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DIFFERENT TYPES OF SPEED CONTROLLERS FOR BRUSHLESS DC MOTOR – A REVIEW

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***Abstract* -** With the advancement of motor drives, there is an increase in efficiency and reliability. Some applications such as refrigerator and air conditioning use conventional motor drive technology which results in low efficiency and high maintenance. A Brushless DC Motor drive is characterized by higher efficiency, lower maintenance, higher cost, silent operation & compact form. This paper describes basic operation of BLDC Motor, different control techniques and its comparison to other motors. There is a significant rise in popularity of BLDC motors in motion control Applications. There is several techniques to control BLDC Motor like PI controller, PID controller, Fuzzy logic, Genetic algorithms, Neural Network, PWM Control and Sensor less Control etc. The Fuzzy control has an importance in field of control of BLDC motor whereas GA based PID controller is used for speed control of BLDC Motor. Due to their favorable electrical and mechanical properties BLDC motors are used in applications such as automotive, aerospace, medical, instrumentation, machine tools, robotics and actuations etc.

Keywords: Brushless dc (BLDC) motor, Fuzzy control, Genetic algorithms, Speed control.

I. INTRODUCTION

Brushless DC motors are very popular in a wide variety of applications. Compared with a DC Motor, the BLDC motor uses an electronic commutator rather than a mechanical commutator [1]. As the name implies, BLDC motors do not use brushes for commutation instead they are electronically commutated [2]. Basically BLDC motors are synchronous motor. BLDC motors do not experience slip factor. BLDC motors are in different configurations like single phase, 2-phase and 3-phase. Out of these, 3-phase motors are popular and widely used. Brushless DC (BLDC) motors have the advantage of higher power density than other motors such as induction motors because of having no copper losses on the rotor side and they do not need mechanical commutation mechanisms as compared with DC motors, which result in compact and robust structures. With these features, BLDC motors have become more popular in the applications where efficiency is a critical issue, or where spikes caused by mechanical commutations are not allowed. A BLDC motor requires an inverter and a rotor position sensor to perform commutation process because a permanent magnet synchronous motor do not have brushes and commutators in DC motors [3].

Many Papers have presented different control schemes for BLDC motor. In [4] a PI controller has been used to control BLDC motor. The PI controller is only suitable for linear motor control. Most widely used controllers are conventional controllers PI and PID. Due to various uncertainties like payload variation, friction and many other external disturbances, PI controller does not provide better control. So Genetic algorithm based PID controller used for speed control of BLDCM. Fuzzy control is a versatile & effective approach to deal with nonlinear & uncertain system.

Genetic Algorithm is a robust optimization technique based on natural selection. The basic goal of GA to optimize the fitness function [5].

II. PRICIPLE OF OPERATION

The working of BLDC motor is similar to the conventional DC motor with the mechanical commutation replaced by an electronically controlled commutation system [6]. BLDC motors generally have the rotating permanent magnets and stationary armature. BLDC motors are used as star connected as well as delta connected motors. With the help of intelligent electronic controller, we can control power distribution. The electronic controller must have rotor position information for proper commutation of currents in the respective stator windings. Hall effect sensors are used to sense the rotor position. These sensors are embedded in the stator and thus stator windings are energized accordingly.

There are two types of BLDC motor drive control 1.sensor mode 2.sensorless mode. Use of sensor less control offers the advantage of reduced cost. The sensor less control offers low performance at transients or low speed range with increase in complexity of the control electronics. So we use Hall sensors for effective control of BLDC motor.

A brushless dc motor consists of a permanent magnet synchronous motor that converts electrical energy to mechanical energy, a position sensor and an inverter [7]. It consist of a permanent magnet rotor with a three-phase stator winding connected in star connection. BLDC motor is driven by a three-phase inverter which is triggered from the rotor position with respect to stator reference. Hall sensor, resolver or encoder can be position sensors used to detect the rotor position and commutation is based on these sensor inputs [8]. The cross section view of BLDC motor is shown below in fig. 1.

