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## RESEARCH ARTICLE

# MODELING, SIMULATION AND PERFORMANCE ANALYSIS OF THE THREE PHASE PERMANENT MAGNET BRUSHLESS DIRECT CURRENT (PMBLDC) MOTOR USING NEURO-FUZZY CONTROLLERBASED GENETIC ALGORITHM

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### ABSTRACT

In this paper, modeling, simulation and performance analysis of the three phase permanent magnet brushless direct current (PMBLDC) motor using Fuzzy Logic Controller (FLC), hybrid Fuzzy-Genetic Algorithm controller (FGAC), hybrid Neuro-Genetic Algorithm Controller (NGAC), Hybrid Neuro-Fuzzy controller (NFC) and Hybrid Neuro-Fuzzy controller (NFC) based on Genetic Algorithm (GA) under the effect of external load for improving the transient and steady state response is presented. The applications of the three phase permanent magnet brushless direct current (PMBLDC) motor are increasing day by day. In order to have proper utilization of these motors and to control them effectively it is important to have proper mathematical modeling of these motors. Similarly effective control these motors are also essential to have successful application of the devices across multiple domains. This paper handles both these important aspects. A mathematical model has been derived to represent a three phase permanent magnet brushless direct current (PMBLDC) motor model, its utility can be noted from the fact that different motors can be analyzed easily using the proposed model. The mathematical model was subjected to open loop and closed loop analysis to study the stability and performance. In this paper in order to validate the approach a MATLAB/SIMULINK model having intelligent controllers are constructed to control the modeled three phase permanent magnet brushless direct current (PMBLDC) motor under the effect of external disturbances for enhancement of static & dynamic response.

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## INTRODUCTION

Conventional DC motors have many attractive properties such as high efficiency and linear torque-speed characteristics. The control of DC motors is also simple and does not require complex hardware. However, the main drawback of the DC motor is the need of periodic maintenance. The brushes of the mechanical commutator eventually wear out and need to be replaced. The mechanical commutator has other undesirable effect such as sparks, acoustic noise and carbon particles coming from the brushes. Permanent magnet brushless direct current (PMBLDC) motors can in many cases replace conventional DC motors. Despite the name, PMBLDC motors are actually a type of permanent magnet synchronous motors. They are driven by DC voltage but current commutation is done by solid state switches. The commutation instants are determined by the rotor position and the position of the rotor is detected either by position sensors or by sensorless techniques. PMBLDC motors have many advantages over conventional DC motors. A few of these are (1-2): Long operating life, high dynamic response, high efficiency, better speed vs. torque characteristics, noiseless operation, higher speed range and higher torque-weight ratio. PMBLDC motors are available in many different power ratings, from very small motors as used in hard disk drives to large motors used in electric vehicles.

Three-phase motors are most common but two-phase motors are also found in many application. The purpose of this paper is to build a simple, accurate and fast running Matlab model of a three phase permanent magnet brushless direct current (PMBLDC) motor. In addition to that, modeling, control, simulation and performance analysis of the three phase permanent magnet brushless direct current (PMBLDC) motor using Fuzzy Logic Controller (FLC), hybrid Fuzzy-Genetic Algorithm controller (FGAC), hybrid Neuro-Genetic Algorithm Controller (NGAC), Hybrid Neuro-Fuzzy controller (NFC) and Hybrid Neuro-Fuzzy controller (NFC) based on Genetic Algorithm (GA) under the effect of external disturbances for improving the transient and steady state response is presented. This paper is organized as follows. Mathematical modeling of the three-phase permanent magnet brushless direct current (PMBLDC) motor is given in Sec. II. Materials and methods are given in Sec. III. Analysis of Simulation Results is given in Sec. IV. Conclusion is demonstrated in Sec. V.

## MATHEMATICAL MODELING OF THE THREE PHASE PERMANENT MAGNET BRUSHLESS DIRECT CURRENT (PMBLDC) MOTOR

The mathematical model of the three phase PMBLDC motor is fundamental for the corresponding performance analysis and control system design. The common mathematical models, which mainly include differential equation model, transfer function model, and state-space model, are presented as follow:

**Differential Equation:** The differential equation model is built for a three-phase two-pole PMBLDC motor (3–5). Hence, the simplified schematic diagram of the motor can be obtained as shown in Fig. 1.

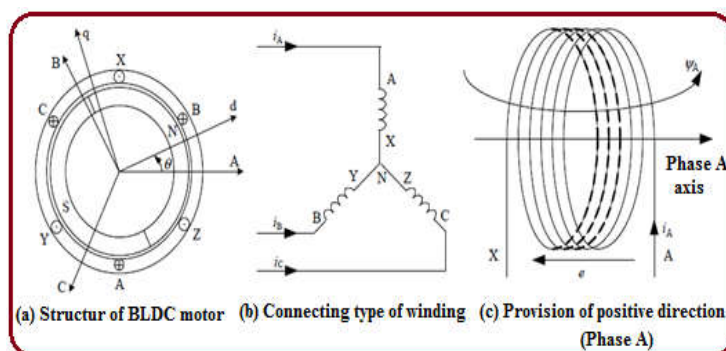


Fig. 1 . Schematic diagram of the PMBLDC motor

Under the positive direction shown in Fig.1, the phase voltage of each winding, which includes the resistance voltage drop and the induced EMF, can be expressed as

$$V_x = R_x i_x + e_{\psi x} \quad (1)$$

Where

$V_x$ :  $\rightarrow$  phase voltage, in which subscript  $x$  denotes phase  $A$ ,  $B$  and  $C$ ;

$i_x$ :  $\rightarrow$  phase current.

