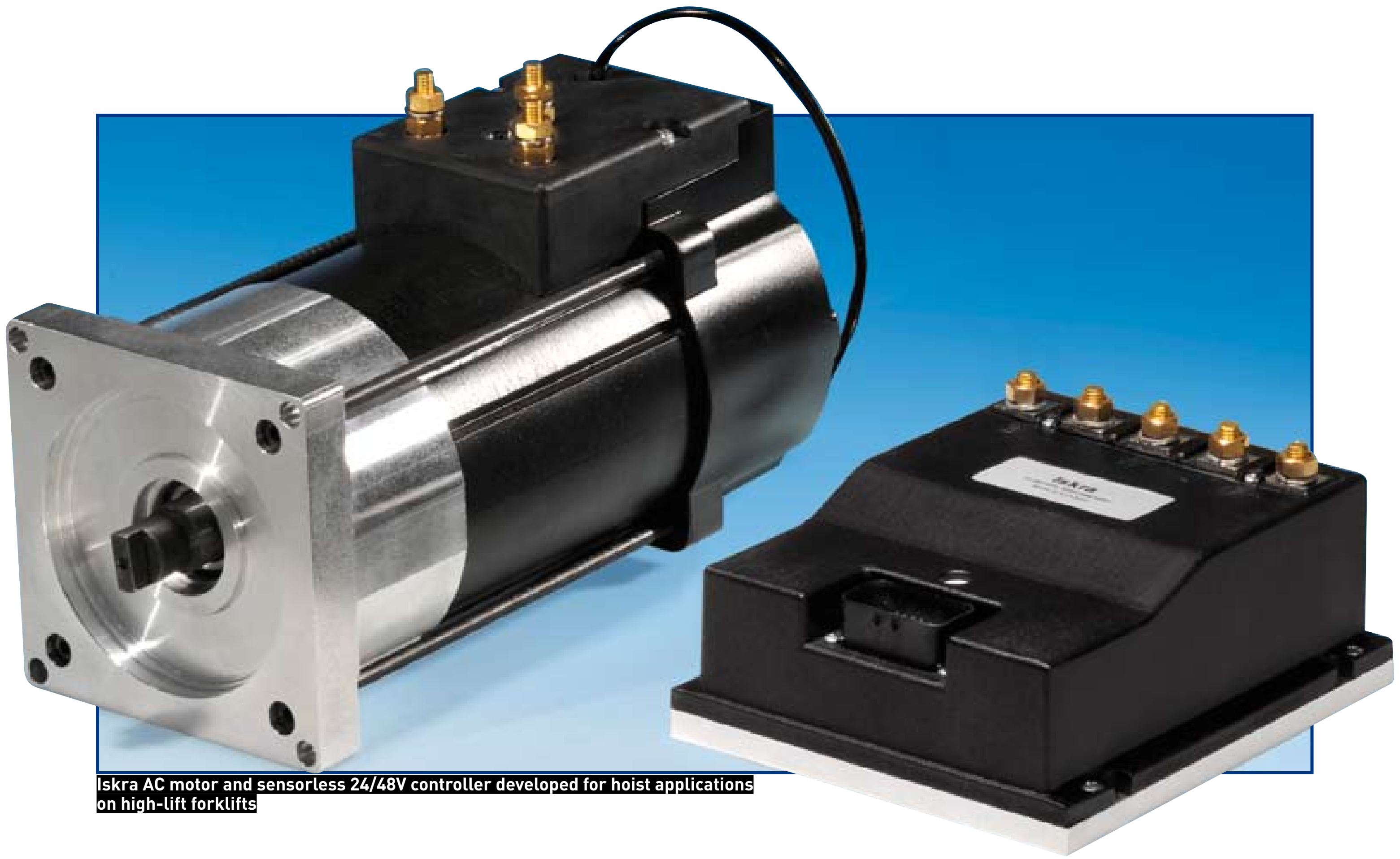
IZTOK SPACAPAN

GOING DOWN FAST

LOWERING THE LOADED FORKS OF HIGH-LIFT FORKLIFTS RETURNS ENERGY TO THE BATTERIES MAKING FOR A RELIABLE AND COST-EFFECTIVE AC SYSTEM



Iskra AC motor and sensorless 24/48V controller developed for hoist applications on high-lift forklifts

AC induction motors are the best choice for traction motors used in various electric vehicles. They are robust, have good dynamic behaviour and better regeneration than any other motor (four quadrant operation).

Experience of traction applications gives the basis for development of AC systems that can be used in hydraulic systems for high-lift forklifts up to 12m. The idea is to transform the gravitational energy to electric energy and charge the batteries during the load-lowering phase. To produce an efficient system percentage of returned energy, it is very important to decide which type of electric motor is best. In conjunction with new generation controllers using advanced control algorithms and improved switching sequences, AC systems can be ideal for applications in hydraulic fields.

