# DOUBLE FUZZY-PI CONTROLLER BASED SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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ABSTRACT

*In high performance industrial application, Permanent Magnet Synchronous Motor (PMSM) becomes the main competitor for AC motor. PMSM has some advantages such as high efficiency, small size, high power density, large torque to inertia ratio, and low maintenance. PMSM is also very popular compared to DC motors in applications of machine tools, servo and robots, electric vehicle, and ship propulsions. Speed control of PMSM widely uses the conventional proportional integral (PI) controller, but PI controller has difficulty in speed changes, parameter variations and load disturbances. This paper presents double fuzzy logic controllers to tune the parameters of PI controller applied in the speed control of PMSM. Double fuzzy-PI (DFPI) controller is verified using simulation process for normal and disturbance conditions. DFPI controller has better performance compared to the conventional PI controller during change of operating condition. Simulation results of DFPI controller show that PMSM quickly achieve the speed reference, has small steady state error, no overshoot and reduce the speed oscillation during load disturbance condition.*

**Keywords**: *Permanent Magnet Synchronous Motor, Speed Control, PI, Double Fuzzy Logic*

## 1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) are becoming the main competitor to other types of AC motors in high performance motor drives applications. PMSM have some advantages such as high efficiency, small size, high power density, large torque to inertia ratio, and low maintenance. PMSM are also very popular compared to DC motors in applications of machine tools, servo and robots, electric vehicle, and ship propulsions [1,2]. Some criteria of high performance motor drives applications are insensitivity to parameter variation, fast speed responses, and quick speed achievement to a speed reference during load disturbance occurs. The conversional proportional integral (PI) controller has been widely employed as speed controller for PMSM drives. In order to obtain the best results of speed control, the axial reactance parameters of the d-q PMSM should be correctly known. However, the conversional PI controller has difficulty in speed changes, parameter variations and load disturbances [1-6].

To solve these disadvantages of PI controller, various artificial intelligent (AI) techniques have been applied in motor drives systems to control the speed of motor. Fuzzy logic controller (FLC) can be considered to improve the performance of conventional PI controller. FLC can provide nonlinear control action by selecting the appropriate parameters. In this way, the success key of designing an FLC is to define well its parameters such as knowledge base, rule base and scale factor (3-9). Nowadays, a method of control at the base of double fuzzy controller and a proportional integral (PI) controller has been developed [10, 11].

This paper presents the usage of AI methods especially double fuzzy logic (FL) to tune the parameters of PI controller applied in the speed control of PMSM. The effectiveness of the proposed systems is verified by simulation process using SIMULINK-MATLAB. Therefore, performance of Double Fuzzy-PI controller is compared with the conventional PI controller during change of operating condition based on the performance of induction motor.

## 2. SPEED CONTROL OF PMSM

Block diagram of PMSM drives system used in this paper is shown in Figure 1. PMSM is connected to pulse width modulation (PWM) inverter using current control. PMSM currents are decomposed into $i_d$ and $i_q$ components. These components represent flux and torque components in d-q coordinate system.

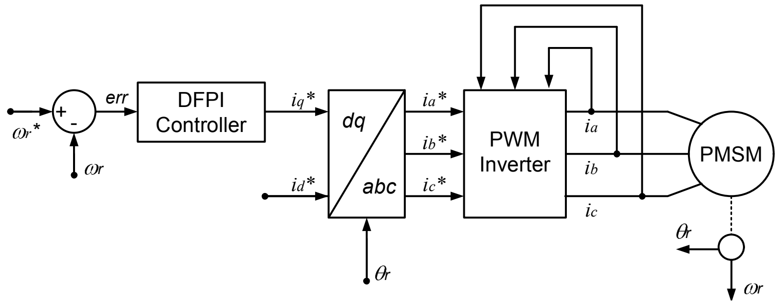


*Figure 1. Block Diagram of PMSM Speed Control with DFPI Controller.*

## 3. MATHEMATIC MODEL OF PMSM

The d-q model of the wound rotor synchronous machines is simply adapted to learn the dynamic performance of PMSM [1,2,4]. Back e.m.f. produced by permanent magnet is equal to produced by excited coil. Therefore, the d-q model of PMSM in the rotor reference frame can be seen in Equation (1).

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_d \\ \phi_q \end{bmatrix} + \omega_r \begin{bmatrix} -\phi_q \\ \phi_d \end{bmatrix} \qquad (1)$$

where $u_d$, $u_q$, $i_d$, $i_q$ , $\omega_r$, $R_s$, $\phi_d$ and $\phi_q$ are stator voltage and current in d-q frame, rotor speed, stator resistance, flux linkage in d-q frame, respectively.

Dynamic behaviour and electromagnetic torque of PMSM can be expressed in Equation (2) and Equation (3).

$$\frac{J}{p}\frac{d\omega_r}{dt} + \frac{f}{p}\omega_r = T_{em} - T_L \qquad (2)$$

$$T_{em} = \frac{3}{2} p\left\{\phi_f i_q + (L_d - L_q) i_d i_q\right\} \qquad (3)$$

where $J$, $p$, $f$, $L_d$, $L_q$, $T_{em}$, and $T_L$ are rotor inertia, pole number, reactance linkage d-q frame, electromagnetic torque and load torque, respectively.

## 4. DESIGN OF DOUBLE FUZZY PI (DFPI) CONTROLLER

Fuzzy logic controller (FLC) is one of most popular artificial intelligence (AI). FLC is used to solve nonlinear control problem or whenever the system model is unknown or difficult to build. The FLC is built from three steps: fuzzification, control rules evaluation and defuzzification. The fuzzy rules are obtained through knowledge of the process systems which automatically extracted from sample process [3-11]. Figure 2 show the control algorithm of PMSM speed based on a double fuzzy PI controller. The speed of PMSM is compared with the reference to obtain the error speed shown by Equation (4).

$$e(t) = \omega_m^*(t) - \omega_m(t) \qquad (4)$$

where $e(t)$, $\omega_m^*(t)$ and $\omega_m(t)$ are error speed, reference speed, and motor speed respectively.
The change of error speed is given by Equation (5).

