PSO Based Energy Efficient Control and Operation of Partially Loaded Three Phase Induction Motor Drives

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***Abstract*—** This paper illustrates the importance of controllers on energy saving opportunity of a partially loaded three-phase induction motor drive in variable load and speed applications. An overview of various controllers: loss model controller, search controller and their hybridization are given. Fuzzy Pre-Compensated Proportional Integral (FPPI) is used to improve motor's dynamic performances during the activation of optimal energy controllers. The economics of a 100 HP induction motor is investigated with two topologies namely constant Volt/frequency (V/f) controller and Particle Swarm Optimization (PSO) controller in steady-state conditions. In this study, the flux level in a machine has been considered to be adjusted to give minimum operating cost for a given load/speed.

Keywords-- **Economics, induction motor, loss minimization, mine hoist, particle swarm optimization, loss model controller, search controller, fuzzy precompensated controller.**

I. Introduction

THREE-PHASE induction motors 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 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 reported several strategies using different variables to minimize losses in IM. Some algorithms use slip speed [4], [15], rotor flux [10], [6], [7], power input [10], [8], and voltage [9]. This paper considers rotor flux as a variable and searches its optimum by PSO.

II. Methods For Efficiency Optimization

In this section, we discuss the various types of controllers for efficiency optimization which are used to operate the motor with reduced operating cost at partial load. These are as follows:

A. *PSO based Loss Model Controller*

The PSO based Loss Model Controller is applied to a vector Controlled Induction Motor Drive as shown in fig (1). In vector control, the variables are controlled in magnitude and phase. The motor operates at light load frequently. For Vector Control, the flux component keeps constantly rated flux as a result the efficiency of the motor is very low[22]. The part load efficiency of the induction motor can be improved by adjusting the flux level of the motor with the help of optimal energy controllers like PSO based Loss Model Controller and Search Controller[28].

The loss model controller measures the speed and stator current and through the motor loss model and determines the optimal air-gap flux [10].

B. *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 . This technique is slow for reaching the optimum value and a ripple in steady state torque is always present [4].The desirable feature of all the controllers are to provide minimum loss operation of the drive besides maintaining a fast convergence towards the minimum loss operational point and real time implementation must be easy and simple[23].

C. *Hybrid Controller*

Hybrid flux controller is used to retain good features of individual controllers, while eliminating their major drawbacks [25],[27]. By this hybrid controller, slow convergence (drawback of search control) and parameter variation (drawback of LMC) due to saturation and temperature variations can be eliminated and good results can be achieved with rough knowledge of parameters. To implement this controller, activate loss model control first to find the initial estimate of the ids* and then activate search control to get more optimum value of control variable. In the present work, PSO is used to calculate optimal value of i_{ds}* when LMC is activated and ramp search method is used when SC is activated

D. *Scalar or Constant V/f Control*

Constant V/f control is the scalar (variables are controlled in magnitude only) type control as shown in fig (2) for minimizing the losses of induction motor at light load. The idea is to calculate, for specific operating point, the optimal V/f ratio (in other words the optimal flux), that assures minimum losses still allowing the required speed and torque [15]

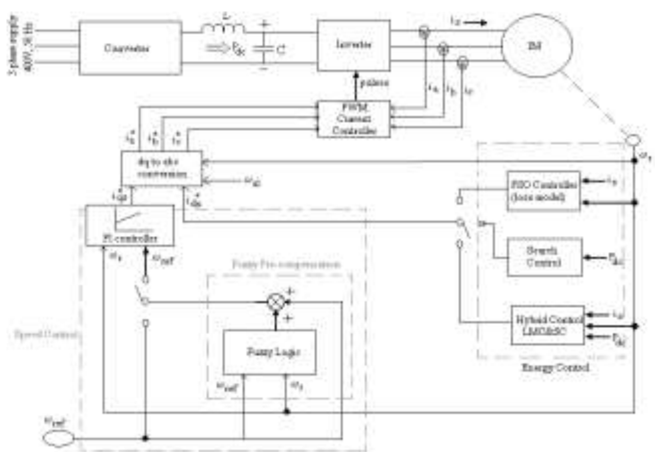

Fig.1: Operating Cost Optimization using PSO based Loss Model Controller and Search Controller.

