Non-Linear and Optimal Direct Torque Control of AC Drive using Fuzzy-GA

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Abstract
This paper implements and compares Fuzzy-GA Direct Torque Control of AC drive with a fuzzy logic stand alone control architecture model. Fuzzy rules are generated by designers using trial and error method. Genetic Algorithm based fuzzy rules increase effectiveness and feasibility of control system. Direct Torque Control induction motors are characterized by complex, highly non-linear and time varying dynamics and inaccessibility of some states and output for measurements. The flux and torque control techniques are helpful to a certain extent to motor problems but they eventually deteriorate the performance. Intelligent controllers are considered to be the potential solution to such an application. Here, Genetic algorithms are combined with fuzzy logic model in order to enhance the reliability of the system.
Keywords:
Genetic Algorithm, Fuzzy GA systems, Fuzzy Logic, Induction motor, Direct Control Torque.

1. Introduction

For many years, the application of fuzzy logic has been carried out successfully in several of fields, such as power system, digital image processing, analog and digital design, process control e*tc.* The effectiveness of the fuzzy logic method is due to its ability to solve difficult nonlinear process control problems without the exact model of the controlled system. There always exists trial-and-error in building a satisfactory fuzzy rule base for controlling a nonlinear system or an un-modeled system. In order to avoid trial-and-error method and in turn complex mathematical calculations, different hybrid approaches to prepare the fuzzy logic rule base has been proposed. One of these hybrid approaches is to use genetic algorithm in developing fuzzy logic rule base. Genetic algorithm, one of the best search techniques has successfully been used in searching proper fuzzy rule bases with an assumed structure [4]. Fuzzy systems require a thorough understanding of the fuzzy variables and membership functions, of the input-output relationships, as well as the good judgment to select the fuzzy rules that contribute the most to the solution of the application. As for the Fuzzy inference system there is a need of membership rules for fuzzy categories. It is difficult to deduce these membership rules with a given set of complex data. Genetic algorithms and fuzzy systems, although very different, have close relationship: they work with impression in a space that is not defined by crisp, deterministic boundaries. Genetic algorithms network can be used to define fuzzy rules for the fuzzy inference system. Initially treated with skepticism, the flexibility and power of fuzzy systems is now well recognized. One major application of fuzzy systems has been in controlling manufacturing processes and various appliances such as air conditioners and video cameras [2, 3].

Increasingly fuzzy logic is being combined with other intelligent system methodologies to develop hybrid fuzzy expert, neuro-fuzzy, or fuzzy-GA systems [8]. For some practical systems including nonlinear elements, which cannot be expressed accurately in mathematics, the fuzzy logic control, has been proved to be one of the most efficient and systematic approaches to deal with such kinds of problems in that its control capability arises from emulating human logic instead of accurate mathematical model [1,7,10] .

Recently there has been a fast growth in industrial applications of the Direct Torque Control technique. This is due to its quick torque response, simplicity and less sensitivity against motor parameter variation. Compared with a vector control scheme, Direct Torque Control provides a similar dynamic performance with simpler controller architecture. However, Direct Torque Control is characterized by higher torque ripple compared to vector control in addition to its sensitivity to stator resistance variation. This paper combines the fuzzy logic rule base with GA and compares the response of the direct torque control induction motor drive (process control case study) with stand alone design of the system (using only fuzzy logic) With the help of an adequate fitness function and mutation operation GA will produce the fuzzy rule base spontaneously which has the small number of rules and will have well positioned fuzzy sets. The generated fuzzy

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rule base can be the used as a fuzzy logic controller of a closed loop control system.

2. Direct Torque Control Strategy

Consider direct torque control of three-phase induction motors as shown in figure 1.

