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Problematika stability elektromechanických systémů s vysokorychlostními stroji s permanentními magnety

Stability issues of electromechanical systems with high-speed permanent magnet machines

Summary

The purpose of this lecture is to show specific problems in the field of high-speed permanent magnet synchronous machines (PMSM). During design, control or stability analyses for such machines, it is necessary to consider properties not present in traditional ""low speed" PMSM. From the machine modeling point of view it is e.g. the air friction. In high-speed machines, this can cause more losses that bearing friction. From the controller point of view, both linear possibilities of control are handled. It is the control of instantaneous current values and field-oriented control (FOC). The focus is however on FOC as it provides a higher dynamic of the system. Results from the experimental setup created at the Czech Technical University in Prague, faculty of mechanical engineering are show. Stability issues in both open loop V/f control and FOC are handled next. The stability analysis in open loop shows interesting results and gives directions for the choice of stator resistance/inductance ration and the influence of load. It also shows that the machine parameters change due to temperature of variable frequency have a significant impact on stability. For closed loop FOC the influence of time delay in the controller on stability is examined. It is shown, that for a stable FOC, the controller delay has to be lower that around 1/20 of the electrical time constant of the machine. Else the control loop becomes unstable. For traditional "low speed" PMSM, the relatively slow controller is not a problem. For high-speed PMSM, this can however be the key issue as the electrical time constant of the machine can be in the order of tens μs. For a standard Digital Signal Processor (DPS) controller, the time delay is also in the same order. For this reason, the last chapter contains some information about the newly developed Field Programmable Gate Array (FPGA) controller. The comparison with DSP shows that the FPGA controller has about 150x lover time delay. The calculation period was in this case 440ns. It is therefore suitable for present and future high-speed PMSM while maintaining the advantage of FOC; its high dynamic.

Souhrn

Záměrem této přednášky je ukázat specifika vysokorychlostních synchronních strojů s permanentními magnety (PMSM). U této skupiny speciálních strojů je třeba při jejich návrhu, řízení a analýze stability brát v úvahu vlastnosti, které se u tradičních "pomaloběžných" PMSM nevyskytují. Z hlediska modelování se ukazuje nezbytnost pro vysoké otáčky uvažovat tření vzduchu. To může způsobovat větší ztráty něž např. ztráty v ložiskách a vést tak k nepřesnému modelu stroje. Z hlediska řízení jsou shrnuty oba používané lineární algoritmy a to řízení okamžitých hodnot proudů a vektorové řízení. S ohledem na vyšší dynamiku vektorového řízení je důraz kladen především na vektorové řízení. Jsou ukázány konkrétní výsledky na experimentálním pracovišti vybudovaném na strojní fakultě ČVUT. Dále je zkoumána stabilita synchronního stroje a to jak z hlediska řízení v otevřené smyčce U/f, tak i při zpětnovazebním vektorovém řízení. Z výsledků analýzy stability v otevřené smyčce plynou důležité závěry pro konstrukci stroje, konkrétně pro omezení vhodného poměru odporu statorového vinutí, indukčnosti, zatížení atd. Také změna parametrů stroje např. při změně teploty má podstatný vliv na stabilitu. V uzavřené smyčce vektorového regulátoru je řešen vliv dopravního zpoždění způsobeného algoritmem regulátoru na stabilitu. Je ukázáno, že pro stabilní řídicí obvod je nutné, aby doba výpočtu regulátoru nepřesahovala cca 1/20 elektrické časové konstanty stroje, jinak je regulační obvod nestabilní. U klasických synchronních strojů, kde je elektrická časová konstanta velká, a relativně pomalý regulátor nehrozí riziko nestability. U vysokorychlostních strojů, kde elektrická časová konstanta může být v řádu desítek µs, není ale možné použití klasického DSP regulátoru. Ten má zpoždění také v řádu desítek µs a vedl by k nestabilnímu regulačnímu obvodu. Proto je v poslední kapitole práce ukázána možnost realizace vysokorychlostního vektorového regulátoru s využitím programovatelné logiky (FPGA). Jsou srovnány zpoždění DSP a FPGA regulátoru a ukázáno, že FPGA regulátor dosahuje cca 150x menšího zpoždění než DSP regulátor. Doba výpočtu je cca 440ns. Proto je vhodný pro současné i budoucí vysokorychlostní PMSM, kde umožňuje využití vysoké dynamiky vektorového řízení i u vysokorychlostních strojů.

Klíčová slova: synchronní stroj s permanentními magnety; matematické model synchronního stroje; tření vzduchu; vektorové řízení, DSP regulátor; stabilita v otevřené smyčče, stabilita při vektorovém řízení; dopravní zpoždění; FPGA regulátor

Keywords: permanent magnet synchronous motor; PMSM modeling; air friction; vector control; field-oriented control, DSP controller; stability in open loop; field-oriented control stability; time delay; FPGA controller

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Introduction

In the last years, a new trend in electrical machines is emerging. It is the usage of high-speed machines. The permanent magnets from rare earth elements like Sm, Co, Nd, Fe, B etc. allow to create high magnetic flux in a restricted area. This allows the construction of powerful motors with small size. Compared to same power and same application, an induction machine is usually smaller than DC machine and so is the synchronous machine compared to an induction machine. The trend is clearly visible in Table 1.

There are already many applications for high speed machines that the normal user is not aware of. Let me take an ordinary hand drill as an example. For the reasons of constraints of size and weight the motor driving the drill is not a DC or induction machine. Another example, an electrically driven turbo compressor is shown in [30] *"As an example, one large turbo compressor can be replaced with 16 compressors, each with a volume of 1/64 of the conventional compressor, which together has the same output power but requires only a quarter of the volume of the conventional compressor. The diameter of the small units would be ¼ of the original one and the rotational speed would therefore increase by a factor of at least 4….. Downscaling of a macro turbo machine for constant specific speed and lower volume flow therefore leads to an increase in rotational speed…. The overall volume of the electrical machines in the example above is also ¼ of the original one."*

From this comes the idea to use high speed machines also in other applications with size constraints. As it was shown in [32] *"The target maximum speed of the motor is 240,000rpm. The rated output is 5kW but the motor dimensions are small enough; the stator diameter is 60mm, core stuck size is 40mm and rotor diameter is only 20mm."*

There is a high industrial demand for high-speed machines as can be seen in [24]. Applications such as micro gas turbines, compressors, blowers, pumps, hybrid electric vehicles, turbo molecular pumps, machine tool spindles are mentioned. Some of them are a 556 kW, 3000 rad/s induction generator, 3300 kW, 1100 rad/s turbo compressor, 1000 kW, 1500 rad/s PMSM generator, 10 kW or 18000 rad/s induction motor.