$e_{\psi x}$ :  $\rightarrow$  phase-induced EMF.

$R_x$ :  $\rightarrow$  phase resistance. For three-phase symmetrical winding, there exists  $R_A = R_B = R_C = R$ .

The winding-induced EMF is equal to the change rate of the flux, the induced EMF can be written as

$$e_{\psi x} = \frac{d\psi_x}{dt} \quad (2)$$

Taking phase  $A$  for example, the flux is given as

$$\psi_A = L_A i_A + M_{AB} i_B + M_{AC} i_C + \psi_{pm}(\theta) \quad (3)$$

Where

$\psi_{pm}(\theta)$ :  $\rightarrow$  is permanent magnet (PM) flux linkage of phase ( $A$ ,  $B$ ,  $C$ ).

$\theta$ :  $\rightarrow$  is position angle of rotor, the angle between rotor  $d$ -axis and the axis of phase  $A$  or  $B$  or  $C$ .

$L_A = L_B = L_C$ :  $\rightarrow$  is self-inductance of phase  $A$  or phase  $B$  or phase  $C$ .

$M_{BA} = M_{CA} = M_{CB}$ :  $\rightarrow$  is mutual inductance of phase  $A$  with phase  $B$  and phase  $C$  with phase  $B$  and phase  $C$ .

The PM flux of phase  $A$  is

$$\psi_{pm}(\theta) = N\phi_{pm}(\alpha) \quad (4)$$

$$\phi_{pm}(\alpha) = \int_{\frac{\pi}{2}+\alpha}^{\frac{\pi}{2}+\alpha} B(\theta)Sd\theta \quad (5)$$

Where

$\psi_{pm}(\alpha)$  :→ PM flux of phase A when the rotor position angle is  $\alpha$  ;

$B(\theta)$  :→ PM rotor radial flux density in the air gap, which is in a trapezoidal distribution along  $\theta$

$N$  :→ turns of winding;

$S$  :→ product of rotor radius and effective length of conductors.

Substituting Equations (2)–(5) into Equation (1), we can get

$$V_A = Ri_A + \frac{d}{dt}(L_A i_A + M_{AB} i_B + M_{AC} i_C + \psi_{pm})$$

$$V_A = Ri_A + \frac{d}{dt}(L_A i_A + M_{AB} i_B + M_{AC} i_C) + \frac{d}{dt} \left[ NS \int_{\frac{\pi}{2}+\theta}^{\frac{\pi}{2}+\theta} B(x) dx \right]$$

$$V_A = Ri_A + \frac{d}{dt}(L_A i_A + M_{AB} i_B + M_{AC} i_C) + e_A \quad (6)$$

where

$e_A$ :→ represents the back-EMF of phase A.

The three-phase stator windings are symmetrical, the self-inductances will be equal, and so as the mutual inductance. That is  $L_A=L_B=L_C=L$ .

$$M_{BA}=M_{AB}=M_{CA}=M_{AC}=M_{CB}=M_{BC}=M.$$

Substituting them into Equation (6), we can get

$$V_A = Ri_A + L \frac{di_A}{dt} + M \frac{di_B}{dt} + M \frac{di_C}{dt} + e_A \quad (7)$$

Then, the  $\theta$  -dependent back-EMF wave of phase A is  $\pi/2$  ahead of the distribution of the magnetic density in air gap, and  $e_A$  can be expressed as

$$e_A = \omega \psi_m f_A(\theta) \quad (8)$$

Where

$\omega$ :→ is the electrical angular speed of motor.

$\psi_m$  :→ maximum value of PM flux linkage of each winding,  $\psi_m=2NSB_m$ ;

$B_m$  :→ maximum value of PM density distribution in air gap;

$f_A(\theta)$  :→ back-EMF waveform function of phase A.

As for the three-phase symmetrical windings, there also exist  $f_B(\theta) = f_A(\theta - 2\pi/3)$ , and  $f_C(\theta) = f_A(\theta + 2\pi/3)$ . As the currents of the three phases satisfy

$$i_A + i_B + i_C = 0 \quad (9)$$

Equation (6) can be further simplified as

$$V_A = Ri_A + (L - M) \frac{di_A}{dt} + e_A \quad (10)$$

Then, the matrix form of phase voltage equation of PMBLDC motor can be expressed as

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L - M & 0 & 0 \\ 0 & L - M & 0 \\ 0 & 0 & L - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \quad (11)$$

According to Equation (11), the equivalent circuit of the PBLDC motor can be shown as in Fig.3.

