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Energy efficiency of machines: The smart choice of motorization

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Executive summary

Industry and infrastructure consume more than 31% of the available energy in the world, and electrical motors alone represent more than 60% of that energy consumption. Designing a more energy efficient machine creates cost savings over the lifetime of the equipment. This lower cost can then be passed directly to end users. This paper compares the technological capabilities and limitations of AC and synchronous motors, quantifying that a synchronous motor allows up to 20% energy savings while increasing performance.

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Executive summary

Industry and infrastructure consume more than 31% of the available energy in the world and electrical motors alone represent more than 60% of that energy consumption.

As fossil fuels become rarer, energy derived from these sources is becoming more costly. Therefore, intelligent use of electricity is a major concern for users and manufacturers.

When considering the decision to purchase a new machine, companies should take into account the amount of energy that will be consumed by the machine during its lifespan. Among expenses from acquisition to dismantling, the purchase price accounts for only 2 to 3% of the overall costs, the remainder of the expense primarily being energy consumption.

Designing a more energy efficient machine creates cost savings over the lifetime of the equipment. This lower cost can then be passed directly to end users, making your company more competitive.

Many solutions exist to improve the energy efficiency of your machines, such as:

- Enhancing machine efficiency
- Operating modes that switch off an unloaded machine
- Utilizing variable speed drives
- Creating more efficient motion control solutions
- Using high efficiency motors

Forward

Machines are designed according to performance criteria and productivity. The goal of the engineer is to find the most efficient, economic, and competitive solutions for these measures. Motor selection is the result of these choices.

Generally, motor selection is finalized when the mechanical part has been largely defined and long-term power consumption is not always taken into account.

However, the growing cost of energy demands new strategies. The choice of the motor should be the starting point in order to reduce the power demand.

Considering the mechanical requests, the motors that will outfit the machine must match several criteria.

First, they allow the machine to have continuous operation and provide the needed torque at the rated speed. This consideration determines the motor size. The designer must also consider the motor torque required to start the machine. Eventually, the motor may have to be oversized.

Duty cycle is another key point. Any time the machine is started, a motor heats and it should not exceed a limit that will lead to the failure of the motor. The ultimate decision is based on environmental conditions and will take into account the temperature and altitude at which the machine will operate.

When all evaluations are made, the selected motor is usually larger than necessary for continuous operation. Since the motor is not running at its rated power, its efficiency is reduced, which leads to increased energy consumption. Due to motor and machine efficiency, part of this energy is wasted.

In order to save fossil fuel resources, the European Union stated that by 2020, all motors in the field must be IE3, in other words, high-efficiency motors.

With the use of high-efficiency motors and available solutions, energy savings could reach 202 TWh per year in Europe alone. This represents 45 nuclear power plants in the 1,000 MW range, 130 power stations using fuel, or 3.8 times the totality of the energy produced by wind farms (value 2007).

Effects on the environment can be estimated at 79 million tons of CO_2 reduction and a drastic reduction of nitrogen and sulfur oxides.

Introduction

On the expense side, curves of the energy cost (graphs opposite from the Observatory of Energy according to Eurostat - January 2007) clearly show a continuous growth from 2004.

Depletion of fossil energy reserves will accentuate this growth.

Motor choice is paramount for energy savings.

Part of the energy taken from the network is wasted in heating. According to the technology of the selected motor, these losses are more or less important.
They also vary between suppliers.

Traditionally, an AC motor is used in machines. This motor is designed to operate at a constant speed. However, using electronic drives with this motor improves the flexibility of the machines.

The synchronous motor is another solution.

