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Improved rotor speed brushless DC motor using fuzzy controller

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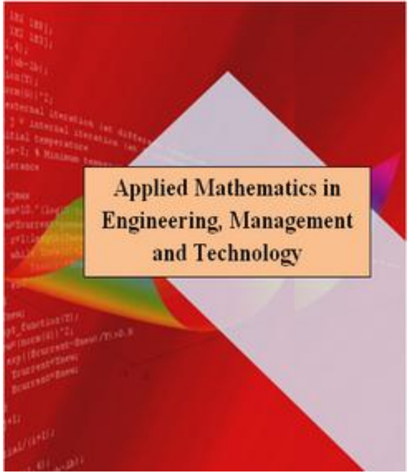

Abstract

A brushless DC (BLDC) Motors have advantages over brushed, direct current (DC) Motors and, Induction motor (IM). They have better speed verses torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, and rugged construction. Also, torque delivered to motor size is higher, making it useful in application where space and weight are critical factors. With these advantages BLDC motors find wide spread application in automotive appliance, aerospace medical, and instrumentation and automation industries This paper can be seen as fuzzy controllers compared to PI control BLDC motor rotor speed has improved significantly and better result can be achieve .

Keywords: Bldc, matlab/simulink, PID controller, PID fuzzy controller

Introduction

Brushless motor technology makes it possible to achieve high reliability with high efficiency, and for a lower cost in comparison with brush motors. Although the brushless characteristic can be apply to several kinds of motors AC synchronous motors, stepper motors, switched reluctance motors, AC induction motors the BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back, Electric Magnetic Fields (EMF) waveform shape. Permanent magnet synchronous machines with trapezoidal Back-EMF and (120 electrical degrees wide) rectangular stator currents are widely used as they offer the following advantages first, assuming the motor has pure trapezoidal Back EMF and that the stator phases commutation process is accurate, the mechanical torque developed by the motor is constant   secondly, the Brushless DC drives show a very high mechanical power density. Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and instrumentation (Millner, 1994, Wei, 2000), As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. BLDC Motors are available in many different power ratings, from very small motors as used in hard disk drives to larger motors used in electric vehicles. Purpose of this article IS improve the performance of BLDC rotor speed By using fuzzy control and compared with PI controller

2. Working Of Bldc Motor

The BLDC motor is an AC synchronous motor with permanent magnets on the rotor (moving part) and windings on the stator (6 part). Permanent magnets create the rotor flux and the energized stator windings create electromagnet poles. The rotor (equivalent to a bar magnet) is attracted by the energized stator phase. By using the appropriate sequence to supply the stator phases, a rotating field on the stator is created and maintained. This action of the rotor - chasing after the electromagnet poles on the stator is the fundamental action used in synchronous permanent magnet motors (Hemati and Leu, 1992). The lead between the rotor and the rotating field must be controlled to produce torque and this synchronization implies knowledge of the rotor position.

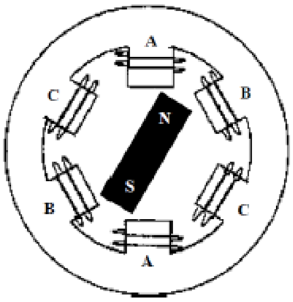

Figure1. A three-phase synchronous motor with a one permanent magnet pair pole rotor

On the stator side, stator is three phase similar to induction motor These offer a good compromise between precise control and the number of power electronic devices required to control the stator currents. For the rotor, a greater number of poles usually create a greater torque for the same level of current. On the other hand, by adding more magnets, a point is reached where, because of the space needed between magnets, the torque no longer increases. The manufacturing cost also increases with the number of poles. As a consequence, the number of poles is a compromise between cost, torque and volume (Pillay Krishnan, 1987). Permanent magnet synchronous motors can be classified in many ways, one of these that is of particular interest to us is that depending on back EMF profiles: Brushless Direct Current Motor (BLDC) and Permanent Magnet Synchronous Motor (PMSM). This terminology defines the shape of the back EMF of the synchronous motor. Both BLDC and PMSM motors have permanent magnets on the rotor but differ in the flux distributions and back EMF profiles. To get the best performance out of the synchronous motor, it is important to identify the type of motor in order to apply the most appropriate type of control is described. We have seen that the principle of the BLDC motor is, at all times, to energize the phase pair which can produce the highest torque. To optimize this effect the Back EMF shape is trapezoidal. The combination of a DC current with a trapezoidal Back EMF makes it theoretically possible to produce a constant torque. In practice, the current cannot be established instantaneously in a motor phase; as a consequence the torque ripple is present at each 60° degree phase commutation (Park et al., 2012)

