Fault Tolerant Actuator for Steer-By-Wire Application

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Abstract: Reliability and safety of steer-by-wire concepts 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. In contrast to usual drives, the phases of the machine are separated electrically. This design allows driving the machine with two instead of three phases in case of a fault. 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

Keywords: permanent magnet synchronous motor (PMSM), redundancy, fault tolerance, automotive auxiliary drive, actuator

1. INTRODUCTION

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

In spite of this obvious advantage, the electric steering system discussed in this paper drops the mechanic shaft to get several other benefits:

- 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 easy to implement
- possibility of a variable gearing ratio
- use of the steering as a part of the chassis control system
- basis for future steering concepts

Fig. 1 depicts a block diagram of this steering system. Two actuators replace the mechanic steering shaft: First, the wheel actuator to adjust the wheels according to the drivers demand. Second, the force feedback actuator to simulate reacting forces at the steering wheel. The reacting forces provide an impression of the driving situation (speed, condition of the roadway etc.). Both actuators are co-ordinated by the superimposed steering controller.

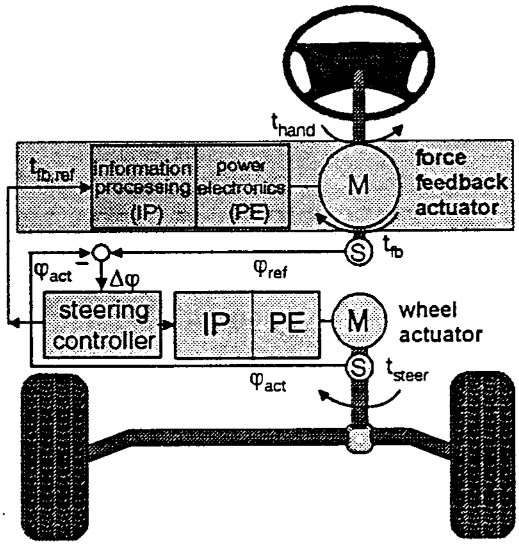


Fig. 1: Steer by wire system

This paper concentrates on the force feedback actuator. The force feedback must never break down – the driver always must feel the reacting forces. Since safety is one of the most important issues, the new design must be proved to be as save as its mechanic counterpart.

2. CONCEPTION OF REDUNDANCY

Reliability of a drive can be improved by special motor designs (Jahns, 1980; Mecrow, et al., 1996) or by means of remedial operation strategies (Spée and Wallace, 1990; Elch-Heb, et al., 1994). The aim of this paper is to show how a standard three-phase permanent magnet synchronous machine (PMSM) can be used as a fault tolerant actuator.

To guarantee the save operation a redundant concept is developed (Fig. 2). 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-

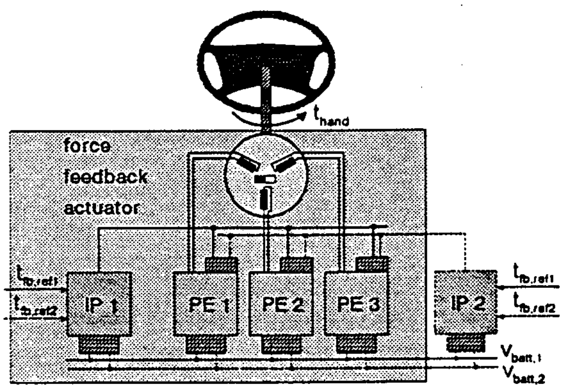
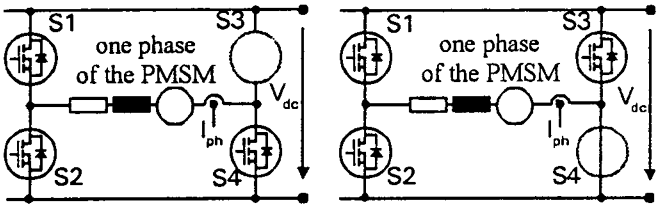


