Differential Evolution based Optimal Control of Induction Motor Serving to Textile Industry

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***Abstract*— This paper illustrates the importance of controllers on energy saving opportunity of partial loaded three-phase induction motor in textile mill (ring spinning frame) applications. The economics of a scalar controlled 100 HP induction motor is investigated with three topologies namely star-delta (S/D) connection, constant Volt/frequency (V/f) controller and Differential Evolution (DE) controller in steady-state conditions. In this study, the flux level in a machine has been considered to adjust to give minimum operating cost for the textile mill load. The flux controller improves the economics in terms of operating cost (energy cost and demand charge cost) and the test results show that the flux level in the most economic motor will be adjusted according to load and speed, particularly at light load. Standard benchmark problems (Rastingin and Griewank) have been considered for validation of the proposed DE controller for induction motor operating cost minimization. Case study also presented in this paper.**

***Index Terms*— Differential evolution, economics, induction motor, loss minimization.**

I. Introduction

Three-phase induction motors (IM) 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]. Textile industries are found to be energy-intensive (4% energy cost in total input cost) compared to other industries like chemical, food, computer manufacturing, etc., 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 so that efficiency will be maximized.

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], [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 DE.

The DE [11] algorithm was introduced by Storn and Price in 1995. It is a population based algorithm using mutation, crossover and selection as like as Genetic Algorithm. The main difference in constructing better solutions is that Genetic Algorithm relies on crossover while DE relies on mutation operation [12]. This paper is organized as follows. Section II, discusses the textile ring spinning frame and its load diagram, section III review some of the present methods of efficiency optimization techniques, section IV and V derive the loss and operating cost models of the IM, section VI briefly discuses DE algorithm and its objective function, section VII presents the simulation results of 100 hp motor and analyzes the economical comparison of DE controller in energy saving opportunities in the same induction motor for a textile mill load diagram. Validation of DE and case study are presented in section VIII and IX respectively.

II. Textile Spinning Machine

A ring spinning frame manufactures the cotton into yarn that winded in spindles (Fig. 1) and used to feed cone winding machine. After that it can be used to make end products such as clothing with the help of weaving machine. The main drive, with a power rating in the range of 25 kW to 75 kW and its shaft load determines by the quantity of yarn in the spindles. The quantity of the yarn in the spindles varies from zero (when the process starts) to full (when process completes), hence the motor shaft load varies from zero to rated.

Fig. 1. Textile spinning ring frame

In this paper, 100 hp motor has been considered for

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economical analysis. In order to illustrate the importance of efficient controllers in the industrial processes, considered the real load diagram of ring spinning frame in a textile industry (Fig. 2). 'T' is the time consumption for the completion of one process.

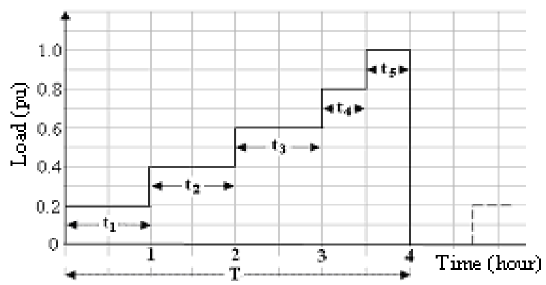
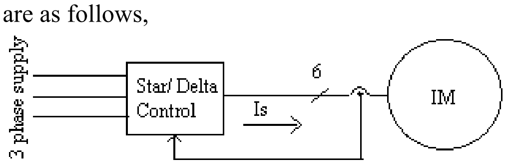


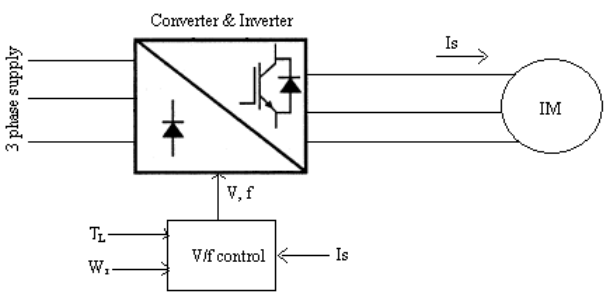
Fig. 2. Average load diagram of a typical spinning ring frame drive motor

