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Separately Excited DC Motor Optimal Efficiency Controller

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***Abstract*— The aim of this research is improving the performance of the direct current drive system by optimizing the efficiency of separately excited dc motor based on loss model under different loading conditions. The separately excited dc motor efficiency controller designed to determine the optimal field current which produces the optimal flux depending on the mechanical load torque applied to motor shaft. A Fuzzy Logic Controller is used to maintain a motor speed at predetermined level running at different load torque. The dc drive system is modeled and simulated using Matlab Simulink toolbox and the results are validated by comparing power parameters of both open loop and optimal fuzzy drive systems.**

***Index Terms*— Direct Current Motor, Optimal Efficiency, Fuzzy Logic, Modeling, Simulation.**

I. INTRODUCTION

The electric motor drive is widely used in industries. A large proportion of electrical energy is consumed by electric motors. Electric motors, taken together, make up the single largest end use of electricity. In industrial applications, electric motors account for roughly 60% of electricity consumption; in the process industries, electric motors account for more than 70% of electricity use [1].

Electric motors provide efficient, reliable, long-lasting service, and most require comparatively little maintenance. Despite these advantages, however, they can be inefficient and costly to operate if they are not properly selected and maintained. Industrial plants can avoid unnecessary increases in energy consumption, maintenance, and costs, by selecting motors that are well suited to their applications and making sure that they are well maintained. It's also important to know if a particular motor is the proper size for its application to ensure that a motor is properly sized for optimum energy efficiency [2]. The high cost of energy has placed a premium on finding ways to reduce the energy consumption by equipment and systems in industrial applications. Presently, the energy saving is the interesting issue for the engineers, Therefore, the electrical energy reduction by just few percent has a major impact in total electrical energy consumption [3]. In spite of the development of power electronics resources, the direct current machine became more and more useful; the energy efficiency of its drive systems could be improved by reducing the energy losses in the system and by improving the efficiency of the motors [4], [5].

[1] This work has been carried out during sabbatical leave granted to Dr.Rateb Hamdan Issa from Al-Balqa' Applied University (BAU) during the academic year 2012-2013.

The optimal control systems techniques which represent an opportunity for energy saving could be implemented in the static and transient periods of an electrical drive operation [6], [7]. Motor drives losses can be reduced considerably by independently controlling and the field current and armature voltage of d c motors for any torque and speed operating point. The quantities to be controlled are already accessible in phase-controlled rectifier dc power converters [8].

The control signals can be supplied by an open- loop controller which solves the loss minimization equations using preset drive parameters, or by an optimizing controller that measures or calculates the losses and finds the combination of quantities that minimizes the losses [9].

Motor operation under rated conditions is highly efficient. However, in many applications, a motor operates far from the rated point. Under these circumstances, it is not possible to improve the motor performance by motor design or by supply waveform shaping technique. So, a suitable control algorithm that minimizes the motor losses will rather take place [10].

This research presents the power loss identification and the idea to minimize power loss of the separately excited dc motor using mathematical approach. Separately excited direct current motor operating efficiency is optimized through the control of the motor field controlled rectifier as a function of actual motor load torque, actual field current and desired motor speed in order to produce optimal motor field flux which minimizes motor losses and optimizes motor efficiency.

The optimal efficiency control design bases on the proposed power loss model. Using dc drive system optimal efficiency controller under different loading conditions will give significant energy savings. The open loop drive system and optimal fuzzy dc drive system will be modeled and simulated using Matlab Simulink toolbox.

II. OPTIMAL DC DRIVE SYSTEM FUNCTIONAL DIAGRAM

The optimal dc drive system functional diagram is shown in Fig. 1 and it consists of the following components:

A. Separately Excited DC Motor

Separately excited dc motor consists of armature circuit and field circuit, when a motor is excited by a field current and armature current flows in the circuit, and then the motor develops a back emf and a torque to balance the load torque at a particular speed.