Iskra's first development goal was to concentrate on efficiency and performance in lifting the load. The next challenge was to develop an optimised system that would be effective when lowering the load, providing good controllability (position and speed regulation) and a high level of returned energy.

Generator mode

An induction AC motor is capable of braking (generating negative torque) in two ways: with inverse braking (slip higher than 1) where the motor needs energy from the source, or with recuperation braking (negative slip) where the motor, because of external energy, is forced to rotate with a speed higher than its own speed. The motor's generated currents can be transferred to the battery, and the three-phase AC controller acts like a rectifier.

The Kloss equation:

$$M = M_m \cdot \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}}$$

describes an induction motor torque characteristic in motor and generator mode. *M* is motor torque; *Mm* is max motor torque, *s* is slip (relative difference between rotor mechanical frequency and frequency of voltages applied on stator), and *sm* is slip at *Mm*.

The motor torque curve for slips from -0.4 to 0.55 valid for 4kW/15V (24V DC) induction motors is seen in Figure 1 (valid for a frequency of 60Hz). Positive slips indicate the motor mode, while negative slips show the generator mode (where the motor is braking with negative torque).

The unique characteristic of the induction motor (compared to other motor types) is the fact that it is capable of generating higher torque levels in the generator mode than in motor mode. This is valid for the complete frequency range, although frequencies from 2-250Hz are usually used in AC systems for electric vehicles; but it also depends on the number of motor poles. Figure 1 highlights a 60Hz stator frequency, where maximum torque in the motor mode is 48Nm, and 82Nm in generator mode. Higher generated torque results, of course, in a higher level of recuperated current.

Implementing AC systems

Traction AC motors are in recuperation mode when the vehicle is braking (during deceleration), transforming kinetic energy into electric energy. This same idea can be used in a hydraulic hoist application; the difference being that here the gravitational energy is transformed into electric energy during the lowering of the load on the forks, especially on 12m lift-height forklifts where the time to lower the load to ground level is over 10 seconds.

Using the basic physics equation $E = m \cdot g \cdot \Delta h$ [$kg \cdot m^2/s^2$=Joule] (*m* is load weight, *g* is gravitational acceleration: $9.81 m/s^2$, Δh is height difference), it is easy to calculate the amount of gravitational energy which can be theoretically transformed into electric energy during the load lowering phase.

There are certain losses in hydraulic and electric systems, and with extensive testing, Iskra has proven that this energy can be high and important for vehicle autonomy. It means that run time between battery charges can be increased.

The motor operation was divided into three scenarios: lifting of loads, lowering of light loads and lowering of heavy loads. During lifting, the motor rotates the pump, forcing the oil to flow from the reservoir to the cylinders and lift the forks, while the motor takes energy from the battery.

Typically, a proportional valve (with its current consumption) is used for lowering loads (independent of their weight) to return the oil to the reservoir. Motor and pump are not engaged in this case.

