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ELECTROMAGNETIC AND DESIGN ASPECTS OF MAGNETIC MINI-ACTUATORS

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Abstract: Actuators are systems transferring commands coming from a control system into mechanical motion. The advantage of electromagnetic energy transducers as elements of an actuator is that the control system and the energy transducer have the same type of signals, making the interfacing in principle rather simple. Two main elements can be distinguished in an actuator: the transducer transforming electric energy into mechanic power and the power electronic converter, changing the supply characteristics into quantities required by the electromagnetic energy transducer. The control circuit interacts both with the power electronic converter, to which it sends signals, and often (but not always) receives signals from the electromagnetic energy transducer and/or the converter. The paper reviews some major developments in the area and tries to link them with different applications.

Introduction

In general terms, an actuator consists of three elements:

- converter changing the characteristics of the supplied power into those required by the electromagnetic converter; almost always, this is a power electronic converter;
- electromechanical converter transferring the electric energy into mechanical energy; as piezo-electric, electrostatic, and other type of actuators are treated in different sessions, this paper is limited to electromagnetic transducers;
- control circuit, interfacing the input signals with the actuator and also interacting with both the power electronic and the electromechanical converter.

The paper gives a review of the state of the art of the two converters. It also addresses some technical developments that can influence the actuator design in the near future, if this is not already so, such as design techniques, advanced simulation methods and new control systems.

Electromechanical converter

A well known type of actuator system is the stepper motor drive [1]. Classical applications are producing a discrete and non-continuous motion. There, the input to the stepper motor is digital. Stepper motors are used primarily to control motion, i.e. position, speed, or acceleration. Low cost systems are operated in open loop and as such avoid complexity with feedback control. The number of input pulses determines the position, while the pulse frequency yields the velocity. The system is free of drift, does not show cumulative errors, is highly reliable and especially when using permanent magnets (PM), the torque per input ampère is the highest for a given package size, also at standstill. Different types of constructions exist: reluctance, permanent magnet and hybrid (then the torque is developed by both, reluctance and PM interaction). Within each designation, there is a wide diversity of configurations and sha-pes in both, rotary and linear designs. Stepper motors are “doubly salient”, i.e. both rotor and stator are constructed with salient or projecting poles. This saliency is also their inherent drawback. The torque is produced by the overall change of the stored magnetic energy. Building up and taking out this energy requires a finite amount of time, being an inherent limitation of this motor type [2] introducing torque, speed and position oscillations, and leading to voltage and current peaks. Dynamic stability may be troublesome [3].

The reluctance configuration is the simplest and lowest-cost type of stepper motor. It is also used these days for continuous motion, as the so-called switched reluctance motor, in which a position feedback is used to control the power electronic switches [4]. This very simple motor configuration already clarifies the difficulty in trying to set up a classification for actuator systems: the same (or similar) electromechanical converters, with the same power electronic systems, but with a different feedback control (i.e. none for the stepper motor and position feedback in the switched reluctance motor) leads to an inherently different behavior.

Hybrid stepper motors contain permanent magnets and are often called PM stepper motors, particularly when the contribution to the overall torque of the reluctance variation is limited. Hybrid stepper motors generally develop the highest torque to current ratio of any type of motor. As a result, their weight and volume are often less than those of other motor types. Both machines with radial as well as axial flux distribution are found. The latter ones classically were equipped with Al-Ni-Co magnets. For radial flux machines, ferrites are used if the torque requirements are limited or if costs are a major factor, as e.g. in automotive applications or other mass product designs, while Sm-Co are preferred when high performances are key.

All other classical motors in principle can be used to act as an electromechanical transducer in an actuator. The advantage of the regular type of motors (dc motors, brushless dc, rotating field machines, both induction and synchronous) is that the stored magnetic energy in the airgap remains constant when the machine is at steady state. In this case, almost no cogging occurs. However, in order to use these machines in an actuator, some kind of feedback is essential. Mostly a speed or position measurement is introduced (or a combination of both), making the system more complex. However, the intrinsic performance of such a system is better than the stepper motor.

Dc motors, with their commutator and brushes, are replaced by machines with a rotary field. If used, the dc motors are of the permanent magnet type [5]. The brushless dc motor and the permanent magnet synchronous motor both have a moving permanent magnet system, the first one being supplied by block shaped currents, while the latter one uses a three phase variable frequency to obtain the variable speed. The synchronous motor has the best overall performance with regard to torque density and dynamic behavior, but requires a more elaborated position feedback (highly accurate pulse disk or resolver) than the brushless dc motor, that only needs some Hall or optical sensor. The induction motor with an appropriate control (field orientation or direct torque control) may find its way into actuator systems, provided that numerical computing power required for these advanced control schemes, becomes cheaper. However, the power density of the induction motor is lower than the permanent magnet designs.

