Improving Motor Current Control Using Decoupling Technique

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***Abstract*— This paper reports advances in the design and development of decoupling method in motor control of electric power assisted steering (EPAS) systems. A motor model for permanent magnet synchronous machines (PMSM) is described. Implementation details, simulation and measurement results are also presented.**

***Keywords*— Decoupling, electric power assisted steering (EPAS) systems, field oriented control (FOC), motor control, permanent magnet synchronous machines (PMSM).**

I. Introduction

IN ELECTRIC power assisted steering (EPAS) systems an electric machine is connected to the mechanical steering system to reduce driver's work by generating torque in the appropriate direction. Electric actuators have great advantages compared to hydraulic systems. Steering properties can be changed on line according to vehicle speed, road surface quality or other significant parameters. They are also environment friendly, because of their higher efficiency and they do not contain environmentally harmful hydraulic steering fluid.

Automotive environment demands special requirements for motor control application, e.g. high reliability, working with varying and usually low voltage level, providing high torque at high speeds with small size and high efficiency. Nowadays three phase permanent magnet synchronous machines (PMSM) are used in steering systems because of their compact design and high efficiency.

In a prototype electric power assisted steering system developed by ThyssenKrupp Nothelfer Kft., there were over current problems occurred during torque reversing at high speed operation. These over currents appeared at transient states where the controllers was not fast enough to compensate for internal changes of the motor.

To solve these problems controllers were improved with decoupling calculation. Main purpose of introducing decoupling technique in the system was to improve reliability of the application without loosing output torque or decreasing system dynamic properties.

The implementation will be described in the following order: first a motor model will be presented to understand the coupling between two controller loops caused by electric machine [1]. It will be followed by a short description of the presently used and the new controller structure. In the next section we will write about a recently implemented saturation system. In the following sections simulation and measurement results will be introduced and evaluated. Finally a conclusion will be presented.

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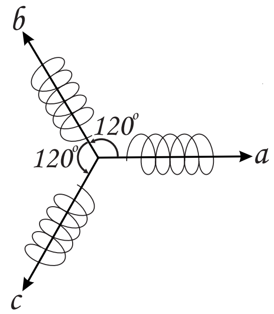

Fig. 1. Phase windings orientation

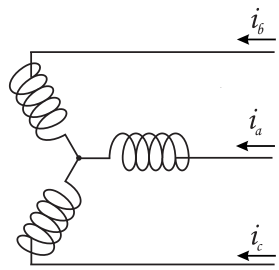

Fig. 2. Motor phase currents

II. Motor Model

Electric machines contain two magnetic fields: stator and rotor fields. Rotating stator field forces rotor field to follow it and generate torque. In the PMSM type of electric machines rotor magnetic field is generated by permanent magnets which are mounted on the rotor surface. Stator magnetic field is generated by stator windings. In this paper the theoretical motor winding structure is used where the real phase windings are reduced to three phases (a,b and c) [2], [3]. This windings a, b and c are physically spaced 120 degrees apart from each other (Fig. 1) [1]. Magnetic field orientation of each coil is parallel to its winding's axis.

Permanent magnet synchronous machines are controlled by field oriented control (FOC), which requires to convert 3 phase stator oriented reference frame (a,b,c) into magnetizing (d) and torque producing (q) components. If machine's star point is not connected then currents in a, b and c windings can be calculated using (1), where i_a, i_b, i_c are the phase currents, as it can be seen in Fig. 2.