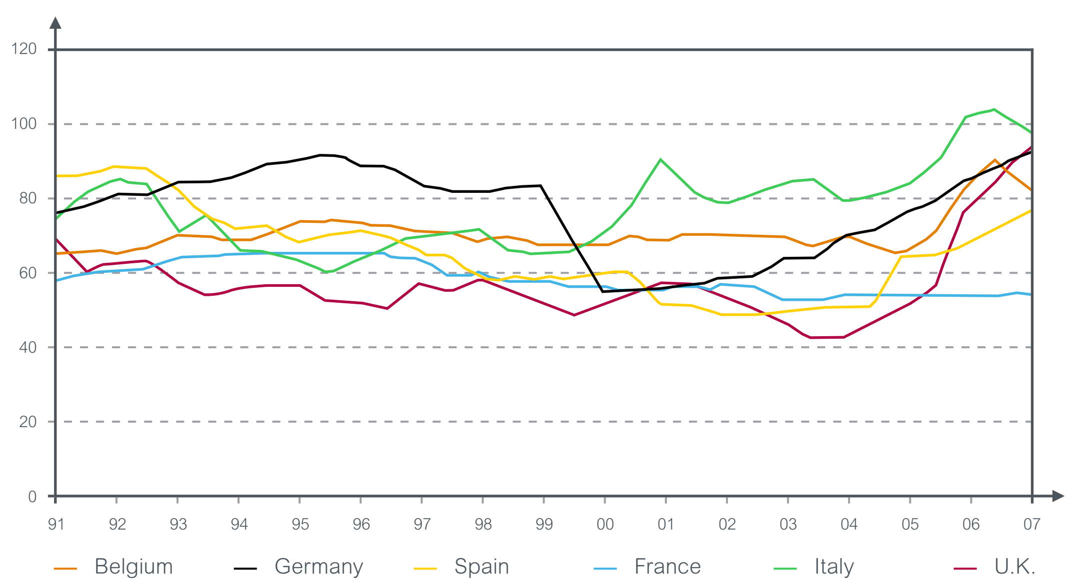
The goal of this White Paper is to compare these two technologies, estimate the limitations, and provide information to the designer and user in order to make a smart choice.

For this comparison, the two motors were fed through an Altivar™ 32 variable speed drive (VSD).

Use of a VSD eliminates most AC motor weaknesses including:

- Inrush current
- Power factor (cosine φ)
- Effects of voltage fluctuations on motor torque
- Speed drop when the motor supplied through a flux vector control VSD
- Unloaded current

Figure 1



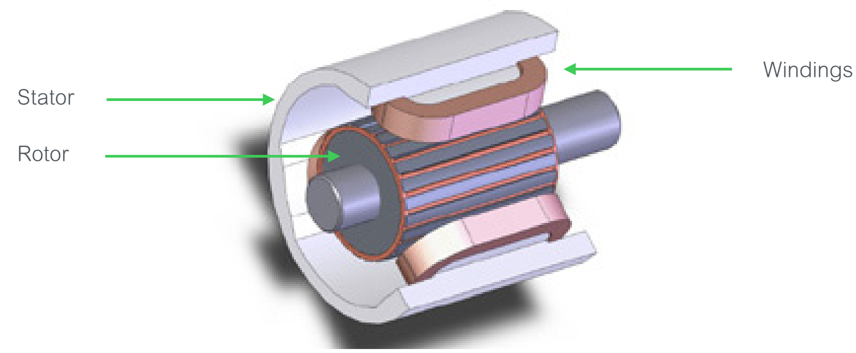
The smart choice of motorization

The AC motor

Basic motor components

The components of an asynchronous or induction motor, commonly called an AC motor or squirrel cage motor, include a stator made of magnetic material with embedded polyphase windings and a rotor also built of magnetic material. The drawing below illustrates the components of this motor.

