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FUZZY LOGIC CONTROLLER (FLC) BASED SPEED AND TORQUE CONTROL OF INDUCTION MOTOR DRIVE

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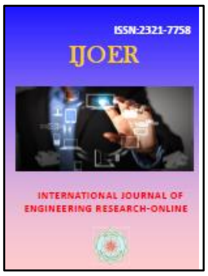


ABSTRACT
This paper presents a composite fuzzy logic controller (flc) with space vector modulation (SVM) for induction motor drive. The SVM method has been improved by using flc instead of PI controller. In this composite controller, simulation is done under Constant Torque - Constant Speed, Variable Torque- Constant Speed, Constant Torque-Variable speed conditions. Comparative results are shown.

I. INTRODUCTION

The induction motor is an important class of electric machines which finds wide applicability in industry and in its single phase form in several domestic applications. More than 85% of industrial motors in use today are in fact, induction motors that are basically a constant speed motor with a shunt characteristic. Various methods have been developed for this purpose, including direct torque control, PD/vector control, etc. But due to their peculiar limitations none of them has been found failure-proof.

Here the speed of an induction motor is successfully controlled over a wide range of operating points with improved accuracy, using Fuzzy Logic Controller (FLC) as a block of vector-control method. In the last few years, fuzzy logic has attracted a growing interest in many motor control applications due to its abilities to handle non-linearities and its independence of the plant's model. The FLC operates in a knowledge-based manner, and its knowledge relies on a lot of linguistic if-then rules, standardized to a human operator. This report will focus on a hybrid FLC based vector-control and examine its effect on the operation of the overall controller.

II. INTRODUCTION OF INDUCTION MOTOR

An induction motor (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction. Another commonly used name is squirrel cage motor due to the fact that the rotor bars with short circuit rings resemble a squirrel cage (hamster wheel). An electric motor converts electrical power to mechanical power in its rotor.

An induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the master position of the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely practiced, especially polyphase induction motors, which are often applied in industrial drives.

The Induction motor is a three phase AC motor and is the most widely used machines. Its characteristic features are-

- Simple and tough structure
- Low cost, minimum maintenance
- High reliability and sufficiently high efficiency
- Needs no extra starting motor and need not be synced

III. VECTOR CONTROL OF INDUCTION MACHINES[1]

Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine. In the case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (side) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by applying transformation to the d-q coordinate system, whose direct axis (d) are aligned with the rotor flux space vector. That signifies that the q-axis portion of the rotor flux space vector is constantly zero:

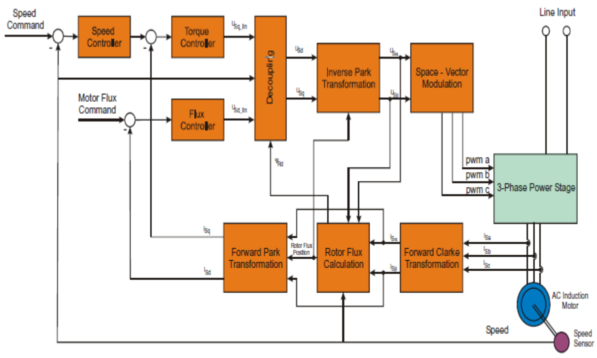
$$\Psi_{rq} = 0 \text{ and } \frac{d}{dt}\Psi_{rq} = 0$$

The rotor flux space vector calculation and transformation to the d-q coordinate system require the high computational power of a microcontroller; a digital signal processor is desirable for this project. The next sections identify the space vector transformations and the rotor flux space vector calculation.

