PIKTRONIK

Piktronik d. o. o.
Cesta k Tamu 17
SI – 2000 Maribor, Slovenia

Phone: +386-2-460-2250 Fax: +386-2-460-2255 e-mail: info@piktronik.com www.piktronik.com

Sensorless AC motor control for traction applications

Authors: **Dušan Drevenšek, Branko Premzel**

Introduction

New technologies are continuously enabling new engineering solutions. Continued advancements in AC drive technology, computer technology, and the need for better efficiency and reliability have propelled a strong trend in replacing DC drives with AC drives in various electrical vehicles in the last years. The main advantages of the AC drives are less maintenance, better efficiency and decreased motor size. But the story continues. The next step can be reduction of the component count and cost of AC drives, increased reliability, which can be made by further advancements in AC drive technology and faster embedded microcomputers. The idea here is removal of the speed or position sensors from the motors and it is called sensorless control. As always with new technologies and new approaches, there is some reluctance by the industry, but with the maturing of the sensorless drives they will find their way into the market of electrical vehicles more and more. Sensorless control can be applied to all popular kinds of AC motors: induction motor (IM), permanent magnet synchronous motor (PMSM) and switched reluctance motors (SRM).

Of course, even very sophisticated control algorithms running on fast microprocessors can not replace physical measurements with the same or better accuracy. Thus the sensorless control principle can not compete with AC control principle incorporating incremental encoder in all applications, but there are many applications, where the sensorless control has clear advantages, especially where a very high reliability is required, where there is a high cost of replacement or repair or in price sensitive applications.

This article will discuss the advantages and drawbacks of sensorless motor control and its opportunities in the market of electrical vehicles and similar applications.

Sensorless AC motor control – how does it work?

The main function of the AC motor controller is electrical energy conversion from a DC source (battery) to the three–phase system with variable voltage and current amplitude and frequency, which supplies the motor. The conversion is achieved by microprocessor controlled pulse width modulation. The three–phase voltage has to produce at the command the required motor behavior, which is mostly either speed or torque control.

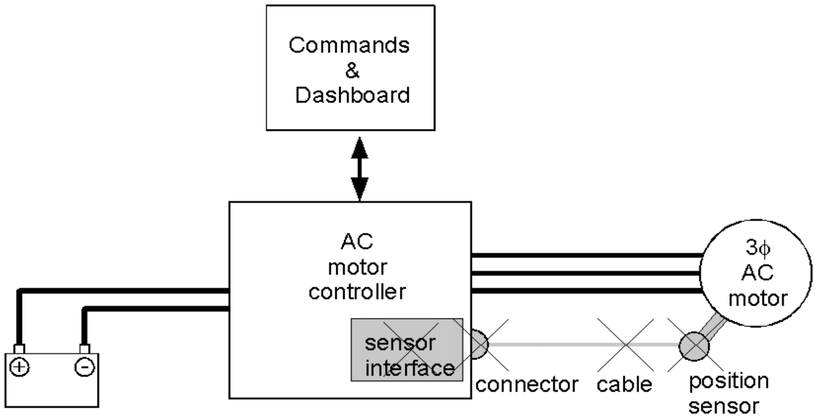

Fig. 1: Grayed components are not needed for sensorless AC drive

Classical vector control drives use either position or speed sensor on the motor shaft. Incremental encoder is mainly used for this purpose. The function of the sensor is not only speed measurement. For proper flux vector orientation the rotor position and speed are very important pieces of information which enable vector control. The main characteristic of the sensorless drive is the absence of the position or speed sensor on the motor shaft (see fig. 1). Although different AC motor types have different properties, the sensorless control can be applied to all of them. The shaft position/speed that is needed for the proper control of the AC machine is in this case not directly available from the incremental encoder mounted on the motor shaft, but from other variables that are available to the motor controller. Measured physical values in sensorless drives are motor phase currents and DC link (battery) voltage. Using the mathematical model of the motor and knowing its electrical parameters, it is possible to estimate unmeasured motor variables as back EMF, flux, torque, rotor speed and position. Although mathematical models for different kinds of motors differ and there is a variety of different possible sensorless methods, the main sensorless principle is based on back EMF of the motor. Other sensorless principles try to use secondary effects (stator core saturation, rotor saliency) for flux position detection, and they can be used supplementally, but they usually require additional processing power, control algorithms are getting very sophisticated, analog to digital converters have to be more accurate, and nonetheless, such methods may require a special motor design.

Advantages and drawbacks of AC sensorless motor control

The main advantages of the sensorless motor control are:

- lower system costs due to the lower component count - position/speed sensor, corresponding cables, connectors and signal interface are not needed,
- increased reliability,
- no problems with the sensor and sensor interface noise,
- extended motor temperature range (the temperature is not limited by any semiconductor sensor mounted inside or on the motor).

Since the sensorless controller does not measure the shaft position/speed, it can only be estimated from the available motor phase currents and voltages. The speed estimation can only be accurate as long as the rotor speed is reflected to the stator, and this is possible through back EMF of the motor. The critical point is when the back EMF becomes zero. At that operating point, there is no information about the motor flux angle and proper control of the motor is not possible. For PMSM and SRM this happens at zero speed, which also equals to the stator current zero frequency. For IM this happens only at the stator zero frequency, but not necessarily at zero speed. Of course, it is not just one frequency that makes trouble, but it is the area around zero frequency. The size of the frequency range around zero with poorer control performance depends on the control implementation. At higher speeds, the sensorless drive performance is not much different as with the classical AC drive. It is very important that the efficiency of the drive is not deteriorated by the sensorless control principle; moreover, the motor control principle can be combined with efficiency optimizing algorithms, as this is the case with Piktronik's motor controllers. Efficiency optimization can contribute to lower operating costs, reduced component stress and the increased autonomy of the battery powered system.
The accuracy of the estimated values inside the controller depends on the control algorithm, mathematical model of the motor, accuracy of the parameters and the quality of the measured currents and voltages. Therefore sensorless control algorithms are sensitive to the perturbation of motor parameters. Motor parameters are not the constants. The stator resistance depends on the winding temperature, inductances of the motor depend on the saturation level of the core. At low speeds the control performance mostly depends on the accuracy of the stator resistance. If the motor temperature is measured, the stator resistance can be easily estimated, otherwise there are some sophisticated algorithms for stator resistance estimation. At higher speeds the stator resistance becomes less important.
Performances of the sensorless drives depend on the motor type. For widely used motor types such as IM and PMSM, the main features are described separately.