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 (up to about 15% of the rated value), energy saving work can reduce power loss by even 70-90% [13]. In this section, discuss three types of controllers which are used to operate the motor with reduced operating cost at partial load. These are as follows,



(a)



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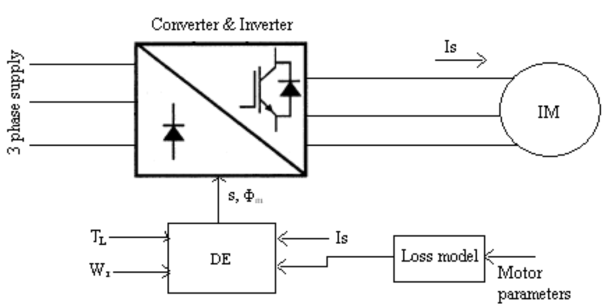


(c)

Fig. 3. Efficiency optimization controllers (a) star/delta, (b) v/f control, (c) DE controller

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 1.732. 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 and is shown in figure 3 (a).

B. Loss Model Controller

The loss model controller measures the speed and stator current and through the motor loss model determines the optimal air-gap flux [10]. 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 [14]. The inner part control algorithm may be in scalar or vector. Optimal searching techniques like DE shown in Fig. 3 (c), particle swarm optimization, and genetic algorithm can be used for searching optimal flux level.

Constant V/f control is the scalar (variables are controlled in magnitude only) type control shown in Fig. 3(b) 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]. Scalar control technique is somewhat simple to implement, but the inherent coupling effect results sluggish response and the system is easily prove to instability becomes of higher order system effect [16].

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.

C. Search Controller for Minimum Input Power

This controller measures the input power of the machine drive continuously and searches for an optimal flux value which results in minimum power input to the motor 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].

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 [18].

Nomenclature:

R_s	Stator resistance
$R_r^{'}$	Rotor resistance
X_{ls}	Stator leakage reactance
X_{lr}	Rotor leakage reactance
X_m	Magnetizing reactance
R_c	Cable resistance
ω	Speed
T_e	Electromagnetic torque
φ_m	Air-gap flux
E	Air-gap voltage
a, w_e	Supply frequency
s	Slip
as	Slip frequency
ω_r	Rotor speed
ω_b	Base speed
I_s	Stator current
$I_r^{'}$	Rotor current
I_m	Magnetizing current
P_c	Copper losses in Stator and Rotor
P_i	Iron losses
P_{conv}	Converter losses
P_{cable}	Cable losses
P_{loss}	Total losses
k_h , k_e	Eddy current and hysteresis coefficients
S_1, S_2, S_3	Magnetizing curve coefficients
C_{fw}	Mechanical loss coefficients
C_{str}	Stray loss coefficients
K_1, K_2	Switching loss coefficients

The per-phase IM equations (1) – (5) are given in the per-unit systems [10]

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

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

$$I_r' = \frac{\Phi_m}{\sqrt{(\frac{R_r'}{sa})^2 + X_{lr}'^{\,2}}} \tag{3}$$

Equation 2 can also be written including magnetic saturation effects as

$$I_m = S_1\Phi_m + S_2\Phi_m{}^3 + S_3\Phi_m{}^5 \tag{4}$$

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

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

The equation of efficiency is given by

$$\eta = \frac{output}{input} \tag{6}$$

In case of IM drive, the output is the power supplied by the motor to drive the load (product of shaft load and its speed) and the input is the power consumed by the total system including motor, converter circuits and cables. Since the efficiency of IM or any system is depends on the total losses associated with it, (6) rewritten as

$$\eta = \frac{output}{output + losses} \tag{7}$$

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 shown in Fig. 4 comprises 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, converter loses due to the resistance offered by the solid state switches and finally the cable losses due to the resistance offered by the cable. Power output is the product of shaft load and its speed.