An important issue with high-speed PM machines is theirs control modeling and stability. I will address some of the problems I have been working on in this thesis.

Table 1 - Power density of different machine types[1]

Type	DC motor	Synchronous wound rotor	Induction Motor	PMSM	High-speed PMSM 1	High-speed PMSM 2	High-speed PMSM 3
Power [kW]	535	1130	1020	720	0,1/0,2 Without/with cooling	3	2
Weight [kg]	1560	1525	1260	720	0,038	1,4	1,3/2,4 (with cooling)
Power density [kg/kW]	2,9	1,35	1,23	1,00	0,38/0,19	0,47	0,65/1,2
Nominal speed [rpm]	4000[2]	4000[2]	4000[2]	4000[2]	500k	240k	200k
Applica-tion	TGV Paris-Sud est (1981) [1]	TGV Atlantique (1989) [1]	Eurostar (1994) [1]	AGV (2004) [1]	Celerotron CM-2-500[2][3]	Micro-Combined Heat and Power, MTT, Eindhoven[4]	[3][5]

Modeling high-speed PM machines

In order to estimate the controller setting and handle controller and stability issues, many models of PM machines have been created [20],[25] - [29]. For high-speed machines, more parameters have to be considered in the model like e.g. air friction losses [22]. In traditional "low" speed machines, this can be safely neglected, but for high speed machines air friction can be more significant that bearing losses [31].

[1] It should be stated here that the comparison is not really fair; the motors are for different applications. The comparison is here purely to give an idea about power density

[2] TGVweb, Under the Hood of TGV, online, accesed 23.10.2012, available on <http://www.trainweb.org/tgvpages/motrice.html>

[3] Weight obtained on 26.9.2012 from Arda Tuysuz, ETH Zurich, Power Electronic System Laboratory

[4] Data obtained on 25.10.2012 from Aleksandar Borisavljevic, Electromechanics and Power Electronics group, Eindhoven University of technology

[5] Dimensions and material data obtained on 22.9.2012 from Pierre-Daniel Pfister, Moving Magnet Technologies SA (MMT), Besançon, France

The simplifications and assumptions of the model I have developed are stated in the full version of my thesis [nm1].

$$\frac{di_d}{dt} = \frac{-R_s}{L_d} i_d + \frac{1}{L_d} v_d + \frac{L_q}{L_d} i_q \omega + \frac{3}{2} \frac{p_p}{J} \left(L_d - L_q \right) i_d i_q \tag{1}$$

$$\frac{di_q}{dt} = \frac{-R_s}{L_q} i_q - \frac{\psi_m}{L_q} + \frac{1}{L_q} v_q - \frac{L_d}{L_q} i_d \omega \tag{2}$$

$$\frac{d\omega}{dt} = \frac{3}{2} \frac{p_p^2}{J} \psi_m i_q - \frac{p_p B}{J} \omega - \frac{p_p}{J} T_L - \frac{p_p K_{air\_friction}}{J} \omega^2 \tag{3}$$

When the model is developed, the individual properties of the model have to be identified. To identify electrical parameters, one can use the transient method from [28]. The motor winding is powered with DC current, a transient (either on or off) is created, and winding inductance is calculated from the time constant. The winding resistance has to be measured as well to allow inductance calculations. The magnetic flux linkage Ψ_m is usually calculated from the machine nameplate data.
The used motor nameplate data used in my experiments are summarized in Table 2.

Table 2 - PMSM nameplate data

Motor type: 2AML406B-090-10-170	Manufacturer: VUES Brno
V_{dc} = 560 V	n_n = 25 000 min^{-1} , n_{max} = 42 000 min^{-1}
I_{n_rms} = 11 A	K_E = 7,3 V/ kRPM
T_n = 1,2 Nm	

As we have shown in **[nm2],** the mechanical parameters such as moment of inertia and friction can be estimated from motor start-up and spin-down. The moment of inertia is

$$J = T \frac{\Delta t}{\Delta \omega} = 0{,}98 \cdot \frac{0{,}4}{2\pi \cdot 572} = 0{,}11 \cdot 10^{-3} \qquad \left[kgm^2 \right] \tag{4}$$

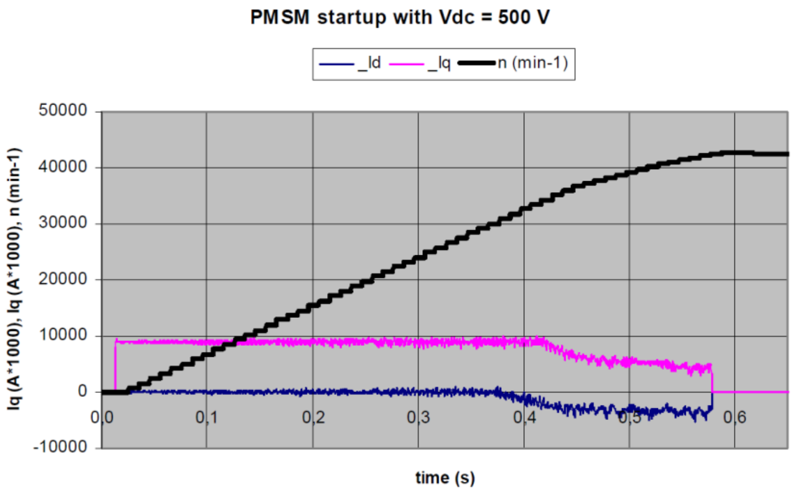

Fig 1 – DSP Controller PMSM startup with Vdc = 500 V, _Iqreq = 9 A [nm2]

As can be seen from the model, air friction losses are considered. This is important for high-speed machines as the losses caused by air friction can have the same size as friction losses in bearings.