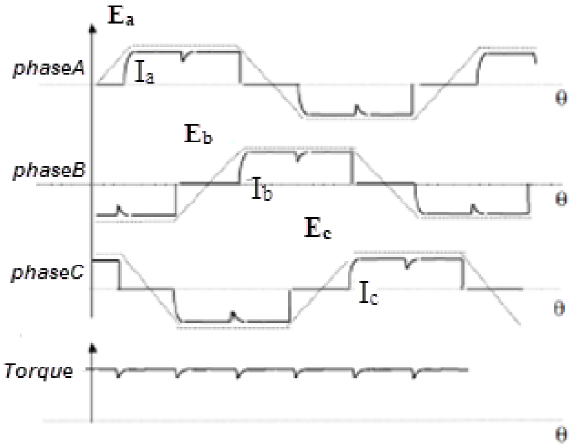

Figure 2.Electrical Waveforms in the Two Phase ON Operation and Torque Ripple

2.1. Mathematical Model Of Bldcm

As shown in figure 3, a dynamic equivalent circuit of the BLDC motor. For this model, the stator phase voltage equations in the stator reference frame of the BLDC Motor are given as in Eq. (1,5) which are provided below. The following assumptions are made:1) the three phase windings are symmetrical, 2) magnetic saturation is neglected, 3) hysteresis and eddy current losses is not considered, and 4) the inherent resistance of each of the motor windings is R ,the self-inductance is L, and the mutual inductance is M.

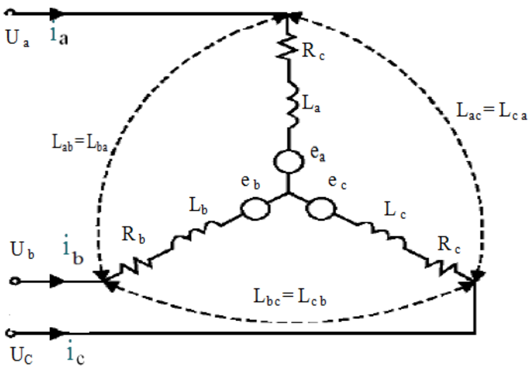

Figure3. Dynamic equalent circuit

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{(L-M)}\left\{\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_C \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \omega_r \Psi_m \begin{bmatrix} f_a(\theta) \\ f_b(\theta) \\ f_c(\theta) \end{bmatrix}\right\} \tag{1}$$

Where, Ua, Ub and Uc are the phase voltage of three-phase windings, ia, ib and ic are the phase current, and ea, eb and ec are the back EMF.

$$\begin{aligned} f_a(\theta_r) &= 1 \quad 0^\circ \ \angle \ \theta_r \angle \ 180^\circ \\ &= (\frac{6}{\pi})\ (\pi - \theta_r)\ -1 \quad 120^\circ \angle \ \theta_r \angle \ 180^\circ \\ &= -1 \quad 180^\circ \angle \theta_r \ \angle 300^\circ \\ &= (\frac{6}{\pi})(\theta_r - 2\pi)\ +1300^\circ \ \angle \theta_r \angle \ 360^\circ \end{aligned} \tag{2}$$

Electrical power of motor can be calculated using Eq. (3)

$$P = e_a i_a + e_b i_b + e_c i_c \tag{3}$$

Electromagnetic torque can also be expressed as Eq. (4). Speed is derived from rotor position Ɵr as in Eq. (5)

$$T_e = j(\frac{2}{p})\frac{d}{dt}\omega_r + B_m(\frac{2}{p})\omega_r + T\,1 \tag{4}$$

$$\frac{d}{dt}\omega_r = (\frac{p}{2j})(T_e - B_m(\frac{2}{p})\omega_r + T\ \ 1) \tag{5}$$

$$\frac{d}{dt}\theta_r = \omega_r \tag{6}$$

From the above equations, BLDC motor can be modeled (Philip, and Meenakshy, 2012).

3. A review on utilized systems

3.1. Implementation of PID fuzzy controller for BLDC

In this section implementation of Fuzzy Inference System for nonlinear fuzzy PID control is explicated using control system toolbox of Simulink. As mentioned before a fuzzy inference system maps known inputs to outputs using fuzzy logic. For instance, mapping of a controller can be stated by a three dimensional diagram. This diagram is called control surface. The following figure illustrates a hypothetical control surface.

