CONTROLLED ELECTRICAL DRIVES – STATUS OF TECHNOLOGY

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Abstract - *In the past decade, electric drives with electronic speed control were advantageously used in industrial applications, appliances and automotive field. AC and DC motors in machine tools, industrial robots, automated presses, elevators, conveyers, rolling mills, compressors, pumps, fans, electrical vehicles, cranes and many other applications spend more than 2/3 of all the electric energy produced in an industrialized country. Complex tasks of the process and the motor control are performed with the help of high throughput digital controllers and subminiature signal processors capable of performing 10^8 operations per second. The frequency of the pulse width modulation in the drive power converter section is increasing steadily due to advancements in the field of high power semiconductor switches. The increase in the PWM frequency offers faster response of the current and torque control loops and improves the overall drive performance.*

Most drive problems are already settled. Mature technology of electrical drives offers widely accepted solutions for the power converter topology, basic control algorithms and most of the drive functions. Therefore, no significant changes in the drive structure will take place in the years to come. A widespread use of controlled electrical drives is primarily limited by the cost of the drive package. Therefore, a significant research effort is directed towards motor and drive integration, development of low cost intelligent power devices and invention of reduced topologies of the drive power converter. The elimination of the shaft sensor and the phase current sensors contribute to the cost decrease, simplified cabling and an increased reliability of the drive. Sensorless drives call for the development of robust, nonlinear state observers and parameter estimators capable of acquiring the information on the drive states that are not directly measured. The indirect state and parameter evaluation based on the secondary phenomena such as the slot harmonics, leakage inductance modulation, and the spatially distributed saturation call for a highly evolved signal processing and the spectrum estimation techniques. The problems of sensorless drive realization attract attention of significant R/D forces all over the world.

High performance servo drives are exposed to an ever increasing demand for higher response speed and precision. The evolution of production technology and development of new tool materials require the servo loop bandwidths of well above 200 Hz. Improvements in the drive dynamic response must go with highly evolved decision making functions built into the drive software package. To shorten the installation, replacement and to speed up the production process change, the drive should be equipped with adaptation features, self commissioning procedures and the decision making routines capable of replacing or eliminating the intervention of human operator.

This article outlines the status of technology for the drive power converters, motors, sensors, and control algorithms and gives a brief overview of the trends and perspectives in the field of digitally controlled electric drives. Pointed out are the cutting edge applications that incite further improvements of the drive performances and the advances in the motor and semiconductor technology that make such developments possible.

1. INTRODUCTION

From the beginning of this century, electric drives have been replacing fluid power actuators and IC machines in both high performance and general purpose applications, the growth of electric drives application being determined by the current level of technology. High reliability, long lifetime, relatively low maintenance and short startup times of electric drives are in consort with their ecological compatibility: low emission of pollutants. The quality of electric drives is extended by a high efficiency, low no-load losses, high overload capability, fast dynamic response, the possibility of recuperation, and immediate readiness for the full-featured operation after the drive startup. Electric drives are available in a wide range of rated speeds, torques and power, they allow for a continuous speed regulation, reversal capability, and they easily adapt to different environment conditions such as the explosive atmosphere or clean room requirements. Unlike the IC engines, electric motors provide for a ripple-free, continuous torque and secure a smooth drive operation. At present, electric drives absorb 60-70% of all the electric energy produced in an industrial country [1,2].

During the past two decades, the evolution of powerful digital microcontrollers allowed for a full-digital control of the electromechanical conversion processes taking place in an electrical drives. The process automation made significant progress in the fifties, thanks to the introduction of numerical control (NC). Although not flexible and fully programmable, NC systems replaced relays and mechanical timers common on the factory floor in the first half of the century. As the first reliable and commercially available microcontrollers were made in the sixties, they were advantageously used for the purpose of a flexible control of electric drives in production machines. As from then, the hydraulic and pneumatic actuators gradually disappear and give space to DC and AC electric motors.

Although more robust and easier to produce than the DC motors, the AC electric motors were mostly used in constant speed applications and supplied from the mains [3] until the technological breakthroughs in the early seventies. It took the development of transistorized three phase inverters with digital PWM to provide for a variable frequency supply of induction motors. The invention of IGBT transistors and high speed digital controllers made the variable speed AC drives reliable and acceptable for the drive market. Dunfoss in 1968. produced the legendary VLT 5 frequency converter weighing 54kg, suitable for the speed regulation of 4kW induction motors (recent versions of the same converter weigh 3.5 kg [4]). Among the first applications of variable speed frequency controlled AC drives were pumps, fans and compressors, where the speed regulation feature eliminated mechanical damping of the fluid flow and reduced the associated power losses and turbulence. For their increased reliability, low maintenance, and better characteristics, the frequency controlled induction motors gradually replaced DC drives in many of their traditional fields of application. At this level, the reign of DC drives reduced to high speed servo applications.

In early eighties, the frequency controlled AC drives are widely accepted, but their prices still level those of DC drives. The cost of an AC drive package has a 30% motor + 70% power converter structure, while in the case of a DC drive the motor is worth 70% of the package cost [12]. The prices of power- and signal- semiconductors will presumably decline, while the cost of electric motors will remain tied to the copper and iron prices. For that reason, the AC drives have the perspective of decreasing the package cost, evermore cheaper than their DC counterparts. Further technological improvements are likely to make the frequency controlled AC drives the cheapest actuators ever. At present, in an industrialized country the AC drives substitute DC motors at a pace of 15% per year [1]. More than 20% of the drives are frequency controlled, while the remaining 80% operate at a constant speed.