Sensorless control of induction motor (IM)

With sensorless control, the IM is capable of developing a full starting torque, thus acceleration from zero is not deteriorated. At higher speeds the behavior is practically equal to classical vector control. Piktronik's sensorless controllers also incorporate efficiency optimizing, which means that the magnetizing level depends on the load torque and the efficiency in the low torque area is therefore much better than with classical control without energy optimizing.

The weak point of sensorless control with induction motor is zero frequency. This happens at low motor speed when the signs of the speed and torque are at the exact opposite. Practically this means poor braking at very low speeds. Despite this drawback, we use sensorless control for traction applications and driving performance is satisfactory. We drive leisure vehicles in torque mode, which means that the vehicle responds faster to driver’s commands and thus the fun factor is greater than with the same vehicle using the controller with sensors and the speed control loop.

We see the performance of the sensorless AC control principle to be adequate for:

- traction of electric pallet trucks,
- hydraulic pumps for forklifts,
- floor cleaning machines,
- propulsion drives for boats, yachts in battery powered or hybrid systems,
- leisure vehicles,
- industrial, airport and similar electrical vehicles.

Sensorless control of permanent magnet synchronous motor (PMSM)

With PMSM, the zero frequency problem arises at zero speed. Consequently, the operating area where the motor is not controllable is around zero speed. This makes the PMSM unattractive for traction application, where full torque is usually required for acceleration at zero speed. However, this doesn't mean that such system can not start. If the load has such characteristics that it can be moved without long delay after the torque has been applied to it (small inertia moment), then the motor can be started by applying small frequency to the stator current. When the rotor moves, the back-EMF becomes available from the motor and the drive system can operate normally from that point on. In other words, such system can be used in applications with reduced starting torque. Such applications can be fans or pumps. We use sensorless control for electric boat propulsion successfully.

If one needs the full starting torque with PMSM, there are two cheap solutions.

The first solution relies on cheap hall sensors that can be built into the motor. These sensors do not need to have analog outputs, it is sufficient to have digital outputs. With three sensors, it is possible to determine the rotor position in sectors of 60 electrical degrees, which makes it possible to develop the full torque at zero speed. When the rotor reaches some minimal speed, the controller does not need sensor information anymore. This is not a pure sensorless solution because it uses sensors for the rotor position, but there is no need for the costly position sensor.

The second solution is a true sensorless system, but it can not be applied generally. It could only be used with a motor where the rotor position could be detected by inductance changes that are caused by stator core saturation, spatially distributed in dependence on the rotor position. The drawback of this solution is that it can not be used with all motors because the motor needs to have certain properties, and secondly, this method causes additional acoustical noise, induced by high frequency voltage injection.

Some application examples

Sensorless AC motor drives in battery powered systems already exist. In the figure 2 (bellow), three applications using Piktronik's sensorless motor controllers are presented.

On the left there is an EV targeted for elderly people with a 48V battery and a SAC0 motor controller driving an IM (two-seater, top speed 15km/h).

In the middle there is a leisure EV with a 36V-battery system, a SAC0 driving an IM, top speed 45km/h.

On the right there is an electric boat, 216V battery, SAC40 driving 40kW IM

Fig.2: Sensorless AC motor control is already used in traction drives (left, center) and boat propulsion drives (right)

Conclusion

Sensorless control of AC motors for applications in electric vehicles is a new concept. It can be advantageously used in applications where its limitations are not important for the application performance. We do not recommend using sensorless control for all applications. It is not optimal to use sensorless control for traction drives in forklifts because a sensorless drive can not operate as smoothly as a drive with an encoder at very low speeds. If the drive requires holding the vehicle on a ramp with a speed or position loop, we wouldn't recommend sensorless control either. But on the other side, there are plenty of applications where sensorless dynamical characteristics completely meet the requirements and outperform classical drives with sensors in terms of costs, reliability, ease of installation and temperature range of the motor.
Performance of sensorless drives has been practically proven in electric vehicles and electric boats. It has been shown that the sensorless AC drives with IM or PMSM can not be used only for simple applications like pumps or electric boats but also in traction applications.

Piktronik's motor controllers can control either in speed or torque mode both the IM and the PMSM, where the motor type is selected by parameter. They include safety functions for electric vehicles and battery protection functions that prevent deep discharging and overcharging, and they can be controlled via analog/digital inputs or via CAN bus.

We see a great opportunity for sensorless AC drives to enter the market of utility vehicles and we hope the industry will recognize the chance for the next technology step. And there are plenty of other applications which can also profit from this new technology.

Company Piktronik is active in the field of battery powered systems such as sensorless AC and DC motor control technologies and programmable battery chargers. (Fig.3 shows the family of sensorless AC motor controllers)

Fig.3: Piktronik's sensorless motor controllers (left: SAC40, center: SAC0. right: SAC4), which cover the range 1kW - 50kW