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Direct Torque Control of a Bldc Motor Based on Computing Technique

Sajitha P[1], Mr. Jashper Ali M[2]
Assistant Professor Department Of Electrical And Electronics Engineering Shm Engineering College Kadakkal
Assistant Professor Department of Electrical and Electronics Engineering Prist University Trichy

Abstract: *This paper discusses about the speed control technique for brushless DC motors with non-sinusoidal back electromotive force. In order to solve the problems associated with conventional PI speed controller, a new speed control based on o fuzzy inference system is proposed to eliminate overshoot in the torque and speed responses, simplify designing and reduce complexity of math formulas. The effectiveness of proposed system has been validated by simulation results.*
Keywords: *Brushless DC Motor, Fuzzy Logic Controller, PI Controller.*

I. Introduction

Permanent Magnet Brushless Direct Current (PMBLDC) is becoming prominent as the demand for efficiency, precise speed and torque control, reliability and ruggedness increases. Brushless (BLDC) provide high efficiency and exemplary precision of control when compared to conventional motors. It has the best torque Vs. weight or efficiency characteristics. They are used in military, grinding, aircraft, automotive applications, communications equipment etc [1]. The theory of brushless dc motors was presented in 1962 by T.G. Wilson and P. H. Trickey. But the limitations in magnet and power switching have prevented them to bring into real life. In 1980, Power tec. Industrial Corporation started manufacturing them [2&3]. Brushless, as the name implies there are no brushes and commutators. In conventional motors, the switching of current in the armature coils is done using the combination of brushes and commutators whereas in the brushless, the commutation is performed with the help of electronic circuit, which reduces the mechanic losses and improves the efficiency. There are many other merits of brushless motors over the conventional motors.

- The brushless machines require less maintenance.
- Speed/torque characteristics are flat which enables operation at all speeds with rated load. Whereas brushed dc motors have moderately flat characteristics.
- The electric noise generation is low for brushless dc motor.
- Brushless motors have low rotor inertia which improves dynamic response.
- They have higher speed range and output power to frame size ratio.

Direct Torque Control (DTC) method proposed in [1], [2] has been utilized to drive the BLDC motors. DTC which is a lso known as conventional DTC has features such as fast torque response, simple and robust design. These features have made it popular in industrial applications. This control method operates in a two-phase conduction mode which is simplified to just a torque controlled drive by intentionally keeping the stator flux linkage amplitude almost constant by eliminating the flux control in the constant torque region. Because of sharp changes in commutation region, amplitude of stator flux linkage cannot easily be controlled. Recently, fuzzy inference system (FIS) is widely used because of its good performance, specially in cases when the system or process is complicated and classical method cannot work well. Additionally, fuzzy system formulates human knowledge in systematic manner and puts them into engineering systems. But there is a problem associated with FIS, which is the time consuming process to tune the parameters of FIS relying on human knowledge by trial and error. So, there has been recently a surge of interest to combine neural network and FIS because of its both advantages of fuzzy inference systems and artificial neural networks, [3]. An adaptive Neuro-Fuzzy Inference System (ANFIS), developed in 1993 by Jyh-S Roger Jang, [4].

In this paper an Fuzzy controller, is proposed for a BLDC motor. A comparison study is done with a PI controller, for which the proportional and integral constants are tuned.

II. Brushless Dc Motor

Brushless DC Motors are driven by DC voltage, but current commutation, is controlled by solid state switches. The commutation instants are determined by the rotor position[1]. Sensorless techniques need extra computation time and external circuitry to estimate the back-EMF, than the sensor-based systems. Moreover, sensorless techniques demand high performance processors, large program codes, and large memory. In sensor based system the Hall sensors are used to determine the position of the rotor at any instant of time [2][3].The rotor shaft position is sensed by a Hall Effect sensor, which provides signals to the respective switches.

Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating either N or S pole is passing near the sensors.The numbers shown around the peripheral of the motor diagram in figure 1 represent the sensor position code. The north pole of the rotor points to the code that is output at that rotor position. The numbers are the sensor logic levels where the Most Significant bit is sensor C and the Least Significant bit is sensor A.