$$de(t) = e(t) - e(t-1) \qquad (5)$$

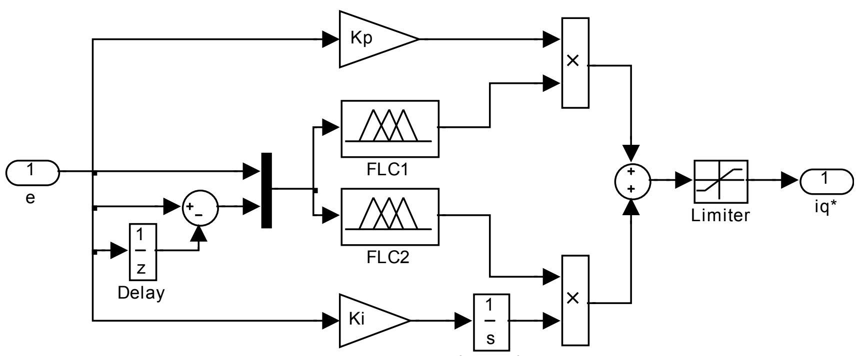


***Figure 2**. The DFPI Controller for speed control of PMSM*

In this paper, FLC has five membership functions (MF) for two inputs and an output. Two inputs and an output are error (*e*), change of error (*de*) and promotional parameter ($K_p$) or integral parameter ($K_i$) respectively. The membership functions are built to represent its input and output value. The fuzzy sets of two input signals are as follows: ZE = Zero, PB = Positive Big, PS = Positive Small, NB = Negative Big and NS = Negative Small respectively. Whereas, the fuzzy sets of an output signals are as follows: S = Small, MS = Medium Small, M = Medium, MB = Medium Big and B = Big, respectively. Figure 3 and Figure 4 show the fuzzy sets and corresponding triangular MF description of two input signals and an output signals. The rule base of the FLC is shown in Table 1. Table 1 show that there may be 5 x 5 = 25 possible rules.

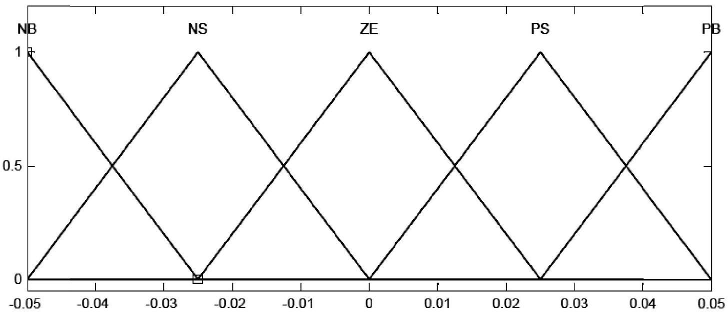


***Figure 3.** Membership Functions for inputs of FLC*

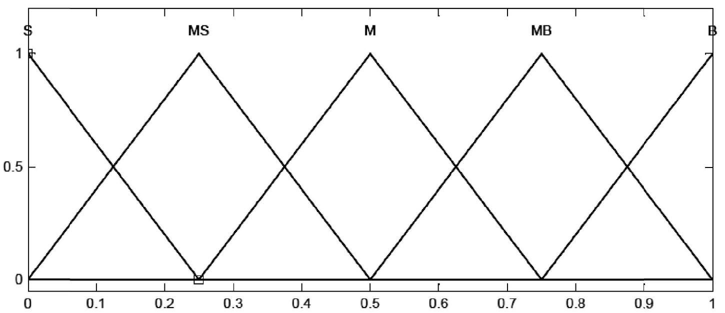


**Figure 4.** Membership Functions for output of FLC

***Table 1.** Rule Base of FLC*

| error (*e*) | change of error (*de*) | | | | |
|---|---|---|---|---|---|
| | NB | NS | ZE | PS | PB |
| NB | S | S | S | MS | M |
| NS | S | S | MS | M | MB |
| ZE | S | MS | M | MB | B |
| PS | MS | M | MB | B | B |
| PB | M | MB | B | B | B |

## 5. RESULTS

The effectiveness of the proposed Double Fuzzy-PI (DFPI) controller is clarified by simulation process. Simulation process is conducted in conditions of normal and disturbance. The parameters of permanent magnet synchronous motor (PMSM) used in this simulation is as follows: motor power of 1 HP, nominal voltage of 220 V, stator resistance of 2.875 Ω, direct inductance of 0.0085 H, quadrature inductance of 0.0085 H, 4 poles, inertia moment of 0.0008 kg.m$^2$, friction coefficient of 8x10$^{-5}$ N.m.s, motor flux of 0.175 Weber. Figure 5 shows simulation model in SIMULINK-MATLAB.

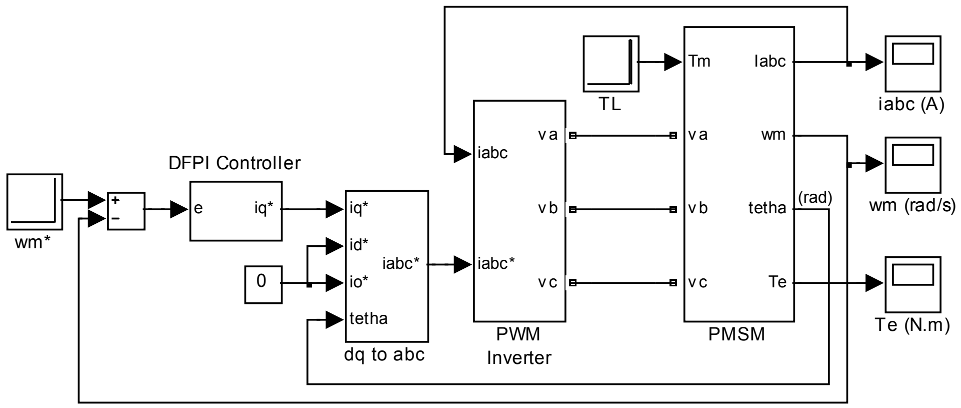


***Figure 5**. Simulation PMSM model using SIMULINK-MATLAB*

Figure 6 shows speed response of PI controller and DFPI controller for speed reference of 700 rad/s. DFPI controller yields settling time of 0.008 s, no overshoot and small steady state error of 0.5 rad/s. Whereas, PI controller yields settling time of 0.013 s, overshoot of 4.1 % and also small steady state error of 1.1 rad/s. From their simulation results show that DFPI controller provide the improvement of performance compared to PI controller.