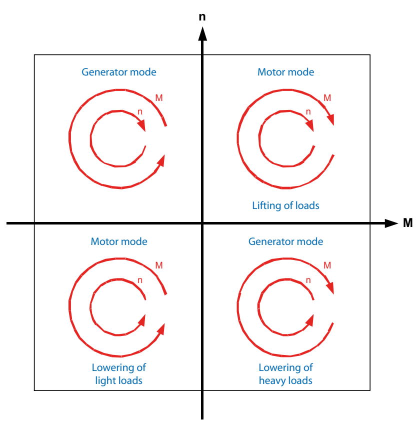


FIGURE 2: **Motor scenarios during lifting and lowering of load**

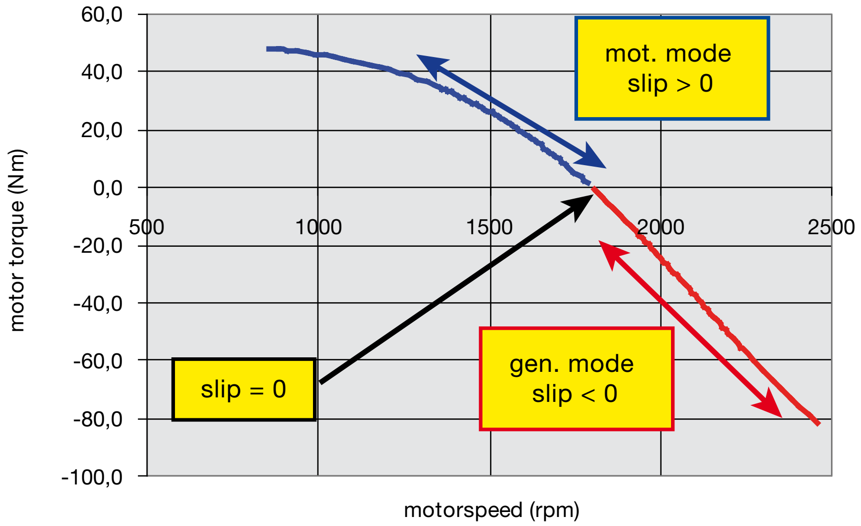


FIGURE 1: **Induction motor curve (motor mode and generator mode)**

But this presents two scenarios. If there is a heavy load on the forks, then it is wise to use the gravitational energy, go into recuperation mode and charge the battery. The AC controller controls the lowering procedure precisely (the safety level is very important here!)

If there is a light load or no load, then the operator will usually want to lower quickly. Recuperation mode in this case will take too much time because there is low gravitational energy, and the level of returned energy will be practically negligible. It is better to run the pump motor in motor mode with reverse direction and driving the pump in reverse, which enables the oil to flow from the cylinder back to the reservoir. As gravitation helps the motor rotate, motor current consumption is very low and the motor is close to synchronism, with *slip* a little bit higher than 0 and almost comparable with proportional valve consumption.

How does the system know if there is light or heavy load on the forks? In principal, a pressure switch (or pressure sensor) is needed in the hydraulic system. However, Iskra has developed special software where this pressure switch or sensor is not needed. The system itself recognises the load, and decides which lowering scenario to take. Of course, the threshold pressure is set by the end user, or lift-truck OEM.

All three motor operating scenarios are illustrated in Figure 2. The simplified equation for the ratio between DC battery charging current in the generator mode during lowering the load, and DC current needed in motor mode when lifting the load is: $i = \eta_{el}^2 \cdot \eta_h^2$

From the theoretical knowledge of electric efficiencies (induction motor+ controller) and hydraulic efficiencies (pump+tubes+valves+cylinders), the expected ratio is in the range from 0.5-0.62. Measurements performed on real 24V and 48V applications confirm these starting suppositions.

In present systems, the motors and corresponding controllers are engaged only while lifting, while during lowering a proportional valve controls the hydraulic flow flowing from cylinders to the reservoir. The electric motor, controller and pump are not operating at that time. In the solution described above, there are currents running through the motor and controller also during the lowering phase (recuperation mode) and they additionally heat up the motor and controller. Special care must be taken when designing such a motor and controller. With the new motor design approach (optimised lamination design, modified windings, improved heat dissipation) the motor size will not need to be increased. Neither is controller size and life time problematic, provided an Iskra advanced power stage with optimized construction and improved heat dissipation is used.

Sensorless solutions

There is always a question of system reliability where there is a presence of encoder (or other electronic devices) in the system. For this reason, sophisticated software that does not require motor speed information was developed. The only connection between motor and controller needed are the three power cables.

A typical sensorless solution is problematic when the motor operates at speeds close to zero. The sensorless solutions are very complicated because traction applications are very frequently in the situation of working with very low speeds (around zero) and changing the direction of rotation.

Hydraulic applications are different, in that motors usually do not operate close to zero speed, because some minimum speed is typically critical for pump life. So, this is perfect opportunity to use a sensorless solution.

The hardware connection is shown in Figure 3. Such a controller does not need a speed sensor and consequently the sensor interface is not required – there are no sensor cables and connectors. So the use of a sensorless AC controller results in a less expensive, mechanically simpler, more compact, and more reliable system.

The main difference between a sensor and a sensorless control lies in the software. Rotor speed is calculated from two applied voltages and two measured currents; a task that is usually performed with software system observers or estimators. The mathematical model of the motor is very important, because knowing the exact values of the motor parameters ($L\sigma s$, $L\sigma r'$, Lm, Rs, Rr', p) is necessary. The latest improved self-teaching procedures are very helpful here.

Sensorless algorithms are quite complicated and sensitive to the changes of motor parameters due to temperature and saturation effects. Software modules for compensating purposes were implemented to reduce these negative effects.

Features of Iskra's sensorless control algorithm include:

- Full starting torque at zero speed;
- A selectable torque/speed working mode;
- A built-in auto-tuning procedure for measurement of motor parameters and adjustment of the most important control parameters;
- Tunable acceleration/deceleration ramps and protections;
- Optimised efficiency for a defined working point;
- Possibility to adapt the parameters of the controller for an optimal motor control at different working temperatures;
- Control of the controller and motor via analogue inputs and switches or over the CANbus.

