Particle Swarm and Fuzzy Logic Based Optimal Energy Control of Induction Motor for a Mine Hoist Load Diagram

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***Abstract*— This paper investigates the importance of controllers on energy saving opportunity of partial loaded three-phase induction motor in mine hoist applications. The input power of a vector controlled 1 HP induction motor is investigated with three topologies namely constant flux operation, loss model based flux controller using Particle Swarm Optimization (PSO) and search controller in steady-state conditions. In this study, the flux level in a machine has been considered to adjust to give minimum input power for a given load of the motor. Even though flux controllers improve the performance of the motor in terms of minimum input power, they offer ripples in torque and speed of the motor (lower stability). To increase the stability of the motor drive during variable speed and load operation, Fuzzy Pre-compensated Proportional Integral (FPPI) Controller is used and compared its results with conventional Proportional Integral (PI) controller. According to the test results DE along with fuzzy logic outperforms the conventional controllers and saves 100 W power in the test motor. Four benchmark problems are used to validate PSO algorithm. C++ code is used for PSO implementation.**

***Index Terms*— particle swarm optimization, fuzzy logic, induction motor, loss minimization, mine hoist.**

I. Introduction

Three-phase induction motors (IMs) are the most frequently used machines in various electrical drives. About 70% of all industrial loads on a utility are represented by induction motors [1]. Recently oil prices, on which electricity and other public utility rates are highly dependent, are rapidly increasing. It, therefore, becomes imperative that major attention be paid to the efficiency of induction motors [2]. Process industries are found to be energy-intensive and hence extensive research has been focused on such industries in the past to reduce the energy cost and the total input cost [3].

Generally, induction motors have a high efficiency at rated speed and torque. However, at light loads, iron losses increase dramatically, reducing considerably the efficiency [4] – [5]. The efficiency and power factor can be improved by making the motor excitation a monotone increasing function of the load. To achieve this goal, the induction motor should either be redesigned or fed through an inverter [6]. Simply, the flux must be reduced, obtaining a balance between copper and iron losses [5].

In general, there are three different approaches to improve the induction motor efficiency especially under light-load conditions [4], namely, loss model controller (LMC), search controller (SC), and lookup table scheme. Many researchers have been reported several strategies using different variables to minimize losses in IM. Some algorithms use slip speed [4], [7], rotor flux [6], [8]-[10], power input [8], [11], and voltage [12]. This paper considers rotor flux as a variable and searches its optimum through losses of model incase of PSO controller or direct search in case of search controller. PSO is similar to genetic algorithm (GA) in that the system is initialized with a population of random solutions. It is unlike a GA, however, in that each potential solution also assigned a randomized velocity, and the potential solutions, called particles, are then flown through the problem space [13].

Due to the changes in flux or flux producing current to achieve minimum input power, system offers low stability in terms of ripples in torque and speed of the motor. FPPI controller is used in this paper to improve the stability of the drive when optimal energy controller is activated. The block diagram of the proposed controller is shown in Fig. 1. Torque producing current (i_{qs}) is generated by PI controller and flux producing current (i_{ds}) is generated by energy controller and are converted into three phase quantities. PWM current controller generates the pulses for inverter triggering circuits according to the error in the currents between reference and actual values.

The organization of this paper is as follows. Section II briefly explain the mine hoist load, section III review some of the present methods of efficiency optimization techniques, section IV derive the loss model of the IM, section V briefly discuses PSO algorithm and its objective function, section VI explains FPPI controller, section VII presents the simulation results of 1 hp motor and analyzes the operation of the motor in concentration with optimal energy and speed control, and section VIII validates PSO algorithm with four standard bench mark problems.

II. Mine Hoist Load Diagram

In order to illustrate the importance of efficient controllers in the industrial processes, considered the real load diagram of mine hoist in a mineral industry (Fig. 2) [14]. A motor, normally 2000 hp rated, is employing with mine hoist and is operated with variable load and speed as shown in Fig. 2.

Manuscript received May 2, 2008.

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(Advance online publication: 17 February 2009)