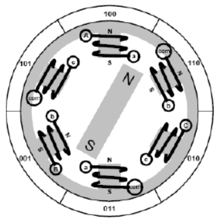


Figure 1: BLDC Motor Star connected

Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.These signals are decoded by combinational logic to provide the firing signals for 120° conduction on each of the three phases. The rotor position decoder has six outputs which control the upper and lower phase leg MOSFETs of figure 2 [4]-[8].The rotor shaft position is sensed by a Hall Effect sensor, which provides signals as represented in Table 1.

In the figure 2 shown below, at any specific instant, one MOSFET in the upper leg and one MOSFET in the lower leg will be switched ON. The respective PWM pulses are received from the controller, at appropriate time.

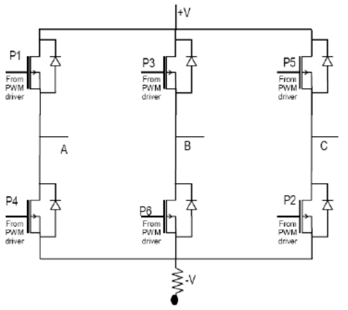


Figure 2: Three Phase Inverter Circuit to BLDC Motor

H_a	H_b	H_c	emf_a	emf_b	emf_c	S_1	S_2	S_3	S_4	S_5	S_6
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
0	1	1	-1	0	+1	0	1	0	0	1	0
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0
1	1	0	0	-1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

Table1: Clockwise Hall Sensor Signals, Phase Voltages and Drive Signal

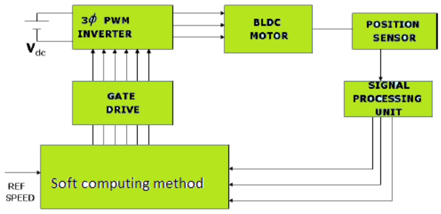
2.1 Four Quadrant Operation

There are four possible modes or quadrants of operation using a Brushless DC Motor. In an X-Y plot of speed versus torque, Quadrant I is forward speed and forward torque. The torque is propelling the motor in the forward direction. Conversely, Quadrant III is reverse speed and reverse torque. Now the motor is “motoring” in the reverse direction, spinning backwards with the reverse torque. Quadrant II is where the motor is spinning in the forward direction, but torque is being applied in reverse. Torque is being used to “brake” the motor, and the motor is now generating power as a result. Finally, Quadrant IV is exactly the opposite. The motor is spinning in the reverse direction, but the torque is being applied in the forward direction. Again, torque is being applied, to attempt to slow the motor and change its direction to forward again. Once again, power is being generated by the motor.The BLDC motor is initially made to rotate in clockwise direction, but when the speed reversal command is obtained, the control goes into the clockwise regeneration mode [7], which brings the rotor to the standstill position. Instead of waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Therefore, there is the necessity for determining the instant when the rotor of the machine is ideally positioned for reversal.

Hall-effect sensors are used to ascertain the rotor position and from the Hall sensor outputs, it is determined whether the machine has reversed its direction. This is the ideal moment for energizing the stator phase so that the machine can start motoring in the counter clockwise direction.

III. Proposed System

In recent years , scientists have obtained important improvement on various types of control technique These control methods, intelligent control algorithms, which ara usually regard as the Combination of FL, NN, genetic algorithm and expert system, has presented special superiorities. The FLC method can be used in systems that have ambiguity or uncertainty. Membership functions with values between 0 and 1 are used in FLC to deal with the control puzzle, such as non-linearity, load disturbance and parameter variation.



3.1 Advantages of the fuzzy systems

. Ability to depict inherent uncertainties of the human knowledge with linguistic variables;
· Simple interaction of the expert of the domain with the engineer designer of the system;
· Easy explanation of the results, because of the natural rules representation;
· Easy extension of the base of knowledge through the addition of new rules;
· Robustness in relation of the possible disturbances in the system .

3.2The disadvantages

· Lacking ability to generalize, or either, it only answers to what is written in its rule-base;
· Not robust in relation the topological variations of the system, such changes would demand alterations in the rule base;
· Depends on the existence of an expert to detect the inference logical rules.

