

## Fault tolerant force feedback actuator for steer-by-wire

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### Introduction

Nowadays most cars are equipped with hydraulic, electro-hydraulic or electric power steering systems. These systems always have a mechanic connection between the steering-wheel and the wheels that acts as a backup system in case the power steering fails.

In spite of this obvious advantage some drawbacks arise from the mechanic connection, which are overcome if it is omitted:

- no intrusion of the steering-column and the steering-wheel in case of an accident
- no constructive restrictions near the power train
- right/left side driver equipment is easier to implement
- possibility of a variable gearing ratio
- use of the steering as a part of the active body control
- basis for future steering concepts (e.g. side-stick)

Figure 1 depicts a block diagram of an electrical steering system. Instead of the mechanic connection there is an actuator to adjust the wheels – wheel actuator – and a second one to simulate reacting forces at the steering wheel – the force feedback actuator. Both actuators are co-ordinated by the superimposed steering controller. The mechanic connection is replaced by communication lines, the driver is steering ‘by-wire’. This paper concentrates on the force feedback actuator.

Safety is one of the most important issues of the vehicle steering system. Such a new system can only be successful, if it can be proved that it is as safe as its mechanic counterpart.

In case of a single fault:

- the steering wheel must not be blocked – the driver always must be able to control the car
- the steering wheel must not move unintentional – pretending a steering command
- the force feedback must not break down – the driver always must feel the reacting forces

### Torque producing of the permanent magnet synchronous motor (PMSM)

The reliability of a drive can be improved by special motor designs [JAH-80], [MEC-96] or by means of remedial operation strategies [SPE-90], [ELC-94]. The aim of this paper is to show how a standard three phase permanent magnet synchronous machine can be used as a fault tolerant actuator that can fulfil the safety demands. For that, the following section describes in a first step a more detailed approach how the torque of the machine is produced.

The electromagnetic torque of an electric machine generally can be written as

$$t_{el}(\mathbf{g}) = r \cdot l \cdot \int_0^{2p} \mathbf{q}(\Gamma, \mathbf{g}) \cdot \mathbf{b}(\Gamma, \mathbf{g}) d\Gamma. \quad (1)$$

$\Gamma$  – stator angle

$\gamma$  – rotor angle  
 $r$  – rotor radius  
 $l$  – stack length

The magnetomotive force (m.m.f.) curve  $\mathbf{q}_q(\Gamma, \gamma)$  of a single phase is produced by the phase current  $i_q(\gamma)$  flowing in the winding whose contribution is represented by a Fourier series.

$$\mathbf{q}_q(\Gamma) = i_q(\mathbf{g}) \cdot \sum_{n=1}^{\infty} c\mathbf{q}_n \cdot \cos(n(\Gamma - \mathbf{j}_q)) \quad (2)$$

$c\mathbf{q}_n$  – Fourier coefficients of the phase m.m.f. curve  $\mathbf{q}_q$   
 $\varphi_q$  – phase shift angles  
 $q$  – phase number

The air-gap flux density provided by the permanent magnets can also be described as a Fourier series:

$$b(\Gamma, \mathbf{g}) = \sum_{n=1}^{\infty} cb_n \cdot \cos(n(\Gamma - \mathbf{g})) \quad (3)$$

$cb_n$  – Fourier coefficients of the air-gap flux density

After inserting equations (2) and (3) into equation (1) and some transformation steps, the torque, produced by one phase, is

$$t_{el,q}(\mathbf{g}) = \mathbf{p} \cdot l \cdot r \cdot i_q(\mathbf{g}) \sum_{n=1}^{\infty} c\mathbf{q}_n \cdot cb_n \cdot \cos(n(\mathbf{g} - \mathbf{j}_q)) \quad (4)$$

The machine used in the experimental set-up is a 12 pole machine with a fractional-slot winding within 54 stator slots. Figure 2 depicts the rotor-angle-dependent torque of this sample machine over one pole pair produced only by phase 1 that is fed by a constant dc current ( $i_l(\mathbf{g}) = \text{const.}$ ). In contrast to the infinite sum in equation (4), its Fourier analysis only shows the fundamental, a dominant 3. harmonic with 11% amplitude of the fundamental and a very small 18. harmonic due to cogging torque that can be neglected. This figure shall give an impression of the torque producing capability of a single motor phase of the real machine.