BLOCK DIAGRAM OF THE VECTOR CONTROL

The image demonstrates the basic construction of the vector control of the AC induction motor. To perform vector control, follow these steps:

- Measure the motor quantities (phase voltages and currents)
- Transform them to the 2-phase system (α,β) using a Clarke transformation
- Count on the rotor flux space vector magnitude and position angle
- Transform stator currents to the d-q coordinate system using a Park transformation
- The stator current torque- (isq) and flux- (isd) producing components are separately controlled
- The output stator voltage space vector is computed using the decoupling block
- An inverse Park transformation transforms the stator voltage space vector back from d-q coordinate system to the 2-phase system fixed with the stator
- Utilizing the space vector modulation, the output 3-phase voltage is brought forth



Design: Block Diagram of the AC Induction Motor Vector Control

FORWARD AND INVERSE CLARKE TRANSFORMATION (A, B, C TO Α, Β AND BACKWARDS)

The forward Clarke transformation converts a 3-phase system (a, b, c) to a 2-phase coordinate system (α, β). The figure shows graphical construction of the space vector and projection of the space vector to the quadrature-phase components α, β.

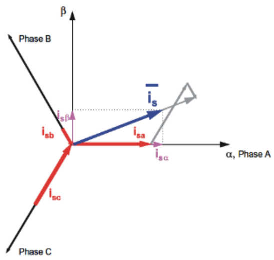


Figure 3.1 Clarke Transformation

Assuming that the a axis and the α axis are in the same direction, the quadrature-phase stator currents isα and isβ are related to the actual 3-phase stator currents as follows:

$$i_{s\alpha} = k\left[i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}\right]$$

$$i_{s\beta} = k\frac{\sqrt{3}}{2}(i_{sb} - i_{sc})$$

where:

- isa = Actual current of the motor Phase A [A]

- isb = Actual current of the motor Phase B [A]
- isα,β = Actual current of the motor Phase C [A]

The constant k equals k = 2/3 for the non-power-invariant transformation. In this case, the quantities isa and isα are equal. If it's assumed that $i_{sa} + i_{sb} + i_{sc} = 0$, the quadrature-phase components can be expressed utilizing only two phases of the 3-phase system:

$$i_{s\alpha} = i_{sa}$$

$$i_{s\beta} = \frac{1}{\sqrt{3}} i_{sa} + \frac{2}{\sqrt{3}} i_{sb}$$

The inverse Clarke transformation goes from a 2-phase (α, β) to a 3-phase isa, isb, isc system. For constant k = 2/3, it is calculated by the following equations:

$$i_{sa} = i_{s\alpha}$$

$$i_{sb} = -\frac{1}{2} i_{s\alpha} + \frac{\sqrt{3}}{2} i_{s\beta}$$

$$i_{sc} = -\frac{1}{2} i_{s\alpha} - \frac{\sqrt{3}}{2} i_{s\beta}$$

FORWARD AND INVERSE PARK TRANSFORMATION (A, B TO D-Q AND BACKWARDS)

The components isα and isβ, calculated with a Clarke transformation, are attached to the stator reference frame α, β. In vector control, all quantities must be expressed in the same reference frame. The stator reference frame is not suitable for the control process. The space vector has rotated at a rate equal to the angular frequency of the phase currents. The components isα and isβ depend on time and speed. These components can be transformed from the stator reference frame to the d-q reference frame rotating at the same speed as the angular frequency of the phase currents. The isd and isq components do not then depend on time and speed. If the d-axis is aligned with the rotor flux, the transformation is illustrated in Figure 3-2, where θ =Field is the rotor flux position.

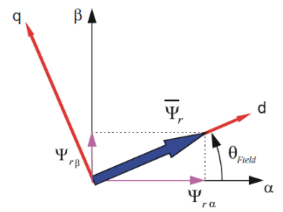


Figure 3.2. Park Transformation

The components isd and isq of the current space vector in the d-q reference frame are determined by the following equations:

The component *isd* is called the direct axis component (the flux-producing component) and *isq* is called the quadrature axis component (the torque-producing component). They are time invariant; flux and torque control with them is easy. To avoid using trigonometric functions on the hybrid controller, directly calculate sinθ*Field* and cosθ*Field* using division, defined by the following equations:

$$\Psi_{rd} = \sqrt{\Psi_{r\alpha}^2 + \Psi_{r\beta}^2}$$

$$\sin\theta_{Field} = \frac{\Psi_{r\beta}}{\Psi_{rd}}$$

$$\cos\theta_{Field} = \frac{\Psi_{r\alpha}}{\Psi_{rd}}$$

The inverse Park transformation from the d-q to the α, β coordinate system is found by the following equations:

$$i_{s\alpha} = i_{sd}\cos\theta_{Field} - i_{sq}\sin\theta_{Field}$$

$$i_{s\beta} = i_{sd}\sin\theta_{Field} + i_{sq}\cos\theta_{Field}$$

ROTOR FLUX MODEL

Knowledge of the rotor flux space vector magnitude and position is key information for AC induction motor vector control. With the rotor magnetic flux space vector, the rotational coordinate system (d-q) can be established. There are several methods for obtaining the rotor magnetic flux space vector. The flux model implemented here utilizes monitored rotor speed and stator voltages and currents. It is calculated in the stationary reference frame (α, β) attached to the stator. The error in the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model.

The rotor flux space vector is obtained by solving the differential equations and, which are resolved into the α and β components. The equations are derived from the equations of the AC induction motor model;

$$[(1-\sigma)T_s + T_r]\frac{d\Psi_{r\alpha}}{dt} = \frac{L_m}{R_s}u_{s\alpha} - \Psi_{r\alpha} - \omega T_r \Psi_{r\beta} - \sigma L_m T_s \frac{di_{s\alpha}}{dt}$$

$$[(1-\sigma)T_s + T_r]\frac{d\Psi_{r\beta}}{dt} = \frac{L_m}{R_s}u_{s\beta} + \omega T_r \Psi_{r\alpha} - \Psi_{r\beta} - \sigma L_m T_s \frac{di_{s\beta}}{dt}$$

Where:

Ls = Self-inductance of the stator [H]
Lr = Self-inductance of the rotor [H]
Lm = Magnetizing inductance [H]
Rr= Resistance of a rotor phase winding [Ohm]
Rs = Resistance of a stator phase winding [Ohm]
ω= Angular rotor speed [rad.s-1]
pp = Number of motor pole pairs
Tr = Lr/Rr= Rotor time constant [s]
Ts = Ls/Rs= Stator time constant [s]
$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ = Resultant leakage constant [-]

The α, β components of the stator voltage, currents and rotor flux space vectors are usα, usβ, isα, isβ, Ψrα, Ψrβ.

DECOUPLING CIRCUIT [4]

For purposes of the rotor flux-oriented vector control, the direct-axis stator current isd (the rotor flux-producing component) and the quadrature-axis stator current isq (the torque-producing component) must be controlled independently. However, the equations of the stator voltage components are coupled. The direct axis component usd also depends on isq and the quadrature axis component usq also depends on isd. The stator voltage components usd and usq cannot be considered as decoupled control variables for the rotor flux and electromagnetic torque. The stator currents isd and isq can only be independently controlled (decoupled control) if the stator voltage equations are decoupled and the stator current components isd and isq are indirectly controlled by controlling the terminal voltages of the induction motor.

The equations of the stator voltage components in the d-q coordinate system can be reformulated and separated into two components:

- Linear components $u_{sd}^{lin}, u_{sq}^{lin}$
- Decoupling components $u_{sd}^{decouple}, u_{sq}^{decouple}$.