According to information from [31], where speed was 52000 rad/s, friction losses caused by air friction were 8 W, whereas bearing losses were 10 W for two bearings. In this application the motor had power 100 W, the friction and bearing losses represented almost 20 percent of the losses.

As the machine used for this research has maximal speed 4200 rad/s, it can be expected that air friction losses will be much lower. The reason for this is that according to [31] power losses caused by air friction are given

$$P_{f\_air} = c_f \pi \rho_{air} \omega^3 r^4 l \tag{5}$$

Where c_f is friction coefficient, ρ_{air} is density of air at given temperature and pressure, ω is rotor angular mechanical speed, r is rotor radius and l is rotor length.

Air friction torque is then

$$T_{f\_air} = c_f \pi \rho_{air} \omega^3 r^4 l / \omega \tag{6}$$

And therefore the friction torque is a function of ω^2 as it is used in the model. The viscous friction coefficient itself is dependent on the size of air gap and air flow in the air gap given by Reynolds and Taylor numbers. Unfortunately, none of those parameters could not be measured or determined precisely analytically.

For this reason an attempt was made to at least estimate bearing and air friction with an experiment. It consists of accelerating the motor to maximal speed and turning off the inverter. The rotor will spin down naturally. The deceleration of the rotor is measured as a function of time. It is obvious that when the motor is un-powered and unloaded, its mechanical speed will decrease with losses until a complete halt. This is described by the following dynamic equation

$$\frac{d\omega}{dt} = -\frac{p_p B}{J}\omega - \frac{p_p K_{air\_friction}}{J}\omega^2 \tag{7}$$

It has to be noted here that this equation does not represent all losses in the motor.

The solution of (7) is

$$\omega(t) = \frac{B \cdot \omega(0)}{B \cdot e^{\left(\frac{B \cdot t}{J}\right)} - K_{air\_friction} \cdot \omega(0) + K_{air\_friction} \cdot \omega(0) \cdot e^{\left(\frac{B \cdot t}{J}\right)}} \tag{8}$$

Equation (8) was used to find coefficients B and $K_{air\_friction}$ from experimentally measured PMSM rotor deceleration. The search was done with a least square method in Matlab.

The comparison on Fig 2 is a best match that could be achieved by varying just parameters B and $K_{air\_friction}$. As can be seen, the match good for high speed, but bad for low speeds. The reason is that other losses in the motor have been neglected. One is the loss caused by eddy currents. As the permanent magnet is rotating, it induces currents to the stator windings and stator iron. Also there is an interaction between the permanent magnet and those currents. Stator core losses could be determined by the Steinmetz equation [35],[36].

$$P_{core} = C_m \cdot f^{\alpha} \cdot B_{mat\_m}^{\beta} \tag{9}$$

Where C_m, α and β are material constant, B_{mat_m} is peak flux density and f is frequency of the current.

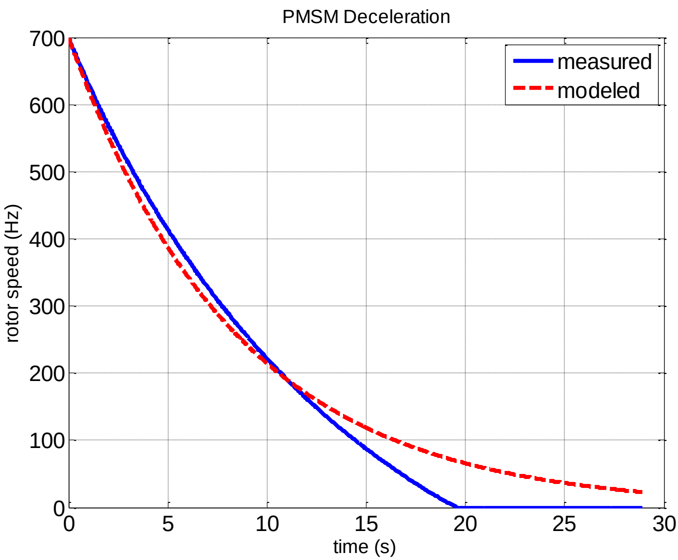

Fig 2 – Comparison between measured (blue, solid line) and modeled PMSM deceleration (red, dashed)[nm1]

It can be seen that losses are a function of frequency i.e. rotational speed. The function is nonlinear. Unfortunately this calculation is impossible as the stator material is not known for our motor. Considering those simplification, the presented fit can be considered an approximate model. The model parameters determined in this chapter are summarized in Table 3. Compared to standard low speed machine models, more parameters have to be taken into consideration like air friction or bearing losses.

Table 3 - PMSM model parameters

Model parameter	Value and units	note
R (mΩ)	210 [mΩ]	
L (μH)	1,1 [mH]	for $I = I_n = 11$ A
ψ_m	0.072 [Wb]	
J	$0.11 \cdot 10^{-3}$ [kgm^2]	
B	$8.2 \cdot 10^{-5}$ [$N.m.s.rad^{-1}$]	
$K_{air\_friction}$	$1{,}3 \cdot 10^{-10}$ [$N.m.s.rad^{-1}$]	Very small, could be significant for higher speeds

For high-speed machines, especially ones with lower power rating, around 100 W those losses can represent around 20 percent [31] of the rated power and it is not possible to neglect them any longer in mathematical modeling. For medium power high speed machines, those losses can be neglected only when the speed is relatively low or the lower model precision is sufficient. To improve model precision more parameters like eddy current losses, reluctance torque etc. could be also taken into consideration.

