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**Article**

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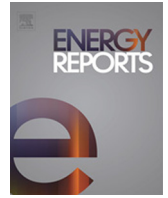
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# Efficient energy management measures in steel industry for economic utilization



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## HIGHLIGHTS

- Replacement with energy efficient induction machines of suitable rating.
- Significant energy savings and good monetary gains by techno-economics.
- Rescheduling of transformer loads for better performance and increased life span.
- Proposes non-intrusive efficiency estimation for in-service induction machines.
- Stray load and friction-windage loss according to IEC standard.

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## ABSTRACT

The application of energy efficient Induction Machines (IM) is explained in reference to power consumption savings. In energy efficient IM, losses for various Horse Power (HP) ratings are summarized for bringing effective changes in design. Emphasis is laid on how load factor, speed & power quality affect machine's efficiency. Replacement of conventional IM of higher power rating is done with required energy efficient Doubly Fed Induction Machine (DFIM) to enhance the performance at variable speeds near rated power outputs. Results of the proposed approach will give substantial savings in energy & loss reduction. The field data of Jindal Steel Rolling Mill (JSRM) at Hisar, Haryana (India) is taken into consideration. This paper proposes a non-intrusive air gap torque method for efficiency estimation of in-service IMs. This approach gives results considering stray-load and friction-windage loss according to IEC standard and IEEE112-B standard. The proposed method is validated experimentally whose effectiveness is witnessed using MATLAB/SIMULINK.

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## 1. Introduction

Electric motors in various countries, account to consume more than 71% of the total electric power produced (Andreas, 2002). The ever-increasing imbalance of energy supply & demand is driving us towards energy audit & energy management.

In 1970s, Induction Machines (IM) were designed to have low initial cost. The value of efficiency was selected to satisfy temperature rise requirements only. The amount of copper wire & steel stampings were selected to give satisfactory performance. In 1980's, with the increasing power costs, the trend for searching the IM with lesser losses & lesser power consumption was started. In late nineties, energy efficient machines were developed. For 2

Horse-Power (HP) to 200 HP, reduction in watt loss is in the range of 24%–48% (Andreas, 2002).

During a case study taken for fan motor in industrial boilers in Malaysia (Bose, 2000), energy savings & reduction of emission is done using energy audit data. The potential to save energy lies with induction machines. In higher HP rating, incremental gain in efficiency is very tedious task but this reduces losses to great extent & thereby results in greater savings. For higher HP ratings of IM, watt losses cannot be ignored. They are significant from designer's aspect. The efficiency & power factor of the machine has remarkable impact on running cost. Energy efficient IM designed for higher efficiencies will show a higher payback period. This has significant importance in energy auditing.

In the industrial sector, steel rolling mills are the major absorbers of electrical power. Incremental rise in efficiency of installed IMs results in great savings. From the accumulated data, decisions to install energy efficient IMs in place of existing substandard or standard IMs must be taken promptly.

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**Table 1**  
Loss distribution summary.

S. No.	Component of loss	Loss (%)
1.	Stator copper loss	37
2.	Rotor copper loss	18
3.	Magnetic core loss	20
4.	Friction & windage loss	09
5.	Stray load loss	16

**Table 2**  
IM efficiency vs.% power loss.

HP rating	Efficiency (%)	Raised efficiency (%)	% Decrease in power loss
1	73	74	8
5	83	84	11
25	89	90	16
100	91.5	92.5	28

In this paper, field work and data collection for case-study is taken up at Jindal Steel Rolling Mill (JSRM) at Hisar, Haryana (India) (Habetler and Harley, 2006). It has been found that major numbers of IMs are operated at around 50% under load conditions. Load sharing between transformers is inadequate. During sudden drastic changes in load close to their rated limits, ten large IMs for variable speed operations got tripped resulting in shut down. The mill has poor power factor due to which greater currents were drawn resulting in overloading the equipment at times of full load. Also, operation at poor power factor results in higher penalties from public utility.