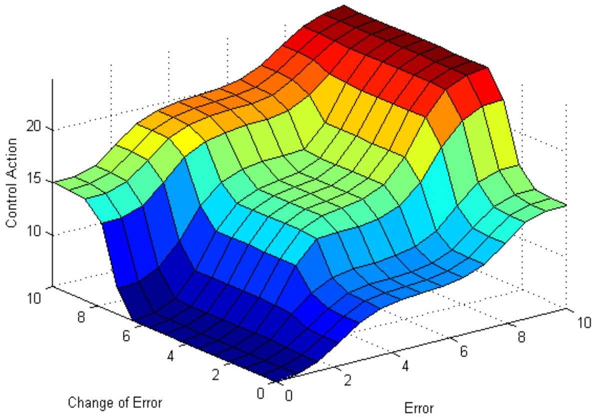

Figure4: an example of a control surface

Error signal *e(k)* and error variation signal *(e(k)-e(k-1))* are common inputs of FIS. The output of FIS is a control operation which is inferred from fuzzy rules.
In our study, utilized system is a BLDC model, single input- single output, which is discretized. The control objective is tracking reference signal.

3.2.Structure of fuzzy PID controller

The exploited fuzzy controller is a feedback loop which operates similar to PID which is calculated by fuzzy inference. The closed loop structure in SimuLink is as follows. It can be observed by typing the undergoing instruction.
Open-system ('Fuzzy_PID')

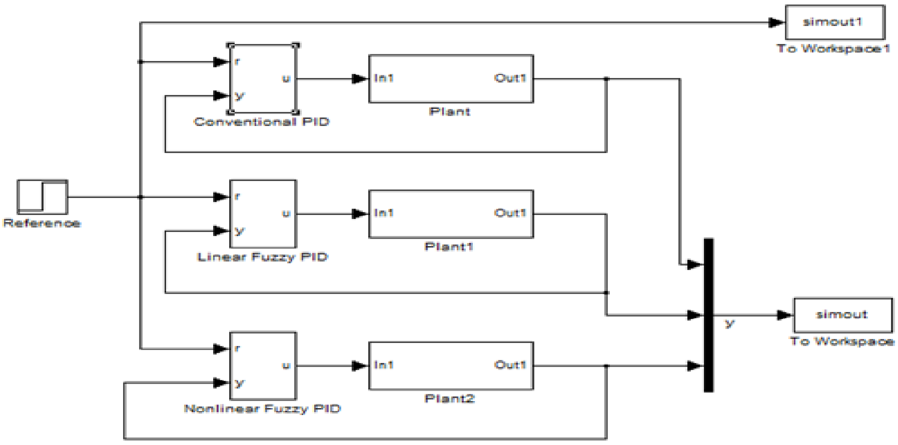

Figure 5. Closed loop structure in SimuLink

Three controllers depicted in the above figure are respectively conventional PID, linear fuzzy PID controller and nonlinear fuzzy PID controller. We will see that it is necessary to design conventional and linear fuzzy PID controllers to design nonlinear fuzzy controller. Parallel structure is utilized to implement fuzzy controller. It is a combination of fuzzy PI and fuzzy PD controllers. The structure of fuzzy controller is demonstrated in figure below.

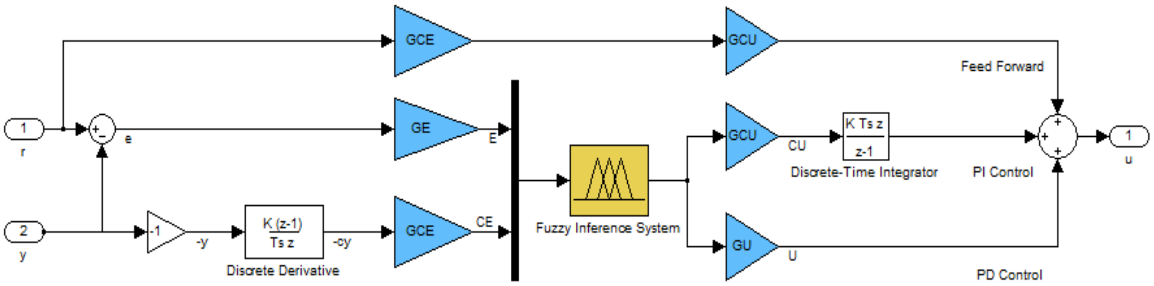

Figure6. Structure of fuzzy controller

The magnitude of *-(y(k)-y(k-1))* is used instead of signal changes. It is done in this way to avoid direct stimulation of derivative signal by step changes in input reference. Two gain blocks, GCE and GCU, are employed in the feedforward path. These two blocks guarantee that error signal *e*, is used proportional when the fuzzy PI controller is linear

3.3.Design procedure for fuzzy PID controller

Design of fuzzy controller includes configuration of fuzzy inference system and substitution of GE, GCU, GCE and GU scaling factors. Here, the following steps are taken for controller design.