Control of high-speed PM machines

There are basically two linear possibilities of PM machine control. The first is to control the instantaneous value of currents in phase windings; the second is field-oriented control. Although I have been working on both methods, I will present here only some results with the second. As can be seen in paper [18] high-speed PMSM controller system and experimental results can be obtained. In this case the application was centrifugal compressor for a cryo-cooler. The parameters of the used motor were : 4-pole PMSM, 100 W, 10000 rad/s, 28 V. The controller is based on a TI TMS320LF2407A Digital Signal Processor. As it is clear from the paper, there is in fact only an open loop control, without a feedback from the motor to the controller. The authors use a classic V/f control to achieve the desired speed. The described system in [19] is running at 52000 rad/s, 1kW, 400 V, 1 pole-pair. The controller is based on a Microchip dsPIC30F5016 Digital Signal Processor and it is using a sensor-less rotor position estimation based on stator-flux zero crossing detection with a discrete integrator and comparator circuit. Rotor position and speed calculation is then done on the DSP. *"Since all considered applications need only low dynamics of the speed control, simple torque control via the dc current is sufficient, which allows for a single, non-isolated shunt current measurement. The current reference is set by the speed controller"* [19]. If high dynamics would be required, this approach would not be sufficient. Control of a high-speed PMSM motor is described in paper [23]. It shows the calculation of an optimal V/f profile. The specific PMSM has rated speed 5200 rad/s, 28 V, 4 pole, 5 A. Based on this motor parameters the authors provide means to optimal V/f profile calculation. The normal linear V/f profile cannot be used, as according to the authors the stator resistance is always higher that reactive impedance in the operating range. There is no feedback control in this system. The general block diagram of a controller system that uses this approach is shown on Fig 3. It has two parts. One is the power electronics, the second is the main controller.

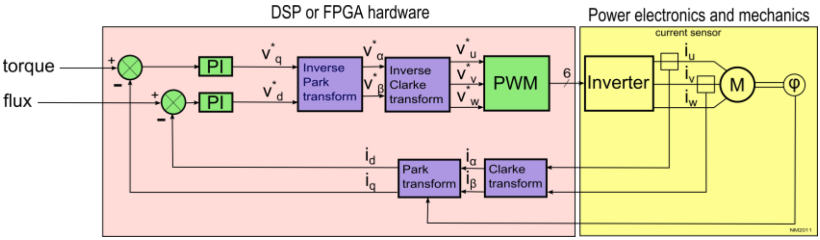

Fig 3 - Block diagram of controller system [nm1]

I have been working on both controller design and on the design of power electronics in scope of our projects. The input to the controller is the desired value of machine torque and flux. In case of an induction machine the desired flux has to be non-zero. In case of PMSM the desired flux is either zero for full magnetic flux mode or negative for flux weakening mode. The flux weakening mode allows decreasing the magnetic flux of permanent magnets. This allows reaching higher speed for the cost of lower achievable torque. From the block diagram on Fig 3 it can be seen that two phase currents i_u and i_v are measured. They are recalculated to the i_α and i_β currents with the Clarke transform from with equations (10) and (11).

$$i_\alpha = i_u \tag{10}$$

$$i_\beta = \frac{1}{\sqrt{3}} i_u + \frac{2}{\sqrt{3}} i_v = \frac{1}{\sqrt{3}} \left(i_u + 2 i_v \right) \tag{11}$$

Together with the instantaneous rotor position Θ they are then used to calculate the values of currents i_d and i_q with Park equations (12) and (13).

$$i_d = i_\beta \sin(\Theta) + i_\alpha \cos(\Theta) \tag{12}$$

$$i_q = i_\beta \cos(\Theta) - i_\alpha \sin(\Theta) \tag{13}$$

The controller compares the difference between the desired value of torque/flux and values of currents i_d and i_q and produces the corresponding control actions. The outputs of the controllers are voltages v^*_q and v^*_d. The inverse Park transform using equations (14) and (15) produces voltages v^*_α and v^*_β.

$$v^*_\alpha = v^*_d \cos(\Theta) - v^*_q \sin(\Theta) \tag{14}$$

$$v^*_\beta = v^*_d \sin(\Theta) + v^*_q \cos(\Theta) \tag{15}$$

They are used as inputs to the inverse Clarke transform block - equations Output voltages v^*_u, v^*_v, v^*_w are used as inputs to the PWM, this is connected to the power inverter driving the motor. One was a project for control of high-speed PMSM for an electric automotive turbocharger, the other the control of an electric power splitter for hybrid vehicles. The results of the turbocharger project were published in e.g. [nm3],[nm4],[nm5],[nm6],[nm7],[nm8].

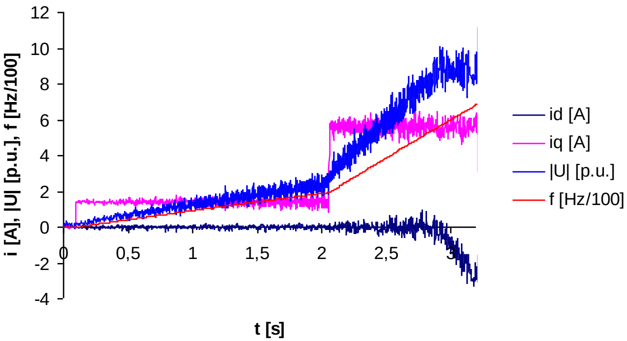

Fig 4 - Curves of current components id , iq , amplitude reference voltage and revolutions (frequency) during no load starting up till 4200 rad/s at load torque changing suddenly from 0,11Nm to 0,44Nm - [nm3] [nm7]

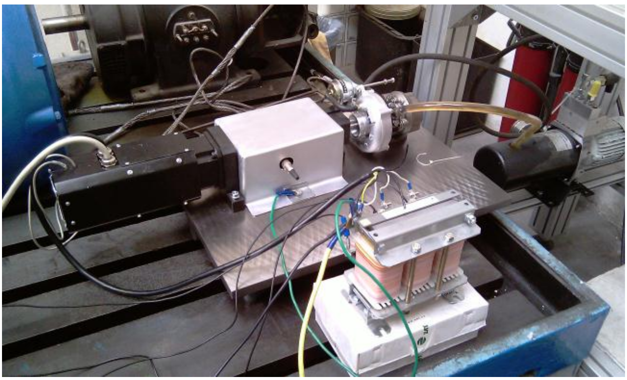

Fig 5 – Test bench with coupled high-speed PMSM, torque sensor, turbocharger and inductor