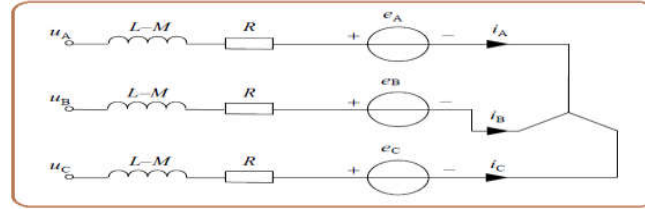


Fig. 3. Equivalent circuit of the PBLDC motor

The line voltage equation can be obtained through subtraction calculation of the phase voltage equation as

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A - e_B \\ e_B - e_C \\ e_C - e_A \end{bmatrix} \quad (12)$$

The power transferred to the rotor, which is called the electromagnetic power, equals the sum of the product of current and back-EMF of the three phases. That is

$$P_e = e_A i_A + e_B i_B + e_C i_C \quad (13)$$

Ignoring the mechanical loss and stray loss, the electromagnetic power is totally turned into kinetic energy, so

$$P_e = T_e \omega \quad (14)$$

Where

$T_e$ : → electromagnetic torque;

$\omega$ : → angular velocity of rotation.

Hence, from Equations (13) and (14), we can get

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\omega} \quad (15)$$

Substituting Equation (8) into Equation (15), another form of the torque equation can be

$$T_e = P[\psi_m f_A(\theta) i_A + \psi_m f_B(\theta) i_B + \psi_m f_C(\theta) i_C] \quad (16)$$

Where

$P$ : → is the number of pole pairs. The currents that have the same amplitude and the opposite direction only flow through two-phase windings of the Y-connected motor at any time, so Equation (16) can be further simplified as represented as

$$T_e = 2P\psi_m i_A = K_T i \quad (17)$$

where

$K_T$ : → the torque coefficient;

$i$ : → the steady phase current.

In order to build a complete mathematical model of the electromechanical system, the motion equation has to be included as

$$T_e - T_L = J \frac{d\omega}{dt} + B_v \omega \quad (18)$$

Where

$T_L$ : → load torque;

$J$ : → rotor moment of inertia;

$B_v$ : → viscous friction coefficient.

Thus, Equations (11), (15) and (18) constitute the differential equation mathematical model of the PMBLDC motor.

**Transfer Functions:** Suppose that the three-phase PMBLDC motor is controlled by the full-bridge driving in the two-phase conduction mode, then when the windings of phase A and B are conducted, there exists

$$\begin{cases} i_A = -i_B = i \\ \frac{di_A}{dt} = -\frac{di_B}{dt} = \frac{di}{dt} \end{cases} \tag{19}$$

Thus, the line-voltage  $V_{AB}$  in Equation (12) can be rewritten as

$$V_{AB} = 2Ri + 2(L - M)\frac{di}{dt} + (e_A - e_B) \tag{20}$$

Take the transient process out of consideration (i.e. ignore the trapezoid bevel edge), then the steady  $e_A$  and  $e_B$  are equal in amplitude and opposite in direction when phases A and B are turned on. So, Equation (20) can be expressed as

$$\begin{aligned} V_{AB} &= V_d = 2Ri + 2(L - M)\frac{di}{dt} + 2e_A \\ V_{AB} &= V_d = r_a i + L_a \frac{di}{dt} + k_e \omega \end{aligned} \tag{21}$$

where

- $V_d$ : → DC bus voltage;
- $r_a$ : → line resistance of winding,  $r_a = 2R$  ;
- $L_a$ : → equivalent line inductance of winding,  $L_a = 2(L - M)$  ;
- $k_e$ : → coefficient of line back-EMF,
- $k_e = 2p\psi_m = 4pNSB_m$ .

Equation (21) is exactly the armature voltage loop equation when two phase windings are excited, and the corresponding equivalent circuit is shown in Fig. 3.

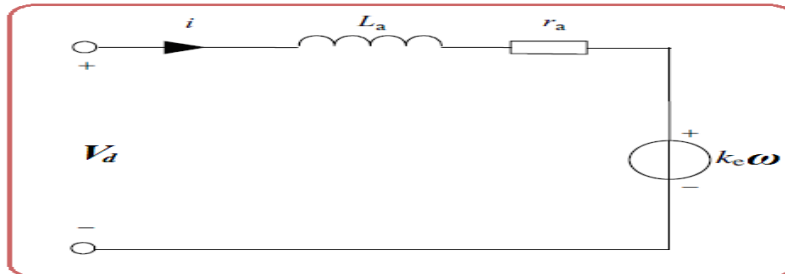


Fig. 4. Equivalent circuit of the PMBLDC motor with two phase windings excited.

