Voltage Controller for Efficiency Improvement of Three-Phase Induction Motor

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Abstract— **In the industries, induction motors are the commonly chosen due to their efficiency, reliability, strength, cost and rugged building. The main percentage of spent energy in manufacturing is spent by induction motors. Therefore, even a modest development in the energy efficiency of induction motor drives can suggest large energy-savings. In this study, efficiency improvement technique is produced for squirrel cage induction motor that works at less than 75% of its full load taking the advantage of the core loss which consider constant losses and make them variable. The improvement is achieved over managing the voltage administered to the stator winding over the use of the three phase AC voltage controller. Voltage control scheme is developed by tracking the change in voltage and current and determined the reference slip, error of slip will be input to fuzzy logic controller and sex back-by-back thyristors will be trigging through the output signals of fuzzy logic controller to get the best voltage that gives the best efficiency for specific load torque. The simulation proofs are done in MATLAB/Simulink. The results show that the proposed scheme gives high improvement in efficiency at light and medium load and gives a good energy-savings.**

Keywords: Three-phase induction motors Stator voltage control

1.Introduction

Energy is a fundamental requirement for several purposes in mechanical workplaces around the globe. Gigantic measure of energy required for nations with rapider economic development. Energy is subsequently a significant factor for financial seriousness and work. Though, worldwide populace and energy needs are expanded connected at the hip. This worry should be tended to by the worldwide local area to beat any lack of energy assets later on. World showcased energy utilization is projected to increment by 33% from 2010 to 2030 [1]. The industry area represented 37% of complete worldwide last energy use in 2017. This addresses a 1% yearly expansion in energy utilization since 2010, with 1.7% development in 2017 after much more slow development of 0.1% the earlier year. Development in energy utilization has been driven to a great extent by a continuous long-haul pattern of rising creation in energy-serious industry subsectors (for example synthetics, iron and steel, concrete, mash and paper and aluminum) [2].

Induction motors (IMs) rule the world market (over 85% of electrical engines) [1] with wide applications in ventures, public administrations and family electrical apparatuses [2,3]. As per measurements on modernly created countries, IMs add to over 60% of absolute mechanical power utilization [4].

The IM developed in 1888 by Nikola Tesla [3] and Dolivo Dobrowolski broadened its design in 1890, which was identified as squirrel-confine engine. In fact, the proficiency pace of an IM is usually high when it runs on under the full burden. For the most part, the effectiveness rate is higher than 75%. Although, the productivity of the acceptance engine drive framework is lower if an induction motors working at light loads or medium burdens. Along these lines, that the energy proficiency of acceptance engine drives and its improvement show colossal energy saving [5]. Many energy saving procedures have been utilized as arrangement to online and offline systems [6]. In the disconnected, the energy saving is accomplished by choosing appropriate rating of engine comparing to stack, by choosing effective engine though in Europe changing to energy proficient engine driven framework can set aside to 202 billion KW in power use [7]. Also by choosing reasonable capacitance that will limit the misfortunes because of responsive influence in IMs and by select a decent quality curls that will limit the misfortunes of the conductors that increment pair to the expanding in temperature [8].

Online loss minimization techniques (LMTs) use data about activity and machine boundary evaluations to limit misfortunes ceaselessly though the drive is running. In IM, the control variables could be the flux, voltage, current, slip frequency, or combinations the three classifications of online LMTs are [9] model-based, search-based, and crossovers that join these. Model-based LMTs depend on engine boundaries and force misfortune models. Search-based LMTs use input and quest for the base misfortune working point. Cross breed LMTs utilize both engine boundaries and input. The online strategies rely upon the application (variable speed or variable torques). Utilizing variable frequency drives (VFDs) for IMs can save energy particularly for that gear which changing their force as indicated by changing in their speed like siphons, variable force fans and blowers. In the United States, an expected 60-65% of electrical energy is utilized to supply engines, 75% of which are variable-force fan, siphon, and blowers load [10]. Other method, for example, variable voltage drive (VVD) is utilized for variable force application [11].

The evaluated efficiency of an IM is large while it works under the full load or more than 75% of the full load. Generally, the evaluated efficiency is more than 80%. Though, the operating efficiency of the IM drive system will be weak if an IM is not designated properly or does not match its load suitably and it works at load less than 75% of the full load. So, even a diffident upgrading in the energy efficiency of IM drives can suggest large energy-savings. This work is an attempt to minimize the IMs losses using energy-savings of squirrel cage IM drive . A control scheme is proposed for energy savings of three-phase squirrel cage IM drive systems with fast response to the sudden change in load torque when it operates at less than 75% of full loads in constant speed applications constructed on the variable voltage control (VVC).

The main objective of this paper is to develop losses minimize scheme that can control the supply voltage to motor according to the operation load, and minimize the losses in induction motor and improve the efficiency.

2.Methodology

Figure 1.is a schematic diagram that shows the general methodology since it consists of six phases: IM power analysis, identify the power losses Problem, Determined the relation between the input Voltage and power losses, AC voltage controller, Develop proposed scheme for efficiency improvement and design (FLC) and Do the simulation in MATLAB/Simulink and discuss the result.