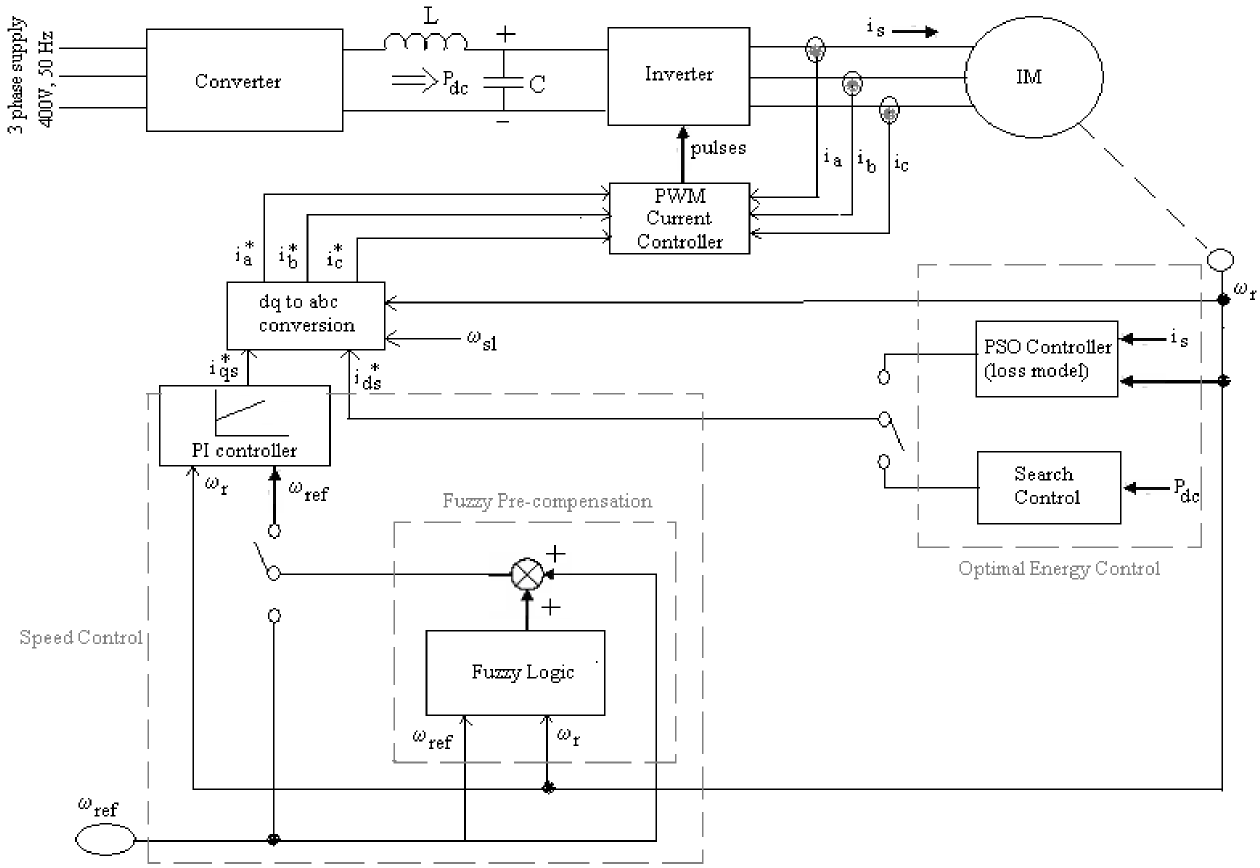

Fig. 1. Block diagram of optimal energy and speed control using PSO and fuzzy logic

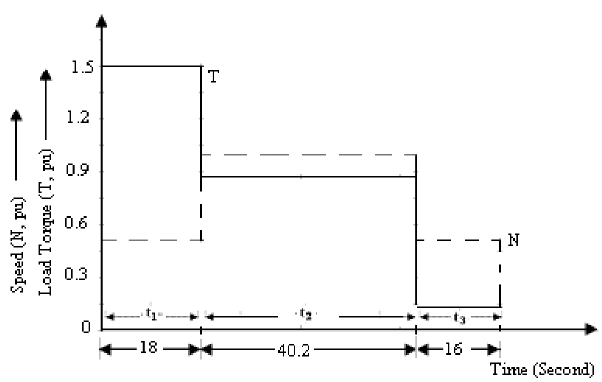

Fig. 2. Mine hoist load diagram\

Region 't_3' of this load diagram offers light load (0.14 pu) and half rated speed of the motor. In the present study, authors mainly focus this region for energy optimal control using PSO because the adjustment of flux level is mainly required at lightly loaded condition [4]-[12], [15].

III. Methods for Efficiency Optimization

The induction machine should operate with the rated flux for the rated value of load torque, where as for load torque less than rated, the reduction of flux causes a reduction in iron losses and magnetizing current. For a very low load torque (upto about 15% of the rated value), energy saving work can reduce power loss by even 70-90% [16]. In this section, discuss different types of controllers which are used to operate the motor with reduced operating energy cost at partial load. These are as follows,

A. Operate the Motor at Star Mode

Induction motors operate at light load, require less torque. Keep the motor connection in star results reduced power consumption. When the motor run in star mode, the voltage applied to stator phase winding is reduced by the factor $\sqrt{3}$. Since the torque developed in the motor is directly proportional to square of the voltage, the developed torque in star mode is also reduced by the factor 3. Therefore, the motor can be operated in star mode up to 0.33 p.u loads. In this case, the torque developed should be measured and find sufficient to drive the connected systems and also measure the temperature to be normal. This method is not suitable for wide range of partial loads. This controller is not offering converter losses due to the absence of power electronic circuits.

