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Energy Conservation Studies on a Spinning Drive Motor with Scalar and Vector Controllers

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***Abstract*—This paper discusses 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 50 HP induction motor is investigated with three topologies namely Full Voltage (FV), Reduced Voltage (RV) and Vector Control (VC) in steady-state conditions for different loads. In RV, the reduced voltage is applied to machine while VC is used to provide minimum flux level, to maintain required load. The machine has been considered to adjust to give minimum operating cost for the textile mill load. The flux controller in VC improves the economics in terms of operating cost (energy cost and demand charge cost), according to load and speed, particularly at light load.**

Keywords-economics; energy efficiency; induction motor; textile industry;

I. INTRODUCTION

To conserve electrical energy in the industrial sector through a reduction in losses of induction motor, it is particularly interesting to deal with energy intensive industries like textile industry and mine industry. Because 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. [1], and hence such industries are considered in the present work to reduce the energy cost and the total input cost.

Generally, induction motor is a high efficiency electrical machine when working closed to its rated torque and speed. However, at light loads, no balance in between copper and iron losses, results considerable reduction in the efficiency. The part-load efficiency and power factor can be improved by adjusting the motor excitation in accordance with load and speed. To implement the above goal, the induction motor should either be fed through an inverter or redesigned with optimization algorithms [2].

A simplest method to improve efficiency of induction motor operate at light load is to keep the motor connection in star results reduced power consumption. In the operation of motor at star mode, however, the developed torque and temperature rise are to be measured and keep at normal [3]. In addition, there are two different approaches to improve the induction motor efficiency especially under light-load conditions, namely, loss model controller (LMC) and search controller (SC). In this paper reduced voltage and reduced flux is applied to the machine at light loads to reduce the energy cost and the total input cost. Apart from optimal control, the induction motor efficiency can also be improved by modifying materials and construction with the help of advanced optimization techniques. In Ref. [4], a design optimization of textile spinning motor is proposed by using modified differential evolution algorithms. A review of the developments in both the field of efficiency optimization of three-phase induction motor through optimal control and design techniques is discussed in [5].

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 derive the loss and operating cost models of the IM, section V presents the simulation results of 50 hp motor and analyzes the economical comparison, section VI presents case study, section VII presents the alternate solution for energy saving in textile industry and finally section VIII concludes the paper.

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 [3].

Figure 1. Textile spinning ring frame

In this paper, 50 hp motor has been considered for 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

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a textile industry (Fig. 2). ‘T’ is the time consumption for the completion of one process. Although load diagram is continuous but we have considered the discrete load diagram for easy analysis shown in Fig. 2.

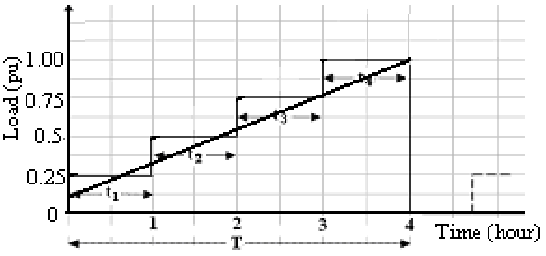


Figure 2. Average load diagram of a typical spinning ring frame drive motor

III. METHODS FOR EFFICIENCY OPTIMIZATION

In this section, discuss different types of controllers which are used to operate the motor with reduced operating cost at partial load. These are as follows,

A. Reduced Voltage

Since core loss are proportional to applied voltage so Instead of running induction motor with rated voltage for different load (less than rated), it can be operated at reduced voltage to decrease core losses and to obtain energy conservation. For different load (less than rated), the applied voltage is decreased in steps of 10 V from rated value and the machine is running at the voltage which is capable to maintain the required load. For considerable reduction in load (about 25% of full load) the induction motor can be operated at voltages as low as 50% of rated voltage. This substantially reduces the input power consumption of the motor.