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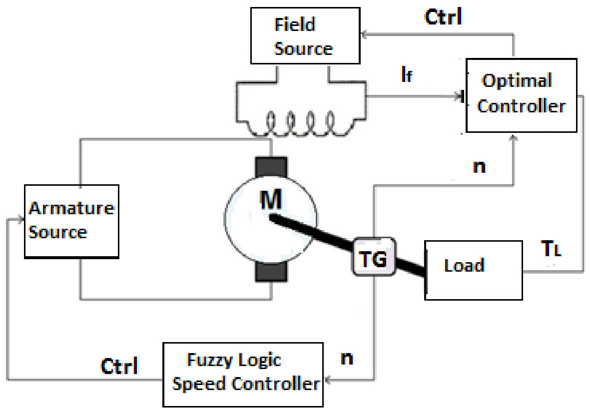

Fig 1.Optimal DC Drive System Functional Diagram

Separately excited dc motor nominal data are given in table I.

Table I. Separately Excited DC Motor Nominal Data

Parameter	Symbol	Value
Nominal Armature Voltage	V_a	220 V
Nominal Field Voltage	V_f	120 V
Nominal Armature Current	I_a	3.5 A
Nominal Field Current	I_f	0.4473 A
Armature Resistance	R_a	8.4155 Ω
Armature Inductance	L_a	0.08717 H
Field Resistance	R_f	286.2 Ω
Field Inductance	L_f	5.91 H
Mutual Inductance	L_{af}	1.534 H
Nominal Angular Speed	ω_n	280.3 rad/sec
Nominal Torque	T_n	2.26 N.m

The mathematical model that represents separately excited dc motor could be built using the following equations [11] in S-domain:

I- Armature Circuit equations:

1- Electrical Part equations:

$$V_a(S) = E_a(S) + I_a(S)R_a + L_a I_a(S)S \tag{1}$$

Where:

V_a : Armature voltage in volts.

E_a : Motor back electromotive force in volts.

I_a : Armature current in amperes.

R_a : Armature resistance in ohms.

L_a : Armature inductance in Henry.

Electrical part output signal is written as:

$$I_a(S) = [V_a(S) - E_a(S)]\frac{1}{R_a}[1/(1+\tau_e S)] \tag{2}$$

Where:

τ_e : Armature electromagnetic time constant.

Motor Back electromotive force equation:

$$E_a(S) = K\Phi\ \omega(S) \tag{3}$$

Where:

K : Motor constant.

Φ : Motor Magnetic Field flux in (Wb).

ω : Motor angular speed in (rad/sec).

2- Mechanical Part Equations:

$$T_e(S) - T_L(S) - T_f(S) = J\,\omega(S)S \tag{4}$$

Where:

T_L : Load torque in (N.m).

T_e : Motor torque in (N.m).

T_f : Friction torque in (N.m)

J : Moment of inertia in (kg/m²).

Mechanical Part output signal is written as:

$$\omega(S) = [K\Phi I_a(S) - T_L(S) - T_f(S)][1/JS] \tag{5}$$

II- Motor Field Circuit Equations:

$$V_f(S) = I_f(S)R_f + L_f I_f(S)S \tag{6}$$

Where:

V_f : Field voltage in volts.

I_f : Field current in amperes.

R_f : Field resistance in ohms.

L_f : Field inductance in Henry

Field current Signal is written as:

$$I_f(S) = V_f(S)\frac{1}{R_f}[1/(1+\tau_f S)] \tag{7}$$

Where:

τ_f : Field electromagnetic time constant.

Motor field constant signal is:

$$K\Phi(S) = L_{af} I_f(S) \tag{8}$$

Where:

L_{af} : Mutual inductance.

Fig. 2 shows S-domain block diagram of separately excited dc motor.

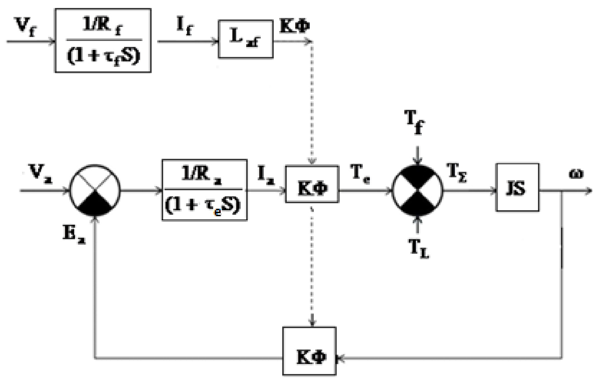

Fig 2.S-Domain Block Diagram of Separately Excited DC Motor

A. Separately Excited DC Motor losses:

In general, the dc motor losses are divided into the followings [12]:

1-Armuture losses: losses by the active resistance of the armature winding equal to $(I_a^2 R_a)$.