Various suggestions have been put forth to reduce energy consumption in the mill. First, the replacement of substandard or standard IMs is required to be done by energy efficient IMs of suitable rating. Second, energy efficient DFIMs are proposed for implementation for variable speed operations near to machine rating applications. Lastly, transformer loads have to be rescheduled to obtain better performances and increased life-span.

By implementing these approaches, reduction in energy bill & connected load can be achieved. An analysis has been done on the field data for payback time with the proposed approach of replacing conventional IMs with energy efficient IMs. By calculating payback time, total savings per year can be evaluated.

## 2. Loss distribution in summarized form

For various HP ratings, changes in design are shown in summarized form to achieve improvised efficiency. Distribution of losses is given as shown in Table 1.

The level of difficulty in raising the efficiency increases with the rise in HP rating of the machine. Keeping the same HP rating, if efficiency of machine is raised by 1%, significant loss reduction is needed (Andreas, 2002). This loss distribution reveals the importance of changes in electric machine design to raise the efficiency of IM. To raise efficiency of IM by 1%, requirement of reduction in power loss is quite high as IM efficiency increases as shown in Table 2.

For machines in ratings of hundreds or thousands of HP, larger reduction in per unit loss is needed. IMs are designed for maximum efficiency at rated loads. As load factor decreases, efficiency declines. This results in reduction of power factor. Partially loaded motors of higher HP ratings can be replaced by IMs of suitable ratings to achieve correct amount of power for each portion of duty cycle.

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ratings can be replaced by IMs to achieve correct amount of power for each portion of duty cycle.

For voltage drop of 6%, running torque & starting torque decreases by 11% thereby resulting in full load current by more than 5% of its rated value. With the rise in voltage drop, there is increase of temperature in the windings. Without keeping voltage rise to its limits, machine windings may burn out. Voltage variation in any of the phases of machine causes varying currents in the machine winding. This increases the losses by inappropriate margin which has to be avoided by all means.

Conventional as well as energy efficient IMs for same input will have higher efficiencies & higher power factors at high speeds. If operation is done at lower voltage than rated voltage for longer period of time, there is rise of stator as well as rotor currents which will increase the loss. This will further lower the flux density and magnetizing current. So, power factor will be enhanced. The main point is that with changes in  $I^2R$  loss, there would be little change in efficiency of the machine indicating little rise or fall in its value.

## 3. Design criteria for energy efficient IM

To improve the efficiency, reduction in losses is must. Brief description of what needs to be done to minimize various losses in induction machines is discussed below.

### 3.1. Stator & rotor copper loss

These losses are function of conductor resistance, having smaller values at no load but rises to major proportions during full load. They form 45%–65% of total losses. By increase of conductor's area of cross-section to reduce the resistance, these losses can be minimized. Resistance can also be reduced with lesser overhang. It is the magnetizing component of the total stator current which gives the net flux across air-gap. Reduction in motor current can be done by decreasing the magnetizing current which involves the reduction of flux density & possibly reducing the air-gap. The interdependent relation between power factor & efficiency is given as

$$\text{Stator current} = \frac{HP \text{ (Output)} \times 746}{\sqrt{3} \times \text{voltage} \times \text{power factor} \times \text{efficiency}} \quad (1)$$

$$\text{Rotor losses} = \frac{(HP \text{ output} \times 746 + \text{Frictional losses}) \times \text{slip}}{1 - \text{Slip}} \quad (2)$$

It can be observed that if efficiency is increased, power factor decreases. To keep power factor constant, stator current must decrease in proportion to the rise in efficiency. Since resistance has inverse relation to weight of wire in stator, so more conductor material in stator will result in lowering the losses. Reduction in rotor slip can be obtained by increasing the total flux in the air-gap in rotor. By increasing the conductor material in the rotor, the slip of rotor can be reduced. Reduced value of rotor bars will reduce the starting torque. This will increase the starting current as well as rise in efficiency.