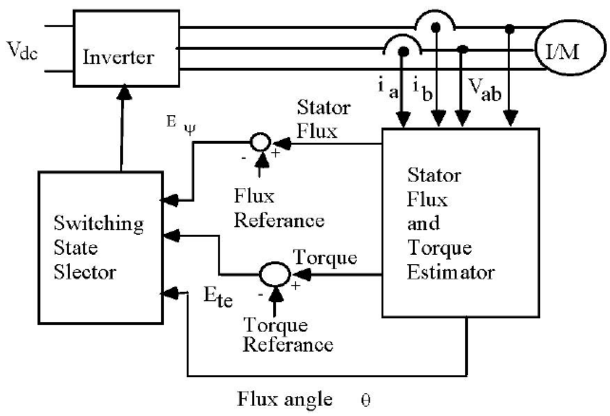

Figure 1: Direct Torque Control of three-phase induction Motor

Direct Torque Control is a direct hysteresis stator flux and electromagnetic torque control which triggers one of the eight available discrete space voltage vectors generated by a Voltage Source [4, 6, 7]. Direct Torque Control describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor. The correct application allows a decoupled control of flux and torque. The errors of stator flux magnitude “|ψs|” and electromechanical torque “Γe” are detected and digitalized. Optimum switching determines the status of three switches S1, S2, S3 and the corresponding voltage space vector depending on stator flux region. Stator flux position (θs) is determined by dividing the d-q plane into six 60 degrees regions. Direct Torque Control provides precise torque control without the need for a feedback device.

It provides 1 to 2% torque repeatability of the nominal torque across the speed range, speed accuracy of 0.01%.

3. Problem Formulation (Direct Torque Control using Fuzzy Logic)

In Direct Torque Control induction motor drive, there are torque and flux ripples because none of the inverter states is able to generate the exact voltage value required to make zero both the torque electromagnetic error and the stator flux error The suggested technique is based on applying switching state to the inverter and the selected active state just enough time to achieve the torque and flux references values. A null state is selected for the remaining switching period, which won't almost change both the torque and the flux. Therefore, the switching state has to be determined based on the values of torque error, flux error and stator flux angle. Exact value of stator flux angle (θ) determines where stator flux lies.

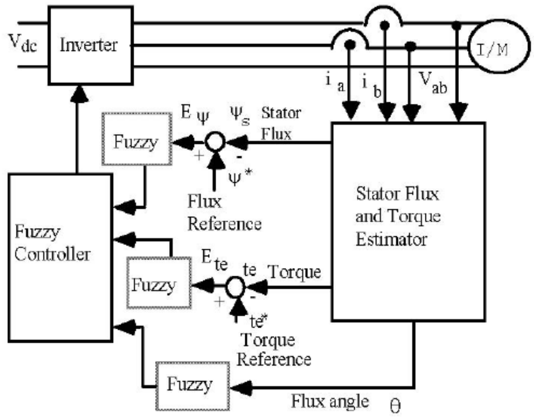

Figure 2:- Fuzzy logic Direct Torque Control logic

The schematic of fuzzy logic direct torque control scheme for induction motor drive is shown in figure 2. The fuzzy output of torque, flux errors and stator flux angle are given as input variables to fuzzy controller and output variable obtained from the fuzzy controller is switching state of the inverter. Switching state of the inverter is a crisp value. The input variables membership functions are shown in figure 3:

The motor variables to be controlled are torque and flux errors. In the proposed control scheme, the motor torque error and the flux error are used as input variables to Fuzzy controller. The error and error change for both flux and torque are scaled using appropriate scaling factors. These scaled input data are then converted into linguistic variables, which may be viewed as labels of fuzzy sets. The linguistic variables, which are used for the input variables, are shown in figure 3 above. For simplicity, the triangular shaped functions are used here.

In the Table 1, ‘1’ represents the upper limb switches and ‘0’ represents the lower limb switches of the inverter. Switching states of the inverter varies from V_0 to V_7. Here, $V_0=V_7$ these are null states, V_0 and V_7 are zero vectors.

Fuzzy rules are shown in Table 2 for stator flux angle T1, T2 and T3. For every combination of inputs and outputs, one rule is applied. There are twelve-stator flux angles from T1 to T12 and 180 rules are formed. With the help of these rules, corresponding switching state of the inverter is selected.