2-Magnetic losses (iron losses): these losses have a proportional relation to the flux density in the air gab (B_g) and the rotational speed (n).

3-Excitation circuit losses are equal $(I_f^2 R_f)$.

4-Mechanical losses are proportional to the speed (n).

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5- Stray losses are proportional to armature current (I_a) and rotational speed (n).

So the total losses equation will be as the following:

$$\Delta P_\Sigma = I_a^2 R_a + I_f^2 R_f + K_I B_g^2 n^2 + K_m n^3 + K_{st} I_a^2 n^2 \qquad (9)$$

To have the minimum losses at specific torque–speed characteristic and at determined field current, equation (9) should have a partial derivative with respect to field current then equalized to zero:

$$(\partial \Delta P_\Sigma / \partial I_f) = (\partial / \partial I_f)\left[I_a^2 R_a + I_a^2 K_{st} n^2\right] + \\ + (\partial / \partial I_f)\left[I_f^2 R_f + B_g^2 K_I n^2 + K_m n^3\right] = 0 \qquad (10)$$

Where:

K_{st} : Stray constant.

K_I : Air gap constant.

K_m : Motor constant.

B. Armature and Field Controlled sources

This simulation assumes that the used rectifier is ideal rectifier. In which there are no SCRs resistances and the output will be a pure dc current without any harmonic or ripples.

So the circuit could be built using a controlled voltage source with a control signal that present the average value of the real three phase full controlled rectifier.

Three phase full converter is a fully controlled bridge rectifier using six SCRs connected in the form of a full wave bridge configuration. All the six SCRs are controlled switches which are turned on at appropriate times by applying suitable gate trigger signals.

This convertor will be used to convert ac voltage signal to dc signal, since the motor is a dc type [13].

The average output voltage of the controlled rectifier is determined according to the following equation:

$$V_{av} = (3\sqrt{6}/\pi) V_{rms} \cos(\alpha) \qquad (11)$$

Where:

α : SCR firing (triggering) Angle.

V_{rms} : Input voltage root mean square value.

C. Optimal Field Current controller

The optimal controller will optimize the motor field current (I_f), which will optimize the motor flux (Φ), leading to optimize the drive system total losses and efficiency.

The floating controller is used to the field current error, which is the difference between the optimal field current and the actual field current, this error changes the control angle of the field controlled source, leading to the change of the field voltage.

The drive system efficiency expression is:

$$\eta = P_{out}/P_{in} = [T_L\ \omega / (V_a I_a + V_f I_f)] \qquad (12)$$

Where:

P_{out} - Drive system output power.

P_{in} - Drive system input power.

The drive system total losses could be calculated as follows:

$$\Delta P_\Sigma = P_{in} - P_{out} \qquad (13)$$

Algorithm of Optimal Field Current

In this section the optimal field current relationship will be derived, depending on motor loading coefficient (λ), motor load torque (T_L), motor angular speed (ω) and motor physical constants.

Motor loading coefficient relationship is:

$$\lambda = (T_{max}/T_L) = (I_{sh}/I_a) = 1 + (E_a / I_a R_a) \qquad (14)$$

Where:

T_{max} : Maximum motor torque.

I_{sh} : Motor short circuit current.

E_a : Developed back electromotive force.

Developed motor torque relationship is:

$$T = K_E B_g I_a = (I_f I_a K_E K_F / K_{St}) \qquad (15)$$

Using equation (15), we get:

$$I_a = (T K_{St} / I_f K_F K_E) \qquad (16)$$

Developed back electromotive force relationship is:

$$E_a = K_E B_g \omega = \frac{K_E K_F}{K_{St}} I_f\ \omega \qquad (17)$$

Where:

K_E : Voltage constant for given motor design and winding.

K_F : Field factor.

K_{St} : Saturation factor.

