Efficient use of an Induction Motor

P.N. SALARIA,
Design Officer,
Crompton Greaves Ltd.,
Worli, Mumbai

Abstract

The paper explains the principle of Delta-Star Scheme for efficient use of a squirrel cage induction motor. It is suggested that a delta connected motor should be run in star if it is operating at less than half of It's rated output. To assess the performance in star connection a method is given to draw the performance curves from corresponding curves with Delta connection. Generalised performance curves are given for 2 and 4 pole motors. These curves can be used for any motor. By measuring current and speed and using the generalised curves a procedure is given for calculation of energy and cost saving. Cost benefit of using a solid state power saver is also worked out for comparison with proposed scheme. The scheme is exemplified with the help of a case study.

1. Nomenclature

CDF - Cyclic Duty Factor (It is the ratio of time duration at given duty point to cycle time).
COST - Total cost of an energy saving Scheme.
DEP - % Depreciation rate.
EFFI - Efficiency.
EFFI$_1$ - Operating efficiency of the motor at given per unit output (PUO).
EFFI$_2$ - Improved efficiency at the same PUO with the help of energy saving scheme.
EXP - Burden in Rs. due to interest and depreciation on cost.
H - Working hours per day.
I - Load current in Amps.
INTR - % interest rate.
KW - Rated output in kW.
N - No.of working days in a year.
OP - Output.
PUO - Per Unit Output. It is the ratio of given output to rated output.
RPM - Speed in Revolution per minute.
SAVING - Saving obtained in Rs. because of energy saving scheme.
T - Time duration in seconds for given duty point, turns per coil.
TARRIF - Cost of electricity in Rs. per unit.

V - Voltage/ phase.
a - Area per turn in mm^2
i - Ration of given current to full load current.
pf - Power factor.

Suffixes

1,2 …..	- Running numbers for different load position in a given duty cycle.
(n,1)	- A quantity determined for nth duty point with the help of current curves.
(n,2)	- A quantity determined for nth duty point with the help of RPM curve.
e	- Existing design.
fl	- Full load.
n1	- No. load.
p	- Proposed design.

2. Introduction

A large percentage of electrical energy is utilized in running motors in industries. A wide variety of motors are used depending upon the application. Amongst all three phase squirrel cage induction motors are most popular due to their simplicity in construction and reliability in operation. The capacity range of motors is from a few watts to megawatts.

Parameters like load duty cycle, variations in supply, ambient conditions, etc. are considered while selecting the squirrel cage induction motors. When motors above 15/20 kW are selected all the parameters can be looked into in detail and a proper rating can be arrived at. Such motors operate at their optimum efficiency and pf. For motors below 10/15 kW there are diverse applications. The parameters mentioned earlier are also not well defined. To account for all these uncertainties as a practice, over rated motors are used. These motors work at lower efficiency and pf than a properly selected one. The poor efficiency and pf make both, the user and supplier of electrical energy to incur more losses. Therefore, it is necessary to have a scheme which would bring back the efficiency and pf to their optimum values.

An electronic power saver checks the operating pf and corrects (normally reduces) the voltage to the motor so as to bring the pf back to a predetermined value. Such voltage correction also improves the efficiency of the motor but not to the optimum. The harmonic rich supply from the electronic power saver will increase the losses which will further deviate the efficiency from it’s optimum value. The cost benefit worked out for use of power saver on 3.7 kW and 7.5 kW 4-Pole motors in Annexure –I show that the saving in tariff cannot offset the interest and depreciation burden of investment in power saver. Hence while examining any scheme for optimizing working efficiency; it is necessary to also examine cost benefit before making a decision to implement any scheme.