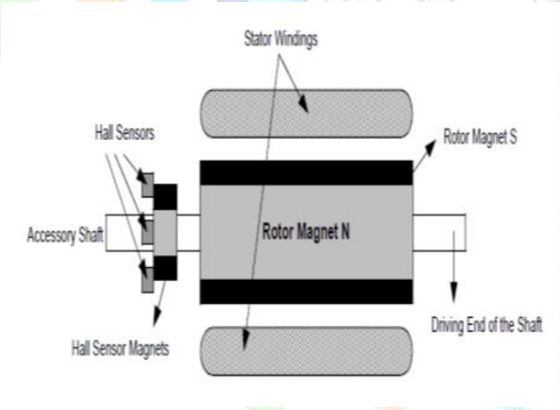

Fig. 1. Cross section view of BLDC Motor

The power electronic driver of a BLDC motor can be an IGBT based inverter or MOSFET based inverter. The MOSFET based inverter is shown below in fig. 2.

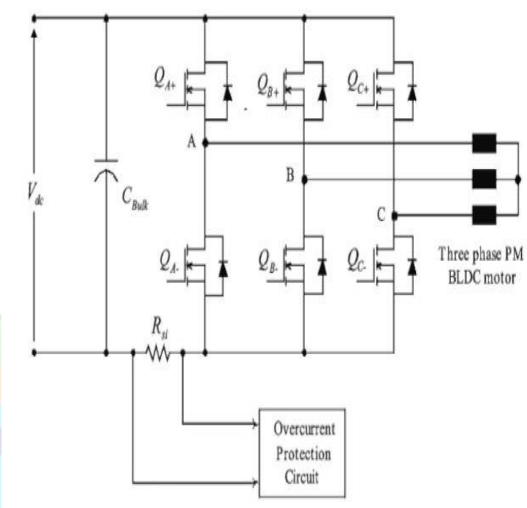

Fig. 2. Three-phase MOSFET inverter driven BLDC motor

Sensing rotor positions enables commutation logic for the three phase inverter circuits that contain MOSFET switches. Where Q1 - Q6 represents the MOSFETs in the Switching circuit and H_a, H_b, H_c represents the Hall sensor signals [11]. The Hall sensors should be kept 120° apart. This is done to obtain symmetrical operation of motor phases. After sensing rotor positions, three bit codes of Hall sensed signal is obtained as shown in TABLE I. Each code specifies the rotor position and the corresponding stator windings that are to be energized. The status of H_a, H_b, H_c signals are high or low depending whether the sensor is near the N or S pole of the rotor magnets. Depending on these signals the MOSFETs switches Q1 - Q6 are ON/OFF. From TABLE I it is concluded that whenever H_b is high, the switch Q_2-Q_3 conducts energizing the corresponding stator windings are energized [12].

TABLE I

Clockwise Hall Sensor Signals and Drive Signals

H_a	H_b	H_c	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1

1	1	1	0	0	0	0	0	0

III. SPEED CONTROL SYSTEM OF BLDC MOTOR

The complete block diagram of speed control of three phase BLDC Motor is below Fig. 1. There are two control loops. These loops are used to control the speed of BLDC motor. The inner loop does synchronization between the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage [13].

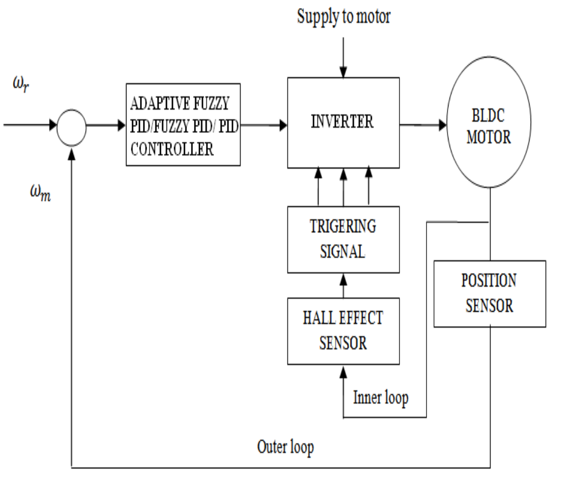

Fig. 3 Block Diagram of speed control of BLDC Motor

The Drive circuit consists of three phase power convertors, which use six power transistors to energize two BLDC motor phases concurrently. The rotor position determines the switching sequence of the MOSFET transistors. The rotor position is detected by means of 3 Hall sensors mounted on the stator. By using Hall sensor and the sign of reference current (produced by Reference current generator), Decoder block generates signal vector of back EMF.