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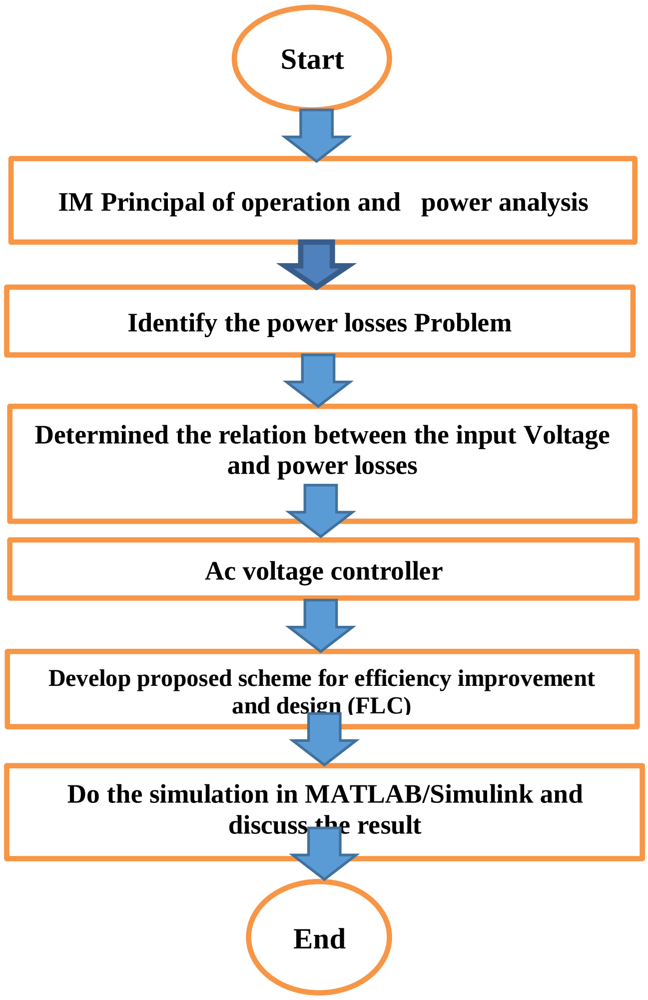

2.1 Induction Motor.

Three phase induction motors are a "mature technology" [12]. Motors produce useful work by causing the shaft to rotate thus converting electrical energy into mechanical energy.

IM is a greatly efficient electrical machine when running near its evaluated torque and rotation speed. But at low loads, symmetry between copper and iron losses disturbs due to which efficiency is considerably reduced. The working efficiency and power factor can be enhanced by making adjustments in excitation as per load and rotation speed requirements.

2.1.1 Construction of Induction Motor

Figure 2 show the design of IM is straightforward and comprises of two primary parts, a stator and a rotor. The stator center is fixed inside the engine house and is made of overlaid electrical steel sheets. The stator center has spaces that are loaded up with copper windings. Its motivation is making a pivoting magnetic field. The rotor is the turning part of the engine and is made of a steel with aluminum windings. With the utilization of the pivoting magnetic field from the stator, the rotor can create force. The rotor body is connected to the shaft to communicate the made force from inside the engine to the determined application.

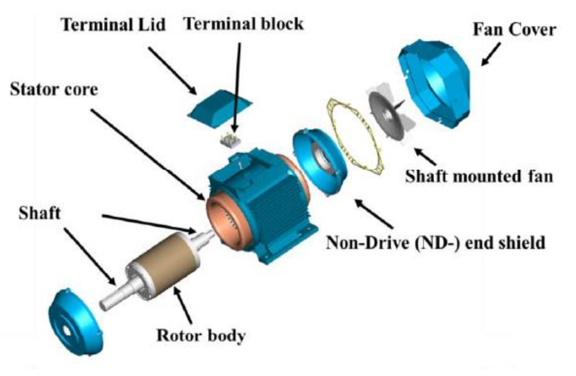

Fig.2. the construction of IM

2.1.2 Principle of rotating magnetic field (RMF)

Applying a reasonable three-stage set of charge to a three-stage stator winding makes a turning attractive field noticeable all around hole between the stator and rotor. Figure 3 shows the cross-section of the engine. The stator cores are not appeared; rather, the stator turning attractive field is addressed by the North Pole at the top and the South Pole at the base. Motion from the North Pole enters the air hole from the stator and crosses to the rotor, as appeared. For the South Pole, the motion leaves the rotor, crosses the air hole, and reenters the stator. The rotor is appeared with a squirrel-confine twisting (for clearness, just a few of the rotor bars are appeared and the end ring has been taken out).

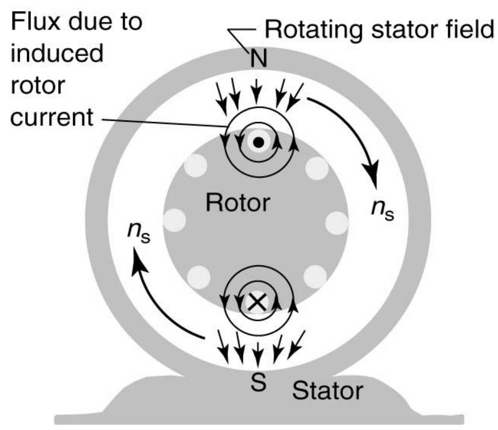

Fig.3. Induction of the rotor current by rotating stator magnetic field.

In Figure 3, the field is rotating clockwise; however undoubtedly, it seems as though the stator field was fixed and the rotor conductor was moving counterclockwise. In this way, by the right-hand generator rule, a current is actuated in the top rotor bar toward the path appeared (emerging from the page). At the lower part of the rotor, the South Pole is moving and the current instigated in the base rotor bar is into the page. These prompted flows have their own attractive field, obviously, which are shown encompassing the rotor conductors. Note that for the top rotor bar, the motion brought about by the current in the rotor bar adds to the stator transition on the left side and diminishes the stator motion on the correct side. The rule of motion bundling will apply. Since there is more motion on the left half of the conductor, there will be an electromagnetic power on the conductor to one side. The inverse is valid for the base rotor bar–its power is to one side.

