# Speed controlled single spindle drives for textile machines

**Volker S. Bosch**
volker.bosch@z.zgs.de

*Abstract*—

**In the past, electrical single spindle drives have been rarely used in textile machines. Only spindles with high power requirement – e. g. cabling machines – are provided with inverter fed induction motors. In case of spindles with smaller power requirements – for example ring spinning machines – the classical belt drive still dominates.**

**This report describes the development of an economic electrical single spindle drive for textile machines. In addition to manufacturing costs, the demands for a high degree of efficiency and exact speed control have to be considered.**

**A comparison of different electrical motors – and the associated frequency converters – shows the advantages of a brushless DC motor design. The rotor position sensing of the described brushless DC motor spindle drive can be realized without sensors by monitoring the motor voltages.**

## SYMBOLS

| **Symbol** | **Description** | **Unit** |
|---|---|---|
| $f$ | Frequency | Hz |
| $t$ | Time | s |
| $T$ | Periodic time of motor voltages | s |
| $u_1$ | Motor voltage (EMF), phase 1 | V |
| $u_{1,I}$ | Fundamental voltage, phase 1 | V |
| $u_{2,I}$ | Fundamental voltage, phase 2 | V |
| $u_{1,conv}$ | Voltage of converter phase 1 | V |
| $u_{1,III}$ | $3^{rd}$ harmonic voltage, phase 1 | V |
| $u_y$ | Voltage of the motor wye connection | V |

## ABBREVIATIONS

| **Abbreviation** | **Description** |
|---|---|
| ADC | Analog digital converter |
| ASM | Induction motor |
| CONV | Converter |
| el. | electrical |
| MUX | Multiplexer |
| $\mu$C | Micro controller |
| PM | Permanent magnet |
| PWM | Pulse width modulation |
| SM | Synchronous machine |
| Y | Wye |

## I. INTRODUCTION

Textile machines consist of a huge amount of spindles, e. g. ring spinning machines have up to 1200 spindles. Even today most of these spindles are belt driven by one central motor in the textile machine. Merely spindles with high power requirement – e. g. cabling machines – are provided with inverter fed induction motors. But these are most often drives with a common frequency converter, feeding a common three phase AC link. Both types of spindles, the belt driven and the induction motor driven, need additional sensors to monitor the work of the spindle – e. g. speed sensors or sensors to detect the breakage of a filament.

An 'intelligent' single spindle drive could take over the functions of these sensors, reduce noise and save energies. The textile machine would become more flexible with the ability to controll each spindle separately.

The main demands are small processing costs and a high degree of efficiency. Furthermore, a speed control is required, as well as a communication interface to the controller of the textile machine. The electronic devices should be integrated into the motor housing. The substitution of external sensors requires the measuring of the shaft torque [1], [2].

The main demands on the drive are:

- Low manufacturing costs
- Low material costs
- High power efficiency
- Long service life time
- High accuracy of rotation speed
- Monitoring of the textile process without sensors
- Synchronized speed of spindles and auxiliary drives
- Integration of power electronics into the motor housing

## II. COMPARISON OF THE RELEVANT MOTOR DESIGNS

An electrical single spindle drive could be realized with one of the following types of motors:

- DC motor
- Three phase induction motors (ASM)
- Three phase synchronous motors (SM)
- Reluctance motors (RM)
- Hybrid motors (combined ASM and SM)
- Brushless DC motor

Reluctance and hybrid motors will not be considered here, because they have the same disadvantages and no additional advantages compared to induction motors or synchronous motors for usage as textile machine single spindle drive.

### *A. Permanent magnet excited DC motor*

The main advantages of a permanent magnet excited DC motor are the high power efficiency and the comparatively low costs of the DC/DC converter, needed for speed control. The speed can be controlled very simply by the armature voltage. The torque is proportional to the armature current, which can be measured very simply. It is possible to manufacture the DC motor automatically, what leads to a cost reduction.

The most important disadvantage is the requirement of maintenance caused by the mechanical wear out of brushes and commutator. The low armature voltage, limited by the number of commutator segments, leads to thick wires in the DC link.

Another disadvantage is, that each motor requires its own DC/DC converter for speed control. This is necessary because each spindle must be shut down independent in case of an error – e.g. the breaking of a filament – and run up after the error is cleared.