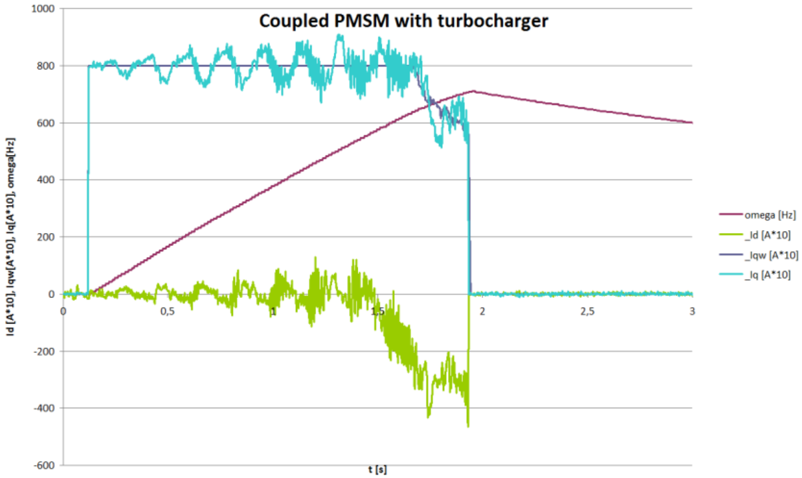

Fig 6 –Coupled high-speed PMSM start-up, currents and speed

The second project is a microturbine power generator. The project is still running. Currently maximal speed has been achieved. Experimental results show that the turbocharger is only a light load for the motor. As can be seen from the obtained measured results, there are some stability problems and therefore system stability has to be discussed as well.

Stability of high-speed PM machines

The stability of the Permanent Magnet Synchronous Machine (PMSM) is an important issue. Although it may not seem so, the machine itself can become unstable due to variance of machine parameters with temperature, current and even applied frequency from the inverter. By frequency, the fundamental current harmonics - variable with speed - is meant here. Therefore for high-speed PMSM´s it is crucial to investigate not the stability of the whole system but that of the machine itself. Two areas will be handled here, the stability of the machine itself due to design parameters such as winding resistance or inductance and the stability of the whole feedback control system.

Inherent stability of PMSM

Although it may not be obvious on the first view, PMSM can be inherently unstable. High speed PMSM's are usually not equipped with damper windings due to space or losses constraints [4][5]. For some applications an open loop V/f control is used. This has lower dynamic than vector control, is however less computationally intense and suitable for applications with predictive load characteristics like fans or compressors. When the inverter applies frequency exceeding a certain range, the machine can become unstable [6]. Because both inductance and resistance of the PMSM vary significantly with frequency, a significant margin in motor stability is required [7]. The mechanical analogy of the studied magnetic field in a PMSM can be a spring and a dampener. When too much force is applied (from the stator field) or when the frequency is too high, the permanent magnet is not able to follow and the stator-rotor linkage breaks. This is equivalent to applying too much force on the mechanical spring. The maximal load angle is limited to 90° as shown in Fig 7.

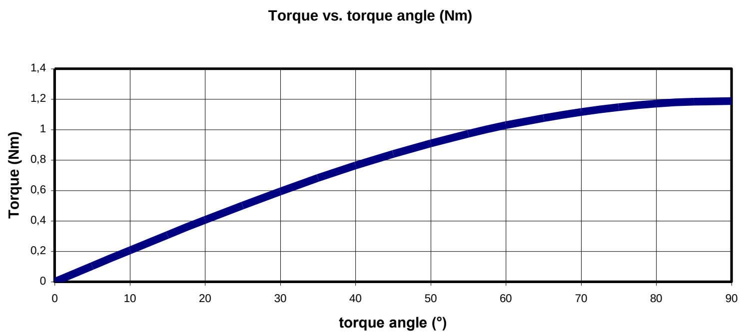

Fig 7 – Synchronous motor characteristics (T versus δ)

To study stability, one has to examine the PMSM model described by equations (1)-(3). As I have shown in chapter 1, the air friction losses of the motor under test are still low, even this is a high speed machine. For this reason I will assume a simplified machine model without air friction losses for this open loop stability analysis. The PMSM model in (1)-(3) can be viewed as a non-linear MIMO space state model in matrix form [6].

$$[\dot{x}] = [f(x,u)] \tag{16}$$

Where *[x]* is a state space vector, *f(x,u)* is a non-linear function of state vector x and input control vector u. The input control vector u is a function of torque angle δ (function of machine load T), supply voltage V and frequency ω_s.

In order to use standard methods for stability analysis, it is convenient to use small signal linearization of (16) by examining small perturbations $[\Delta x]$ in the space state model. The linearized version if the model is [6]

$$\left[\Delta\dot{x}\right]=\left[\frac{\partial f}{\partial x}\right]_{[x_0]}\left[\Delta x\right] \tag{17}$$

The eigenvalues of in such a way obtained matrix give complete information about stability of the system. The system is stable when all eigenvalues have negative real part.

$$\begin{bmatrix}\Delta\dot{i}_d\\ \Delta\dot{i}_q\\ \Delta\dot{\omega}_r\\ \Delta\dot{\delta}\end{bmatrix}=\begin{bmatrix}\frac{-R_s}{L_d} & \frac{L_q}{L_d}\omega_r & \frac{L_q}{L_d}i_q & \frac{-V}{L_d}\cos\delta\\ \frac{-L_d}{L_q}\omega_r & \frac{-R_s}{L_q} & \frac{-L_d}{L_q}i_d & \frac{-V}{L_q}\sin\delta\\ \frac{3}{2}\frac{p_p^2}{J}\left(L_d-L_q\right)i_q & \frac{3}{2}\frac{p_p^2}{J}\left\{\psi_m+\left(L_d-L_q\right)i_d\right\} & \frac{-B}{J} & 0\\ 0 & 0 & -1 & 0\end{bmatrix}\begin{bmatrix}\Delta i_d\\ \Delta i_q\\ \Delta\omega_r\\ \Delta\delta\end{bmatrix} \tag{18}$$