The force (F=B.I.L) following up on the conductors make a force on the rotor. On the off chance that the rotor is allowed to move (and if the power is sufficient to defeat rubbing and dormancy), the rotor will start to turn. Nonetheless, that the rotor is kept from turning (this is known as an impeded rotor). All things considered, the stator motion would clear by the rotor conductor at coordinated speed, instigating flows in the rotor conductors that have similar recurrence as the stator flows. The flows incited in the rotor cause a second pivoting rotor attractive field, which additionally turns around the air hole at coordinated speed.

2.1.3 Equivalent Circuit

The equivalent circuit of any electric machine such as induction machines and synchronous machines shows various parameters which represent the resistances and reactance of the machine windings. The corresponding circuit of a three phase IM is similar to that of an electric transformer, but the frequency, reactance, current and induced voltage emf of the rotor windings of the three phase IM are directly proportional to the motor slip as shown in Figure 4.

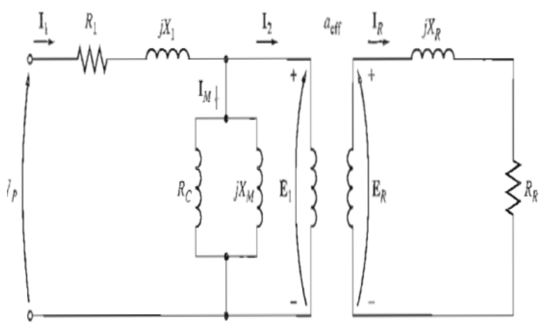

Fig.4. Equivalent circuit of a three phase IM per phase [13].

The equivalent circuit in Figure 4 can be redrawn by referring rotor circuit to the stator circuit called equivalent circuit referred to stator. The two circuits (stator and rotor) Figure 4 can be replaced with one circuit as shown in Figure 5.

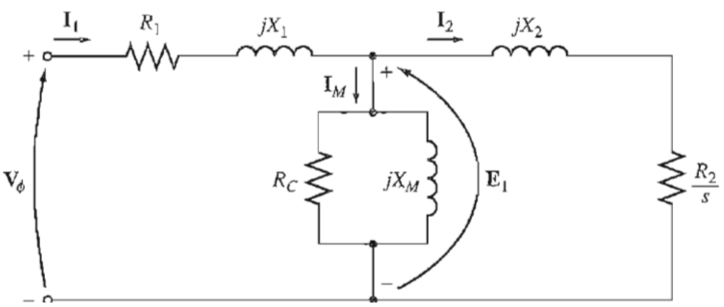

Fig.5. Equivalent circuit of a three phase IM per phase referred to stator [13].

Where [12]:R_1 is stator winding resistance.$X_1$is stator winding reactance. $R_c$is iron losses resistance. X_m is magnetizing reactance. $R_2$is rotor winding resistance referred to stator. $X_2$is rotor reactance referred to stator (the rotor is in standstill). $V_\emptyset$ is the applied voltage to the stator. I_1 is stator phase current. I_m is magnetizing and iron losses current. E_1 is rotor induced emf referred to stator (the rotor is in standstill). I_2 is rotor phase current referred to stator (under running conditions).

2.2 AC Voltage Controller Circuits (RMS Voltage Controllers)

AC voltage regulators (ac line voltage regulators) are utilized to fluctuate the RMS estimation of the exchanging voltage applied to a load circuit by presenting thyristors between the load and a steady voltage ac source. The RMS estimation of substituting voltage applied to a load circuit is constrained by controlling the setting off point of the thyristors in the air conditioner voltage regulator circuits. In short, an air conditioner voltage regulator is a sort of thyristor power converter which is utilized to change over a fixed voltage, fixed recurrence ac input supply to acquire a variable voltage ac yield. The RMS estimation of the air conditioner yield voltage and the air conditioner power stream to the load is constrained by (changing) the trigger point 'α' [14,15].

2.2.1 Three-phase AC–AC Voltage Controllers

The unidirectional regulators, which contain dc input current and higher consonant substance because of the uneven idea of the yield voltage waveform, are not regularly utilized in ac engine drives; a three-stage bidirectional control is usually utilized. The circuit outline of a three-stage full-wave (or bidirectional) regulator is appeared in Figure 6 with a Y-associated resistive burden. The terminating arrangement of thyristors is T1, T2, T3, T4, T5, and T6.

If we define the instantaneous input phase voltages as

$$Van = \sqrt{2}\, Vs \sin \omega t \qquad (1)$$

$$Vbn = \sqrt{2}\, Vs \sin(\omega t - 120°) \qquad (2)$$

$$Vcn = \sqrt{2}\, Vs \sin(\omega t - 240°) \qquad (3)$$

The instantaneous input line voltages are

$$V_{ab} = \sqrt{6}\, V_s \sin(wt + 30°) \qquad (4)$$

$$V_{ab} = \sqrt{6}\, V_s \sin(wt - 90°) \qquad (5)$$

$$V_{ab} = \sqrt{6}\, V_s \sin(wt - 210°) \qquad (6)$$

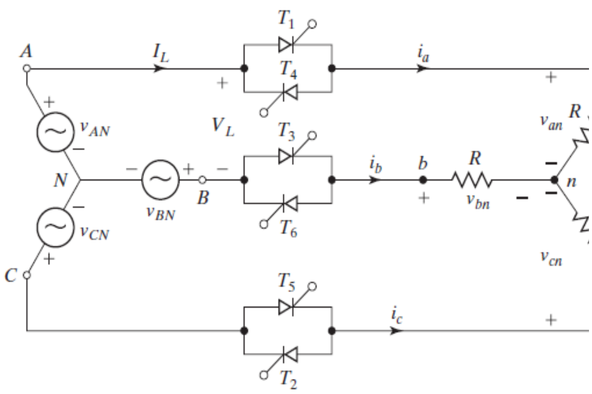

Fig.6. Three-phase bidirectional controller.

