An Adaptive Neuro-Fuzzy Inference System for Speed Control of Three-Phase Induction Motor

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ABSTRACT

Conventional Proportional Integral (PI) controller of A.C drives are widely used in industry and many other applications, because of its simplicity, but it does not give high degree of speed control of induction motor. There are many types of controller: Proportional (P), Proportional Integral (PI), Proportional Integral Derivative (PID), and Intelligent controllers. The intelligent controller becomes a powerful tool for control nonlinear system in present time. This paper proposes the Adaptive Neuro-Fuzzy Inference System as an intelligent controller of the induction motor. In addition, the PI controller is presented in this paper as a conventional controller. The mathematical representation and simulation of the 3-phase induction motor is represented too. Also, a 3-phase voltage-fed Sinusoidal Pulse Width Modulation (SPWM) inverter is demonstrated and simulated. The overall system for both PI and ANFIS controllers are simulated using MATLAB/SIMULINK program. The comparison of simulation results between the conventional PI and the proposed ANFIS performances shows that: the ANFIS controller gives superior performance than the conventional PI controller for wide range of speed variation.

Keywords*:* Sinusoidal PWM, Speed control of induction motor, PI controller, ANFIS controller.

نظام الأستدلال العصبي-الضبابي المكيّف للسيطرة على سرعة المحرك الحثي الثلاثي الطور

الخلاصة

يستخدم المسيطر التناسبي التكاملي التقليدي بشكل واسع للسيطرة على سواقات التيار المتناوب في الصناعة وفي عدّة تطبيقات أخرى، بسبب بساطته ولكنه لايعطي درجة عالية من السيطرة على سرعة المحرك الحثي. هناك عدة أنواع من المسيطرات: التناسبي، التناسبي التكاملي، التناسبي التكاملي التفاضلي، والمسيطرات الذكية. أصبحت المسيطرات الذكية في الوقت الحاضر أداة قوية للسيطرة على الأنظمة اللاخطية. يقدم هذا البحث نظام الأستدلال العصبي-الضبابي المكيّف كمسيطر ذكي للمحرك الحثي. أضافة لذلك تم أستعراض المسيطر التناسقي التكاملي في هذا البحث كمسيطر تقليدي. كما وتم أستعراض التمثيل الرياضي ومحاكاة المحرك الحثي الثلاثي الطور. وأيضاً تم شرح ومحاكاة عاكس مضمن عرض النبضة الجيبي الثلاثي الطور المغذي-للجهد. تمت محاكاة النظام النهائي لكلا المسيطرين التناسقي التكاملي والعصبي-الضبابي بأستخدام برنامج

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MATLAB/SIMULINK. أن المقارنة بين النتائج المستحصل عليها من المحاكاة للمسيطر التناسقي التكاملي التقليدي والمسيطر العصبي-الضبابي المقترح أظهرت أن المسيطر العصبي-الضبابي قدم أداءً فائقاً عن أداء المسيطر التقليدي لمدى واسع من تغيير السرعة.

INTRODUCTION

Scalar control of induction motor, by Volt/Hz control of stator supply voltage, is somewhat simple to implement, but the inherent coupling effect for both torque and flux are functions of voltage or current and frequency (i.e. during volt/Hz variation both torque and flux be varied too), which gives sluggish response and the system is easily prone to instability because of high order system effect [1, 2].

In this method of speed regulation of an induction motor is done by using conventional PI controller, which gives a satisfactory speed tracking performance for most industrial applications. But, in high performance demand the PI controller can't gives the requirement speed tracking, because of the coupling effect for torque and flux.

Nowadays, the Artificial Intelligent System (AIS) has penetrated deeply into electrical engineering field and their applications in power electronics and motion control appears very promising [1, 3]. Intelligent Adaptive Neuro-Fuzzy Inference System (ANFIS) is one of the most powerful intelligent controllers with improved design and performance features, which has a simple control law and is considered to be robust. Furthermore, fuzzy control can take into account uncertainties of un-modeled dynamics since the mathematical model of the power system is not needed. Hence, fuzzy control seems to be quite suitable for controlling an induction motor [4, 5].

These high features of the ANFIS were employed in this paper to control the induction motor speed. This paper presents the procedure to design by an adaptive control for a neuro-fuzzy inference controller, and its performance is compared with conventional PI controller.

The outlines of this paper can be divided into three main steps:

i- Illustrate the mathematical model of the three phase induction motor.

ii- Design of the three phase voltage-fed Sinusoidal Pulse Width Modulation (SPWM) inverter.

iii- Demonstrate the conventional PI controller, and investigate its performance.

iv- Demonstrate the proposed adaptive neuro-fuzzy inference controller, and examine its performance and compare with that of PI controller.

VOLT/HZ CONTROL

During the variation of Volt/Hz control the characteristics of 3-phase induction motor have different forms as the variation of input voltage and frequency. The operation characteristics can be divided into three regions [1, 6]:

i- Constant torque region; where the volt/Hz is kept constant to maintain flux and pull-out torque at their maximum limits.

ii- Constant power region 1; where the stator voltage reaches rated value and the frequency increased beyond synchronous frequency. The air-gap flux decreases but the stator current maintained constant by increasing the slip.

iii-Constant power region 2; where the torque is inversely proportion with square of speed, because of both of current and flux reduce with speed increasing.