The AC drives were used in high performance applications only after the development of the field oriented control concept. Following the introduction of space vectors [6], direct (DFOC) and indirect (IFOC) field orientation control structures were devised, also known as the vector control [7,8]. Although invented in sixties, the vector control concept was put in use only some twenty years latter [11].

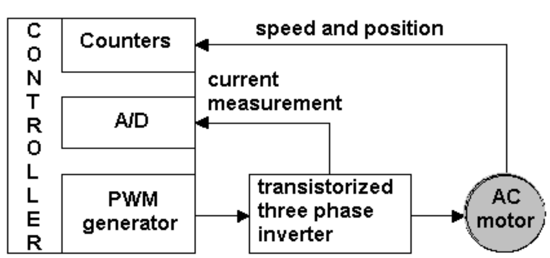

Fig.1 *Basic functions of the feedback signal acquisition and the control of the power conversion process in a typical induction motor electric drive.*

Numerically intensive, vector control structures required high-throughput 16/32-b digital controllers and signal processors [13]. Aside from high performance drives, general purpose and application specific digital drive controllers are found nowadays even in commodity products. In most of high volume applications of digitally controlled electric motors, microcontroller executes both the drive control functions [15,16] and the application specific functions such as the handling of the washing, rinsing and drying in the case of modern dishwashers and washing machines. Compact digital controllers emulate the functions traditionally implemented in the analog form and allow also the execution of nonlinear and complex functions that could not have been completed by analog circuitry (ANN, nonlinear estimators, spectrum estimation and others).

The vector control concept empowered the AC machines to conquer the high performance drives market. Although effective, both the IFOC and the DFOC structures rely on motor parameters and exhibit considerable sensitivity to parameter fluctuation [17,18]. Therefore, both the DFOC and IFOC controllers must be equipped with proper means for the parameter identification [24] at the installation phase (self-commissioning) [19] and during the drive regular operation [20] (on-line tuning). Besides the adaptation routines, most applications require high performance digital current control [21] and on-line power loss minimization routines. Numerically intensive, such algorithms require the use of fast transputer networks [9,22] and digital signal processors within the drive control section. Powerful and flexible, the DSP based drive controllers [22] create the potential for significant performance increase through the application of advanced control concepts [23,25]. Highly evolved observers of the drive states allow reduction of the number of sensors. The drives with minimum number of sensors and the shaft sensorless drives are more robust and reliable than their sensored counterparts. The lack of sensors and associated cables makes the drive cheaper and the installation simpler and faster. In the development phase are the advanced parallel control structures such as the direct and incremental torque control (DTC, IncTC) that make the use of a large numerical throughput to implement a non-cascade control concept thereupon augmenting the response speed and overall drive dynamic performance.

2. ECONOMIC IMPORTANCE OF DIGITALLY CONTROLLED ELECTRIC DRIVES

The number of general purpose drives installed each year considerably exceeds the number of new high performance servo drives. According to *Frost & Sullivan Market Intelligence* data for 1997, 52.7% of new drive installations in U.K. used Tesla’s induction motor, some 33.7% were the DC drives, while the remaining 13.9% corresponds to fluid power and other non-electric actuators. According to the same source, the AC drive growth in 1998. is predicted to be 3.9%. Market analysis performed 1994. in North America show that more than 90% of the motor units are in the fractional horsepower range (P < 1 HP). Most of the FHP motors produced in the U.S. are the universal or single phase motors; Tesla’s induction motor is less diffused than in Europe. Each year, some 550 x 10^6 general purpose FHP motors are produced in U.S. with the total value of \$6.1 x 10^9. The number of high performance drives produced each year is much lower, but their value in the U.S. \$ reach \$1.06 x 10^9 per year.

In Europe, the three phase supply is much more accessible than in the U.S., which rouses frequent use of Tesla's induction motor. AC motors above 75kW account for 29% of European annual production, the motors rated 7.5 – 75kW correspond to 31% and the induction motors below 7.5kW are worth the remaining 40%. The AC drives expansion to home appliance field is sluggish due to extraordinary low prices required by the market. The production cost of electronic speed controlled AC drives ranging 0.5 - 1 kW must drop below $20 threshold for the final products be competitive to their open-loop counterparts. With the present growth rate, this might happen in 2001.-2002.

The growth of high performance drives depends on the investments in new production sites. R/D efforts and production of servo drives take place in highly industrialised countries: Japan and Germany make each 25% of the world production of industrial robots and machine tools, while China produces more than 20%. *Frost & Sullivan* report on annual high performance drives growth of 5% in Europe, while *Motion Tech Trends* study predicts the servo drives sales in the U.S. to grow up to $ 4.5 x 10^9 in the year 2000. More than 52% of high performance drives employ Tesla's induction motors, the step motors are used in 4.2% of the cases, the DC servo motors cover 22% of the market, while the permanent magnet synchronous motors account for some 20% of the market. Relatively high cost and low volume of high performance drives make their development relatively slow with respect to general purpose drive. Lengthy and expensive R/D efforts restrain the servo drives design and production to few highly developed industrialised countries.