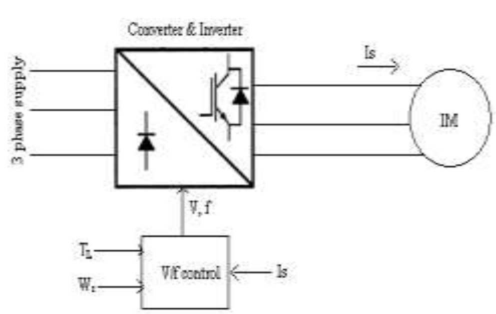

Fig.2: Scalar or Constant V/f Control

III. Induction Motor Loss Model

Besides dynamic performance, power efficiency is also an important factor to be considered in the controller design of induction motors. This can be achieved by decoupling of motor speed(torque) and rotor flux[24]. Loss Model Controller is a feed-forward approach, which calculates the optimum set of variables of the machine, depending on optimization (maximize or minimize) of an objective function, defined using machine parameters. The objective function is usually an analytical expression representing either the loss or the efficiency or the total input power. The optimum variable may be operating flux of the machine or slip frequency or some other variable depending upon objective function[25],[27]. In this work rotor flux has been taken as optimum variable and total loss as objective function. [28]

The total loss in IM drive system is given by

$$P_{loss} = R_s I_s^2 + R_r^{'} I_r^{'2} + ([K_e(1+s^2)a^2 + K_h(1+s)a]\Phi_m^2) + C_{str} w^2 I_r^{'2} + C_{fw} w^2 + P_{eddy}^{PWM} + P_{cu}^{PWM}$$

It can be written as $P_{loss} = f(a, \varphi_m, w_r)$ (1)

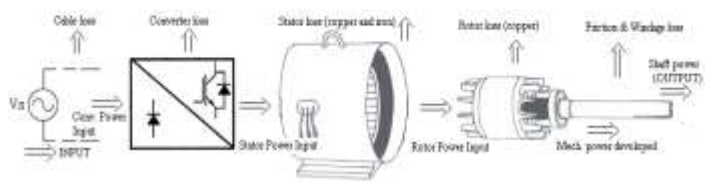

Fig. 3: Losses in the IM drive system

IV. Operating Cost Model of Induction Motor

From the equation (1), losses can be minimized by selecting optimal value of flux level. There are two main types of operating cost in the induction motor related to energy consumption by the motor. Energy cost and demand cost are these two.

A. *Energy Cost*

The energy cost of the induction motor should be calculated over the whole life cycle of the motor [9] and is given below. Power factor penalty is not considered in this paper because almost all the industries have centralized power factor correction equipments.

$$S = C_e * T * N * P_{out} * (\frac{1}{\eta} - 1) \quad (2)$$

where:

S Energy cost for life periods
C_e Energy cost (US $/KWH)

T Total operating hour/year
N Motor’s evaluated life in years
P_{out} Output power of the motor (KW)
η Efficiency of the motor

Equation (2) can be rewritten in terms of total losses (KW) which is given below

$$S = C_e * T * N * P_{loss} \quad (3)$$

B. *Demand cost*

Demand charge cost consumed by the motor over the whole life of the motor can be calculated by using the equation (4) and is given below

$$D = C_d * 12 * N * P_{loss} \quad (4)$$

where:
D Demand cost for the life periods
C_d Demand cost per month (US $)

The total energy cost (TEC) of the motor for the complete life is the summation of two individual energy costs and is given by

$$TEC = P_{loss} * N * \{(C_e * T) + (C_d * 12)\} \quad (5)$$

From the equation (5), TEC = function (Flux), which can be minimized by searching optimal flux value.

V. PSO for Motor Energy Cost Minimization

Many recent developments in science, economics and engineering demand numerical techniques for searching global optima to corresponding optimization problems [18]. PSO technique is a population based stochastic search technique first introduced by Kennedy and Eberhart [19].

PSO can be represented by the concept of velocity and position [20]. 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

$$v_{id} = wv_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \quad (6)$$

$$x_{id} = x_{id} + v_{id} \quad (7)$$

The first part of equation (6) 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 co-operation among particles and is therefore named as the social component [18]. Acceleration constants c_1, c_2 [19] and inertia weight ω [20] are the predefined by the user and r_1, r_2 are the uniformly generated random numbers in the range of [0, 1].

Energy cost minimization of the induction motor can be formulated as shown in (8) by considering (5) as objective function.

$$\text{MINIMIZE TEC } (T_E, W, \Phi_M) \quad (8)$$

VI. Simulation Result and Discussion

In the initial part of simulation the input power of a vector controlled 1 HP induction motor was investigated with four topologies namely constant flux operation, flux controller using PSO, search control and hybrid controller in steady-state conditions.

