Comparing the energy savings impact of a permanent magnet motor and induction motor in adjustable speed drive applications

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***Abstract*—How much energy can be saved if a Permanent Magnet Motor (PMM) is used in an adjustable speed drive (ASD) application? The paper will show test results and an efficiency comparison of a PMM to an IE3 class Induction Motor. Motor drive system efficiency is evaluated for constant and variable torque applications. Both motors will be tested in a laboratory. Full and partial loads will be applied by a dynamometer. The motors efficiency is calculated based on measured torque, speed and kilowatt input for various loads and speeds. Energy losses, cost savings and reduced carbon footprint are illustrated for both motor drive systems.**

***Topic*—Permanent Magnet Motor, Efficiency, Energy Savings Impact**

I. Introduction

The worldwide quest for energy savings has generated a global drive for efficiency which in its turn has instigated an inrush of new developments in clean technologies. New clean technologies designed to meet and exceed recent energy standards and regulations, as well as a system efficiency approach are expected to significantly reduce the world carbon footprint.

Adjustable speed drives can save up to 50% energy when used with induction motors on variable speed applications. Using a drive with an IE4 class motor can achieve even higher efficiencies when running variable speed, and constant torque applications.

But how much more energy can be saved if a Permanent Magnet Motor (PMM) is used in an adjustable speed drive (ASD) application? In order to assess the savings, an evaluation of the existing methods to measure motor efficiency, new efficiency levels standards, and recent efficiency test procedures of motor, and ASD are needed [1-4]. Yet, test methodologies and accuracy are being evaluated and revised especially for variable speed applications and new permanent magnet motor technology.

To find out how much more energy is saved using a PMM instead of an induction motor (IM) we will put each motor on a test bench and we will show: 1) The test results and efficiency comparison of a PMM to an IE3 class IM. 2) The overall system efficiency comparison for an IM-drive and a PMM-drive system. 3) The energy savings will be evaluated for a constant and a variable torque application. 4) The return of investment (ROI) and the reduced carbon footprint will be illustrated. Both motor-drive systems will be tested in a laboratory. Full and partial loads will be applied by a dynamometer.

The main goal of this paper is to obtain a practical number that the end user can simply associate with the percentage savings in power and energy if using a PMM-drive system instead of an induction motor-drive system.

The test results presented in this paper are for a 7.5 kW motor drive system it is the author's view that the power saving percentage number can serve as a suitable estimation for low power motor ratings

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TABLE 1 MOTORS NAMEPLATE DATA. NEMA PREMIUMIS AN IE3 CLASS INDUCTION MOTOR

	NEMA Premium	***PM Motor IE4***
Rated Power	10 HP	7.5 kW
RPM	1760	1800
Torque	29.4 lb-ft	40 Nm
Efficiency	91.7 %	94 %
Rated Current	12.3 A	12 A

II. MOTOR EFFICIENCY COMPARISON

Indirect methods or segregation of losses for measuring permanent magnet motor efficiency were not used, but rather the direct method was chosen, especially as the mechanical output power of the motors under test can be measured accurately.

Finite Element Analysis (FEA), or the use of semi-analytic motor models to obtain efficiency maps still need motor efficiency experimental data.

A. Motors to test

Motor nameplate data is shown in Table 1. Two motors of equivalent power rating are placed on a motor test bench: Motor "A" is a 10HP induction motor and Motor "B" is a 7.5kw PM motor. Motor "A" is a NEMA Premium efficiency induction motor equivalent to an IE3 efficiency class motor and Motor B is a slightly higher than IE4 or Super Premium efficiency level.

The test motor nameplate efficiency values are for rated speed and load; and in the case of the induction motor the given efficiency is for utility power. Inverter power impacts these values. In our bench test each motor will be run from inverter power.

B. Test Bench and Measurement System Set-up

The test motor system set-up is shown in Fig. 1. Please note the inverter as part of the test system. The test system power range is from 1.5 to 7.5 kW (2HP to 10HP), the torque range from 4 to 40 Nm, and the speed range from 30 to 2500 rpm.

Motor electrical input power is measured by a high precision, Yokogawa WT1600 power analyzer. Measurements are taken immediately after a motor heat run (motor loaded with rated torque that has reached a stable operation temperature).

Full and partial loads are applied to each motor by a dynamometer. Motor torque and speed are measured by a Himmelstein, MCRT, torque-meter with a torque sensor of 0.2% accuracy. An inverter rated 7.5kW, 460V and set at 4kHz PWM switching frequency is used to run each motor.