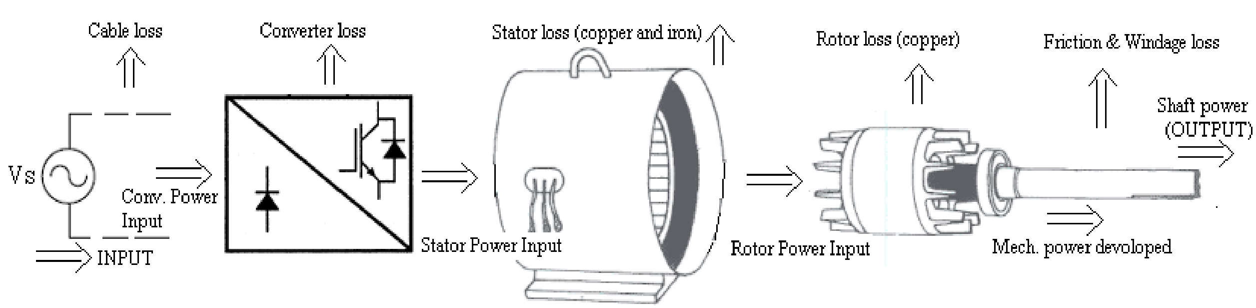


Fig. 4. Losses in the IM drive system

Copper and iron losses in the stator and rotor are more severe than others. The individual loss equations in the IM are given by [10]

Copper losses $P_c = R_s I_s^2 + R_r' I_r'^2$ (8)

Iron losses $P_i = [K_e(1+s^2)a^2 + K_h(1+s)a]\Phi_m^2$ (9)

Stray losses $P_{str} = C_{str}\omega^2 I_r'^2$ (10)

Mechanical losses $P_m = C_{fw}\omega^2$ (11)

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

$$P_{conv} = K_1 I_s^2 + K_2 I_s \quad (12)$$

The approximate losses in the cable to connect motor drive system to the supply mains (grid), is given by

$$P_{cable} = I_s^2 * R_c \quad (13)$$

From Equations (8)-(13), the total losses in IM drive system is given by

$$P_{loss} = P_c + P_i + P_{str} + P_m + P_{conv} + P_{cable} \quad (14)$$

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

$$P_{loss} = R_s I_s^2 + R_r' I_r'^2 + [K_e(1+s^2)a^2 + K_h(1+s)a]\Phi_m^2 + C_{str}\omega^2 I_r'^2 + C_{fw}\omega^2 + K_1 I_s^2 + K_2 I_s + I_s^2 * R_c \quad (15)$$

V. Operating Cost Model of Induction Motor

From (15), 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 [4] and is given below. Power factor penalty is not considered in this paper because almost all the industries have centralized power factor correction equipments.

$$S = C_e * T * N * P_{out} * (\frac{1}{\eta} - 1) \quad (16)$$

where

- S Energy cost for life periods
- C_e Energy cost (US $/KWH)
- T Total operating hour/year
- N Motor's evaluation life in years
- P_{out} Output power of the motor (KW)
- η Efficiency of the motor

Equation (16) can be rewritten in terms of total losses (KW) which is given below

$$S = C_e * T * N * P_{loss} \quad (17)$$

B. *Demand cost*

Demand charge cost consumed by the motor over the whole life of the motor can be calculated by using the equation (18) and is given below

$$D = C_d * 12 * N * P_{loss} \quad (18)$$

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

$$TEC = P_{loss} * N * ((C_e * T) + (C_d * 12)) \quad (19)$$

From (19), TEC = function (Flux), which can be minimized by searching optimal flux value.

VI. DE for Motor's Energy Cost Minimization

Many recent developments in science, economics and engineering demand numerical techniques for searching global optima to corresponding optimization problems [19]. DE is a parallel direct search method [20], which first set the initial values of the parameters in the population. Fig. 5 shows the flow of DE algorithm.