The last two regions are known as field weakening region [1, 6].

VOLTAGE SOURCE PWM INVERTER

Voltage source inverter (VSI) should have a stiff source at the input [1], that is, its Thevenin impedance ideally is zero. Thus, a large capacitor can be connected at the input if the voltage source is not stiff. A practical (VSI) consist of power bridge devices with three output legs, each consist of two power switches and two freewheeling diodes, the inverter is supplied from D.C. voltage source via LC or C filter. The pulse width modulation techniques have wide simple and complex types, the Sinusoidal Pulse Width Modulation (SPWM) is the most popular used method of A.C. drives. In sinusoidal PWM the three output legs considered as three independent push-pull amplifiers [1, 7]. The gating signals of each push-pull stage generated by comparing a constant level triangle signal of frequency (f_c) called "carrier signal", with 3-phase sinusoidal signals of frequency (f_r) called "reference signals", which has variable amplitude to get the desired output voltage, this comparison leads to generate a sequence of variable width pulses used to gating each switch in the push-pull stage.

The output phase voltage:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix} \quad \ldots\ldots (1)$$

Where:

V_{ao} = is the output phase voltage measured to the center of the input D.C. voltage.

V_{an} = is the output phase voltage measured to isolated neutral of three-phase load such as induction motor.

$$V_{ao} = 0.5mV_d \sin(\omega t) + \text{high-frequency } (M\,\omega_c \pm N\omega)\ [1] \quad \ldots (2)$$

Where: ω = fundamental frequency; ω_c=carrier frequency; M and N are integers and M+N =odd, m = modulation index is defined as [1, 7]:

$$m = \frac{V_P}{V_T} \quad \ldots (3)$$

Where: V_P = peak of modulating signal, V_T = peak of triangle signal. At m= 1, the maximum value of fundamental peak = $0.5V_d$ which is 78.54% of the peak fundamental voltage of the square-wave ($2V_d/\pi$) which called the linear modulation region. To further increase the amplitude of the output voltage, the amplitude of the modulating signals exceeds the amplitude of the carrier signal which leads to enter into quasi-PWM region called "over modulating region" causing increase in the low order harmonics. Further increasing modulation index tends to obtain square wave at maximum possible output fundamental ($2V_d/\pi$) [1, 7].

Figure (2) illustrated the complete simulation of SPWM inverter, by using MATLAB/SIMULINK PROGRAM. And the output phase voltage can be shown in figure (3).

DYNAMIC MODEL OF 3-PHASE I.M.

The machine model can be described by differential equation with time varying mutual inductances, but such model tends to be very complex. Therefore, axis transformation is applied to transfer the three phase parameters (voltage, current and flux) to two–axis frame called (dq-axis stationary frame or park transformation). Park transformation is applied to refer the stator variables to a synchronously rotating reference frame fixed in the rotor, by such transformation the stator and rotor parameters rotate in synchronous speed and all simulated variables in the stationary frame appear as d.c. quantities in the synchronously rotating reference frame [1].

The per-phase equivalent circuit diagrams of an I.M. in two- axis synchronously rotating reference frame are illustrated in figure (4). From the circuit diagram and putting V_{qr}=0 & V_{dr}=0 for squirrel cage I.M, the following equations can be written [1, 7, and 8]:

● Stator equation:

$$\frac{d\Psi_{qs}}{dt} = V_{qs}^{e} - R_s i_{qs}^{e} - w_e \Psi_{ds} \quad ....(4)$$

$$\frac{d\Psi_{ds}^{e}}{dt} = V_{ds}^{e} - R_s i_{ds}^{e} + w_e \Psi_{qs} \quad ....(5)$$

● Rotor equation:

$$\frac{d\Psi_{qr}}{dt} = -R_r i_{qr}^{e} - (w_e - w_r)\Psi_{dr} \quad ....(6)$$

$$\frac{d\Psi_{dr}}{dt} = -R_r i_{dr}^{e} + (w_e - w_r)\Psi_{qr} \quad ...(7)$$

Where:

$R_s, \Psi_{qs}, V_{qs}, i_{qs}$ are the stator resistance, q-axis flux, voltage, current respectively,

$\Psi_{ds}, V_{ds}, i_{ds}$ are the stator resistance, d-axis flux, voltage, current respectively,

R_r, Ψ_{qr}, i_{qr} are the rotor resistance, q-axis flux, current respectively,

Ψ_{dr}, i_{dr} are the rotor resistance, d-axis flux, current respectively, and

The superscript notation "*e*" referred to the synchronously rotating reference frame quantities.

● The development torque by interaction of air gap flux and rotor current can be found as:

$$T_e=(3/2)(P/2)\overrightarrow{\Psi_m} \times \overrightarrow{I_r} \quad ......(8)$$

By resolving the variables into d^e-q^e components:

$$T_e=(3/2)(P/2)(\Psi_{ds} i_{qs}^{\ e} - \Psi_{qs} i_{ds}^{\ e}) \qquad ....(9)$$

- The dynamic torque equation of the rotor:

$$T_e = T_L + \left(\frac{2}{P}\right) J \frac{dw_r}{dt} \qquad ......(10)$$

Where: ω_r = is the rotor speed; P: no. of poles; J= rotor inertia; T_L= load torque.