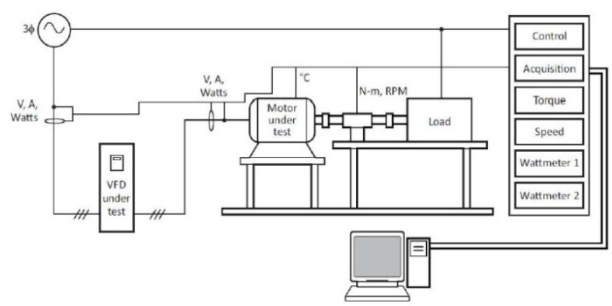


Figure 1Test Bench and Measurement System Set-up

C. Test Matrix -Set-Points

Motors manufacturers provide motor nominal (rated) efficiency, and sometimes the efficiency values at 75% and 50% rated load. These torque-speed operating points can be represented as (X,Y) points or (100%, 100%), (100%, 75%), (100%, 50%), where X is the speed and Y is the torque operating point, in percentage of rated.

The efficiency at the three points mentioned above need test validation as the motor is run on inverter power. Three more load test points would be added, 60%, 50%, 40% ,in this way obtaining six load points at rated speed (the matrix top row).

Six load points at 75% speed will be also monitored, that is obtaining the second matrix row; and so on 60%, 50%, 40% and 25% speed. Thus, thirty-six torque- speed combinations.

A similar matrix of torque-speed combinations will be monitored for the permanent magnet motor, to sum up a total of 72 files of motor electrical and mechanical measured data, each file pertaining to one torque-speed matrix element.

Larger monitored matrix can be recommended to obtain extensive efficiency maps with help of finite element analysis (FEA) or semi-analytical motor models.

D. Test Results. Motors Efficiency on inverter power.

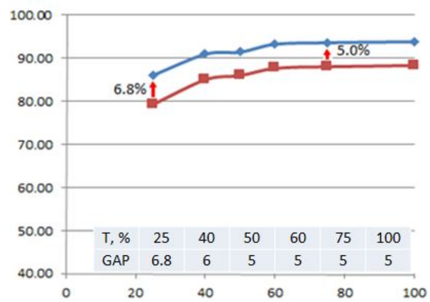


Figure 2 Efficiency vs Load (rated speed)

The test results at full speed are shown in Fig. 2. The PM motor efficiency (blue line) is about five points higher than the induction motor (red line)

This relatively constant gap of five percent between the efficiency lines slightly widens at about forty percent rated load. This corroborates to the effective efficiency load range, for which induction motors are typically designed.

We also know that induction motor efficiency decreases at partial loads and even more if the speed is reduced.

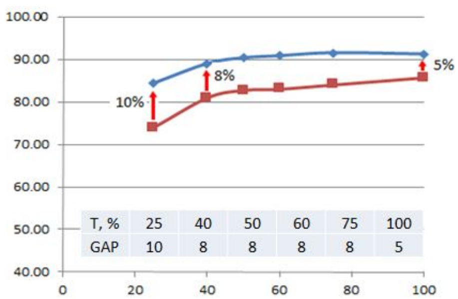


Figure 3 Efficiency vs. Load (50% rated speed)

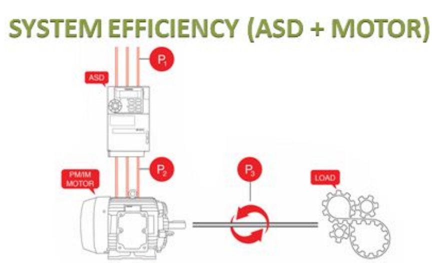
However, the PM motor efficiency performance at half speed shown in Fig. 3 (blue line) indicates nearly the same efficiency level.as at full speed, and throughout most of the operational load range (just about one percent less compared to Fig. 2).

Meanwhile, the induction motor performance (red line) gets worse at reduced speed. The 5% gap at rated load quickly widens to 8% and 10% at 25% load (see Fig.3). This validates the fact that induction motors have mainly evolved as fixed speed designs.

III. SYSTEM EFFICIENCY COMPARISON

Until now we have obtained and compared motors efficiencies at various loads and speeds. But what the end-user is interested to know is the energy consumption savings of the entire motor-drive system.

In order to calculate the energy savings, the efficiency of the overall system is needed as illustrated in **Fig**.4.



$$\eta_a = SYS_{IM} = \frac{P_{3a}}{P_{1a}} \qquad \eta_b = SYS_{PM} = \frac{P_{3b}}{P_{1b}}$$

Figure 4. System Efficiency

where, η_a is the system efficiency: ASD-induction motor; P_{3A} is the mechanical power at the motor shaft; P_{1A} the Watts input power to the drive; Similarly η_b is the system efficiency: ASD-PM motor.