B. Vector Control

Many schemes have been proposed for the control of induction motor drives, among which the field oriented control or vector control, or converter inverter control. That has been accepted as one of the most effective methods. The vector control of AC motor was introduced by K. Hasse and Siemens' F. Blaschke in 1968. In this the variables are controlled in magnitude and phase. Vector control of the induction motor is running in a closed-loop with the speed sensor coupled to the shaft shown in Fig. 3. This control strategy is formulated in such a way that the stator current phasor, in the two-axis synchronously rotating reference frame, has two components: magnetizing current component and torque-producing current component. The generated motor torque is the product of the two. By keeping the magnetizing current component at a constant rated value, the motor torque is linearly proportional to current producing element, which is quite similar to the control of a separately excited DC motor.

i. 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. 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.

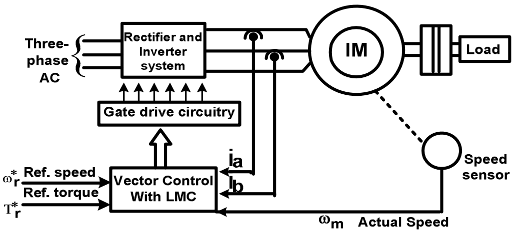


Figure 3. Efficiency optimization of IM using vector control

Constant V/f control is the scalar (variables are controlled in magnitude only) type control for minimizing the losses of induction motor at light load. 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.

ii. Search controller

It measures the input power and then iteratively searches for the flux level (or its equivalent variables) until the minimum input power is detected for a given torque and speed. Drawbacks of this technique are slow convergence and torque ripples.

IV. INDUCTION MOTOR LOSS MODEL AND OPERATING COST MODEL

The per-phase IM equations (1) – (5) are given in the per-unit systems [2]

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

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

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

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

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

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

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

The individual loss equations in the IM are given by [10]

Copper losses $P_c = R_s I_s^2 + R_r^{'} I_r^{'2}$ (6)

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

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

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

The total losses in IM drive system is given by

$P_{loss} = P_c + P_i + P_{str} + P_m$ (10)

From equations (7) - (11), the total losses (without considering converter losses) in terms of slip speed is given by

$$P_{loss} = R_s I_s^2 + R_r' I_r'^2 + ([k_e(1+s^2)a^2 + kh1+sa\emptyset m2)+Cstr\omega 2Ir'2+Cf\omega\omega 2 \qquad (11)$$

Where P_{in}- Represents the electrical power absorbed by the motor and P_{loss} is the motor losses. The equation for efficiency is given below

$$\eta = \frac{P_{out}}{P_{out}+P_{loss}} \qquad (12)$$

From (11), 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 costs [3]

The energy cost of the induction motor should be calculated over the whole life cycle of the motor [6] and is given below. Power factor penalty is not considered in this paper because almost all the industries have centralized power factor correction equipments.

$$S = C_e * T * N * P_{in} \qquad (13)$$

Where		
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_{in}	Input power of the motor (KW)

B. Demand charge cost [3]

Demand charge cost consumed by the motor over the whole life of the motor can be calculated by using the equation (16) and is given below

$$D = C_d * 12 * N * P_{in} \qquad (14)$$

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

$$TEC = P_{in} * N * \{(C_e * T) + (C_d * 12)\} \qquad (15)$$

From the equation (16), TEC = function (Flux), which can be minimized by reducing applied voltage to the stator or reducing flux producing current (in vector control).

