performance analysis of pole amplitude modulated
three phase squirrel-cage induction motor

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Abstract— There are various methods of speed control of
induction motors are available and also present are innumerable
applications. But not all the methods are suitable for all
applications. The two main methods of speed control using a
Robust, Reliable Squirrel-cage induction motor are:
1. Variable Frequency drives &
2. Variation of number of poles.

There are many occasions where only two distinct speeds are
required with almost no additional cost to that of the motor like
pump , fan and windmill generator applications. In such
applications VFD drives are not viable economically especially
for large rating of induction motors. However Speed control by
simple pole changing best suit these applications. Speed control
using pole-changing for 2:1 is an old concept (consequent pole
method) and is simple. For ratios other than 2:1, the design is
complicated.

This project is aimed at developing an 8/6/4 pole-changing
induction motor not by mere coil reconnections. The technique
used for this is Sinusoidal Premodulation (PAM) Technique.
By this method we can achieve the desired discrete speeds /
rating using single motor with simple pole change drive
mechanism thus reducing the capital cost of investment on VFD
drives and energy saving on operating cost of the complete
system.

Index Terms— Pole Amplitude Modulation (PAM),
Squirrel-cage Induction motor (SQIM), High speed (HS), Low
speed (LS)

I. INTRODUCTION

There are many occasions where variable speed a.c.
induction drives are required and these drives can be
grouped as either discrete speed changing devices or
continuously speed changing power drive. If discrete
speed-changing device is required the motor should be one
such that it runs continuously at one or two desired speeds and
the induction motor of squirrel cage type is undoubtedly
favored. If continuously variable speed is absolutely required,
one must go necessarily for complicated arrangement with
attendant maintenance problems.

The most important need for speed-changing occurs in
processes like driving drills and in certain other applications
where the cutting speed need to be changed with a change
of the material being handled. An equally important need for
speed change is to save energy.

The objective of this work is to design a pole changing
winding for a single winding 3-phase 3-speed SQIM with
a pole ratio 8/6/4 using PAM technique and to analyse the
performance parameter. Generally, this pole changing can be
done by two different methods. One is the normal 8/6/4 pole
changing by constructing independent windings for each pole
in the same stator (top/ bottom / front / rear of the stator core)
needing more space in the stator and thus more loss, less
efficient and very expensive.

Other is the Pole Amplitude Modulation (PAM)
technique through which the windings are held in two sections
per phase and reversing the current direction in one section of
each phase with respect to the other. This technique applies
the logic of amplitude-modulation to the space-distribution of
the windings of an electrical machine. The whole process of
design is based on trigonometrical equations. To simulate the
design of Speed cum rating change electronic drive
mechanism to control the speed/rating of 3-speed SQIM and
to obtain speed and acceleration curves.

Ever since the invention of cage rotor induction machines,
there have been innumerable attempts to make it a variable
speed one. The investigators followed two distinct routes: One
approach has been to achieve a continuously variable
speed control, and the other approach aims at discrete speed
control. Dahlander’s well known pole-changing motor has
been in use since 1897 for 1:2 pole ratio. In contrast, the
speed changing motors devised by Rawcliffe use normal coils
and his work relates to the application of Logic known as:

Pole Amplitude Modulation with specific reference to three
phase machines requiring 12 terminals only in many cases.

II. BRIEF REVIEW OF SPEED CONTROL

An important basis of speed variation of induction motors is
given by the equation:

\[
\text{Synchronous Speed in r.p.s., } n=2f/p
\]

Where f is the frequency in Hz, and p is the number of poles.
Thus we have the following methods:

1. Frequency Variation:
   May be used for both Squirrel-cage and wound rotor
   induction motors.
2. Variation of number of poles:
   A. Using multiple windings
   B. Using “Consequent–Pole” technique
   C. By Pole Amplitude Modulation