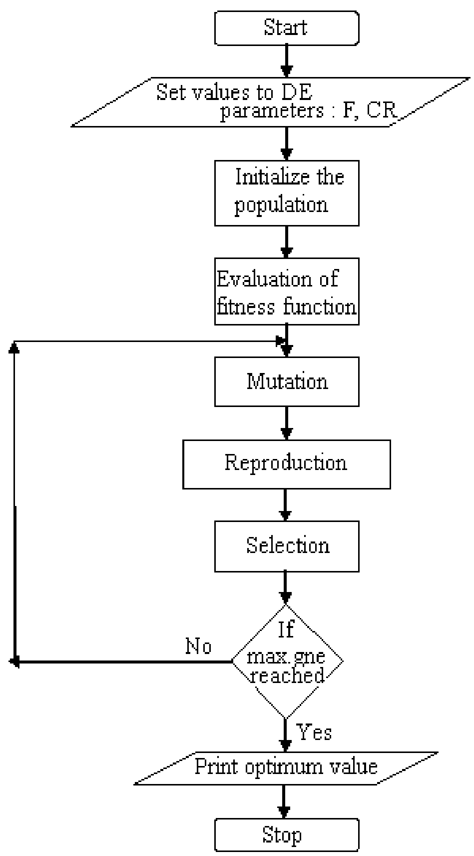


Fig. 5 Flow of DE algorithm.

The mutation operator chooses three different vectors from the population and creates the mutant vector, is given by [21],

$$v_{i,g+1} = x_{r_1,g} + F*(x_{r_2,g} - x_{r_3,g}) \quad (20)$$

where $r_1, r_2, r_3 \in \{1,2,....,NP\}$ are randomly chosen integers, must be different from each other and also different from the running index i. F (>0) is a scaling factor.

To do the recombination step, the following equation is used [21]

$$u_{ji,g+1} = \begin{cases} v_{ji,g+1} & if\ (rand_j \le CR)\ \ or\ \ (j = j_{rand}) \\ x_{ji,g} & if\ (rand_j > CR)\ \ and\ \ (j \ne j_{rand}) \end{cases} \quad (21)$$

where j = 1, 2,……, D; $rand_j \in [0,1]$; CR is the crossover constant takes values in the range [0, 1] and $j_{rand} \in (1,2,.....,D)$ is the randomly chosen index.

Selection is the step to choose the vector between the target vector and the trial vector with the aim of creating an individual for the next generation. These operators will continue up to an optimum solution is found or the number of maximum iteration (set by user) has been reached. Energy cost minimization of the induction motor can be formulated as shown in (22) by considering (19) as objective function.

Minimize TEC (Te, w, Φ_m) (22)

VII. Simulation Results and Discussion

In this section, a 100 HP motor operating with the given load diagram (Fig. 2) in textile mill applications (ring spinning frame) has considered for economic analysis. Referring to the induction motor (100 hp) parameters presented in [10], total energy cost comparison is performed with three types of controllers. The motor parameters are R_s =0.029, $R_r^{'}$ =0.020, X_m =1.88, X_{lr} =0.067, k_e =0.006, k_h =0.006, C_{str} =0.025, C_{fw} =0.010, S_1=0.4, S_2=-0.30, S_3=0.45, K_1=0.000031307, K_2= 0.025, R_c= 0.000916. The block diagram of proposed controller is shown in Fig. 6. In this controller, optimum slip speed is searched by DE so that motor will be operated with optimum flux.

Total losses, energy cost, and stator current comparison of the constant speed (rated) IM for a textile mill load diagram with the following electricity tariff (Tamil Nadu Electricity Board, HT tariff I for the industries situated in rural areas) and assuming 5 processes repeated per day (motor running period = 20 hours per day), 355 days of operation/year and life time of the motor (N) is assumed as 15 years are summarized in Table I, and II. Individual losses comparison is shown in Table III.

Maximum demand (KVA) charges: US $ 6.66/month
Energy (kWh) charges: US $ 0.077/kWh
(1 US $= Indian Rupees 45 approximately).