3. CLASSIFICATION OF CONTROLLED ELECTRIC DRIVES

Digitally controlled electric drives may be ranked according to the application, characteristics, voltage and power range, and the power converter topology. Five basic categories may be distinguished: i) High performance servo drives; ii) General purpose drives; iii) Electronic speed controlled drives in homes, offices and automotive applications; iv) Medium voltage high power drives; and v) Electric propulsion applications.

The article discusses the problems and future trends in each group of electric drives. Particular attention is paid to the motion control algorithms and to the developments in the power conversion control. Specific influence of an ever increased number crunching capability of modern digital controllers on the drive controller structures is probed deeply. Performance enhancements of semiconductor power switches are outlined and their influence on the drive converter topology and characteristics is briefly analyzed. Finally, the needs and the possibilities are outlined for a digitally controlled drive to assume versatile adaptation and self -commissioning features [33,34], reducing in such a way the need for the operators intervention in both the installation and regular operation phases.

4. GENERAL PURPOSE ELECTRIC DRIVES

General purpose drives are mostly used in pump, fan and compressor applications (PFC) in industry and the heating, ventilation, and air conditioning (HVAC) systems in home and office buildings, and other non-servo industrial and domestic applications. The workhorse of these applications is Tesla's induction motor accompanied by the IGBT three phase inverter. Fast response of the speed loop is generally not required. Majority of applications require only a relatively slow speed adjustments to the process needs, and the motors are usually installed without the shaft sensor. Response of the speed loop can be sluggish, yet the drive is expected to provide the speed regulation in a wide range. The drive controller task is providing the stable operation at very low speeds, characterized by the supply frequencies below 1 Hz. At he same time, it is essential to support the field weakening operation up to the speeds exceeding the rated one by 2-3 times. Preferred drive characteristics are high efficiency, environmental friendliness, high starting torque, low maintenance, large mean time between failures (MTBF), simplicity of the installation, commissioning and a low cost of the drive package. Speed sensorless operation is essential for many reasons. The shaft sensor usage increases the system cost, decreases reliability and makes the cabling more complex. Moreover, sensored drives must use non-standard motors, since all the general purpose, series produced induction motors include no shaft sensors nor the means for the sensor installation. A variety of different schemes for speed sensorless operation of Tesla's induction motor have been proposed in the past decade. Most of them ensure a very good dynamic performance in a fairly large speed range.

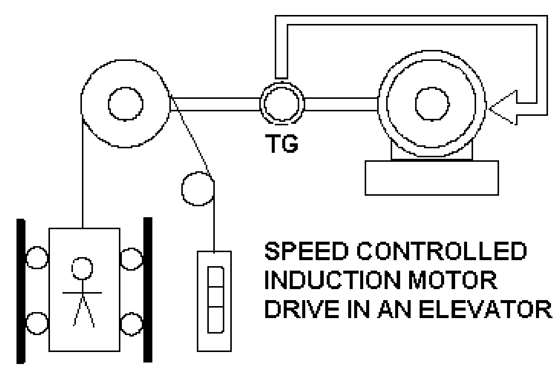

Fig.2 *Speed controlled induction motor drive used in a passenger elevator*

However, at low stator frequencies, performances notably deteriorate. The motor flux linkages cannot be directly measured. Instead, the states of interest are derived from the motor terminal quantities by means of motor fitted nonlinear state observers and estimators. The information on the motor flux is contained in the stator voltages as the back electromotive force. As the supply frequency drops down towards zero, the stator resistance voltage drop prevails in the terminal voltages making the flux derivation more difficult. The stator flux estimation is particularly sensitive to an inaccurate stator resistance value in the estimation model. This inaccuracy causes estimation errors both in the amplitude and the estimated angle of the stator flux vector. The flux error and variations of other machine parameters continue to impair the accuracy of the estimated mechanical rotor speed, particularly under load. The crucial parameter for the speed estimation is the rotor resistance, while a detuned value of the leakage inductance affects the flux and speed observers and estimators only to a limited extent. Lacking a conventional speed estimator with adequate performances, the shaft speed of Tesla's induction motor may be derived relying on secondary effects and the motor imperfections such as the spatial distributed saturation and the slot induced harmonics in the motor terminal quantities. The speed extraction based on the evaluation of rotor slot harmonics does permit very precise estimation in the steady state, but lacks the possibility of tracking fast changes in the rotor speed. Hence, the sensorless drive with the slot harmonics feedback is bound to have a poor dynamic performance. This is due to the very low number of rotor slots normally encountered in induction machines, which imposes severe bandwidth restrictions on the obtained speed signal. An accurate speed signal is extracted, which serves for model parameter tuning. This method requires considerable computing power, which inhibits implementation in standard microcontroller hardware. For this reason, most authors propose the additional, slot harmonic derived information be used for the parameter adaptation purposes. Provided correct values of the motor parameters, DFOC controller will secure the flux, torque and the speed control in all the general purpose drives operating modes.

5. LOW COST ELECTRIC DRIVES IN HOUSEHOLD, OFFICE AND AUTOMOTIVE APPLIANCES

Many commodity products demand the motion control functionality. Some of them are the vacuum cleaners, washing machines and dish washers. Similar characteristics and the power range have the auxiliary drives in the automotive field. The servo steering, motorized windows, automated seat adjustment and active suspension systems require low cost, robust and reliable electric drives. Having the cost reduction as the primary goal, significant research resources are assigned to development of simple converter topologies [26,29], new types of electric motors [27] and algorithms for the sensorless speed control [28].