These methods are normally restricted to be used with
Squirrel-cage type, since for steady production of
electromagnetic torque change of stator poles must be
accompanied with change of rotor poles, and whereas a
Squirrel-cage rotor adjusts on the number of poles of the
stator in which it is inserted, a wound rotor has the number of
poles for which it is wound.
3. Variation of supply voltage:
   For both Squirrel-cage and wound rotor types
4. Variation of motor parameters:
   A. Rotor Resistance – For wound rotor type
   B. Stator Resistance – For both types
   C. Stator and Rotor Reactance – For wound rotor type
5. Control of Rotor slip-power: For wound rotor motor

**A. VARIATION OF NUMBER OF POLES**

Since number of poles can only be changed in even numbers, speed control by this method is stepped. For example, by changing number of poles of a 50Hz motor speeds such as 3000, 1500, 1000, 750 r.p.m. etc., could be obtained. This method is effectively applicable to squirrel cage type only as for steady torque production, both stator and rotor number of poles should be equal, and a change in the number of stator poles must be accomplished with a change in the number of rotor poles.

**Pole changing can be effected to by any of the following methods.**

1. **USING MULTIPLE WINDINGS**
   The stator has separate windings each wound for different number of poles. In the two separate windings case, normally six terminals are brought out, three for high speed and three for low speed winding. Change over from one speed to another is made by a TPDT switch. To avoid circulating current and resulting overheating, the idle winding should be kept open-circuited.

2. **USING CONSEQUENT POLE TECHNIQUE**
   The most popular and practical single-winding arrangement for 2:1 speed ratio was the Dahlander’s Pole changing motor using the consequent pole technique. In this method the two speeds are achieved by switching winding connections in such a way that the direction of current is reversed in one half of the coils. The 2:1 speed ratio is accomplished by connecting all the stator coils in one phase in series as shown in Fig.1a and for the other speed coils are connected in series parallel as shown in Fig.1 As shown in Fig.1a, successive south poles are formed. As a consequence of this consequent North poles are induced in the space between these coils (i.e.8-pole) and to obtain symmetrical MMF pattern the coils are separated by an amount equal to a pole pitch. If the current in every alternate coil is reversed as shown in Fig.1b then within the coils the polarities are successively north and South Pole and therefore the number of poles is halved (i.e.4-pole).

Thus if all the three phases are arranged in the same pattern and connected in a two parallel series circuit in each phase, it results in changing the number of poles formed. However the above consequent pole method is limited to 2:1 speed ratio only. (Ex.3000/1500, 1500/750, 1000/500 RPM, etc.).
connected in series delta for high speed and parallel star low speed. Therefore \( T_1/T_2 = N_2^2/N_1^2 \).

For example the torque that can be delivered at 750rpm connection would be twice that at 1500rpm connection.

Dual speed motors of this type are used for lathes and other machine tools that often require a constant rate of power.

(c) Variable torque motors with rated torque directly proportional to speed at either high or low speed. These motors are connected in parallel star for high speed and series star for low speed. Therefore \( T_1/T_2 = N_1^2/N_2^2 \) and 

\[
\text{Power}_1/\text{Power}_2 = N_2^2/N_1^2.
\]

For example torque developed at a 750rpm connection would be half that at the 1500rpm connection.

Dual speed motors of this type are used for fans, centrifugal pumps or other loads with similar characteristics. Since the power rating for fans directly proportional to \( N^3 \), lower speed connection requires significantly less power.

III. POLE AMPLITUDE MODULATION TECHNIQUE

The whole process of design is based on trigonometrical equations. The production of these windings might be described as the embodiment of sets of such equations in suitable coppermorngy and ironmongry [5].