Figure 2



Operation and limitations

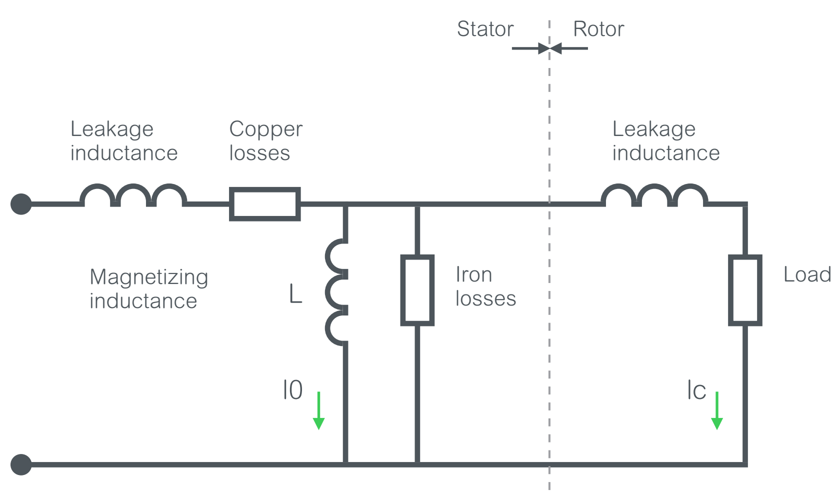
In spite of the efforts by manufacturers, AC motors have, by design, physical limitations impossible to circumvent. Class IE3 reaches the limit of what can be done in an economic way. Limitations are linked to the very principle of this motor. We analyzed these limitations when an AC motor was supplied from a drive in order to compare it with more promising and available solutions.

First limitation: Generation of the magnetic field and its consequences

With any electrical motor, torque generation is linked to the existence of a magnetic flux in the machine. This flux, noted φ, is produced by the stator windings, which, when they are connected to a polyphase alternating network, create a rotating field.

We studied what occurred in a theoretical machine represented by the following diagram.

Figure 3



If we neglected the windings' resistance, we saw that the voltage applied to the magnetizing coil noted L created a current named I0.

Flux expression is $\varphi = kI0$

Inevitably, this magnetizing current created iron losses.

Output power is represented by the voltage across an imaginary resistance, which simulates the load. Noting Ic, the current in this resistance, torque can be written as:

$T = kI0\ Ic$

We immediately saw that if the supply voltage decreased, flux and current Ic decreased simultaneously in the same ratio and that torque varies like the square of voltage. Use of a drive that controlled this voltage eliminated this weakness.

Second limitation: Slip

Current applied to the rotor creates torque. This current is the result of Lenz's law, which says "An induced current is always in such a direction as to oppose the motion or change causing it."

The magnitude of this current, which is a function of the difference between the rotating field and the rotor RPM, creates torque. This difference is called "slip" (S) and is expressed in %, the speed of synchronism.

$g = [(Ns - N) / Ns] \times 100$

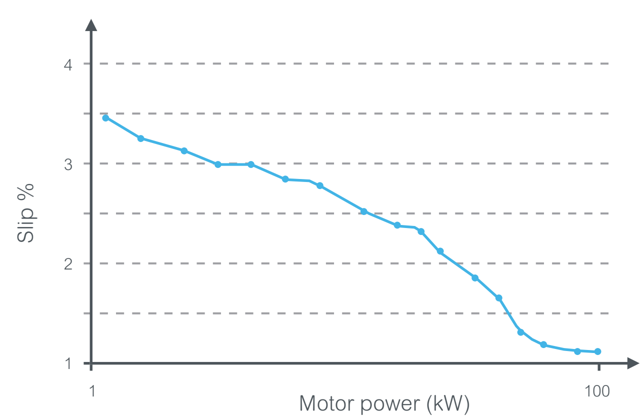
In no case can slip be equal to zero, because there would be no induced current and, as a consequence, no torque.

Slip is a necessary evil generating unwanted losses.

Special care used in manufacturing the motor allows a slip reduction, but it is impossible to eliminate it. It varies between 4 and 1%.

The following diagram represents slip for EFF1 (high-efficiency motors) from 1 to 90 kW.

Figure 4



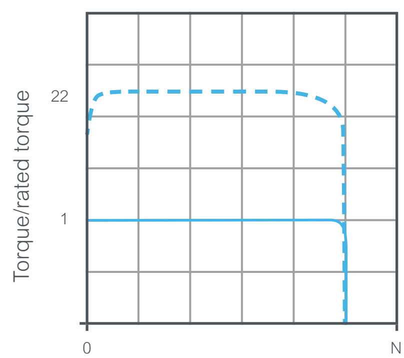
Third limitation: Maximum available torque

AC motors have limited torque performance. The diagram below represents the characteristic of an AC motor associated with a drive.