### 3.2. Magnetic core loss

Even at no load, the induction machines take sizeable amount of magnetizing current. For DFIM, full magnetizing current needed by the machine is taken from the mains. Even at low loads, it draws magnetizing current from the mains though unnecessary at constant terminal voltage. Power factor can be observed as useful parameter of non useful energy drawn from supply reactive volt-amperes rather than watts. Lesser power factor means more non useful energy drawn. Core loss accounts for 20%–25% of total loss. Using 29 gauge or 32 gauge laminations of CRGO (cold rolled

grain oriented steel), core losses can be reduced. The length of magnetic structure can be increased. This reduces flux density & reduction in magnetizing current would be there. So, ultimate goal of improvement in power factor can be achieved.

### 3.3. Frictional loss

These losses account for 5%–8% of total loss. Friction in bearings, windage loss of fan & other rotating parts causes these losses. Reduction of windage loss refers to reduction in noise level of the machine. For making machine design more efficient, windage loss reduces with the diameter of the fan. This is the important aspect to bring this sort of loss to negligible values.

### 3.4. Stray load loss

These account for 4%–5% of total loss. They have circulating current losses in stator & harmonic losses in the rotor under load. Damage in the core or end shields affect the air-gap symmetry. These may increase stray load loss. These can be minimized by critically designing the ratio of air-gap length to slot opening of rotor, air gap flux density, welding of rotor bars to rotor laminations. These are very hard to determine by calculation & direct measurement.

## 4. Loss studies and energy savings for case study

High efficiency induction machines save significant energy charges over the machine life by performing the techno-economics analysis (IEEE, 2004; Personal, 2014; Phumphak and Chat-uthai, 2005). After crossing breakeven point, energy efficient machines save more energy & gain monetary returns till the life of machine. Payback periods are calculated to know the annual savings in energy in form of monthly bills till expected machine's life. Formulas involved are given as:

$$\text{Annual savings} = 0.746 \times H \times U \times R \left[ \frac{100}{S1} - \frac{100}{S2} \right]. \quad (3)$$

Here,  $H$  = Horse Power rating

$U$  = Power cost (RS/kilowatt Hour)  
 $R$  = Running time in Hours/Annum  
 $S1$ & $S2$  = Efficiencies to be compared.

For power cost to be constant

$$\text{Present Worth} = [1/(1+v)^b] \times \text{Annual savings}. \quad (4)$$

Here,  $v$  = rate of interest annually,  $b$  = saving years.

This holds well if power costs are constant. This approach results in reduction in savings and increases the payback period. The present worth (PW) calculations can be made simpler for a period of years by equation shown as:

$$\text{Present worth} = \text{Annual savings} \left[ \frac{(1+v)^b - 1}{v(1+v)^b} \right]. \quad (5)$$

Generally, there is a continuous projected trend of increasing power cost. This impacts present worth calculations. So, annual savings will not be constant but will increase in geometric pattern every year in series form as shown.

$$S(1+I_{pg}) + S(1+I_{pg})^2 + \dots + S(1+I_{pg})^b. \quad (6)$$

Here,  $I_{pg}$  = Annual percent rise in cost of power;  $M$  = year;  $S$  = annual savings This gives the present worth of series of savings as Present worth

$$= \text{Annual savings} \left[ \frac{1+I_{pg}}{1+I_{ri}} + \frac{(1+I_{pg})^2}{(1+I_{ri})^2} + \dots \right]. \quad (7)$$

Here,

**Table 3**

HP rating of IMs with their quantitative numbers in JSRM.

Ratings of IM in HP	No. of IM
1 HP	57
2 HP	24
3.8 HP	36
5.1 HP	27
25 HP	140
40.8 HP	14
102 HP	26
200 HP	10

$I_{pg}$  = Annual percent rise in cost of electric power  
 $I_{ri}$  = Annual interest rate.