The equations are decoupled as follows:

Where:

$$K_R = R_s + \frac{L_m^2}{L_r^2} R_r$$

$$K_L = L_s - \frac{L_m^2}{L_r}$$

The voltage components $u_{sd}^{lin}, u_{sq}^{lin}$ are the outputs of the current controllers which control isd and isq components. They are added to the decoupling voltage components to yield direct and quadrature components of the terminal output voltage. This means the voltage on the outputs of the current controllers is:

$$u_{sd}^{lin} = K_R i_{sd} + K_L \frac{d}{dt} i_{sd}$$

$$u_{sq}^{lin} = K_R i_{sq} + K_L \frac{d}{dt} i_{sq}$$

The decoupling components are:

$$u_{sd}^{decouple} = -\left(\omega_s K_L i_{sq} + \frac{L_m}{L_r T_r} \Psi_{rd}\right)$$

$$u_{sq}^{decouple} = \left(\omega_s K_L i_{sd} + \frac{L_m}{L_r} \omega \Psi_{rd}\right)$$

As shown, the decoupling algorithm transforms the nonlinear motor model to linear equations which can be controlled by general PI or PID controllers instead of complicated controllers[5],[6].

IV. FUZZY LOGIC CONTROLLER (FLC)

In recent years, the number and variety of applications of fuzzy logic have increased significantly[2]. The applications range of consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

To understand why the use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of flc. Even in its narrowest definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of

FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of the solution.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL).

Although FDCL is not used explicitly in the toolbox, it is effectively one of its principal constituents. In most of the applications of fuzzy logic, a fuzzy logic solution is, in reality, a translation of a humane solution into FDCL.

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neural computing and genetic algorithms. More generally, fuzzy logic, Neurocomputing, and genetic algorithms may be viewed as the principal constituents of what might be called soft computing. Unlike the traditional, hard computing, soft computing accommodates the imprecision of the real world.

The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems whose MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.

Among various combinations of methodologies in soft computing, the one that has high visibility at this juncture is that of fuzzy logic and neural computing, leading to Neuro-fuzzy systems. Within fuzzy logic, such systems play a particularly important role in the induction of rules from observations. An effective method developed by Dr. Roger Jang for this purpose is called ANFIS (Adaptive Neuro-Fuzzy Inference System). This method is an important component of the toolbox.

The fuzzy logic toolbox is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to the methodology of fuzzy logic and its wide ranging applications.

V. MODELLING OF CASE STUDY

VECTOR CONTROL OVER VIEW [3]

The required steps for vector-control are summarized as follows

Step1. The 3-phase stator currents *Ia, Ib, Ic* and the rotor velocity ωr are measured.

Step2. The 3-phase currents are converted to a 2-axis system as shown in Fig. This conversion provides the variables iα and iβ from the measured ia, ib and ic values. iα and iβ are time varying quadrature current values as viewed from the perspective of the stator.

Step3. The above 2-axis coordinate system is then rotated to align with the rotor flux using a transformation angle information calculated at the last iteration of the control loop. This conversion provides the id and iq variables from iα and iβ. id and iq are the quadrature currents transformed to the rotating coordinate system. For steady state conditions, id and iq will be constant.

Step4. Error signals are formed using id, iq and their reference values for each. The id reference is used to control the rotor magnetizing flux. The iq reference is used to control the rotor output of the motor. The error signals are the inputs to the PD controller. The output of the controller provides Vd and Vq, which is a voltage vector that will be sent to the motor.

Step5. A new coordinate transformation angle is calculated. The motor speed, the rotor electrical time constant and id and iq are the inputs of this transformation.

Step6. The Vd and Vq output values from the PI controller are rotated back to the stationary reference frame using the new angle. This calculation provides quadrature voltage values vα and vβ .

Step7. The vα and vβ values are transformed back to 3-phase voltage values which are then used to calculate new PWM duty cycle values that generate the desired voltage vector.