- Designing conventional PI controller
- Designing equivalent linear fuzzy PID controller
- Adjusting fuzzy inference system to obtain nonlinear control surface (designing nonlinear fuzzy PID controller)
- Optimum adjustment of nonlinear fuzzy PID controller

3.3.1.The first step: designing conventional PID controller

.To implement PID controller, the parallel structure, which is shown below, is exploited

$$K_p + K_i \frac{T_s z}{z-1} + K_d \frac{z-1}{T_s z} \quad .$$

The mentioned controller is implemented as follows in the SimuLink.

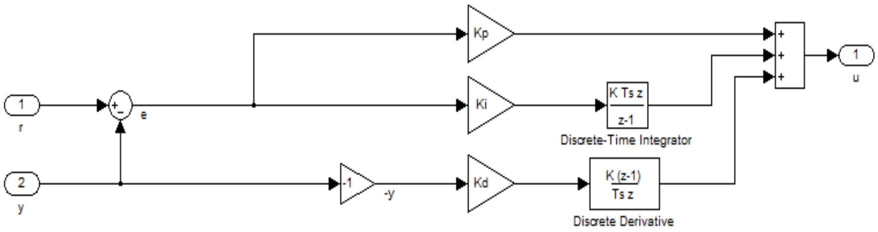

Figure 7. PID structure in the Simulink environment

Similar to fuzzy PID controller the input signal for derivative operator is *–y(k)*.
PID coefficients might be adjusted manually or using adjustment rules. The following instructions might be utilized to adjust PID controller coefficients in control tool box.

```
% Designing Conventional PID
C0  =  pid(1,1,1,'Ts',Ts,'IF','B','DF','B'); % define PID structure
C  =  pidtune (plant,C0); % design PID
```

```
[Kp  Ki  Kd]  =  piddata(C); % obtain PID gains
```

3.3.2.Second step: designing equivalent fuzzy PID controller

With FIS configuration and selecting four scaling coefficients, a fuzzy controller is derived whose performance is exactly the same as conventional PID.

First off, fuzzy system is configured. As a result a linear control surface is achieved from E and CE as inputs to U as output. The structure of utilized inference system is summarized as follows.

- Mamdani inference system is employed.
- Algebraic multiplication is used instead of AND.
- The input range is considered to be [-10,10]
- The fuzzy sets are triangular and they intersect their neighbors in 0.5 membership value.
- The output range is [-20, 20].
- The outputs are single-valued determined by sum of peak positions of input sets.
- The center of gravity method is used for deffuzification.

Values of input and output ranges and membership function parameters must be assigned so that the relation between input and output of the system is equal to an identity function. In the next section the coefficients of fuzzy PID controller are derived by assuming the identity function for relation of fuzzy inference system.

The following instruction is used to build fuzzy inference system.

```
%Designing Linear Fuzzy Inference System
FIS2 = newfis('FIS2','mamdani','prod','probor','prod','sum');
```

and

The fuzzy rules are also defined as follows:

- *If E is Negative and CE is Negative then u is -20*
- *If E is Negative and CE is Zero then u is -10*
- *If E is Negative and CE is Positive then u is 0*
- *If E is zero and CE is Negative then u is -10*
- *If E is Zero and CE is Zero then u is 0*
- *If E is Zero and CE is Positive then u is 10*
- *If E is Positive and CE is Negative then u is 0*
- *If E is Positive and CE is Zero then u is 10*
- *If E is Positive and CE is Positive then u is 20*

Here we utilized fuzzy tool box instructions to create FIS; however, corresponding GUI might be used as well.