In the article principle a Delta-Star changeover scheme is discussed. The scheme suggests if a motor is running at less than half of rated output, it should be re-connected to star. As such when a motors is re-connected to star from delta, it’s rated output drops to 1/3 of delta configuration keeping declared performance unchanged. A method is given for plotting of performance curves for star from delta. A demarking line drawn at intersection of star and delta efficiency curves is called a changeover line. With reference to the changeover line star and delta zones are defined. In Star zone efficiency and pf of a motor are better for star connection then delta. Whereas in delta zone the efficiency is only better throughout compared to star. The line is at about 50% of rated output. As the scheme needs only a delta star changeover, the device required for this will be more or less equivalent to a star delta starter. The cost of such starter is several times lower than the electronic power saver. Therefore, the interest and depreciation burden because of investment in changeover device would be much less giving a possibility of saving.

In order to facilitate the implementation of the scheme, generalised performance curves are prepared for 2 and 4 pole motors. The curves are useful for:

1. Determination of load on motor by measuring current and RPM.
2. Identification of its location in either Star or Delta Zone.
3. Arriving at approx, efficiency and pf for both the connections so that energy and cost saving can be worked out.

Finally, a case study of a hydraulic power pack shows that for broaching of stator packs upto IEC 90 frame the motor can run in star throughout. Only a star delta switch is to be provided so that the motor is star connected wherever stator packs upto IEC 90 frame are broached. The cost of the switch is so low that for calculation of cost benefit there is no need of considering interest and depreciation burden on the investment. The investment itself can be paid off in a few months time.

3. The Scheme

In the following subsection the working principle of the scheme is developed right from understanding the effects of changeover from Delta to Star connection on a motor.

3.1 Effects of Delta Star Change Over

For a given geometry and linearity of magnetic material assumed, it can be shown that if a motor is redesigned with the help of the following equations

$$T_p = T_e \text{ X } \frac{V_p}{V_e} \sqrt{\frac{KW_e}{KW_p}} \quad \text{.....(1)}$$

$$a_e \text{ X } T_e = a_p \text{ X } T_p \quad \text{.........(2)}$$

the declared performance of both the designs will remain the same. It means efficiency, pf, % starting current, % breakway, pull-up and break down torques and full load RPM would remain the same for both the kWs.

When a normally delta connected motor is reconnected in star then.

$T_p = T_e$ and $V_p = V_e / \sqrt{3}$

substituting the value in eq (1)

$$KW_p = \frac{KW_e}{3} \quad \text{.........(3)}$$

Thus changeover from delta to star connection will result into the motor’s rated power dropping to one third and the performance unaltered.

3.2 Performance Curves at Delta Connection

The full lines in Fig. 1 show typical performance curves for a Delta connected 3.7 kW (5 HP) 4-Pole motor. Per unit output (PUO) is on the abscissa per unit current, efficiency, pf and RPM are on ordinate.

3.3 Performance Curves at Star Connection

As explained in 3.1, changeover to star connection from delta would mean the same declare performance at 1/3 of delta output. Therefore making curves for a star connection is a simple procedure of shifting efficiency, pf and RPM points to 1/3 of delta PUO. For example, from the efficiency plot of delta connection in fig. 1, at 0.3, 0.6, 0.9 1.2 and 1.5 PUO the efficiencies are 71%, 80.5%, 82%, 81% and 78% respectively. At star connection the same efficiencies i.e. 71%, 80.5%, 82%, 81% and 78% are to be plotted at 0.1, 0.2, 0.3, 0.4 and 0.5 PUO respectively. RPM and pf could also be plotted in a similar way. Referring efficiency and pf from the performance curves at respective PUO the current can be found with the help of following equation:

$$I = \frac{\text{PUO x KW}}{\text{EFFI x pf x V x } \sqrt{3}} \quad \text{..... (4)}$$

Thus the performance curves of a normally delta connected motor under star connection is fully available and are shown by chained line in Fig. 1.

3.4 Changeover Line and Labling of Zones

A vertical line drawn at the point of intersection of dotted and chained efficiency curves is the changeover line. The space between the no-load to changeover line is labled as star zone and the space between changeover line and full load point as delta zone. Thus we have a clear demarkation of the ‘STAR ZONE’ and the ‘DELTA ZONE’.