The torque curve can be scaled by the amount and direction of the phase current. One single phase only produces alternating torque when fed by dc current. There are two rotor positions within one pole pair where the sign of the torque changes and where therefore never any torque can be delivered.

Phases 2 and 3 will produce identical torque curves but they are shifted by  $2\pi/3$  and  $4\pi/3$  respectively. Thus, the superposition of the torque of two phases will already deliver the desired demand at any rotor position, if the phase currents are chosen properly. But this is only possible if the phase currents can be controlled individually for each phase [KRA-99b].

In general all three phases of the machine are used. They are supplied by symmetrical sinusoidal phase currents. Three phase operation has some well known advantages, e.g. a good utilisation of the machine. A second advantage concerns the torque harmonics. If the machine is supplied by a symmetrical set of currents, the contribution of the third harmonic disappears:

With the symmetrical phase currents

$$i_1 = \hat{i} \cdot \cos \mathbf{g}, \quad i_2 = \hat{i} \cdot \cos(\mathbf{g} - 2\mathbf{p}/3), \quad i_3 = \hat{i} \cdot \cos(\mathbf{g} - 4\mathbf{p}/3) \quad (5)$$

the torque contribution of the third harmonic of the three phases is

$$\begin{aligned} t_{el,3}(\mathbf{g}) &= \mathbf{p} \cdot l \cdot r \cdot \hat{i} \cdot \cos \mathbf{g} \cdot c\mathbf{q}_3 \cdot cb_3 \cdot \cos 3\mathbf{g} \\ &\quad + \mathbf{p} \cdot l \cdot r \cdot \hat{i} \cdot \cos(\mathbf{g} - 2\mathbf{p}/3) \cdot c\mathbf{q}_3 \cdot cb_3 \cdot \cos(3(\mathbf{g} - 2\mathbf{p}/3)) \\ &\quad + \mathbf{p} \cdot l \cdot r \cdot \hat{i} \cdot \cos(\mathbf{g} - 4\mathbf{p}/3) \cdot c\mathbf{q}_3 \cdot cb_3 \cdot \cos(3(\mathbf{g} - 4\mathbf{p}/3)) \\ &= \mathbf{p} \cdot l \cdot r \cdot \hat{i} \cdot c\mathbf{q}_3 \cdot cb_3 \cdot \cos 3\mathbf{g} \cdot [\cos \mathbf{g} + \cos(\mathbf{g} - 2\mathbf{p}/3) + \cos(\mathbf{g} - 4\mathbf{p}/3)] \\ &= 0 \end{aligned} \quad (6)$$

With unbalanced phase currents a torque contribution caused by the third harmonic always remains. It can be measured as a torque ripple.

### Conception of redundancy

To guarantee the save operation of the actuator a redundant concept is developed (figure 3). It uses two principles:

Information processing, power supply and sensors are designed regarding the two-channel 'fail-silent'-principle. It is based on self-monitoring of each channel and on the ability to disconnect itself from the process and to rest silent in case of a fault. Then, the second channel provides all functions.

Motor and power electronics are designed 'fail-operational'. The inverter is divided into three single phase bridges (PE1, PE2, PE3) that supply one motor phase each. Thus, the three phases are decoupled electrically. In the usual operation mode the machine is driven with symmetrical phase currents. In case of a fault the affected phase is turned off and the desired torque is delivered by the remaining two phases. The advantage of this design is that no second electromechanical transducer is necessary. Here the inherent redundancy of a standard machine is used.

### Reconfiguration

To change from three phase to two phase operation mode the drive system has to be reconfigured. Additional functions are necessary to do so. Figure 4 shows the principle of the fault tolerant set-up.

Behind the inner current control loops, that are simplified to first-order time-delay elements, fault currents are added as disturbances. In normal operation they are equal to zero. In case of a fault, fault currents may arise from the permanent excitation. A superimposed torque control loop is necessary to compensate the influence of a fault current on the one hand and to compensate the torque ripple in two phase operation mode on the other.

