Digital Control of Industrial Servo Drives for Machine Tools

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Keywords
Adjustable speed drives, Brushless drives, Drives, Industrial Applications, Machine tool drives, Motion control, Servo drives, Variable speed drives

Abstract

After completing the development of industrial servo drives with complete digital control further improvements are to be expected in the field of smooth operation, EMC and safe operation. This paper shows the state of the art concerning these issues and indicates the directions of further developments.

Servo Drives in Industry

Recently new generations of servo drive with completely digital control have been introduced to market by several manufacturers. This shows, that the commutation from analogue to digital drive control is now completed even in industrial products with high production quantities.

The features of these drives commonly are:

- No drifts and no offsets in speed and position
- Digital interface [1] (providing full access to all relevant data of the servo drive – e.g. reference values and real values in the real-time control)
- Reduced number of wiring and cables

Besides that there are some advantages provided only by digitally controlled servo drives of the newest generation:

- Completely digital control of position, speed and current [2]
• Field oriented control for asynchronous machines as well as for synchronous machines (it is not necessary any more to differ between feed drives and spindle drives; identical inverter hardwares and control schemes are used in both cases)
• Simple start-up optimization of the drive control by reading some information from the electrical machine connected to the inverter on-site (examples: giving the motor type as an input to the drive control, reading a chip card with motor information, reading an „electronic name plate“ which is integrated in the motor itself)
• High resolution optical encoders for simultaneous sensing of position and speed provide resolutions of several million positions per revolution
• Intelligent start-up and installation tools (detailed text messages via digital interface for diagnostics and service purposes; use of sophisticated service equipment - e. g. PCs - giving access to all parameters and data of the servo drives and assisting the customer’s optimizations and adjustments; e. g. [6])
• Power supply with reduced line harmonics [3] (viewing the mains as an electrical machine with very special characteristics enables the use of the same field oriented control as on the inverter’s drive side; the current control provides very low harmonics in the mains)
• Voltage control in the DC link (providing a voltage tolerance of about 1% leads to a better design of the electrical machines, as it is not necessary to consider big tolerances in the operation point; narrow tolerances and a high DC link voltage lead to better drive efficiencies and better use of field weakening ranges of asynchronous machines)

The characteristics mentioned above have introduced servo drives with digital control to many industrial applications within and outside the machine tool industry in spite of slightly increased prizes in comparison with analogue controls ([4],[5],[6]).

The following remarks deal with drive features becoming more important than in the past when using servo drives with digital control.

**Smooth Operation**

Smooth operation of a servo drive has become more difficult when replacing servo drives with analogue control by digital control. As the cycle time of the control has to become shorter and shorter to provide improvements in drive behaviour, the resolution of an encoder used in the drive also must increase more and more. Otherwise in many control cycles there will be only few or even no information from the encoder during low speeds. Fig 1 shows the comparison between a modern optical encoder and a well-known resolver concerning angle accuracy. The deviation of the position error is a measure for the ability of smooth operation at very low speeds.

![Position error of a resolver and a modern optical encoder](image)

*Fig. 1  position error (angle error) of a resolver and a modern optical encoder*
To operate a servo drive with the speed of a clock’s hour-hand – which is not unusual – an encoder resolution of several million positions per revolution is necessary to guarantee really smooth operation.

Of course, it is nearly impossible to design encoders like this. Today’s compromise is to use optical encoders with rather high line numbers (e.g. 5000) with sinusoidal output signals and to interpolate the signals in the drive’s electronics by an additional factor (e.g. 256).

In spite of the fact that this is still far away from a standard (not brushless!) tachogenerator’s speed resolution, the smooth operation behaviour of servo drives with digital control has improved significantly. One of the reasons for that is the use of servo motors with sinusoidal quantities instead of so-called BLDC-(brushless DC-)motors and EC-(electronically commutated) motors.

Fig. 2, Fig. 3 and Fig. 4 compare the smooth operation of servo drives with a brushless tachogenerator, with a resolver and with an optical encoder.

Fig. 2  speed behaviour of a servo drive with brushless tachogenerator
Fig. 3  speed behaviour of a servo drive with resolver

Fig. 4  speed behaviour of a servo drive with high resolution optical encoder

Even with a low resolution resolver there is an improvement of about factor 2 compared with a brushless tachogenerator. The commutation of the tachogenerator produces significant speed deviations which cannot be compensated by the drive control, because the tachogenerator is a component of the feedback loop. The use of more or less sinusoidal signals produces a better speed behaviour without better physical conditions within the sensor. An optical encoder improves the
smooth operation at least by factor 8 – 10 in comparison to brushless tachogenerators, which are commonly used with analogue drive control.

**Synchronized Control**

To control synchronous and asynchronous machines the servo drive uses the same control structure (e.g. field oriented control). Depending on the type of servo motor connected to the inverter the microcomputer activates some software subroutines. Any hardware or software change is not necessary. This concept supports a modular design of servo drive systems. Any drive system can be composed of inverter modules (different powers), servo motors (different types and powers), control modules (different interfaces and different encoders) and power supplies (different powers) according to the special needs of the application.

The cycle times of modern drive controls are:

- $< 250 \mu s$ for position control
- $< 40 \mu s$ for speed control
- $< 40 \mu s$ for current control

Within each drive, cycle/switching/recovery times of inverter, control, interface, encoder and microcomputer services have to be perfectly combined to achieve same or better performance as it is known by servo drives with analogue control. It is necessary to synchronize internally all parts taking part in the drive control. Fig. 5 and 6 show the difference in the drive currents between servo drives with digital control without and with internal synchronization.