Fig. 2. Conception of redundancy

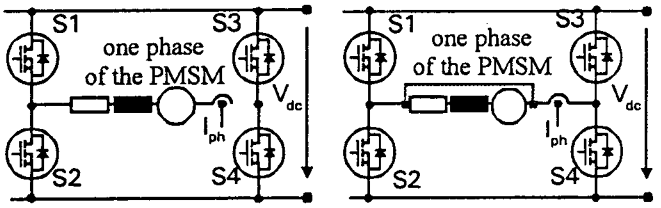
operational'. The inverter is split up into three single-phase bridges (PE1, PE2, PE3) that supply one motor phase each. In normal operation the machine is driven with symmetrical phase currents. In case of a fault the affected phase is turned off immediately and the desired torque is delivered by the remaining two phases. Here, the inherent redundancy of a standard 3-phase machine is used.

3. OCCURRENCE OF A FAULT

This paper concentrates on the three-channel fail operational part, i.e. inverter (including current controllers) and the motor. It is assumed that only one fault occurs at a given time. Possible faults are short- and open-circuits of the power devices as well as the windings and malfunction of the current controllers. They are detected by monitoring the phase currents and by interpreting the error signals of the primary protection circuitry (Krautstrunk and Mutschler, 1999a). The primary protection uses v_{CE}-monitoring to detect over-current. Also, open circuit, i.e. i_C=0 despite of applied gate voltage, is sensed.



a) Power device open circuit   b) Power device short circuit



c) Winding open circuit   d) Winding short circuit

Fig. 3: Faults within a single-phase inverter bridge (PE)

Fig. 3 shows some of the possible faults within one phase.

With an open circuit of one power device (e.g. S3 in Fig. 3a) the proper operation of the inverter bridge is no longer possible. The other devices have to be turned off to prevent further damage due to missing freewheeling paths.

Fig. 3b depicts the short circuit of S4. This fault becomes serious as soon as the second switch (S3) of the same inverter leg is turned on. The shorted d.c. link results in excessive current. Fast primary protection is necessary to prevent further damage. A short circuit current driven by the motor e.m.f. can be conducted into one direction by the faulted power device (S4) and the freewheeling diode of S2. If this short circuit current is low, its influence on the torque of the motor can be compensated by properly adjusting the two remaining phase currents. The limit of compensation is reached if phase currents exceed their nominal values.

If a winding is open circuited, there will be no current to generate any torque contribution (Fig. 3c). The difference between reference value and actual current value indicates the open circuit.

As a result of a winding short circuit the d.c. link will be shorted if the phase is turned on (Fig. 3d). The same over-current protection is needed here as for the short circuit of a power device. Winding short circuits are a special problem, because the short circuit current driven by the e.m.f. may bypasses the current sensing device. Then compensation methods as mentioned above are not available. If only parts of the winding are shorted, the phase inductance decreases with square-law characteristic. Therefore the rise of current di/dt increases, giving information about the amount of damage.

The result of these faults can be summarized in two categories: no current in the affected phase (e.g. winding open-circuit) or any unknown current (e.g. driven by the e.m.f.). In both cases the phase current is no longer under control. The phase has to be turned off immediately and the remaining phases get new reference values to provide the same torque as before.

4. CONTROL LOOPS

Fig. 4 shows the block diagram of the controller.

In the synchronous 0dq-reference frame, the torque controller produces $i_{q,ref}$. If there is no fault, $i_{0,ref}$ is zero. If a fault occurs, the corresponding H-bridge is blocked by the primary protection (i_{ph}=0). Then the processor identifies the faulted phase and generates a value for $i_{0,ref}$ according to Fig. 4. As one phase is blocked, the two remaining phases have to produce the torque.