When each phase winding is modulated by the same sinusoidal modulating wave, then total modulated MMF is given by:

\[
N_1 N_2 = \text{Nm}_1 Nm_2 = \text{A SinPm}\theta
\]

the resultant is \( N_1 + N_2 + N_3 \),

where \( N_1 = A/2[\cos(P-Pm)\theta - \cos(P+Pm)\theta] \) \( (1) \)

\[
N_2 = A/2[\cos [(P-Pm)\theta - 2\pi/3]] - \cos [(P+Pm)\theta - 2\pi/3] \] \( (2) \)

\[
N_3 = A/2[\cos [(P-Pm)\theta - 4\pi/3]] - \cos [(P+Pm)\theta - 4\pi/3] \] \( (3) \)

\[
\theta = \text{Amplitude and } P = \text{Pole pairs}
\]

In the above equations the first terms together represents (P-Pm) Pole pairs; the second terms together represents the parasitic rotating field of (P+Pm)pole pairs. The parasitic rotating field of (P+Pm) pole pairs can be easily eliminated by chording. Thus the rotating field corresponds to either (P-Pm) pole pairs or (P+Pm) pole pairs by keeping the angle between its phase axes in multiple of \( 2\pi \).

By this technique the windings are held in two sections per phase and reversing the current in one section of each phase with respect to the other and these changes of connections are equivalent to the multiplication of the original mmf wave by the modulating wave. In general, the reversal of half a phase-winding with respect to the rest basically corresponds to total modulation by a wave with an odd number of pole-pairs: that is, to odd cycle modulation.

**Total modulation to get three speeds**

In 2-speed PAM windings the connections of the three phase windings were 2-parallel-star / series-delta.

For 3-speed PAM windings, three speeds are made possible by using 4-parallel-star/ 2-parallel-star/ series delta switching, using the circuit shown in Fig.2. 

Fig. 2 Circuit diagram for 3 speed pole-amplitude modulation

<table>
<thead>
<tr>
<th>Speed I</th>
<th>Speed II</th>
<th>Speed III</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4-Parallel-star)</td>
<td>(2-Parallel-star)</td>
<td>(Series-delta)</td>
</tr>
<tr>
<td>Join ( a_1 ), ( b_1 ), ( c_1 )</td>
<td>Join ( a_2 ), ( a_4 ), ( \bar{b}_1 ), ( \bar{b}_2 ), ( \bar{b}_4 ), ( c_4 )</td>
<td>Isolate ( a_2 ), ( a_4 ), ( \bar{b}_1 ), ( \bar{b}_2 ), ( \bar{b}_4 ), ( c_4 )</td>
</tr>
<tr>
<td>Join ( a_2 ), ( a_4 ), ( \bar{b}_1 ), ( \bar{b}_2 ), ( \bar{b}_4 ), ( c_4 )</td>
<td>Supply ( a_2 ), ( a_4 ), ( \bar{b}_1 ), ( \bar{b}_2 ), ( \bar{b}_4 ), ( c_4 )</td>
<td>Supply ( a_1 ), ( b_1 ), ( c_1 )</td>
</tr>
</tbody>
</table>

The terminals \( a_1, a_3, b_1, b_3, c_1, c_3 \) are the six terminals of a 2-speed PAM winding. The other six terminals \( a_2, a_4; b_2, b_4; c_2, c_4 \) enable the third speed to be obtained, in 4-parallel-star connection.

The 2-speed element in this winding does not differ in principle from the established forms of 2-speed PAM windings. But the order in which the coils in each half phase-winding are connected may be dictated by the requirement to use 4-parallel switching for the third speed. In addition, the actual coil-grouping in the 2-speed element may be more complicated than would be required for a 2-speed winding. However, the principles involved are unaffected. The switching sequence is given in Fig.2. Assuming that the 3-phase power is given by a separate 3-pole main switch for each speed, the additional switching to obtain three speeds, is achieved by using seven auxiliary (electronic) switches which can on and off when dead. This is a small price to pay for the possibility of obtaining three speeds from one winding.