Among other requirements, electric drives in household and office appliances are expected to be environmentally friendly; low thermal, acoustic and electromagnetic emissions are forced by government regulations and international standards. The level of the electromagnetic interference strongly depends on the power section layout and might be improved by the introduction of newly developed power switches with spatially distributed lifetime control (CAL). At the same time, the cost reduction of the power switches would give a strong incentive to a more frequent use of electronic controlled drives in the appliance field.

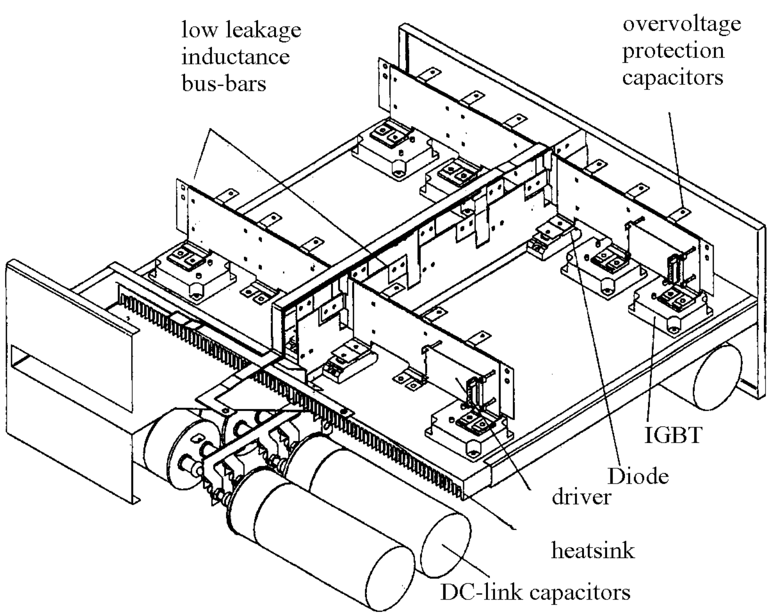

Fig.3 *The three phase power converter for a 500 kW AC motor drive.*

Power semiconductors are used within the drive converter for accurate control of the energy flow between the power source (i.e. the mains) and the motor. They have extremely short response times and low dissipation. The dramatic developments in IC technology, particularly during the last ten years, have made possible the design of modern, self-protected components, with simple, lowloss drive characteristics, wide dynamic control range, switching power levels up to the megawatt range, and a direct interface to microelectronic systems.

6. TRACTION DRIVES

Electric propulsion of autonomous, battery supplied electric vehicles (EV) such as the electric cars and buses require efficient, robust and light weight drives with fast and accurate traction effort response. The EV drive controller habitually encompasses the means for suppression of resonance modes in the transmission and the vehicle mechanical parts [29]. Simple construction of Tesla's induction motor with the squirrel cage rotor makes it an ideal candidate for advanced traction motor designs such as the linear motor (LIM) and the tubular axle induction motor (TAIM).

7. LARGE POWER, MEDIUM VOLTAGE DRIVES

Large power AC drives are found in rolling mills, petroleum industry, water supply and many other applications where the rated power exceeds 300 kW and the nominal stator voltage falling into the medium voltage range (2300, 4160 or 6600 V) [30-32]. The main problem in this class of electric drives is the design of controlled three phase variable frequency source in the megawatt range. Until recently, the variable frequency, medium voltage drives were not available due to the absence of high voltage semiconductor power switches. The need for the economic use of energy, miniaturization of electrical systems, and reactive power compensation have been the motives for the revolutionary development of high voltage, high current power semiconductors. For their high power rating, Gate turn off thyristors (GTO) are considered the main switching device for the construction of multi-level high power three phase inverters. The power losses occurring in the GTO at turnoff limit the GTO's normal operating voltage to the range from 30 to 40% of the breakdown voltage, thus limiting the dc-link voltage of a conventional GTO inverter to 1500-2500 V.

High-power inverters with dc-link voltage up to 4000 V and existing GTO's cannot be made with conventional six-switch topology. Several converter configurations for the realization of a large capacity inverter with more than 4000 V dc-link voltage are possible. One of them is the six-switch configuration with each of the switching elements being made out of several series connected GTO's. However, the direct series connection method of GTO's has the problem of blocking voltage unbalance during turn-off transient, due to the different turn-off characteristics of each device. Whenever additional equipment is used to overcome this problem, the overall system becomes more complex and expensive. Besides the circuit complexity, a limited switching frequency of GTO's causes large harmonic components of the output voltage and current. Split DC-link voltage three-level converter topologies configurations are being developed for the large capacity inverters, capable of solving the above mentioned problems. Appreciable research effort is devoted to switching rules for a multilevel inverter capable of reducing the commutation stress while maintaining at the same time an acceptable ripple amplitude and the spectral content of the output current.

8. BASIC CHARACTERISTICS OF HIGH PERFORMANCE DRIVES

High performance servo drives are used in production machines, machine tools, industrial robots, automated presses, and many other applications where the speed and position control loops are indispensable. Most frequently used are the AC induction and the permanent magnet synchronous motor drives [5],[14] with the rated power ranging from 50 W to 200 kW. Required bandwidth of the torque, speed and the position loops is roughly 1kHz, 200Hz and 60Hz respectively. Every year, the number of high performance DC drives increases by 3% while the annual growth of AC servo drives exceeds 12%.

