Modern Electrical Drives:
Design and Future Trends

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Abstract—**Electrical drives efficiently convert electrical power into mechanical power. As factory automation, comfortable lifestyle and energy conservation are growing businesses, the number of drives produced worldwide keeps growing. The increased use of information technology (computers, digital control) and communication systems not only has created new markets for drives, e.g. disc drives but also enforces more electrical drives to be used in systems as actuators and mechatronic systems. In this paper, the author reviews the present state of development of drive technology and probes into future application and technology trends.**

Keywords- electrical drives, electrical machines, power electronics, embedded control, rapid control prototyping

I.   INTRODUCTION

In general, as illustrated in Fig. 1, an electrical drive can be defined as a power conversion means characterized by its capability to efficiently convert electrical power from an electrical power source (voltage and current) into mechanical power (torque and speed) to control a mechanical load or process. In some cases, this power flow is reversed or can even be bi-directional. Today, modern drives make use of power electronic converters to (digitally) control this electro-mechanical energy conversion process. In addition, as drives are being integrated more and more in systems, communication links to higher level computer networks are essential to support commissioning, initialization, diagnostics and higher level process control. Consequently, the main drive components consist of an electro-mechanical energy converter (typically an electro-magnetic machine or actuator), a power electronic electrical-to-electrical power converter and an embedded digital control unit. The digital control unit directly controls the power electronic semiconductor switches of the power electronic converter. To this end not only suitable control hardware, sensors, high-speed digital logic devices and processors are needed but also suitable control algorithms. From this perspective, drive technology is a fairly modern development. Indeed, although electrical machines were first developed over 150 years ago, power electronic converter have been available for only 45 years, dynamic torque control algorithms for induction machines (field oriented control) have been around for

about 30 years and high-speed digital control using DSPs have been available for less than 25 years. Even today, with all components (machine, power electronics, control hardware and software) being developed, drive technology is still evolving at a rapid pace. Over the past 20 years, new machine types have been developed, optimized and investigated, such as linear machines, surface PM magnet and buried PM magnet machines, switched reluctance machines, transversal flux machines, axial flux machines, etc. Each machine type requires its specific control and sensors. During the past 10 years, (position) sensorless drives have been investigated to eliminate expensive sensors and make drives more robust (reliable).
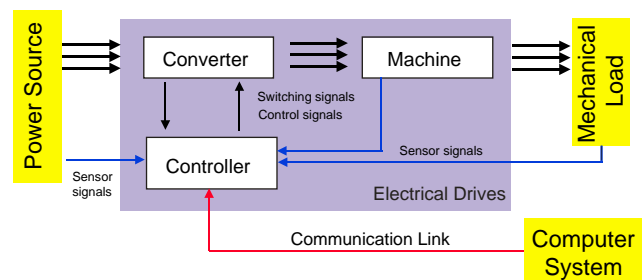

Figure 1.   Electrical Drive System

The power range of modern drives spans many decades, from milliwatts up to hundreds of megawatts, which demonstrates the flexibility and the broad application of this technology.
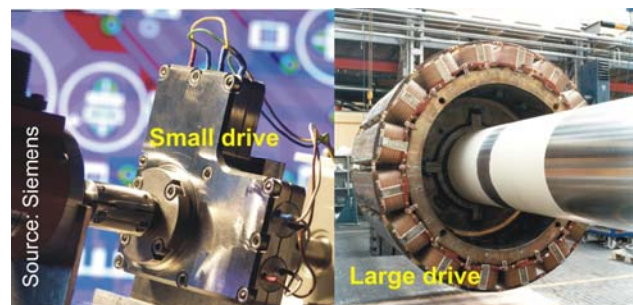

Figure 2.   Drive technology can scale from very small power (less than 1 W) to high power (more than 10 MW)

In the following several technology trends of state-of-the-art drives are being discussed. An attempt is made to derive future trends based on the development of drives over the past 25 years.

II. MARKET TRENDS

A recently published report of ZVEI, illustrates the market of electrical drives in Germany [1]. Production technology, primarily driven by continued automation of industrial processes, energy efficiency and automotive applications has steadily increased over the past 10 years with a growth rate of 5-6 % annually. Sales are reaching 9 billion € creating work for at least 60,000 people, not including maintenance and service personnel.