V. SIMULATION RESULTS AND DISCISSION

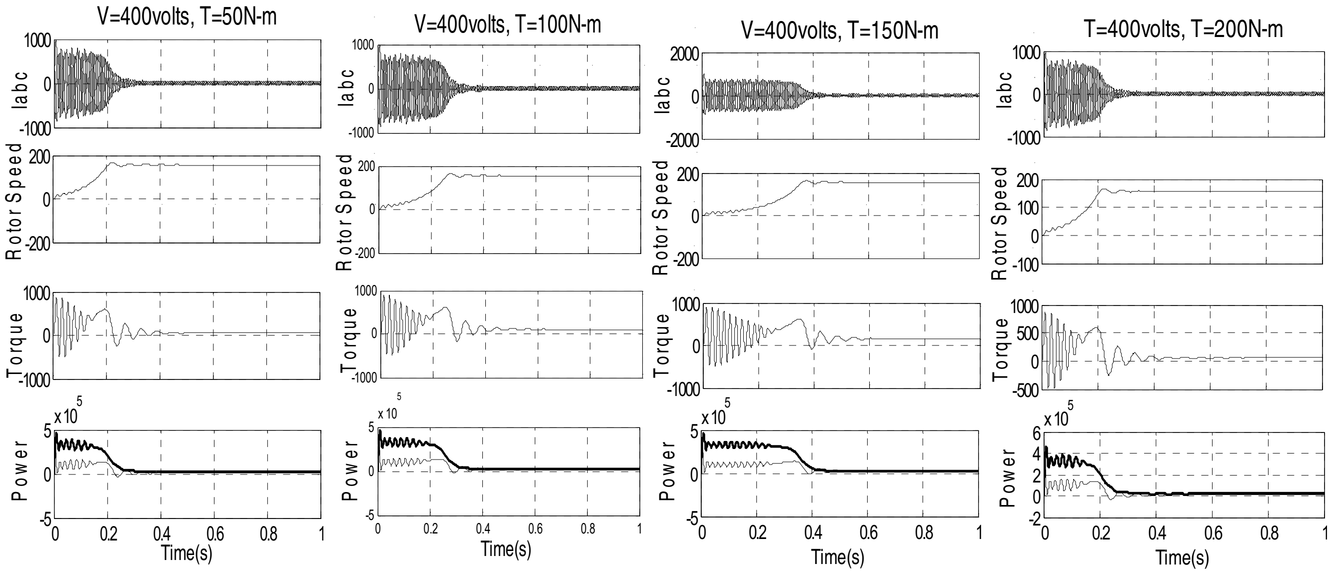
In this section, a 50 HP motor operating with the given load diagram (Fig. 2) in textile mill applications (ring spinning frame) has considered for economic analysis.

Input Power, energy cost and total energy cost comparison of the constant speed (rated) IM for a textile mill load diagram with the following electricity tariff 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.

Maximum demand (KVA) charges: US $ 6.0/month
Energy (kWh) charges: US $ 0.077/kWh
(1 US $= Indian Rupees 50 approximately).

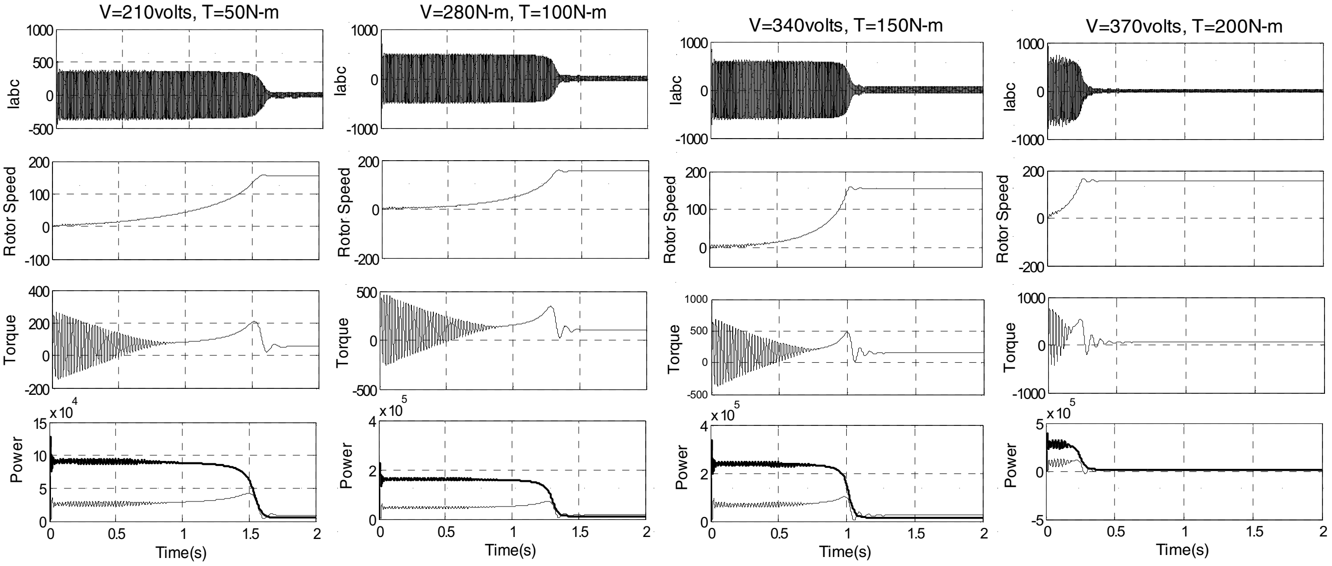
Simulation results for Stator current, rotor speed, input power is shown in Fig.4, Fig.5 and Fig.6 for FV, RV and VC (reduced flux) for 0.25pu, 0.50pu, 0.75pu and 1.00pu loads respectively.