- The stator current can be found by:

$$i_{ds}^{\ e} = \frac{\Psi_{ds} - \Psi_{qm}}{L_s} \qquad ....(11)$$

$$i_{qs}^{\ e} = \frac{\Psi_{qs} - \Psi_{dm}}{L_s} \qquad ....(12)$$

- The air gap flux:

$$\Psi_{qm} = \frac{L_{m1}}{L_s}\Psi_{qs} + \frac{L_{m1}}{L_r}\Psi_{qr} \qquad ....(13)$$

$$\Psi_{dm} = \frac{L_{m1}}{L_s}\Psi_{ds} + \frac{L_{m1}}{L_r}\Psi_{dr} \qquad ....(14)$$

Where:

$$L_{m1} = \frac{1}{\left(\frac{1}{L_m} + \frac{1}{L_s} + \frac{1}{L_r}\right)} \qquad ....(15)$$

From the previous equations the dynamic model of an induction motor is simulated as shown in figure (5).

OPEN LOOP SPEED CONTROL

This type of A.C. drive consists of variable-voltage variable-frequency inverter such as SPWM inverter, which is connected directly to an induction motor. The speed command signal controls both voltage and frequency without any feedback signal or monitoring to the motor quantities like current, speed, torque or flux. As the frequency becomes small at low speed, the stator resistance tends to absorb the major amount of the stator voltage thus weakening the flux, a boost voltage (V_o) is added so that the rated flux, and corresponding full-load torque become available down to zero speed [1]. Figure (6) illustrates the overall open loop system simulation which couples the SPWM model with the I.M. model. The used squirrel cage induction motor name plate is:

3-ph I.M, 380 v., 2.2 kw, 2 poles, 50 Hz, L_s= 13.6 mH, L_r= 11.4 mH, R_s=2.3 Ω, R_r= 3.4 Ω, rotor inertia= $4.5*10^{-3}$ kg/m^2.

The operation performance for different speed commands at full-load condition is shown in figure (7). By studying the behavior of the motor speed, torque and flux the following notes can be recorded:

- The rotor speed at full-load is lower than commands speed for different speed commands by small slip (w_{sl}) which increases in the field weakening regions.
- The air gap flux varies with speed variation, which causes reduction in operation torque.

Therefore, to improve system performance and get exact speed tracking with constant air gap flux, close loop control must be implemented [1, 8].

PI CONTROLLER OF I.M DRIVE

The main control techniques including scalar control, vector or field oriented control, direct torque and flux control, adaptive control, and intelligent control. The simplest and popular used method is scalar slip regulation of rotor speed, in which the actual rotor speed measured by means of tacho-meter [1]. The difference between the command speed (w_e^*) and the actual rotor speed (w_r) gives the slip speed (w_{sl}) which is represents the error signal. The PI controller will treats the error signal through proportion and integral controller to obtain new speed command fed to the inverter. With step-up speed command the motor accelerates freely with a slip limit that corresponds to the torque limit, and then settles down to steady value. With step-down speed command the drive goes into regenerative or dynamic breaking mode and decelerates with constant negative slip $(-w_{sl})$. The overall PI controller system simulation is illustrated in figure (8). The tuning of the proportional gain (K_p) and integral gain (K_i) of the PI controller is done by using trial and error method which gives: K_p=0.3, K_i=1.3. The operation performance of different speed commands under full-load condition is shown in figure (9). From these results the following notes can be recorded:

- The rotor speed tracks the reference speed during step-up and step-down speed variation, but with slower rise time about 2 sec.
- The air-gap flux behavior is better than of open loop operation, but it still varies in small amount during speed variation.
- This deviation of air-gap flux may cause torque fluctuation.

FUZZY LOGIC CONTROL (FLC)

Since fuzzy logic (FL) was introduced by Lotfi Zadeh in 1965, it had many successful applications mostly in control. One of the main advantages of fuzzy logic system is the design on the basis of incomplete and approximate information, thus providing simple and fast approximations of the unknown or too complicated models [3, 4].

The main idea of fuzzy control, which had proved to be a very successful method, is to build a model of human control expert who is capable of controlling the plant without thinking in terms of mathematical model. However, the main benefits provided by the Fuzzy Logic Controllers (FLCs) are listed below [3]:

- FLCs can deal with ill-defined systems of unknown dynamics that do not require a priori mathematical model of the plant for implementation, as required by many traditional adaptive controllers.
- FLCs provide a formal methodology for representing, manipulating, and implementing human heuristic knowledge about how to control a system.
- FLCs are customizable, since it is easier to understand and modify their rules, which do not only use a human operator's strategy but also are expressed in natural linguistic terms.
- Software design and hardware implementation supports are suitable for real time applications

Sugeno fuzzy-control technique belongs to the robust controller category, which deals with model uncertainties of simplified model. These uncertainties may come from un-modeled dynamics, variations in system parameters, or approximations of complex plant behaviors. The Sugeno fuzzy-controller is a particular type of varying structure system featuring prescribed behavior of the closed system and robustness to parameter variations and external disturbances. Sugeno fuzzy-control is a powerful approach to solve system state tracking problems. The architecture of Sugeno fuzzy-control is simple and its design is directly oriented toward nonlinear systems, no linearization is needed [4, 5].

ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

The design of the Membership Functions (MFs) and rules table of a fuzzy inference system was based on the experience of the operator or designer of the system. This means that there is no systematic method for design of a fuzzy system. On the other hand, in a neural network the experimental or simulation input/output data can be used to train a network. The network then represents the model which satisfies that data. These techniques can be brought into a hybrid neuro-fuzzy system to build a more powerful intelligent system with improved design and performance features called Adaptive Neuro-Fazzy Inference System ANFIS [9, 10]. As name indicates, a fuzzy inference system is designed systematically using the neural network design method [3, 11]. This means that if the desired input/output data patterns are available for a fuzzy system, the MFs and rules table can be designed using the neural network training method. Usually the sugeno method is used in adaptive neuro-fuzzy system. For example: if X & Y are the inputs of the fuzzy system, and "*F*" is the output signal:

IF X is A_1 *AND* Y is B_1 *THEN* $z=f_1$
IF X is A_2 *AND* Y is B_2 *THEN* $z=f_2$

The output "F" can be constructed as:

$$F = \frac{W_1}{W_1+W_2} f_1 + \frac{W_2}{W_1+W_2} f_2 \qquad \dots (16)$$

Where: A_1, A_2, B_1, B_2 are the input MFs, f_1 and f_2 are the output singleton MFs, and w_1 and w_2 are the Degree Of Fulfillments (DOF) of rule 1 & 2, which can be adaptive by using any training algorithm to satisfied the input/output data [3, 12, 13].

DESIGN OF AN ADAPTIVE NEURO-FUZZY CONTROLLER

A discrete adaptive neuro-fuzzy controller can be implemented to control the slip of an induction motor. This type of controller can be adapted to modify the nonlinearity feedback signal of the I.M. rotor speed to track the input reference speed command. The designed fuzzy controller has two inputs: first, the error signal (deference between reference speed and actual rotor speed) and second, is the derivative of error ($^{d\,(error)}/_{dt}$), which must be recognize the state of the system

and predicts a suitable linear feedback signal. According to that function of the fuzzy controller, an adaptive controller of two inputs and three triangle MFs of each input is used in this work which has the structure shown in figure (10). The output MFs and rules are adapted by using neural training algorithm of large number of input and output data set, by using hybrid optimization training method. The fuzzy system input/output surface performance is shown in figure (11). The accuracy performance of the designed neuro-fuzzy inference system between the desired output and fuzzy output is shown in figure (12). The overall fuzzy control simulation is shown in figure (13) and the performance of the I.M. with neuro-fuzzy inference controller under full-load condition is illustrated in figure (14). Figure (15) shows a comparison performance between the open loop, PI controller, and the proposed neuro-fuzzy controller.

From these results the following notes can be recorded.

- The rotor speed tracks the command speed for different variation steps.
- There is no overshoot occur in the transient response.
- The motor has excellent performance in different step-up and step-down steps, also in the field weakening regions.
- The air gap-flux gives an excellent and unexpected performance in different speed variation steps, and it behaves as same as field oriented control or vector control method.

CONCLUSIONS

The conclusions of this work can be summarized in three steps as following:

1- Obviously, the induction motor cannot tracks the command speed in the open loop operation, which gives high steady state error. In addition the air gap flux varies with speed variation.

2- In the conventional PI controller, the induction motor gives an acceptable behavior for deferent command speed under full-load condition with respect to the open loop performance which can be illustrated as follow:

- Rise time response for unit-step input: 1.9 sec.
- Settling time of 2% steady state error: 4 sec. in no-load and 2 sec. in full-load.
- Maximum overshot for unit step response: about 12%.

● Steady state error: less than 1% under full-load operating condition.

3- In the nruro-fuzzy controller the induction motor gives superior speed tracking performance in deferent speed operating regions and full-load condition as follow:
● Rise time for unit-step input: 1.5 sec.
● Settling time of 2% steady state error: 1.5 sec.
● Maximum overshot for unit step response: 0%.
● Steady state error: 0% under full-load operating condition.

From which one can deduced that; the proposed ANFIS Neuro-Fuzzy controller has the best response than others because it's highly improved the speed tracking step response. Therefore, it can be used successfully instead of traditional controllers.

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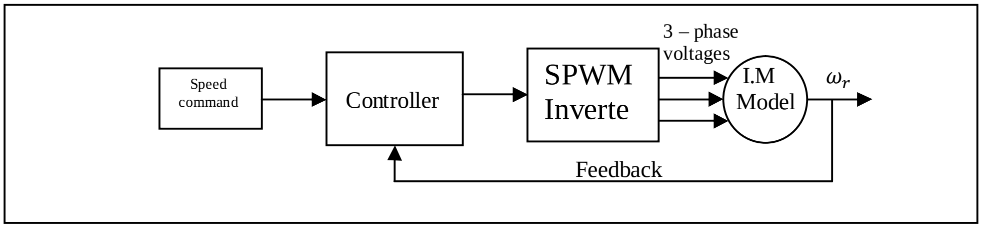