In general, the reversal of half a phase-winding with respect to the rest basically corresponds to total modulation by a wave with an odd number of pole pairs, which is to odd-cycle modulation. All close-ratio PAM windings are of this type. Division of a phase-winding into four sections, and connection in four parallel paths in the way shown in Fig.1, must correspond to total modulation by a wave of an even number of pole-pairs, since each half of the phase-winding is necessarily modulated by an integral number of pole-pairs: usually by an odd number. Connection in four parallel paths is therefore inherently an embodiment of even-cycle modulation. The two halves of the phase winding, to which even-cycle modulation is to be applied, may themselves be connected either in series or in parallel; and the two halves are
simultaneously modulated in the same way, to give even-cycle modulation. Even-cycle modulation may therefore be obtained by switching between a 4-parallel circuit and either a series circuit or a 2-parallel circuit. The two alternatives are shown in Figs 3a and 3b, respectively. As shown in Fig.3 the phase-winding is divided into four sections (marked I, II, III & IV) and that the two forms of 4-parallel circuit are identical. The coils which from each of the four sections are distributed around all or most of the stator perimeter, but all the sections have comparable patterns as they are to be connected in parallel. The disposition of the sections around the stator perimeter, taking each section as a unit, is the same as the sequence in which the sections are connected (I, II, III, IV) for the form of modulation shown at a in Fig.3. For the other form of modulation however, as shown at b, the disposition of the sections around the perimeter is in the sequence I, II, IV, III. For this reason, reversal of the two consecutive sections II and III, as at b, thus corresponds to even cycle modulation. Therefore the winding can be switched from a 4-parallel circuit to a series circuit, or to a 2-parallel circuit and it may be again modulated from a series circuit to a 2-parallel circuit, or vice versa.

Fig. 3  The two alternative forms of even-cycle modulation

*The four sections in series are I, II, III & IV.*

*For a the sequence is I II III IV and*

*For b the sequence is I II IV III.*

The available pole-combination:

Suppose the three pole-numbers W, X, and Z are respectively given 4-parallel, 2-parallel and series connection. It has been shown that the change from W poles to either Z poles or X poles can be effected by even-cycle modulation and that the change from Z poles to X poles can be effected by odd-cycle modulation. It follows that the change from W poles to either X poles or Z poles must also be effected by odd-cycle modulation. The two general classes of 3-speed PAM winding thus give two series of possible pole-combinations, as follows:

### TABLE 1

| W to Z: even-cycle modulation; Z to X and W to X: odd-cycle modulation |
|-----------------------------|-----------------------------|
| **W**                  | **X**                  | **Z**                  |
| 4-parallel                | 2-parallel                | Series                 |
| W + 2                    | W + 4                    |                         |
| W                        | W + 6                    | W + 8                  |
| W + 10                   | W + 12                   |                         |
| W + 14                   | W + 16                   |                         |

etc. etc.

### TABLE 2

| W to X: even-cycle modulation; X to Z and W to X: odd-cycle modulation |
|-----------------------------|-----------------------------|
| **W**                  | **X**                  | **Z**                  |
| 4-parallel                | 2-parallel                | Series                 |
| W + 4                    | W + 2                    |                         |
| W                        | W + 8                    | W + 6                  |
| W + 12                   | W + 10                   |                         |
| W + 16                   | W + 14                   |                         |

etc. etc.

As far as effecting modulation is concerned, the switching circuit of Fig.2 can thus be obtained by using any one of the pole-combination in these two series in either of two ways. The modulation process itself determines only the basic pole-number(s) which appear and it has no essential connection with the relative air-gap flux-densities for the various pole-numbers. The method of modulation which gives \( W < X < Z \) used to be chosen, especially when the ratio between \( W \) and \( X \), and/or between \( X \) and \( Z \), is considerably greater than unity. The reason for this choice is that it will ordinarily be desired to obtain comparable values for the air-gap flux-densities for the three pole-numbers. To do this it is necessary that the series connection \( Z \), which gives the largest number of conductors in series, shall correspond to the largest pole-number; that the 2-parallel connection \( X \) which gives an intermediate number of conductors in series shall correspond to the middle pole-number and the 4-parallel connection \( W \) with the fewest conductors in series shall correspond to the smallest pole-number.
Whilst there is no absolute freedom of choice in relation to the possible pole-combinations, it is clear that there is a sufficiently wide choice to meet almost any possible application, within ordinary industrial tolerances.