The sensorless control algorithm can be implemented in a variety of Iskra controllers. The main problems of sensorless algorithms in the past was to get the full torque from the motor at start-up, to hold that torque for a prolonged time and to start rotating the motor shaft with (relatively high) torque already present on the motor shaft. Great efforts were made improving these algorithms and the solution is here.

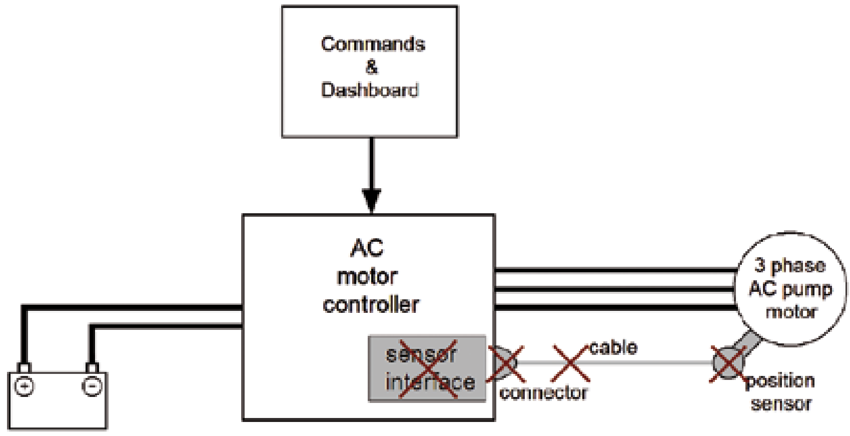


FIGURE 3: **Elimination of the speed sensor in hydraulic/hoist AC application**

Figure 4 shows the comparison of speed responses with encoder and without encoder. Reference speed was 2,000rpm, with the motor starting to run with a load already present on the shaft (approximately 20Nm).

It can be seen that a sensorless algorithm initially takes approximately 0.2 sec for initialisation – after that it can normally follow the reference. About 95% of reference speed can be reached approximately one second after the encoder solution – completely acceptable for most hydraulic systems.

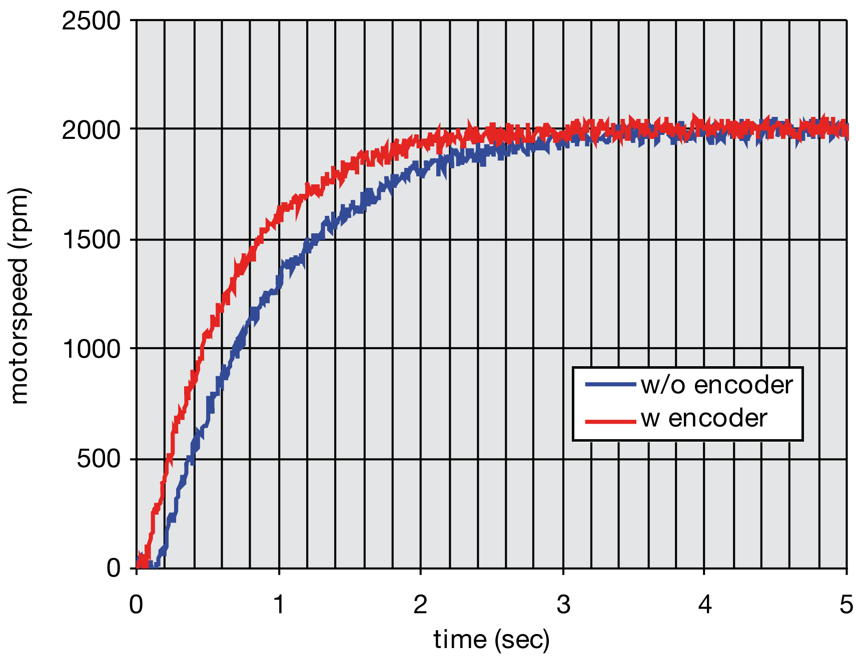


FIGURE 4: **Comparison of motor speed responses: with/without speed sensor**

Summary

The challenge at the beginning of the project was to make a system which will be efficient in both motor and generator modes with a minimum number of additional electronic devices. Tests on real systems prove that, using advanced software solutions, three electronic devices can be eliminated from the system: the AC motor encoder, the pressure sensor/switch which determines whether it is a light or heavy load, and the proportional valve.

Iskra is offering a full range of AC motors from 1-20kW that can be used in hydraulic hoist systems together with 24V and 48V families of advanced AC controllers. The new line of AC controllers use an improved vector field algorithm in combination with space vector modulation (SVM) where switching losses and higher harmonics are minimised.

The system described above has been tested and proven on actual hydraulic system applications and will be on the near future. **iVT**

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