Figure (1) Block Diagram of the I.M. Control System

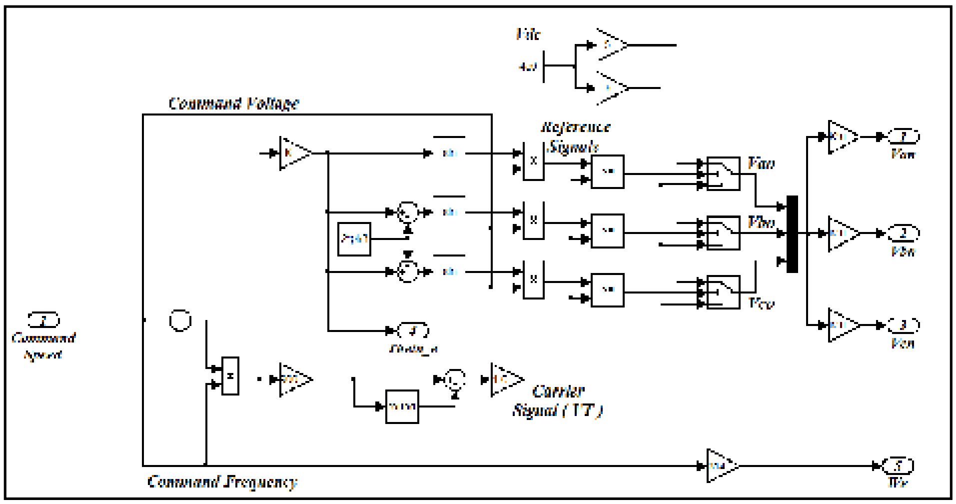

Figure (2) SPWM Inverter Simulation

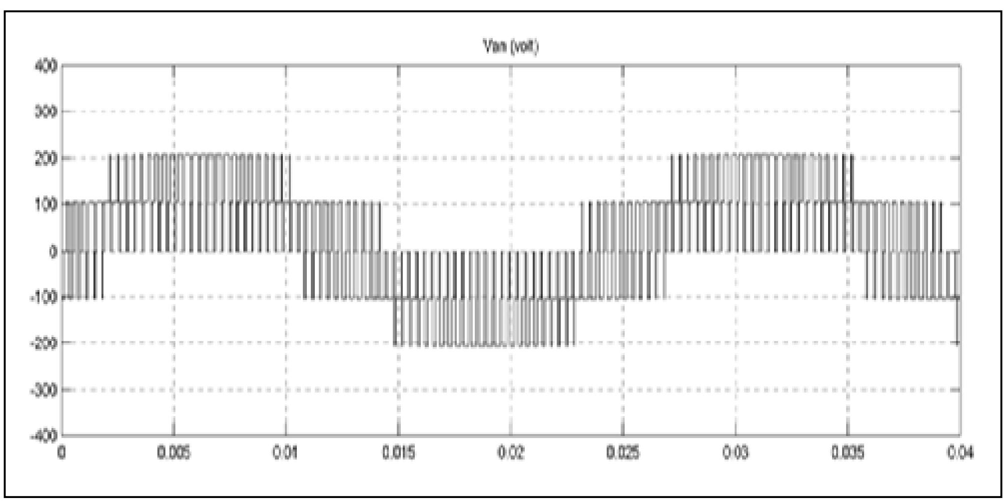

Figure (3) Output Phase Voltage of the SPWM Inverter

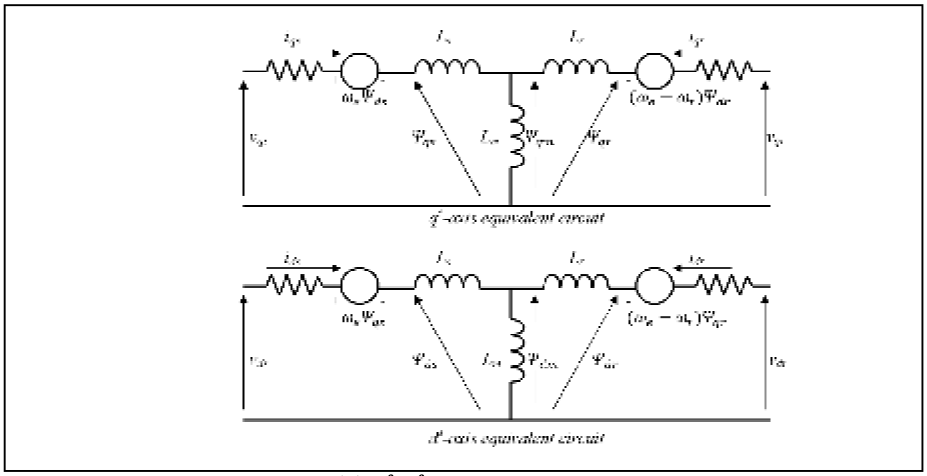

Figure (4) d^e-q^e *I.M Equivalent Circuit*