$$i_a + i_b + i_c = 0 \quad (1)$$

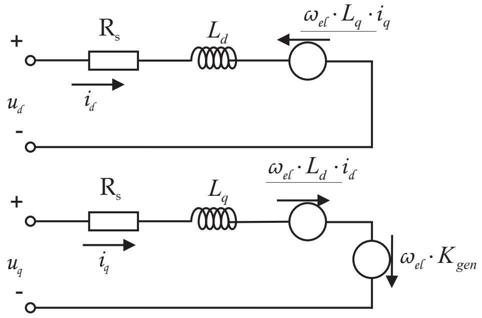

Fig. 3. Motor model in stator oriented reference frame

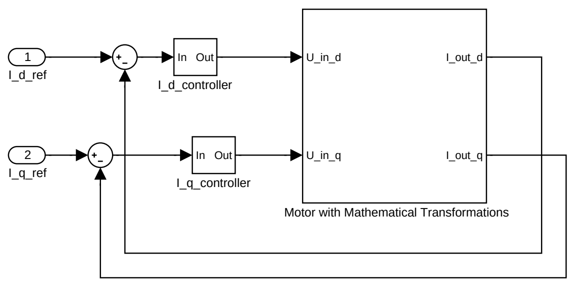

Fig. 4. Old current control model

To change from stator to rotor oriented reference frame Clarke (2) and Park (3) transformations are used, where $i_\alpha,\ i_\beta$ are real and imaginary currents in a stator oriented complex reference frame, Θ_{el} is the electric angle between stator phase flux direction and rotor magnetic flux direction (d) and $i_d,\ i_q$ are currents in the rotor oriented reference frame [3], [4], [5]. Electric angle measures the magnetic flux change of the rotor. If rotor rotates by one magnetic pole pair, electric angle counts 2π. A relationship between electric and mechanical angle can be seen in (5), where Θ_{el} is the electric angle, n_p is the number of rotor magnetic pole pairs and Θ_{mech} is the mechanical angle between phase a direction and rotor magnetic flux direction.

$$\begin{aligned} i_\alpha &= \frac{2}{3}\cdot \Re e\ \left\{ i_a + i_b \cdot e^{j\cdot\frac{2\pi}{3}} + i_c \cdot e^{j\cdot\frac{4\pi}{3}} \right\} = i_a \\ i_\beta &= \frac{2}{3}\cdot \Im m \left\{ i_a + i_b \cdot e^{j\cdot\frac{2\pi}{3}} + i_c \cdot e^{j\cdot\frac{4\pi}{3}} \right\} = \frac{2\cdot i_b + i_a}{\sqrt{3}} \end{aligned} \tag{2}$$

$$\begin{aligned} i_d &= \cos\theta_{el}\cdot i_\alpha + \sin\theta_{el}\cdot i_\beta \\ i_q &= -\sin\theta_{el}\cdot i_\alpha + \cos\theta_{el}\cdot i_\beta \end{aligned} \tag{3}$$

Clarke transformation changes from stator oriented 3 axes reference frame (a,b,c) into stator oriented orthogonal 2 axes frame (α,β). Park transformation rotates stator oriented reference frame (α,β) synchronously to rotor, which results a steady reference frame (d,q) from rotor point of view. Queer (q) component is perpendicular to rotor's magnetic field; it is used to generate torque. Direct (d) component is parallel with rotor's magnetic field and is used to decrease the induced voltage generated by rotor magnetic field in stator windings (field weakening) [6].

A motor model in rotor oriented (d,q) reference frame can be seen in Fig. 3. This motor model is described with (4) [7], where $u_d,\ u_q$ are voltage inputs, $i_d,\ i_q$ are loop currents, R_s is the resistance, L_d and L_q are the inductances, K_{gen} is the generator constant, ω_{el} is the rotor electric speed. ω_{el} is calculated from (6), where ω_{mech} is the rotor mechanical speed and n_p is the number of rotor magnetic pole pairs. The parameters are derived from motor physical constants.

$$\begin{aligned} u_d &= R_s\cdot i_d + L_d\cdot\frac{di_d}{dt} - \underline{L_q\cdot\omega_{el}\cdot i_q} \\ u_q &= R_s\cdot i_q + L_q\cdot\frac{di_q}{dt} + \underline{L_d\cdot\omega_{el}\cdot i_d} + \omega_{el}\cdot K_{gen} \end{aligned} \tag{4}$$

$$\Theta_{el} = n_p\cdot\Theta_{mech} \tag{5}$$

$$\omega_{el} = n_p\cdot\omega_{mech} \tag{6}$$

In motor windings there are mutual impedances. This mutual impedances cause couplings between motor windings inducing voltage in one phase winding if current changes in an other phase. In Fig. 3 and in (4) the underlined terms are the cross coupling between d and q loops.