As it was shown in [5], the eigenvalues of the transition matrix vary significantly with frequency and with load. There are basically two categories of eigenvalues. The first category is well damper and stable poles from the stator, the second category is lightly or negatively damped [9] complex conjugate pole coming from the rotor. This is shown on Fig 8. The well damped stator and lightly damped poles can be clearly seen. It can also be seen than for an increasing power supply frequency, the rotor poles tend to approach the unstable region with positive real part of the eigenvalues. In a real high-speed machine, the machine parameters vary with temperature, but also with current (torque). As the stator winding resistance R_s is usually small for high-speed machines (at least for low voltage machines [9]), it varies considerably with load (temperature). For high-speed machines, R_s is large compared to stator reactance and cannot be neglected anymore. Also the value of inductance is not constant, it varies with saturation, i.e. with the machine operating point. Moreover, the permanent magnet flux linkage ψ_m is varying also with motor current (load). As it can be seen from the analysis of a 50 000 RPM axial flux PM motor in [9] the eigenvalues go into the unstable region with variations of stator frequency and stator resistance R_s. It is therefore imperative to conclude the machine stability analysis already in the motor design phase.

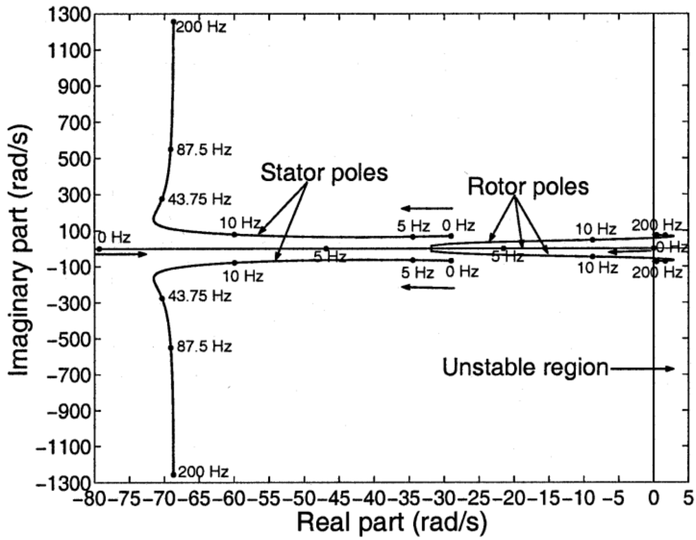

Fig 8 – Eigenvalue plot under no load, as a function of the applied frequency - reprinted with permissions from [5] © 2002 IEEE

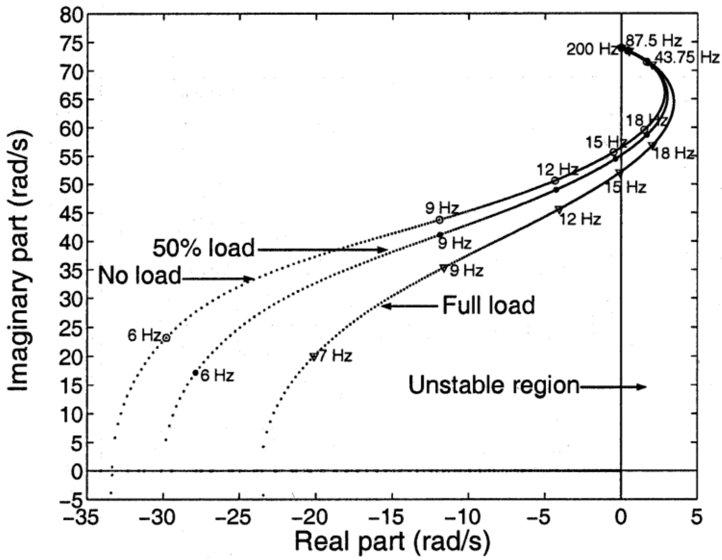

Fig 9 – Loci of the rotor poles under different load conditions, as a function of the applied frequency - reprinted with permissions from [5] © 2002 IEEE

Stability of PMSM with feedback vector control

Even if the motor is designed to be inheritably stable in open-loop mode, as shown in the previous chapter, if a high dynamic is required, a filed oriented controller has to be used. The principles of field-oriented control (FOC) are shown in chapter 2. The main advantage of FOC is the ability to achieve higher dynamic of the machine and the possibility to control the machine torque precisely. On the other hand, this requires a significant amount of computational power available in the controller. As will be shown here, in the case of high-speed machines there is also an issue of stability. Due to the small stator resistance and inductance, the electrical time constant of the machine is small. In the case of the herein described motor it is 5,2 ms. The mechanical time constant of the motor is about 250x higher, in this case 1,3s. As the mechanical time constant is significantly higher, the mechanical speed it is usually considered a constant in the analysis [10].

It was shown in the literature [13],[9] that the electrical time constant can be as small as 26μs. Then the delay added by multiple sources in the system, such as anti-aliasing filter, A/D converter, PI controller algorithm, inverter dead-time etc. can be significant. The final system is a system with time delay and without proper precautions it can be hardly controllable or even easily become unstable. It is therefore important for high-speed machine control system to estimate the influence of delays on the system stability.

The classical feedback control system for a PMSM was already discussed in chapter 2, together with an example application. The system diagram together with the estimate of the time delays in the system is shown on Fig 10. From the estimated time delays in the system, it can be seen that the most significant delay is in the controller itself. It is 66μs compared to the electrical time constant of 5,2ms. This is acceptable for this application, for the high-speed motor with electrical time constant 26μs in [9] it is not.