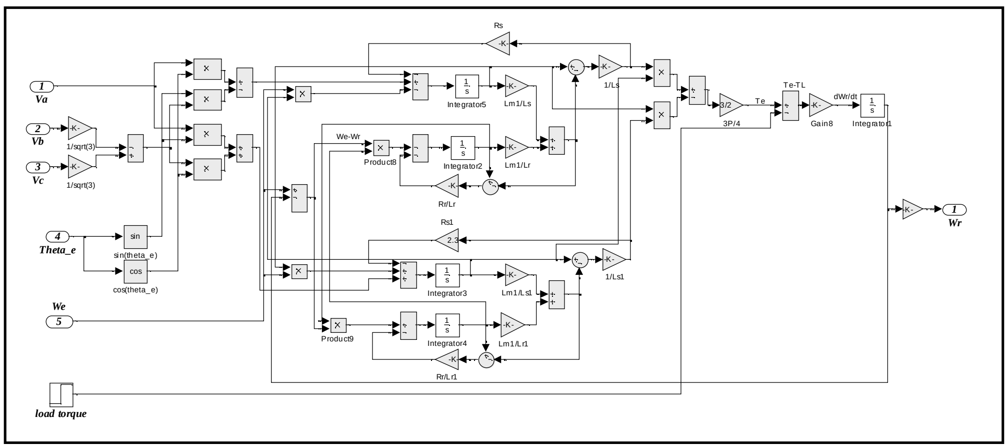

Figure (5) I.M Simulation

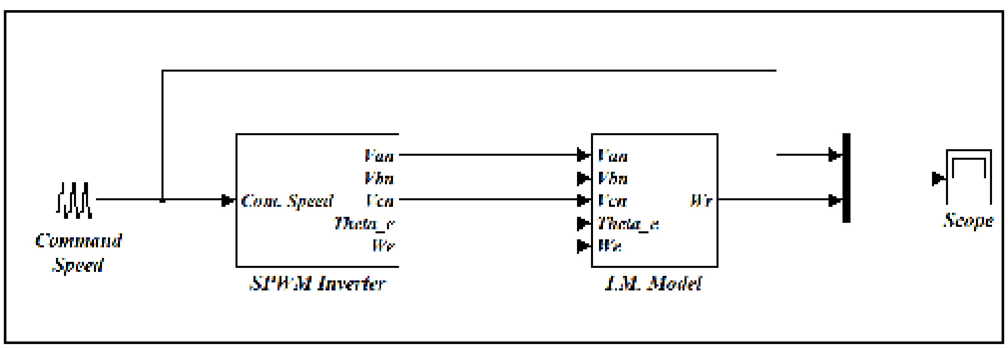

Figure (6) Open Loop Speed Control Simulation of I.M.

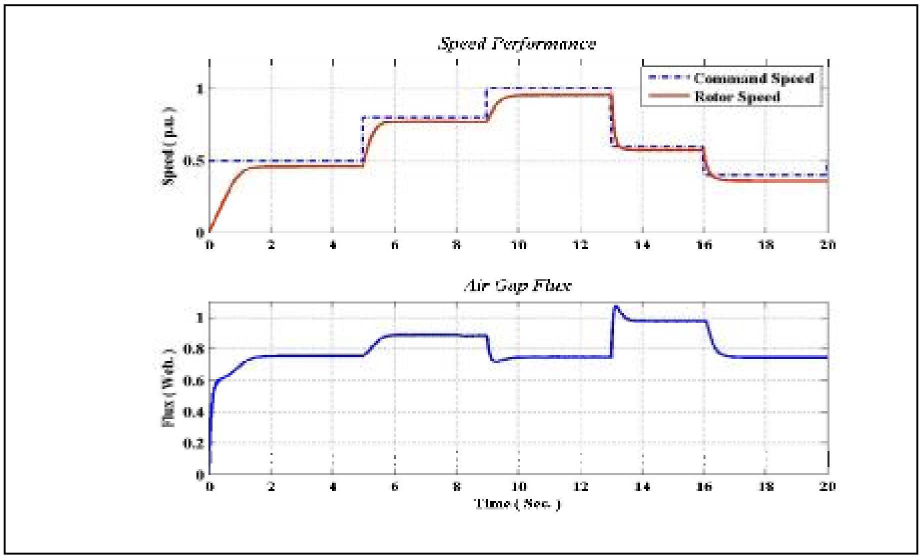

Figure (7) Open Loop Performance of I.M.

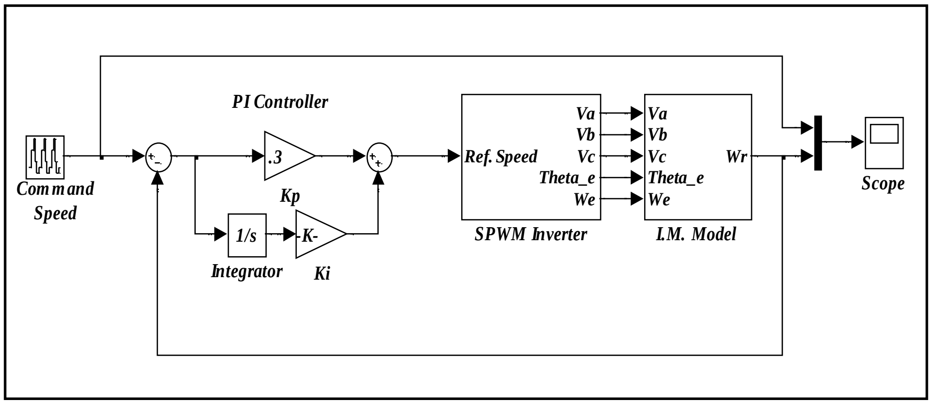

Figure (8) PI Control Simulation of I.M.