All the loads S/D offered low TEC due to absence of converter losses and DE performed much better than V/f. Fig. 7 shows the variation of TEC (T is assumed as 8000) by adjusting flux level in the motor at variable load and speed applications and it reveal that minimum TEC occurred at rated flux (1pu) for rated load and rated speed applications but need to adjust the same at lightly loaded conditions. Hence flux adjustment is mainly required in the motor at lightly loaded condition for energy saving.

VIII. Validation of DE with Standard Benchmark Problems

To validate the performance of DE program, standard benchmark problem, Rastringin (f_1) and Griewank (f_2) functions are used, shown in Table IV. Fig. 8 and 9 show the convergence graphs of the above benchmark problems respectively. From the convergence graphs, we come to conclude that DE is working properly.

IX. Case Study

A privately owned medium size spinning and sewing thread industry in Tamil Nadu, producing 15 tons of yarn and 10 tons of sewing thread/ day, is having 96 ring frames [3] has considered in this section. For this textile mill, the economical benefits of spinning drive motor by using different controllers are shown in Table V.

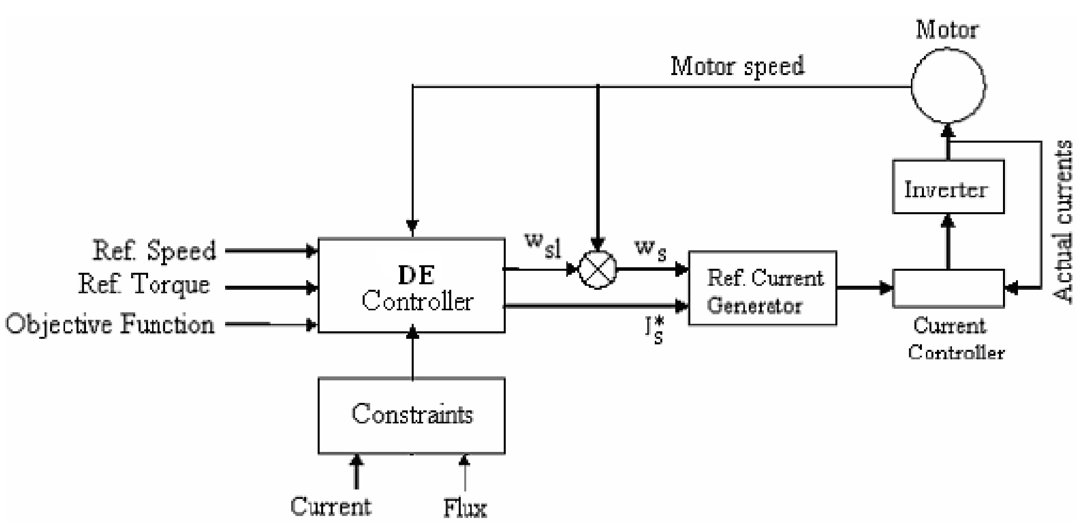
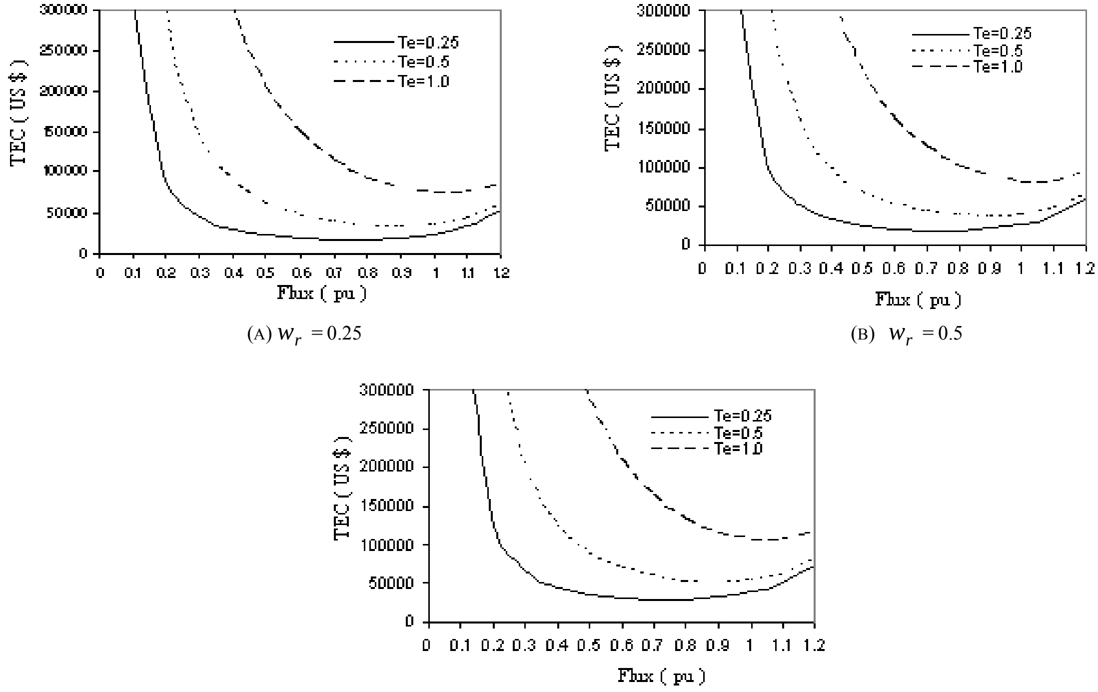