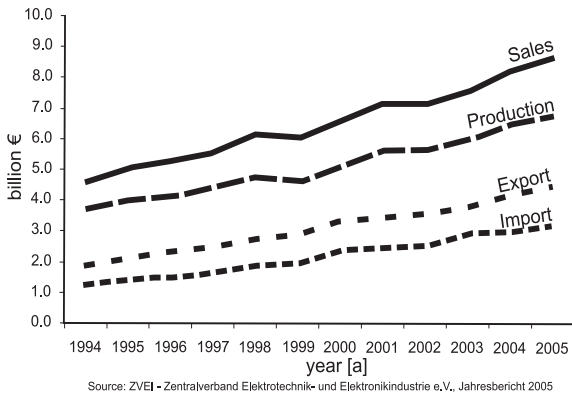Source: ZVEI - Zentralverband Elektrotechnik- und Elektronikindustrie e.V., Jahresbericht 2005

Figure 3. Sales, production of electrical drives in Germany.

Similar growth rates can be noticed in the US [2]. Figure 4 shows a breakdown of the different drive technologies. Interestingly, the classical dc machine drives (with field excitation winding or with permanent magnets) maintain a constant (in absolute numbers) market share of around 1 billion $. The market increase is primarily due to the increased sales of ac induction machines but also PM synchronous (brushless DC) and switched reluctance machines.

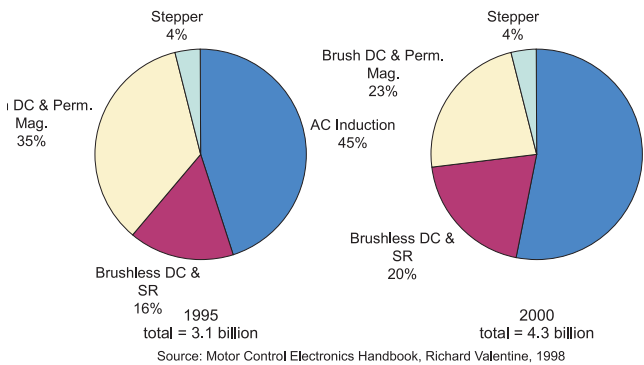Source: Motor Control Electronics Handbook, Richard Valentine, 1998

Figure 4. Growth and market share of electrical drives in U.S.

Clearly, electrical drive technology represents growing markets, albeit less spectacular than recent IT and nano-technologies, but has proven to be a robust market segment which has been affected less by speculation and global market fluctuations or crisis. One can say that electrical drives literally are robust systems which keep the world's economy moving towards higher prosperity (more work done by machines) and more efficient use of primary energy (as variable speed drives are more efficient when production rates need to be adapted).

III. TECHNOLOGY TRENDS

A. Electrical machines

As was shown above, most drives sold today are based on induction machines, PM synchronous machines and increasingly switched reluctance machines (SRM) (see Fig. 5).

a) Induction Machine

b) Permanent Magnet Synchronous Machine
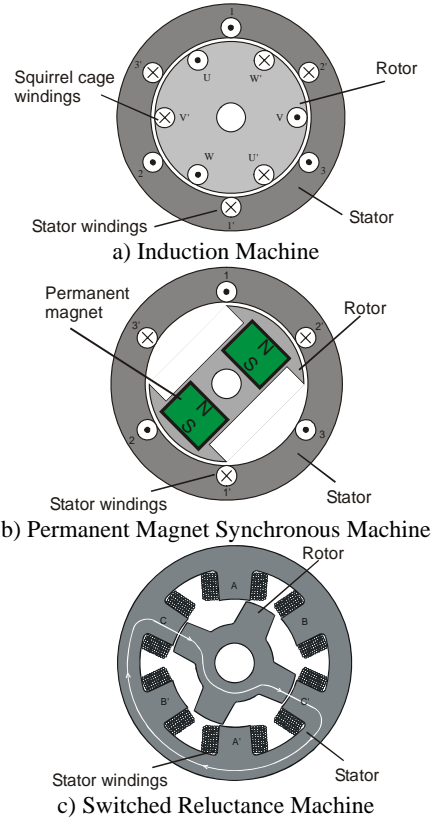
c) Switched Reluctance Machine

