do not depict the exactness of the entity that is being measured but the advantage is the nearby approximation that can be varying in nature but related to the measured entity in subtle way. The basis of fuzzy logic is created on these closeness and estimation of the state of the entity. They are more a linguistic way of addressing the state rather than using the exact or fixed operations [8].

The numerical range, in order to calculate error, corresponds to the linguistic function in fuzzy logic. The linguistic notation shows the error in speed with the actual and desired speed. Table 1 shows these notations below.

TABLE 1 LINGUAL RANGE OF ERROR

| Lingual Exp. | Notation | Values |
|---|---|---|
| Min Low | ML | -0.25 to 0.25 |
| Small Negative | SN | 0 to 0.25 to 0.5 |
| Zero | Z | 0.25 to 0.5 to 0.75 |
| Small Positive | SP | 0.5 to 1 |
| Min High | MH | 0.75 to 1.25 |

The paper discusses the speed optimization based upon the controlling methodologies of fuzzy sets. The implementation of the algorithm is to reduce the speed error because it is directly proportional to the controller input. The change in the error is what utilized by the fuzzy logic controller. The state variable extracted from the system equation (10) derives the output variable. The output of the controller is the reflection of the change in the control variables driving the motor. The $X_2$ variable depicts the angular value and determined the duty cycle of the converter. The project motor model designed reaches to minimum when the motor is running in the normal condition or conversely in the nominal state.

The system was put on the simulation under a no load condition and the results yielded that the error reduces to the minimum when the motor goes to nominal state (Shown in Figure 7).

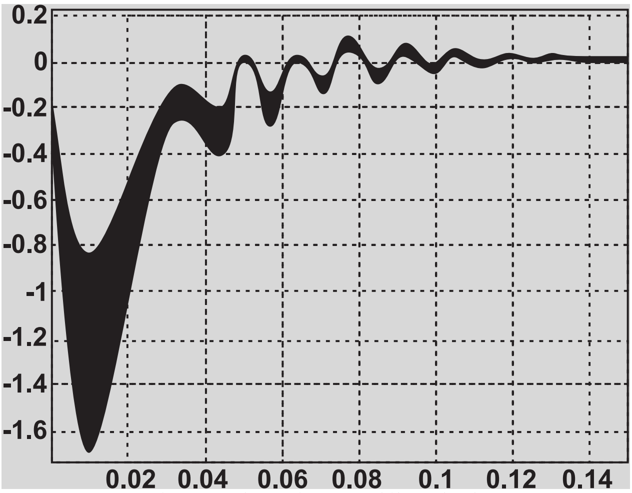



Figure 7. Change in error while no load.

However, the system goes in error state in the interval from -1.6 to 0.1 and then the system stabilized in the range -1 to 1. The optimization in the error control is performed after some mathematical calculations by adjusting a gain values to each of the intervals and simulating the condition again.

The optimization performed by adjusting the gain values results in the form of a table where the error and cumulative error are compared for the response and a negativity and positivity of the error determines the control of the speed of the motor and associated control element. Figure 8 shows the fuzzy implementation signal analysis.

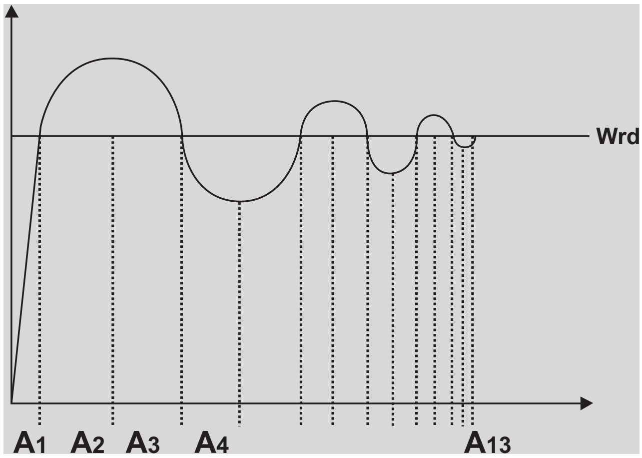



Figure 8. Fuzzy implementation signal analysis.

The above response can be analyzed from the help of table shown in Table 2 where the value of '$e$' and '$c_e$' decides that response time for the motor. For example, if the error value is very large and change of error is a negative value but larger than the output the alpha will be change largely. Similarly, the condition in $A_2$ depicts the exact situation where the motor is trying to increase the speed despite the fact that current value is much larger than the referenced value which is a worst condition in terms of motor control.