9. THE PROBLEMS AND DEVELOPMENT TRENDS OF MOTION CONTROL ALGORITHMS

The structure of a typical motion control system includes two basic types of control functions:

i) 'External loop' dedicated to the mechanical subsystem where the speed control, position tracking and multiple axis synchronization functions are executed. The servo motor is considered the torque actuator with a response time much faster than the mechanical subsystem dynamics;

ii) 'Internal loop' handling the motor flux and torque control, with the drive power converter used as an actuator and the motor electric subsystem as the plant to be controlled. Control objective is making the electromagnetic torque and the flux linkage track the reference values imposed by the master (external) loop.

The internal loop is motor dependent and changes as a different type of servo actuator is used. The vector controller is the most frequently encountered controller for AC servo drives with the parameter sensitivity being the main unresolved problem. On the other hand, the external loop copes with moving the production machine tools and parts in the work space with ever higher speed and precision. The main problems of the external part of the motion controller are the transmission imperfections, the torque ripple, compliance and mechanical resonance problems, as well as rapid changes in the motion profiles and the mechanical parameters of the system.

Variable structure systems ensure sufficient robustness and guarantee the reference trajectory be reached whatever the initial conditions. However, sustained oscillations and a permanent driving force chatter exist even in the steady state, producing a periodic space error and making the VSS inadequate for most motion control applications. Nonlinear nature of fuzzy control structures sustains some of the VSS controller robustness and suppresses the chattering problem. Based on Zadeh-s set theory [38], fuzzy controllers are inherently suboptimal. Even though, in some applications [37] they can permit significant improvements in the servo loop response time.

Aiming at an increase in both the operation quality and the production volume, recent production machines require the servo loop bandwidths surpassing 200Hz. Major impetus to the servo performance increase is the torque ripple of the servo motor, the imperfection of position sensor, transmission dynamics, nonlinear friction and unpredictable cutting resistance. All of deficiencies mentioned above are deterministic and cyclical in nature, some of them having the spatial period relative to one motor turn, and the others repeating the same way within each operating cycle. In essence, the said disturbances may be predicted and compensated for, eliminating in such a way the associated space tracking error. Many of disturbance components (such as the torque ripple [43]) are nonlinear functions with multiple arguments, such arguments being the states of both the electrical and mechanical subsystem. In most cases, disturbance prediction functions depend on the operating point, temperature and change in time due to the ware and other factors. Consequently, disturbance predictor must be a very complex function with some self learning features built into the structure. Good results are achieved by the application of artificial neural networks (ANN) [39,40,41] equipped with an on-line re-training mechanism. Unpredictable in itself, an ANN is hardly used for the operation critical tasks. Rather than that, production machines employ the ANN for advanced secondary functions such as the monitoring, diagnosis, recognition of specific defects, slow adaptation and similar. In recent times [42], some authors have proposed the neuro-fuzzy match for the position tracking tasks, expecting the ANN-fuzzy marriage to bring both the fuzzy robustness and the ANN advanced self learning and adaptation features into the servo loop.

10. ELECTRIC SERVO DRIVES IN AUTOMATED PRODUCTION MACHINES

Position and speed controlled servomechanisms exhibit a significant growth in the past years. From 1994. to 1997, the value of servo actuators produced in Germany increased from 203×10^9 DM to 264×10^9 DM. This growth is followed by the introduction of new production technologies such as the pressurized injection molding , water beam and laser cutting machines.

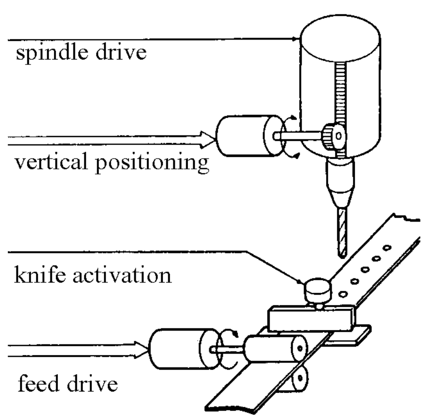

Fig.4 *A typical feed drive application.*

Development of new tool materials allows for an increased cutting speeds. In turn, the spindle drives are required to reach the rotation speed above 50.000 rpm with the rated power of 10 - 20 kW. The tool servo axis and the manipulator drives are expected to track desired trajectory with the top speed well above 100 m/min and the precision better than 0.2 – 1 µm. Particular cases, such as the hard disk drive production lines, require tracking error inferior to 10 nm and use piezoelectric actuators.

The main problem of tracking the exact tool position is the variable cutting resistance of the material. To suppress the space errors, position control stiffness of 100-1000 N/m is required in most of the cases. In some applications, such as the automated tool production and the diamond cutting, necessary stiffness might reach 10000 N/m, which cannot possibly be achieved by hydraulic and pneumatic actuators and the employment of high performance AC servo drives is required.

Many production processes require mixed force-position control in some phases of the production cycle. Industrial manipulators that clutch and move the objects must include a superimposed force control loop, in particular when grabbing and holding fragile objects like crystal glasses [35].