The curve represented by the dotted line is the transitory available torque. This value (approximately 2.2 times motor nominal torque) is a limitation imposed by the motor and not by the drive. This extra torque allows moving inertia of the machine and overcoming static frictions, but the dynamic speed performance is weak.

Permanent torque (solid line) is limited at low speed by motor losses and inefficient motor cooling.

Figure 5



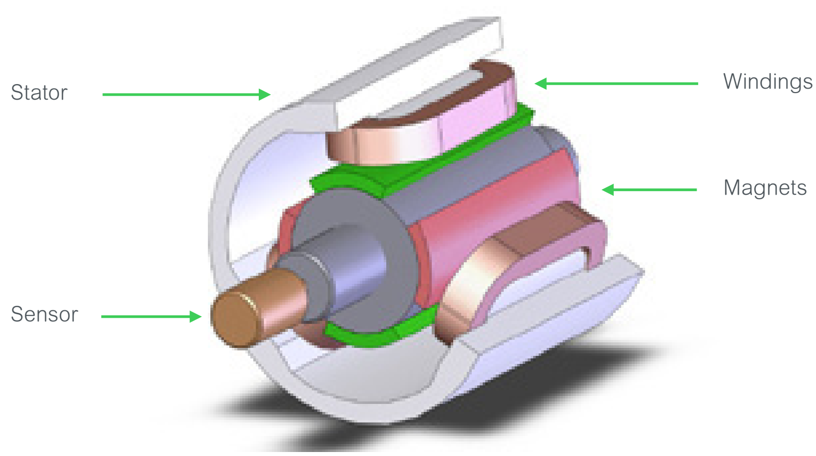
The synchronous motor

Basic motor components

The synchronous motor is another solution for low range power. Like an AC motor, components include a stator and rotor separated by an air-gap.

The drawing below represents such a motor.

Figure 6



The stator has an embedded three-phase winding. The rotor, made of both north pole and south pole magnetic materials, are represented in green and red. The synchronous motor is connected to an electronic drive that ensures the servo control. This is why it's represented as a sensor connected to the shaft.

The principle of this concept is beyond the scope of this document. For additional information, please consult publications such as "Automation Solution Guide" from Schneider-Electric.com or "Motion Control" from Gimelec.fr for further information.

Correctly used, it does not present any limitations as seen in the AC motor.

Operation

Magnetic field generation and consequences

Flux in the air-gap is not due to a component of the stator current, but to permanent magnets placed onto the rotor, which produces a constant flux.

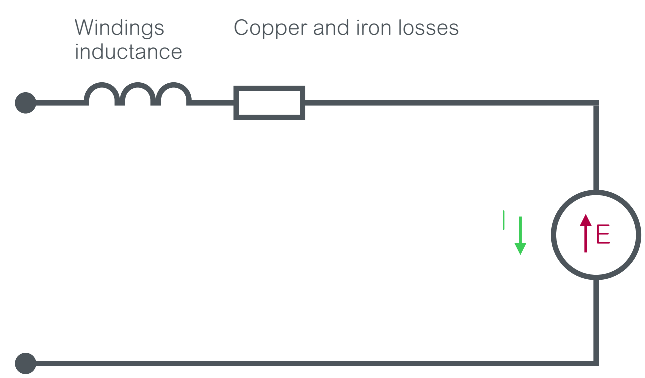
With the use of rare earth magnets made of neodymium or samarium material, high values of flux can be obtained in a reduced volume and, therefore, in very compact motors.

Torque has as the general expression: $T=kI\varphi$

There are neither magnetizing current nor related losses.

The synchronous motor is represented as follows:

Figure 7



E is an image of the electromotive force of the machine, which depends on flux created by the magnets and the number of revolutions ω.

Power can be written: $P=EI = k\varphi\omega$

Generation of electromagnetic torque

Unlike an AC motor, electromagnetic torque does not depend on current induced in the rotor.

The permanent field created by the magnets is aligned with the rotating field created by the stator. Torque is generated by the angular shift between rotating field position of the stator and that of the rotor.

Rotors, unlike an AC motor, turn without slip at the speed of the rotating field created by the stator. There is neither loss nor heating within the rotor. There is no risk of expansion and the air-gap can be reduced, which is beneficial to torque developed by the motor.