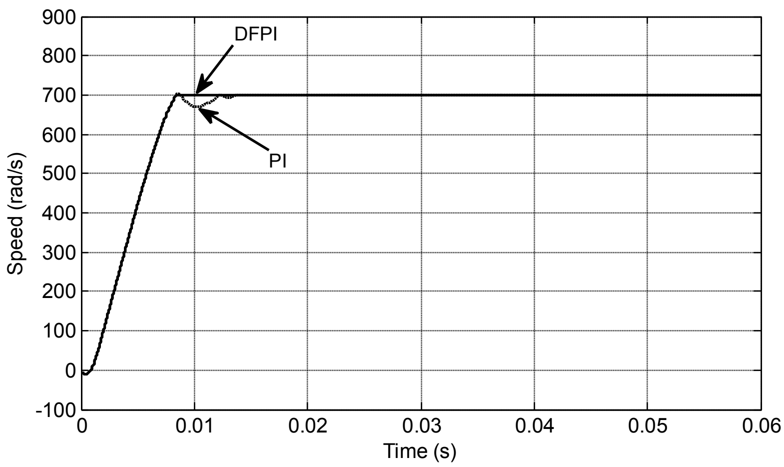


***Figure 6.** Speed response for speed reference of 700 rad/s.*

Figure 7 shows comparison of the electromagnetic torque response between PI controller and DFPI controller. PI controller needs the greater electromagnetic torque than DFPI controller. These electromagnetic torques are used both controller to rapidly reach the speed reference, however PI controller causes speed oscillation.

Current of PMSM for PI and DFPI controllers are shown in Figure 8 and Figure 9. Both figures show that the change of electromagnetic torque causes the change of PMSM current.

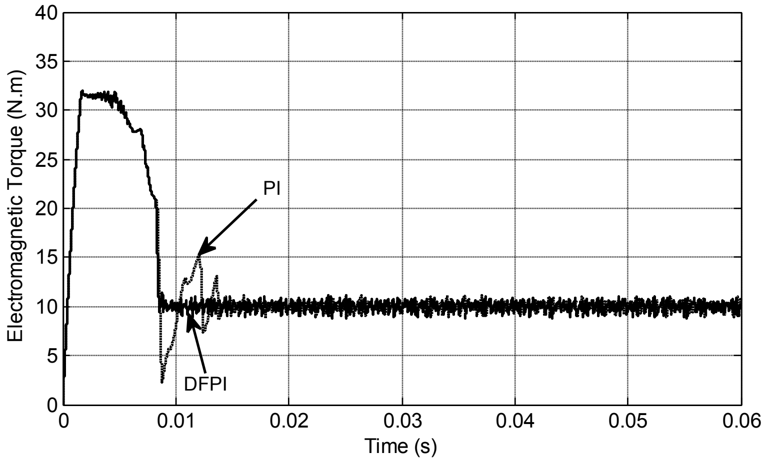


***Figure 7.*** *Electromagnetic torque responses for PI and DFPI controllers.*

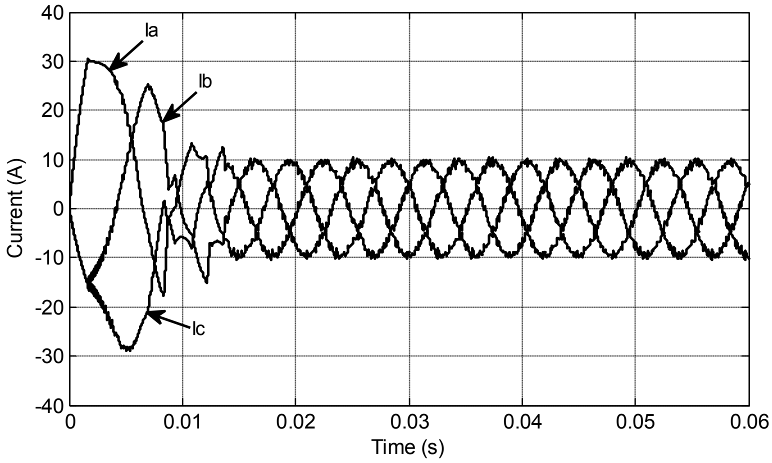


***Figure 8.*** *Current of PMSM with PI Controller*

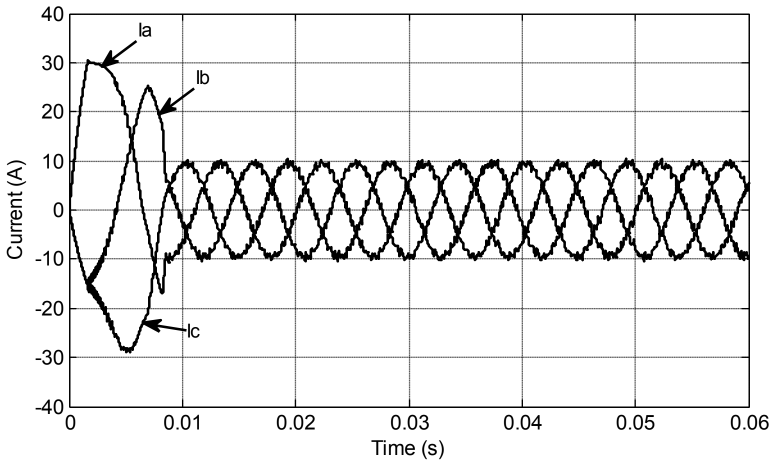


***Figure 9.*** *Current of PMSM with DFPI Controller*

For disturbance conditions, the load torque of PMSM suddenly changes from 10 N.m to 15 N.m at t = 0.04 s and also returns again to 10 N.m at t = 0.041 s. The change of load torque affects the electromagnetic torque of PMSM shown in Figure 10. PI controller requests the greater electromagnetic torque than DFPI Controller. Disturbance also causes change of PMSM speed shown in Figure 11. Simulation result shows that speed error for PI controller is better than DFPI controller but PI Controller still produce speed fluctuation.