The 3d surface is achieved as follows

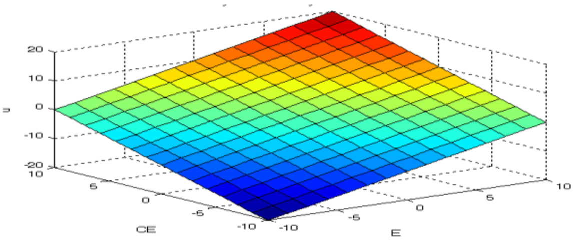

Figure8**.** 3D diagram of control surface in fuzzy PID controller

The input and output membership functions are shown below.

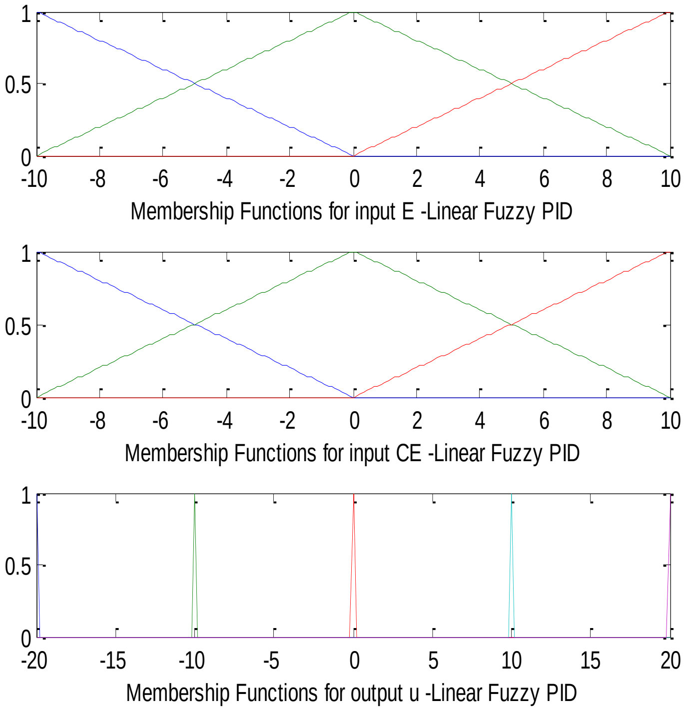

Figure9**.** Input and output membership functions for linear fuzzy PID controller

In the next stage, four scaling factors are calculated using coefficients of conventional PID controller. The input-output relation in fuzzy inference system is considered to be in the form of identity function; therefore, the corresponding relations are as shown in the following equations.

$$k_p = GCU \times GCE + GU \times GE$$
$$k_i = GCU \times GE$$
$$k_d = GU \times GCE$$

If the maximum input step is considered as 1 the maximum error value would be 1.
Since input range equals to [-10, 10], considering GE=10, GCE, GCU and GU are derived from following equations.

$$GE = 10$$
$$GCSE = GE \times {}^{k_p - sqrt\left(k_p{}^2 - 4k_ik_d\right)}\!\big/_{2\times k_i}$$
$$GCU = {}^{k_i}\!/_{GE}$$
$$GU = {}^{k_d}\!/_{GCE}$$

The above values are calculated in the corresponding m-file using the following instructions. They are used in Simulink plant file together with controller.

3.3.3.Third step: designing fuzzy PID controller with nonlinear control surface

First we make sure that fuzzy PID controller is properly designed. Afterwards, FIS adjustments such as, type, functions, membership, fuzzy rules and so on are changed so that desired nonlinear control surface is achieved.

For this purpose Sugeno inference system is utilized. Moreover, for each input merely two states, positive and negative, are considered which reduces the number of rules to four.

The fuzzy rule set is defined as follows.

- *If E is Negative and CE is Negative then u is -20*
- *If E is Negative and CE is Positive then u is 0*
- *If E is Positive and CE is Negative then u is 0*
- *If E is Positive and CE is Positive then u is 20*

The 3D diagram of nonlinear control surface is depicted in figure, As shown in figure 10