IV. MACHINE PARAMETERS

Selected rating of three speeds namely 8/6/4-pole single winding 3 phase SQIM as 2.2KW- 4 pole / 1.5KW- 6 pole / 1.1KW – 8 pole. The machine parameters values are calculated for all the three speeds and tabulated as per the SQIM equivalent circuit shown in Fig.4 below.

![Induction motor’s equivalent circuit](image)

**Fig. 4 Induction motor’s equivalent circuit**

Where:
- $R_1$ - Stator resistance
- $R_2$ - Stator leakage reactance
- $R_i$ - Resistance representing the iron losses
- $X_m$ – Magnetisation Reactance
- $R_2'$ – Rotor resistance referred to the stator
- $X_2'$ – Rotor leakage reactance referred to the stator

All the above values are per phase values.

**TABLE 3**

Technical Parameters obtained by calculation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>4 Pole</th>
<th>6 Pole</th>
<th>8 Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$ (Ω)</td>
<td>3.0</td>
<td>6.6</td>
<td>9.6</td>
</tr>
<tr>
<td>$R_2$ (Ω)</td>
<td>2.9</td>
<td>6.0</td>
<td>8.4</td>
</tr>
<tr>
<td>$X_1$ (Ω)</td>
<td>5.0</td>
<td>4.4</td>
<td>5.0</td>
</tr>
<tr>
<td>$X_2$ (Ω)</td>
<td>5.0</td>
<td>4.4</td>
<td>5.0</td>
</tr>
<tr>
<td>$X_m$ (Ω)</td>
<td>110</td>
<td>90</td>
<td>115</td>
</tr>
<tr>
<td>$R_i$ (Ω)</td>
<td>958</td>
<td>700</td>
<td>888</td>
</tr>
</tbody>
</table>

With the above steady-state induction motor equivalent circuit parameters the motor’s performance characteristics can be evaluated using the SQIM equivalent circuit shown in Fig.4 as above and the results are recorded in Table 4

**TABLE 4**

Motor’s Performance Characteristics, ignoring stray losses:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>4 - Pole</th>
<th>6-Pole</th>
<th>8-Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating KW(HP)</td>
<td>2.2 (3)</td>
<td>1.5 (2)</td>
<td>1.1 (1.5)</td>
</tr>
<tr>
<td>Syn.Speed / Rotor Speed in rpm</td>
<td>1500 / 1420</td>
<td>1000 / 925</td>
<td>750/ 690</td>
</tr>
<tr>
<td>Slip s</td>
<td>0.053</td>
<td>0.075</td>
<td>0.08</td>
</tr>
<tr>
<td>Stator Current (A) NLC/ FLC</td>
<td>2.1/ 4.8A</td>
<td>2.6/ 3.9A</td>
<td>2/ 3A</td>
</tr>
<tr>
<td>Stator copper loss (W)</td>
<td>207</td>
<td>301</td>
<td>260</td>
</tr>
<tr>
<td>Rotor copper loss (W)</td>
<td>125</td>
<td>114</td>
<td>91</td>
</tr>
<tr>
<td>Pc loss (core+ wind+friction) (W)</td>
<td>167</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td>Total losses (W)</td>
<td>499</td>
<td>515</td>
<td>416</td>
</tr>
<tr>
<td>Power input (W)</td>
<td>2760</td>
<td>1972</td>
<td>1517</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>80</td>
<td>74</td>
<td>72</td>
</tr>
<tr>
<td>Power factor at no load</td>
<td>0.114</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Power factor full load</td>
<td>0.83</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>Output Torque (Nm)</td>
<td>14.79</td>
<td>14.325</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Connections
- 4-parallel-star
- 2-parallel-star
- Series-delta
V. SIMULATION RESULTS

After developing the proposed 3 phase 3 speed SQIM, the simulation results are obtained towards performance analysis for all the three speeds as below:

The speed – torque curve of 4,6,& 8-pole speed operation has been obtained by selecting the respective pole motor parameter fed simulation circuit and obtained rated speed at rated torque as per the calculated result and the same is recorded in Figures below.