Substituting equations (16) and (17) in equation (14) we get:

$$\lambda = 1 + (K_E K_F / K_{St})^2 (I_f^2\ \omega / T R_a) \qquad (18)$$

The optimal field current value is determined for constant motor loading coefficient and nominal angular speed at different load torque values as follows:

$$I_{f\,opt} = (K_{st}/K_E K_F)\sqrt{(T R_a (\lambda - 1)/\omega_n)} \qquad (19)$$

The optimal field voltage relationship is:

$$V_{f\,opt} = I_{f\,opt} R_f \qquad (20)$$

D. Fuzzy Logic 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. The operation of a FLC is based on qualitative knowledge about the system being controlled. It doesn't need any difficult mathematical calculation like the others control system [14]. 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 [15]. A fuzzy logic controller has four main components as shown in Fig. 3.

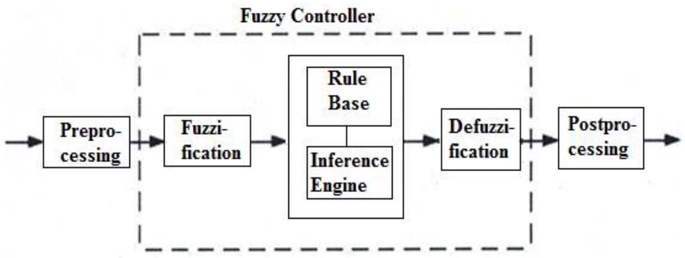

Fig3. Fuzzy Logic Controller Components

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1. *Fuzzification*

The first step in designing a fuzzy controller is to decide which state variables represent the system dynamic performance must be taken as the input signal to the controller. Fuzzy logic uses linguistic variables instead of numerical variables. The process of converting a numerical variable (real number or crisp variables) into a linguistic variable (fuzzy number) is called fuzzification. This is achieved with the trapezoidal or triangular fuzzifier. The fuzzy logic controller has two inputs:

- Motor speed error (input 1).
- Motor speed integrated error (input 2).

Fig. 4 shows motor speed error fuzzification (input 1).

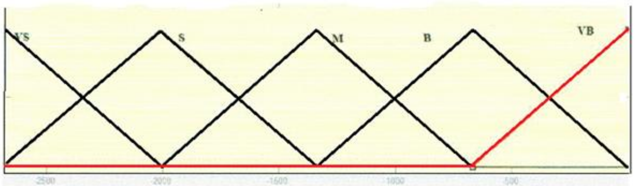

Fig4. Motor Speed Error Fuzzification (Input 1)

Fig. 5 shows motor speed integrated error fuzzification (input 2).

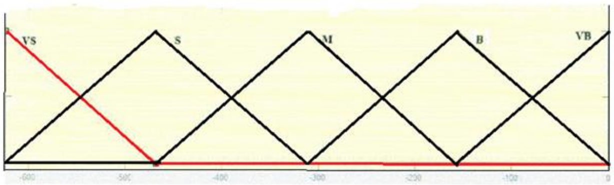

Fig5. Motor Speed Integrated Error Fuzzification (Input 2)

2. *Rule Base*

A decision making logic which is, simulating a human decision process, inters fuzzy control action from the knowledge of the control rules and linguistic variable definitions.

The rules are in "If Then" format and formally the If side is called the conditions and the Then side is called the conclusion. The computer is able to execute the rules and compute a control signal depending on the measured inputs error (e) and change in error (de). In a rule based controller the control strategy is stored in a more or less natural language. A rule base controller is easy to understand and easy to maintain for a non- specialist end user and an equivalent controller could be implemented using conventional techniques. Table II shows rule base.

Table II. Rule Base

	VS	S	M	B	VB
VS	0	0	-1461	-1684	-1341
S	0	-481.1	-1692	-1349	-1005
M	-41.56	-1698	-1357	-1114	0
B	-1705	-1366	-1025	0	0
VB	-1374	-1035	0	0	0

3. *Inference System*

Inference engine is defined as the Software code which processes the rules, cases, objects or other type of knowledge and expertise based on the facts of a given situation. When there is a problem to be solved that involves logic rather than fencing skills, we take a series of inference steps that may include deduction, association, recognition, and decision making. An inference engine is an information processing system (such as a computer program) that systematically employs inference steps similar to that of a human brain. An inference system could be one of two types: mamdani or sugeno. We used the sugeno type. The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant.