### *B. Induction motor*

Induction motors can be feed from one frequency converter in the common AC link. High supply voltage is possible leading to a reduction of the diameter of the cabling in the textile machine. The motor needs no maintenance.

The main disadvantage of the induction motor is its need of reactive power which leads to an oversized frequency inverter. Because of the rotor slip each spindle needs its own speed sensor. Different loads of the spindles lead to different speeds. The slip losses reduce the degree of efficiency. Because of the reactive current the motor current is not proportional to the spindle torque – measuring the shaft torque via the motor current is therefore quite complex.

At least the production of the induction motor is quite expensive because of the small air gap, the rotor lamination and the aluminum cage.

### *C. Permanent magnet excited synchronous motor*

The permanent magnet excited synchronous motor has no excitation losses. It is free of wear out and therefore needs no maintenance. The synchronous motor needs no speed sensor – all spindles run at exactly the same speed.

The construction of a permanent magnet excited synchronous motor is cost efficient because the air gap might be wider compared to an induction motor. The rotor of smaller machines consists only of a simple ring magnet, sticked on the shaft [1]. The motor can be fed with a high voltage to reduce the diameter of the copper wires in the textile machine.

This kind of permanent magnet excited synchronous motor needs a low frequency to start up, because there is no damping cage on the rotor, which would allow a induction start. So each spindle needs its own frequency inverter. Another disadvantage is, that the permanent magnet excited synchronous motor will not operate at higher speeds because of instability caused by the small damping – a result of the high power efficiency [3]

The reactive current depends on the load, so torque and current are not proportional. To reach a high power efficiency reactive current must be controlled by the frequency inverter.

### *D. Brushless DC motor*

The brushless DC motor combines many of the advantages of the permanent excited DC motor and the synchronous motor. It has no exciting losses, and no wear out. The brushless DC motor needs low reactive current, so similar to the DC motor, the current is proportional to the torque. Measuring the shaft torque is therefore easy to realize by detecting the DC current in the DC link. High supply voltage is allowed – only limited by the power transistors in the frequency inverter and the winding insulation of the motor.

Like the DC motor, the brushless DC motor needs a speed control and a speed sensor. Like the synchronous motor it needs its own frequency inverter.

#### D.1 Principle of the brushless DC motor

The brushless DC motor is the combination of a permanent excited synchronous motor and a frequency inverter. The inverter has to replace the commutator of a conventional DC motor. Fig. 1 and Fig. 2 show how a brushless DC motor can be derived from a mechanically commutated DC motor with three armature slots. Its armature winding corresponds to a three phase winding in delta connection. The commutator acts like a three phase frequency converter. Stator (excitation) and rotor (armature) change places.

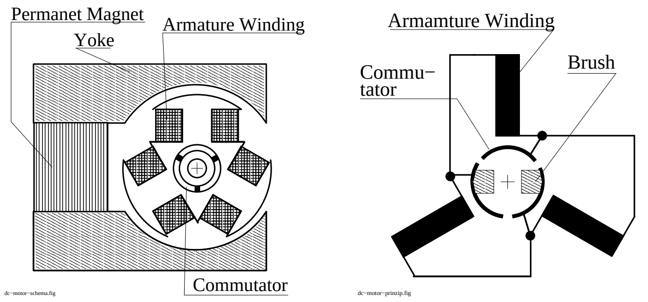

Fig. 1. Principle of a permanent magnet excited DC motor – left: construction, right: wiring

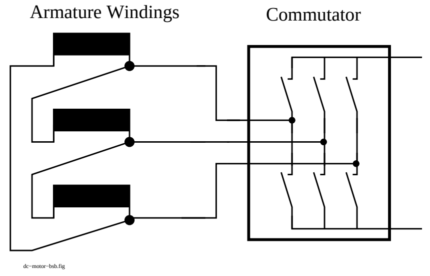

Fig. 2. Principle of a permanent magnet excited DC motor – equivalent circuit

The commutation of a brushless DC motor depends on the position of the rotor. The angle between the magnetomotive forces of stator and rotor is fixed to 90° (el.), so the motor produces maximum torque and needs low reactive current – it might be useful to advance commutation by few degrees to compensate the effects of the stray inductance and minimize reactive current.

Speed can only be controlled by the the motor voltage. The motor behaves like a DC motor. Unlike the synchronous motor there are no problems with instability at any speed.