In the next stage of simulation, a 100 HP motor operating with variable load and speed has been considered for economic analysis. Referring to the induction motor (100 hp) parameters presented in [6], total energy cost comparison is performed with two types of controllers.

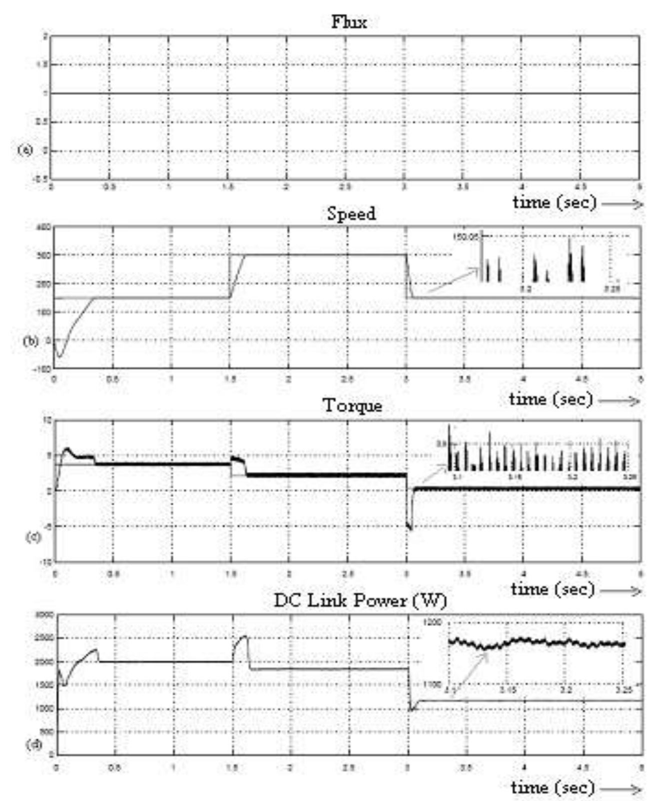

Fig. 4. Simulated results of constant flux operation of motor with PI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

At all the loads and speeds PSO performed much better than V/f. Figures 8 -11 show the variation of TEC (Operating hour, T is assumed as 8000) by adjusting flux level in the motor at variable load and speed applications and it reveals that less TEC occurred in PSO at light loads.

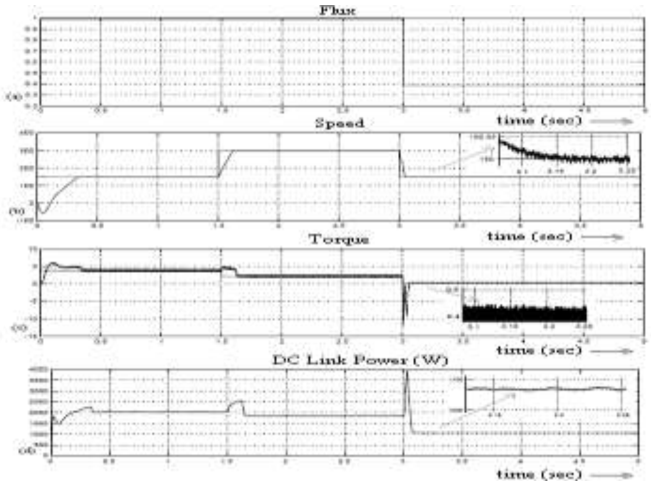

Fig. 5. Simulated results of loss model based control (PSO) of motor with FPPI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

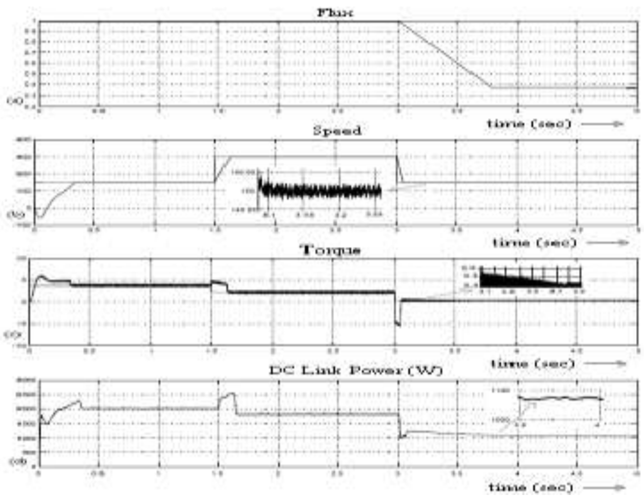

Fig. 6. Simulated results of search control of motor with FPPI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