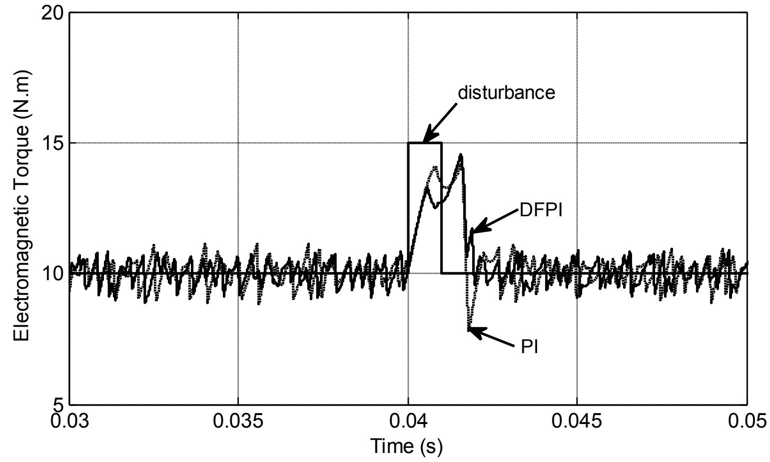


***Figure 10.*** *Electromagnetic torque of PMSM for disturbance condition*

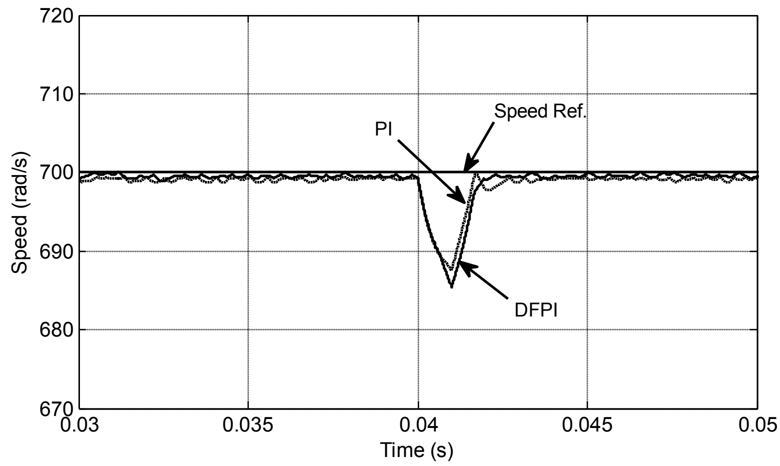


***Figure 11.*** *Speed responses for disturbance condition*

Figure 8 and Figure show PMSM current of PI and DFPI controllers during disturbance condition. Both figures show that the disturbance causes the change of PMSM current. Simulation results show that PMSM current for DFPI controller is better than PI controller.

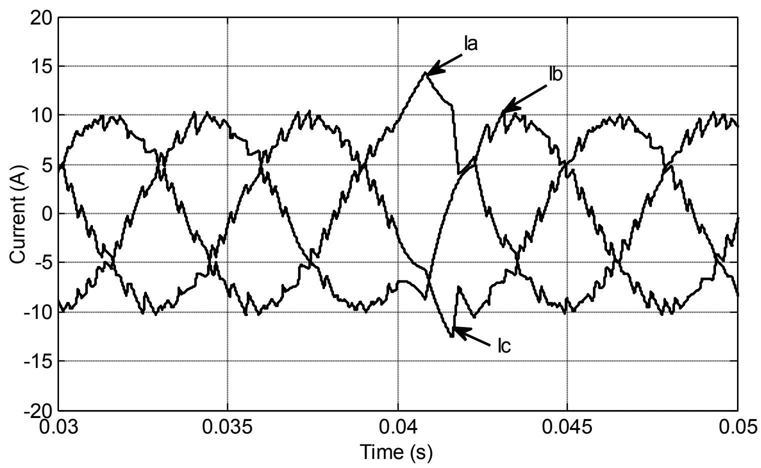


***Figure 12.*** *Current of PMSM for PI Controller*

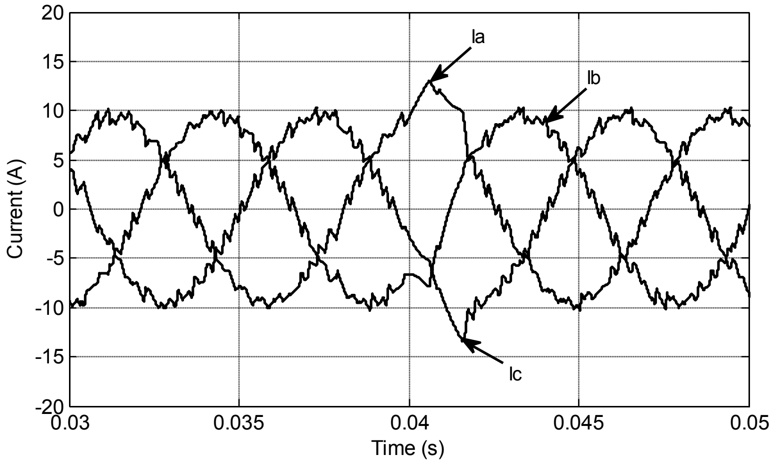


***Figure 13.*** *Current of PMSM for DFPI Controller*

## 6. CONCLUSION

Double fuzzy proportional integral (DFPI) controller applied in speed control of PMSM has been presented and discussed. Double fuzzy logic technique is used to adjust the parameters of PI controller (*Kp* and *Ki*). Double fuzzy logic can improve the performance of PI controller when there are changes of PMSM parameters. DFPI controller proposed is verified by simulation process. Simulation results show that DFPI controller produces better performance compared to PI controller. DFPI controller rapidly achieves the speed reference, has small steady state error, no overshoot and decreases speed oscillation during load disturbance condition. The settling times of PI and DFPI controllers are 0.008 s and 0.013 s respectively. Whereas, steady state errors of PI and DFPI controllers are 0.5 rad/s and 1.1 rad/s respectively.