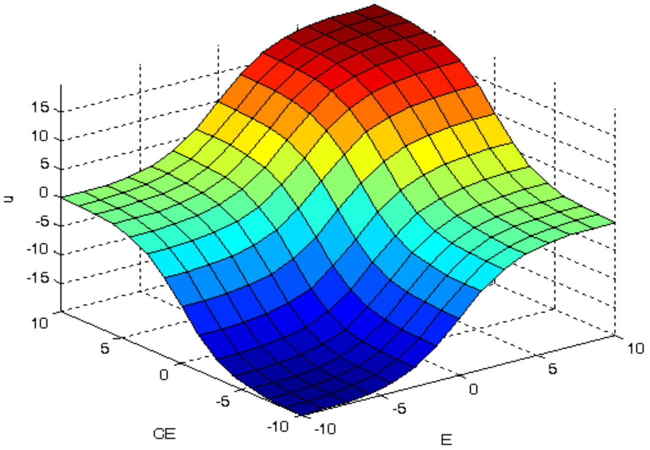

Figure 10. 3D diagram of control surface for nonlinear fuzzy PID controller

As can be seen we have a nonlinear control surface. According to above mentioned control surface, it can be seen that the control surface has considerable gain in the vicinity of center of E and CE plane. As a result when error is small it will decrease more rapidly. When the error is large, the variations of controller are small. It limits control operation and avoids probable saturation. The membership functions for inputs of fuzzy inference system are demonstrated as shown in figure 11.

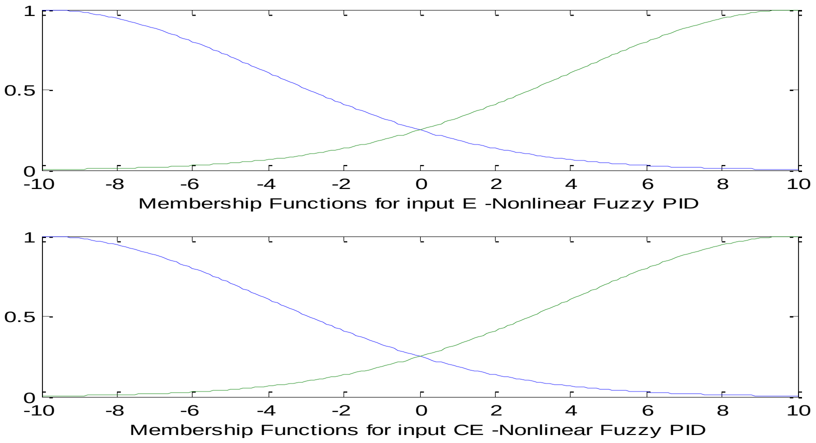

Figure 11. Input and output membership functions associated with nonlinear fuzzy PID controller

As shown in figure 13, response of system with mentioned controllers is depicted for step input and at t=1s.

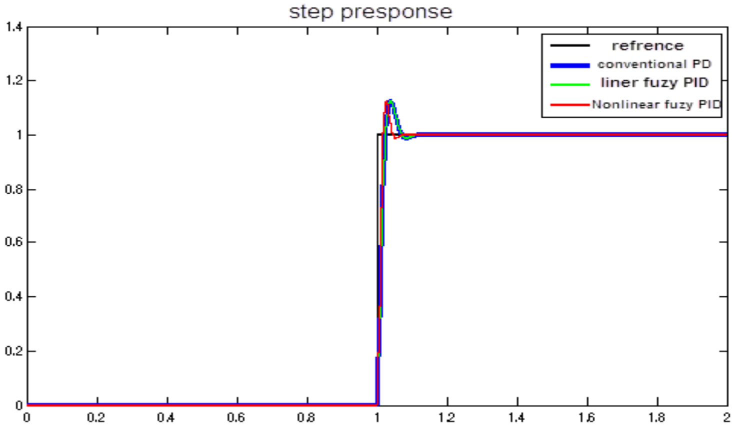

Figure 12. The response of closed loop system with conventional PID, linear fuzzy and nonlinear fuzzy controllers

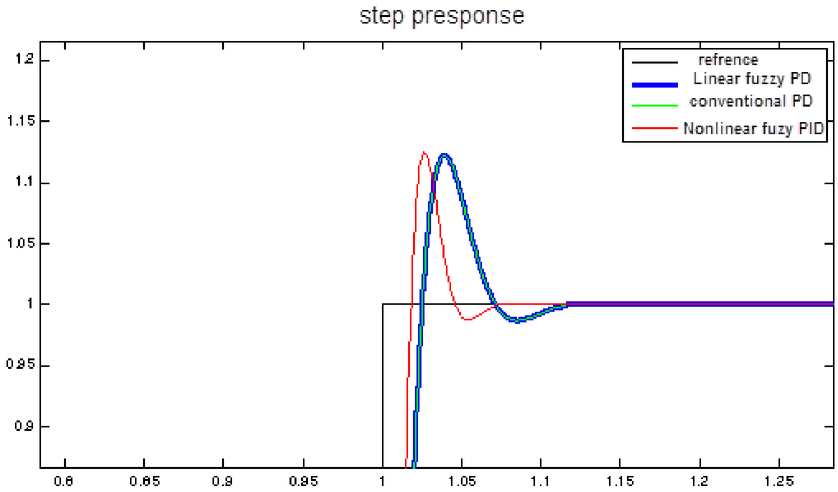

Figure 13. Closed loop system response with conventional PID, linear fuzzy PID and nonlinear fuzzy PID controllers