For all the loads VC offered low TEC and it performed much better than RV shown in Table II. Fig. 7 shows the variation of Input Power, Energy Cost and Demand Cost by adjusting voltage and flux level in the motor at variable load and speed applications.



(a) 25% of load (b) 50% of load (c) 75% of load (d) 100% load

Figure 4. Stator currents, rotor speed, torque and total input power at full voltage for different loads



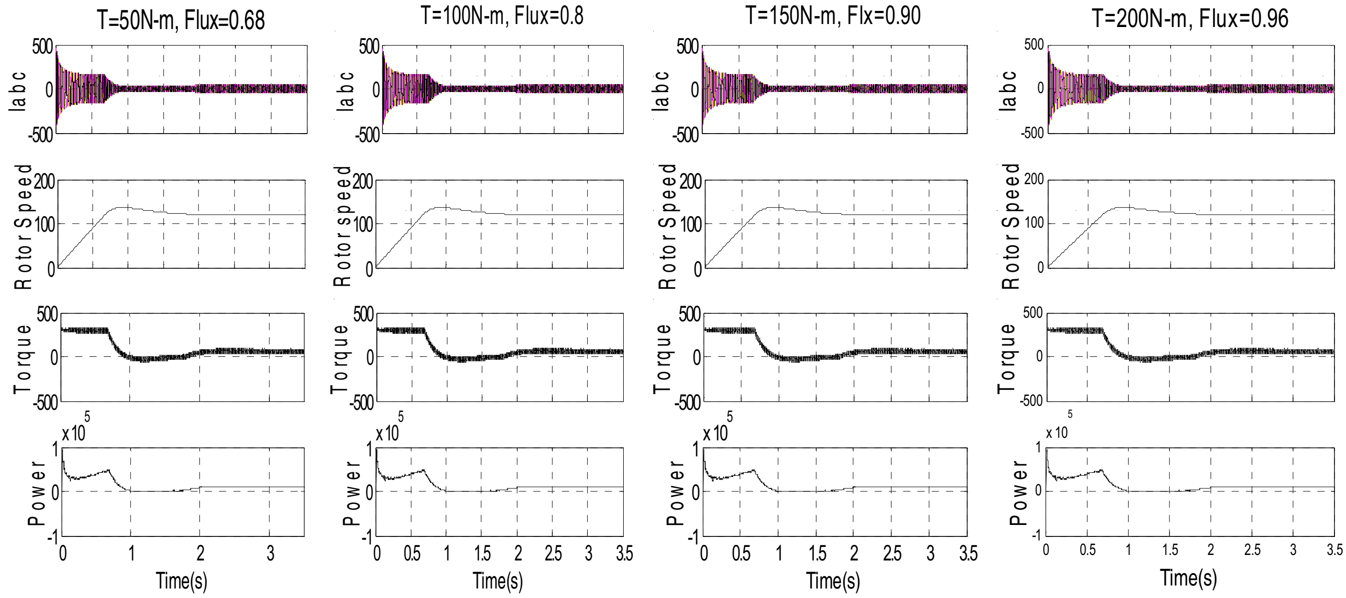
(a) 25% of load

(b) 50% of load

(c) 75% of load

(d) 100% load

Figure 5. Stator currents, rotor speed, torque and total input power at reduced voltage for different loads



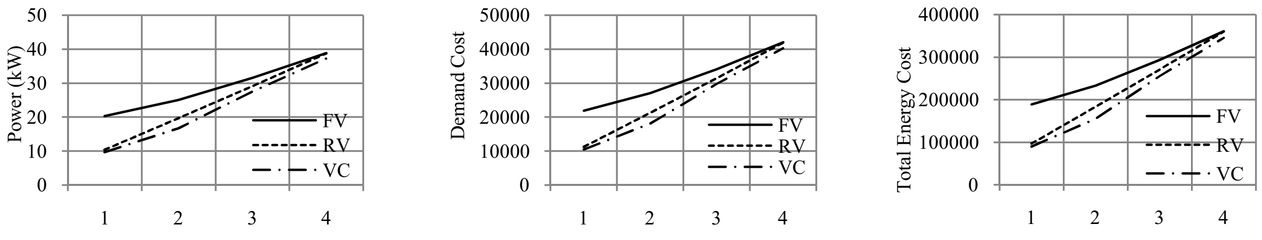
(a) 25% of load

(b) 50% of load

(c) 75% of load

(d) 100% load

Figure 6. Stator currents, rotor speed, torque and total input power at reduced voltage for different loads



(a) Plot of power for FV, RV and VC

(b) Plot of Demand cost for FV, RV and VC

(c) Plot of Energy cost for FV, RV and VC

Figure 7. Comparison for different topologies

TABLE I. Table I Voltage, Stator Current and Total Input Power in 50 hp IM For a Textile Mill Load Diagram

Time(hr)	Te(pu)	Voltage (Volts)			I_s(Amperes)			P_{in}(kW)		
		FV	RV	VC	FV	RV	VC	FV	RV	VC
1	0.25	400	210	460	41.5	40.55	47.2	20.327	10.429	9.7
2	0.5	400	280	460	51.35	57.53	67.1	25.09	19.728	16.76
3	0.75	400	340	460	64.5	70	82.5	31.592	29.158	27.54