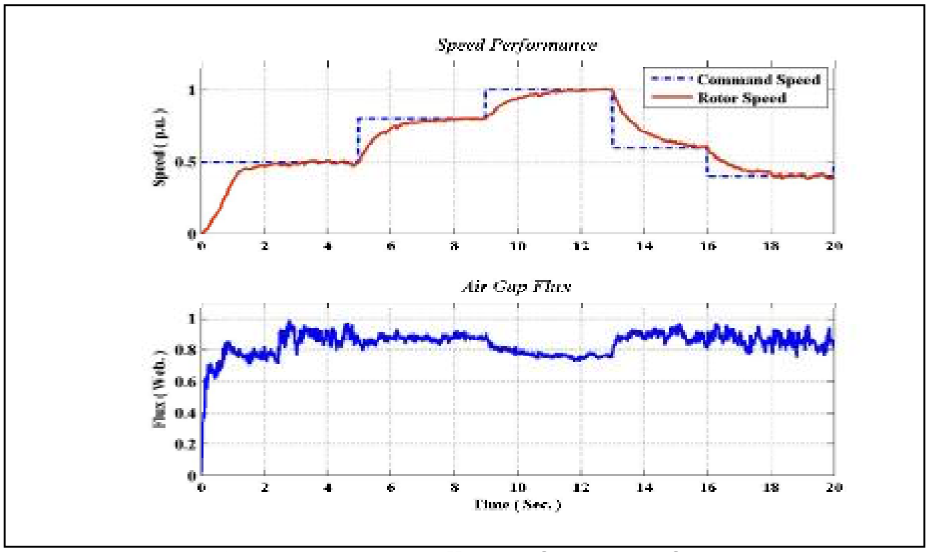

Figure (9) PI Controller Performance of I.M.