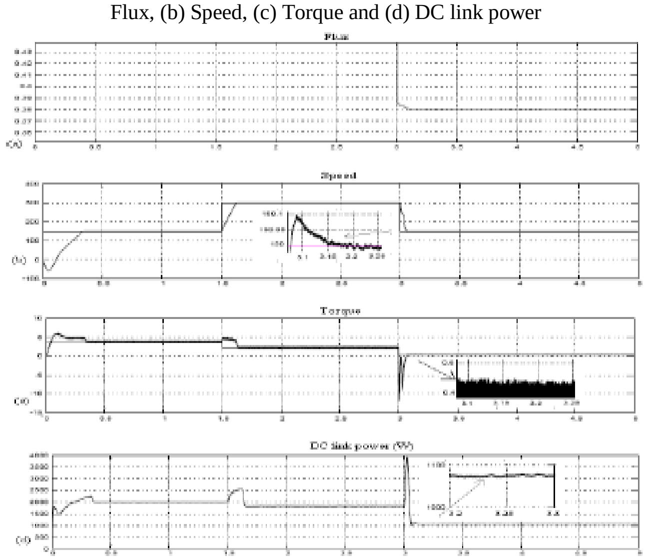

Fig. 7. Simulated results of hybrid flux control of motor with FPPI controller: (a) Flux, (b) Speed, (c) Torque and (d) DC link power

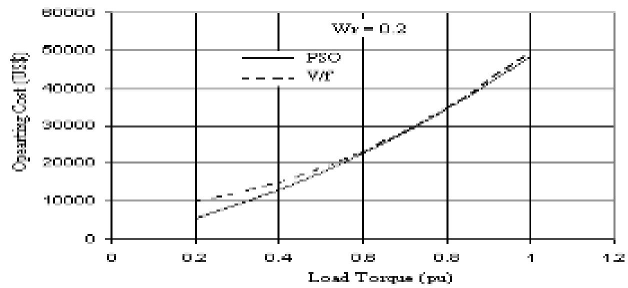

Fig. 8. TEC verses load torque at Wr = 0.2

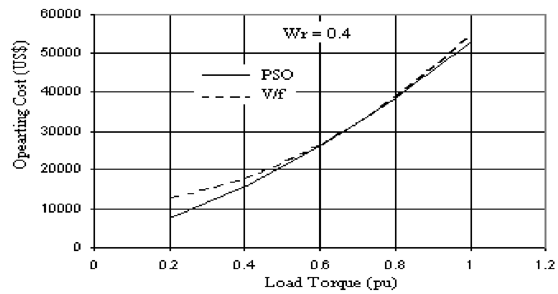

Fig. 9. TEC verses load torque at Wr =0.4

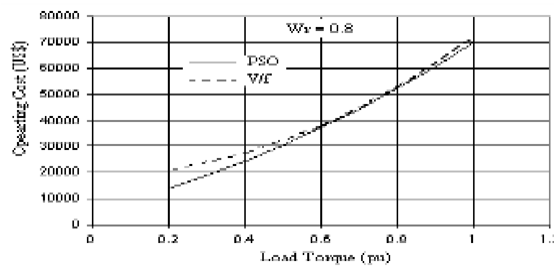

Fig. 10. TEC verses load torque at Wr = 0.8

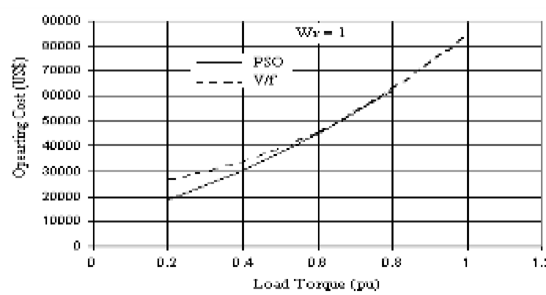

Fig. 11. TEC verses load torque at Wr = 1

VII. 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 four topologies namely constant flux operation, flux controller using Particle Swarm Optimization, search control and hybrid controller in steady-state conditions. According to the test results hybrid flux controller 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.

The next stage of simulation investigated the influence of controllers in the economics of a vector controlled 100 hp induction motor in variable load/speed applications. It is noted that PSO produced better results than V/f in all instances (motor load and speed). From the case study, US $ 6186 per 100 hp motor for mine hoist load diagram can be saved when we used PSO controller over V/f controller to select optimum flux level of the IM.

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