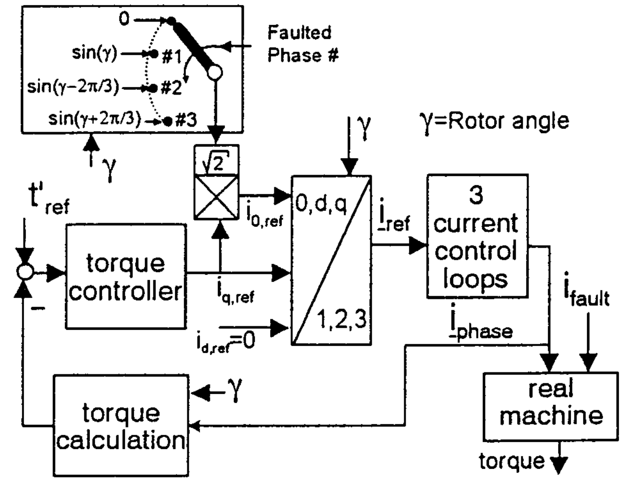


Fig. 4: Block diagram of the controller

In two phase operation with a constant $i_{q,ref}$, the torque of the real machine varies considerably with the angle γ, i.e. with the angular position of the steering wheel. Reasons for this torque-ripple are spatial harmonics of the mmf-curve as well as spatial harmonics of the air gap flux density produced by the permanent magnets. In the

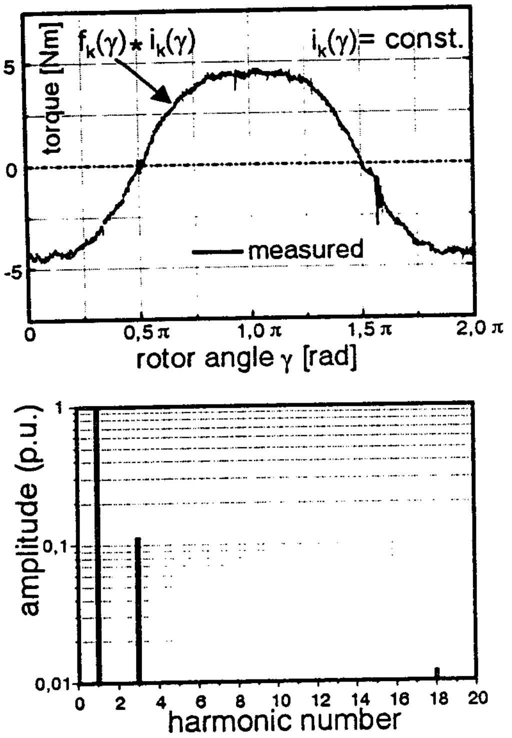


Fig. 5: Rotor-angle-dependent phase torque and Fourier analysis of the measured curve

normal 3-phase operation, the dominant third-order harmonics cancel out resulting in low torque ripple. But in two-phase operation, large low-order harmonics remain in the torque. To reduce this torque ripple, the Blocks "torque calculation" and "torque controller" are introduced in Fig. 4.

The torque, produced by one phase "k" only, generally can be written as

$$t_{el,k}(\gamma) = i_k(\gamma) \cdot f_k(\gamma) \tag{1}$$

This can be understood as the product of the phase current with the torque curve $f_k(\gamma)$, a term that describes the motor design. This term is measured off-line (Fig. 5) and stored as a look-up table in the block "torque calculation". Phases 2 and 3 have identical torque curves but they are shifted by 2π/3 and 4π/3 respectively. The superposition of the three torque curves provides the actual torque value of the machine.

The machine used in the experimental set-up is a 12-pole machine with a fractional-slot winding within 54 stator slots. Fig. 5 depicts the rotor-angle-dependent torque $f_k(\gamma)$ of this machine over one pole pair produced by phase 1 which is fed by a constant dc current ($i_1(\gamma)$ = const.). The Fourier analysis shows the fundamental, a dominant third harmonic with 11% amplitude of the fundamental and a very small 18th harmonic due to cogging torque that can be neglected.