B. Variable Voltage Fixed frequency (VVFF) Control

Instead of starting induction motor with full voltage soft starter can be used to start the motor which offers low starting current. The job of soft starter is to apply a voltage to the motor, which is gradually increased in a ramp wise manner, thus enabling the motor to start. Three-phase voltage controller is used which consists of two thyristors per phase in anti parallel connection, where the input is connected to the respective phase of the mains supply and the output to each motor phase. Soft starter is aimed at the application of a reduced voltage to the motor for its start and reduction of voltage at motor is low load. In this case the iron losses are decreased and energy conservation is achieved.

C. Constant V/f Control

Constant V/f control is the scalar (variables are controlled in magnitude only) type control shown in figure 3 (a) which realizes simple design and low cost. Optimum performance of the motor can be achieved by adjusting voltage and frequency (keeping their ratio constant to maintain maximum torque) with minimum losses. It is suitable to open loop speed control and is mainly used in pump and fan loads.

D. Vector or Field Oriented Control

In vector control, the variables are controlled in magnitude and phase. This technique of control needs more calculations than the standard V/f control [17]. In this control, the complex induction motor can be modeled as a DC motor by performing simple transformations. The field oriented controller generates the required reference currents to drive the motor. These currents are based on the reference torque.

E. Displacement power Factor Control

If slip varying in induction motor, the motor terminal impedance and hence power factor, current and efficiency all vary. When maintain constant optimal slip by using voltage-controller the terminal impedance and hence power factor and efficiency remain constant at optimal values irrespective of load [18]. Even though power factor control implementation is so simple because of not requiring speed information, it is only valid one specific motor [19].

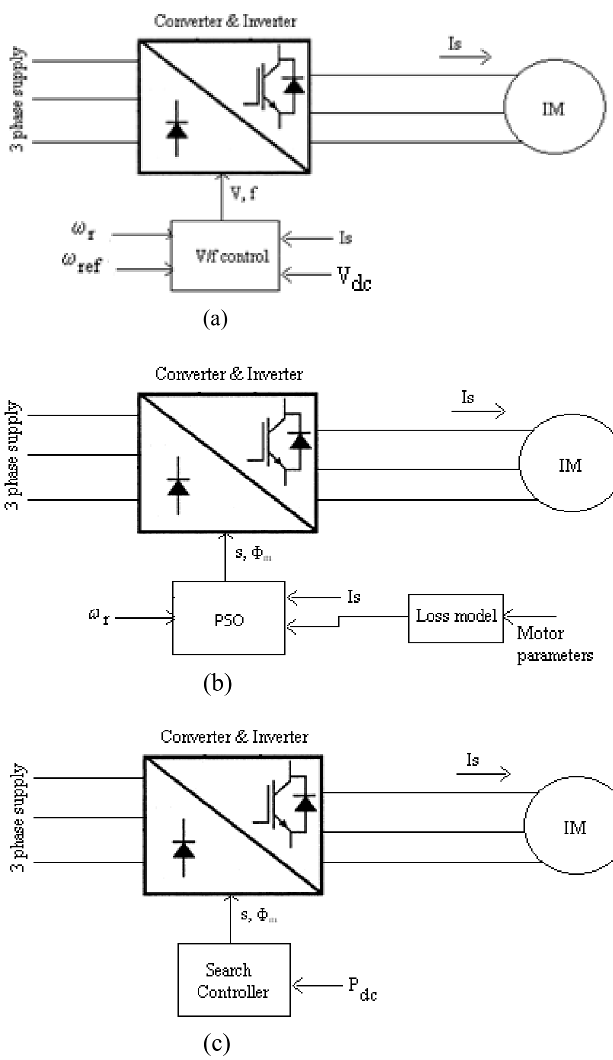

Fig. 3. Efficiency optimization controllers (a) v/f control, (b) loss model based PSO controller, (c) search controller

F. Rotor Slip Frequency Control

In this control, optimum rotor slip frequency is calculated to wide range of speed and torque of given motor and constructed a look up table. The objective function shown in may be maximum power factor or efficiency. The optimal efficiency slip can be calculated by using the equivalent circuit parameters of an induction motor. Since the presence of harmonics in inverter supply optimal slip calculation may not be accurate. The optimal slip frequency can also be calculated from the measurement of input power, output power of the motor, inverter frequency and slip frequency [20]. Stochastic algorithms can be used to search/find optimal value of slip within a short duration. In no case the constraints (line current and flux) should not be exceeded than rated.

G. Loss Model Controller

The loss model controller shown in Fig. 3 (b) measures the speed and stator current and through the motor loss model determines the optimal air-gap flux [8]. The main problem of this approach is that it requires the exact values of machine parameters which include core losses and main inductance flux saturation [4]. The inner part control algorithm may be in scalar or vector. Stochastic techniques like PSO or genetic algorithm can be used for searching optimal flux level from the loss model of the motor.

H. Search Controller for Minimum Input Power

This controller measures the input power of the machine drive regularly at fixed intervals and searches for the flux value which results in minimum power input for given values of speed and torque shown in figure 3 (c). This technique is slow for reaching the optimum value and a ripple in steady state torque is always present [4].