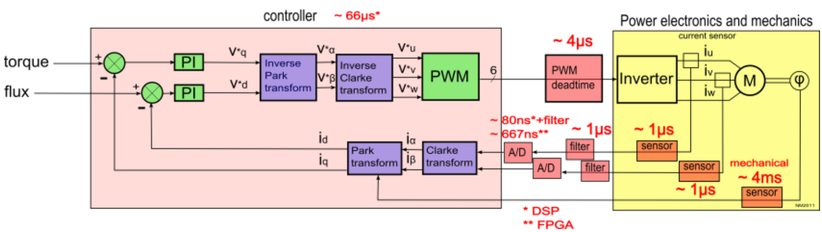

Fig 10 – Control system block diagram with an estimate of time delays – adapted from [nm1]

A detailed analysis of a PMSM time delay model with stability has been done in [10]. It is based on the representation of all system blocks in the dq-frame, inverse Laplace transform and Nyquist stability criteria. The inverse Park transform can be represented in matrix form as in [10]

$$P(t)^{-1} = \begin{bmatrix} \cos(\omega_r t) & -\sin(\omega_r t) \\ \sin(\omega_r t) & \cos(\omega_r t) \end{bmatrix} = \\ = \frac{1}{2}\begin{bmatrix} e^{j\omega_r t} + e^{-j\omega_r t} & j\left(e^{j\omega_r t} - e^{-j\omega_r t}\right) \\ -j\left(e^{j\omega_r t} - e^{-j\omega_r t}\right) & e^{j\omega_r t} + e^{-j\omega_r t} \end{bmatrix} \tag{19}$$

Considering an input in the dq frame, the output in αβ is

$$x_{\alpha\beta}(s) = L\left\{P(t)^{-1} \cdot x_{dq}(t)\right\} = \\ = \frac{1}{2}\begin{bmatrix} x_d(s+j\omega_r) + x_d(s-j\omega_r) - j\left(x_q(s+j\omega_r) - x_q(s-j\omega_r)\right) \\ j\left(x_d(s+j\omega_r) - x_d(s-j\omega_r) + x_q(s+j\omega_r) + x_q(s-j\omega_r)\right) \end{bmatrix} \tag{20}$$

Similarly, other transformations can be shown as well in the dq-frame [10]. An example how to estimate the delay of an anti-aliasing filter in the A/D converter is shown in [11]. For the case of a sinc^3-filter [12] and an often used ΣΔ converter, the filter can be described as

$$H(j\omega) = \left(\frac{1}{M}\frac{\sin\left(\frac{\omega \cdot M}{2 f_{\Sigma\Delta}}\right)}{\sin\left(\frac{\omega}{2 f_{\Sigma\Delta}}\right)}\right)^3 \left(e^{j\omega\left(\frac{M-1}{2 f_{\Sigma\Delta}}\right)}\right)^3 \tag{21}$$

Where M is the filter decimation ration, $f_{\Sigma\Delta}$ is the ΣΔ modulation frequency. The filter time constant can then be estimated as

$$\tau_{filter} \approx \frac{3 \cdot M}{2 f_{\Sigma\Delta}} \tag{22}$$

The stability of a MIMO system can be assessed with the multivariable Nyquist theorem [14],[15],[16][17] or directly by calculating the roots of the circuit.
With regard to the slow mechanical time constant (1,3s) and to the fact that the PI controllers control electrical properties with time constant about 5,2ms, the linearized PMSM model described by (18) can be further simplified. As the mechanical speed ω is changing slowly compared to electrical properties, it can be taken as (pseudo) constant yielding:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_d} & \frac{L_q}{L_d}\omega \\ \frac{-L_d}{L_q}\omega & \frac{-R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{23}$$

The stability analysis is then done by calculating the roots of the closed-circuit system. There are two PI controllers, each described by its corresponding transfer function ***REG***

$$REG = \begin{bmatrix} \frac{k_p s + k_I}{s} & -L_q \cdot \omega \\ L_d \cdot \omega & \frac{k_P s + k_I}{s} \end{bmatrix} \tag{24}$$

Together with the variable time delay D, the roots can be easily calculated. The result is shown on Fig 11. The presented results have been obtained with a time delay algorithm described in [37][38][39]. Some interesting facts can be identified in the picture. First off all, the time delay in the controller has to be quite small to for a stable system. The maximal time delay identified here for a stable system is around 250µs. The real controller delay is 66µs for the DSP system, rendering a stable system. However, the time delay 250µs is very small compared to the electrical time constant of PMSM, in this case 5,2ms. It can be seen that the controller delay has to be at least 20x lower than the electrical time constant. For a faster system such as the one in [9] - 26µs, the controller time delay would have to be around 1µs. This is non achievable with a DSP system. For this reason I believe the future is in FPGA based controller systems, at least for field-oriented control of high-speed permanent magnet motors.

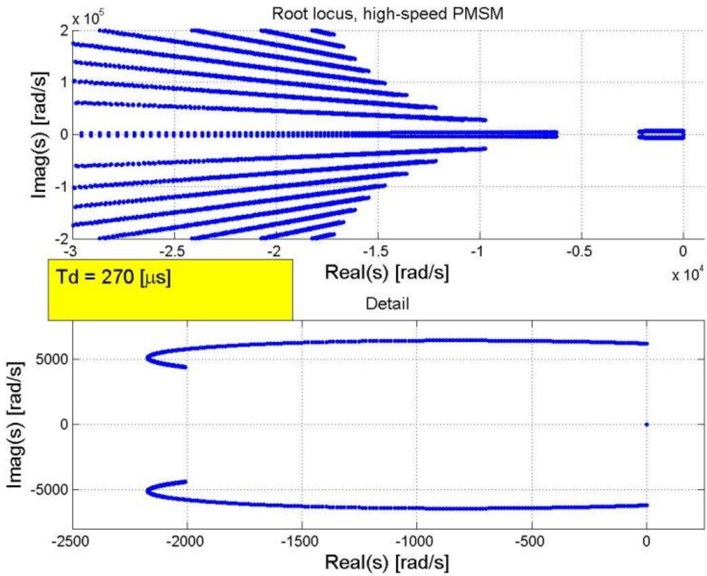

Fig 11 – Root locus of PMSM - Controller model with time delay - detail around origin

FPGA Control of high-speed PM machines

As it was shown in the previous chapter, one of the key issues in controlling high-speed PM machines is to minimize delays in the control loop. Delay cause problem in control system stability and have therefore to be removed if possible. One possibility how this can be achieved is to replace the DSP controller with Field-Programmable Gate Arrays (FPGA). The advantage is that the control loop can run much faster than DSP, on the other hand, the implementation, testing and tuning is significantly more complicated. For this reason, there are only very few actual applications described in the literature [28],[33],[34]. As our experiments with the DSP controller implementation have shown a digital signal processor is quite suitable for a field-oriented controller implementation. The described experiments with high speed motor could be done up to the motors maximal speed of 4400 rad/s. The DSP had sufficient computational power for this speed, but for higher speed its use could be problematic as it was running almost on the limit.