Secondary force control loop is needed for the purpose of stabilisation of human-like robots, which generally involves the installation of additional force and position sensors as well as the use of acceleration observers. Performance improvement of existing linear and rotary sensors and design of novel solutions attract the attention of many research engineers in the motion control field. The sales of position sensors alone have reached $\$1.7 \times 10^9$ in the U.S. Standard solutions include potentiometers, LVDT (*linear displacement to analog out),* resolvers, tachometers and optical encoders.

New-sprang position sensing techniques include interferometer-based devices with the He-Ne laser. According to recent reports, the laser sensors reach the resolution of 5 nm with 500 nm repeatability. Relatively expensive, the laser position sensors are used mostly in high productivity laser cutting machines where the sensor cost is not a hurdle. Among conventional sensors, the optical encoders are the most precise but still affordable solution. Disadvantage of absolute and incremental encoders is the temperature sensitivity of their photo sensitive semiconductor devices. In production machines, the operating temperature frequently exceeds the 125^{o}C limit, thus precluding the usage of optical encoders. Position measurement in dusty and oil contaminated environment is frequently performed by industrial cameras with dedicated frame grabbers and associated image processing routines.

Along with fast and precise position tracking, servo drives are expected to support the high speed digital communication protocols on the factory floor level. The CNC, sensors and servoamplifiers need the information exchange in both the installation and running phases. Fast serial link between the communication nodes allows for an easy, noise free interchange of the reference and the feedback values, inspection and change of control parameters, and flexible monitoring and diagnostic features.

11. LINEAR ELECTRIC SERVO MOTORS

Most of the operations of an automated production machine involve linear translation of machine parts, work pieces and tools. On the other hand, common electric motors are rotary electromechanical converters producing the torque at the output shaft. Transmission mechanisms such as the rack and pinion, ball screw and gear systems convert the rotary into linear motion. Dry friction, backlash, elastic coupling and the torsional resonance intrinsic to all the rotary – to – linear transducers severely limit the servo loop bandwidth.

Relatively large rotational masses constrain the peak acceleration of the system. On the other hand, large equivalent inertia filters out the torque ripple and the quantization excited +/- 1 LSB torque chatter, alleviating in such a way the tracking error. Imperfection of the transmission mechanism may be eliminated by the application of direct drive concept with linear electric motors. As the tolls are coupled directly to the motor moving parts, the problems of mechanical resonance exist no more. The absence of rotational masses results in a much larger peak acceleration of the overall system, while the ratio between the peak driving force and the friction increases several time when compared to a servo axis with a rotational actuator

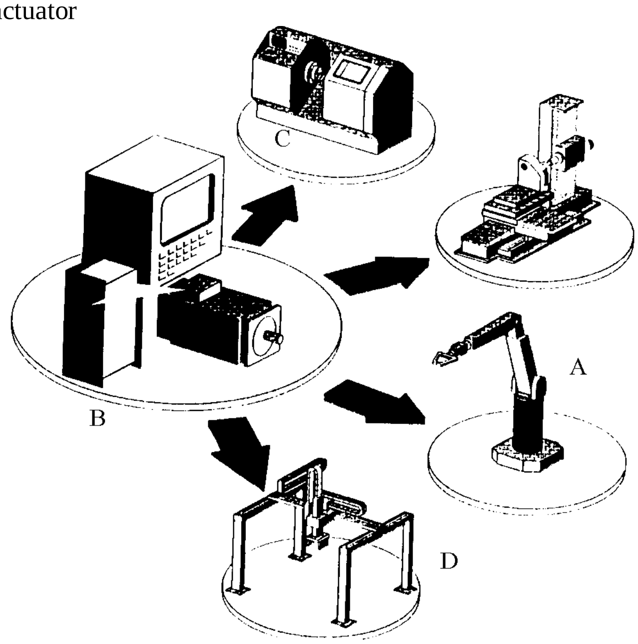

Fig.5 *Position controlled drives in automated production processes: a) Industrial robot for cutting, welding and paining b) CNC, c) Machining and metal forming centre d) Gate entry.*

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Contemporary linear motors exhibit the top speed of 3-5 m/s and offer the positioning accuracy down to 1 μm. Exceptionally low inertia stresses the torque ripple and the chatter related problems. Due to the motor imperfection and the finite resolution of the sensors, the driving force exhibits (the same way as the driving torque of a rotational servo motor) high frequency oscillations – the chatter – with an amplitude of 1-3 LSB. The smaller the inertia, the larger the speed and position fluctuations caused by the jitter in the driving force. Dissipativity based [36] approaches to the servo loop synthesis permit significant reduction of the chattering problems, but do not solve completely the torque/force ripple problems. For this reason, the force ripple minimization is one of the main design requirements for linear electric servo actuators.

Modern linear motors are mostly asynchronous or synchronous permanent magnet motors. They have magnetic, hydrostatic or the air bearings [44]. The stiffness coefficient of linear motors (200 N/m) is much better than the stiffness of the fluid power actuators (50 N/m). It is possible to move the weights above 50 kg and attain the driving forces up to 2000 N. Low equivalent inertia of motion control systems employing linear motors results in a speed loop bandwidth of 130-200 Hz and the peak acceleration well above 100 m/s^2.