The actual value of the torque is calculated by multiplying the phase currents by the normalised torque curves (eq. 4). It serves as an input for the torque controller whose design will be treated in detail in the final paper. The output of the controller is the reference current in the torque generating q-axis. The field producing current in the d-axis is set to zero, due to the permanent magnet excitation.

$$\begin{aligned} i_{q,ref} &= k_t \cdot t_{el,ref} \\ i_{d,ref} &= 0 \end{aligned} \quad (7)$$

The block 'reference current generator' provides the reference values for the inner current control loops. It contains the transform matrix from the rotary hdq-reference frame to the stationary 123-reference frame:

$$\begin{bmatrix} i_{1,ref} \\ i_{2,ref} \\ i_{3,ref} \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} & \cos \mathbf{g} & -\sin \mathbf{g} \\ 1/\sqrt{2} & \cos(\mathbf{g}-2\mathbf{p}/3) & -\sin(\mathbf{g}-2\mathbf{p}/3) \\ 1/\sqrt{2} & \cos(\mathbf{g}-4\mathbf{p}/3) & -\sin(\mathbf{g}-4\mathbf{p}/3) \end{bmatrix} \cdot \begin{bmatrix} i_{h,ref} \\ i_{d,ref} \\ i_{q,ref} \end{bmatrix} \quad (8)$$

Since the transform rules contain only three equations, a third quantity has to be fixed. In three phase operation the obvious choice is to set the homopolar component to zero ( $i_{h,ref} = 0$ ). This leads to a symmetric current system (eq. 5) with its advantages described above. There will be no system deviation because neither torque ripple nor fault current occurs. Thus the superimposed torque controller will be inactive.

If one phase is faulted, it should be turned off and two phase operation mode should be entered [KRA-99b]. The turn off of one phase is described by setting its reference value to zero

( $i_{1,ref} = 0$  or  $i_{2,ref} = 0$  or  $i_{3,ref} = 0$ ). Then only a fault current can produce additional torque, but this will be adjusted by the torque controller.

### Realisation

Phase currents can either be controlled in a stationary or in a rotary reference frame. The practical realisation uses linear controllers in the rotary dq-system (figure 5). Again the current in the q-axis is proportional to the torque demand and the current in the d-axis is equal to zero (eq. 7). The modulator transforms the controller outputs to voltage vector demands for the voltage source inverter. A switching table translates these demands into firing signals for the inverter bridges. When the operation mode has to be changed only this switching table is changed. It contains all the information concerning how a phase is turned off and how the remaining phases have to be influenced.

The fault detection monitors the drive currents and voltages and detects deviations from normal operation [KRA-99a]. When a fault in a phase occurs, an error message is sent to the switching table to reconfigure it to two phase operation. The superimposed torque controller is the same as in the example above.

### Experimental results

As experimental results, figure 6 depicts the phase currents and the torque when phase 1 is turned off and no fault current is flowing. This situation occurs e.g. if the terminals of winding 1 are open circuited. The left side shows the results without torque controller whereas on the right side it was active. In the first case torque harmonics occur. In the latter case, it can be seen that the phase currents are modified a little and that the delivered motor torque is smoothed.

Figure 7 shows the results with a fault current in phase 1. In this experiment, the winding is short circuited and the e.m.f. drives a sinusoidal short circuit current. Although the amount of fault current is significant, the torque is nearly smooth.

Further results will be presented in the final paper.

### Summary

Steer-by-wire concepts provide several advantages. Comparable reliability and safety can be achieved by redundant designs. This paper discusses the design of a fault tolerant concept for a force feedback actuator with a standard three phase PMSM. Only the phases of the machine are separated electrically. This allows in case of a fault to drive the machine with two instead of three phases. A superimposed torque controller adjusts the influence of fault currents and torque harmonics in two phase operation and guarantees smooth torque at the steering wheel.