**Fig. 5** current shape of a servo drive without internal synchronization between inverter switching and control cycles [7]
Fig. 6 current shape of a servo drive with internal synchronization between inverter switching and control cycles [7]

Fig. 7 and 8 show the fourier spectrums of drive currents without and with internal synchronization of the digital current control.

Fig. 7 fourier spectrum of a servo drive’s current without internal synchronization

Fig. 8 fourier spectrum of a servo drive’s current with internal synchronization
In Fig. 8 the parameters of the digital current controller have been increased by more than factor 3, which would lead to a completely unstable operation of the control without synchronization. Synchronization reduces current harmonics (and torque ripples) and additionally enables to increase the controller parameters for less control deviation.

Today’s servo drives provide 24 bit or 32 bit control processors and internal cycle synchronization to improve the drive’s behaviour and to avoid any drawback like additional torque or current ripple.

Applying several servo drives as a whole system for multidimensional motion control the additional challenge to synchronize not only the components within each drive, but also the drives taking part in the coordinated motion with each other. This is only possible by using a special synchronization interface or – what is more sophisticated – by using a digital interface with integrated synchronization procedure (e.g. SERCOS interface [1]).

EMC

The development of „digital“ servo drives meant integrating microcomputers into inverter modules. This is possible today without internal negative interferences between power stage and micro computer. Using identical inverter structures and inverter controls on both the drive side and the line side it is possible to reduce interferences on the mains as well. The mains can be viewed as a big synchronous machine and therefore be controlled by a drive controller. Using a 3 phase (or field oriented) current control the line currents can be forced to any demanded shape (e.g. sinusoidal). All ideas, which have been developed in the past to reduce the ripple currents in inverter supplied electrical machines can be used for line currents as well. The result is a significant reduction of harmonics in the line currents. The 5th harmonic can be easily reduced by a factor of 8 – 10 ([3]). Controlled inverters in the power supply are the best way to meet the newest demands and requirements of the EMC directive and the standards related to it.

Safe Operation

A significant reduction of encoder costs has introduced multi-turn absolute encoders to standard industrial applications. This has opened the way to provide servo drives with integrated „safe operation“ features ([8]). This allows to operate the machine even with opened doors (e.g. during teaching), because the drive guarantees a safe speed limit or standstill even when producing torque.

Each drive has its own processor control – using field oriented control the processor has all informations to define the drive’s position and/or speed. For safety functions the processor can do that based on information from the electrical machine only and without considering any information from the encoder (speed/position sensor). The servo motor itself is used as a speed/position sensor by the microprocessor (for control purposes – accuracy etc. - of course, the encoder’s information is used by the processor as well). When using a processor independant encoder hardware to define the drive’s position and/or speed, a second (redundant) channel comes into being which can be used for safe operation of the servo drive. Both channels – the encoder hardware as well as the microcomputer compare the real speeds/positions with each other. In the case of a difference both channels switch off the drive – this type of emergency action is performed in two independant channels : the encoder hardware blocks the drive’s inverter and the microcomputer switches off the main switch of the drive system. This procedure provides sufficient safety even when staff is operating directly at the machine tool.
To avoid any danger during standard operation (which is not a safe operation condition) it is advantageous to integrate the locking mechanism of the machinery into the drive’s equipment. The drive only releases the door to be opened when safe operation condition is required and reached or the power of the drive system is switched off completely. Without closing the door the safe operation condition cannot be left by the drive. All information necessary is provided in more than one channel to meet the safety standards. Similar influence is provided by connecting the machine tool’s emergency switch off as a double channel signal to the servo drive. When there is a separate power supply with microcomputer control in a multi-axis servo drive system, it is not too difficult to deal with emergency and safety supervision and switch off in a double way – in the power supply’s control equipment and in each drive’s control equipment. The information exchange between the different microcomputers takes place by active and dynamic signals indicating each interruption at once to each controller.

In spite of using only one encoder per drive the whole system is completely redundant concerning speed/position supervision, power switch off and door and emergency switch off interface. Therefore the system was certified by a Swiss safety agency as a safety related component. This means that using this system a manufacturer of machine tools or similar safety critical machinery has much less problems than in the past.

**Conclusion**

The resolution of the encoders can be viewed as the narrow-gap in servo drives with digital control. Nevertheless today’s servo drives fulfill nearly all requirements in the market – therefore the increase of resolution in encoder concepts or the development of control algorithms being satisfied with low encoder resolutions is not a very big issue in industry’s research. With respect to many applications their effort is concentrated more to develop drives without or with very simple encoders and sufficient drive behaviour. Whenever a further increase of drive performance will be necessary, encoder technology will be one of the first issues to be dealt with.

After reaching a rather high standard in servo drive performance, issues like EMC behaviour and torque ripple get out of the background. Many new directives, laws and standards force especially inverter and drive engineers to increase their efforts. Reducing the drives’ torque ripples it is not sufficient any more to design a proper magnetic circuit of the electrical machine – control synchronization to the inverter’s switching and the encoder characteristic gets more and more important.

Besides that the industries requirements for servo drives manufacturers include additional features like safe operation or door management. In the next future servo drives will compete by offering more or less of these additional – not necessarily drive typical – features.

**References**