Figure 7 shows the input and output voltage waves and the thyristor phase when the firing angle is $\alpha = 60°$. For $0 \le \alpha \le 60°$, directly before the firing of T_1, two thyristors conduct. Once T_1 , is turned on, three thyristors conduct. A thyristor turns off when its current attempts to reverse. The thyristor turns off when the current is reversed, and so the two parts operate when the current is alternating.

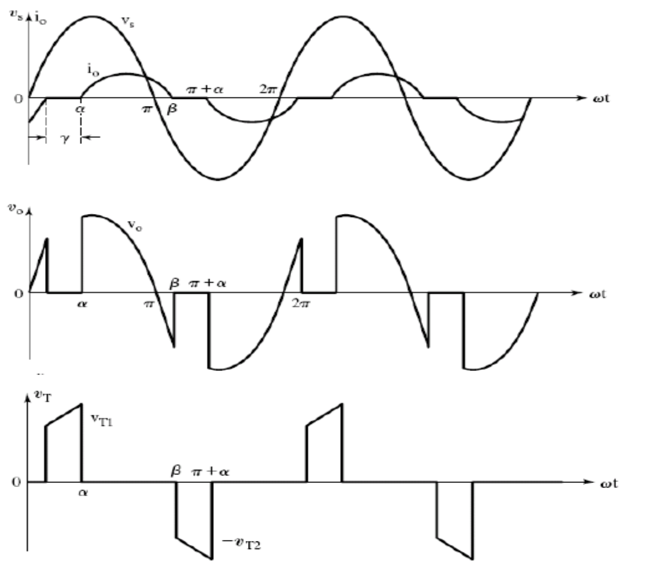

Fig.7. Waveforms of Input supply voltage, Load Current, Load Voltage and Thyristor Voltage across T_1 and T_2.

For $60° \le \alpha \le 90°$ only two thyristors conduct at any time. For $90° \le \alpha \le 150°$, although two thyristors conduct at any time, there are periods when no thyristors are on. For $\alpha \ge 150°$ there is no period for two conducting thyristors and the output voltage becomes zero at $\alpha = 150°$ The range of delay angle is $0 \le \alpha \le 150°$.

Like to half-wave managers, the expression for the rms output stage voltage hangs on the variety of delay angles.

2.3 DESIGN OF FUZZY BASED CONTROL

The overall goal of a design is to achieve good performance using simple methods for controlling complex systems. For designing the controller, firstly choose the reference slip. Then select the inputs. Select

membership functions for both input and output variable and then prepare a rule-base.
Inputs for the controller are A. Slip error (e). B. Change or derivative of slip error. C. The load ratio where, Output from the controller rising or reducing the firing angle.
The Fuzzy control is applied via selection of MFs for both input and output, Fuzzy Variables and MF for input (Ratio of actual load to the full load of the motor), (Slip error) and (The derivative of the slip error) are showing in Figures 8,9 and10 .
Where, the MF for the output is the change in firing angle which is shown in figure 11.
The tringle MF is used for all of the input variable and also for the output we use the triangle MFp

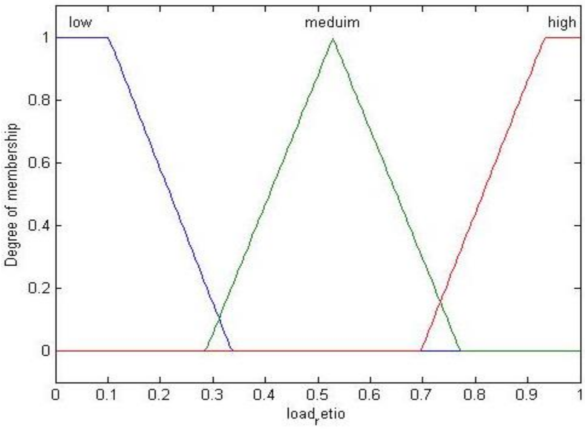

Fig.8. load ratio MF

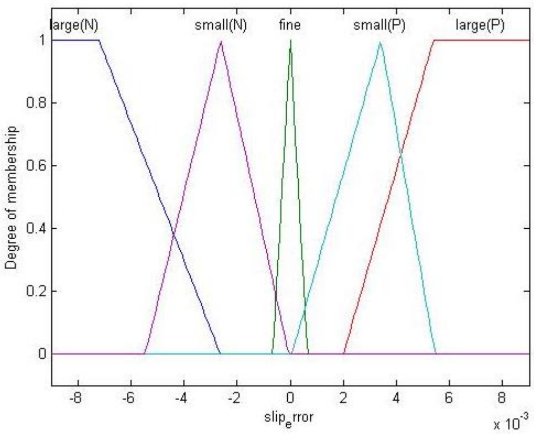

Fig.9. slip error MF

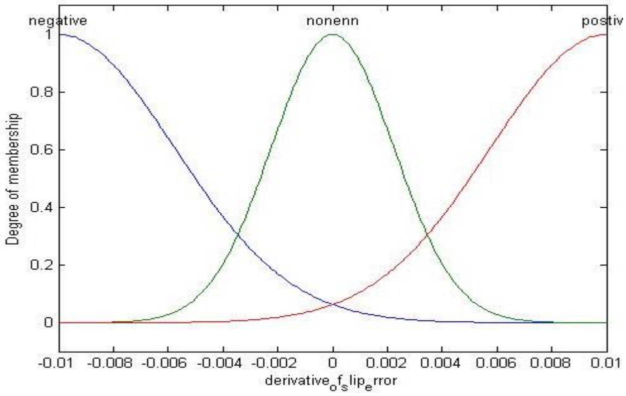

Fig.10 Derivative of slip error MF

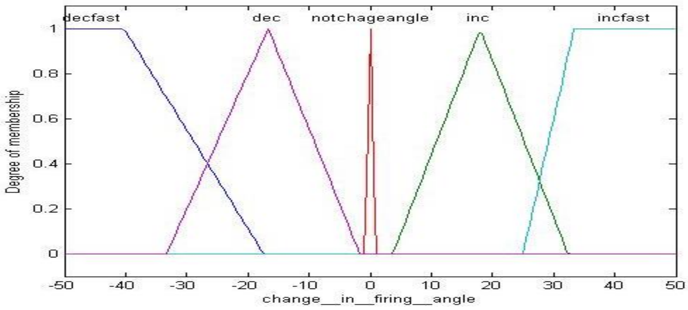

Fig.11. The output of the FLC (change in the firing angle

2.4 Designed Rule-Base

The 11/1/knowledge-based rules according to which the output of the fuzzy inference system is decided consists of 14. The following set of If- Then rules are used for designing FLC:

- *If (load_ratio is low) and (slip_error is large(N)) then (output1 is decfast)*
- *If (load_ratio is low) and (slip_error is small(N)) then (output1 is decfast)*
- *If (load_ratio is low) and (slip_error is fine) and (derivative_of_slip_error is positive) then (output1 is dec)*
- *If (load_ratio is low) and (slip_error is fine) and (derivative_of_slip_error is nonenn) then (output1 is notchageangle)*
- *If (load_ratio is low) and (slip_error is fine) and (derivative_of_slip_error is negative) then (output1 is inc)*
- *If (load_ratio is low) and (slip_error is small(P)) then (output1 is incfast)*

- *If (load_ratio is low) and (slip_error is large(P)) then (output1 is incfast)*
- *If (load_ratio is meduim) and (slip_error is large(N)) then (output1 is decfast)*
- *If (load_ratio is meduim) and (slip_error is small(N)) then (output1 is decfast)*
- *If (load_ratio is meduim) and (slip_error is fine) and (derivative_of_slip_error is positive) then (output1 is dec)*
- *If (load_ratio is meduim) and (slip_error is fine) and (derivative_of_slip_error is nonenn) then (output1 is notchageangle)*
- *If (load_ratio is meduim) and (slip_error is fine) and (derivative_of_slip_error is negative) then (output1 is inc)*
- *If (load_ratio is meduim) and (slip_error is small(P)) then (output1 is incfast)*
- *If (load_ratio is meduim) and (slip_error is large(P)) then (output1 is incfast)*
- *. If (load_ratio is high) then (output1 is decfast).*

3.MATLAB Simulation and Results

3.1 Simulink Model for Energy Efficient Control

In Induction motor energy efficiency control, the two required input variables for FLC are: the slip error (e) and its derivative, which represents the change of slip error and the load ratio. Slip error is calculated by comparing desired slip and actual slip (by feedback). The controller output is the firing angle of the thyristor which lead to change in the voltage supply fed to induction motor. The output of fuzzy based controller is applied to the back-by-back thyristor to produce waveform with variable voltage to control the power fed induction motor.

Based on the reference point and feedback, FLC produces the control signal which will be added or subtracted from instantaneous firing angle to control the supply voltage feed induction motor.

The closed loop control system of FLC and Three-phase AC–AC Voltage Controller is simulated using SIMULINK software. The FLC has proved to be very advantageous in the industries as it has the capability to control the complex nonlinear systems. As shown in the Figure 12, the system consists of the control unit, the electrical feeding unit, and the induction motor unit which is a model found in the MATLAB/Simulink SYMPOWER library. And the unit of measurement to monitor the current, voltage and motor speed.

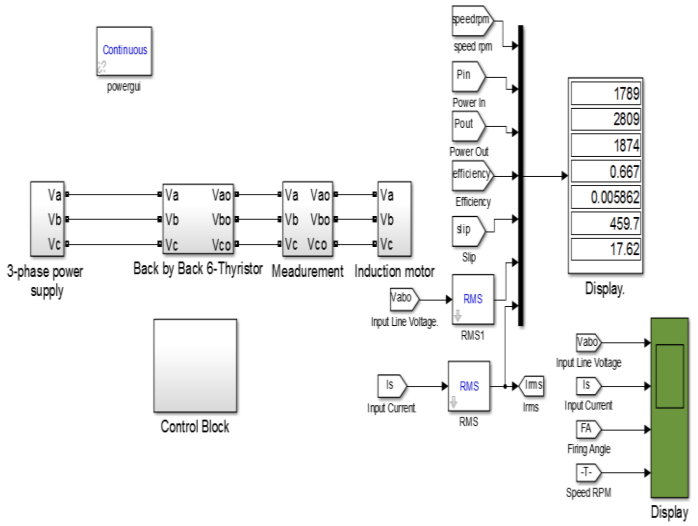

Fig.12. Simulation and analysis of fuzzy logic control ac voltage fed IM

This simulation was done to validate the hypotheses in conserving energy by reducing the input power of the IM in light and medium loads and increasing the efficiency of the IM. The power was reduced by reducing the input voltage of the IM using 6 back-by-back thyristors which they are controlled by fuzzy logic controller which show fast response to the sudden change in load the controller will make the firing angle zero as the load is above 75% of the rated full load that will let the rated voltage supply the IM again this well be done fast to avoid the high current which could cause a failure in the stator coils the three main components of the system that are used to validate this study are explain, the IM , the VVC and the FLC.

3.2 Simulation

3.2.1 Induction motor parameters and block

The induction motor specific parameters and block in MATLAB /Simulink are shown in Table 1 and Figure 13 respectively.