A. System Efficiency "A": Induction Motor + ASD

As can be seen from the 3-D plots or efficiency map in the Fig.6 system efficiencies of 80 to 85% for half of the speed-torque operational range, and higher than 75% for the lower half of the operational range

B. System Efficiency "B" Permanent Magnet Motor + ASD

The permanent magnet motor system shows the best efficiency at practically any point: Efficiencies of 85 to 90% through most of the operational range (see Fig.5)

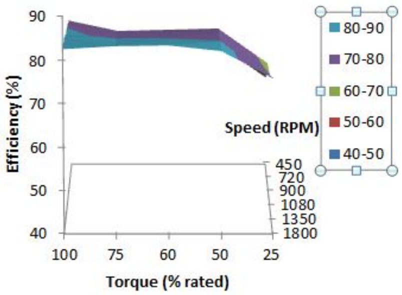


Figure 6 System Efficiency IM-ASD

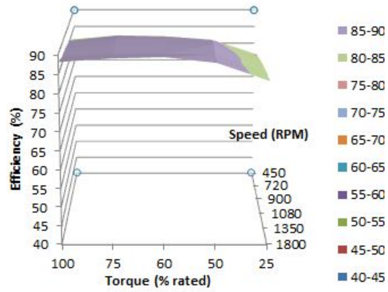


Figure 5 System Efficiency PMM-ASD

IV. Energy Savings

We monitored seventy-two speed-torque combinations, obtaining the respective system efficiencies. The energy saving can be calculated using the following formula as well as based on the measured electrical input power to the system and output mechanical power

$$E_{sav}(\eta_h, P_h) = \sum_{h=1}^{8760} Pshaft(\frac{1}{\eta_{ah}} - \frac{1}{\eta_{bh}}) \quad (1)$$

where $\eta_h = f(\omega, T, \theta)$ is the system efficiency, function of speed, torque and ambient temperature;

$\sum_{h=1}^{8760}$, is the time hours of the load profile

As we see from the formula the energy savings depends on the motor mechanical power or shaft power (P shaft), which also varies with the load.

We will consider two cases or two load profile types: 1) a load profile for a typical Constant Torque (CT) application; and 2) a load profile for a typical Variable Torque (VT) application

A. *Power Savings*

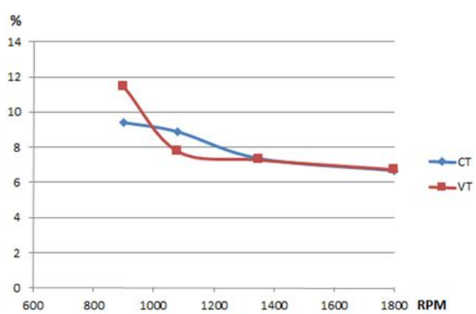


Figure 7 Power Savings (%)

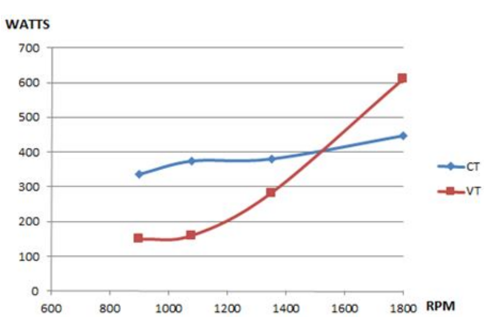


Figure 8 Power Savings (Watts)

The Variable Torque type profile showed power savings of seven percent and up to twelve percent as speed halves. This is due to the motor efficiency line gaps growing faster with square torque type loads (Fig. 7)

The Constant Torque type profile showed the same level power savings (about 7%) and as speed is reduced the power savings can increase up to 9.5% at half speed (just slightly less than variable torque).

Also we found out that if operating in the rated speed area down to 75% speed, the power savings is about 7% for both VT and CT applications.

The saved Watts absolute value (Fig.8) shows that Constant Torque applications can yield higher savings especially at lower speeds. This can be explained from the "*energy savings equation*" (1) due to higher shaft power in CT applications rather than in VT.

B. *Energy savings, carbon footprint reduction and return of investment.*

Table 3 shows the annual savings for a typical constant torque and variable torque load profile, estimated at 8568 operation hours, 10 cents/kWh.

The payback or return of investment (ROI) is estimated at a price difference between the PM and induction motor of one hundred dollars (see "PM premium $"in Table 3). Even if the price difference triplicates to 300 dollars the ROI is still less than one year.

	CT LOAD	VT LOAD
SAVED **kWh**/year	3284	3373
SAVED $/year	328.4	337.3
PM PREMIUM $	100	100
% SAVINGS	7.44	8.31
ROI	111 days	108 days
CO2 REDUCTION	1.72 Tons CO2	1.77 Tons CO2

Figure 9 Summary (Savings, ROI, CO2 reduction)

The carbon footprint (CO2) reduction is calculated at 0.525 kgCO2

All these savings are yearly. If we consider a twenty year motor life, , the energy savings, the dollar savings and the carbon footprint reduction are increased 20 times

V. CONCLUSIONS

The tested PM motor-drive system vs. the induction motor-drive system demonstrated the following energy savings potential. 1) Six percent higher efficiency at full speed and ten percent at half speed. 2) Seven to eight percent savings on average depending on the actual load profile. The lower the load or speed the higher the percent energy savings and superior system performance; 3) less than four months return of investment; 4) 1.7 Tons carbon footprint reduction

Although the test results presented in this paper are for a 7.5 kW motor drive system it is the author's view that the power saving percentage number can serve as a suitable estimation for low power motor ratings.

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