III. Controller Structure

In recently used motor control applications (Fig. 4) electrical system is considered as two independent current control loops [8]. Each loop has an input reference current ($i_{d\_ref},\ i_{q\_ref}$) derived from steering requirements and the system mechanical state.

The difference between actual and required current is regulated by a PI controller. The controller outputs are proportional to the voltage applied to the motor phases. Because of mutual inductances in electric machine these control loops are not independent. If we change desired current in one loop the coupling causes current peaks in the other. Even in advanced motor control applications these cross coupling terms are not taken intro account [8]. Our goal was to calculate coupling terms to reduce transient current peaks [7]. Modification of the old control model (Fig. 4) is in Fig. 5. It contains also a limitation system which is described in the next section.

Decoupling sub model implements underlined calculations detailed in (4) as it can be seen in Fig. 6.

IV. Saturation System

Decoupling terms perform open loop control and they can drive the system into physically unrealizable states. For this reason they have to be limited to provide higher priority to closed loop control signals.

The vectorial sum of two controller outputs can not be higher as the nominal supply voltage. This criterion is described in (7),

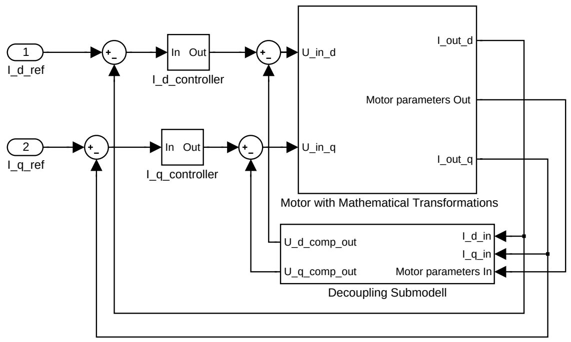

Fig. 5. New current control model

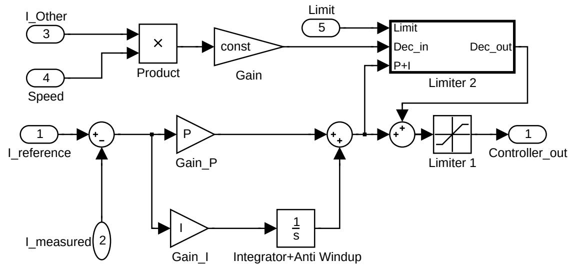

Fig. 6. Decoupling calculation model

$$\frac{\sqrt{(C_d^{out})^2 + (C_q^{out})^2}}{U_{nom}} \leq 1 \qquad (7)$$

where C_d^{out} is the controller output of d loop , C_q^{out} is the controller output of q loop and U_{nom} is the nominal value of the power supply.

In the motor control application C_d^{out} is also limited using (8).

$$C_d^{out} \leq \text{const } (\approx 0.9) \qquad (8)$$

A limitation system – which considers (7) and (8) – was originally built into the system (Limiter 1 in Fig. 6), but it was not suitable for limiting decoupling part of PI controller because it was not giving priority to the closed loop control signals. An additional and more complex limitation (Limiter 2 in Fig. 6) was built into system which considers both the external limit and the internal state of controller. The saturation system has to decrease correction terms if the sum of controller proportional (P), integral (I) and decoupling (DEC) terms approaches the output limit of the controller.

V. Simulation Results

Controller behavior was tested in an existing simulation model to verify transient reducing efficiency of proposed modifications. Simulation model involves motor control software and a motor model which was described in this paper. Motor speed was set to 40% of it's maximal speed. Current in one control loop was changed from I_{max} to $-I_{max}$, and current peak in the other loop was measured. Decoupling calculations worked excellently, reducing current peak from 32 A (Fig. 7) to 700 mA (Fig. 8).