In normal 3-phase operation mode nearly no torque ripple occurs. Consequently, the superimposed torque controller (Fig. 4) will be inactive.

In two-phase operation mode, characterized by unbalanced phase currents, a torque contribution caused by harmonics of the torque curve $f_k(\gamma)$ always remains and can be measured as a torque ripple. The torque ripple ends up in a torque error, which the torque controller easily compensates. Examples are given in the experimental results.

5. REALIZATION

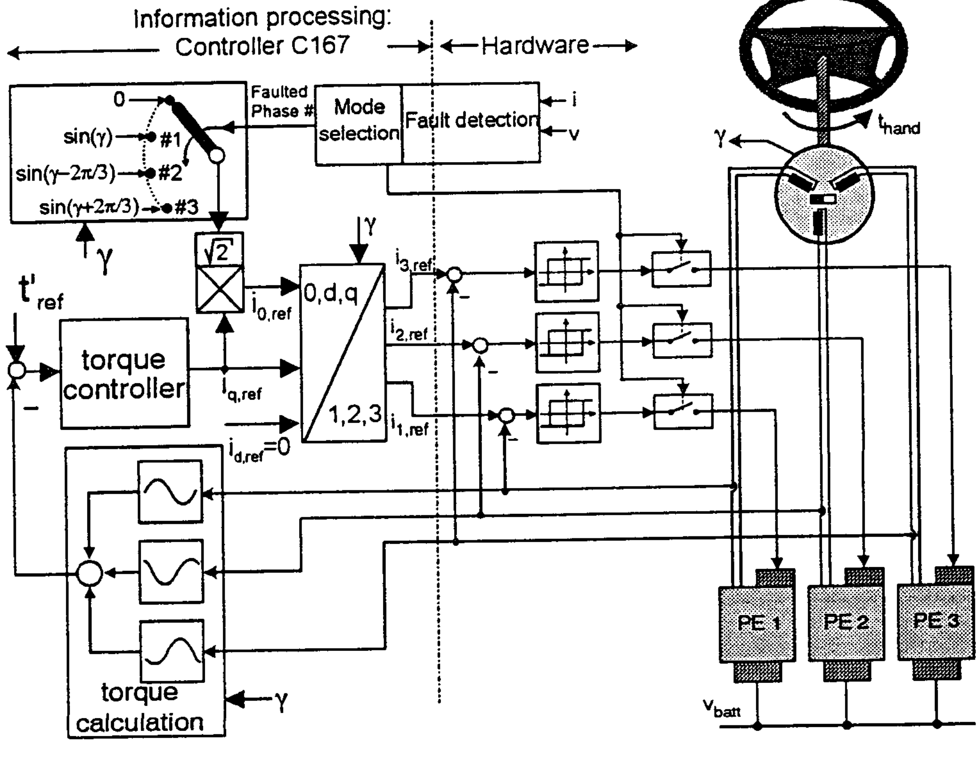


Fig. 6: Practical realization of the fault tolerant set-up

Phase currents can be controlled in any frame of reference. The experimental set-up uses the stationary frame of reference with one hysteresis controller for each phase (Fig. 6). It is well known, that for normal, i.e. Y-connected stator windings, three hysteresis-controllers may interfere, resulting in limit cycles with high switching frequency. The reason is, that in 3 Y-connected windings only 2 currents are independent, but 3 controllers try to control 2 currents. As we have 3 electrically independent (but magnetically coupled) windings in our system, there is no problem with 3 controllers.

The fault detection monitors the drive currents and voltages and detects deviations from normal operation (Krautstrunk and Mutschler, 1999a). When a fault occurs, an error message is sent to the mode selection block that reconfigures the drive system to two-phase operation: It selects the correct zero-component and switches off the affected phase. The superimposed torque controller works as described above. It is designed as an I-controller. The torque curve that is used to calculate the actual torque value is stored as a look-up table. The information processing is implemented on a C167CR µ-Controller. The hysteresis controllers are implemented in hardware.