TABLE 2 SIGNAL FORMULATION FOR INTERVALS

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | $A_8$ | $A_9$ | $A_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| e | + | - | - | + | + | - | - | + | + | - |
| $c_e$ | - | - | + | + | - | - | + | + | - | - |

DOI 10.5013/ IJSSST.a.17.26.36

ISSN: 1473-804x online, 1473-8031 print

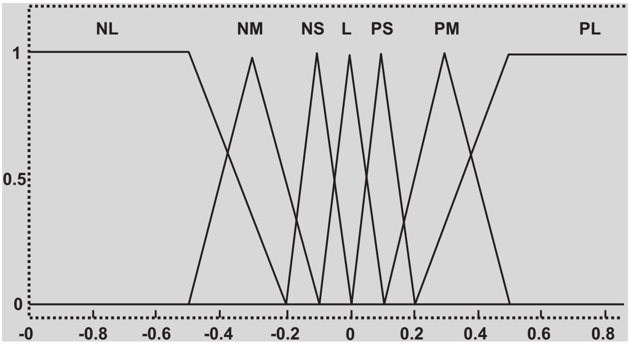



Figure 9. Change of error in speed control

The state discussed above also yields as a reducing agent for the motor where the alpha is lesser in value compared to the reference and thus can be increased by giving an appropriate value at the output. This condition depicts that the motor voltages are decreasing [8]. These changes can be seen in Figure 9 where the change of error together with its impact to the speed as well as the change corresponding in alpha. The inputs are currently in Boolean form or more appropriately in a crusty form and they must be converted to fuzzy set theory. The inputs are converted using the fuzzy functions which are defined in the range of -1 to 1 for this paper. Therefore, now the processing is done on simple numbers. The fuzzy calculation is also processed in a shorter time. The fuzzy computational terms are shown in this paper in the form linguistics [9]. The Table 3 shows the database rule table for the fuzzy calculations showing the PL and several fuzzy methods.

TABLE 3 THE FUZZY METHOD DATABASE

| $c_e$ / e | NL | NM | NS | Z | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | PL | PL | PL | PL | NM | Z | Z |
| NM | PL | PL | PL | PM | PS | Z | Z |
| NS | PL | PM | PS | PS | PS | Z | Z |
| Z | PL | PM | PS | Z | NS | NM | NL |
| PS | Z | Z | NM | NS | NS | NM | NL |
| PM | Z | Z | NS | NM | NL | NL | NL |
| PL | Z | Z | NM | NL | NL | NL | NL |

The motor model uses the DC choppers as the driver behind the speed control however the input is in the form of current but the control is mostly executed by the cutting of the signal and fiberizes them before reaching the field winding of the generator section [10].

The simulation is performed by using the positive chopper where the signal is always takes a positive value, if the load inductance is very small regarding to the functionality of the motor. The chopper circuit controls the output voltage pulse by implementing the pulse width modulation. The fundamental principle of operation is the analysis of the two incoming signals and then applying the fuzzy methods to reduce the change of error and in turn reducing the error in speed of the motor [11]. Alpha time interval is used in simulation as $U_1$ and nested under a conditional block to analyze the triangular input waveform [12-14]. The procedure is shown in Figure 10

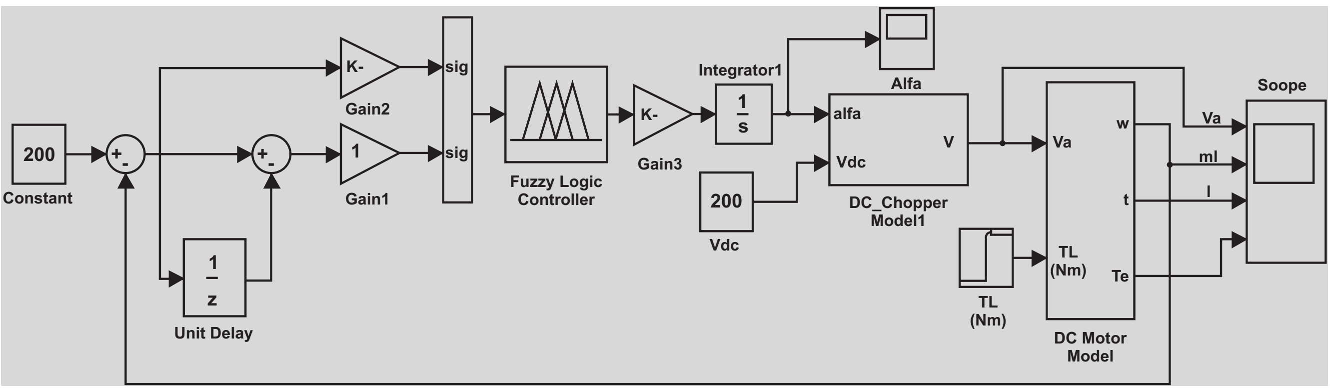
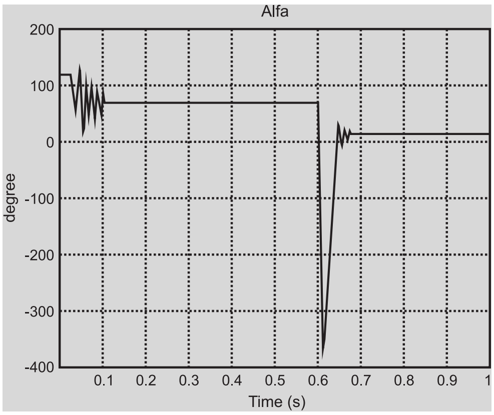
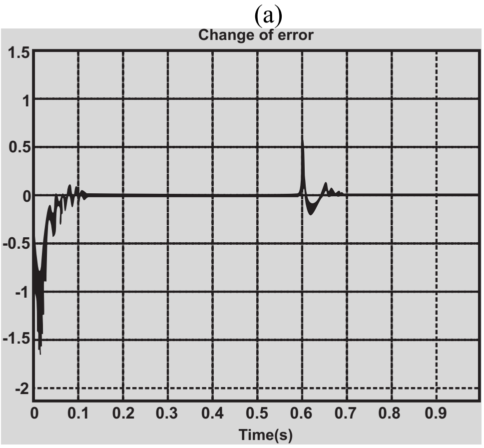