IV. INDUCTION MOTOR LOSS MODEL

The equivalent circuit of the induction motor is similar to that for a transformer and it is also called as rotating transformer. Moreover induction motor parameters are derived from no-load and blocked rotor tests and can be easily represented by per-unit quantities. Stator and rotor circuits can be merged by adjusting the values of the rotor components in accordance with the effective turns ratio as like as the transformer [21]. Scalar loss model of the induction motor is considered in this paper.

The per-phase IM equations (1) – (5) are given in the per-unit systems [6]

$$a = \frac{\omega_e}{\omega_b} = \frac{\omega}{1-s} \tag{1}$$

The magnetizing current in terms of the air-gap flux and the magnetizing reactance is given by

$$I_m = \frac{E/a}{X_m} = \frac{\Phi_m}{X_m} \tag{2}$$

The rotor current reflected in to the stator in terms of the air gap flux is given by

$$I'_r = \frac{\Phi_m}{\sqrt{(\frac{R'_r}{sa})^2 + X'^2_{lr}}} \quad (3)$$

Equation (2) can also be written including magnetic saturation effects as

$$I_m = S_1\Phi_m + S_2\Phi_m^{\ 3} + S_3\Phi_m^{\ 5} \quad (4)$$

The stator current in terms of rotor current and magnetizing current is given by

$$I_s = \sqrt{(S_1\Phi_m + S_2\Phi_m^{\ 3} + S_3\Phi_m^{\ 5})^2 + (1 + 2\frac{X'^2_{lr}}{X_m})\frac{T_e^{\ 2}}{\Phi_m^{\ 2}}} \quad (5)$$

The losses in the IM drive system are divided into a number of loss terms, connected with specific parts of the machine. The total losses comprise of copper losses in stator and rotor, iron losses due to eddy current and hysteresis, stray losses arise on the copper and iron of the motor, friction losses and finally converter loses due to the resistance offered by the solid state switches. Copper and iron losses in the stator and rotor are more severe than others.

The individual loss equations without considering converter and cable losses in the IM are given by [6]

Copper losses $P_c = R_s I_s^{\ 2} + R'_r I'^2_r$ (6)

Iron losses $P_i = [K_e(1+s^2)a^2 + K_h(1+s)a]\Phi_m^{\ 2}$ (7)

Stray losses $P_{str} = C_{str}\omega^2 I'^2_r$ (8)

Mechanical losses $P_m = C_{fw}\omega^2$ (9)

The approximate losses in the converter and inverter of the IM drive is given by [4]

$$P_{conv} = K_1 I_s^{\ 2} + K_2 I_s \quad (10)$$

From Equations (6)-(10), the total losses in IM drive system is given by

$$P_{loss} = P_c + P_i + P_{str} + P_m + P_{conv} \quad (11)$$

The total losses in terms of air-gap flux is given by

$$P_{loss} = R_s I_s^{\ 2} + R'_r I'^2_r + [K_e(1+s^2)a^2 + K_h(1+s)a]\Phi_m^{\ 2} + C_{str}\omega^2 I'^2_r + C_{fw}\omega^2 + K_1 I_s^{\ 2} + K_2 I_s \quad (12)$$

V. PSO FOR MOTOR LOSS MINIMIZATION

Many recent developments in science, economics and engineering demand numerical techniques for searching global optima to corresponding optimization problems [22]. PSO technique is a population based stochastic search technique first introduced by Kennedy and Eberhart [23]. The mechanism of PSO is inspired from the complex social behavior shown by the natural species.

PSO can be represented by the concept of velocity and position [24]. The two basic equations which govern the working of PSO are that of velocity vector (v_{id}) and position vector (X_{id}) are given by

$$v_{id} = wv_{id} + c_1 r_1(p_{id} - x_{id}) + c_2 r_2(p_{gd} - x_{id}) \quad (13)$$

$$x_{id} = x_{id} + v_{id} \quad (14)$$

The first part of equation (13) represents the inertia of the previous velocity, the second part is the cognition part and it tells us about the personal thinking of the particle, the third part represents the cooperation among particles and is therefore named as the social component [25]. Acceleration constants c_1, c_2 [26] and inertia weight ω [27] are the predefined by the user and r_1, r_2 are the uniformly generated random numbers in the range of [0, 1].

Loss minimization of the induction motor can be formulated as shown in (15) by considering (12) as objective function. PSO searches optimal flux with the consideration of their maximum limit.

Minimize P_{loss} (Te, ω_r ,Φ_m) (15)

VI. FUZZY PRE-COMPENSATED PI CONTROLLER

Generally the speed error, which is the difference of reference speed and actual speed, is given as input to speed controller. This controller processes the speed error and gives torque component current (i_{qs}*) as an output. The speed error at any *n*th instant of time is given as:

$$\omega_{r\,e\,(n)} = \omega_{r\,(n)}^{\ *} - \omega_{r(n)} \quad (16)$$

where $\omega_{r(n)}^{\ *}$ is the reference speed of the motor

$\omega_{r(n)}$ is the actual speed of the motor

The PI speed controller is the simplest speed controller and its gain parameters are selected by trial and error basis by observing their effects on the response of the drive. This controller is very sensitive to parameter variations, load disturbances and suffer from poor performance when applied directly to systems with significant nonlinearities [28], [29].