Figure 5. Construction of most common electrical machine types

Back in 1980, it was thought that power density of electrical machines was saturating according to the classical S-curve, which is typical for a maturing technology. For example, Fig. 6, shows the evolution of power density of traction machines in 1980. This view was based on the fact that the materials used to build electrical machines were well developed and no innovations to improve power density (requires higher operating temperatures or less lossy materials) were to be expected. Furthermore, market demand had settled on standard machines with speeds up to 3,000 or 3,600 rpm as bearing life seemed to be limited at higher speeds.
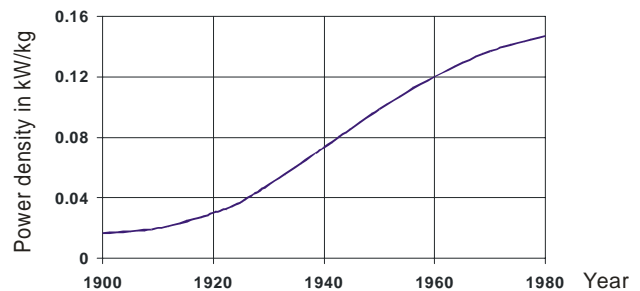

Figure 6. Development of power density of electrical machines for traction applications.
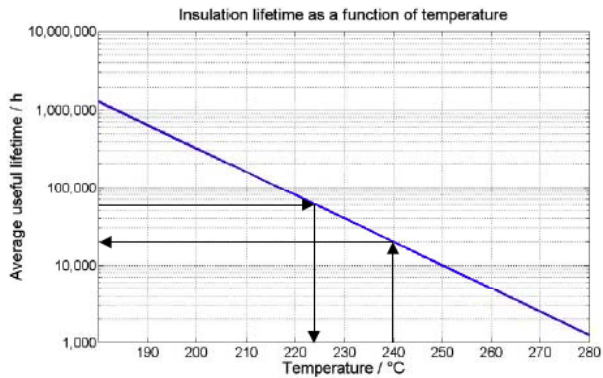
Figure 7. Insulation materials useful lifetime versus temperature

Note that power density of all electrical machines strongly depends on its maximum operating speed as power equals torque times speed and rated torque is the key variable which determines machine size in the first place. So, for constant power applications, higher speed machines have lower torque requirements and consequently can be built smaller and lighter.

Today, electrical machines still are built with the same silicon-steel alloys (max. induction still about 2 Tesla) for the laminations, copper or aluminum for the windings (same losses) and insulation materials, although the latter now reach somewhat higher maximum allowable hot spot temperatures of up to 225 °C for 50,000 hours operating life, as shown in Fig. 7. We can conclude that, in contrast to the first century of machine development, which relied greatly on material improvements, it were several engineering achievements which have allowed over the past 25 years to improve significantly power density of traction and industrial machines up to 1.2 kW/kg. These engineering developments can be situated in several areas:

- Improved quality control, automated production as well as new production techniques, for example copper injection (instead of aluminum) to form squirrel cage induction machines [3].
- Improved design tools (finite elements and physics based dynamic models linked to inverter and control simulations) allow the analysis of the drive under varying loading conditions and controls. Hence, they allow designs (synthesis) with less derating.
- Improved cooling avoids local hot spots, which allows for a better utilization of the available materials while keeping life constant (insulation materials with better thermal conductivity and improved thermal design of the cooling system)
- Reduced derating (used to be at least 15%) of inverter fed machines because less harmonics are being produced by power converters as higher switching frequencies are attainable today without compromising efficiency and cost of the inverter
- Applications have moved, with improved bearing and gear technology as well as improved converter technology, to higher speed applications. Fig. 8 shows an integrated inverter-machine drive with gear capable to operate above 3000 rpm [7].
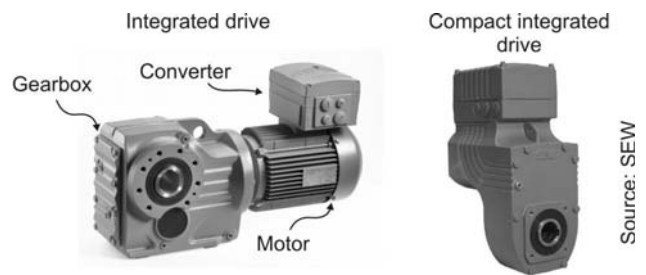

Figure 8. Integrated drives and gears using induction machines[7]

The latter can also be seen, for example, in modern traction applications which are now pushing machine speeds over 6,000 rpm. In electrical and hybrid vehicles electrical machines typically operate up to 16,000 rpm. Large high-power compressor drives operate up to 25,000 rpm. Recently, several manufacturers have implemented high-speed switched reluctance machines in vacuum cleaners at speeds reaching 100,000 rpm, well above the practical limits of universal dc machines. These machines reach, due to their high speed and inherent excellent cooling, power densities up to 3.5 kW/kg.