Because of the PWM frequency inverter, variation of the motor voltage can be achieved easily by changing the duty cycle of the pulse width modulation. Suitable PWM techniques allow regenerative breaking, which increases dynamic and efficiency of the drive.

## III. Structure of the system

The design of the spindle drive is based on autonomous drives, which are supplied with electric power by a common DC link. Fig. 3 shows the schematic diagram of the spindle drives in a textile machine.

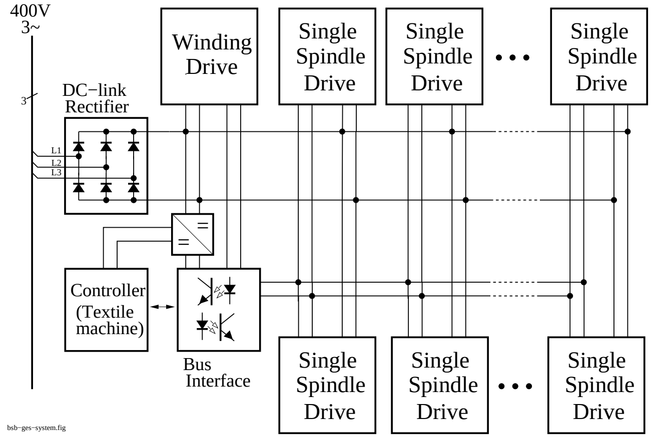

Fig. 3. Schematic diagram of the textile machine

The common DC link is fed from the 400V/3 ∼ power line by a rectifier. If the auxiliary drives, like these for winding up etc. and the controller of the textile machine are fed from this DC link, the kinetic energies, stored in the spindles could span a failure of the mains. This would be a great advantage for the operation of the textile machine in countries with weak power grids. In case of a failure the whole machine can be shut down correctly even without an emergency power supply.

If the line rectifier is not able to feed power back into the mains, other consumers – like the drives for winding up – have to be fed by the DC link. It might be advantageous to use an AC/DC converter instead of the passive rectifier not only because of regenerative breaking, but the textile machine could easily be adjusted to many different line voltages. An adjustable AC/DC converter might also compensate reactive power in the mains, caused by other consumers [4].

## IV. Rotor position sensing

The brushless DC-motor needs a rotor position sensor. There are several possible methods of detecting the rotor position, using sensors like Hall elements or optical sensors (explicit position sensing). On the other hand there are some possibilities of a sensorless detection of the rotor position (implicit sensing), which can be integrated advantageously into a brushless DC motor.

### *A. Explicit position sensors*

Several sensors for detecting the rotor position are available, e.g. incremental indicators or resolvers. Unfortunately they are too expensive for usage in a low cost drive. On the other hand, there is no need for high resolution position sensors in this brushless DC motor design, because the commutation of this motor needs only one pulse every 60° (el.). This low resolution can be achieved by using an optical sensor, detecting marks on the rotor shaft or by placing a hall sensor in the motor windings, detecting the rotor stray field. Optical sensors must not be used in textile machines because of the dust, resulting from the textile fibers. Hall sensors in the motor windings are difficult to mount – and therefore quite expensive. They are sensitive to distortion, e. g. the one caused by PWM.

In any case, explicit position sensors need additional wiring which increases the risk of failure as well as the costs of mounting.

### *B. Implicit rotor position detection*

Implicit rotor position detection by using the motor voltages or currents, reduces the costs of the drives and increases reliability and life time of the drive.

#### B.1 Detecting the saturation of the phase inductance

The stator is saturated by the magnetic field of the rotor in different axis, depending on the rotor position. The saturation results in a reduction of the motor winding inductance. The variation of the inductance can be detected with a high frequency voltage applied to the motor windings. The resulting high frequency currents are modulated by the varying winding inductance.

If the machine is connected to a pulse width modulated frequency inverter the PWM frequency works as a carrier frequency for the rotor position detection [5].

This sensorless method of detecting the rotor position works even in the standstill of the machine. Unfortunately this circuit is quite complex and therfore expensive – in at least two of the three motor phases the current has to be detected.

Using this sensorless detecting on a motor with a high power efficiency will not work correctly, because there is very low saturation in the iron.

#### B.2 Detecting the backward EMF

A very popular method of detecting the rotor position is the monitoring of the EMF. If the motor is fed with 120° voltage blocks, there are 60° intervals when each phase leads no current. During this interval the EMF in the related phase crosses zero. This zero crossing can be detect to determine the rotor position [6].