In order to overcome the drawbacks of PI control, FPPI speed controller is used in this paper. Fuzzy pre-compensation means that the reference speed signal ($\omega_r^{\ *}$) is altered in advance using Fuzzy Logic (FL) in accordance with the rotor speed (ω_r), so that a new reference speed signal ($\omega_{r1}^{\ *}$) is obtained. Some specific features such as overshoot and undershoot occurring in the speed response which are obtained with PI controller can be eliminated [30] and this controller much useful to mine hoist load where torque/speed varies time to time.

As usual, the inputs to the FL are speed error ($\omega_{re\ (n)}^{\ *}$) and the change in speed error ($\Delta\omega_{e\,(n)}$) and the output of the FL controller is added to the reference speed to generate a pre-compensated reference speed (δ), which is to be used as a reference speed signal by the PI controller shown in Fig. 1.The fuzzy pre-compensator can be mathematically modeled as follows [28]:

$$\omega_{r\,e\,(n)} = \omega_{r\,(n)}^{\ *} - \omega_{r\,(n)} \quad (17)$$

$$\Delta\omega_{e\,(n)} = \omega_{e\,(n)} - \omega_{e\,(n-1)} \quad (18)$$

$$\delta_{(n)} = F\,[\omega e_{(n)}, \Delta\omega_{e(n)}] \quad (19)$$

$$\omega_{r1}^{\ *} = \delta_{(n)} + \omega_{r(n)} \quad (20)$$

where F is fuzzy logic mapping

Fuzzy sets and logic rules considered for speed control shown in Fig. 4 and Table 1 respectively [28], [30]. NB stands for negative-big, NM for negative-medium, NS for negative-small, ZE for zero, PB for positive-big, PM for positive-medium and PS for positive small.

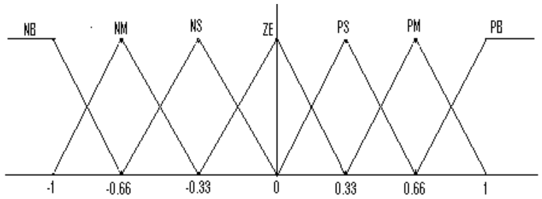

Fig. 4. Fuzzy sets considered for speed control

TABLE 1 LOGIC RULES FOR FPPI CONTROLLER

$\Delta\omega_{re}$ ↓ / ω_{re} →	NB	NM	NS	ZE	PS	PM	PL
NB				NB	NB		
NM	NB			NB	NB		
NS	NB			NM	NM	NM	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM		PS	PS	PM		
PM				PM	PB	PB	
PL			PM	PM	PB		

VII. SIMULATION RESULTS AND DISCUSSION

In this section, a 1 HP motor operating with variable load and speed (mine hoist applications) has considered for analysis in terms of optimal energy and speed control as shown in Fig. 1. Referring to the induction motor (1 hp) parameters presented in [6] and inverter losses in [4], input power minimization is performed with three types of controllers, namely constant flux controller, loss model based PSO controller and search controller. In order to improve the stability of drive, FPPI controller is used and its performance is compared with conventional PI controller.

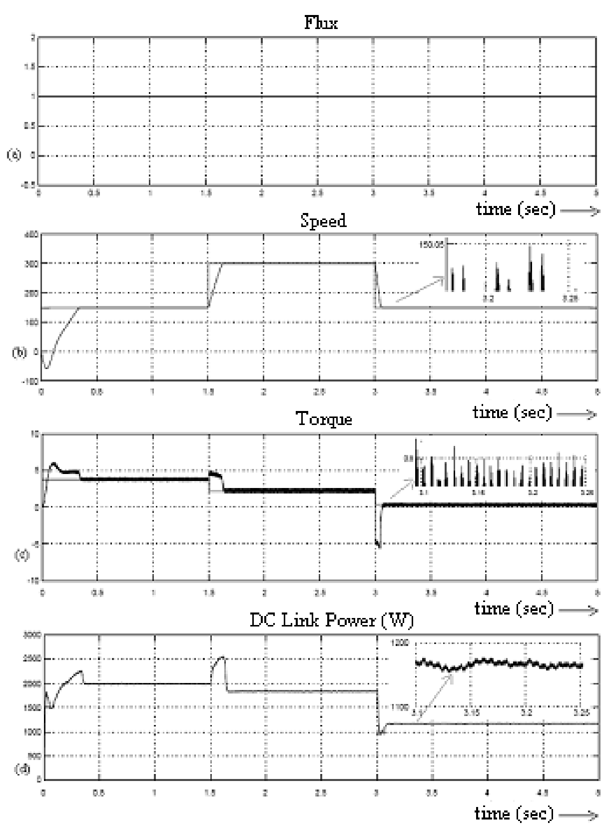

Fig. 5. Simulated results of constant flux operation of motor with PI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