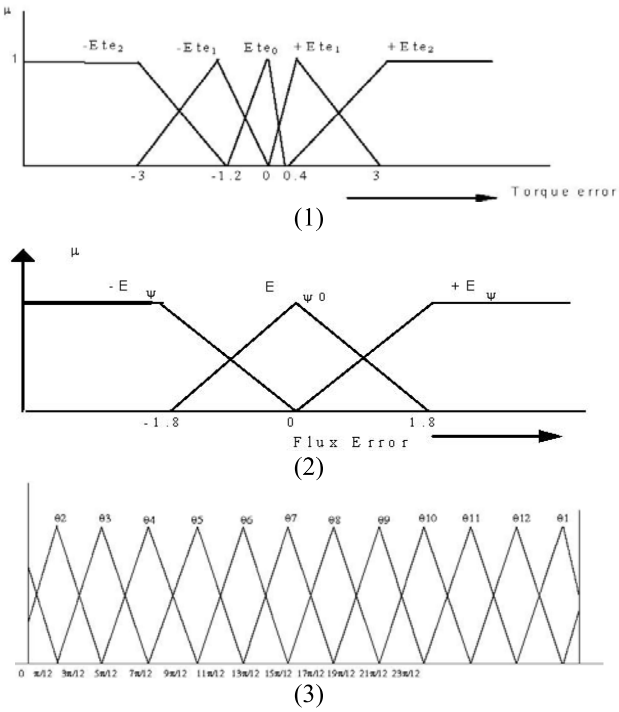

Figure 3: (1) Membership functions of the torque error (2) Membership function of the flux error (3) Membership function of the stator flux angle error

Table 1:-Rules for Direct Torque Control Scheme

States	S_1	S_2	S_3
V0	0	0	0
V1	0	0	1
V2	0	1	0
V3	0	1	1
V4	1	0	0
V5	1	0	1
V6	1	1	0
V7	1	1	1

Table 2 tabulates fuzzy rules for stator flux angle T1

Table 2: Fuzzy rules for T1

	P	Z	N
PL	V1	V2	V2
PS	V7	V7	V7
ZE	V2	V3	V2
NL	V3	V0	V3
NS	V6	V5	V6

Table 3 tabulates fuzzy rules for stator flux angle T2

Table 3:- Fuzzy rules for T2

	P	Z	N
PL	V2	V2	V3
PS	V0	V0	V0
ZE	V3	V3	V3
NL	V2	V4	V6
NS	V1	V3	V5

Table 4 tabulates fuzzy rules for stator flux angle T3

Table 4: Fuzzy rules for T3

	P	Z	N
PL	V2	V3	V3
PS	V0	V0	V2
ZE	V7	V7	V0
NL	V2	V4	V4
NS	V1s	V3	V3

Fuzzy inference equations are formed as below

$$\alpha_i = \min(\mu A_i(E_\psi), \mu B_i(E_{te}), \mu C_i(\theta)) \quad (1)$$

$$\mu N_i'(n) = \min(\alpha_i, \mu N_i(n)) \quad (2)$$

$$\mu N(n) = \max \sum_{i=1}^{180} \mu N_i'(n) \quad (3)$$

A 1-kW induction motor is taken up as a case study. The parameters of the machine are determined experimentally and these are given as below:

Power	1KW
Phase	3
Stator Resistance	6.2 ohms
Rotor Resistance	7.3 ohms
Magnetic Inductance	0.6014 H
Stator and Rotor Inductance	0.0391 H
Nominal Speed	1300 r.p.m
Nominal Torque	5.2 Nm
Moment of Inertia	0.006 kg-m2

The simulations have been carried out in MATLAB. Genetic Algorithms architecture used here is as shown in figure 4.