12. THE STRUCTURE OF MODERN DIGITAL DRIVE CONTROLLERS

Digital motion controllers mostly use compact microcontrollers as the brain of the drive control hardware. Recently, digital signal processors have been introduced to the area of industrial control adding a new dimension to this field of application. Based on the Harvard architecture, DSP's are characterised by a high speed

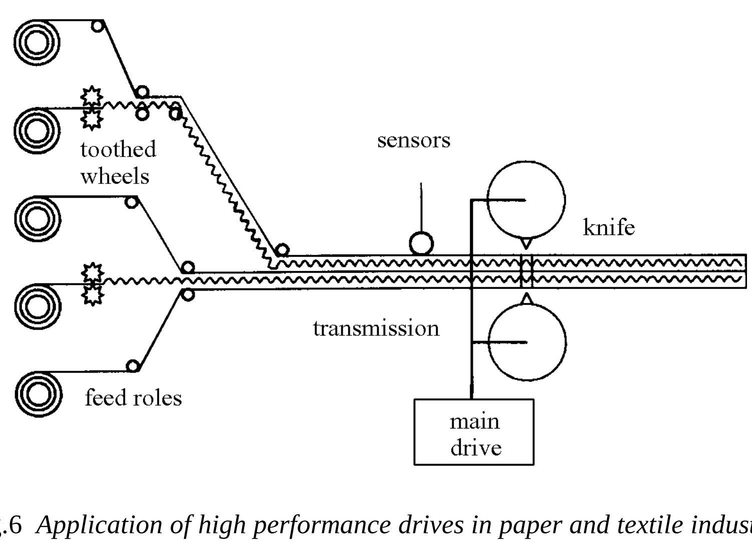


Fig.6 *Application of high performance drives in paper and textile industry.*

execution permitting the implementation of sophisticated control algorithms. The processor can also perform other tasks such as the real time generation of complex velocity profiles and position trajectories for multi-axis systems. The resulting design of the control hardware is simple, more flexible and more reliable. Digital implementation results in discrete time nature of compensators and involves a finite precision arithmetic. When using 8-bit and 16-bit microcontrollers, the state variables and relevant parameters are often represented as 16-b or 32-b numbers:

Software development for high precision arithmetic is neither short nor convenient, while the execution time of such programs is usually long. Due to a finite word length quantization error, the actual compensator differs from the designed one. In some recursive algorithms, even the lack of numerical stability may occur. Without a floating-point core, a designer is compelled to choose a controller structure that is least sensitive to the quantization errors and inaccurate coefficient storage. As an example, a higher order filter can be implemented as parallel or cascade combination of first and second order blocks, reducing in such a way the response sensitivity to coefficient variations and the finite wordlength problems. Hence, even high order digital filters may be implemented on 8-b and 16-b microcontrollers, though with a limited sampling time and a large software overhead necessary to achieve required precision and numerical stability. Numeric throughput of existing general purpose 16-b microcontrollers (Table I) is not sufficient for most high performance AC drives and many sensorless, general purpose drives. The vector control alone requires several transformations of the voltage and current vectors from the d-q synchronous to $\alpha-\beta$ stationary frame. Parameter estimation and the state observers parallel to the flux, speed and position control may require more than 10^7 operations per second, exceeding several times the capability of a conventional CPU [11].

Reduced execution time owed to the hardware implemented multiply-accumulate operations along with long 16/32-b words and the instruction set suitable for digital signal processing make the DSP based (see Table I) microcontrollers the prime candidates for the execution of the drive control tasks. Presently, several compact DSP - based microcontrollers exist, fitted with on-board peripheral modules needed for the drive signal acquisition and control. Many of them [21] allow for a numerical throughput of 20-40 x 10^6 operations per second. Although very high, even such levels of the number crunching capability are insufficient for the implementation of recent nonlinear state estimators based on the parametric spectrum estimation techniques. The requirements of time critical, numerically intensive drive control functions might be fulfilled by the use of the latest parallel architecture signal processors [22], capable of executing more than 10^9 instructions per second. Though, the price and the noise sensitivity of the said DSP chips prevents their use within the drive control hardware. Instead, in numerous high performance drive designs the fastest control functions are executed in digital hardware based on flexible, high gate density with FPGA chips (Fig. 8).