### B.3 Detecting the harmonics of the induced motor voltages

The induced motor voltages show harmonics with odd ordinal number ($\nu = 3, 5, 7, 9\ldots$), because the flux in the air gap has a rectangular distribution. Harmonic voltages with ordinal numbers divisible by three, create zero phase-sequence systems, which are not accessible by the connections of three phase conductors. As shown in Fig. 4, all third harmonics are in correct phase – they cancel each other out between the three phase conductors and can therefore not be detected from the three phases of the motor in wye connection.

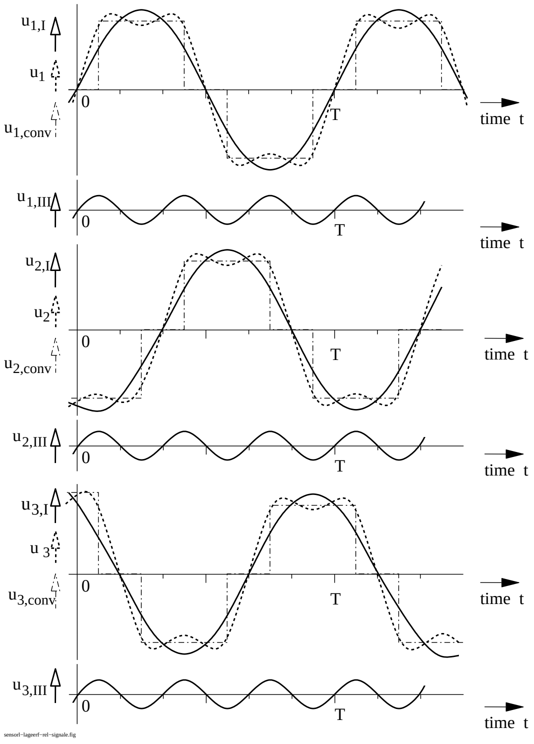

Fig. 4. Induced voltages ($u_\nu$), their fundamentals ($u_{\nu,I}$) and third harmonics ($u_{\nu,III}$) in the three motor phases ($\nu = 1, 2, 3$) and the idealized output voltage of the frquency converter ($u_{\nu,conv}$). Signals according to the equivalent circuit shown in Fig. 5

If the wye connection of the motor is accessible, the zero phase-sequence systems can be detected between this and a virtual wye connection, realized with three resistors. Fig. 5 shows the corresponding circuit. The voltages are tapped off by potential dividers. The reference potential of the sensing circuit may be anywhere between the positive or the negative potential of the DC link.

## V. STRUCTURE OF THE SINGLE SPINDLE DRIVE

The single spindle drive was realized as a brushless DC motor with sensorless detection of the rotor position by monitoring the third harmonic of the EMF. This fits perfectly to the simple frequency converter of the brushless motor, which can only produce 120° voltage blocks. The minimum and maximum of the third harmonic voltage correspond with the commutation points.

Each drive has its own frequency converter and DC/DC power supply. The converter bridge is controlled by a programmable logic device (PLD) – or later on by an ASIC. The logic devices can be connected to almost any micro controller.

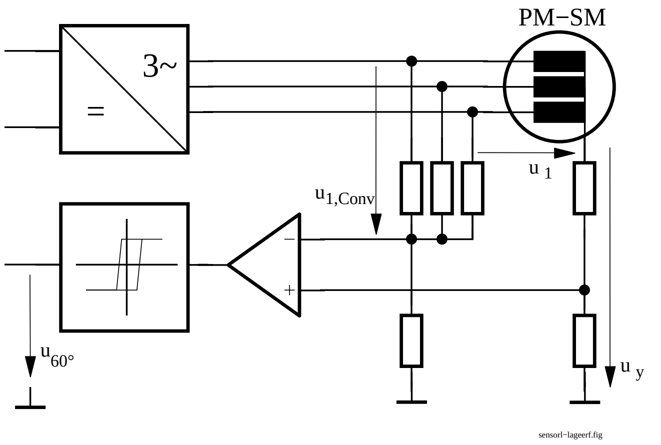

Fig. 5. System for the sensorless detection of the rotor position, using the third harmonic of the induced voltage

Fig. 6 shows the schematic diagram of the single spindle drive.