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# SIMSOYA3D: A DATA-DRIVEN'S SIMULATOR OF SOYBEAN'S GROWTH MODELING USING TRAINABLE PARAMETRIC L-SYSTEM AND ANFIS ALGORITHM

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ABSTRACT

*The purpose of this study was to design and build a system that is able to predict plant's growth patterns as a function of the nutrients obtained from fertilization pattern. The simulator is represented in 3-dimentional to perform animated models. As the object of research is Soybean (Glycine max (L.) Merrill).*

*The output parameters are long growth trunk / branches (L), a wide cross section of the leaf (W), and branch growth (B), as a function of changes in the fertilizing elements Nitrogen (N), Phosphate (P) and potassium (K), as input parameters of the system. Modeling done on the vegetative phase of the soybean crop.*

*The training phase of ANFIS are to obtain the values of Parametric L-system's constantas as a change of N-P-K you L-W-B values. In the implementation phase, using obtained constantas, the user's inputed datas could processed bythe Trained Parametric L-system to perform simulation of growth's function, and finally to perform 3-dimentional's animated models.*

*The test results on the system to grow plants pattern proves that ANFIS method is quite adaptive to variation of N-P-K values changes, and able to predict the output values of L-W-B. The visualization of 3D-animated models as the results of Trainable Parametric L-system has proven to be influenced by variations in the composition of input parameters(N-P-K values). Overall, the system has been running as expected. column as it is here, below the author information.*

**Keywords**: *Parametric L-system, ANFIS, Plant growth simulation, Data driven modeling, 3D Plant growth animation*

## 1. INTRODUCTION

The purpose of this study was to design and build a system that is able to predict plant's growth patterns as a function of the nutrients obtained from fertilization pattern. The simulator is represented in 3-dimentional to perform animated models. As the object of research is Soybean (Glycine max (L.) Merrill). The modeling of plant growth patterns is combination of multidisciplinary scientific include: botany, agronomy, plant physiology, meteorology, soil science, and mathematics and computer science and has been used widely in agriculture, including to support the decision-making system [8]. Plant growth is categorized in two phases, namely vegetative phase (which includes the growth of roots, stems / branches, and leaves), and generative phase (characterized by the growth of flowers and fruit) [1]. The research of the characteristics of plant growth models are dynamic and very complex, so it is very difficult to approach using mathematical equations and conventional geometric [12]. The modeling of plant growth includes the natural process of biological systems of plant life, following the influence of environmental characteristics. For that purpose, artificial intelligence system approach, such as neuro-fuzzy method, is used. According to [4], neuro-fuzzy system is the mechanism of fuzzy inference system mapped into the architecture of artificial neural network. In the field of graphical computing, mathematical formulation of the plant growth structure that is widely applied is Lindenmayer system (L-system). The result of L-system is a string in L-system's grammar.

To display in 3-D graphically, the L-system result needs to be translated into the formation of 3-D coordinates using Turtle Geometry [9] [10]. With displayed in 3-D, the representation of the plant growth model as the function of environmental factors is expected to be more easily understood [3].

## 2. RESEARCH METHODS

The research began by identifying the parameters that influence plant growth, both internal and external, as the input and output of the system [8]. It can be concluded that the parameters such as nutrients, water, oxygen, and sunlight generally affect the growth of the trunk and branches and increment of leaves number [3].

### 2.1 System Architecture and User Interfaces

The final result of system's user interface is shown in Fig. 1. The architecture of plant growth simulation system that was built in this research is shown in Fig. 2, which describes the usage steps of plant growth simulation system. The flowchart of the system is shown in Fig. 3.