Figure 10. Fuzzy model for the motor.

The change of error shows a dislocation at the start while at the end, the property of the algorithm using the fuzzy logic and fuzzy set methods, are showing in the nominal state of the motor speed control where the function does not over burn the differences in the control set point and speed current value.




(a)




(b)

Figure 11. Simulink results.

The Simulink model of the fuzzy logic speed control is shown in the Figure 11.(a) and also the response graphs are also shown in Figure 11.(b). The gains in the simulation are segregated into three types including error, change of error and alpha. The motor while running in a loaded condition is applied to a load of 50 Nm.
The fuzzy controller is designed to be simulated for various load conditions starting from no load to 50 Nm. various values for gains are also used and different K coefficients are included. The results are summarized in Table 4 showing the comparison between the conventional speed control and speed control with fuzzy set theory. The controlling using the fuzzy logic performing better than the conventional methods of control reducing the error and change in the speed control error.

TABLE 4 COMPARISON OF FLC WITH PI ON DIFFERENT LOADS

| | Load | 10N | 50N |
|---|---|---|---|
| PI | $C_{1(e)}$ | -0.354 | -0.198 |
| | $C_{2(e)}$ | -.285 | -0.15 |
| FLC | e | 0.0057 | -0.0042 |

The optimization from the fuzzy logic can be clearly a plus for the speed controlling while another aspect is also applied in the reducing the error between the reference and current values and the technique used in Bayesian network which is discussed in the section below.

## V. COMPARISON ANALYSIS

It can be seen from figure below that the algorithm developed produced aspiring results on the brushless DC motors. The comparisons with other optimization method have been shown Figure 12.

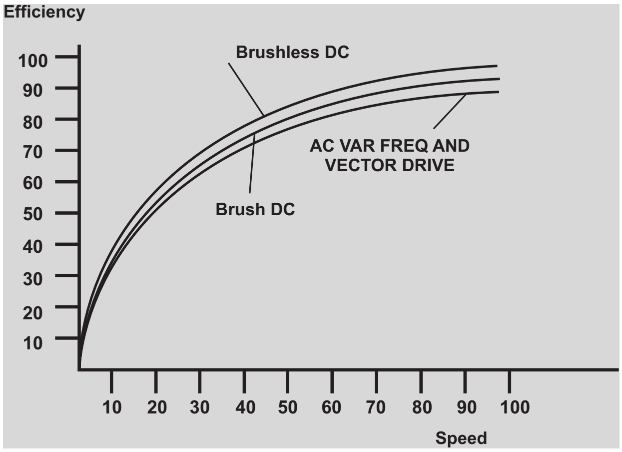



Figure 12. Efficiency vs. speed graph.