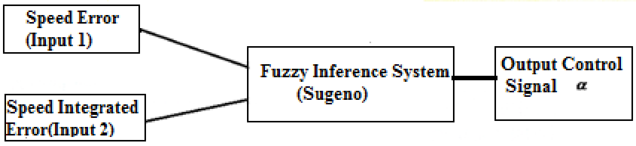

Fig 6. Fuzzy Inference System

4. *Defuzzification*

The reverse of Fuzzification is called Defuzzification. The use of Fuzzy Logic Controller (FLC) produces required output in a linguistic variable (fuzzy number). According to real world requirements, the linguistic variables have to be transformed to crisp output. Sugeno fuzzy model is used. Implementation of an FLC requires the choice of four key factors:

1) Number of fuzzy sets that constitute linguistic variables.
2) Mapping of the measurements onto the support sets.
3) Control protocol that determines the controller behavior.
4) Shape of membership functions.

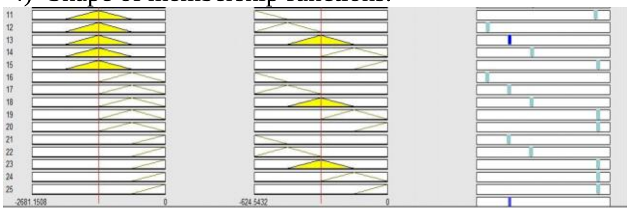

Fig7. Example of Defuzzification

Fig. 8 shows 3-D Output Surface, which give the dependence of fuzzy controller output signal on the value of the two input signals of fuzzy controller.

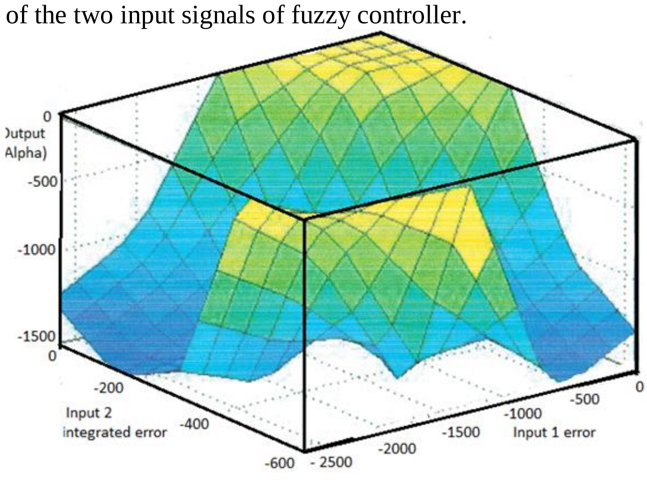

Fig8. 3-D Output Surface

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III. MODELING AND SIMULATION OF OPEN LOOP DC DRIVE SYSTEM USING MATLAB SIMULINK TOOLBOX

Open loop dc drive system model consists of separately excited dc motor model and motor efficiency calculation model as shown in Fig. 9.

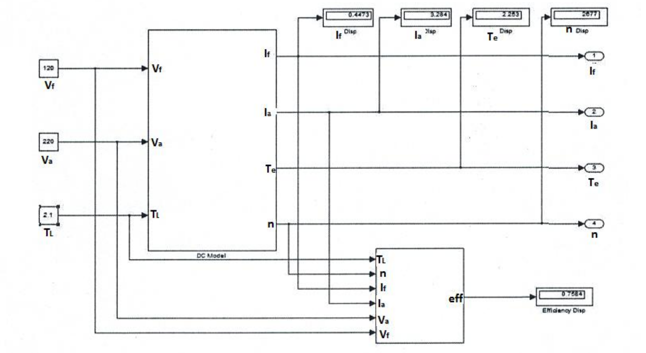

Fig 9. Open Loop DC Drive System Model

A. *Separately Excited DC Motor Model*

Fig. 10 shows the separately excited dc motor model which is built using S-domain block diagram of separately excited dc motor shown in Fig. 2 and dc motor nominal data given in table 1...

B. *Motor Efficiency Calculation Model*

The motor efficiency calculation model is built using equation (12) as shown in Fig. 11.