Effective interest rate can be given as a function of percent increase in power cost and rate of return.

$$I_{re} = \text{Effective interest rate} = \frac{1+I_{ri}}{1+I_{pg}} - 1. \quad (8)$$

Present worth can then be obtained as

$$\text{Present worth (PW)} = \text{Annual savings} \left[ \frac{(1+I_{re})^b - 1}{I_{re}(1+I_{re})^b} \right]. \quad (9)$$

To include the impact of taxes or depreciation on present worth, net present worth (NPW) has two parts.

$$\text{NPW} = \text{NPW}_{es} + \text{NPW}_{dep}. \quad (10)$$

Here,  $\text{NPW}_{es}$  = Energy saving present worth & is given as:

$$\text{NPW}_{es} = \text{PW}(1 - \text{Tax rate}). \quad (11)$$

$\text{NPW}_{dep}$  = Present worth of depreciation on investment & is given as:

$$\text{NPW}_{dep} = \left[ \frac{\text{NPW}_{es}}{M} \right] \left[ \frac{(1+I_{ri})^b - 1}{I_{ri}(1+I_{ri})^b} \right] \times \text{tax rate}. \quad (12)$$

So, net present worth is found by adding Eqs. (11) and (12).

## 5. Payback analysis for Jindal Steel Rolling Mill

JSRM in Hisar, Haryana, India has varied ranges of IM running for furnaces, compressors, pumps, mechanical governors etc. It has been found that most of the IM are working at under loaded conditions, say 50%, approximately. The plant has a large number of IM of different HP ratings as shown in Table 3 (Habetler and Harley, 2006).

Under-loading propels to focus for the opportunities to explore ways of energy savings. In this work, energy auditing is done specifically for 25 HP motors since maximum numbers of motors employed are of this rating. For detailed energy audit, complete list of Table 3 could be considered as the case study. Standard IM are replaced with their energy efficient counterparts of desired HP ratings. The economics of replacing one 25 HP standard IM with energy efficient IM of 15 HP is shown in Table 4. In all calculations, we have assumed life of IM as 15 years, energy charges as INR. 7.0 per unit & demand rate as INR 100.0. Demand rate is defined as the rate for maximum demand in kVA sanctioned to the consumer and the same shall be worked out from sanctioned load in kW using power factor of 0.88.

From analysis of Table 4, it has been found that by replacing IM of 25 HP by energy efficient IM of 15 HP, total savings of INR. 16,296.00 can be achieved due to less energy consumption. The extra capital investment done on new energy efficient IM can be recovered with-in two months. Life time gain of INR 0.23 million could be attained by only one IM replacement i.e. within fifteen years.

**Table 4**  
Replacement of standard IM by energy efficient IM.

Details	Standard IM 25 HP	Energy Efficient IM 15 HP
kW rating	18.65	11.16
Load factor (%)	0.63	0.84
Efficiency (%)	0.84	0.86
Input (kW)	13.98	10.90
Units consumed per day	335.52	261.60
Power factor	0.67	0.83
Demand (kVA) = Input kW/power factor	20.86	13.13
Charges (demand kVA) = Demand kVA × demand rate	2086.00	1313.00
Savings due to demand kVA per month		773.00
Energy charges per month = units consumed in 24 hrs × 30 days a month × unit rate (INR.7/per unit)	70,459.20	54,936.00
Savings due to less energy consumption (INR.)		15,523.20
Total savings (INR.)		16,296.20
Resale value of old motor in INR.	15,000.00	
Investment for new motor in INR.		40,000.00
Net investment in INR.		25,000.00
Payback period = Net investment/total savings		02 months
Life time gain in INR. = Total savings × (life of motor – payback period)		239,551.2

Since 140 motors of 25 HP would be replaced by energy efficient 15 HP, so life time gain would be obtained by multiplying life time gain obtained for one motor from Table 3 by 140 which would be around 32 million INR, a big significant amount that can be saved.