With regard to advanced materials, special winding designs using very expensive conductors (as e.g. gold) may lead to very high power densities in small electromechanical systems [6]. Closer to the market and even already available these days, are high energy density permanent magnets, based on Nd-Fe-B, that certainly at room temperature, possess characteristics far beyond what is feasible by using more classical magnet materials [7]. Also in the soft ferromagnetic material, major advances will be seen in the near future based on the powder metallurgy yielding reduced losses and having an impact on the designs. Due to the isotropic behavior, the flux may have a truly three dimensional pattern, being impossible in classical laminations.

Power electronic converter

Power electronic converters consist of a matrix of power electronic switches, turned off and on at the pace commanded by the control circuit. The classical components such as thyristors and bipolar transistors are replaced by more advanced ones, especially with the emphasis of reducing the power required for controlling the switching status, i.e. the input impedance at the control gate. Two components are now dominating the market in power electronic converters in actuators: Power MOSFET

(Metal- Oxide- Field-Effect-Transistor) and IGBT (Insulated Gate Bipolar Transistor).

Unipolar elements as the power MOSFET have a number of common characteristics:

- very high switching frequencies
- small control power required
- high series resistance: the concentration of carriers in the main current path has to be rather small in order to obtain the required voltage blocking capabilities. This is less important in low voltage applications (U<12 V) making MOSFET particularly attractive there.

Especially the third point is very detrimental in view of the power electronic use when larger power levels are involved. The IGBT combines the advantages of the power-MOSFET and the bipolar transistor. In principle, the IGBT is a p-n-p transistor at the base coupled with a MOSFET. The base electrode behaves as a MOSFET, yielding an extremely low control power. The conduction is the main current path includes a saturated p-n-p bipolar transistor, yielding a relatively low voltage drop across the component when a high blocking capability is needed. The switching off is still slower than in the MOSFET.

Also in power electronics, the integration of individual components is increasing. It is already possible to manufacture several Power MOSFET's or IGBT's onto one substrate and to integrate them into one power electronic converter. The combination of extra components on the substrate can lead to very major advantages. Examples of such components are the control circuit, the overvoltage and minimum voltage protection, overcurrent protection and temperature sensors. Apart from these intrinsically directly with the power component linked elements, also intelligent semiconductor circuits (smart power elements) are being developed. Such applications are already present in the automotive industry. There, two important boundary conditions have to be fulfilled. First the voltage of the battery is limited, and therefore, the currents are high and the power is limited. This is an advantage for the introduction of power electronic systems with new structures as the voltage difference between the power and the information part is small. The second boundary condition is the high operating temperature.

When combining power and control electronics on one substrate, attention has to be paid to the influence of the high voltage of the power circuit on the control elements.

Supporting technologies

Field calculations

Due to the very complex geometrical structure of the electromechanical converters, it is often required to use advanced numerical field calculation techniques. When using high performance permanent magnets, the iron in the magnetic path is saturated. The non-linearity has to be considered, being no problem in the finite element method. Furthermore, it is important to account for the geometrical details that often are linked to parasitic phenomena such as torque vibrations due to cogging. A three dimensional analysis is often required, especially when axial flux systems are used. Also in linear actuators, a 3-D analysis of the structure is essential. Due to the temperature dependence of the magnetic characteristics, a coupled solution, accounting for both temperature and flux density distribution simultaneously is required [8]. In this way the totally different problems encountered e.g. in ferrite based designs (where low temperatures cause problems) or Nd-Fe-B based systems (where irreversible demagnetization at high temperature occurs) may be accounted for. Also the link of the electromechanical transducer and the power electronic converter has to be introduced into the field analysis.

Simulation tools and control

For simulation of the overall actuator system, tools as e.g.Simulink® are available these days. In combination with Mathlab®, it is straightforward to transfer the simulated model into C-code and further on into machine language that can be downloaded to a DSP (Digital Signal Processor). This has a major impact on the time to market of advanced control systems as field oriented control. Also the coupling of different systems is far more easy to accomplish this way. Porting a DSP solution into ASIC's, eventually on the same substrate as the power electronic system is relatively straightforward.

The use of advanced machine models to estimate the position and/or the speed may contribute to avoid the need for extra sensors, thus making the actuator more reliable, and combining the advantages of stepper motors and traveling flux density electromagnetic transducers.

Conclusions

The different components of the actuator are undergoing continuous and rapid changes these days. Several options are open for converting the electrical power into mechanic torque and speed. Motors that traditionally could not be emphasized to be used in position controlled applications, are now possible, bringing along their inherent benefits to overcome the drawbacks of the classical devices. Power electronic converters are becoming more powerful and will be integrated with control electronics onto the same substrate. Numerical field analysis and simulation tools are at the disposal of the designer, shortening the time to the market place significantly.

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