The NN is a computation and information processing method that mimics the process found in biological neurons. The basic element of a NN is the neuron. The relationship between two neurons is defined as the weight, which can be tuned or trained off-line, on-line, or combination of both. However, either FLC or NN has its own drawbacks, which cannot be neglected.

3.3 Advantages of the NNs

· Learning ability;
· Parallel processing;
· Generalization capacity;
· Robustness in relation to disturbances.

3.4 Disadvantages are**:**

· Impossible interpretation of the functionality;
· Difficulty in detection of number of layers and neurons.

Every intelligent technique has special properties (e.g.ability to learn, explanation of decisions) that make them suited for particular applications. For example, while NNs are suitable at recognizing patterns, they are not capable for explaining how they reach their decisions. FL systems, which can reason with imprecise information, are appropriate at explaining their decisions, but they can not automatically acquire the rules they use to make those decisions. These limitations have been a central driving force behind the creation of combination of intelligent systems where two or more techniques are combined in a manner that overcomes the problems and limitations of individual techniques.Usually, all the combinations of techniques based on NNs and FL called NFSs.

3.5 Cooperative Neuro-Fuzzy System

A cooperative system can be considered as a preprocessor wherein NN learning mechanism determines the FIS membership functions or fuzzy rules from the training data. Once the FIS parameters are determined, NN goes to the background.The rule based is usually determined by a clustering approach (self organizing maps) or fuzzy clustering algorithms. Membership functions are usually approximated by NN from the training data. Fig. 1 shows the block diagram of the cooperative NFS.

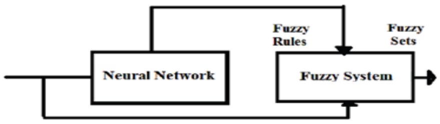


Figure: block diagram of cooperative NFS

IV. Mathematical Modeling Of Bldc Motor

The equivalent circuit of a BLDC motor is shown in Figure. 3. BLDC drive system consists of a BLDC motor, control circuit and sensor for position information. In a BLDC motor drive system position information is obtained from the Hall Effect sensor output. By knowing the position of the rotor and speed error, control circuit will generate the required PWM signals with suitable duty ratio.

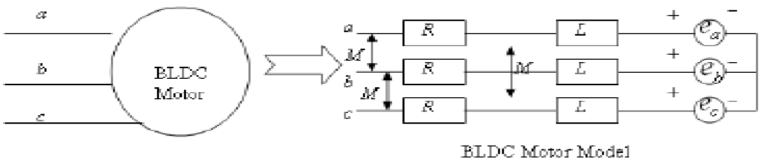


Figure. 3 Structure and Equivalent circuit of BLDC motor

The modeling is based on the following assumptions:
(1) The motor is not saturated.
(2) Stator resistance of all windings is equal and self and mutual inductances are constant.
(3) Power semiconductor devices are ideal.
(4) Iron losses are negligible.

The modeling equations of BLDC motor can be represented in matrix form as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (1)$$

where R_a is the resistance per phase, L_a is the self-inductance per phase, M is the mutual inductance per phase, v_a , v_b , v_c are the stator windings phase-voltage, i_a , i_b , i_c are the stator windings phase-current, e_a , e_b , e_c are the back EMF of stator windings.

The electromagnetic torque is expressed as:

$$T_e = \frac{1}{\omega_r}\left(e_a i_a + e_b i_b + e_c i_c\right) \qquad (2)$$

$$T_e = J\frac{d\omega_r}{dt} + T_L + B\omega_r \qquad (3)$$

Where T_L is the load torque, T_e is the electromagnetic torque, ω_r is motor speed, J is the rotor inertia, B is the damping constant.