In the JSRM, the associated drives with IM are the largest harmonic producing load on the plant's electrical system. Problems develop when nonlinear loads vary over a wide range. They causes sudden inrush of currents causing greater harmonics & unwanted tripping of higher HP IMs takes place. JSRM has employed ten number of 200 HP IM for variable speed operations. Due to greater stress during varying loads & sudden changes in speed the problems such as coil abrasion in the slots, electric stress relief coating deterioration and partial discharges in the end winding will lead to sudden tripping of IMs. Due to heavy inrush of current on sudden rise of load, the maximum demand energy meter gives full scale deflection. This indicates maximum power drawn suddenly from electric utility. JSRM is billed for such full scale deflections in their energy bills. Each time on full scale deflection, the electric utility personnel has to come for resetting of maximum demand energy meter. This situation overburdens their energy bills.

For variable speed operations near to machine rating, energy efficient DFIM is proposed to be implemented. DFIM is preferred over conventional IM because it has lower cost per kW, high efficiency and higher power density. DFIM has magnetizing current shared between stator & rotor windings. DFIM when working as motor at speeds above synchronous speeds, mechanical power goes in to stator & rotor winding. Efficiency of DFIM becomes better. The most extended control strategy implemented for DFIM is the field oriented control or sometimes referred as vector control technique. For AC drives & steel plant applications, direct control techniques are opted. The direct torque control tries to control the torque and amplitude of rotor flux of the machine whereas direct power control tries to handle the active and reactive powers of the stator. Both schemes of direct control guarantee the control over the machine along with achieving good performance. Payback period analysis of replacing conventional IM with energy efficient DFIM for smooth operation in rolling without getting it disconnected at load variation is as shown in Table 5.

In this work, ten 200 HP IMs have been replaced by 200 HP energy efficient DFIM & payback analysis is carried out. Payback analysis has given out the payback period and life time gain of INR 1.4 million approximately. So, greater savings in energy & monthly bills could be attained by replacing ten 200 HP IMs by their energy efficient DFIM counterparts.

At the Steel Rolling Mill, rescheduling of loads between installed transformers is taken up as shown in Table 6.

Shifting 200 kVA load from transformer-I to transformer-II results in energy savings as shown in Table 7.

Table 6 shows that transformer-I has losses of 16.348 kW. After rescheduling, these losses have been reduced to 10.702 kW as shown in Table 7. This clearly shows that the insulation of transformer-I is subjected to lesser stress. This fact increases the life of transformer-I and enhances the savings.

## 6. An inexpensive approach for efficiency estimation of in-service IMs

In industry, majority of IMs are operating close to 55% of their rated load value. They are giving poor efficiencies resulting in wastage of power. Therefore, effective and affordable methods are needed to monitor the energy usage. Energy saving calculations and the relevant decisions are strongly dependent on the IM's efficiency. The majority of standard techniques presented in the IEEE 112 standard are not applicable for *in-situ* efficiency measurement due to their intrusiveness (Yong et al., 2009). Speed and torque transducers are costly and their usage is highly intrusive. In most of the cases, it is impossible to install these transducers due to lack of space.

### 6.1. IM torque estimation with low cost

A possible approach of estimating the efficiency of in-situ IM is to rely on input terminal voltages and currents. In industrial sector, IM terminal voltages and currents are readily available from the motor control room. There is no additional cost incurred on terminal data measurements. So, this approach is non-intrusive in nature and can be easily utilized. This paper put forth a non-intrusive air-gap torque (NIAGT) method for in-service motor efficiency estimation using only motor terminal quantities and nameplate information.

The air gap torque equation for a 3 phase IM is shown as:

$$T_{ag} = \frac{\sqrt{3}P}{6} \left\{ (i_a - i_b) \cdot \int [v_{ca} - R_s(i_c - i_a)] dt - (i_c - i_a) \cdot \int [v_{ab} - R_s(i_a - i_b)] dt \right\} \quad (13)$$

where:

$P$  is the number of poles

$i_a, i_b$  are the line currents and  $v_{ca}, v_{ab}$  are the line voltages

$R_s$  is half the line to line resistance.