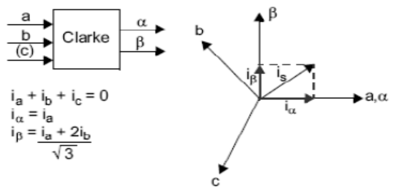


Fig. 5.1 Clarke transformation

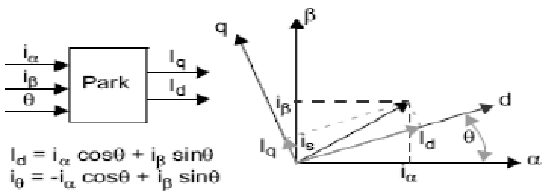


Fig. 5.2 Park transformation

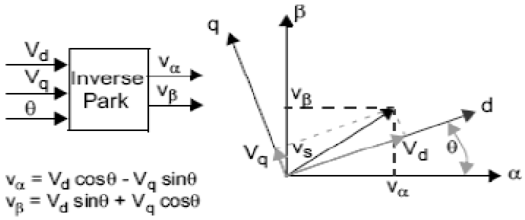


Fig. 5.3 Inverse Park transformation

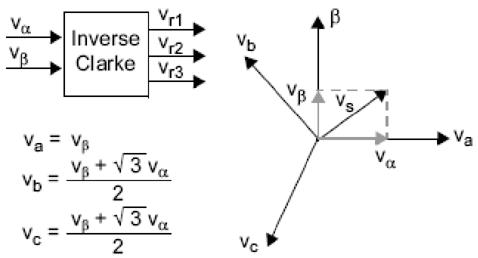


Fig. 5.4 Inverse Clark transformation

DESIGN OF THE FLC

In recent years, Fuzzy Logic Control (FLC) techniques have also been applied to the control of motor drives. The mathematical tool for the FLC is the fuzzy set theory introduced by Dr. Zadeh. In FLC, the linguistic description of human expertise in controlling a process is represented as fuzzy rules or relations. This knowledge base is used by an inference mechanism, in conjunction with some knowledge of the states of the process (say, of measured response variables) in order to determine control actions.

The main advantages of FLC are: (a) There is no need for an exact mathematical model of the system, (b) It can handle nonlinearities of arbitrary complexity, and (c) It is based on linguistic rules with an IF-THEN general structure, which is the basis of human logic. However, standard FLC cannot react to changes in operating conditions. The FLCs need more information to compensate nonlinearities when the operating conditions change. When the number of the fuzzy logic inputs is increased, the dimension of the rule based increases as well, thus, maintenance of the rule base becomes more time-consuming. Another disadvantage of the FLCs is the lack of systematic, effective and useful design methods and adequate analysis, which can use a priori knowledge of the plant dynamics. Moreover, the application of FLC has faced some disadvantages during hardware and software implementation due to its high-computational burden.

VI. MATLAB DESIGNING OF CASE STUDY & RESULTS:

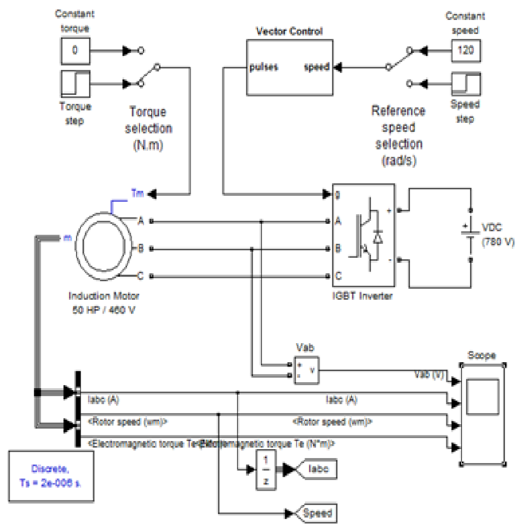


Figure 6.1 Vector Control Drive with PI Controller

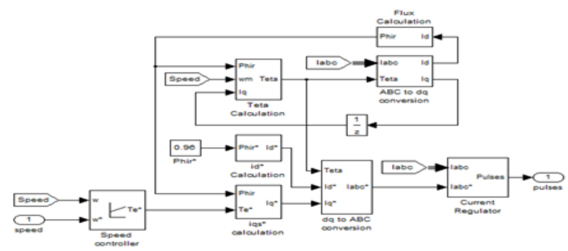


Figure 6.2 Sub Circuit of Vector Control Drive with PI Controller

SIMULATION RESULTS:

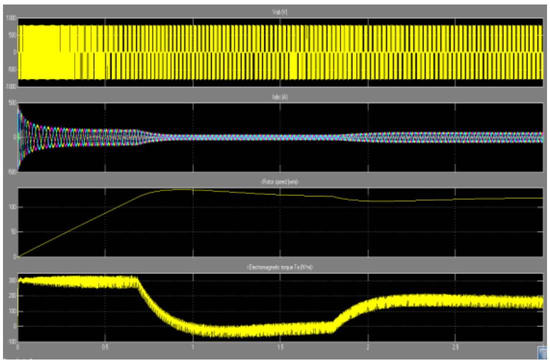


Figure 6.3 Speed, Torque characteristics with PI based vector control (speed constant, Torque variable)

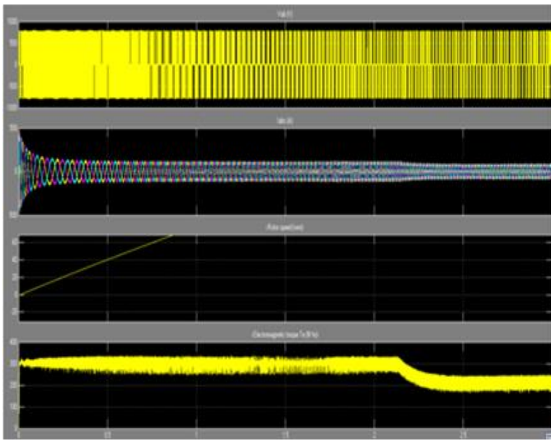


Figure 6.4 Speed, Torque characteristics with PI based vector control (speed variable, Torque constant)

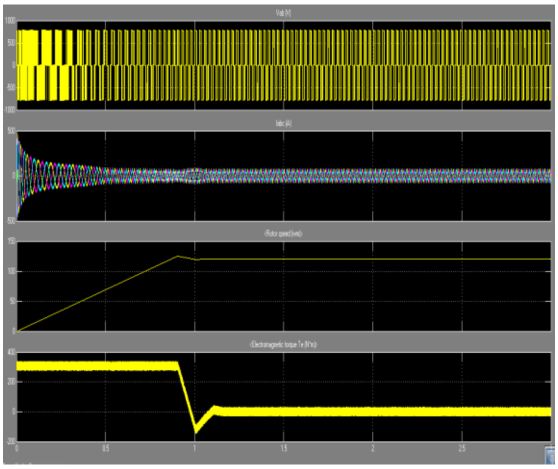


Figure 6.5 Speed, Torque characteristics with PI based vector control (speed constant, Torque constant).