3.5 Operational Logic

With loads in star zone, the values of efficiency and power factor for a motor are higher with star connection than delta connection. Similarly for loads in delta zone, efficiency and pf are higher with delta connection.

RPM and current are the easily measurable quantities for a motor. The same can be measured and super posed in Fig. 1 on delta curves (full line) presuming the motor is with delta connection. The projection of the points of intersection of actual current and RPM with respective delta curves on abscissa will give PUO at given duty point. The position of PUO will identify the zone. The intercept of projection lines with all the other curves will read respective quantities like efficiency and pf.

3.6 Calculation for Saving

The possible saving with the help of the Delta Star changeover scheme for a 3.7 kW motor is worked out and given in Table 1.

TABLE – 1

Saving V/S PUO With The Proposed Scheme For A 3.7 Kw (5hp) 4-Pole Motor

Sr. No.	PUO	EFFI1%	EFFI2%	SAVING Rs Annum
1.	0.1	57.0	75.5	802
2.	0.2	69.7	83.0	857
3.	0.3	75.7	83.0	650
4.	0.4	79.7	82.5	318
5.	0.5	82.0	80.0	-284

Note:

The SAVING as shown in Table-1 (with the proposed scheme) when compared with that of Table-2 of Annexure I (with electronic power saver) it reveals that the SAVINGS in the proposed scheme are comparable with those most optimistic SAVINGS with the help of electronic Power Saver. For the sake of proper comparison the assumptions made and equations used are identical for both the SAVING calculations. Please refer Annexure-I for details.

4. Auditing Motor Application

To implement the scheme it is necessary to identify the zone in which the motor operates. Hence curves similar to Fig. 1 are required for the motor under examination. These curves may or may not be available. Therefore generalized curves are prepared for 4 and 2-pole motors as shown in Fig. 2 and Fig. 3 respectively. A large number of motors upto 10 kW were considered for each polarity for plotting of the curves. The lines in Fig. 1 have become bands in Fig. 2 and Fig. 3. The bands with vertical line are for delta connection and with horizontal lines are for star connection. Due to the bands the changeover line has become a changeover zone. It is shown with hatched lines.

4.1 Data

Following data is required to identify the efficient operating zone of the motor under examination, normally connected in data.

(a) Full load current (If_1) as given on the nameplate.
(b) Full load RPM ($RPMf_1$) as indicated on nameplate.
(c) No-load current (In_1) of the motor. It can be measured by decoupling the motor from load.
(d) Current on load (I_1). It can be measured.
(e) Speed on load in RPM (RPM_1). It can be measured.
(f) Time duration of the above loading.

In case if there is more than one duty point for a given cycle then (d), (e) and (f) are to be repeated at all the points.

4.2 Procedure

Following steps are to be followed for identification of efficient/ operating zone. Please see fig. 2 also.

(i) To determine Ratio $i_{n1} = I_{n1}/I_{f1}$
(ii) Locate i_{n1} point in per unit current section at 0.0 PUO.
(iii) Let the full load point $i_{f1} = 1.0$ be plotted in the same section at 1.0 PUO.
(iv) Join both the points approximately following the curvature pattern of the band making the line $i_{n1} – i_{f1}$. This curve gives the actual per unit current curve for given motor.
(v) Determine the Ratio $i_1 = I_1/I_{f1}$
(vi) Draw a horizontal line at i_1 in the per unit current section and let it intercept i_{f1} - i_{n1} line at i_1.
(vii) Project the point down to intersect PUO axis. Let the point be called as $OP_{(1,1)}$.
(viii) Locate the RPM_{f1} at 1.0 PUO in the RPM section. Let the point be RPM_{f1}
(ix) Let 1500 RPM point be RPM_{n1}.
(x) Join the RPM_{f1} and RPM_{n1} following the curvature pattern of the band, making the RPM_{f1} – RPM_{n1} to yield RPM V/s. PUO curve for given motor.
(xi) Locate the RPM_1 point on the 0.0 PUO in RPM section and draw a horizontal line intersecting the RPM_{f1} – RPM_{n1} line at RPM_1.
(xii) Project the point down to intersect PUO axis at OP $_{(1,2)}$.
(xiii) The point $OP_{(1,1)}$ and $OP_{(1,2)}$ may not co-inside. The actual output of the motor is in between the band of $OP_{(1,1)}$ an $OP_{(1,2)}$.
(xiv) If the lines $OP_{(1,2)}$ and $OP_{(1,2)}$ are in Star Zone then the winding should be reconnected in star to get the energy saving, otherwise it can continue running in delta.