Fig. 5  4-Pole Speed –Torque Curve

Fig. 6  4-Pole Speed & Torque curves w.r.to time

Fig. 7  6-Pole Speed-Torque curve

Fig. 8  6-Pole Speed & Torque curves w.r.to time
Thus simulation is repeated by changing the poles of induction motor to 4 pole, 6 pole, and 8 pole and the readings are tabulated. The efficiency and power factor of the system are calculated for each speed change operation using the equations of SQIM equivalent circuit and model calculation is carried-out as below:

Model calculation of parameters
Consider the 4Pole (2.2KW) case
with rotor speed at rated load = 1420rpm ie s= 0.053
For Zsh= $109.28 \angle 83.45^\circ = 12.465 + j108.57$
For Zth = $5.56 \angle 60.25^\circ = 2.759 + j4.827$
$V_{th} = 220.18 \angle 1.25^\circ$
$I_2' = \frac{V_{th}}{(R_{th}+R_2'/s+ j(X_2'+X_{th}))} = 3.78 \angle -8.45^\circ$
Stator no load current = $I_s = \frac{V_{rms}}{Z_{th}} = 2.11 \angle -83.45^\circ$ ;
$\cos \phi_s = 0.114$
Stator full load Current = $I_1 = I_s + I_2' = 4.78 \angle -33.7^\circ$
= $3.98 - j2.655$ ; $\cos \phi = 0.83$
Pin = \sqrt[3]{3 \times 4.8 \times 400 \times 0.83} = 2760W

P_{cust} = \text{Stator cu.loss} = 3 I_1^2R_1 = 207W

P_{cure} = \text{Rotor Cu.loss} = 3I_2^2R_2' = 125W

P_c = 3I_1^2\text{Real Zsh} = 167W

Total losses = 499W

\[
P_{g} = P_{in} - P_{c} = P_{cure} = 2386W
\]

\[
P_{m} = P_{g} - P_{cure} = 2261
\]

\[
P_{out} = P_{m} - \text{stray loss} = 2261 - 61 = 2200
\]

Efficiency = \frac{2200}{2760} = 0.797 = 0.80

Output Torque = 2200 \times 9.55/1420 = 14.79Nm

VI. ECONOMICS AND APPLICATIONS

Before the invention of pole-changing windings, usually two or more windings have been in use as primaries for cage rotor induction machines-each winding being designed as a regular one for one pole number. Such an arrangement has necessitated costly designs, the primary copper quantities increasing directly with the number of speeds required. Also the slot sizes, and hence the stator iron and volume of the machine increase; so also the labour charges for construction and repairs. The value of a well designed pole-changing winding arrangement lies in that the same single winding serves two or more pole numbers with reduced copper and iron volumes compared to its multi winding parts.

Although the theory of the arrangement of the coil grouping and their connection for optimum performance is complex, the manufacture of the machine is, by contrast, very simple and can be carried out in any workshop making normal induction motors. Furthermore, the design can be reduced to a routine, capable of being carried out as in the case of standard induction motors. This new 2-speed winding is cheap, and simple to make and of great flexibility.