IV. DIFFERENT TYPES OF SPEED CONTROLLERS

There are various types of controllers used for the purpose of speed control of BLDC motor. The main function of speed controller block is to provide a reference torque. This reference torque in turn is converted to reference current and is fed to current reference generator. The output of the speed controller is limited to a proper value. This value must be according to the motor rating to generate the reference torque [14]. The speed controllers used in BLDC motor are PI controller, PID controller, Fuzzy logic controller, Neural Network, Fuzzy PID and Genetic Algorithms.

A. PI Controller

The proportional plus integral (PI) controller is widely used for industrial applications. The input to the PI controller is the speed error (E). The output of the PI controller is used as the input of reference current block. The basic structure of PI controller is shown in fig. 5.

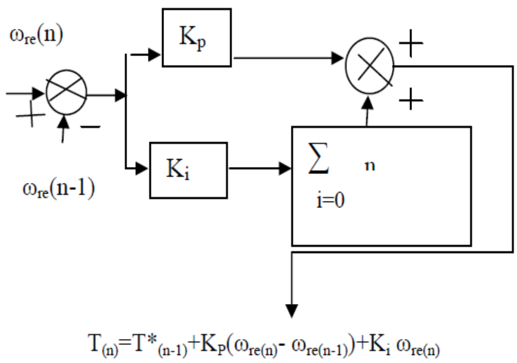

Fig. 4 Basic structure of PI controller

The model of PI speed controller is given by,

$$G(S) = Kp + Ki/S$$

Where G(S) is the controller transfer function which is torque to error ratio in s - domain, Kp is the proportional gain and Ki is the integral gain. The tuning of these parameters is done using Ziegler Nichols method using the phase and gain margin specifications. The specifications of the drive application are usually available in terms of percentage overshoot and settling time. The PI parameters are chosen so as to place the poles at appropriate locations to get the desired response. These parameters are obtained using Ziegler Nichols method which ensures stability. From the dynamic response obtained by simulation, the percentage overshoots Mp and settling time ts which are the measures of transient behavior are obtained [16].

The speed loop of the typical BLDC motor is shown in Figure 5 under no load condition. The closed loop transfer function of the system shown in Figure.6 is given by

$$T(s) = \frac{(K_p s + K_i) / J}{S^2 + (B + K_p) s + K_i / J}$$

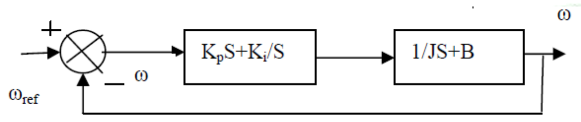

Fig. 5 Speed control using PI controller

Where T(s) is the closed loop transfer function and Kp, Ki are the PI controller parameters, J is the moment of inertia and B is the coefficient of friction. Comparing the characteristic of the transfer function with a standard 2nd order system characteristic equation we get

$$K_p = 2\xi\omega_n J\text{-}B$$

$$Ki = J\,\omega_n^2$$

B. PID Controller

The PID controller is very widely used in the industries. A PID controller is simple three-term controller. The letter P, I and D stand for P-Proportional, I- Integral, D- Derivative. The main function of PID controller is to make plant less sensitive to changes that take place in surroundings. The basic PID controller composes of three terms proportional (P), derivative (D) and integral (I) to stabilize the response of the system. The Ziegler –Nicholas ultimate cycle or closed loop tuning has been widely used. The Ziegler–Nicholas tuning formula based on tuning of ultimate gain Ku and as below

TABLE II

ZIEGLER –NICHOLAS TUNING FORMULA

	PI	PID
Proportional gain	$K_p = 0.5\ K_u$	$K_p = 0.6\ K_u$
Derivative gain	$T_i = 0.85\ t_u$	$T_i = 0.5\ t_u$
Integral gain		$T_d = 0.125t_u$

Where Ku and tu are the empirical knowledge of ultimate gain and ultimate time-period respectively [15]. The PID controller represented by the following equation

$$U = K_p\, e(t) + K_i \int e(t)d(t) + K_d\, de(t)/dt$$

Where Kp, Ki and Kd are the gain of controller.

The transfer function of most basic PID controller is

$$C(s) = K_d\, s^2 + K_{p\,s} + K_i$$

Where K_p = Proportional gain, K_i = Integral gain and K_d = Derivative gain.

The control u from the controller to the plant is equal to the Proportional gain (K_p) times the magnitude of the error plus the Integral gain (Ki) times the integral of the error plus the Derivative gain (Kd) times the derivative of the error.