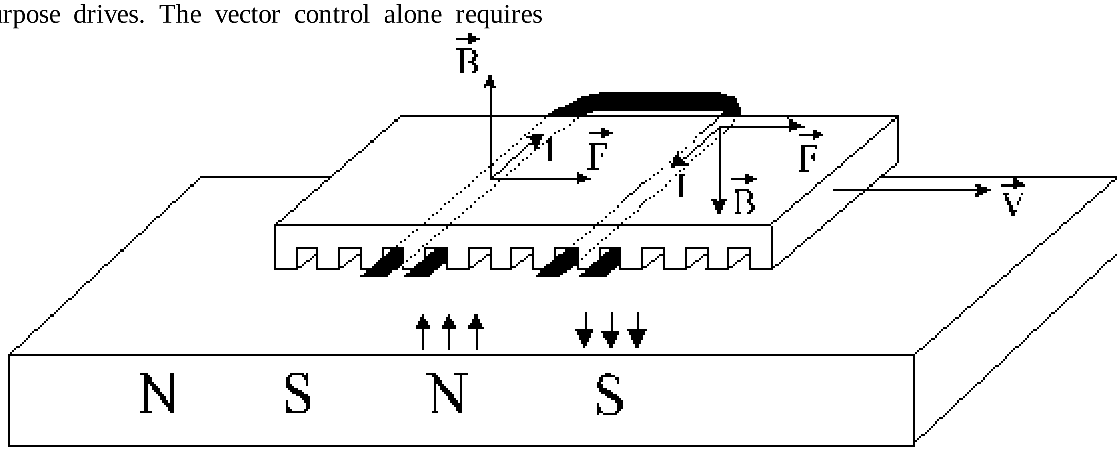


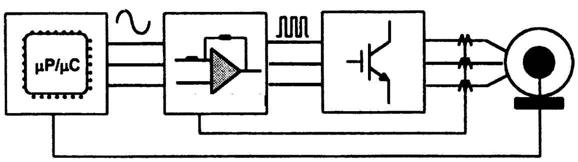
Fig.7 *Linear induction motor: The driving force is generated through electromagnetic interaction between the current carrying conductors in the moving part and the currents induced in the conductive base.*

13. CONCLUSION

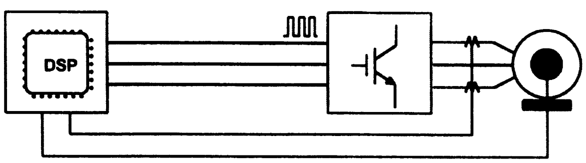
Digitally controlled electric drives have reached mature phase in their development. The increased use of microelectronics in power control circuits enables the implementation of complex control concepts, allowing the production of environmentally acceptable, self optimized motor drives with applications ranging from precision machine tools to traction drives with Tesla's induction motor in high-speed passenger trains. Many elements and modules of the drive system are already consolidated; widely accepted solutions exist for the power converter topology, motor types and basic control structures. These well tested solutions are unlikely to undergo significant changes in the years to come.

The research and development efforts are directed towards the remaining drive problems, where substantial contributions are expected in the future. Some of these problems are: i) Present drives radiate relatively high levels of electromagnetic, acoustic and thermal pollution; ii) The drives use a large number of sensors, the wiring and cabling is fairly complex and the cost of the drive package is still excessive for most applications; iii) Elaborate installation and commissioning make the human operator inevitable in the startup, repair, replacement and run-time situations.

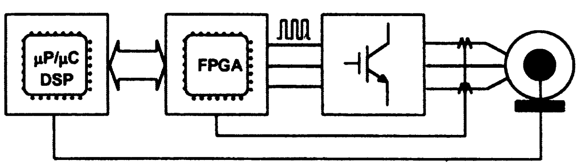
The international EMI regulations and problems with electromagnetic compatibility will incite the changes in the front end converter topology. At present, the front end converter in most of the drives is a six-pulse diode rectifier absorbing a distorted, nonsinusoidal currents from the mains.



hybrid digital / analog implementation



full digital implementation



digital implementation with an external, high density programmable logic device for very fast routines

Fig.8 *Evolution of digital drive controllers from analog to fully digital implementations.*

In the future, full bridge synchronous rectifiers and other PFC topologies will be used at the drive front end. Novel front end topologies are expected to draw the sinusoidal currents from the mains, enable the regenerative braking of the drive and provide for the reduction of the DC-link filtering components.

Integration of the drive power converter into the motor frame allows for a significant cost reduction and more simple installation and wiring. With an integrated motor-converter package, the motor cable exists no more. The cable capacitance, electromagnetic radiation and the reflections of the dV/d*t* wave are cleared away, reducing greatly the problems of the EMI and an early breakdown of the motor insulation. To make the integration concept applicable in the field, it is indispensable to solve complex thermal management problems of the integrated drive package. At the same time, the semiconductor technology is to provide for the power and signal processing devices that can operate safely at motor case temperatures.

The drive capacity to accommodate to the process and parameter changes without the intervention of the operator become ever more significant. In addition to slow adaptation features, most demanding applications of servo drives must possess the robustness with respect to abrupt changes in the system parameters and operating conditions. Performance criteria such as the cycle time, position tracking error, the servo loop bandwidth or some other synthetic performance function must be maintained even with the motor and process parameters changing in an arbitrary way within prescribed boundaries. Novel motion control solutions that might emerge in the years to come will have a direct influence on the work quality and the productivity of automated production machines. Local intelligence built into the drive might simplify and speed up the installation and commissioning. Providing the drive with self-adjustment and decision making routines, the interventions of human operator might be cut down to a minimum. In this way, electrical drives on the factory floor will start replacing the workers brains and not only the muscle.

Although with a mature technology and the basic problems already solved, controlled electrical drives are still in the intense development phase. Numerous control problems and the problems of energy conversion yet need to be solved. The said problems will attract the attention of many young engineers world-wide at Universities, research laboratories and companies involved in controlled electrical drives development and production.

TABLE I: *Typical operations encountered in a control routine: DSP versus µC*

Operation: Digital controller:	TMS320C25	80C196MC-20
Multiply and accumulate	0.5 µs	4 µs
Speed derivation from the encoder pulse width	777 µs (*)	382 µs
Speed derivation from the encoder pulse count	2356 µs (*)	25 µs
(3 x 3) matrix multiplication	14,7 µs	225.9 µs
PID with D-action low pass filtering	0.9 µs	13.5 µs
Band-stop filter – Notch filter	2.3 µs	87 µs
(*) TMS320C25 has no peripherals needed for the pulse width and pulse count measurement. Instead, it is assumed that the DSP emulates the said functions in software.		

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