**Table 5**  
Replacement of existing IM by energy efficient DFIM.

Description	Existing IM 200 HP	Proposed energy efficient DFIM 200 HP
Rating (kW)	148	148
Speed (rpm)	1470	1470
Efficiency (%)	0.91	0.94
Load factor (LF) in percentage	90	90
Input (kW) = kW rating × LF/Efficiency	146.37	141.702
Units consumed in 24 h (kWh)	3512.88	3400.84
Power factor	0.81	0.92
Demand (kVA) = Input kW/power factor	180.703	154.023
Charges (demand kVA) = Demand kVA × demand rate	18,070.3	15,402.3
Savings due to demand kVA per month		2668.00
Energy charges per month = units consumed in 24 hrs × 30 days a month × unit rate (INR.7/per unit)	73,7704.80	71,4176.40
Savings due less energy consumption (INR.)		23,528.40
Total savings (INR.)		26,196.40
Energy used in one year (kWh). Assume working days in an year as 300 days	10,53,864.00	10,20,252.00
Energy difference for one year		33,612.00
Energy rate for one year@ INR.7/- unit		2,35,284.00
Resale value of old motor in Rs.	2,00,000.00	
Investment for new motor in INR.		33,00,000.00
Net investment in INR.		31,00,000.00
Payback period = Net investment/total savings		Nine years
Life time gain in INR.		1 411 704

**Table 6**  
Rescheduling of transformer loading.

Description	Transformer-I (1000 kVA)	Transformer-II (1000 kVA)
Running load (a)	889 kVA	520 kVA
Running amperes (b)	44 A	29 A
No load loss (c)		2.21 kW
Full load loss (d)		17.889 kW
Losses = $c + (a/1000)^2 \times d$	16.348 kW	7.047 kW
Total losses		23.395 kW

**Table 7**  
Rescheduling of transformer loading.

Description	Transformer-I (1000 kVA)	Transformer-II (1000 kVA)
Running load (a)	689 kVA	720 kVA
Running amperes (b)	44 A	29 A
No load loss I		2.21 kW
Full load loss (d)		17.889 kW
Losses = $c + (a/1000)^2 \times d$	10.702 kW	11.483 kW
Total losses		22.185 kW
Reduction in losses after load shifting (e)		1.21 kW
Savings = $e \times$ units consumed in 24 hrs × 300 days a year		8712 units
Energy savings = Savings × unit rate (INR.7/per unit)		INR. 60 984 per year

The above equation can be simplified by utilizing two line voltages and currents. Simplified equation is shown as:

$$T_{ag} = \frac{\sqrt{3}P}{6} \left\{ (i_a - i_b) \cdot \int [v_{ca} + R_s(2i_a + i_b)] dt + (2i_a + i_b) \cdot \int [v_{ab} - R_s(i_a - i_b)] dt \right\}. \quad (14)$$

The input 3 phase power to IM using two wattmeter method can be obtained using the following equation

$$P_{input} = -v_{ca}(i_a + i_b) - v_{ab}i_b \quad (15)$$

where:  $v_{ab}$  and  $v_{ca}$  are the line voltages and  $i_a$ ,  $i_b$ , and  $i_c$  are the phase currents.

## 6.2. IM efficiency estimation

In air-gap torque method, the air-gap torque is the starting point of subtraction. Thus the output shaft torque is the air gap torque minus the friction & windage loss and the rotor stray load

loss.

$$T_{shaft} = T_{ag} - \frac{W_{fw}}{\omega_r} - \frac{W_{LLr}}{\omega_r}. \quad (16)$$

The output shaft power can be obtained from the product of the shaft speed and the shaft torque.