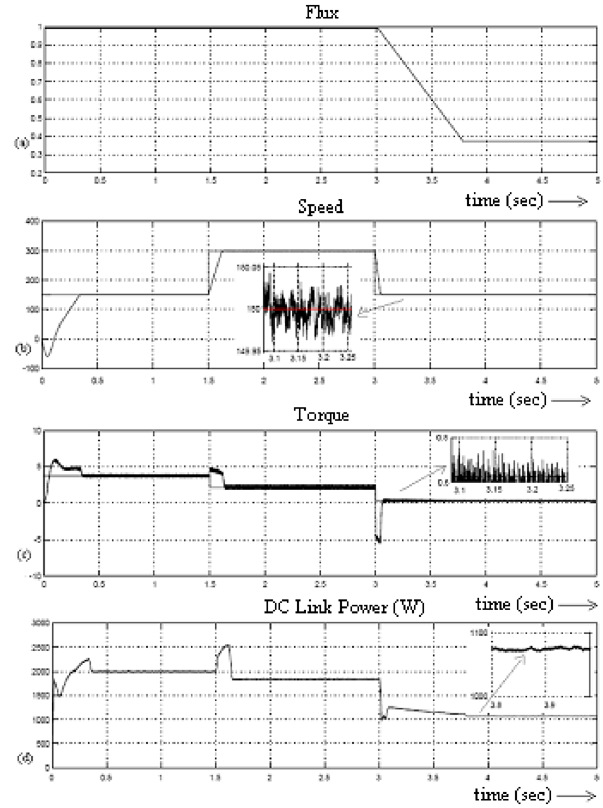

Fig. 6. Simulated results of search control of motor with PI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

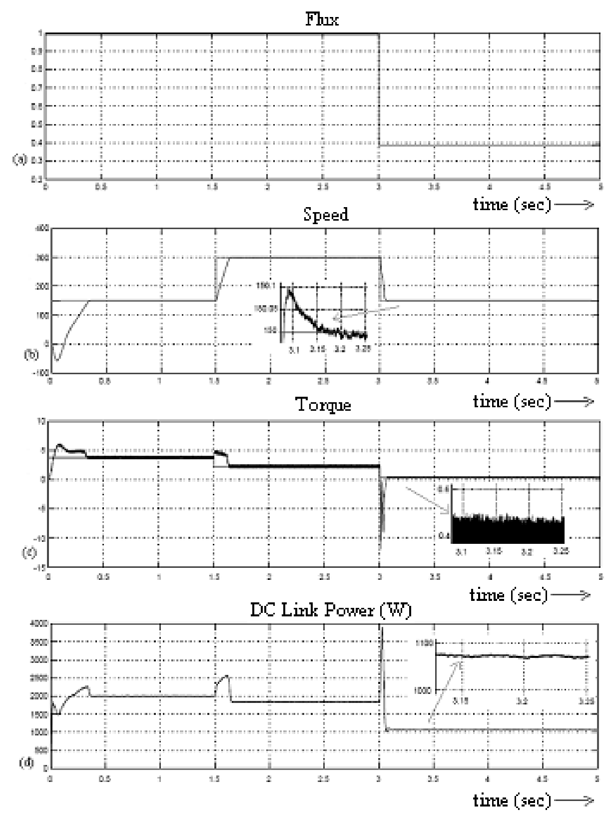

Fig. 7. Simulated results of loss model based control (PSO) of motor with PI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

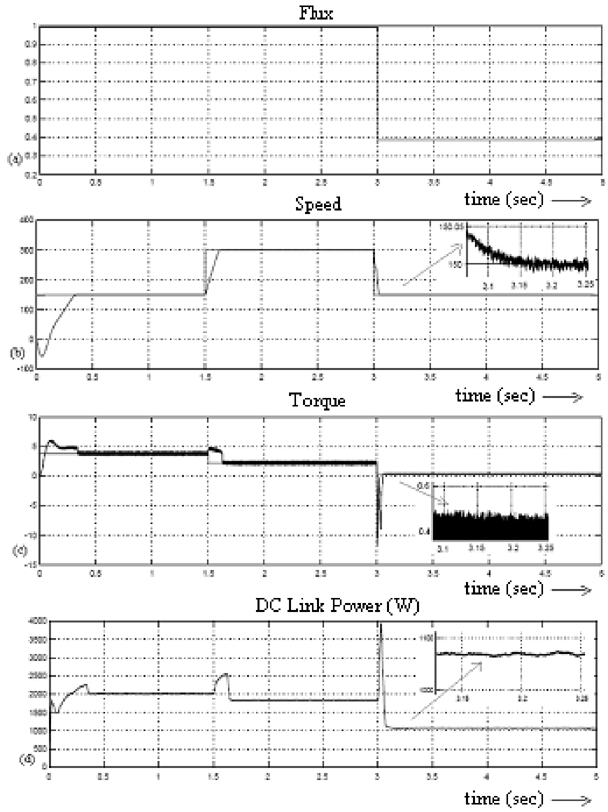

Fig. 8. Simulated results of loss model based control (PSO) of motor with FPPI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