4	1	400	370	460	79.5	82.18	95.5	38.872	38.8	37.243

TABLE II. Operating Cost Of 50 hp Motor Textile Mill Load Diagram

Time(hr)	Te(pu)	S(US$)			D(US$)			TEC(US$)		
		FV	RV	VC	FV	RV	VC	FV	RV	VC
1	0.25	166692	85523	79545	21953	11263	10476	188645	96786	90021
2	0.5	205751	161779	137440	27097	21306	18101	232848	183086	155541
3	0.75	259070	239110	225842	34119	31491	29743	293190	270601	255585
4	1	318770	318179	305411	41982	41904	40222	360752	360083	345634
Total TEC (US $)								1075434	910556	846781

From the results, energy saving in textile industries using variable speed drives (VSD) is significant but attention is to be paid before installing VSD. The following points are important.

1. Inevitable tripping in VSD in textile extrusion process
2. Premature bearing failure in the induction motor driven by VSD
3. Manufacturing of induction motor in VSD application
4. Technical factors to be considered for purchasing VSDs in the process Industries
5. Induction motor operating with long leads and VSD

VI. The Alternate Solutions For Energy Saving In Textile Industry

Apart from optimal control, an alternate solution is to replace standard efficiency motor by Energy Efficient Motor (EEM). They can significantly reduce the energy consumption, particularly at light loads; by using advanced materials. The following points are important before suggesting EEM to industrial sectors [7].