Due to its simplicity and excellent if not optimal performance in many applications, PID controllers are used in more than 95% of closed-loop industrial processes We are most interested in four major characteristics of the closed-loop step response. They are

a. Rise Time: the time it takes for the plant output Y to rise beyond 90% of the desired level for the first time.

b. Overshoot: how much the peak level is higher than the steady state, normalized against the steady state.

c. Settling Time: the time it takes for the system to converge to its steady state.

d. Steady-state Error: the difference between the steady-state output and the desired output.

C. Fuzzy Logic Controller

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The speed control of BLDC drive can be simulated using the fuzzy logic controller. The Fuzzy logic system plays a central role in the controlling of nonlinear systems and in industrial applications where the control and automation plays a vital role. The fuzzy logic control is designed using the fuzzy inference systems with the definition of input and output membership functions. The fuzzy sets and rules are designed and accordingly the drive can be controlled.

In recent years, fuzzy control has emerged as a practical alternative to classical control schemes when one is interested in controlling certain time varying, non-linear, and ill-defined processes. There have in fact been several successful commercial and industrial applications of fuzzy control. Fuzzy controllers are used to control consumer products, such as washing machines, video cameras, and rice cookers, as well as industrial processes, such as cement kilns, underground trains, and robots. Fuzzy control is a control method based on fuzzy logic. Fuzzy logic can be described simply as computing with words rather than numbers; fuzzy control can be described simply as control with sentences rather than equations. A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants.

Fuzzy logic controller (FLC) is capable of improving its performance in the control of a nonlinear system whose dynamics are unknown or uncertain. Fuzzy controller is able to improve its performance without having to identify a model of the plant. Fuzzy control is similar to the classic closed-loop control approaches but differs in that it substitutes imprecise, symbolic notions for precise numeric measures.

Fuzzy controllers are more robust because they can cover a wide range of operating conditions. Fuzzy controllers are more flexible and the modifications of the Fuzzy rules are simpler when compared to the conventional controllers. With these benefits Fuzzy controllers can be utilized as industrial tool for control applications.

The fuzzy controller takes input values from the real world. These crisp input values are mapped to the linguistic values through the membership functions in the fuzzification step. A set of rules that emulates the decision making process of the human expert controlling the system is then applied using certain inference mechanisms to determine the output. Finally, the output is mapped into crisp control actions required in practical applications in the de-fuzzification step.

In a fuzzy controller the data passes through a pre-processing block, a controller, and a post-processing block. Pre-processing consists of a linear or non-linear scaling. Linguistic variables are central to fuzzy logic manipulations. They are non-precise variables that often convey a surprising amount of information. Usually, linguistic variables hold values that are uniformly distributed (μ) between 0 and 1, depending on the relevance of a context dependent linguistic term. The collection of rules is called a rules base and the rules are in the familiar if-then format, and formally the if-side is called the condition and the then-side is called the conclusion. The computer is able to execute the rules and compute a control signal depending on the measured inputs error and change in error. Therefore the rules reflect the strategy that the control signal should be a combination of the reference error and the change in error. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic.

The mapping then provides a basis from which decisions can be made. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules.

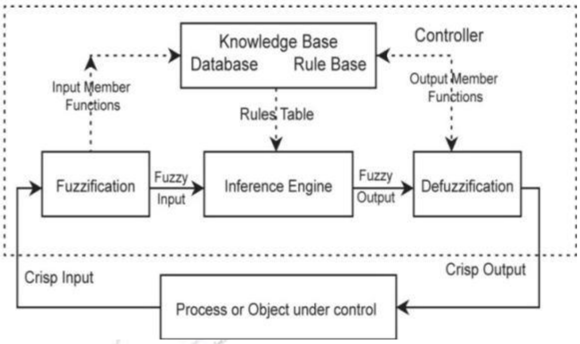

Fig. 7. Basic block diagram of FLC

The basic block diagram of the speed control of BLDC motor drive using Fuzzy logic controller is illustrated in Fig.8.The error signal generated as the result of variation in the reference speed and the actual speed of the motor sensed by the hall signals is utilized for the formulation of Fuzzy rules which results in the generation of the PWM signals to drive the switching circuit and with flexibility of fuzzy controllers wide range of speed can be controlled using this Fuzzy controller [17].