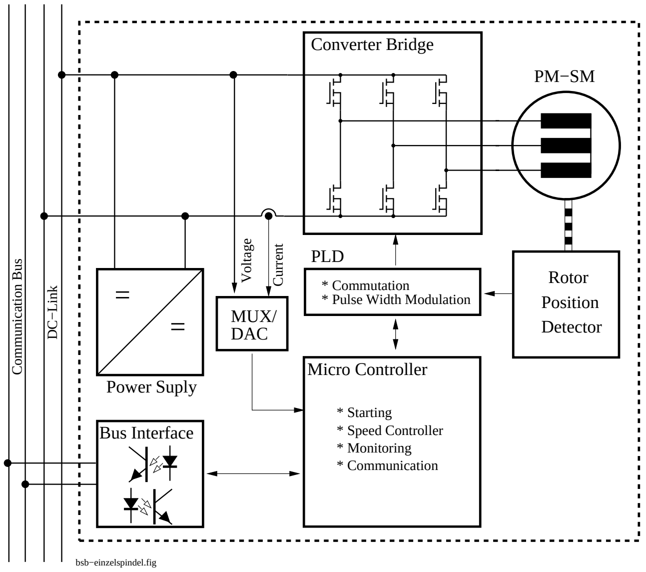

Fig. 6. Schematic diagram of the single spindle drive

The micro controller realizes the communication with the textile machine controller. It also manages the start up of the drive. The sensorless rotor position detection does not work at very low speed (or standstill), so there is a special strategy needed for starting the motor. In a first step, the rotor is forced into a defined position by applying a voltage to the three motor phases. If voltage is applied to each of the three motor phases simultaneously, two of the three phases are therefore shortened in conjunction with the simple PWM strategy. This EMF in the shortened phases effects a current which will suppress the oscillation of the rotor.

Out of this position the motor can be started by performing two commutations shot after each other. Now, the axis of the magneto-motive forces of rotor and stator perform an angle of 120° (el.), the torque is positive, the rotor will start rotating. After a delay time, depending on the moment of inertia of rotor and spindle, the rotor position detection is activated and the motor commutates itself. After a second delay time the speed controller is activated and the spindle runs up to operation speed of the spindle.

The micro controller supervises the textile process by monitoring the spindle torque which is proportional to the motor current. The detection of the current in the DC link can be achieved with low expense. There is no need for a high precision measuring because the breaking of a filament is recognized by the changing of the torque and not by the absolute value.

## VI. Conclusion

The combination of an electrical machine with a power electronic device allows the cheap realization of an efficient drive, especially if both components are adapted to each other and optimized together. The micro controller integrated in the spindle drive allows to realize supervisory functions without additional sensors. Because motor and power electronics belong together, characteristics of the motor can be used – e. g. the third harmonic of the EMF is used to detect the rotor position. For optimization the whole system has to be viewed, not each single component. For example selecting a cheap motor may require an expensive frequency inverter.

## References

[1] Kurt Reutlinger, *Mechatroniksystem für Einzelspindelantriebe in Textilmaschinen*, Dissertation, Universität Stuttgart, 1997.

[2] Kurt Reutlinger, “Elektronische Einzelantriebssysteme für Textilmaschinen,” *etz*, vol. 118, no. 19, pp. 6–10, 9 1997.

[3] Alois Weschta, “Stabilitätsverhalten der frequenzgesteuerten Synchronmaschine mit Dauermagneterregung,” *etz Archiv*, vol. 6, no. 6, pp. 227–229, 1984.

[4] Jürgen Ehrenberg, Jörg Droßmann, Zhiping Fan, and Rolf Eugster, “Aufzugsteuerung vollständig digitalisiert – Motorischer und generatorischer Netzbetrieb,” *Elektronik*, pp. 72–100, 12 1997.

[5] K. J. Binns, D. W. Shimmin, and K. M. Al-Aubidy, “Implicit rotor-position sensing using motor windings for a self-commutating permanent-magnet drive system,” *IEE Proceedings-B*, vol. 138, no. 1, pp. 28–34, Jan. 1991.

[6] J. Xie, *Entwicklung eines Scherwellengenerators für den Einsatz in tiefen Bohrlöchern*, Fortschr.-Ber. VDI Reihe 21 Nr. 139. VDI-Verlag, Düsseldorf, 1993.