5. A Case Study

A 3.7 kW (5 HP) 4-Pole motor is driving a hydraulic power pack which operates a hydraulic press. The press is used for broaching internal diameters of stator packs upto IEC 90 frame.

5.1 Identification of Zone

Following are the operational details of the motor. These are as per (a) to (f) of section 4.1.

(a) $I_{f1} = 7.94$
(b) RPM_{f1} = 1430 RPM

(c) I_{n1} = 3.1A, i_{n1} = 3.1/7.9 = 0.39

(d) I_1 = 4.0A, i_1 = 4.0/7.9 = 0.51
(Broaching operation in progress)
I_2 = 3.4A, i2 = 3.4/7.9 = 0.43
(The broaching tool returns)
I_3 = 3.2A, i3 = 3.2/7.9 = 0.41
(Job changing and power pack idles)

(e) RPM_1 = Not available
RPM_2 = Not available
RPM_3 = Not available

(f) T_1 = 4 Sec.
T_2 = 3 Sec.
T_3 = 5 Sec.

Fig. 2 and Steps form (i) to (vii) from sec. 4.2 are followed. Figure 4 identifies the operating zone. As all the three points $OP_{(1,1)}$. $OP_{(2,1)}$ and $OP_{(3,1)}$ are in Star zone. There is no need of confirming the locations with the help of RPM. The PUO is as follows:

$OP_{(1,1)}$ = 0.35 PUO
$OP_{(2,1)}$ = 0.22 PUO
$OP_{(3,1)}$ = 0.13 PUO

5.2 Conclusions and Recommendation

5.2.1 As all the three operating points are in the Star Zone, the motor can have throughout Star connection when 90 frame stators are broached.

5.2.2 All the frames lower than 90 would be in need of less power. Therefore the motor can continue in Star for lower frames also. Hence for frame 90 and below, with the help of a star delta changeover switch the motor can be connected as desired.

5.3 Cost Benefit Analysis

5.3.1 The cost of Star-Delta Switch would be Rs. 375/-.

5.3.2 Table-2 gives the details of energy and money saving. The $EFFI_1$ and $EFFI_2$ are taken from the bottom lines of Delta and Star bands respectively. The saving is calculated as per method given in Annex. I.H, N and TARIFF are taken as 16 hours/day, 300 days/annum and Rs. 1.05/unit respectively. There is a saving of 1015 unit and 16% saving in tariff and energy.

TABLE-2: Cost Benefit Calculation For Power Pack Drive

Sr. No	Operation	Output		$EFFI_1$ %	$EFFI_2$ %	Duration Sec.	CDF	Saving of Energy Units	Saving in Rs./ Annum
		PUO	KW						
1.	Broaching	0.35	1.30	73.0	81.0	5	0.42	354	372
2.	Tool Returns	0.22	0.81	65.0	80.0	3	0.25	280	294
3.	Job Changing and Power	0.13	0.48	54.0	74.0	4	0.33	381	400
				TOTAL:			1.00	1015	1066

Annexure-I

Cost Benefit Calculation

1. Procedure For Cost Benefit Calculation

A procedure for cost benefit calculation is derived on following assumption:

1.1 The money is borrowed for investing in energy saving scheme.
1.2 The interest and the depreciation per annum on the invested money are treated as expense.

$$EXP = \frac{COST}{100} \times (INTR + DEP) \qquad (1)$$

$$\text{SAVING} = 100 \times \frac{\text{EFFI}_2 - \text{EFFI}_1}{\text{EFFI}_2 \times \text{EFFI}_1} \times \text{PUO} \times \text{KW} \times \text{H} \times \text{N} \times \text{TAR FF} \times \text{CDF}$$

It can be stated that if the SAVING is more than EXP then it is economical to use the energy saving scheme.