So, substituting Equation (17) into Equation (18), we get

$$K_T i - T_L = J \frac{d\omega}{dt} + B_V \omega \tag{22}$$

First, when the PMBLDC motor runs with no load, the current is given as

$$i = \frac{J}{K_T} \frac{d\omega}{dt} + \frac{B_V}{K_T} \omega \tag{23}$$

Substituting Equation (23) into Equation (21), we get

$$V_d = r_a \left( \frac{J}{K_T} \frac{d\omega}{dt} + \frac{B_V}{K_T} \omega \right) + L_a \frac{d}{dt} \left( \frac{J}{K_T} \frac{d\omega}{dt} + \frac{B_V}{K_T} \omega \right) + k_e \omega \tag{24}$$

Also, it can be rearranged as

$$V_d = \frac{L_a J}{K_T} \frac{d^2 \omega}{dt^2} + \frac{r_a J + L_a B_V}{K_T} \frac{d\omega}{dt} + \frac{r_a B_V + K_T k_e}{K_T} \omega \tag{25}$$

By Laplace transformation of Equation (25), the transfer function of a PMBLDC motor can be expressed as

$$G_u(s) = \frac{\omega(s)}{V_d(s)} = \frac{K_T}{L_aJs^2 + (r_aJ + L_aB_V)s + (r_aB_V + K_Tk_e)} \tag{26}$$

Thus, the structure of a PMBLDC motor control system with no load can be built as shown in Fig.5.

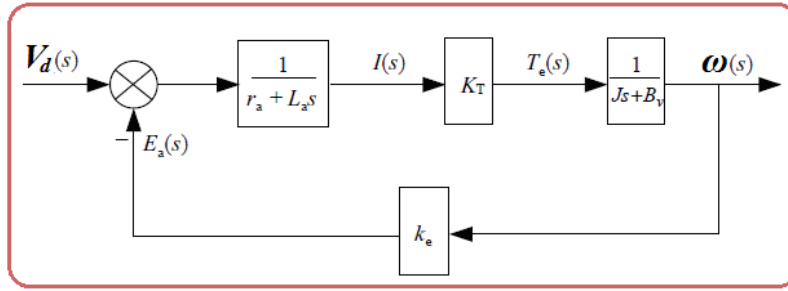


Fig. 5. Structure of PMBLDC motor control system withno load

In the following, the transfer function of a PMBLDC motor when the load torque is not zero, it is shown in Fig. 5.

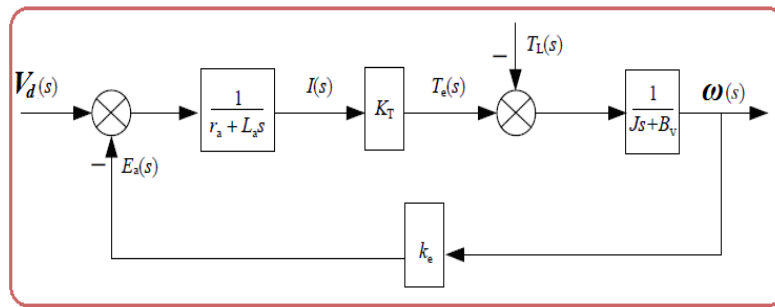


Fig. 6. Structure diagram of PMBLDC motor with load torque

For such a system, the superposition principle holds. Thus, the output of the system equals the sum of outputs when  $V_d(s)$  and  $T_L(s)$  are applied to the system, respectively. In Fig. 6, when  $V_d(s)=0$  holds, then

$$\left[ -k_e \frac{1}{r_a + L_a s} K_T \omega(s) - T_L(s) \right] \frac{1}{Js + B_v} = \omega(s) \tag{26}$$

So

$$\omega(s) \left[ \frac{(r_a + L_a s)(Js + B_v) + K_T k_e}{(r_a + L_a s)} \right] = -T_L(s) \tag{27}$$

Then, the transfer function between load torque and speed is

$$G_L(s) = \frac{\omega(s)}{T_L(s)} = - \frac{r_a + L_a s}{L_a Js^2 + (r_a J + L_a B_V)s + (r_a B_V + K_T k_e)} \tag{28}$$

Therefore, the speed response of a PMBLDC motor affected together by voltage and load torque is given by

$$\omega(s) = G_u(s)V_d(s) + G_L(s)T_L(s)$$

$$\omega(s) = \frac{K_T V_d(s) - (r_a + L_a s)T_L(s)}{L_a Js^2 + (r_a J + L_a B_V)s + (r_a B_V + K_T k_e)} \tag{29}$$

### III. MATERIALS AND METHODS

#### A.A. Fuzzy Logic Controller (FLC)

The concept of fuzzy logic was developed by LotfiZadeh in 1964 to address uncertainty and imprecision which widely exist in engineering problems. Fuzzy modeling is the method of describing the characteristics of a system using fuzzy inference rules. The method has a distinguishing feature in that it can express linguistically complex nonlinear systems. It is however, very hard to identify the rules and tune the membership functions of the fuzzy reasoning. Fuzzy controllers are normally built with the use of fuzzy rules. These fuzzy rules are obtained either from domain experts or by observing the people who are currently doing the control. The membership functions for the fuzzy sets will be derived from the information available from the domain experts and/or observed control actions. The building of such rules and membership functions require tuning. That is, performance of the controller must be measured and the membership functions and rules adjusted based upon the performance. This process will be time consuming. The basic configuration of Fuzzy Logic Controller (FLC) consists of four main parts (i) Fuzzification where