Table 1 Parameters of Induction Motor

PARAMETERS	VALUE
Rated power	7.5 kw
Rated voltage	460 v
Frequency	60 Hz
Rated speed	1760 RPM
Efficiency	86 %
Stator resistance	0.6837 Ω
Rotor resistance	0.451 Ω
Stator leakage	0.004152 H
Rotor leakage	0.004152 H
Magnetizing	0.1486 H
Poles pairs	2
Inertia constant	0.05 kg.m^2
Friction factor	0.008141 N.m.s

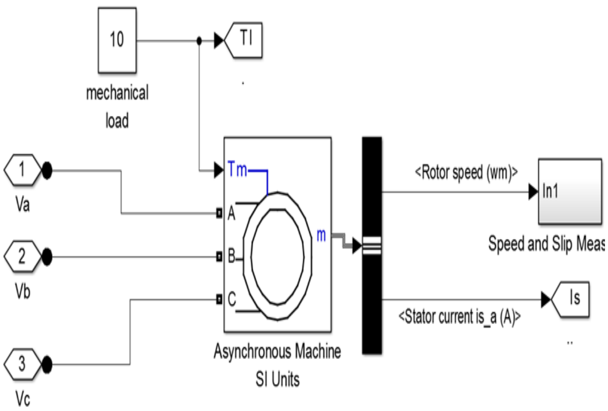

Fig.13. Induction motor block in MATLAB /Simulink.

3.2.2 Back-By-Back Thyristor

It consists of 6 thyristors connected as showing in Figure 14 this unite used to cut the sine wave of the input voltage by means of the firing angle, which is determined by the control unit.

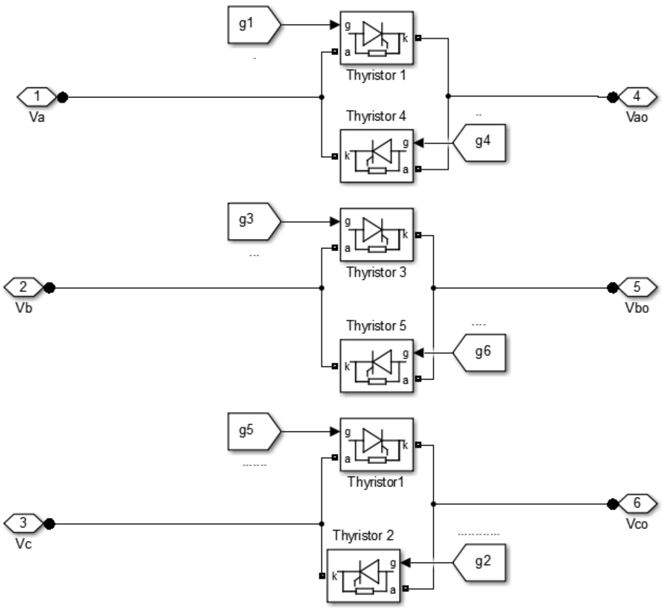

Fig.14. Back-by-Back Thyristor

3.2.3 Control units

The control unit in Figure 15. is responsible for determining the appropriate firing angle for the specific load torque by monitoring the following parameters (voltage, change in current, and change in slip factor) and this is through a search algorithm that works to monitor the parameters angle. The output of the proposed algorithm is the reference slip which.

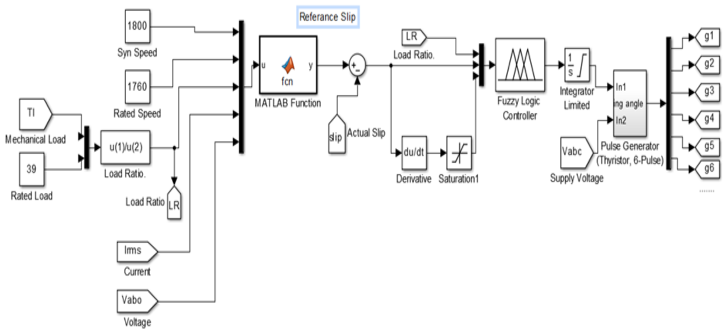

Fig.15. Control unit with the fuzzy logic controller.

3.3 Results.

In this study, the constant-frequency control system was applied to the induction motor at different load conditions and with or without proposed technique. The active power, power losses and efficiency under each load condition was analyzed. Voltage and current waveform are shown in the Figure 16 this waveform is simulated for 12.21 N-m load torque we can see the effect of the phase trigger on the shape of the voltage wave form the RMS voltage is decrease from 460v witch is the rated voltage to 412v, also we can see the effect of the firing angle start from 48° of the voltage waveform because the high inductivity of motor which allow the phase trigger to start effect at specific point depend in overall power factor as we have explained.

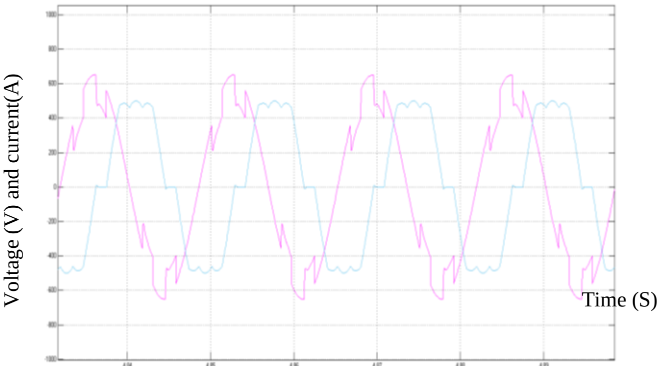

Fig.16. voltage and current waveforms where the current is scaling to 27:1 ,12.21 N-m load torque and 57.78° firing angle.

We can notice that current is lagging the voltage by approximate 78° .and the Figures 17 and 18 we show voltage and current independently.