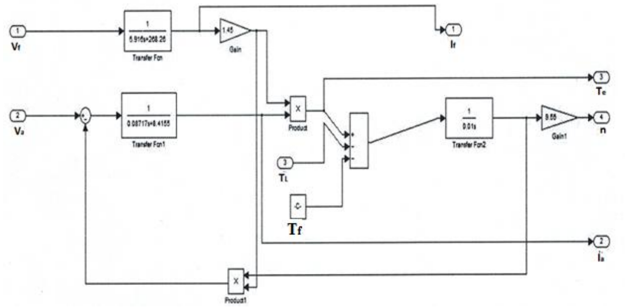

Fig10. Separately Excited DC Motor Model

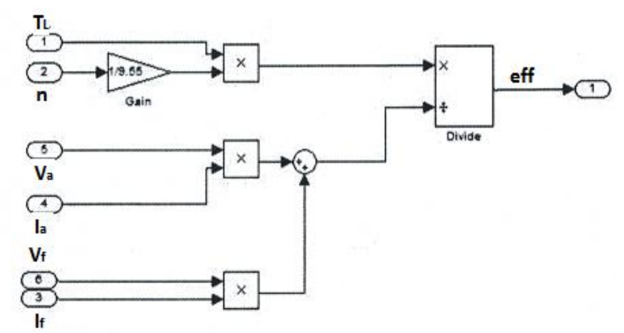

Fig11. Motor Efficiency Calculation Model

IV. MODELING AND SIMULATION OF OPTIMAL FUZZY DC DRIVE SYSTEM USING MATLAB SIMULINK TOOLBOX

Optimal fuzzy dc drive system model consists of open loop dc drive system model, optimal field controller model and armature fuzzy controller model as shown in Fig. 12.

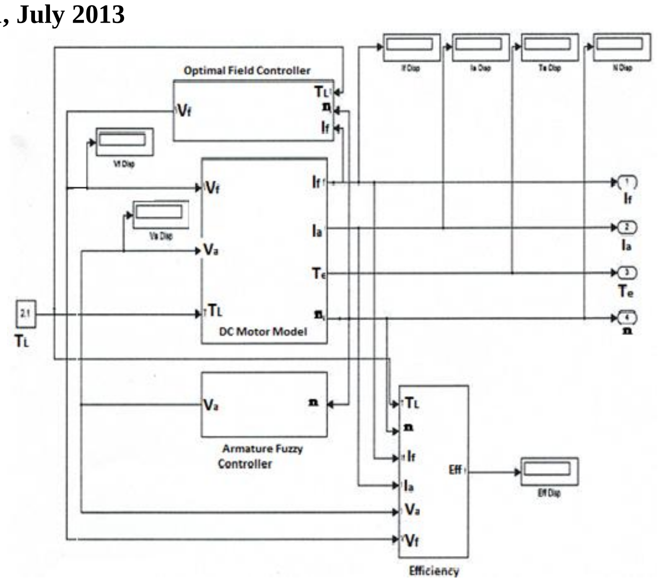

Fig12. Optimal Fuzzy DC Drive System Model

A. *Optimal Field Controller Model*

Optimal field controller model consists of optimal field current model, floating controller model and motor field source model as shown in Fig. 13. Optimal field current model is built using equation (19) as shown in Fig. 14.

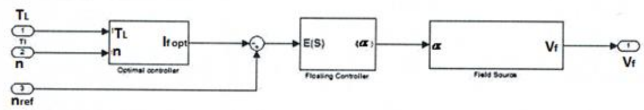

Fig13. Optimal Field Controller Model

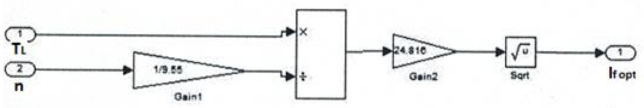

Fig14. Optimal Field Current Model

Floating controller output signal will float (remain constant) at that value achieves the goal of the controller while the error is not go out of the permissible value. The general design of floating controller is a comparator followed by an integrator. The floating controller model is shown in Fig. 15.

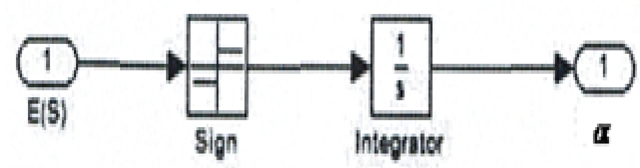

Fig15. Floating Controller Model

The motor field source model is built using equation (11) as shown in Fig. 16.