values of input variables are measured and a scale mapping that transforms the range of values of input variables into corresponding universe of discourse is performed then performs the function of fuzzification that converts input into suitable linguistic values, which may be, viewed labels of fuzzy sets. (ii) Knowledge Base consists of data base and linguistic control rule base. The database provides necessary definitions, which are used to define linguistic control rules and fuzzy data, manipulation in an FLC. The rule base characterizes the control goals and control policy of the domain experts by means of set of linguistic control rules. (iii) The Decision Making Logic, it has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. (iv) The Defuzzification a scale mapping which converts the range of values of input variables into corresponding universe of discourse (6-10). In view to make the controller insensitive to system parameters change, fuzzy logic theory is also implemented by researchers extensively. Indulkar et. al (11) initially designed a controller using fuzzy logic for automatic generation control and responses were compared with classical integral controller. Chang et. al. (12) presented a new approach to study the LFC problem using fuzzy gain scheduling of proportional-integral controllers and proposed scheme has been designed for a four area interconnected power system with control deadbands and generation rate constraints. Ha (13) applied the robust sliding mode technique to LFC problem where, control signal consists of an equivalent control, a switching control and fuzzy control with generation rate constraints and governor's backlash on the other hand the fuzzy controller designed by Chown et. al (14) when implemented not only grid was controlled better but also more economically. Talaq et. al (15) in their research proposed an adaptive controller which requires less training patterns as compared with a neural net based adaptive scheme and performance was observed better than fixed gain controller. Ha et. al (16) proposed an approach which combines the salient features of both variable structure and fuzzy systems to achieve high performance and robustness. Fuzzy logic controller, designed by El-Sherbiny (17), is a two layered fuzzy controller with less overshoot and small settling time as compared with conventional one. Ghoshal (18) presented a self adjusting, fast acting fuzzy gain scheduling scheme for conventional integral gain automatic generation controller for a radial and ring connected three equal power system areas. Yensil et. Al (19) proposed a self tuning fuzzy PID type controller for LFC problem and satisfactory results are found when compared with fuzzy PID type controller without self tuning.

### **Artificial Neural Network Controller (ANNC)**

Artificial Neural Networks are commonly referred as connectionist networks or simply neural networks, have been motivated from the recognition that the brain performs certain tasks much more efficiently in an entirely different way than the conventional digital computers. The neurons are the structural constituents of the brain, which are highly complex non-linear and parallel processing system. ANNs are massively parallel-interconnected networks of simple elements known as artificial neurons and their connectivity is intended to interact with the objects of the real world, in a similar manner as the biological nerves systems do. Neural networks have emerged as a powerful technique for pattern recognition, control, functional mapping and generalization. Neural networks are divided into classes based on network topology, computational element characteristic and training or learning rules. The basis features of neural networks are (i) High computational rates due to the massive parallelism. (ii) Fault tolerance (damage to a few nodes does not significantly implies over all performance) (iii) Learning or training (the network adopts itself, based on the information received from the environment). (iv) Goal-seeking (the performance to achieve the goal is measured and used to self organize the system, programmed rules are not necessary). (v) Primitive computational elements. The starting point of ANN was the training algorithm proposed by Hebb in 1949, which demonstrated how a network of neurons could exhibit learning behavior. The main advantages of ANN technology are: (i) It is fast (ii) It possesses learning ability (iii) It adapts to the data (iv) It is robust (v) It is appropriate for nonlinear modeling (20-25). General information on neural network and their applications in power systems have been presented in literature extensively. Beaufays et. Al (26) describes an application of layered neural network to nonlinear power systems control which latter applied to control the turbine reference power of a computer simulated generator unit while Birch et. al (27) investigated the use of neural networks to act as the control intelligence in conjunction with a standard adaptive load frequency control scheme. El-Metwally et. al (28) applied ANN to integrate the automatic voltage regulator and the conventional power system stabilizer into a single controller. Chaturvedi et al (29) have developed an automatic load frequency controller using ANN to regulate the power output and system frequency by controlling the speed of the generator with the help of water or steam flow control. Salem et. Al (30) in their paper implemented the experimental verification of a simple neuro-controller as an excitation controller for a physical model of a single machine infinite bus power system. Another single ANN controller is designed in (31) which controls the input of each area in the power system together. Comparing the results of both conventional and ANN controllers, performance of ANN controller is found better. Demiroren et. al in (32) designed the controller, taking the governor deadband effect and reheater effect, for two area interconnected power system but in (33) a dynamic neural network model for adaptive load frequency control is designed.

**Genetic Algorithm (GA):** One of the newer and relatively simple optimization approaches is the genetic algorithm (GA). Perhaps one of the most attractive qualities of GA is that it is a derivative free optimization tool. Hence, it does not rely on a detailed model of the system to be optimized. This superiority of GA, over other algorithms or search techniques, becomes apparent when the search space is large or discontinuous; however, it can be equally useful in problems similar to the one at hand, where optimization is performed more than just a few times. The GA starts by randomly creating an initial population of binary strings. Each of these strings is called a chromosome, and it represents a candidate solution to the search problem. The binary strings are then converted to their decimal equivalents and tested to how "fit" they are. A better solution should be reflected in a higher fitness function. The fitness function is an integral part of the algorithm and it is practically the only channel between the algorithm and the problem being solved. Therefore, it should be carefully chosen. GA employs three operators: reproduction, crossover, and mutation. To create new generation, fitness-proportionate reproduction is achieved through a weighted roulette wheel. Consequently, fitter chromosomes have higher probability of reproduction.