Further, the error reduction due to inclusion of Bayesian network and fuzzy logic optimization algorithm have reduced it to under 3 seconds as shown by the following Figure 13

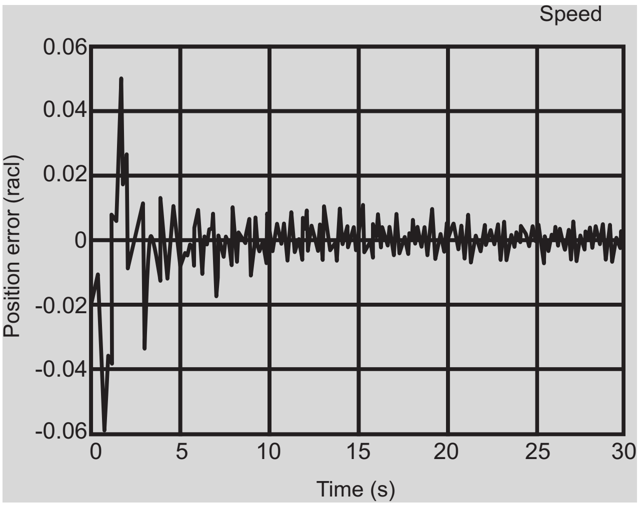



Figure 13. Applied algorithm.

The results before applying the algorithm yields the following Figure 14 and Figure 15.

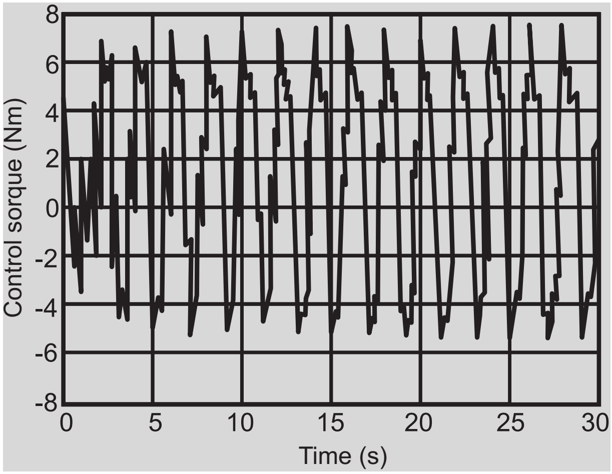



Fig. 14. Before optimization.

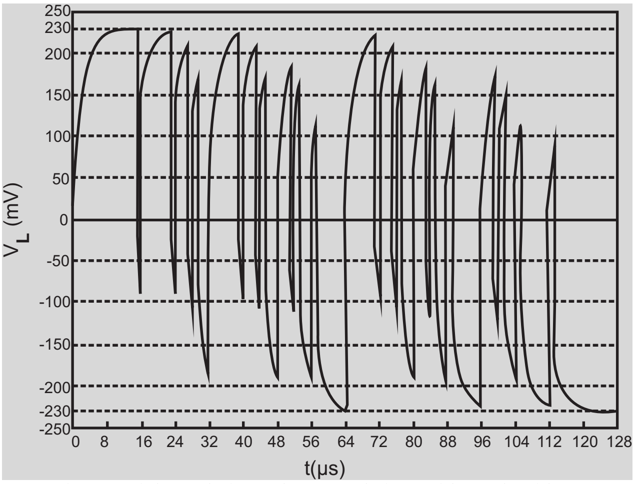



Fig. 15: High-resolution voltage regulations without algorithm.

It can be seen that the variations in speed is most reduced by applying the algorithm and converging the implementation of fuzziness.

## VI. CONCLUSION REMARKS

The experiments have been performed using the Simulink tool in Matlab for the speed control optimization using the fuzzy logic control. Implementation of the motor model can be seen by evaluating and converting the motor torque equation and speed equation to a matrix form and then transform it into a state variable form which shows the transfer function.

Simulation for the fuzzy logic control used to remove the errors in the motor speed reference and actual are providing better results than conventional PI controller. However, the calculations have been performed on both load and no load conditions. Simulations have shown that fuzzy logic controller have performed way better than the PI both in error reduction and steady state error. It is also noted that the fuzzy logic controller has responding in more robust and can deal in sensitive fluctuations in the input. It is also noted that the fuzzy logic controller deals with the disturbances in the load in a better way and initiate a quick response against the fluctuation in the loading conditions on the motor. However, regarding to the PI control, it can be improved by addition in the values of gain but they can become a real problem in scenario compared to the fuzzy logic controllers in the real world. Further, even after increasing the gains, the PI controlling is far more inaccurate than fuzzy logic control in terms of error, change or error and speed error. The experiments and chosen method for network creation shows that the algorithm overrides the simple GA method on most of the complex problems even using large size of the networks. It can be concluded that the proposed algorithm is significantly efficient on loose building nodes in comparison to the GA method. The proposed algorithm operates independently of the order of the variables and instances made. It is also noted that the algorithm works well under highly overlapping nodes and large networks without affecting the performance.

## ACKNOWLEDGEMENT

This work was supported by Science and Research Project of Wenzhou Vocational & Technical College under No.( WZY2015010) and Science and Research Project of Wenzhou City under No.(G20160038).

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