6. EXPERIMENTAL RESULTS

The following figures present measured time characteristics of the phase currents and the torque during different faults. The upper graphs show the results without the torque controller whereas the lower graphs illustrate the influence of the closed loop torque control. The torque reference value is set to 2,5 Nm for all examples.

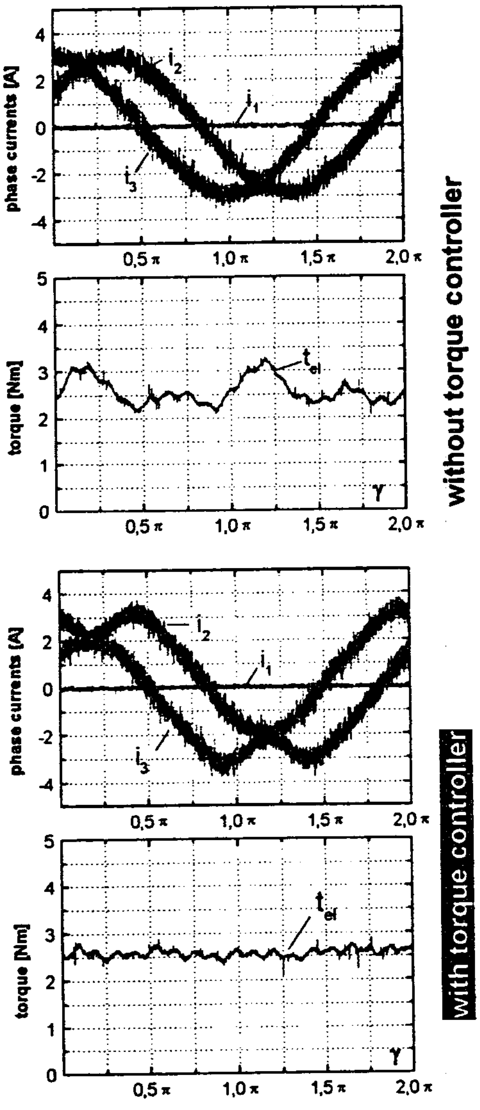


Fig. 7. Measured time characteristics of phase currents and torque.
Fault: phase 1 off, no fault current.

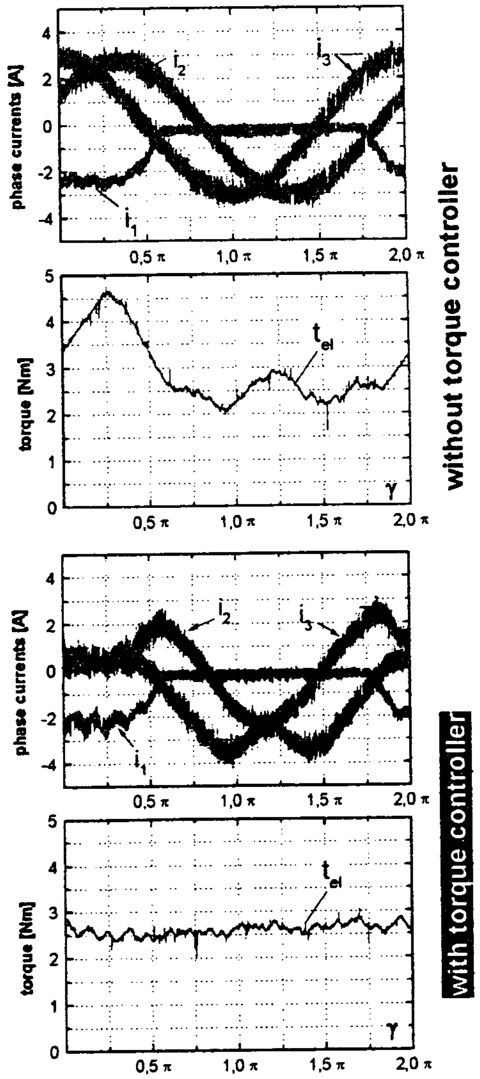


Fig. 8. Measured time characteristics of phase currents and torque.
Fault: phase 1 off, short circuit of one power device.