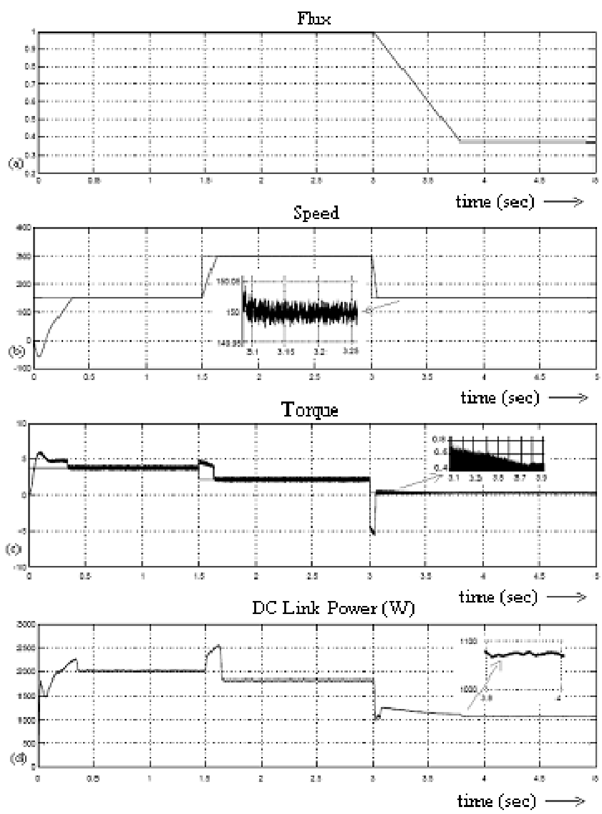

Fig. 9. Simulated results of search control of motor with FPPI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

A. Constant flux control

It is the conventional field oriented control, flux or flux producing current i_{ds} is always constant irrespective of speed and torque shown in Fig. 5 (a). Motor offers DC link power nearly 1170W during the operating region of t_3 shown in Fig. 5(d).

B. Search control

For optimal energy control, input dc link power is focused in this paper and is minimized using search control which adjusts (decrease) i_{ds} step by step with small value and watch the dc link power at every adjustment as shown in Fig.6 (a). Once the dc link power is minimized the adjustment will be stopped and maintain the current flux. To adjust i_{ds} gradient method is used [31]. By using this controller, motor offers DC link power nearly 1070W (Fig.6 (d)) which is lower by 100W as compared with constant flux operation. Apart from energy control, this controller offers less overshoots in speed and torque during the changes in their references as shown in Fig.6 (b) & (c).

C. Loss model based PSO controller

PSO is used to find optimal i_{ds} from the loss model of IM in accordance with motor load and speed. This controller finds optimal i_{ds} instantly, shown in Fig. 7 (a), instead of continuous adjustment in search control. Here, motor offers 1075W as dc link power which is slightly higher than search control. This is because of modeling error of the motor. In case of overshoots in speed and torque, PSO controller offers much better results than search control, shown in Fig.7 (b) and (c).

In Fig 8 & 9, FPPI controller offers less speed overshoots (by 60%) than PI controller without disturbing optimal energy controllers but in case of overshoot in torque, both are offering same results. Thus the combination of PSO and FPPI outperform the conventional controllers like search controller for energy control and PI controller for speed control.

VIII. Validation of PSO with Standard Benchmark Problems

To validate the performance of PSO, standard benchmark problems (shown in Table II) are used. From the numerical results shown in Table III and convergence graphs shown in Figs. 10 - 12, PSO gave better results in all the test problems.