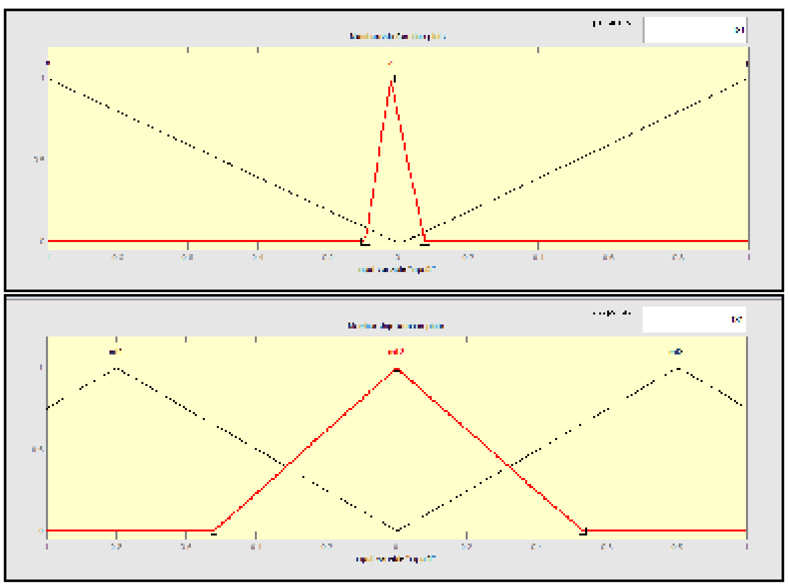

Figure (10) Inputs Membership Functions of the ANFIS Controller

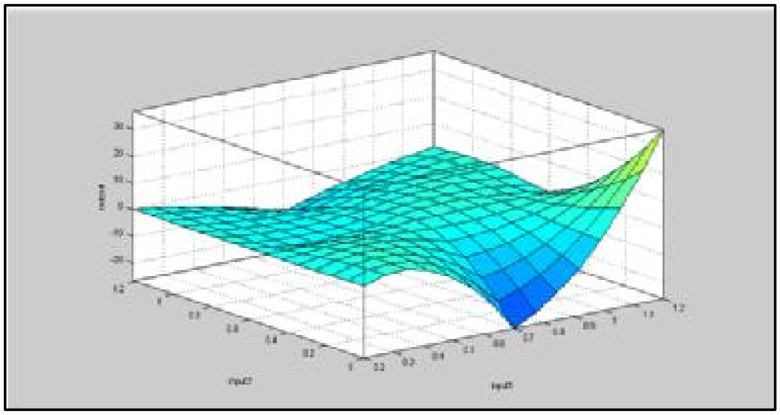

Figure (11) ANFIS Input/output Surface Performance

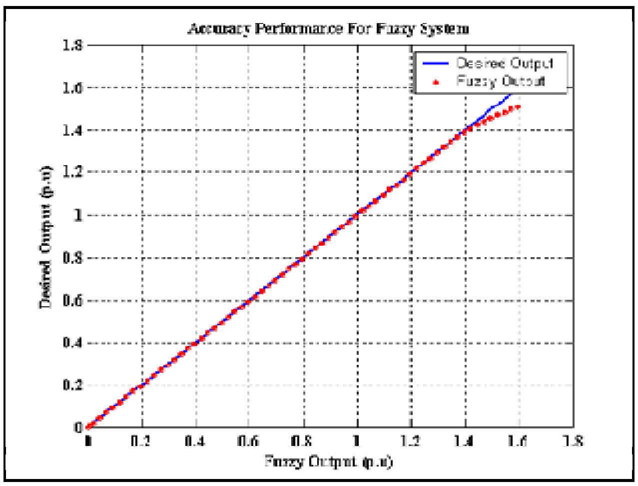

Figure (12) Accuracy Performance for Fuzzy Controller System

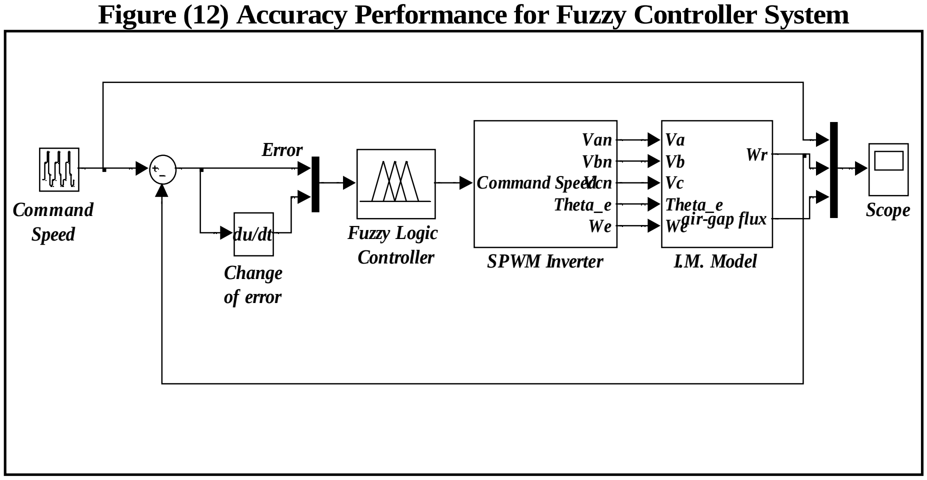

Figure (13) ***ANFIS Controller Simulation of I.M.***

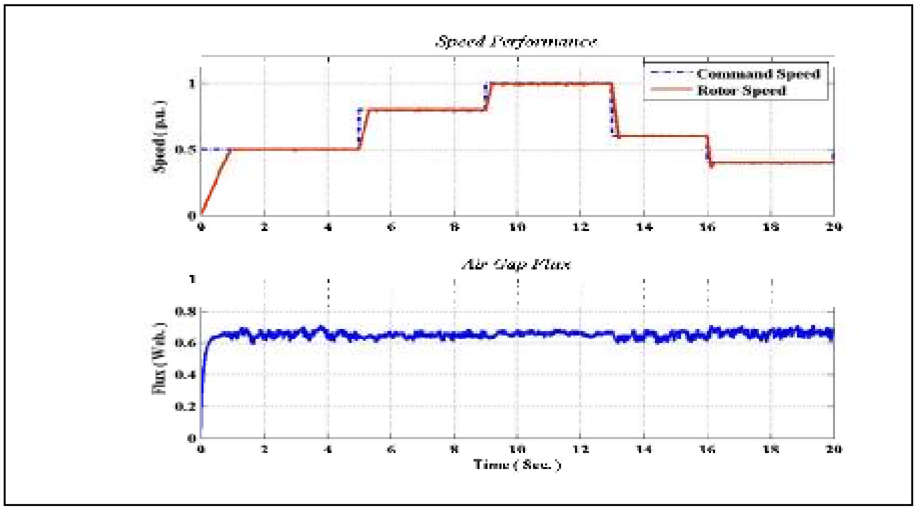

Figure (14) ***ANFIS Controller Performance***

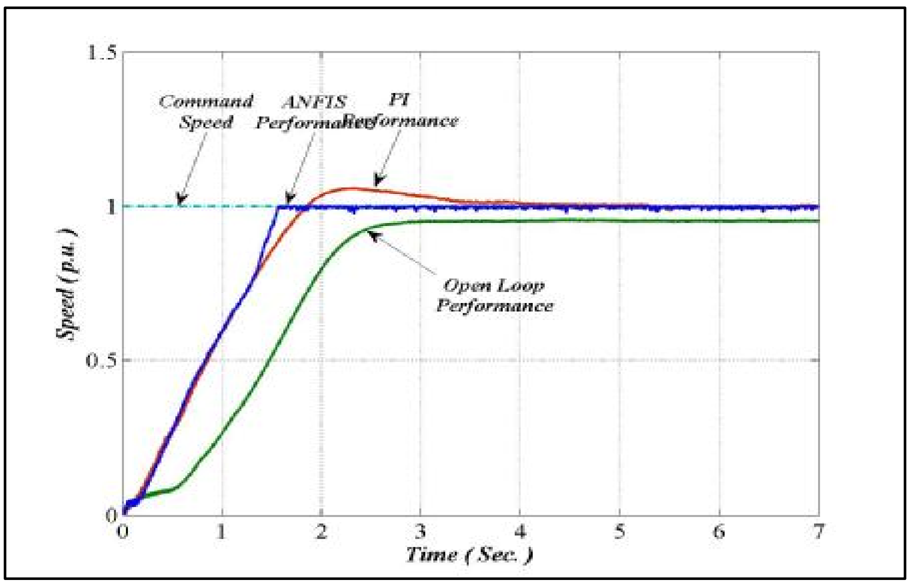

Figure (15) Comparison of I.M. Performance Among: Open loop, PI Controller, and ANFIS Controller