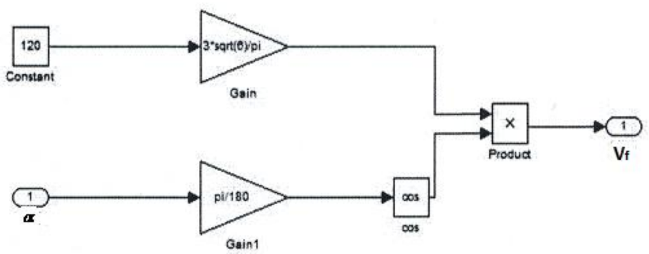

Fig16. Motor Field Source Model

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B. Armature Fuzzy Controller Model

Armature fuzzy controller controller model consists of motor speed fuzzy controller model and motor armature source model as shown in Fig. 17.

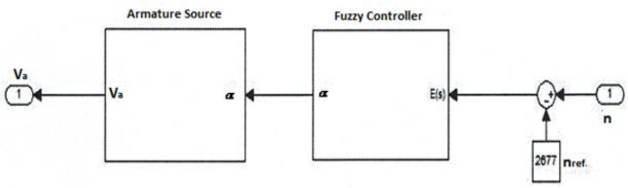

Fig17. Armature Fuzzy Controller Model

Motor speed fuzzy controller model shown in Fig. 18 has motor speed error as first input and integrated motor speed error as second input.

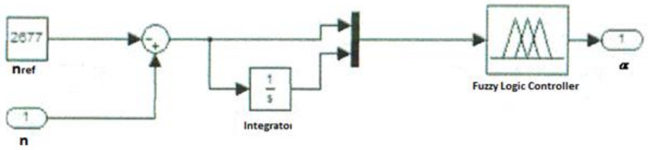

Fig18. Motor Speed Fuzzy Controller Model

The motor armature source model is built using equation (11) as shown in Fig. 19.

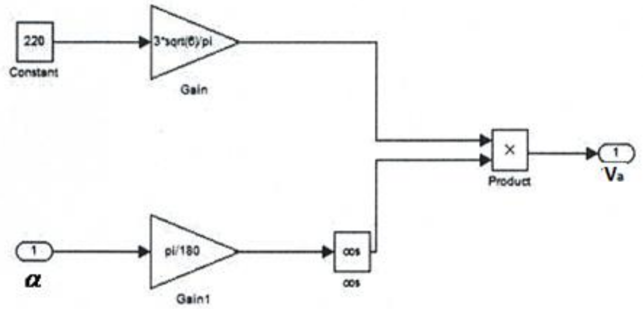

Fig19. Motor Armature Source Model

V. Simulation Results

The simulation results of open loop dc drive system and optimal fuzzy dc drive system are presented. All these results are supported by figures that compare both simulated drive systems.

Fig. (20-23) represent motor power parameters variation versus load torque and Fig. (24, 25) represent real- time motor efficiency and motor total losses variation at different load torques. It is obvious that the optimal fuzzy drive system provides a very good opportunity to improve the motor power parameters.