B. Power converters

It should be noted that power density of power converter systems (including auxiliaries, switchgear, cooling system) has improved even more dramatically over the past 25 years. This can be explained by the fact that power electronic converters are a more recent technology development having more opportunities to improve in several areas. Key to improve power density was the development of improved (less lossy) turn-off power semiconductors, improved heatsink technology, improved control minimizing losses, compact controller design and better design tools which allow the converter designer to "push for the limits" without compromising life of the inverter. However, in the author's opinion, deploying voltage source topologies (instead of current source topologies) and improving design and technology of passive components, in particular of capacitors, had an equally strong impact on power density of converter systems over the past decade.

Over the past 25 years volumetric power density of industrial air-cooled ac-to-ac converter systems improved from 30 kVA/m^3 up to 500 kVA/m^3. Several examples of commercially available converter units and converter systems are shown in Fig. 9 and Fig. 10.
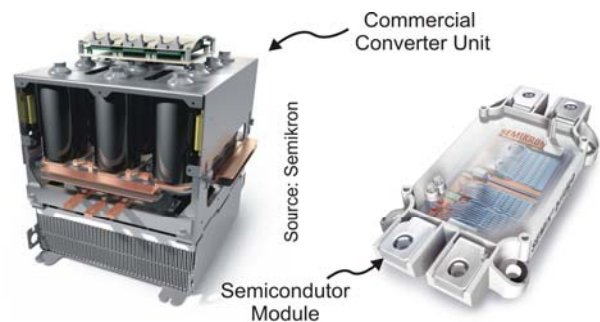

Figure 9. Universal commercial converter building block [8]

Figure 10. Modern vector controlled (FOC) inverters (source Lenze) with standard communication interfaces [9]

The most important limiting factor in designing high-power density converter modules is thermal, i.e. maximum operating temperature and thermal cycle life of power semiconductors and their packages. Significant difference can be noticed between disc type devices [27] and plastic modules with bond wires [28]. Hence, power converter density depends greatly on the specific losses of the devices (less losses requires less heatsinks), coolant temperature and operating conditions.
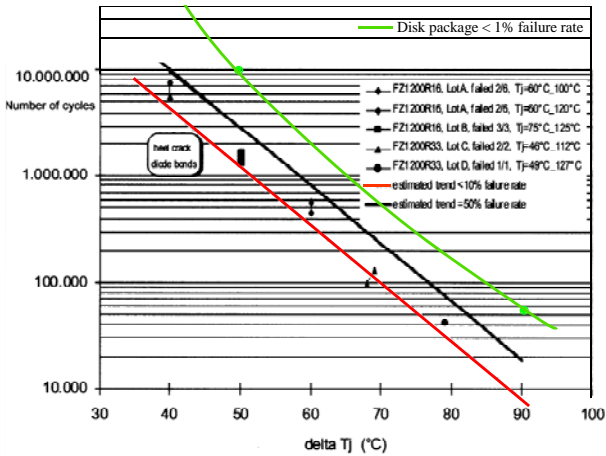
Figure 11. Thermal cycle life as function of temperature excursion of double sided cooled press pack devices (top curve) and power modules for 50 % failure rate (middle curve) and 10% failure rate (bottom).

In electric and hybrid vehicles, where power density plays an important role, it is not uncommon to see optimized liquid cooled dc-to-ac inverter designs with a power density of up to 6,000 kVA/m³ or 6 kVA/l, as illustrated by the 55 kW (peak 75 kW) propulsion unit for electric vehicles shown in Fig.12-14 [4,5]. In this example, a four-phase switched reluctance machine was developed for the propulsion system. The rated power density of the machine is around 1.2 kW/kg. Figure 15 illustrates the efficiency of the drive (tested only up to 10,000 rpm). This demonstrator proved that SRMs can be equally efficient as induction machines (IMs) or PM machines. Testing this propulsion system over different driving cycles showed that the energy consumption was better (up to 5%) than IMs or PM machines because partial load efficiency remains higher. In aerospace applications, power density and weight density are even more critical and converters with a power density of 20 kVA/l have been reported in literature [6].