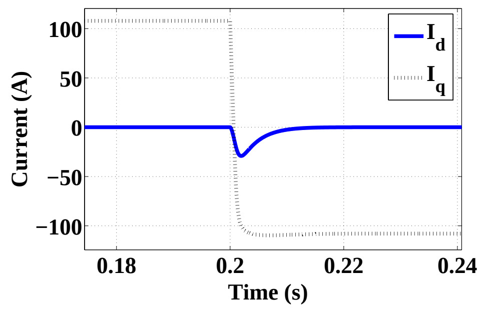

Fig. 7. Simulation result without decoupling

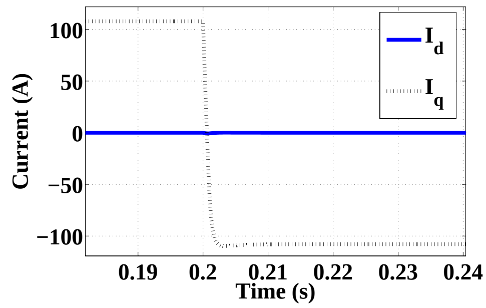

Fig. 8. Simulation result with decoupling

VI. Measurement Results

After promising simulation results decoupling algorithm was implemented on dSpace/Autobox rapid prototyping computer for testing improvement on measurements. Motor control algorithm was run on the computer and a PMSM was used in the test. It was driven at the same speed as in the simulation by an other machine. Measurements on real physical environment reported lower current peaks when decoupling was used,which proofs the usefulness in practice. Without using decoupling equations 42 A current peak was measured (see Fig. 9). With using them peaks were reduced to 22 A amplitude (see Fig. 10).

Although this method reduced current transients by 48% the results should be improved to reach the theoretical possibilities by considering the followings:

- In simulation we calculated internal motor states with the same motor parameter values (phase coil resistance, inductance, rotor magnet flux ...) both in the motor simulation and in the decoupling blocks. On the contrary, during measurements theoretically calculated values are used in the decoupling calcu-

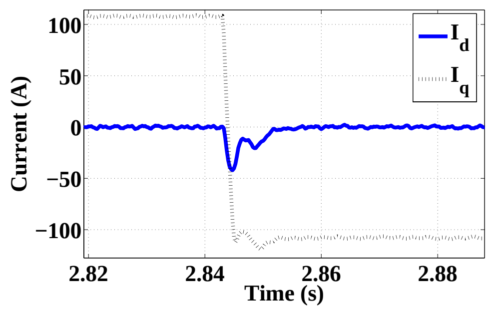

Fig. 9. Measurement result without decoupling

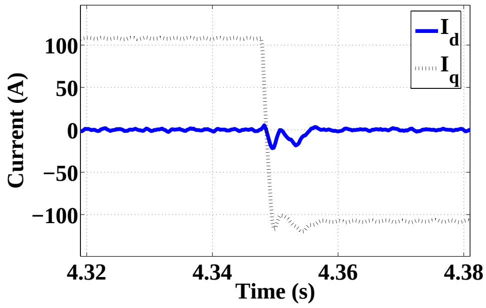

Fig. 10. Measurement result with decoupling

TABLE I

EVALUATING SIMULATION AND MEASUREMENT RESULTS

Method	Current peak [A]		Efficiency [%]
	Without Dec.	With Dec.	
Simulation	32	0.7	98
Measurement	42	22	48

lations to correct the unknown physical values. Off line measured system parameters could increase correction significantly, but on line parameter estimation would be the best method to correctly use decoupling calculations.

- Power supply voltage can not be measured during measurement, however, it is used as a normalization factor in the calculations, so improving measurement hardware could be also advantageous.
- Measured signals contain additive noise which should be filtered better.

VII. CONCLUSION

Aim of our research was to eliminate cross coupling terms caused by mutual inductances in motor to decouple two control loops. Decoupling worked perfectly in simulation reducing current peaks from 32 A to 700 mA. Measurement results proved that decoupling can reduce current peaks efficiently, but considering improvements listed in section VI, performance can be increased.

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