2. Const Benefit Calculation With An Electronic Power Saver

The most widely discussed method of saving the electrical energy is the use of Electronic Power Savers. It works at a constant pf i.e. the phase angle between supply voltage and load current is kept constant at all the loads. It checks the phase angle and corrects (normally reduces) the voltage so as to achieve the predetermined phase angle or pf. Because of the constant pf operation the efficiency improves but it does not reach the level of highest efficiency which is obtainable from the given motor because:

(a) The constant pf operation does not mean a constant efficiency operation at it's best value.
(b) To control the supply volts the phase controlled firing is implemented. The phase controlled firing leads to harmonic rich supply to the motor. It increases the losses, reducing the efficiency.

3.7 kW (5 HP), 5.5 kW (7.5 HP) and 7.5 kW (10 HP) 4-Pole Motors are some of the most popular ratings used for various applications. The cost benefit is worked out for 3.7 kW and 7.5 kW motors alongwith the power saver. For calculation purposes the:

INTR = 18% &
DEP = 10.6% …(3)

2.1 7.5 kW 4-Pole Squirrel Cage Induction Motor

The power saver would cost the user about Rs. 8,000/-. The expense per year, from eqns. (1) and (3).

$$\text{EXP} = \frac{8000}{100} \times (18.0 + 10.6)$$

= 2.288 Rs./annum … (4)

From the motor performance curve, for different PUO corresponding EFFI_1 are taken. Though it is not at all possible to achieve the highest efficiency 87% for the motor, still EFFI_2 is taken as 87% for the first iteration in calculation. KW, H, N, CDF and TARIFF are taken as 7.5 kW, 16 hours per day, 300 days per annum 1.0 and Rs. 1.05 respectively. Table-1 gives the EFFI_1 and SAVING details for loads from 0.1 PUO to 0.6 PUO. The calculation beyond 0.6 PUO not done because for all higher loads saving would be negligible.

TABLE-1: Saving V/S Puo For A 7.5 Kw 4-Pole (10 Hp) Motor Using Electronic Power Saver

Sr No.	PUO	EFFI_1%	SAVING (Rs./ Annum)
1.	0.1	62.5	1703
2.	0.2	75.5	1390
3.	0.3	81.0	966
4.	0.4	84.0	620
5.	0.5	86.0	253
6.	0.6	86.5	151

2.2 3.7 Kw 4-Pole Squirrel Cage Induction Motor

A 3.7 kW electronic Power Saver is expected to have COST = Rs. 6,000/- Referring to eqns (1) and (3).
EXP = 1,716/- Rs./Annum (5)

Following the same procedure and parameters as (2.1) except for kW = 3.7 and EFFI2 = 83%, Table -2 gives the details of $EFFI_1$ and SAVING upto 0.6 PUO using equation (2).

Table-2: Saving V/S Puo For A 3.7 Kw (5 Hp) 4-Pole Motor Using Electronic Power Saver

Sr. No.	PUO	$EFFI_1$%	SAVING (Rs. /Annum)
1.	0.1	57.0	1025
2.	0.2	69.7	857
3.	0.3	75.7	650
4.	0.4	79.5	396
5.	0.5	82.0	137
6.	0.6	82.5	82

The SAVING worked out in Section (2.1) and (2.2) are for operation of at given PUO throughout. Inspite the SAVING is less than respective EXP. Hence it can be concluded that the power saver cannot give any cost saving for the given TARIFF, INTR and DEP.

Reference:

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