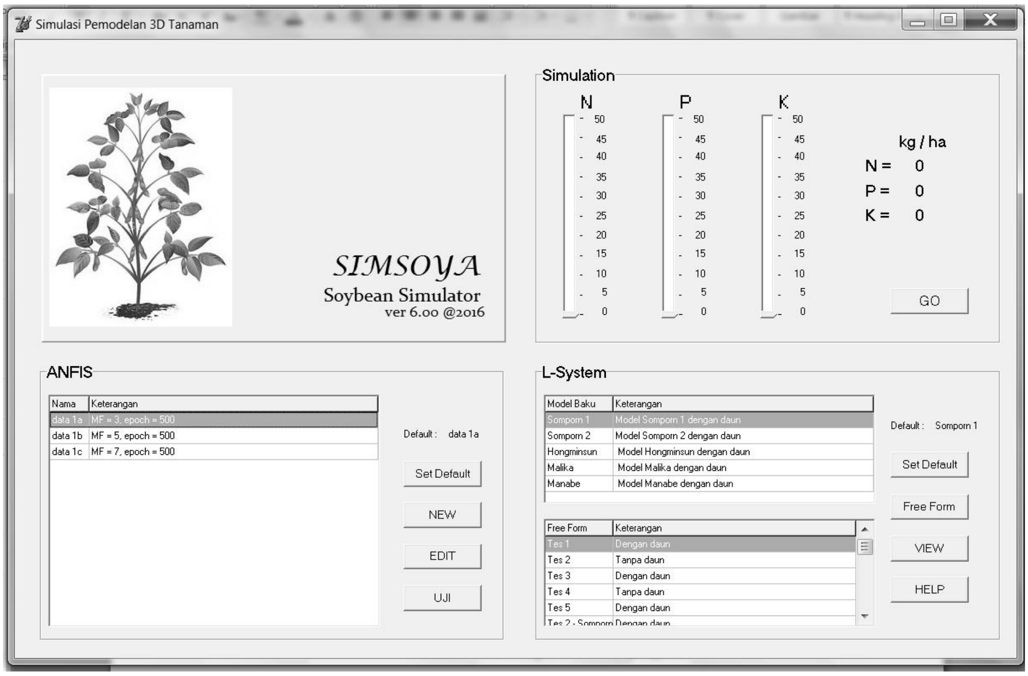


*Figure 1. The user interfaces of plant growth simulation system*

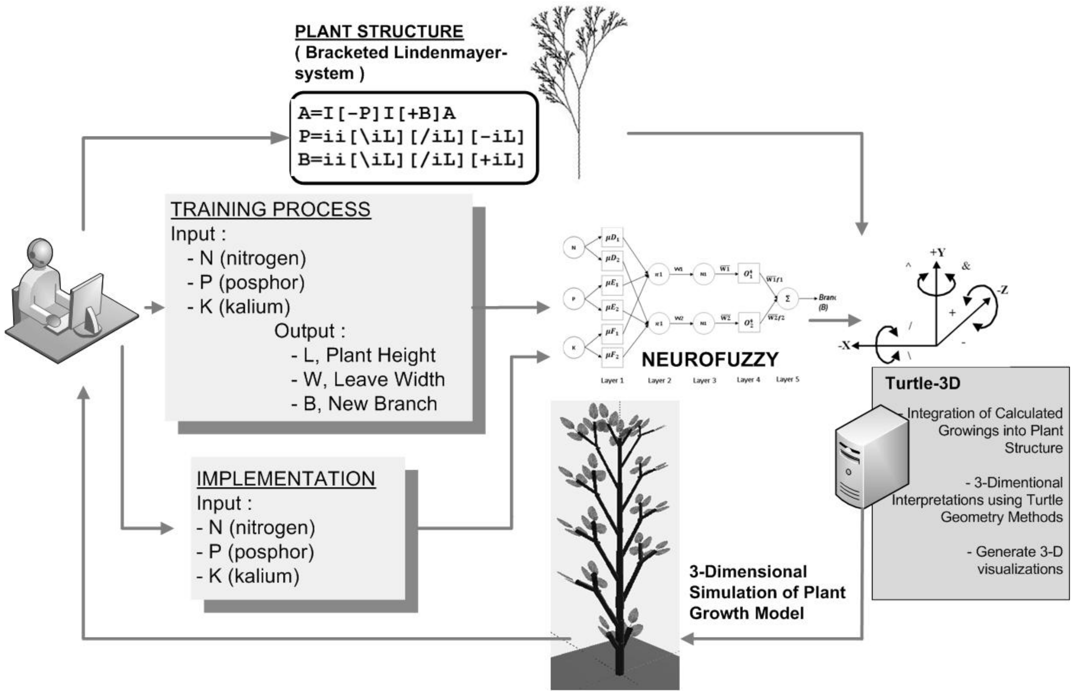


*Figure 2. The architecture of plant growth simulation system*

**2.2 Parametric L-system**

**2.2.1 Parametric L-system with Turtle Geometry Representation**

The L-system design in this research is based on the Parametric L-system method that represented visually in 3-D using Turtle Geometry. As explained in [1] and [9], to display the 3-D visualization of L-system string, the Turtle Geometry method has two steps, which are:

1) Interpret the Parametric L-system string by adding direction symbols which corresponds to Turtle Geometry method.
2) Using the matrix formula of Turtle Geometry to calculate the 3-D coordinates of the points in displaying the plant visually, such as the direction and position of the trunk, branch, twigs, and leaves.

In the first step, several direction symbols, such as shown in Table 1 and Figure 3, is added on the L-system string. Then in the second step, the main concept is to represent the orientation of the current position in a space with three vectors which shown the direction on X, Y, and Z axis. Those three vectors are orthogonal unit vectors. The rotation of the turtle, which represents the plant growth, is expressed by (1) – (3). Using (1) – (3), the coordinates of the next positon of each iteration in interpretation result of Parametric L-system string of plant structure can be calculated [3].

*Table 1. Rules of Turtle Geometry*

$$R_X(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & Cos(\theta) & -Sin(\theta) \\ 0 & Sin(\theta) & Cos(\theta) \end{bmatrix} \qquad (1)$$

$$R_Y(\theta) = \begin{bmatrix} Cos(\theta) & 0 & -Sin(\theta) \\ 0 & 1 & 0 \\ Sin(\theta) & 0 & Cos(\theta) \end{bmatrix} \qquad (2)$$

$$R_z(\theta) = \begin{bmatrix} Cos(\theta) & Sin(\theta) & 0 \\ -Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

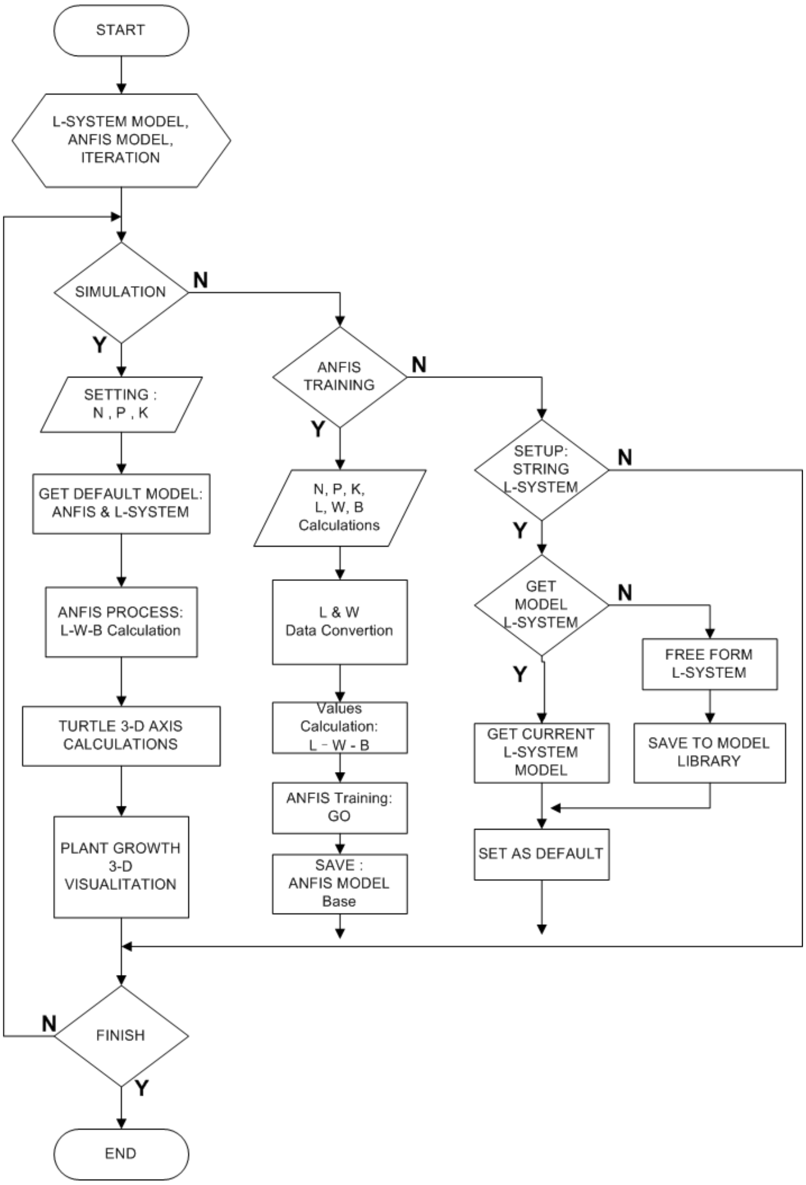


*Figure 3. The flowchart of plant growth simulation system*

### 2.2.2 Standard Model of Parametric L-system for Soybean Plant

Based on [1], the Parametric L-system rules with Turtle Geometry representation when applied to the plant modeling simulation has a frame of reference as follows:

*{*
*Axiom*
*Production Rules*
*End Rule*
*}*

where Axiom is the determinant of growth starting point at each iteration starts, Production Rules are strings production which will produce the effect of plant growth simulation, and End Rule is the string to end the re-writing process. As the standard model in this research, some models of Production Rules that has been produced by earlier researchers are used, as shown in Figure 5 where :

A = apex, the tip of the plant in an iteration,
P = re-writing rule for internode (I) that leads to the left, and
B = re-writing rule for internode (I) that leads to the right.

| Symbol | Meaning |
|---|---|
| I | Add internode (trunk segments) |
| i | Add short-internode (branch segments) |
| L | Add leaf |
| [ | Change position to create new branch |
| ] | Back to the position before creating new branch |
| + | Turn left according to X axis with angle $\alpha$ using rotation matrix $R_H(\alpha_X)$ |
| - | Turn right according to X axis with angle $\alpha$ using rotation matrix $R_H(-\alpha_X)$ |
| & | Pitch down according to Z axis with angle $\alpha$ using rotation matrix $R_U(\alpha_Z)$ |
| ^ | Pitch up according to Z axis with angle $\alpha$ using rotation matrix $R_U(-\alpha_Z)$ |
| \ | Roll left according to Y axis with angle $\alpha$ using rotation matrix $R_L(\alpha_Z)$ |
| / | Roll right according to Y axis with angle $\alpha$ using rotation matrix $R_L(-\alpha_Z)$ |

*Figure 4. THE LIST OF PARAMETRIC L-SYSTEM WITH TURTLE GEOMETRY REPRESENTATION*

| No. | Reference Model | Standard Model of L-system for Soybean Plant |
|---|---|---|
| 1. | Model [8] | *somporn1*<br>*{*<br>*Axiom=I[+iL][-iL]A*<br>*A = I[-P]I[+B]A*<br>*P = IIII[\pL][/pL][-pL]*<br>*B = IIII[\pL][/pL][+pL]*<br>*Endrule*<br>*B = IL*<br>*P = IL*<br>*A = IL*<br>*}* |
| 2. | Model [9] | *Hongminsun*<br>*{*<br>*Axiom=I[+iL][-iL]A*<br>*A = I[+P]A*<br>*Endrule*<br>*P = P[\iL][/iL][-iL]*<br>*}* |
| 3. | Model [3] | *Malika*<br>*{*<br>*Axiom=I[+iL][-iL]A*<br>*A = I[-P]I[+B]A*<br>*P = I[\pL][/pL][-pL]*<br>*B = I[\pL][/pL][+pL]*<br>*Endrule*<br>*B = IL*<br>*P = IL*<br>*A = IL*<br>*}* |
| 4. | Model [10] | *Manabe*<br>*{*<br>*Axiom=F*<br>*F = FF-[[-F][+F][+F]]+[[+F][-F][-F]]*<br>*Endrule*<br>*F = I*<br>*}* |

*Figure 5. Standard model of Parametric L-system for Soybean plant*

**2.2.3 Free-form Model of Parametric L-system for Soybean Plant**

In this free-form mode, Parametric L-system models have a common frame of reference with the standard model. The difference is based on the free-grammar context which is the characteristics of the Parametric L-system that provides the flexibility of defining strings Production Rules, then the Production Rules string may use any letter symbols freely. Which means, the user can define the L-system strings specifically to their own needs. The free-form options are provided to assist the research process and further development of this research.

**2.3 Neuro-Fuzzy (ANFIS) Model**

**2.3.1 Plant Growth Prediction Using ANFIS**

The system is designed to be capable of providing predictions of the growth rate of soybean plants as a function of the N-P-K nutrients composition applied in plants. Function was created as predictor by utilizing the advantages of neuro-fuzzy method (ANFIS). Some advantages of method neuro-fuzzy method (ANFIS) are as follows:

- Able to generate and associate,
- Able to tolerate uncertainty,
- Able to resolve the issue of non-linearity, and
- Can be operated in real-time

Those advantages are utilized in this system to build a pattern model of correlation between the changes of input value N-P-K with the changes of output value L-W-B. Through the simulator system designed in this research, by varying the composition of the input value N-P-K, the changes in the growth amount of soybean plants produced by the simulator can be predicted.

**2.3.2 ANFIS Architecture**

To perform the modeling of soybean growth patterns, it takes ANFIS structure that can accommodate the needs of the growth parameters which are:

- 3 inputs (for fertilizer N, P, K), and
- 3 output (for L, W, and B)

Fundamentally, the ANFIS structure is only possible for one output. Then to accommodate the system which has 3 outputs, three identically structured ANFIS are used, each for output L (growth of trunk / branches / twigs), output W (growth of leaves width), and output B (growth of the branching) as shown in Fig. 6. The number of nodes in the first layer (membership function) can be varied, but to simplify the system, in this research we used the same number of nodes in the first layer.

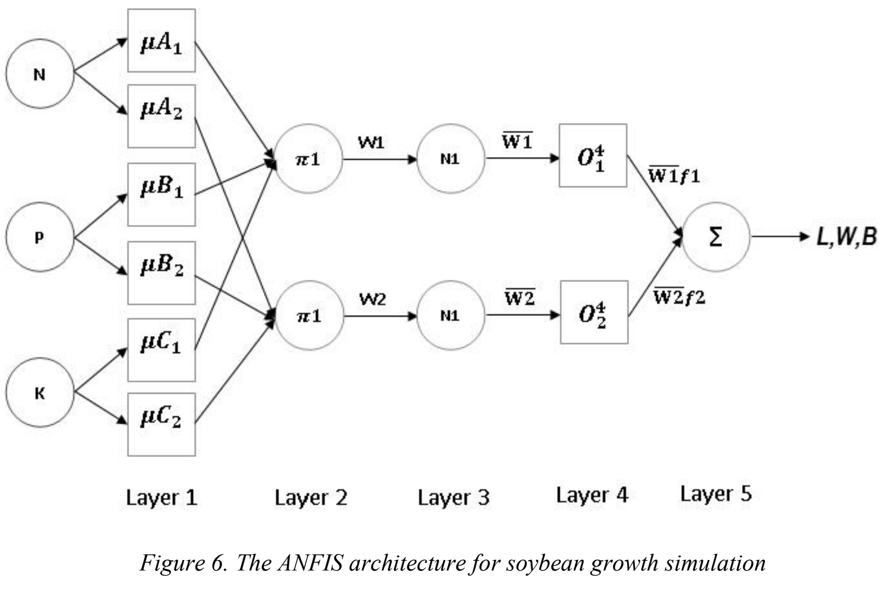


*Figure 6. The ANFIS architecture for soybean growth simulation*

#### 2.3.3 ANFIS Algorithm

To obtain the model of soybean growth patterns, the data that has been inputted into ANFIS structure will be processed using the training process of ANFIS. In ANFIS training process, determination of the parameters to stop the training process is required. The parameters are:

- Error system < 0.01
- Epoch variable, with default value is 500.