Fig. 6. Proposed controller for operating cost minimization



(A) $w_r = 0.25$

(B) $w_r = 0.5$

(c) $w_r = 1$

Fig. 7. TEC verses flux at variable speed and variable load of induction motor

TABLE 1 TOTAL LOSSES, FLUX AND STATOR CURRENT IN 100 HP IM FOR A TEXTILE MILL LOAD DIAGRAM (W_R=1)

Time (hr)	Te (pu)	Φ_m (pu)			I_s (pu)			P_{loss} (KW)		
		S/D	V/f	DE	S/D	V/f	DE	S/D	V/f	DE
t_1	0.2	0.557	1	0.669	0.408	0.587	0.387	1.82	3.64	2.51
t_2	0.4	1	1	0.842	0.688	0.688	0.599	3.25	4.53	4.07
t_3	0.6	1	1	0.940	0.830	0.830	0.802	4.41	5.96	5.86
t_4	0.8	1	1	1.00	0.995	0.995	0.998	6.03	7.89	7.89
t_5	1.0	1	1	1.05	1.175	1.175	1.188	8.13	10.32	10.16

TABLE II OPERATING COST OF 100 HP MOTOR TEXTILE MILL LOAD DIAGRAM (w_r=1)

Time (hr)	Te (pu)	S (US $)			D (US $)			TEC (US $)		
		S/D	V/f	DE	S/D	V/f	DE	S/D	V/f	DE
t_1	0.2	3746	7480	5150	2190	4373	3011	5937	11854	8161
t_2	0.4	6666	9297	8352	3898	5436	4883	10565	14734	13236
t_3	0.6	9046	12218	12016	5289	7144	7026	14335	19363	19042
t_4	0.8	6189	8091	8090	7238	9463	9461	13427	17555	17551
t_5	1.0	8335	10581	10420	9748	12375	12186	18084	22956	22606

TABLE III INDIVIDUAL LOSS TERMS OF 100 HP IM FOR TEXTILE MILL LOAD DIAGRAM (W_R=1)

Te (pu)	P_c (KW)			P_i (KW)			$P_{str} + P_m + P_{conv} + P_{cable}$ (KW)		
	S/D	V/f	DE	S/D	V/f	DE	S/D	V/f	DE
0.2	0.54	0.80	0.45	0.30	0.90	0.40	0.98	1.93	1.64
0.4	1.26	1.26	1.11	0.90	0.90	0.65	1.07	2.36	2.30
0.6	2.02	2.02	2.00	0.91	0.91	0.81	1.46	3.01	3.04
0.8	3.10	3.10	3.10	0.92	0.92	0.93	2.0	3.86	3.85
1.0	4.48	4.48	4.39	0.93	0.93	1.03	2.71	4.90	4.73