Efficiency and Losses comparison [2]:

A typical induction motor efficiency ranges from 93% to 97% when operated at 100% load, while the ASD has its own typical efficiency ranging between 96% and 98%. Efficiency of motors operating at full frequency and non-sinusoidal power are less than nameplate efficiency, as the speed drops, the load drops as per the affinity law. These two electrical systems together produce usable output power. The losses are present based on their own individual efficiencies. One aspect that should be considered in terms of cost of operation is the combined total efficiency of the whole system. It is recognised that the today’s electrical drives are more efficient that 20 years ago. Many different types of ASD’s applied to induction motors exist using similar concepts where the electric AC voltage and frequency is converted and controlled by means of power electronics. There is no ASD with 100 pct efficiency, since the losses are inherent in converting the electrical AC input into DC and then from DC to AC output again. Not enough data have been collected to compare test laboratories result for efficiency between multi-speed motor and single speed motor with ASD. However, many textbooks for ASD’s indicate losses in these devices are present due to high switching frequency. Table I below compares losses at different HP ratings between ASD and a single PAM motor operating at 2 different speeds.

TABLE 5

Comparison of electrical losses between PAM & ASD

<table>
<thead>
<tr>
<th>HP</th>
<th>6500</th>
<th>3500</th>
<th>6000</th>
<th>11000</th>
<th>6000</th>
<th>11000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAM</td>
<td>PAM</td>
<td>Std</td>
<td>+ASD</td>
<td>PAM</td>
<td>PAM</td>
</tr>
<tr>
<td>Volts</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
<td>13200</td>
<td>13200</td>
<td>13200</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
<td>13200</td>
<td>13200</td>
<td>13200</td>
</tr>
<tr>
<td>Amps</td>
<td>834</td>
<td>498</td>
<td>836</td>
<td>324</td>
<td>191</td>
<td>263</td>
</tr>
<tr>
<td>RPM</td>
<td>895</td>
<td>717</td>
<td>896</td>
<td>891</td>
<td>715</td>
<td>895</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.4</td>
<td>96.2</td>
<td>96.9</td>
<td>96.2</td>
<td>95.9</td>
<td>96.9</td>
</tr>
<tr>
<td>Kw Loss</td>
<td>181</td>
<td>103</td>
<td>155</td>
<td>324</td>
<td>191</td>
<td>263</td>
</tr>
<tr>
<td>ASD Losses</td>
<td>N/A</td>
<td>N/A</td>
<td>136</td>
<td>N/A</td>
<td>N/A</td>
<td>236</td>
</tr>
<tr>
<td>Total Kw</td>
<td>181</td>
<td>103</td>
<td>291</td>
<td>324</td>
<td>191</td>
<td>499</td>
</tr>
</tbody>
</table>

*Efficiency of drives varies amongst manufacturer (97-98% were averaged for this analysis)

Table 5 shows two examples of PAM motors with efficiency and losses generated at full load condition for each speed (LS & HS). Also shown next to it is a fixed single speed rating corresponding to the high speed orientation with an ASD. The adjustable speed drive losses were added to the entire electrical system to compare the total KW loss that is present when the motor is fed by ASD. As shown, the total losses are greater if a fixed speed unit plus an electrical drive is used compared to a single PAM unit operation. Considering the total losses of the whole system are suggested when cost savings analyses are made.

Case study for energy saving and payback period calculation

Pole changing machines have a significant role in the industrial applications towards reducing the annual power consumption. There are countless industrial applications of motor drives which do not demand full speed or maximum power all the time but the speed of the motor and its maximum rating must none the less be determined by what may be required from it for some part of its duty cycle. Also the electrical energy is invariably subject to a tariff which is strongly differential in favour of uniform usage together with night usage rather than day usage in so far as heavier loading is required for part of the time.

- As an example consider the case of a pump driven by a 600KW, 6-Pole, fixed speed induction motor, or by a 600/300KW, 6/8 –Pole PAM motor. The cost of such a motor and controller together would be 10 lakhs for a normal IM and, Rs.13 lakhs for a PAM motor.

- Although the initial cost is higher, the working cost for a PAM motor will more than compensate it, depending upon for
how much time, during a day/season, it will be worked at a lower speed. It can be shown that (as in Appendix A):

1. If the PAM motor worked at 8-pole for 80% of the day and at 6-pole for 20% of the day, then the cost of energy saving would be about 3.8 lakhs per annum.