Figure 12. Tailor-made converter for a four-phase 75 kW SRM propulsion drive.

Figure 13. Stator construction of SRM, showing short end-turns and uniform heating of windings.

Figure 14. Test set-up showing mounting details of the propulsion unit.

Figure 15. Speed-Torque diagram, showing efficiency contours of the 75 kW propulsion unit.

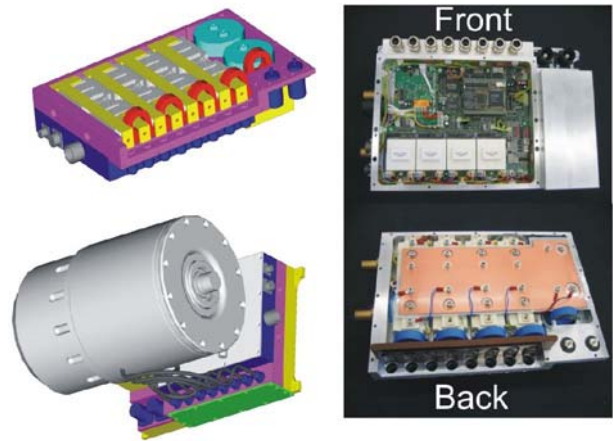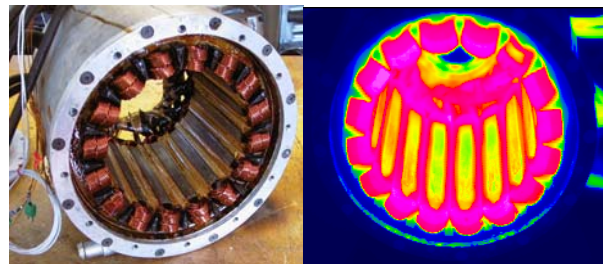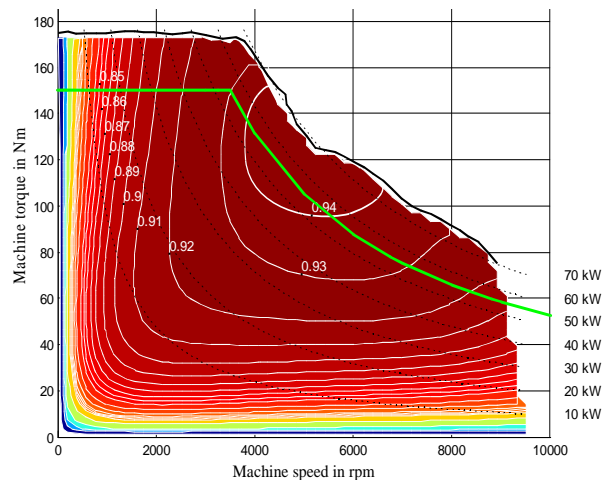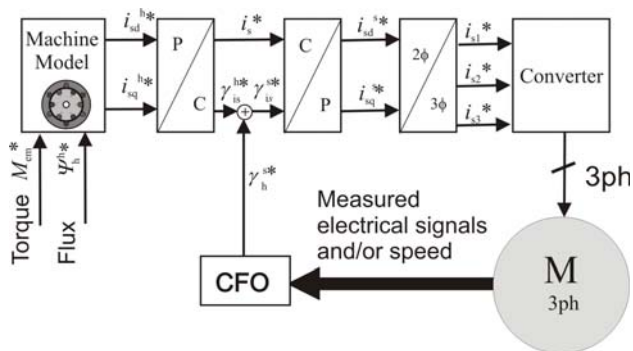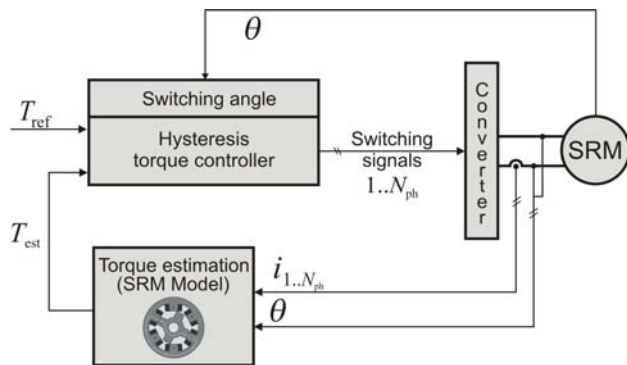Figure 16. Field Oriented Control (FOC) for AC rotating filed machines