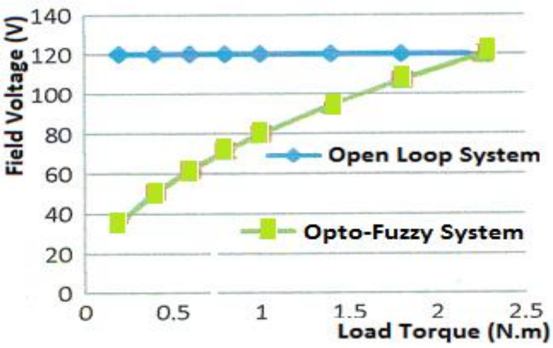

Fig20. Motor Field Voltage versus Load Torque

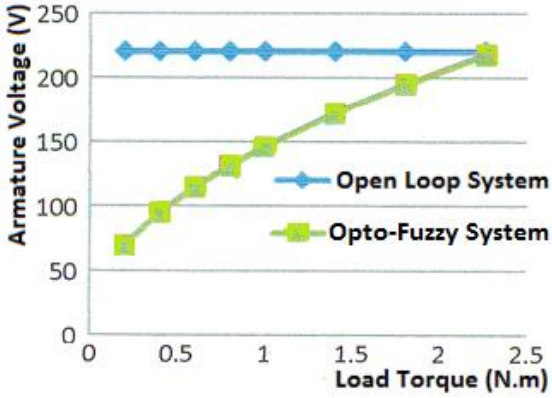

Fig 21. Motor Armature Voltage versus Load Torque

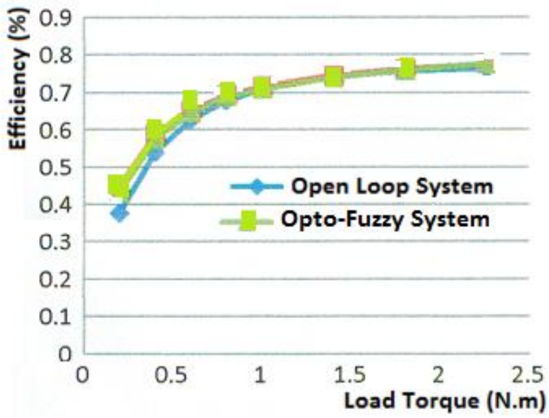

Fig 22. Motor Efficiency versus Load Torque

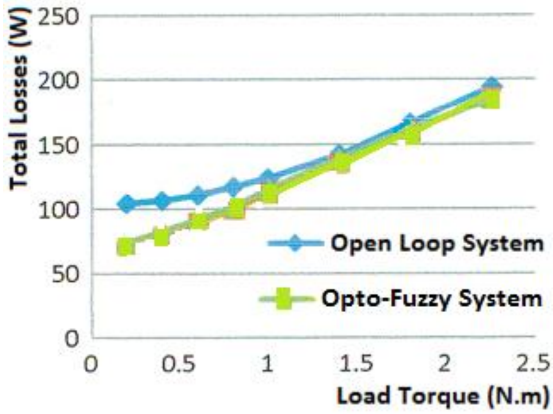

Fig 23. Motor Total Losses versus Load Torque

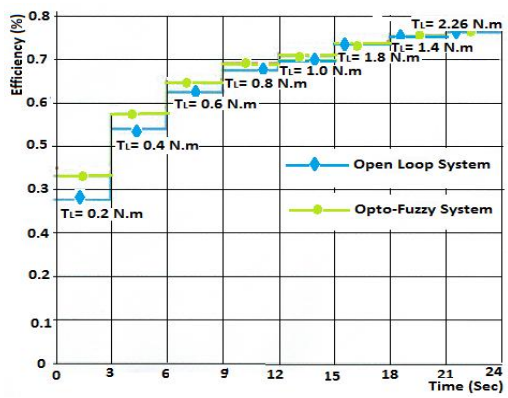

Fig24. Real- Time Motor Efficiency Variation at Different Load Torques

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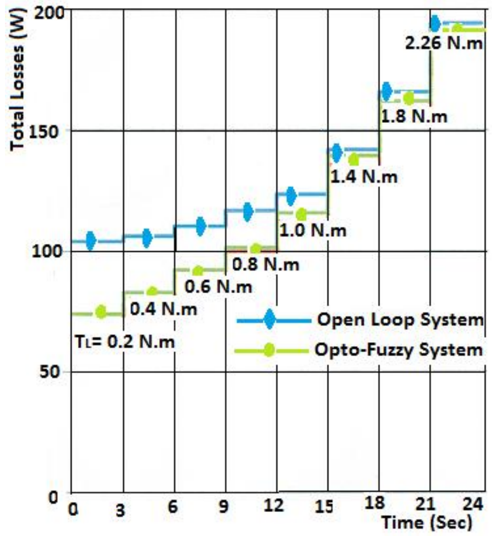

Fig 25. Real- Time Motor Total Losses Variation at Different Load Torques

VI. CONCLUSION

Studying and analyzing the above shown figures of simulation results, we can conclude:

1- The optimal fuzzy dc drive system is effective and efficient by controlling field voltage and armature voltage depending on load torque, leading to minimization of motor total losses and significant energy savings.

2- The optimal efficiency controller has an ability to achieve the optimal efficiency at different loading conditions by finding optimal motor flux value needed for minimization of motor total losses.

3- Using dc motor optimal efficiency controller in industry under light loads, will increase motor life- period by minimizing the consumption of armature current and field current.

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