Next, crossover is performed on two strings (at a time) that are randomly selected from the population. Crossover involves choosing a random position in the two strings and swapping the binary bits that occur after this position. It is performed on only a specified percentage of each generation. The final operation, mutation, is performed providently, typically every 100 or more crossover operations.

It involves choosing a random string and a random bit within the string. The bit is changed from 1 to 0, or visa-versa. By the end of mutation operator, a new generation is complete and the process is repeated by evaluating the new fitness. (34-38). The objective functions are MSE (Mean Square Error), IAE (Integral Absolute Error), ISE (Integral Square Error) and ITAE (Integral Time Absolute Error). The main objective of intelligent controller is to minimize the error signal or in other words, the minimization of performance indices.

$$MSE = \frac{1}{t} \int_0^t ((e(t))^2) dt \tag{33}$$

$$IAE = \int_0^t |e(t)| dt \tag{34}$$

$$ISE = \int_0^t |e(t)|^2 dt \tag{35}$$

$$ITAE = \int_0^t t|e(t)| dt \tag{35}$$

**Hybrid Neuro-Fuzzy Controller (NFC) based on Genetic Algorithm (GA):** To develop more new methods, the new ways is tried. Mixture control that is inter-mixed adaptive, fuzzy logic control method, neural network control method and genetic algorithm control method is predicted the influential method. In this paper, three technologies were focused, namely Neural Network (NN), Fuzzy Logic (FL), and Genetic Algorithms (GA) and their hybrid combinations. As illustrated in above Fig. 8 (39).

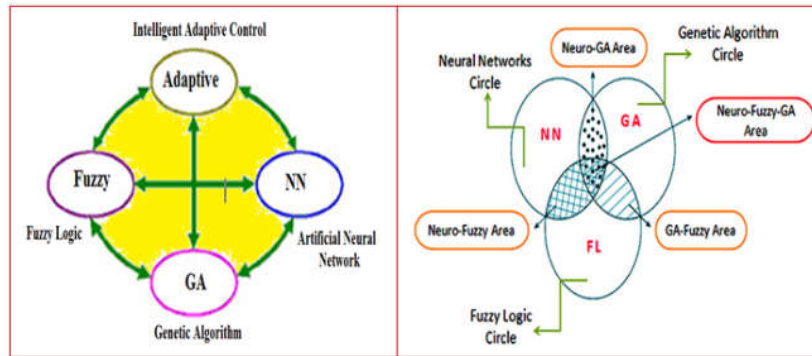


Fig. 8. Combinations of Artificial Neural Networks (ANNs), Fuzzy Logic (FL), and Genetic Algorithm (GA) technologies

Table I. Advantages and disadvantages of the nns, fl and gas

Technology	Advantage	Disadvantage
Artificial Neural Networks (NNS)	Adaptation, learning, approximation	Slow convergence speed, ‘black box’ data processing structure
Fuzzy Logic (FL)	Approximate reasoning	Difficult to tune, lacks effective learning capability
Genetic Algorithm (GA)	Systematic random search, derivative-free optimization	Difficult to tune, no convergence criterion

This paper is consisted of hybrid artificial intelligent controllers that are a mixed fuzzy logic controller (FLC), artificial neural network controller (ANNC) and genetic algorithms (GA). These artificial intelligent controllers control PMBLDC motor with high performance. This paper presents an application of Neuro-Fuzzy controller for PMBLDC motor speed optimized with Genetic Algorithms (GAs). First, the controller is designed according to Fuzzy rules such that the systems are fundamentally robust. Secondly, a Neuro-Fuzzy controller of the PMBLDC motor speed is then designed and simulated; the Neuro-Fuzzy controller has the advantage of expert knowledge of the Fuzzy inference system and the learning capability of neural networks.

Finally, the Neuro-Fuzzy controller is optimized by Genetic Algorithms (GAs). Genetic Algorithm (GA) is a random search technique that imitates natural evolution with Darwinian survival of the fittest approach. GAs perform on the coding of the parameters and not on the exact parameters, therefore, it does not depend on the continuity of the parameter nor the existence of derivatives of the functions as needed in some conventional optimization algorithms. Neuro-Fuzzy logic controller (NFLC) is formulated by using the GA approach (Tuning of the NFLC Parameters by GA), where all the parameters of the NFLC are initially randomized, then being tuned and optimized simultaneously by GA. To descry be the GA optimizationprocess, consider the functional block diagrams shownin Fig. 9.