Figure 17. Direct Instantaneous Torque Control for switched reluctance machines (DITC)

C. Embedded control and communication links

As was shown above, most drives sold today are based on induction machines, PM synchronous machines and increasingly switched reluctance machines (SRM) (see Fig. 4). Each machine type requires dedicated control algorithms, some of which have been developed over the last decades. Note that SRMs were first introduced in the market in 1984. Since then they have been steadily improved upon so that SRM drives can be considered now for high quality servo drive systems, potentially offering lower cost. Control developers made several key contributions which made drives with servo performance possible and cost effective. Several control innovations (algorithms, software and hardware) developed over the past 30 years are worth mentioning:

- Principle of field oriented control (FOC) for ac rotating field machines maximizes torque per ampere of the drive [10-13] (Fig. 16)
- Space vector PWM modulation augmented with 15% the dc bus voltage utilization of three-phase inverters [14]
- Synchronized (space vector) PWM reduces low frequency harmonics and minimizes filter size
- Direct torque control [15-16], in particular of SRMs enables servo drive performance of this simple but highly non-linear drive [17-18], see Fig. 15.
- Position sensor elimination [19,22] or reducing number of current sensors (for example measuring output current via dc link current sensor) as well as sensor integration (integrating current sensor in

power devices) makes drives more robust and cheaper.

- Fast fixed point or floating point digital signal processors (DSPs) and programmable logic devices (PLDs) made implementation of complex control (FOC) and protection algorithms possible in a small space while offering high flexibility and avoiding expensive ASICs [23]
- Higher level programming languages C++ and tools shorten control development time, allowing flexible adaptation of the drive to new applications

As a result, drives have become programmable, tunable devices which can be adjusted for different applications. In the low to medium power level (0.5 to 50 kW), the cost reduction due to higher volume production can offset the cost overhead of the more flexible control hardware, especially when diagnostic functions need to be integrated in the drive. The classical distinction between adjustable speed drives and high performance drives is becoming less an issue as adjustable speed drives can be obtained by leaving out position sensors and fast communication ports while keeping control hardware identical. Plug-and-play concepts are becoming a reality for factory automation by integrating power, sensor wires and communication links in one cable and standardized connectors. Furthermore, more and more drive products can be easily integrated via fast communication links in a larger computer controlled environment.

IV. MODERN DRIVE DESIGN TOOLS

Design of new drive systems more and more uses powerful numerical design tools which can take specifications, fabrication rules and control algorithms into account. Design of drives requires an electro-magnetic design of the electro-mechanical energy converter (machine, actuator), the power electronic converter and control methodology. In some cases, such as ac rotating filed machine, the design of the machine can be greatly decoupled form the design of the converter. However, design of switched reluctance drives requires a coupled design process which includes machine, converter and control aspects. The electro-magnetic calculations of the machine are essential to calculate:

- winding and core losses
- machine efficiency
- hot spot temperatures, temperature cycles and life expectancy
- acoustic performance

Converter design involves:

- calculation of VA ratings of all components to determine weight and size and to select materials
- loss calculations to calculate efficiency, determine cooling concept
- temperature distribution calculation, temperature cycles, life of the converter
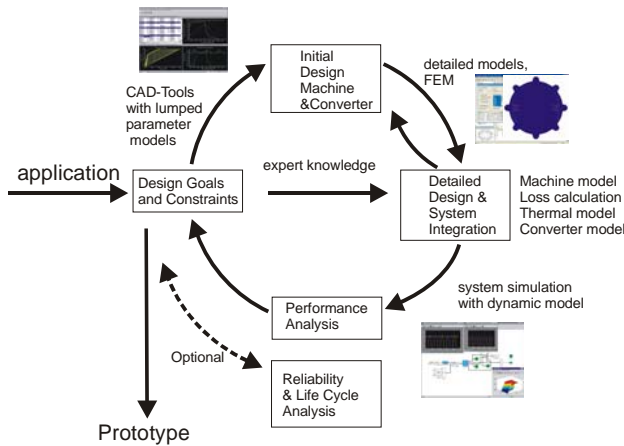- EMI analysis and LF and EMI filter design