Required current

Required current is only that necessary to generate power times efficiency.

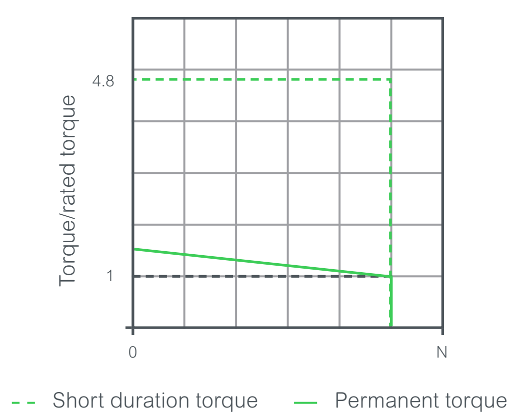
For the same size motor, there are neither losses related to slip nor additional losses due to magnetizing current, so a synchronous motor draws a current appreciably lower than an AC motor.

Available starting torque and maximum torque

Since the flux of synchronous motor is completely independent of the supply voltage, torque characteristics are clearly improved.

The graphic below is that of a BMH1003P motor from Schneider Electric connected to its servo controller.

Figure 8



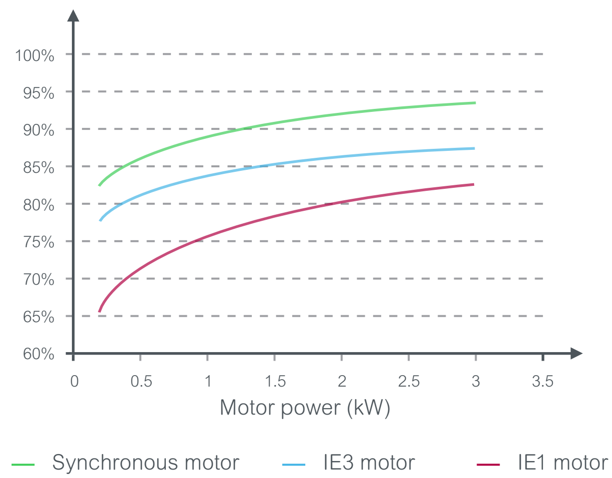
Its nominal torque is 5.2 Nm at 3,000 rpm, which produces 1.6 kW.

Intermittent torque, usable for starting and stopping, is 4.8 times nominal rating.

Motor comparison

Taking into account the absence of slip and current lower for the same power, the synchronous motor outperformed the efficiency of an IE3 AC motor as illustrated on the following graph:

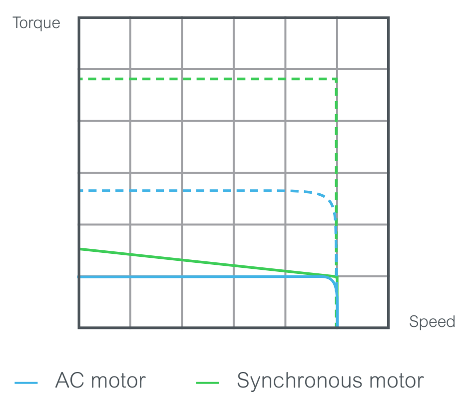
Figure 9



Current VSDs equipped with flux vector control, like an Altivar 32 from Schneider Electric, allow usage of an AC motor or synchronous motor for more and more complex applications and wider speed ranges.

The diagram below represents the performance of two similar sized motors at the same scale.

Figure 10



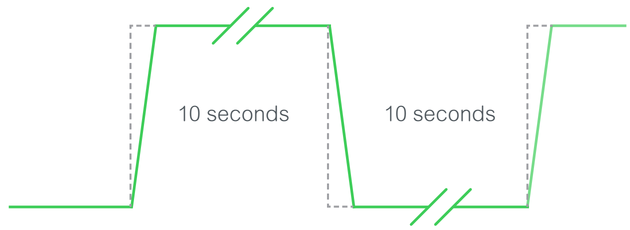
Some of the limitations of an AC motor disappeared, especially in the power factor.