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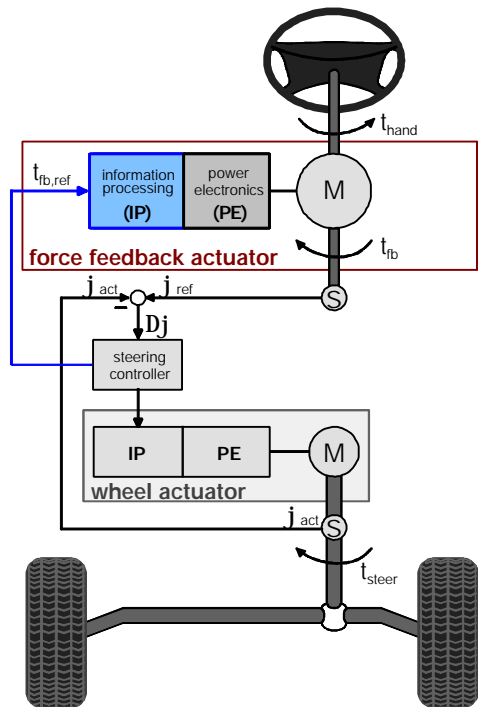


Figure 1: Electrical steering system

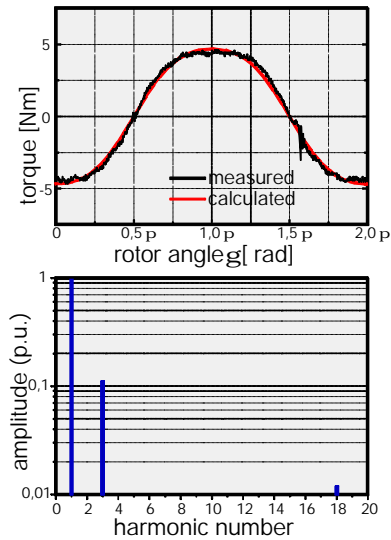


Figure 2: Rotor-angle-dependent phase torque and Fourier analysis

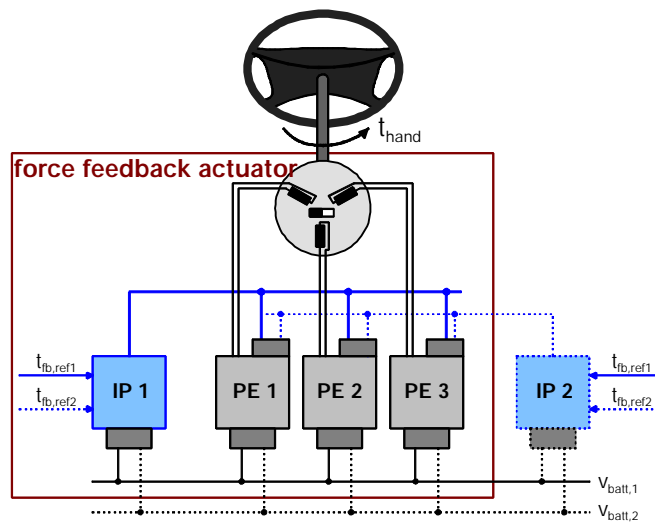


Figure 3: Conception of redundancy

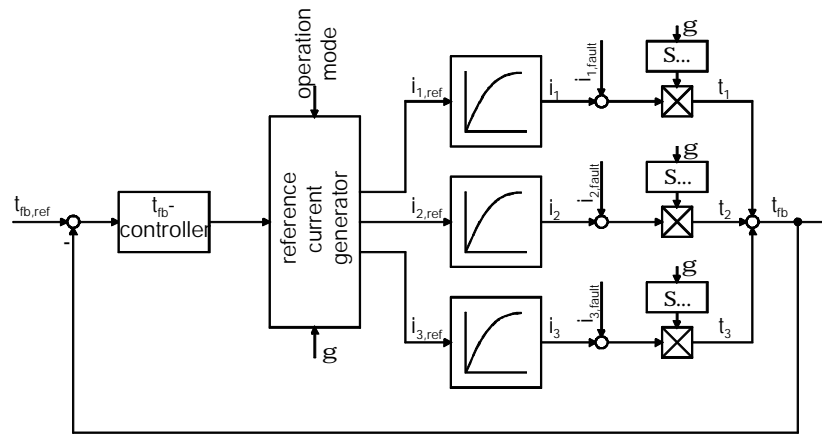


Figure 4: Principle of the fault tolerant set-up

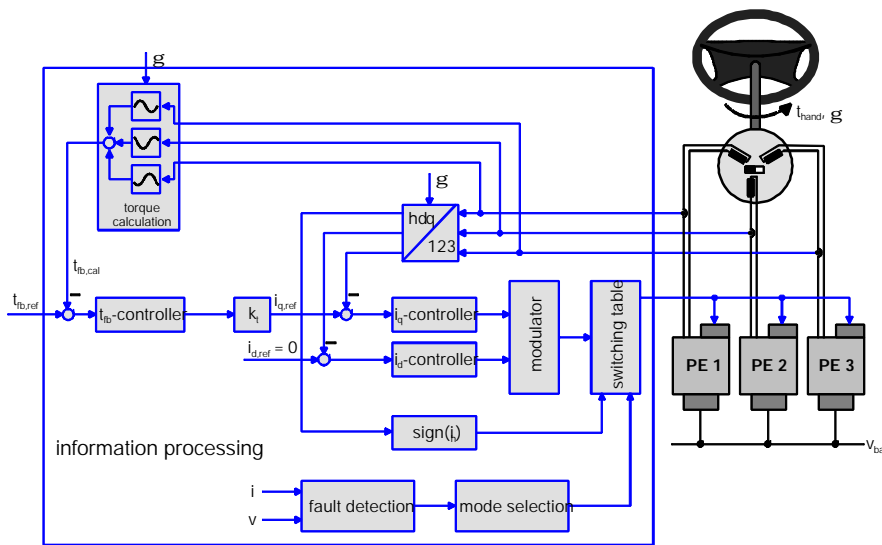