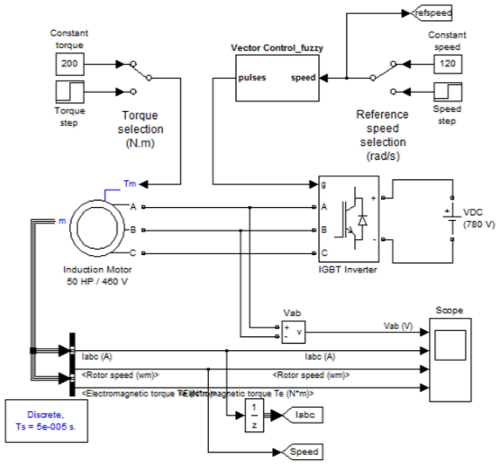


Figure 6.6 Vector Control Drive with Fuzzy Logic Controller

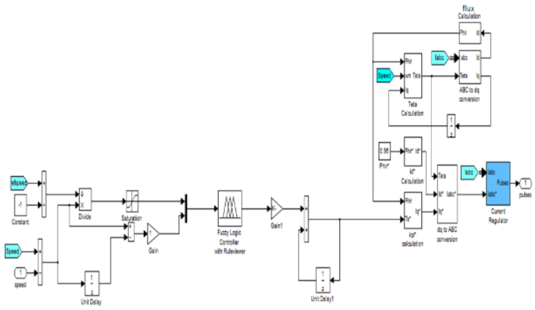


Figure 6.7 Fuzzy Control Logic

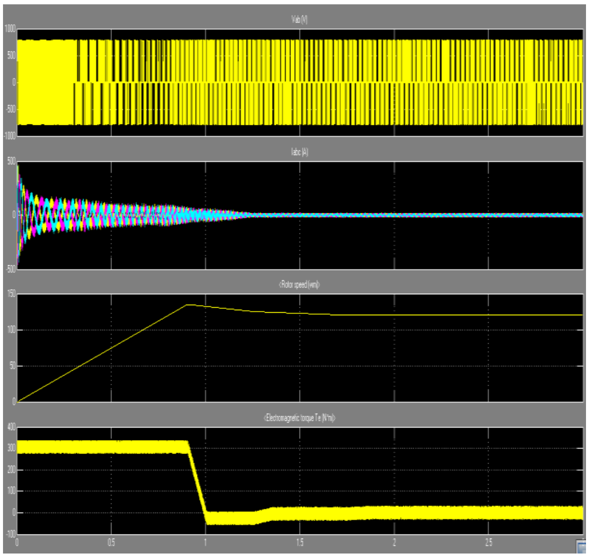


Figure 6.8 Speed, Torque Characteristics with FLC Based Vector Control (Speed Constant, Torque Constant)

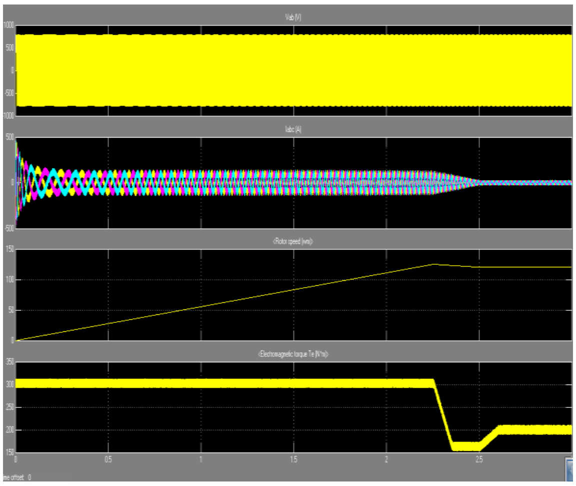


Figure 6.9 Speed, Torque characteristics with FLC based vector control (speed constant, Torque variable).

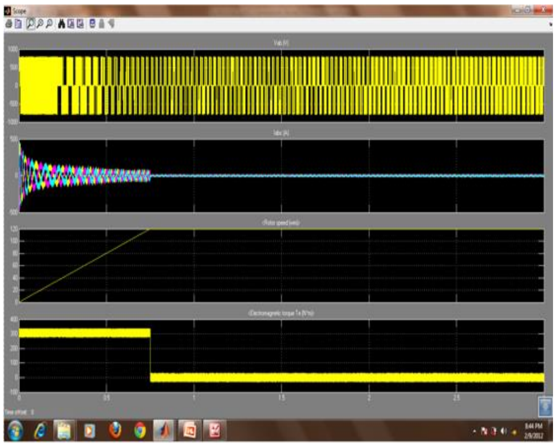


Figure 6.10 Speed, Torque characteristics with FLC based vector control (speed variable, Torque constant).

VII. CONCLUSION

The comparative results of section 6 show that the performance of FLC based vector-control is superior to that with PD/vector-control. Thus, by using FLC the transient and steady state response of the induction motor has been improved noticeably.

The robustness of the response is evident from the results. Since exact system parameters are not required in the implementation of the proposed controller, the performance of the drive system could be claimed to be robust, stable, and insensitive to parameters and operating condition variations. The performance has been investigated at different dynamic operating conditions. It is there for concluding that the proposed FLC based vector-control has shown better performance over the PD/vector-control.

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