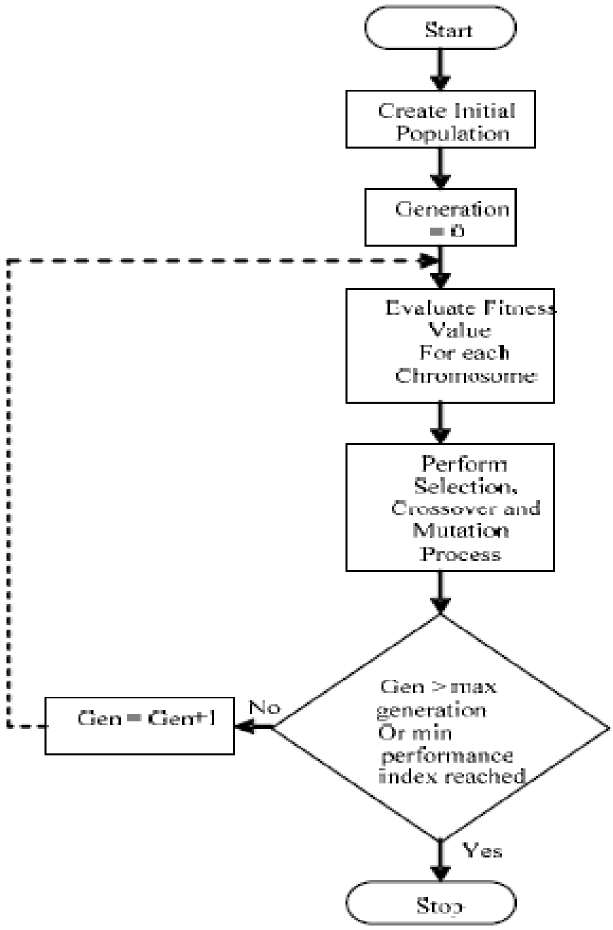

Figure 4: Genetic Algorithms architecture

The population consists of a number of chromosomes. In initialization, all the chromosomes in the population will be initiated with random values. The cost function used to evaluate the individuals of each generation can be chosen to be the Integral Time of Absolute Error (IAE). cost function used here is given below:

$$ITAE = \int_0^t t\left|e(t)\right|dt$$

During the search process GA looks for the optimal setting of the direct control induction drive which minimizes the cost function (ITAE). This function is considered as the GA's evolution criterion which has the advantage of avoiding cancellation of positive and negative errors.

The paper applies evolutionary programs in a two steps fashion to a rule-based fuzzy controller. The type of fuzzy controller considered here consists of triangular membership functions for the fuzzy variables in the premises, and singleton membership functions for the fuzzy variables in the conclusions. The first step in the method produces the singleton conclusions for a reduced set of rules using fixed symmetric triangular membership functions. The second step is then adjusts the membership functions. We considered two ways of performing the first step of rule learning and reduction. In the first case, an evolutionary program was used to select the singleton values of the rules. The basic idea was to maintain a population of chromosomes, each of which represented a proposed rule base. A zero in the string signified that the corresponding rule was not used in the calculation. The fitness function was chosen to combine the error produced by the simulated DC motor and the number of rules with conclusions different from zero. The idea being is to simultaneously reduce the number of rules and the corresponding error. The various GA parameters used for the fuzzy logic rule base are as following:

Table 5: Genetic parameters

Number of Generations	150
Population size	100
Crossover size	0.5
Cross over Type	Single point
Mutation Rate	0.1
Selection Type	Roulette wheel selection

After some experimentation with the genetic parameters and operator, the following settings were used throughout: Populations of 20 chromosomes run for 150 generations, the roulette method for selection with normalized fitness values, one point crossover was applied to selected individuals, and mutation per gens was always applied. As the coding of the chromosomes in this program was realized directly with integers, uniform mutation was used. The chromosomes represented the positions of the triangles and were coded directly as real numbers.

4. Results and Discussions

It is to be noted that switching frequency of the inverter taken for simulation was 10 KHz. Therefore, the sampling time taken for simulation was 0.1millisecond. Torque and flux reference values taken were 2.5 Nm and 0.5 Wb when torque and flux hysteresis values are 0.5 Nm and 0.02 Wb respectively. An index error has been described as the integral of the square error, which is computed by means of the square error instead of just the error. The errors in various control schemes have been compared with each other which are as shown in the table 6 below.

Table 6: Comparison of the integral errors obtained in various control strategies:
Error - Fuzzy architecture Model –Direct Torque Control strategy

Flux error	Torque Error	Operating Conditions
2.5e-3	0.269	a=100% b=100%
0.77e-3	0.022	a=50% b=50%
0.14e-3	0.00125	a=10% b=10%

Table 7 gives error in various control schemes using fuzzy-GA architecture.

Table 7: Error – GA-fuzzy logic Model – Direct torque control Strategy

Flux error	Torque Error	Operating Conditions
1.8e-3	0.159	a=100% b=100%
0.67e-3	0.013	a=50% b=50%
0.08e-3	0.00115	a=10% b=10%

Here, T=Actual torque
TN=Nominal torque = 5 Nm
ω = Actual motor speed
ω_N =Nominal torque = 5 Nm

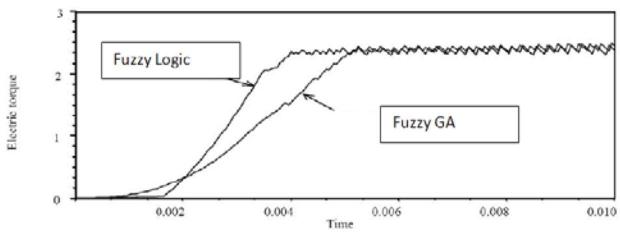

Figure 6: Comparison of Torque error changes for fuzzy architecture and fuzzy GA architecture

Figure 7 illustrates flux error for fuzzy and fuzzy –GA architecture.