Based on the equivalent circuit, the system equations can be expressed by using Laplace transforms as.

$$V_a(s) = L_a I_a(s) + R_a I_a(s) + E(s) \qquad (4)$$

$$E_a(s)=K_E\omega_r(s) \qquad (5)$$

$$T_e(s)=K_T I_a(s) \qquad (6)$$

$$T_e(s) = T_L(s) + sJ\omega(s) + B\omega(s) \qquad (7)$$

For closed loop transfer function put B= 0, then

$G(s) = \frac{\omega_r(s)}{V_a(s)}$ at $T_L(s)=0$

$$G(s) = \frac{1}{K_E(s\tau_m + 1)(s\tau_e + 1)} \quad (8)$$

where Mechanical time constant, $\tau_m = \frac{JR_a}{K_T K_E}$

Electrical time constant, $\tau_e = \frac{L_a}{R_a}$

K_T = torque constant and K_E = back EMF constant.

V. Block Diagram Of Fuzzy Logic Controller

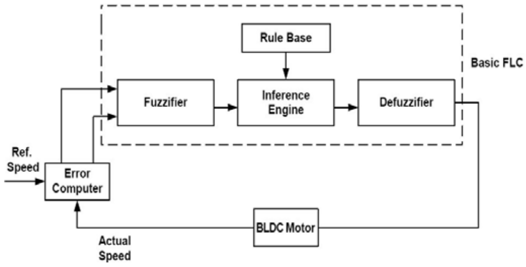


Figure 4:Fuzzy Logic Controller

5.1Fuzzy Controller

Fuzzy logic control is a control algorithm based on a linguistic control strategy, which is derived from expert knowledge into an automatic control strategy. Fuzzy logic control doesn't need any difficult mathematical calculation like the others control system. While the others control system use difficult mathematical calculation to provide a model of the controlled plant, it only uses simple mathematical calculation to simulate the expert knowledge. Although it doesn't need any difficult mathematical calculation, but it can give good performance in a control system. Thus, it can be one of the best available answers today for a broad class of challenging controls problems.

A fuzzy logic control usually consists of the following:

Fuzzification: This process converts or transforms the measured inputs called crisp values, into the fuzzy linguistic values used by the fuzzy reasoning mechanism.

Knowledge Base: A collection of the expert control rules (knowledge) needed to achieve the control goal.

Fuzzy Reasoning Mechanism: This process will perform fuzzy logic operations and result the control action according to the fuzzy inputs.

Defuzzification unit: This process converts the result of fuzzy reasoning mechanism into the required crisp value.

The most important things in fuzzy logic control system designs are the process design of membership functions for inputs, outputs and the process design of fuzzy if-then rule knowledge base. They are very important in fuzzy logic control. The basic structure of Fuzzy Logic Controller is given in Figure. 7. For the DC drive, speed error (E_N) and change in speed error ($d(E_N)/dt$) are taken as the two input for the fuzzy controller.For this, a a seven-member rule base is devised. The rule base for three and five membership function is shown in Tables III .

Advantages of using fuzzy logic technique

1) To control any system mathematical model is not require in fuzzy controller.
2) Human knowledge and experience can be implemented using linguistic variables.
3) Non linear plants can be controlled.

RULE BASE

E \ CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB

Table III: Rule base fuzzy logic controller

5.2. Principles of neuro-fuzzy modeling
The general algorithm for a fuzzy system designer can be synthesized as follows.

5.2.1Fuzzification
1) Normalize of the universes of discourses for the fuzzy input and output vectors.
2) Choose heuristically the number and shape of the membership functions for the fuzzy input and output vectors.
3) Calculate of the membership grades for every crisp value of the fuzzy inputs.

5.2.2 Fuzzy inference
4) Complete the rule base by heuristics from the view point of practical system operation.
5) Identify the valid (active) rules stored in the rule base.
6) Calculate the membership grades contributed by each rule and the final membership grade of the inference, according to the chosen fuzzification method.

5.2.3 Defuzzification
7) Calculate the fuzzy output vector, using an adequate defuzzification method.
8) Simulation tests until desired parameters are obtained.
9) Hardware implementation.

From the beginning, a fuzzy-style inference must be accepted and the most popular are:
MAMDANI-style inference, based on otfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes that expects all output membership functions to be fuzzy sets. It is intuitive,has widespread acceptance, is better suited to human input, but it's main limitation is that the computation for the defuzzification process lasts longer.