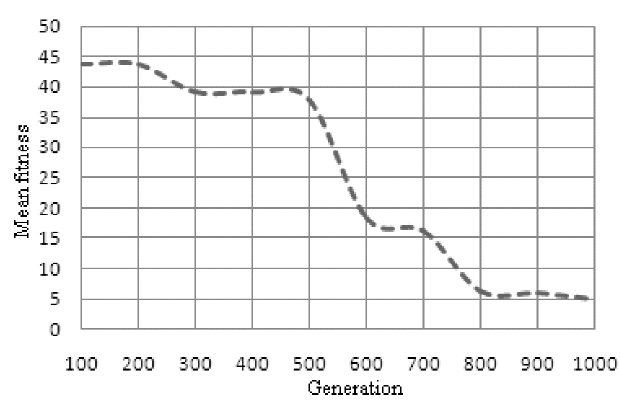

Fig. 10. Convergence graph for function f_1

TABLE II
STANDARD BENCHMARK PROBLEMS FOR VALIDATING PSO

Benchmark Problems	Ranges	Mini. Value
$f_1(x) = \sum_{i=1}^{n}(x_i^2 - 10\cos(2\pi x_i) + 10)$	[-5.12,5.12]	0
$f_2(x) = \sum_{i=1}^{n} x_i^2$	[-5.12,5.12]	0
$f_3(x) = \frac{1}{4000}\sum_{i=0}^{n-1} x_i^2 + \sum_{i=0}^{n-1}\cos(\frac{x_i}{\sqrt{i+1}}) + 1$	[-500,500]	0
$f_4(x) = \sum_{i=0}^{n-1} 100(x_{i+1} - x_i^2)^2 + (x_i - 1)^2$	[-30,30]	0
$f_5(x) = 20 + e - 20\exp(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}) - \exp(\frac{1}{n}\sum_{i=1}^{n}\cos(2\pi x_i))$	[-32,32]	0
$f_6(x) = (\sum_{i=0}^{n-1}(i+1)x_i^4) + rand[0,1]$	[-1. 28,1.28]	0
$f_7(x) = -\sum_{i=1}^{n} x_i \sin(\sqrt{\lvert x_i \rvert})$	[-500,500]	-418.9829*n

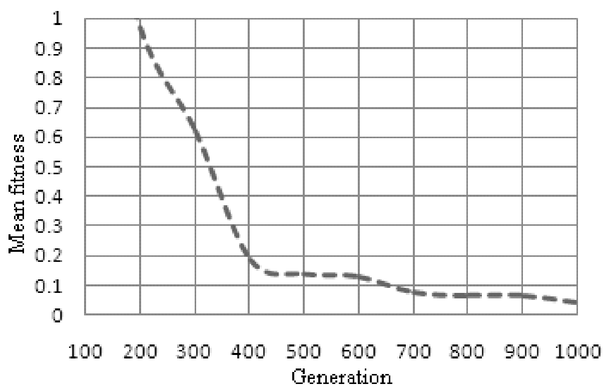

Fig. 11. Convergence graph for function f_2

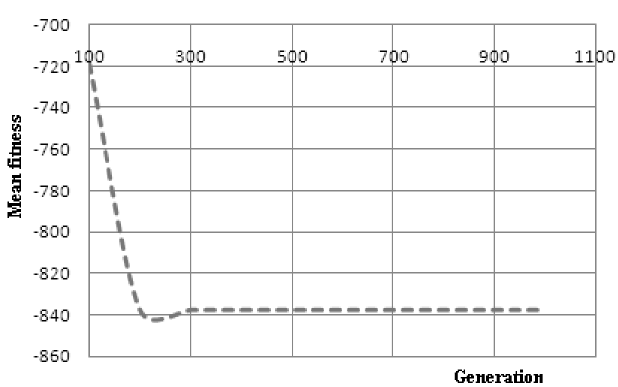

Fig. 12. Convergence graph for function f_7

TABLE III
RESULTS OF PSO IN BENCHMARK PROBLEMS (MEAN FITNESS/STANDARD DEVIATION)

Function	Dim	SPSO
f_1	2	5.57913e-015 1.63684e-014
	10	4.75341 3.07381
f_2	2	3.02769e-022 5.93778e-022
	10	7.27335e-005 2.88549e-004
f_3	2	1.11077e-012 3.3323e-011
	10	0.0197954 0.153591
f_4	2	0.00115649 0.00219637
	10	90.1189 26.9975
f_5	2	1.44633e-016 0.000000
	10	9.9569 9.95228
f_6	2	7.46487e-005 6.72369e-005
	10	0.00534397 0.00287007
f_7	2	-837.966 0.000000
	10	-3368.2 18.8134

IX. Conclusion

This paper investigated the importance of controllers on energy saving opportunity of partial loaded three-phase induction motor in mine hoist applications. The input power of a vector controlled 1 HP induction motor was investigated with three topologies namely constant flux operation, flux controller using Particle Swarm Optimization and search controller in steady-state conditions. To increase the stability of the motor drive during variable speed and load operation, Fuzzy Pre-compensated Proportional Integral (FPPI) Controller were used and compared its results with conventional Proportional Integral (PI) controller. According to the test results PSO and fuzzy logic were outperformed the conventional controllers and saved 100 W power in the tested motor. Since the power rating of the mine hoist motor is high, considerable amount of saving (in kW) is possible. Four bench mark problems were used for validating PSO algorithm.

Acknowledgment

First author would like to thank Ministry of Human Resources and Development (MHRD), Government of India for giving financial support to his research work.

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Appendix 2: Specification of the test motor

Power 1 hp
Voltage 400V
Pole 2
Stator resistance, R_s = 11.124Ω
Rotor resistance, R_r' = 8.9838Ω (refered to stator)
Stator leakage reactance, X_s = 10.48Ω
Rotor leakage reactance X_r' = 10.48Ω (refered to stator)
Magnetizing reactance, X_m = 154.08Ω
Moment of inertia, J = 0.0018 Kg/m^2

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