Figure 18. Typical design process of electrical drives

Control design and simulation is essential to assess stability, response performance of the drive or to optimize for specified design criteria. Clearly, control design can have a profound effect on inverter and machine efficiency, drive power density, EMI and acoustic noise. Usually, a closed loop design process which optimizes the entire drive system is needed. This design process requires iterative design steps, which is time consuming but allows different design tools to be used for each element of the drive and each step in the process as illustrated in Fig. 18.

To validate performance, thermal cycling, etc., the models need to be time domain, dynamic and physics based models which can be calculated quickly but still offer high accuracy and wide applicability. Detailed finite element simulations can be done to extract from complex geometries the parameters for these dynamic models. Most rotating machine can be modeled 2D, however more and more specialized products require 3D simulations. Embedding these FE simulations in dynamic models (including converter and control simulation) is possible but requires powerful computing environments and takes many resources (time). In some case, this coupling between dynamic models and FE is essential when parasitic effects are strongly coupled and difficult to model, for example eddy currents coupled with saturation and heating effects.

Control functions can be modeled in graphical programming environments (e.g. MatLab/Simulink). Pspice simulations are used to study the parasitic effects during switching of the inverter. Several companies offer idealized converter simulation tools which can be linked to the control simulation tools (MatLab/Simulink). These models offer much higher computation speed at the expense of HF details.

Device losses are calculated in postprocessing mode. Advanced control design concepts follow the rapid control prototyping principles, i.e. control software is coded in the off-line simulation the same way as in the actual control hardware. Time delays between inputs and outputs are simulated by the simulator. Real-time simulation of complex drives is becoming reality using high-speed DSP simulators (see Fig. 19) [29].
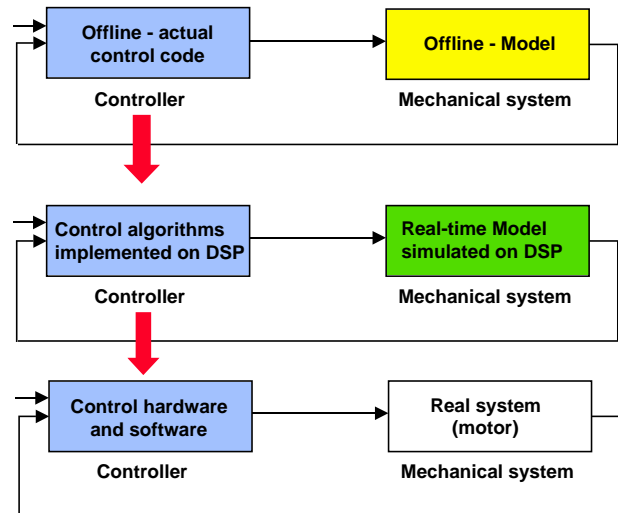
Figure 19. Rapid control prototyping: in all steps of the drive development the same control source can be used.

An example of a complex drive is shown in Fig. 20-21. A spherical machine was developed to integrate three-degrees of motion, providing very high stiffness for robot applications. The spherical machine has 96 independent phases to control the rotor with high torque and high precision (μm scale). Due to the tilt of the rotor, the pole pitch of each magnet appears to be variable from a stator perspective. Each phase was controlled using synchronized current regulators to avoid low-frequency beating and vibrations of the rotor. Six DSPs calculated the transformations and vector rotations such that each active phase was under field oriented control. Several search algorithms were developed to select quickly those phases which can produce the required force vectors most effectively (minimizing force per ampere) [25]. In this project, it was found that off-line simulations of the spherical machine (which was concurrently designed and constructed by other research groups) was too complex and too slow to test control algorithms for all practical purposes. A real-time simulation of the machine was built using the same hardware platform as the control hardware [23, 24]. Complete functionality of the control algorithms was proven within short time by working directly in this real-time environment. Due to small mechanical deviations from its initial design, only little tuning of parameters was required during initial testing when the spherical machine was first taken into service.

Figure 20. Spherical machine with 96-phase converter and control platform based on 6 DSPs in master-slave configuration.