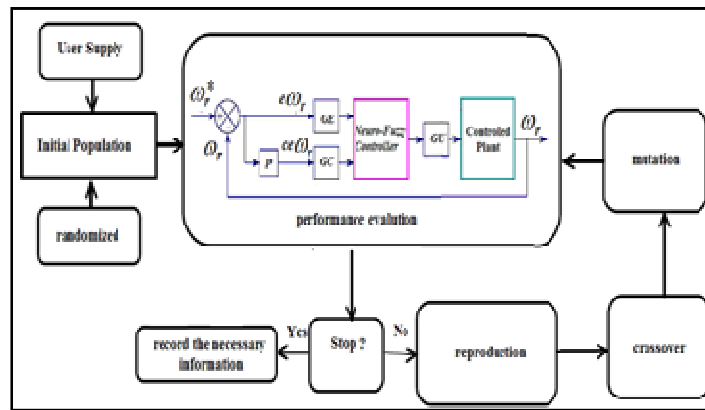


Fig. 9. A functional block diagram showing the GA optimization process

The modeling of three phase permanent magnet brushless direct current (PMBLDC) motor with different types of controllers has been derived. In addition to that, simulation and performance analysis of the three phase PMBLDC motor with and without intelligent controllers have been implemented and investigated by using MATLAB/SIMULINK software.

**Design Requirements of the control system:** The goal of control engineering design is to obtain the configuration, specifications, and identification of the key parameters of a proposed system to meet an actual need. The design process is arranged into three groups (40-41): Establishment of goals and variables to be controlled, The most basic requirement of three phase PMBLDC motor is that it should rotate at the desired output response (desired value or reference input), as well as, intelligent controllers are used for reducing the sensitivity of the actual output response to external load (external disturbances), load variations (changes in the torque opposed by the motor load), noise and parameters changes, where the actual output response variations induced by such disturbances must be minimized. The design requirements for the system in terms of time response specifications as shown on Table II.

Table I I. Design Requirements of the System in Terms of the Time Response (Transient And Steady State Response)

Time Domain Specifications	Design requirements of the system	
Settling Time ( $t_s$ )	< 0.5 sec	or < 500 ms
Maximum Overshoot ( $M_p$ )	< 5%	
Peak Time ( $t_p$ )	< 0.15 sec	or < 150 ms
Rise Time ( $t_r$ )	< 0.1 sec	or < 100 ms
Damping ratio ( $\zeta$ )	$0.65 < \zeta < 0.75$	
Steady state error ( $e_{ss}$ )	< 0.02	or 2%

**Simulation and analysis of Three Phase PMBLDC Motor with Hybrid Neuro-Fuzzy Controller (NFC) Based on Genetic Algorithm (GA)**

The block diagram of PMBLDC motor with neuro-fuzzy controller (NFC) based on genetic algorithm (GA) under the effect of external load is shown in Fig. 11.

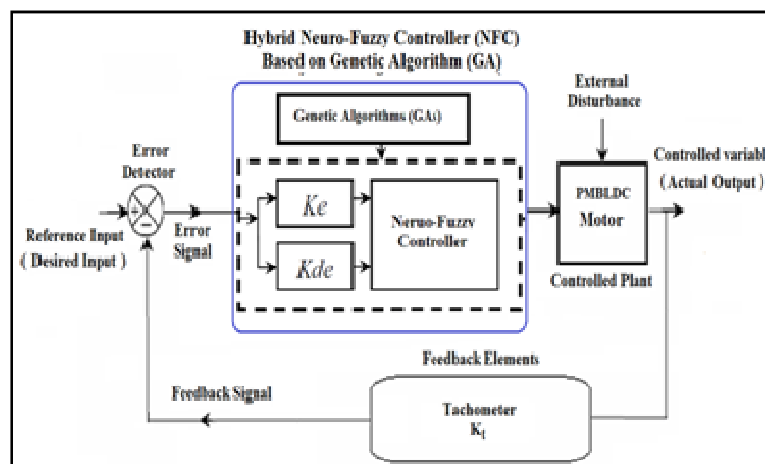


Fig. 11. The block diagram of PMBLDC Motor with Neuro-Fuzzy controller (NFC) based on Genetic Algorithm (GA) under the effect of external load

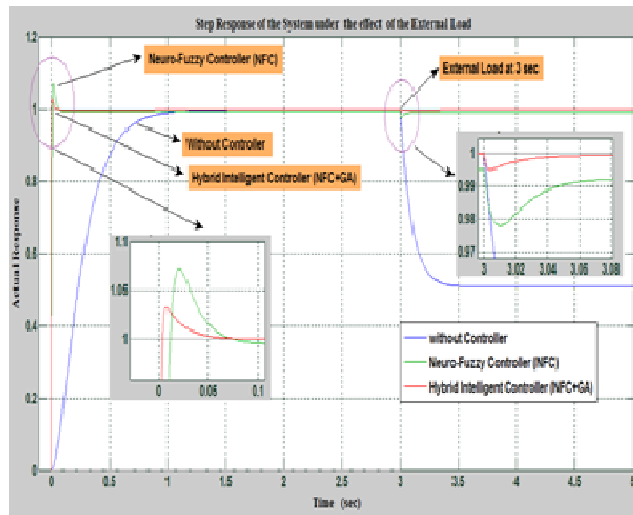


Fig. 12. Simulation of PMBLDC Motor with and without Intelligent Controllers under the effect of external load Table I II The Simulation Results Of Pmbldc Motor With Intelligent Controllers Under The Effect Of External Load