The training process will stop if the epoch has reached the stopping value, although the error value of the system has not reached the stopping value yet. If that happens, then the re-training process is needed with increasing the epoch value until the error value reached the stopping value that has been determined (less than 0.01).

### 2.4 The Merging of Parametric L-System Model with Neuro-Fuzzy Model

Once the L-system string of the plant structure had been obtained, we calculate the coordinates of trunk, branches, twigs, and leaves position. This require the calculation of the final coordinates (x2, y2, z2) of an object based on:

- The coordinates of start position (x1, y1, z1),
- The length or distance to the end position (l), and
- The directions (α degrees) towards the end position.

In 3-D L-system modeling using GL Scene, coordinates of trunk and branch segments are calculated at their segment's midpoint. To determine the L-system coordinates of the trunk and branch, calculation using Turtle Geometry is used.

## 3. RESULTS AND DISCUSSION

Data used in the experiment is secondary data, which means that the data has been obtained by the previous researches of soybean plant, among others was obtained from [1], [3], and [5]. The experimental results of the ANFIS system are shown in Table 2. The experimental results shows that the average error of the system decreases with the increasing number of the membership function (MF). A decrease in the average error value of a system means the increase of ANFIS system performance.

The example of experimental result of the system in 3-D animation which are dynamic and adaptive to the changes of N-P-K input are shown in Fig. 7. All the simulations result in Fig. 7 was performed in 3 iterations and has a same L-system string as follows:

```
{
Axiom : I[+iL][-iL]A  ;
Rule : A=I[-P]I[+B]A ;
  P=ii[\iL][-iL] ;
  B=ii[/iL][+iL] ;
End Rule : A=I[L][+iL][-iL] ;
 P=I[+iL][-iL] ;
 B=I[+iL][-iL]
}.
```

*Table 2. Experimental Results*

| # | Num of ANFIS MF's | Average *Errors* (%) | | |
|---|---|---|---|---|
| | | L | W | B |
| 1 | **3** | 13.4 | 18.4 | 18.8 |
| 2 | **4** | 10.4 | 9.4 | 12 |
| 3 | **5** | 7.4 | 7.5 | 10.6 |

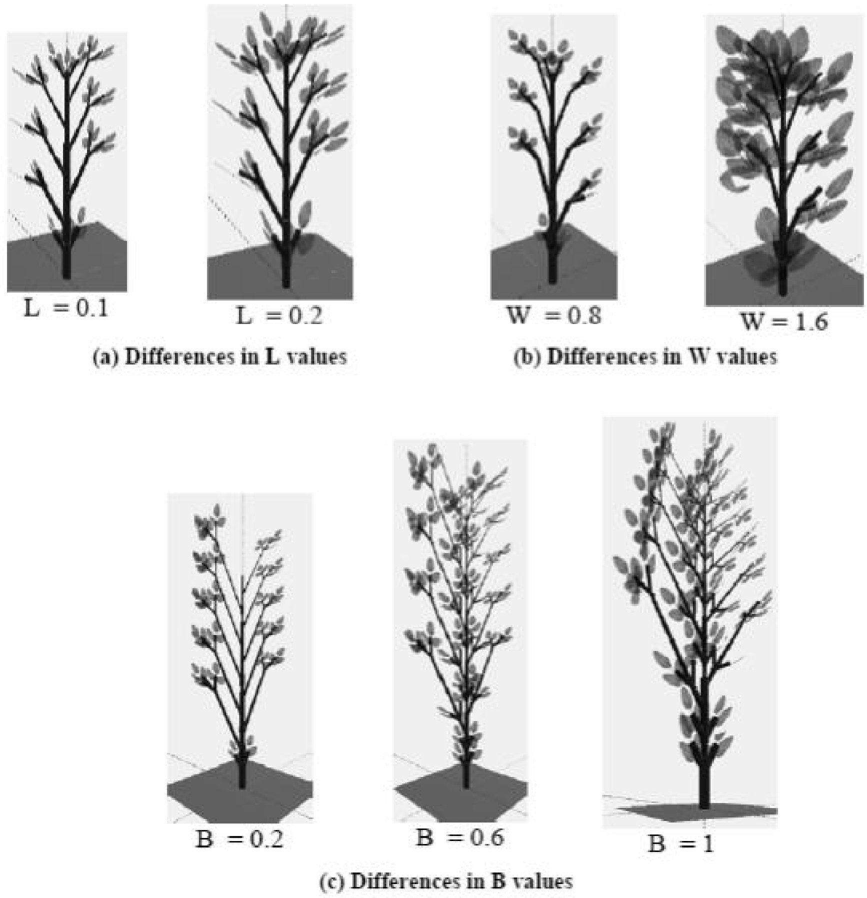


*Figure 7. Simulation results with the difference in L-W-B values*

**4. CONCLUSION**

In this research, a system that can help to model and visualize the growth of soybean plants based on the variation of the given NPK nutrition has been built. ANFIS method can be applied to calculate the input data which are the quantities of N-P-K nutrients and produce the output which are the growth of branch (L), growth of leaf's width (W), and the increase of branch number (B). The final result of L-system string with its visualization has proven to be influenced by the changes in N-P-K values composition. The visualization method with Turtle Geometry has proved able to interpret L-system string into 3-D visualization and adaptively accommodate the differences in N-P-K quantity patterns based on the input-output data in the ANFIS training process.

Based on the experimental results, the increment in number of membership function has correlation with the average error value of the system, as well as the ANFIS training time. The average error value is decreased when the number of membership value is increased, in this research the minimal average value of this system is reached when the number of membership function is 5. The minimal error values for the L, W, and B are 7.4%, 7.5%, and 10.6% respectively.

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