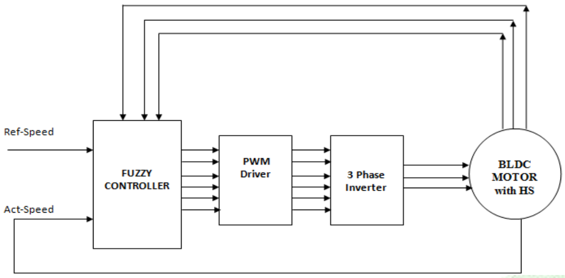

Fig. 8. Block Diagram of Fuzzy Controlled BLDC Motor Drive

Step1: The Fuzzy rules are designed and the rules that are verified are invoked using the membership functions and the truth values obtained.

Step2: The result is mapped to the membership function and the variable to control the output variable.

Step3: The final step is the defuzzification providing the crisp output needed to control the system. The combination of fuzzy operation and rule based inference system provides a fuzzy expert system.

The membership functions illustrated in Fig.6 used to fuzzification two input values and defuzzification output of the fuzzy controller. For seven clusters in the membership functions, seven linguistic variables are defined as: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

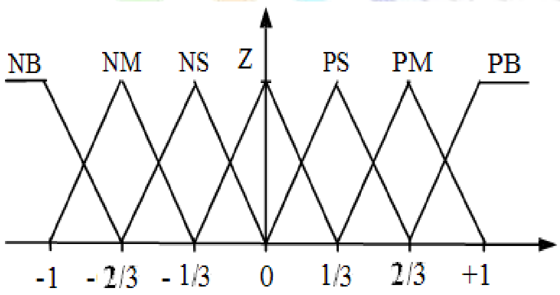

Fig. 9. Membership Function

It has three main components,

1. Fuzzifier

2. Inference engine.

3. Defuzzifier.

By this structure, first we convert crisp value into fuzzy value .it is called fuzzification, & last we convert fuzzy value into crisp value, called defuzzification. Between this two block we do decision making process, in this process we make rule base & get the accurate result.

Fuzzy logic terms are expressed in the form of logical implication. Such as if- then rules. It is called member ship function.

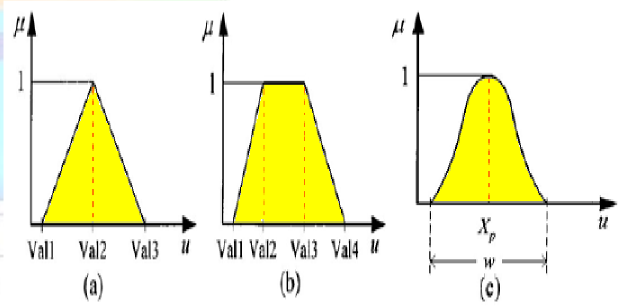

Fig. 10. Triangular, Trapezoidal & Bell Shaped Function

Defuzzification

It converts fuzzy value into crisp value there are three methods for defuzzification,

A. The max criterion method - It produce a point at which membership function reaches maximum value.

B. The height method – The centroid of each membership function for each rule is first evaluated. The final output is then calculated as the average of the individual centroids.

C. Centroid method - It generate the center of gravity of the area by membership function.

There are seven clusters in the membership functions, with seven linguistic variables defined as: Negative Big (NB), Negative (N), Negative Small (NS), Zero (Z), Positive Small (PS), Positive (P), and Positive Big (PB). A sliding mode rule-base, used in the fuzzy logic controller is given in Table 1. The fuzzy inference operation is implemented by using the 49 rules. The min-max compositional rule of inference and the center of gravity method have been used in the “defuzzification” process.

If $p1$ is NB and $p2$ is NB Then *out* is PB, If $p1$ is NB and $p2$ is N Then out is PB,

If $p1$ is NB and $p2$ is NS Then out is P,

If $p1$ is NB and $p2$ is Z Then out is P,

Input p1	Input p2						
	NB	N	NS	Z	PS	P	PB
NB	PB	PB	P	P	PS	PS	Z
N	PB	P	P	PS	PS	Z	NS
NS	P	P	PS	PS	Z	NS	NS
Z	P	PS	PS	Z	NS	NS	N
PS	PS	PS	Z	NS	NS	N	N
P	PS	Z	NS	NS	N	N	NB
PB	Z	NS	NS	N	N	NB	NB

D. Genetic Algorithm

Genetic algorithm is a robust technique for optimization based on natural selection. The main objective of using genetic algorithm is to optimize a function called fitness function. A possible solution of a problem is seen as an individual. The collection of number of individual is called as population [18] [19]. The current population produces new generation, the new generation and new individuals are supposed to be better than the previous one.