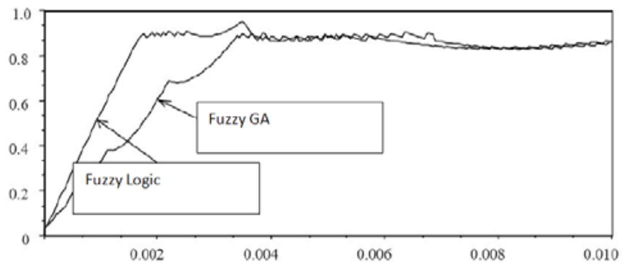

Figure 7: Comparison of Flux error changes for fuzzy architecture and fuzzy GA architecture

From the graphs it is evident that the hybrid system attains the graph quickly in comparison to fuzzy systems. Figure 8 illustrates integral square error in the case of fuzzy architecture.

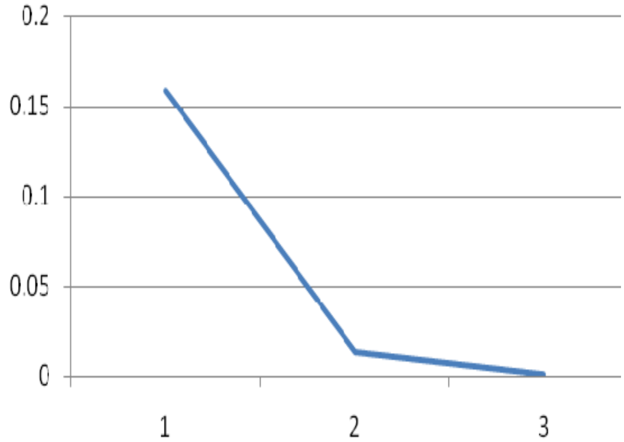

Figure 8: Integral square error for the fuzzy architecture

Figure 9 illustrates square error in the case of fuzzy architecture Integral square error for the fuzzy-GA architecture**.**

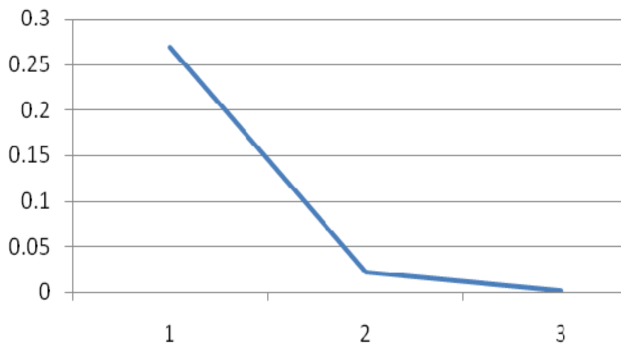

Figure 9: Integral Square Error for the Fuzzy – GA architecture

The above two graphs represents the changes in the integral square error values for Direct Torque control strategy in case of fuzzy logic and fuzzy GA system. It is evident here that error changes are less in case of hybrid system than in case of fuzzy logic system, which results in more efficient and optimized control system.

5. Conclusion

Comparison of Fuzzy GA and (stand alone) model of fuzzy architecture torque and flux error control schemes of the Direct Torque control strategy has been made. The conventional Direct Torque control has disadvantages such as difficulties in torque and flux control at very low speed, variable switching frequency behavior; high noise level at low speed and lack of direct current control, an intelligent adaptive torque controller must be proposed for efficient applications. In this paper, two adaptive intelligent torque and flux controllers have been proposed and results are compared. Fuzzy-GA shows better performance at nominal operating conditions while fuzzy logic proves robustness uncertainty in motor inertia and insensitivity to load torque disturbance as well as faster dynamics at the specified operating conditions. The error changes are less significant in fuzzy GA hybrid architecture than the fuzzy system. Also the hybrid system results in faster attainment of the steady state in comparison to fuzzy logic model. In this paper, we have presented a new method for optimizing fuzzy logic rule base using genetic algorithm. We have used both membership functions and rules in optimization mechanism. Considering that the plant controlled by fuzzy logic is generally nonlinear, we have seen that that eliminating the limitation on symmetric membership functions and rules results in more degree of freedom and consequently better optimization, which is possible with the application of genetic algorithm. Furthermore, the simulation results indicate that the proposed method works well.

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