Figure 5: Practical realization of the fault tolerant set-up

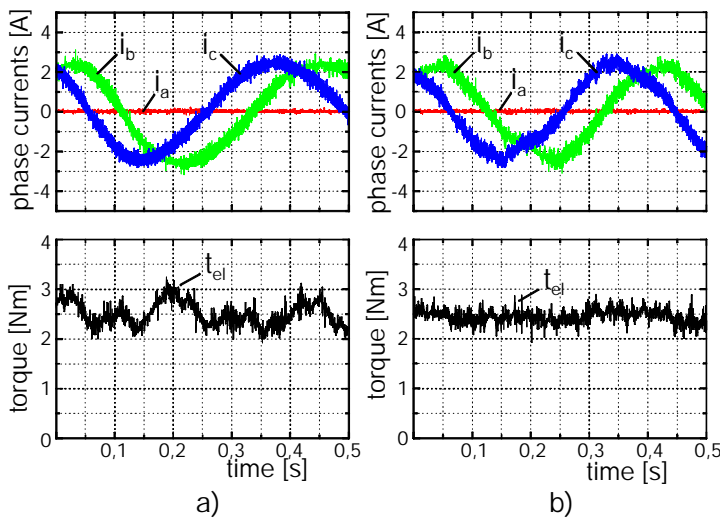


Figure 6: Measured time characteristic of phase currents and torque (phase 1 is turned off, no fault current), a) without torque controller, b) with torque controller

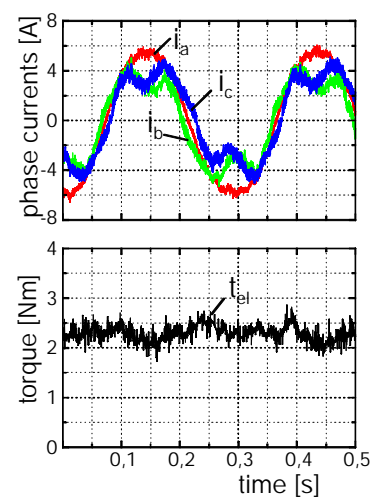


Figure 7: Measured time characteristic of phase currents and torque (phase 1 is turned off, winding short circuit) with torque controller