Fig. 7 depicts the phase currents and the torque when phase 1 is turned off and the fault current is zero. This situation occurs e.g. if the terminals of winding 1 are open circuited. Without the torque controller there is a significant torque ripple of the second and fourth harmonic. This ripple results from the multiplication of the fundamental of the phase currents and the third harmonic of the torque curve in Fig. 5. The torque controller shows good results and the torque is very smooth. The phase currents are adjusted but differ from the sinusoidal form.

The next example (Fig. 8) illustrates the influence of a short circuit of one power device (e.g. power-MOSFET). A short circuit current driven by the motor e.m.f. is conducted by the faulted power device and the freewheeling

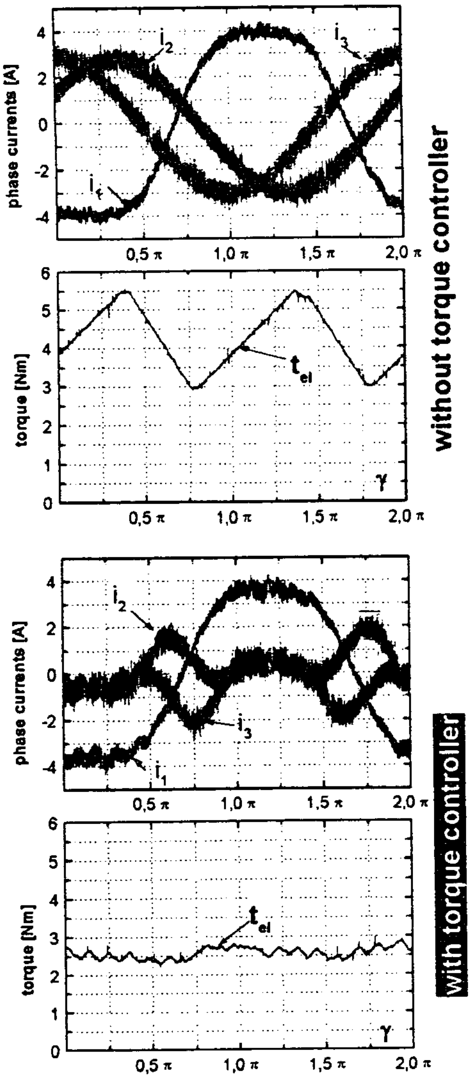


Fig. 9. Measured time characteristics of phase currents and torque.
Fault: phase 1 off, winding short circuit.

diode of the opposite inverter leg. The diode forces the current into one direction.

Fig. 9 shows the performance 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. But the short circuit is located in such a way, that the fault current can be measured by the current transducer. Due to this, the torque calculation can calculate the real torque and the torque controller gets a chance to force the remaining phases to produce currents which result in an overall smooth torque.

Although the amount of fault current is significant, the torque is nearly smooth if the torque controller is used.

7. CONCLUSION

Steer-by-wire systems are safety related systems. Reliability and safety has to be achieved by a redundant design. This paper discusses exemplary the design of a fault tolerant concept for a force feedback actuator that emulates the reacting forces at the steering wheel.
The phases of a PMSM are separated electrically to provide fail-operational behaviour in case of a fault. This design allows driving the machine with two instead of three phases. During this emergency operation fault currents and torque harmonics could cause a considerable torque ripple. But a superimposed closed loop torque control guarantees smooth torque at the steering-wheel

ACKNOWLEDGEMENTS

The authors would like to thank the DaimlerChrysler AG for their support and co-operation.

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