- *Standard efficiency motor is replaced with an energy efficient motor:* Due to lower slip level in energy efficient motor (EEM), operate at slightly higher speeds, and result in operation at a higher point in the load curve of the pump. This increase in load is proportional to approximately the cube of the increase in speed. This means motor must produce more horsepower (ie, EEM may be operating above its rated power). Because the temperature rise in a motor increases slightly less than the square of the horse power output, the net effect is that the temperature rise of the rotor is roughly proportional to the fifth power of the increase in rotor speed.
- *Momentary voltage drop when replacing standard efficiency motors by energy efficient motors:* Calculation of voltage drop during motor starting is usually done during the engineering-elevation stage of motor installation, with a 10% momentary voltage drop generally considered a maximum. However, replacing standard-efficiency motors with energy-efficiency motors may result in higher, and perhaps excessive, voltage drops due to its higher starting current.

  This excessive drop in the utilization voltage may affect high intensity discharge lighting, which is sensitive to voltage variations, may drop out during the starting of an energy efficient motor.
- *Nuisance tripping of circuit breaker when replacing standard efficiency motors by energy efficient motors:*

  To reduce the stator and rotor copper losses in the induction motor, manufacturers seek to reduce the resistance of motor windings. This reduced resistance may cause energy efficient motors (EEM) to draw a higher inrush current and high starting current.

  For some EEM, this current can be as high as 8 times the motor's full load current whereas 5 - 6 times full load current for standard efficiency motors. This is the reason for nuisance tripping of the motor. Nuisance tripping can be avoided by increasing the setting of protective devices to higher levels.
- *Energy efficient motor in industries with unbalanced voltages*: Due to unbalanced stator voltages, the motor experienced significant increase in rotor heating which is higher than standard efficiency motor.
  1. This heating may not be detected by the overload and over current protection circuit of the motor and may lead to serious motor damage.
  2. Energy efficient motor will provide better energy savings compared to standard efficiency motor even unbalanced stator voltages.
- *Selection of starters for energy efficient motor:* When standard efficiency motors are replaced by energy efficient motors, the existing motor starters may not be able to handle the higher starting current even the motors ratings are same. As per national Electric Code (NEC), 1996, conventional motor starters and other motor controllers can be used with Design-E motors as long as the rating of the starter exceeds that of the motor by a factor of 1.4 when the motors between 3 and 100 hp and by a factor of 1.3 for higher motors.

- *Standard efficiency motor winding failure in the process industry:* Select a new energy efficient motor under any of the following conditions:
    1. The motor is less than 40 HP
    2. Choose a new energy efficient motor (up to 100 HP) if it will be used more than 3000 hours / year in the basis of Tamil Nadu Electricity tariff
    3. The cost of the rewind exceeds 65% of the price of a new motor

VII. CONCLUSION

This study investigated the influence of controllers in the economics of a scalar controlled 50 hp spinning drive motor (induction motor) in textile mill applications. It is noted that VC produced better results than FV in all instances (motor load). Although RV also offered less TEC compared to FV, it cannot be applied wide range of variable load and speed applications. Important steps to be undertaken before suggesting an EEM to industrial sectors are also discussed.

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NOMENCLATURE

R_s	Stator resistance
R_r'	Rotor resistance
X_{ls}	Stator leakage reactance
X_{lr}	Rotor leakage reactance
X_m	Magnetizing reactance
ω	Speed
T_e	Electromagnetic torque
Φ_m	Air-gap flux
E	Air-gap voltage
a, ω_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_{str}	Stray losss
P_m	Mechanical losss
P_{loss}	Total losses
k_e, k_h	Eddy current and hysteresis coefficients
C_{fw}	Mechanical loss coefficients
C_{str}	Stray loss coefficients