Figure 21. Spherical machine having 96 phases which need individual control due to the variable pole pitch of the magnets when rotor moves along trajectories and rotates

Figure 22. DSP architecture showing control modularity. Flexibility is guaranteed by using programmable logic devices on all I/O.

Another example of productivity using modern rapid control prototyping is the design of a universal field oriented (UFO) controller for an induction machine, which is part of a students lab at ISEA. A target link in MatLab/Simulink emulates the control hardware and the machine. The DSP control software is entirely written in C-code. The developer (here a student training laboratory session) can focus on the control algorithms because the same C-code is used in the off-line simulation (target link) and the controller of the inverter. The execution time of the UFO controller is less than 50 µs. The total programming time takes less than a few hours including testing the performance of the drive. Just 20 years ago, this exercise would have taken an entire PhD program because none of these tools and algorithms existed!

V. FUTURE DRIVE TRENDS

Although improvements in dynamic performance (torque response) and efficiency (already high) will be incremental (market does not demand major improvements in these areas), it is anticipated that in the next decade drive technology will offer:
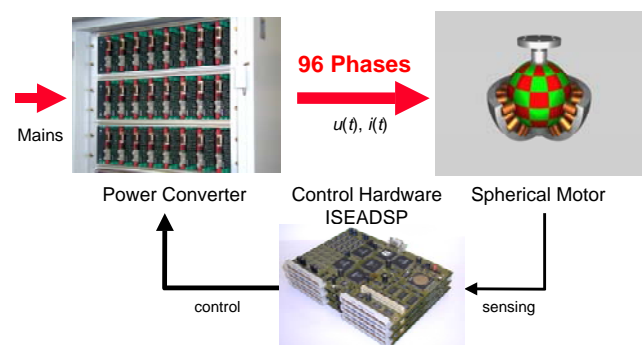
- higher power densities. Indeed, converter designers are just starting to investigate more integrated packaging techniques as well as integrated passive components [26]. In addition, all auxiliaries, such as protective relays, switches, fuses, blowers, which all take considerable space, will be integrated or coordinated more effectively as converters designers are paying more attention to the overall system
- more diversity in machine types. More specialized drives require complete different designs. Amorphous powder metal instead of laminations offers more flexibility to adapt magnetic circuits to particular geometries and applications
- higher speed operation. More drives will operate at higher speeds as it reduces weight of the machine. One can speculate that, from this perspective, more SRM will come to market because SRM rotors can operate at higher speeds due to the fact that no magnets, windings or squirrel cages need to be supported in the rotor.
- high-temperature machines, power converters and control electronics. Machine winding isolation is limited to about 200 C
- propulsion systems with high-torque direct drives. High torque machines using powerful permanent magnets are very efficient at low speeds. Reactive power consumption at high-speed operation can be reduced by proper magnetic circuit design (saturation effects) or using so-called "memory effect" concepts.
- high-temperature superconductors will be used more and more in high power drives. To eliminate the maximum induction (2 Tesla) barrier of Si-steel lamination, large airgap machines or core-less machines are the only viable way to further reduce size of high power machines
- more intelligent drive controllers which takes away the burden of initialization and optimization of the drive performance. More diagnostic tools will be integrated in the drive as sensors at the system level can be avoided. High-speed field bus systems are already common place to transfer all data which can be extracted form a drive system. More drives will link to the Internet the same way as web cameras do today. Plug-and-play will become necessary to serve new applications which directly impact quality of life (domotica, mechatronics, automotive, alternative energy, power quality and medical).

VI. CONCLUSIONS

Judging form experience, publications and recent technology developments, drive technology is still an evolving technology. New applications are constantly emerging. These applications require continued engineering effort to adapt drives to the new requirements. Design tools are becoming mature and will improve over the next decades. New power semiconductor devices will enable higher power-frequency *P.f* products (a measure of utilization of the devices in converters), while losses will continue to decrease.

In conclusion, drive technology is an exciting field of research and development for any young engineer: the more the world moves to automation, computer control, productivity improvements and improvement of the environment and life style, the more electrical energy needs to be converted to mechanical and vice versa. Another reason why drive technology is an attractive engineering field is the fact that it depends on many specialties, such as electrical machines, actuators, power electronics, passive and active components, control hardware and software, sensors technology and sophisticated algorithms and communication links.

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