Nevertheless, the available maximum torque was seldom higher than twice nominal torque and continuous operation at low speed was impossible because of the heat generated by the motor.

The intermittent torque of a synchronous motor was much higher, which led to faster acceleration and deceleration.

To emphasize this characteristic, we took the example of a machine running according to the cycle reproduced below.

Figure 11



Characteristics of the machine were as follows:

- Resistive torque 1.3 Nm
- Motor speed 3,000 rpm
- Load inertia at the motor shaft is 5 10^{-4} m^2 kg

With this data, the required power would be 408 W.

Taking into account the duty cycle, 0.5 in our example, we selected a motor rated at 350 W.

We have two possible choices: A synchronous motor or AC motor. Our objective is to obtain virtually identical dynamic performances.

The synchronous motor, BMHH0701P, was selected from the Lexium™ range. It can be combined with either an Altivar ATV_32H037N4 VSD for speed control or a Lexium LXM32•U60N4 servo drive for position control.

Its principal characteristics are as follows:

Table 1

Rated torque	1.1 Nm
Peak torque	4.2 Nm
Rated power	350 W
Rated speed	3,000 rpm
Inertia	3.2 10^{-4} kg m^2
Weight	1.6 kg

Calculated performance is shown in the table below:

Table 2

Acceleration time	88 ms
Deceleration time	47 ms
Braking energy	40 joules

In trying to obtain identical dynamic performance, we chose an AC motor with a peak torque of at least 4.2 Nm when connected to a VSD. Inevitably, the increase of inertia leads to the requirement for an oversized motor. The Leroy Somer motor LS 71 L was suitable since, when connected to a VSD, its maximum torque was approximately 5.7 Nm.

Its principal characteristics are as follows:

Table 3

Rated torque	2.6 Nm
Peak torque	5.7 Nm
Rated power	0.75 kW
Rated speed	2,748 rpm
Inertia	$6\ 10^{-4}$ kg m²
Weight	8.3 kg

Calculated performance is shown in the following table:

Table 4

Acceleration time	78.18 ms
Deceleration time	49.2 ms
Braking energy	54.3 joules

In a real-life scenario, the acceleration time would be a little longer because this simulation did not take into account the time needed to establish the flux in the machine nor the torque reduction as it would be mandatory to run the motor at 52 Hz to obtain 3,000 rpm.

Based on this example, we considered our performance objectives achieved.

We considered that braking energy was entirely dissipated in a braking resistor.

In addition to this comparison, the AC motor functioned at slightly more than 25% of its rated power and its efficiency was approximately 73%.

With a VSD, efficiency is less than 70%.

On the other hand, the efficiency of the synchronous motor and its drive would be higher than 88%.

The benefit of the synchronous motor was obvious. The table below shows the ratios between AC motors and synchronous motors.

Table 5

Power increase	114%
Weight increase	419%
Losses increase	36%
Efficiency deterioration	-18%

Note: Efficiency deterioration does not take into account wasted braking energy.

Application example

Airport luggage conveyor

Description

Conveyors of this type are used in airports to move luggage onto a belt running continuously behind the ticket counters.

While booking passengers and their luggage, the conveyor is at rest. Once baggage has been processed, the belt becomes energized and moves the bags onto the continuously running conveyor behind the counter.

Operation is, by nature, discontinuous with variable loads from several hundred grams to 50 kg. Stopping is repetitive and must be as accurate as possible, no matter what the load weighs.

To ensure correct operation, the manufacturer (Crisplant A/S Denmark) uses an AC motor connected to a VSD.

The machine is controlled by a programmable logic controller, which manages the various position encoders and transmits speed settings to the drive.

The conditions are challenging as the conveyor is constantly starting and stopping, and load weights can vary dramatically.

Manufacturer objectives

Crisplant A/S Denmark wanted to carry out a comparison between synchronous and AC motors without changing the drive. The goal was to check energy consumption and stopping accuracy with no load and full load.