Thus, efficiency of in-service IM,  $\eta$  is

$$\eta = \frac{P_{output}}{P_{input}} = \frac{T_{shaft} \cdot \omega_r}{P_{output}} = \frac{T_{ag} \cdot \omega_r - W_{fw} - W_{LLr}}{P_{output}} \quad (17)$$

where,

$W_{LLr}$  (Stray load losses)

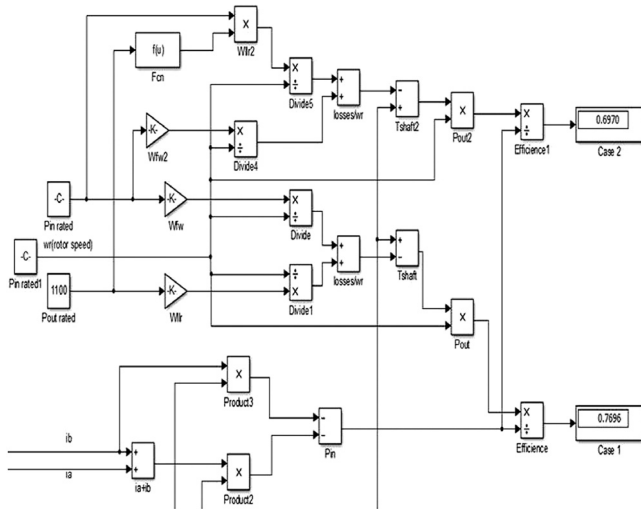
$W_{fw}$  (Friction and windage losses) &  $\omega_r$  (Rotor speed).

## 6.3. Estimation of IM losses

Typically, the no-load losses are obtained by conducting a no load test, which is highly intrusive. So, friction and windage loss and stray load loss are empirically evaluated according to statistical

**Table 8**  
Comparison of estimated & measured efficiencies.

% Load	Torque (N m)		Estimated efficiency (%)		Measured efficiency (%)	
	Estimated	Measured	IEEE Std. 112	IEC 60034-2-1 Std.	IEEE Std. 112	IEC 60034-2-1 Std.
79.4	4.4	4.5	70.5	64.8	70.9	66.5
96.1	7.5	7.53	76.9	69.7	74.8	71.0



**Fig. 1.** MATLAB/SIMULINK structure for efficiency estimation (single column fitting image).

methods. As per IEEE Std. 112,  $W_{fw}$  is 1.2% of rated output power. According to IEC 60034-2-1Std.,  $W_{fw}$  is 3.5% of rated input power.

The stray load losses are yet another component of the NIAGT which needs to be calculated empirically. As per IEEE 112 Std,  $W_{LLr}$  is 1.8% of rated output power and according to IEC Std, the general equation to find  $W_{LLr}$  is based on the predefined curve for the range of IMs tested in the range of (1 kW < P2 < 10 000 kW).  $W_{LLr}$  is obtained as:

$$W_{LLr} = P1 * [0.025 - 0.005 \log_{10} (P2 \div 1 \text{ kw})] \quad (18)$$

where: P1 is the input power and P2 is the rated mechanical power.

**Fig. 1** presents estimating of in-situ IM's efficiency using functional blocks on MATLAB/SIMULINK platform.

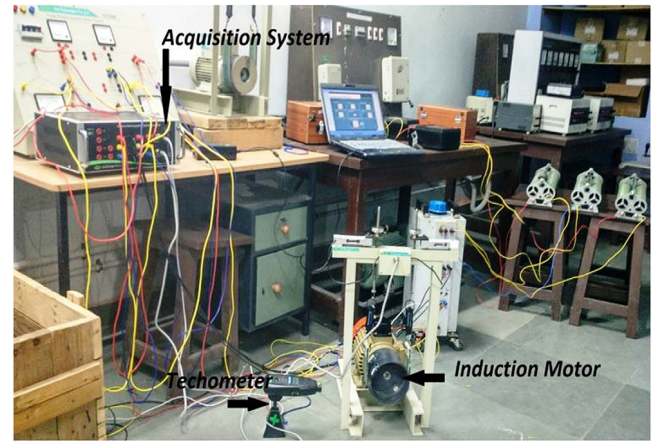
For experimental validation, lab set-up is done as shown in **Fig. 2** where IM is operating on 415 V AC. Line currents, line voltages, speed, torque are measured using NI multifunctional data acquisition system for efficiency estimation calculations. A 3 phase 1.1 kW IM is considered whose nameplate data is depicted in **Appendix A**. Per phase stator resistance of 2.175  $\Omega$  is measured using power quality analyzer.