2. If the PAM motor worked at 8-pole for 40% of the day and at 6-pole for 60% of the day, then the cost of energy saving would be about 1.9 lakhs per annum. (Assuming tariff rate as Rs.5/-unit)

The PAM motor can be used at:

1. Wind driven induction generators where the synchronous speed should be adjusted to suit different operating conditions.

2. Lifts where one speed for up and one speed for down is required.

3. Boiler draught fans where air draught has to be controlled.

4. Winches for pulling the cradle with one speed for docking and another for undocking the ships.

5. The most important need for speed-changing occurs in processes like centrifugal pumps, fans, mixers or agitators, driving drills and in other applications where the cutting speed may need to be changed with a change of the material being handled.

6. Also the PAM motor can be started across the line at lower speed/rating so that the starting inrush current is low and thus minimizes bus disturbance in the power systems. Heating of stator and rotor is also reduced when started on low speed with high inertia loads providing a longer life of the motor.

### APPENDIX A

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>STANDARD MOTOR</th>
<th>PAM MOTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATING</td>
<td>(KW)</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>(hP)</td>
<td>800</td>
</tr>
<tr>
<td>BASIC PRICE</td>
<td>(IN Rs)</td>
<td>10,00,000</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POLES</td>
<td></td>
<td>6 Pole</td>
</tr>
<tr>
<td>SYNCHRONOUS SPEED (rpm)</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Supply Voltage/Frequency</td>
<td></td>
<td>415 V/50 Hz</td>
</tr>
</tbody>
</table>

### FACTORS CONSIDERED

| Efficiency              | FL (600 KW) | 95%       | 95% |
|                        | 50%Load (300 KW) | 87%       | 94% |
| Constant losses (Stray loss= NL Cu loss) | FL (600 KW) | 12 KW | 12 KW |
|                        | 50%Load (300 KW) | 12 KW | 7 KW |

(1) If the PAM motor worked at 8-pole for 80% of the day and at 6-pole for 20% of the day, then the cost of energy saving would be about 3.8 lakhs per annum.

(2) If the PAM motor worked at 8-pole for 40% of the day and at 6-pole for 60% of the day, then the cost of energy saving would be about 1.9 lakhs per annum. (Assuming tariff rate as Rs.5/-unit)
VII. CONCLUSION

The results obtained by parameter analytical calculation and by simulation almost came equal for speed, torque and efficiency values but the values are different for power factor and no load current. Thus the task of simulating for three speeds to operate the motor at constant torque is completed. However the exact performance characteristics can be analysed for parameters like power factor, efficiency and harmonics generation at different pole operation only with actual PAM motor performance analysis.

<table>
<thead>
<tr>
<th>Load losses</th>
<th>FL (600 KW)</th>
<th>18 KW</th>
<th>18 KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% Load (300 KW)</td>
<td>17 KW</td>
<td>11 KW</td>
<td></td>
</tr>
<tr>
<td>Total losses</td>
<td>FL (600 KW)</td>
<td>30 KW</td>
<td>30 KW</td>
</tr>
<tr>
<td>50% Load (300 KW)</td>
<td>29 KW</td>
<td>18 KW</td>
<td></td>
</tr>
</tbody>
</table>

a) If 80% of the day motor worked at 8-Pole+ If 20% of the day motor worked at 6-Pole.

<table>
<thead>
<tr>
<th>Load losses</th>
<th>FL (600 KW)</th>
<th>18 KW</th>
<th>18 KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% Load (300 KW)</td>
<td>17 KW</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>50% Load (300 KW)</td>
<td>29 KW</td>
<td>18 KW</td>
<td></td>
</tr>
</tbody>
</table>

VIII. ACKNOWLEDGMENT

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IX. REFERENCES