Hardware

The hardware was supplied by Schneider Electric. The characteristics of the components are indicated in the following table:

Table 6

Motor	BMH1402P06A1A
Inertia	3 10^{-4} m² kg
Rated current	9.8 A
Rated speed	3,500 rpm
VSD	ATV32BHU40N4

Benchmark testing

The test was performed in a laboratory setting, which correctly reproduced real-life conditions.

The load on the conveyer was adjusted up to 50 kg.

The conveyer was accelerated to 67 Hz (3,500 rpm) then stopped.

Motion was carried out in the two directions of displacement, forward and backward, with and without a load.

Test procedure

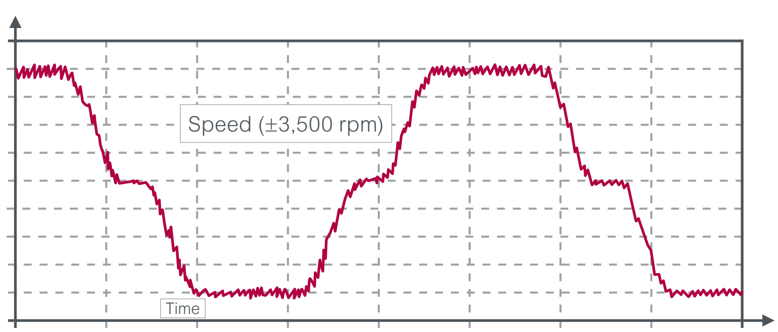
After introduction of the motor parameters, VSD auto tuning was performed, which allowed fast adjustments.

The following records represent the machine speed as a function of time.

No-load test:

A slight oscillation in speed was noted without a noticeable effect on the conveyor displacement. Stop precision, which was one of the key points, stayed within ±1 mm.

Figure 12



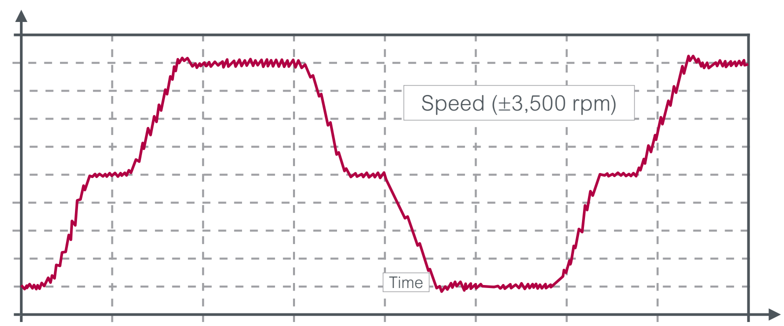
Test with a 50 kg load

Oscillation was well damped and both acceleration and deceleration slopes were identical between no-load and full-load conditions.

An acceptable overshoot was noted for the operation.

Stop precision was within ±2 mm. This difference was insignificant for this application.

Figure 13



There is no doubt that using a dedicated servo drive, like the Lexium 32, which ensures synchronous motor servo control, would have given better positioning accuracy, but the customer requirements were fulfilled.

Energy savings

The following data was given by the conveyor manufacturer.

Tests were done with two similar conveyors, one driven by a synchronous motor, the other by an AC motor.

Motor sizes were identical (1.5 kW).

Table 7

Operating conditions	Synchronous	AC motor	Savings
Running continuously in one direction	320 W	450 W	29%
No load	240 W	340 W	29%
10 kg	280 W	340 W	28%
30 kg	370 W	390 W	28%
50 kg	460 W	640 W	28%

Test results indicated a significant energy savings by the synchronous motor.

Conclusion

In the examples of electrical motor efficiency presented in this document, we have compared AC and synchronous motors based solely on their technological capabilities.

Results indicated that the replacement of a 1.5 kW AC motor with a synchronous motor of an identical size generated nearly 30% more energy savings. The use of a dedicated controller would further improve performance dynamics and efficiency.

We made the choice not to compare other solutions, such as more sophisticated motion control solutions, which would provide even greater efficiency. These processes would allow increased productivity and reduced production time, which is beneficial to the manufacturing chain as a whole.

A closer examination of the machine, its modes of operation, and dynamic performances is the best way to choose the most suitable motor technology. Use of a synchronous motor allows up to 20% energy savings while increasing performance.

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