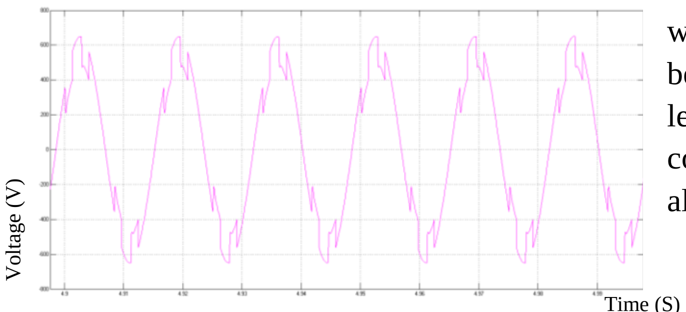

Fig.17. 460v waveform at 12.21 N-m and 57.78° firing angle.

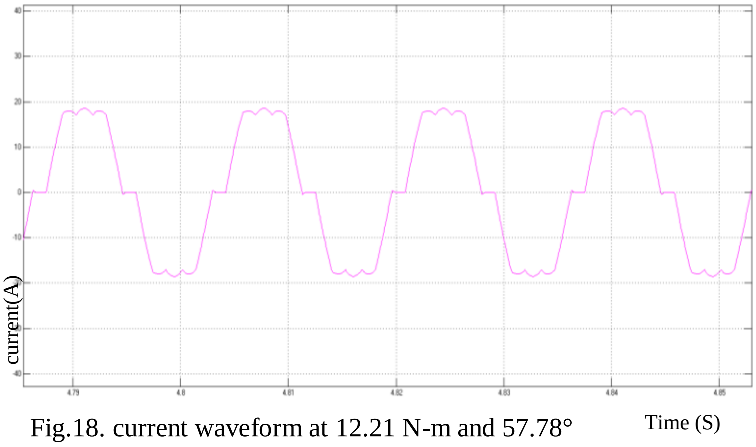

Fig.18. current waveform at 12.21 N-m and 57.78° firing angle.

In Figure 19 we can see the response of the firing angle it starts rising fast till it reaches the point where it effects in the voltage waveform than start to slow till it reaches the point where we get the most improve in efficiency. It takes 2.5 s to the steady state reign.

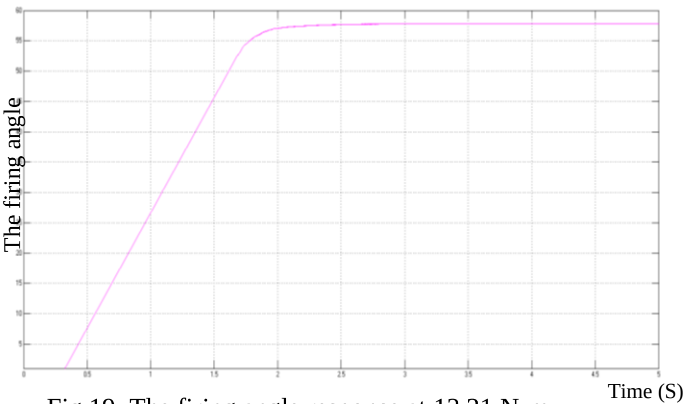

Fig.19. The firing angle response at 12.21 N-m.

It can be observed that the input power in light and medium loads is less, and the proposed method proved its efficiency in light loads better. It observed that losses. which is proportional to input voltage. because of the reducing in the losses and the less input power with keeping approximately constant speed the efficiency get improved all this can be observed in the Figure 20.

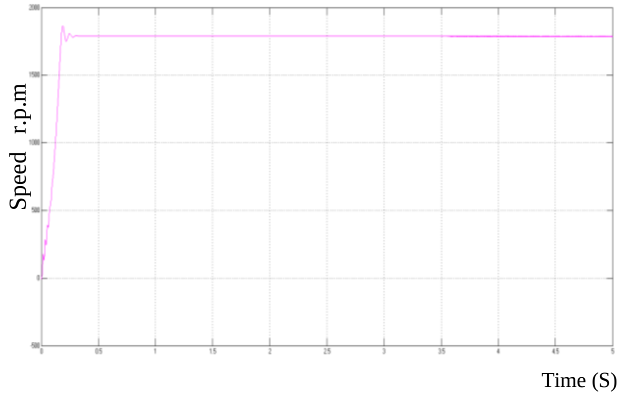

Fig.20. The speed response at 12.21 N-m.

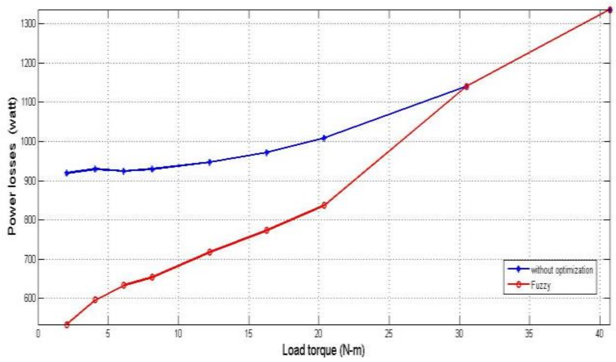

Fig.23. Loss against load variation 2-40 N-m.

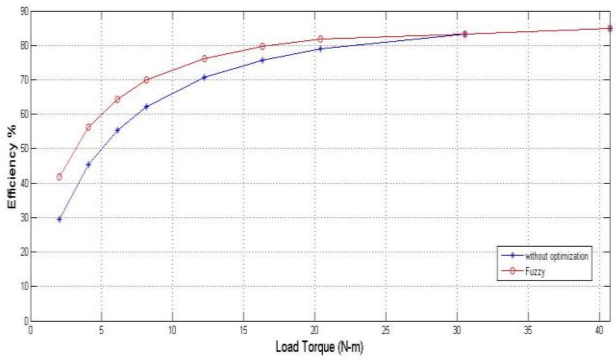

Fig.24. Efficiency against load variation 2-40 N-m.