PMBLDC Motor under the effect of the load External disturbances and noise					
Specifications	Strategy of Control				
	Fuzzy Logic Control Method	Fuzzy-GA Control Method	Neuro-GA Control Method	Neuro-Fuzzy Control Method	Neuro-Fuzzy-GA Control Method
Damping ratio ( $\xi$ )	0.53291	0.64152	0.66926	0.6437	0.74021
Settling Time ( $t_s$ )	0.0609 sec	0.0352 sec	0.04 sec	0.046 sec	0.017 sec
Maximum Overshoot (%Mp)	13.8235 %	7.2429 %	5.9031 %	7.1254 %	3.1631 %
Steady-State Error ( $e_{ss}$ )	0.0000010376	0.00000030897	0.00040787	0.004739	0.0000087453
Peak Time ( $t_p$ )	0.0292 sec	0.0135 sec	0.017 sec	0.0207 sec	0.0075 sec
Rise Time ( $t_r$ )	0.012 sec	0.0048 sec	0.0061 sec	0.0077 sec	0.0023 sec

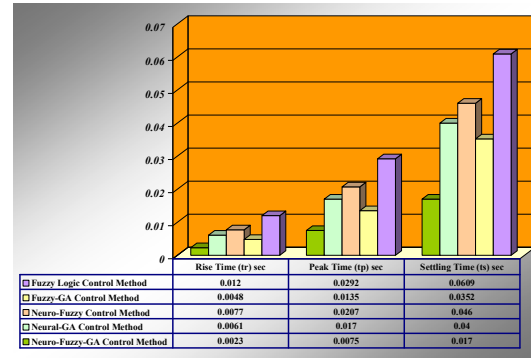


Fig. 13. Comparison of settling time (ts), peak time (tp) and rise time (tr) for intelligent controllers

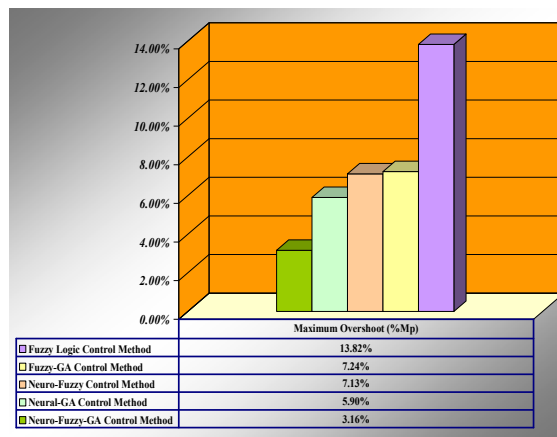


Fig. 14. Comparison of maximum overshoot (%Mp) for intelligent controllers.

PMBLDC motor with intelligent controllers under the effect of the external disturbances and noise 'has been simulated via MATLAB/SIMULINK software as shown in Fig. 12. In order to illustrate the performance of hybrid neuro-fuzzy controller (NFC) based on genetic algorithm (GA) comparison to the other intelligent controllers is used. Table 3 lists the Comparison of the performances of intelligent controllers, to show the effectiveness of the proposed approach (Hybrid Neuro-Fuzzy controller (NFC) based on Genetic Algorithm (GA)). Table 3 shows The simulation results of PMBLDC Motor with intelligent controllers under the effect of external load in terms of time response specifications, hybrid neuro-fuzzy controller (NFC) based on genetic algorithm (GA) shows much low overshoot than the other intelligent controllers. Similarly the settling time ( $t_s$ ), Rise Time ( $t_r$ ), Steady-State Error ( $e_{ss}$ ) and peak time ( $t_p$ ) in hybrid neuro-fuzzy controller (NFC) based on genetic algorithm (GA) is better than the other controllers. Fig. 13 and Fig. 14 show the performance comparison of the various parameters for intelligent controllers.

## CONCLUSION

This paper has demonstrated that the performance of a Neuro-Fuzzy Controller (NFC) can be improved by using a Genetic Algorithm (GA) search procedure. First, the controller is designed according to Fuzzy rules such that the systems are fundamentally robust. Secondly, a Neuro-Fuzzy controller of the PMBLDC motor speed is then designed and simulated; the Neuro-Fuzzy controller has the advantage of expert knowledge of the Fuzzy inference system and the learning capability of neural networks. Finally, the Neuro-Fuzzy controller is optimized by Genetic Algorithms (GAs). The actual output response of the three phase permanent magnet brushless direct current (PMBLDC) Motor is controlled by means of the five different methods (Fuzzy Logic Control method, hybrid Fuzzy-Genetic Algorithm Control method, hybrid Neuro-Genetic Algorithm Control method, Hybrid Neuro-Fuzzy Control method and Hybrid Neuro-Fuzzy based on Genetic Algorithm Control method) for enhancement the stability and accuracy under the effect of load variations, external disturbances, noise and parameters changes. In this paper, with reference to the results of the computer simulation by using (MATLAB & SIMULINK) software, the performance characteristics of intelligent controllers are compared in terms of the time response. The simulation results illustrate that hybrid neuro-fuzzy controller (NFC) based on genetic algorithm (GA) performs better than the other intelligent controllers and has verified all design requirements of the system. hybrid neuro-fuzzy controller (NFC) based on genetic algorithm (GA) is the best Controller which presented satisfactory performances and possesses good robustness. This control seems to have a lot of promise in the applications of power electronics.

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