As expected the response of the system with conventional PID and linear fuzzy PID are the same. The response of the system with nonlinear fuzzy PID controller is faster than two others; nevertheless , it does not show any improvements regarding overshoot .

3.3.4.Fourth step: optimum adjustment of nonlinear fuzzy PID controller

In this section system response is modified by changing the parameters of input membership functions. The following results are achieved by changing membership functions (changing the parameter related to membership function from 6 to 2)

```
%input E
FIS1 = addvar (FIS1,'input','E',[-10 10]);
FIS1 = addmf (FIS1,'input',1,'Negative','gaussmf',[2 -10]);
FIS1 = addmf (FIS1,'input',1,'Positive','gaussmf',[2 10]);
%input CE
FIS1 = addvar (FIS1,'input','CE',[-10 10]);
FIS1 = addmf (FIS1,'input',2,'Negative','gaussmf',[2 -10]);
FIS1 = addmf (FIS1,'input',2,'Positive','gaussmf',[2 10]);
```

The magnified step response is shown in figure 16.

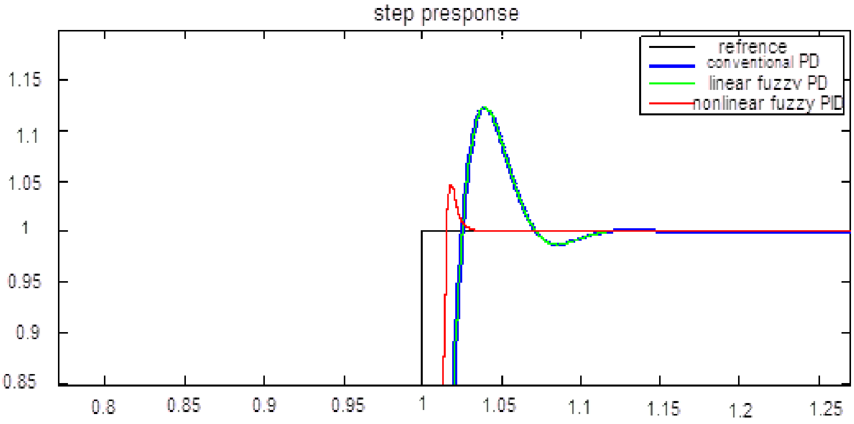

Figure 14. The magnified response of closed loop system with conventional PID, linear fuzzy PID and nonlinear fuzzy PID controllers

As can be seen the response is faster with nonlinear fuzzy PID controller and it has smaller overshoot. Comparing figures 13 and 14 it can be concluded that the system response is significantly improved by changing the parameters.

4. SIMULATION AND RESULTS

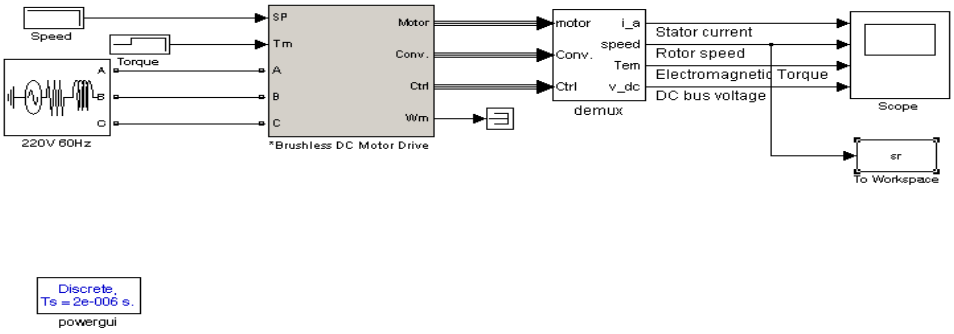

Figure15.Block Diagram of bldc

To design fuzzy PI controller, the following structure is used

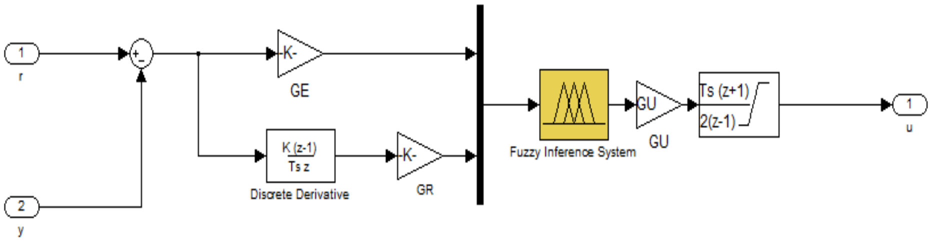

Figure16**.** design fuzzy PI controller,.