SUGENO-style inference, based on Takagi-Sugeno-Kangmethod of fuzzy inference, in their common effort to formalize a systematic approach in generating fuzzy rules from an input-output data set, that expects all membership functions to be a singleton. It has computational efficiency, works well with linear techniques(e.g. PID control, etc.) works well with optimization and a adaptive techniques guaranties continuity of the output surface, is better suited to mathematical analysis. The results are very much similar to Mamdani-style inference.

VI. Simulation Result

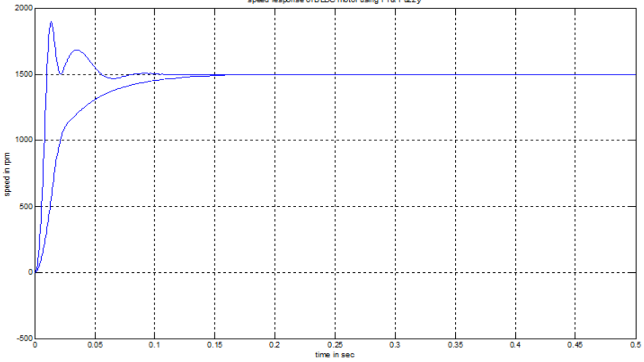


Figure 5:Speed Response using Fuzzy Logic & PI Control

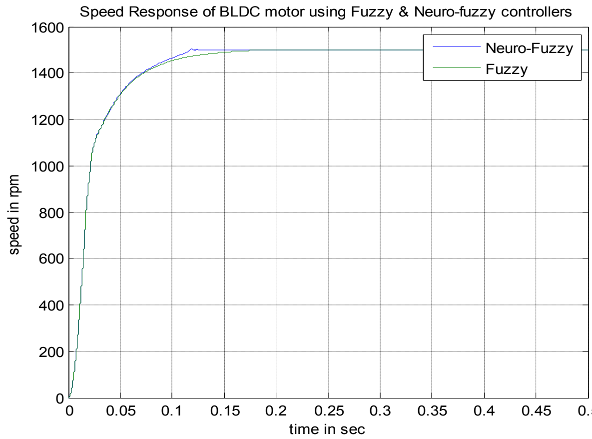


Figure 6:Speed Response using Fuzzy Logic & Neuro-Fuzzy Controller

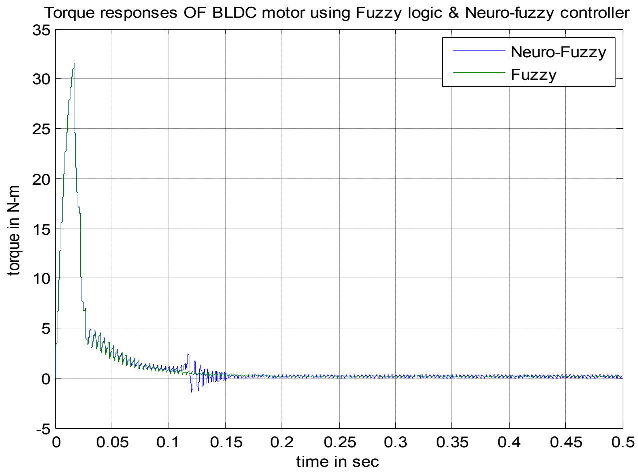


Figure 7:Torque Response using Fuzzy Logic & Neuro-Fuzzy Controller

VII. Conclusion

This paper is intended to compare the tthree controllers namely, P-I,Neuro-Fuzzy & Fuzzy controller for the direct torque control of a BLDC motor. The paper also demonstrates the successful application of fuzzy logic & Neuro-Fuzzy controller. Fuzzy logic and Neuro-Fuzzy was used in the design of torque and speed controllers of the drive system. The performance of the three controllers are compared and it is observed that the performance of fuzzy controller is slightly better than that of conventional PI controller and Neuro-Fuzzy controller is slightly better than that of Fuzzy controller

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Appendix.BLDC motor parameter used for simulation

Parameters	Values
No:of poles	2
Moment of inertia,J	0.004 kg-m^2
DC Link voltage	300V
Stator Resistance,R	0.4Ω
Stator Inductance,L	13mH
Rated Speed in rpm	1500