In Figure 21 show fast response due to change in the load torque, just a few second to reach the steady state region. That prove that the FLC is good controller to deal with non-linear systems.

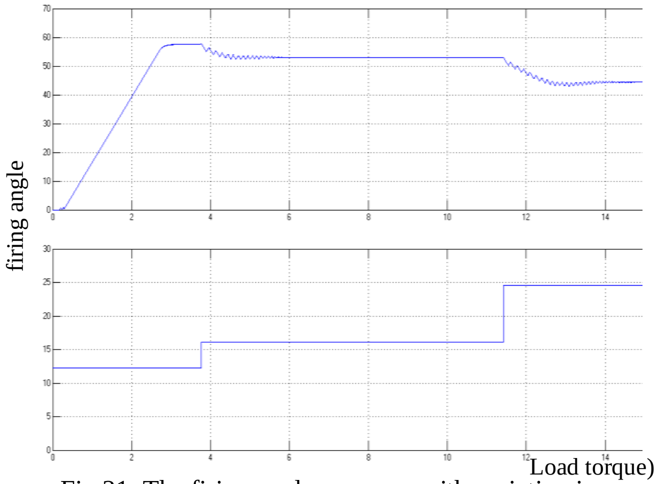

Fig.21. The firing angle response with variation in load torque.

In Figure 22 show the relation between the real input power and the load, we can observe that using the proposed algorithm reducing the input power.

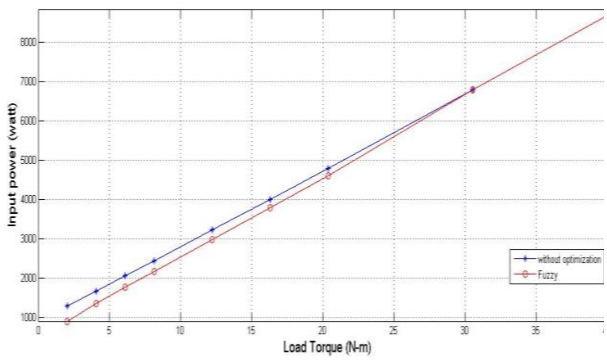

Fig.22. Amount of input power consumption against load variation 2.02 - 40 N-m.

In Figure 23 show the total losses that are consumed and the effect of the proposed algrithm this effect due to the minimize in the core losses which is decrease when the supply voltage decreases In Figure 24 the efficiency improvement is clearly observed.

Table 2 Optimal voltages of variant load torques at nominal frequency.

T(N-m)	40.7	30.525	20.35	16.28	12.21	8.14	6.11	4.07	2.0
V_{opt} [V]	460	460	425	419	413	402	398	388	36

Table 3The input power, efficiency and losses without saving at voltage=460 volt.

Load %	Input Power (watt)	Efficiency %	Power Losses (watt)	Speed (Rpm)
5%	1302	29.4	919	1796
10%	1685	45.39	929	1795
15%	2070	55.39	924	1793
20%	2456	62.18	929	1791
30%	3232	70.72	947	1787
40%	4013	75.77	972	1784
50%	4801	78.99	1008	1779
75%	6792	83.22	1140	1770
100%	8832	85.01	1336	1759

Table4 Comparison the values of efficiency, power factor and losses with saving.

Load %	Input Power (watt)	Efficiency %	Power Losses (watt)	Speed (Rpm)
5%	916	41.72	534	1793
10%	1360	56.2	596	1792
15%	1778	64.41	633	1791
20%	2179	69.94	654	1788
30%	2999	76.05	718	1784
40%	3808	79.71	773	1780
50%	4620	81.92	837	1776
75%	6797	83.22	1140	1770
100%	8832	85.01	1336	1759

Table 2 show the connection between the stator voltage at various burden forces can be gotten by utilizing MATLAB where, the estimation of voltage diminished when decrease the estimation of force. The most extreme effectiveness of enlistment engine can be accomplished when works at full burden. Be that as it may, when lessen the heap force without diminish stator voltage the proficiency, input force and yield power are diminished however misfortunes increment this is meaning the engine work without energy saving as shown in Table 3 where, when the engine works with energy saving the efficiency is improved about 3 to 11 % as shown in Table 4.

4. Discussions

Variable voltage drive that controls voltages is designed by 6 back-by-back thyristor witch its output voltages is controlled by the value of the firing angle of the thyristor. A research algorithm has been developed that works to find the appropriate point in which we obtain high efficiency and minimal losses. The search control method that we developed the algorithm according to it has proven easy to use and fast in response to the variable in load. This algorithm is associated with the fuzzy logic controller, which we designed, as it proved its efficiency in responding quickly to sudden change in loads.

After simulation using MATLAB/Simulink, we found that in very light loads that represent less than 15% of the full load, the efficiency improvement reached approximately 26%. In load that represents 30%, the improvement is 13%, while in medium loads (35% -60%) the improvement is 5%. This improvement was the result of reducing voltages, which leads to the reduction of iron losses, which led to improvement of efficiency with no noticeable change in speed. The proposed method shows no bad effect in the performance of IM at any load point as it can works with loads that change frequently and with different values.

5. Conclusion and Future work

A control plan to actualize energy-reserve funds of three-stage acceptance engine drive frameworks has been introduced. This plan is to change the voltage with the variety in the heap to get the high working productivity. In view of the introduced energy-saving plan, the regulator for energy-investment funds of IM was created using the fuzzy logic controller. We obtained improving in the efficiency, a fast response, a constant rotor speed, and no effect on the performance of the induction motor. The experiment will be applied in practice, as the fuzzy logic controller will be implemented in the programmed logic controller and the results will be compared with the simulation results.

In addition, future work of this topic should apply on single phase IMS as they are widely used for domestic, commercial and industrial purpose and as their power factor and efficiency are low as compared to three phase IMs.

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