TABLE IV BENCHMARK PROBLEMS

Function	Dim	Ranges	Mini. Value
$f_1(x) = \sum_{i=1}^{n} (x_i^2 - 10\cos(2\pi x_i) + 10)$	2	[-5.12,5.12]	$f_1(\bar{0}) = 0$
$f_2(x) = \frac{1}{4000} \sum_{i=0}^{n-1} x_i^2 - \prod_{i=0}^{n-1} \cos(\frac{x_i}{\sqrt{i+1}}) + 1$	2	[-600,600]	$f_2(\bar{0}) = 0$

TABLE V CASE STUDY IN A TYPICAL SPINNING RING FRAME FOR ECONOMIC COMPARISON

Sl. No.	Controller	No. of Ring Frame	TEC (US $)	Savings (US $)
1	Star/ Delta	96	5985408	2314944
2	V/f	96	8300352	--
3	DE	96	7737216	563136

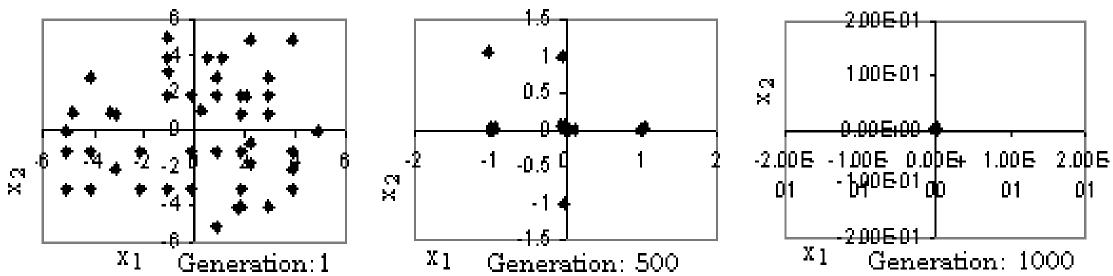


Fig. 8 Convergence graph for Rastringin function

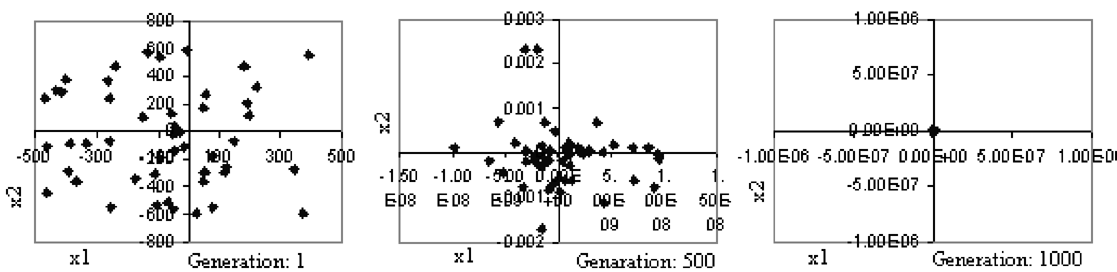


Fig. 9 Convergence graph for Griewank function

X. CONCLUSION

This study investigated the influence of controllers in the economics of a scalar controlled 100 hp spinning drive motor (induction motor) in textile mill applications. It is noted that DE produced better results than V/f in all instances (motor load). Cable losses also accounted in the total losses estimation of the IM. From the case study, US $ 563136 can be saved in a typical medium scale textile industry when used DE controller over v/f controller to select optimum flux level of the IM. Although S/D offered minimum TEC compared to others, it cannot be applied wide range of variable load and speed applications. To validate DE algorithm, standard benchmark problems Rastringin and Griewank functions were used in this paper. C++ code is used for DE implementation.

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