As we know the structure of a conventional PI is as follows:

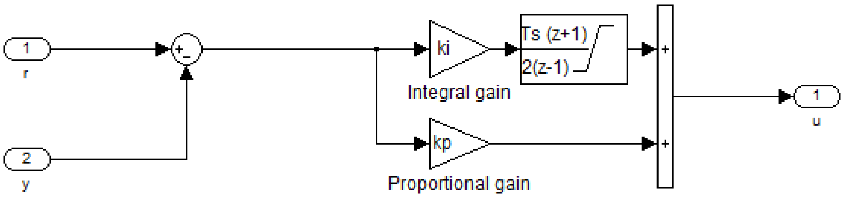

Figure17**.**the structure of a conventional PI

comparing the two structures shows that the two following relationships are established between the coefficients of the controller*:*

$ki = GE \times GU$

$kp = GR \times GU$

In the above equations, the coefficients of conventional PI can be obtained by having fuzzy PI controller. In practice, we need to obtain the coefficients of the fuzzy PI controller. For this purpose, by choosing a value for one of the coefficients such as GU, other coefficients can be achieved. The selected values for GU controller determine the degree of nonlinearity for fuzzy controller Here the input range for fuzzy inference system is considered as [-10.10] and for this reason according to the reference signal amplitude and the estimated value that is approximately equal to 300, the value of GU = 1000 is considered that seems to be a good value , an inference system of Sugeno is used as the fuzzy controller. Only two modes of Positive and Negative are considered for each input and Positive, Zero and Negative modes are considered for each output and the total rules have reduced to 4 rules.

To configure the Fuzzy inference system we run the following commands.

- If E is Negative and CE is Negative then u is Negative
- If E is Negative and CE is Positive then u is Zero
- If E is Positive and CE is Negative then u is Zero
- If E is Positive and CE is Positive then u is Positive

With the definition of fuzzy inference system and using fuzzy PI controller, the rotor speed's results are obtained as follows:

To compare the fuzzy PI controller and conventional PI controller, a PI with coefficients equal to fuzzy PI is used. Results from both controllers and the reference input are shown in the following figure. Values considered for PI controller are.

$ki = 46.35, kp = 1.22$

In the following figure, the system behavior is given with enlargement in one of the corners.

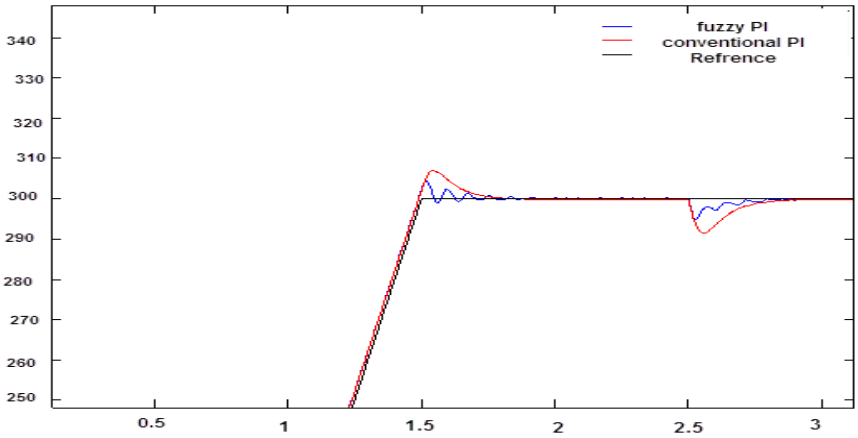

Figure18**.**rotor speed with fuzzy PI controller

As can be seen, the use of fuzzy PI controller significantly improves the system response and the system could follow the reference signal with very good accuracy. By changing the parameters of the membership functions related to the fuzzy inference system, the obtained results can be improved.

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