IM is tested for two load conditions i.e. 79.4% and 96.1% respectively. For 79.4% loading, line current is 1.94 amperes while running at 1370 rpm and for 96.1% loading, line current is 2.35 amperes at speed of 1328 rpm.

In both conditions, estimated and measured efficiencies are calculated considering empirical values of losses according to IEEE standard 112 and IEC 60034-2-1 standard. A comparison of estimated & measured efficiencies is made and presented in **Table 8** as shown:

It has been found that using IEC 60034-2-1 standard, measured and estimated efficiency of IM is close to nameplate value of efficiency. The estimated efficiency is close to measured efficiency (within 2%–5% error). IEEE standard 112 shows exaggerated values of efficiency because it is based on assumption of rated output power. IEEE std. 112 neglects slip changes with load.

This method of efficiency estimation of in-situ IM using IEC 60034-2-1 standard is highly advantageous since it does not need



**Fig. 2.** Lab set-up for efficiency estimation (single column fitting image).

any assumption. Efficiency of IM can be easily obtained from terminal voltages, currents and nameplate data. This approach does not need open circuit and short circuit tests for evaluating the IM parameters.

## 7. Conclusions

The role of energy efficient Induction Machines (IMs) is presented with respect to savings in power consumption. The proposed suggestions on implementation will result in loss reduction and substantial increase in the savings. Energy management is done to exploit the capabilities of installed electrical equipment to the best possible level.

In this paper, field work and data collection is taken up for Jindal Steel Rolling Mill (JSRM), Hisar, Haryana, India. Replacement of standard and substandard IMs by energy efficient IMs and DFIMs of suitable ratings help in tremendous savings in energy. After payback periods, reduction in monthly energy bills can be obtained. Rescheduling of loads on transformers helps in loss reduction and thereby increases insulation life. The capital cost of energy efficient IM is approximately 22% higher as compared to conventional IM but payback analysis carried out indicates that it can be recovered within two to six months of time frame.

Time is not too far when Indian industries will be running on energy efficient machinery with proper energy management for variable speed applications with use in steel rolling mills being the one.

This paper has proposed a non-intrusive air-gap torque method for efficiency estimation on in-service IM. Empirical values of friction & windage and stray load losses are considered as per IEC 60034-2-1 Std. because empirical values depend upon input terminal electrical quantities. The effectiveness of the proposed approach has been experimentally validated by testing IM with different loading. The estimated efficiency is close to measured efficiency (within 2%–5% error). The main merit of this method is that it is based on motor terminal quantities and nameplate data.

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## Appendix

Make	Kirloskar
Rated output power	1.1 kW
Phase	3
Rated speed (rpm)	1400
Rated line voltage (volts)	415 ± 10%
Full load current (amps)	2.45
Nominal power factor	0.81
Nominal efficiency	77

## References

- Andreas, J.C., 2002. *Energy Efficient Electric Motors. Selection & Application*, second ed. Marcel Dekker Inc.
- Bose, Bimal K., 2000. Energy environment & advances in power electronics. *IEEE Trans. Power Electron.* 15 (4), 688–701.
- Habetler, G., Harley, R., 2006. A survey of efficiency estimation methods for in-service induction motor. *IEEE Trans. Ind. Appl.* 42 (4), 924–933.
2004. IEEE Standard test procedure for polyphase induction motors and generators. *IEEE Stand.* 112.
2014. Personal communication with site engineer at Jindal steel rolling mill for plant information.
- Phumphak, T., Chat-uthai, C., 2005. Energy management program for use of induction motors based on efficiency prediction (TENCON). In: *IEEE Region-10 Conference*, pp. 1–6.
- Yong, L., Jiang, T., Lu, L., 2009. Energy measurement audit & its implementation in coal fired power plant. In: *International Conference on Management & Service Science*, pp. 1–4.