A basic structure of GA-PID controller consists of a conventional controller, whose gain coefficients are auto tuned by the GA technique for a given plant. Hence a GA algorithm consists of three basic things, reproduction, crossover and mutation. Reproduction simply retains a fit set of chromosome in the given population. Crossover involves swapping between two parent strings. Mutation involves flipping a random bit in the set of chromosome [20] [21]. A GA based PID controller has been implemented in this section as per the procedure listed below:

A. *Encoding*

Individual binary string consists of three coefficient gain parameter of PID controller Kp,Ki and Kd is used to ensure that the variables are independent. Unsigned binary coding is applied for encoding [22].

B. Initialization

The first population is generated at random within the boundaries. The boundaries for PID controller constant have been chosen such that not too many PID controller constants leading system to be unstable.

C. Objective Function

An essential step for GA is choosing objective function, which is used to evaluate the fitness of each chromosome. For the design of a GA-PID controller we use integral of the squared error (ISE)

$$\textbf{ISE} = {}_0\int^T e(t)^2\, dt$$

D. Fitness Function

To minimize the error signal, the error criterion ISE is employed such a way that the values of different performance criteria (rise time, settling time, overshoot) have been minimized [23],[24].

The fitness value concluded as Fitness value=1/performance index (6) In order to overcome the large energy of controller, we add square term of controller output u(t).Thus fitness function is defined as follows:

$$J = {}_0\int^\infty (\omega_1 Ie(t)I + \omega_2\, u^2(t)d(t) + \omega_3\, t_r$$

Where, w1 w2 and w3 are weight coefficients, u(t) is the output of the controller tr be the rise time of the system and e(t) is the system error.

E. Selection

In our problem design, standard roulette wheel selection has been applied to select individual from the current pool of population. The offspring's are produced based on the selection value. The selection value depends on the fitness value of individual, bigger the fitness value more offspring the individual produce [25]. The reproduce made of each individual can be calculated as

Number of reproduced=N*relative fitness

E. Neural Network Controller

A four-layer neural network as shown in Fig.12.[28].Nodes in the input layer represent input linguistic variables. Nodes in the membership layer act as the membership functions. Moreover, all the nodes in the rule layer form a fuzzy rule base. In the proposed FNN, the units in the input (the i layer), membership (the j layer), rule (the k layer) and output layers (the o layer) are two, six, nine and one, respectively.

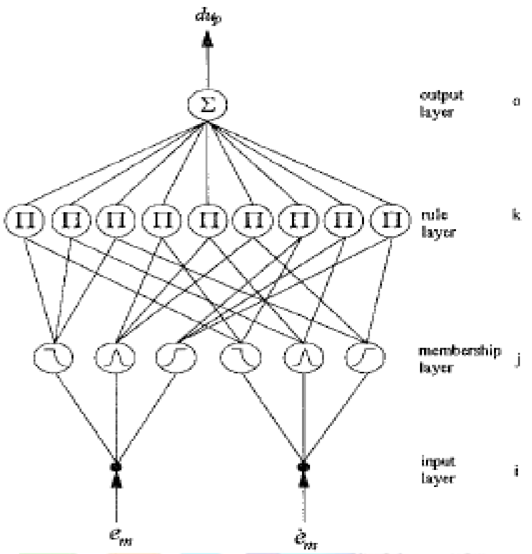

Fig. 11. Neural Network Layers

F. CONCLUSIONS

In this review paper the control scheme for the speed control of BLDC motor using different controllers is shown. The different controllers are: PI controller, PID controller, fuzzy logic controller, neural network controller and genetic algorithm. We can use mixing of these controller like fuzzy PID controller, neuro-fuzzy controller for efficient speed control of BLDC Motor. Basically PI & PID controllers are used for simple speed control. But for nonlinear application we have to use fuzzy logic controller or other one to get better speed of response. In Fuzzy Logic controller, the control the speed of flexible BLDC Motor, proves that the desired speed is attained with a shorter response time, when compared with conventional controllers. Fuzzy controller is a highly controller and is capable of controlling the motor drive over wide speed range. The fuzzy controller proves to be more efficient than the conventional controller.

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