As higher speeds are planed I have decided to develop a novel field-oriented controller based on FPGA. The replacement of the DSP by

FPGA allows to remove the limitations caused by insufficient computational power and to push the controller maximal speed to several ten thousands rad/s. But the limitation of the controller is now removed and it still provides much computational power for other task e.g. motor mathematical model calculation for sensor less control.

The controller is currently based on a Xilinx Spartan 3E development board with some modifications I have done. The implementation results are the following. The FPGA controller itself is running currently on 50 MHz but the speed can be increased to 150 MHz. The limiting factor is the Picoblaze core that is capable to run only on 98 MHz. Therefore the speed is kept on 50 MHz to the time being. The calculation takes 22 clock cycles. For frequency 50 MHz (20 ns) this is 440 ns. The DSP implementation needed 66 μs. As can be seen the FPGA controller is significantly faster, around 150 times. Considering that no optimization of the FPGA implementation has been done, there is a good chance that if required this could be increased. Only by removing the Picoblaze core, the speed increase could be of another 3 times making it around 450 times faster than the DSP. The above given data are valid for implementation of Id and Iq controllers only. When two other PI controllers are added, for flux weakening and speed, an internal loop is created slowing the design significantly. The speed is then around 15MHz. **Nonetheless this is still about 40 times faster than the DSP implementation.**

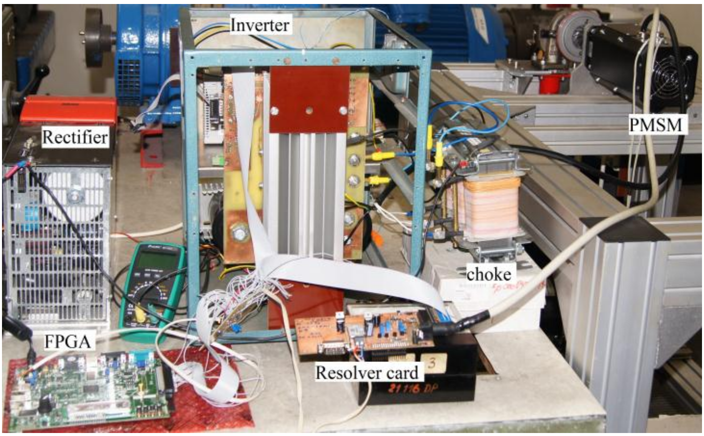

Fig 12 – FPGA controller, resolver board, external inductance and tested motor [nm1]

From those results it can be seen that the FPGA implementation of the PMSM controller removes the limitations imposed by the DSP implementation and that in will allow us to reach higher speed with future motors. In fact, the FPGA is so fast that even a sensor less control could be implemented as it allows calculating a real time model of the motor. This could be required especially for high speed induction motor control. The implementation results are summarized in Table 4 where a selection of the compilation results is presented.

Table 4 - FPGA implementation results [nm1]

Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slice Flip Flops	1,683	9,312	18%
Number of 4 input LUTs	1,383	9,312	14%
Number of occupied Slices	1,161	4,656	24%
Total Number of 4 input LUTs	1,439	9,312	15%
Number of RAMB16s	2	20	10%
Number of BUFGMUXs	6	24	25%
Number of MULT18X18SIOs	14	20	70%

Table 5 - Comparition of DSP and FPGA implementation[6]

Implementation	**Cycle time**	**Speed increase**	**note**
DSP TMS320F218	66 µs	-	Taken as reference, speed = 1, DSP runs on 150MHz.
FPGA	440 ns (22 cycles)	**150x**	Running on 50MHz, with Picoblaze core as user interface
FPGA	150 ns (22 cycles)	**450x**	Around 3x higher frequency possible without the Picoblaze core
FPGA		40x	Maximal frequency 15MHz, with flux weakening and speed controller, not implemented in DSP

[6] It should be noted here that although the speed increase of FPGA compared to DSP is significant, it has to come with an increase of PWM frequency to make sense. This brings higher switching losses in the inverter. There are however new emerging components like high-speed high-voltage FET´s or SiC JFET. Therefore I see the main use of FPGA based controller system in future high performance applications and for e.g. sensor less control or real time model implementation

Conclusions

The motivation for high-speed machine development is mainly the high power density of such machines. In the field of modeling, the current models for standard low speed machines usually do not take into account parameters like eddy current losses, bearing losses, air friction etc. That can be significant for high-speed machines. In the field of control algorithms, high-speed machines are controlled without any feedback with V/f. For this reason, they have lower dynamic response compared as if they would be controlled with field oriented control algorithms. All the present applications are controlled with a DSP that does not allow the application of FOC for really high-speed machines as it has high computational power demands. With the real implementation comes the issue of minimizing delays in the control loop. One possibility how to remove the delay is a faster controller with FPGA. This can be significantly faster that DSP and can help to suppress the time delay problem. Ultra high speed machines have a very promising future. Speeds will increase too much higher levels as this allows the construction of smaller machines with high power density. So it is my belief that high speed machines and theirs high performance control will become a hot topic in the near future with many interesting applications. My contribution is in the creation of a unique test bench and in the creation of the FPGA controller. All this is opening new ways for future development.

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Used symbols

R_s	Stator resistance [Ω]	i_d, i_q	d,q component current [A]
L_d, L_q	d,q component inductance [H]	v_d, v_q	d,q component voltage [V]
Ψ_m	Permanent magnet flux [Wb]	n	Speed [RPM]
p_p	Number of pole-pairs [-]	K_E	Motor flux linkage constant [V/kRPM]
J	Moment of inertia [kgm^2]	P_{f_air}	Air fiction power loss [W]
B	Coefficient of viscous friction [$N.m.s.rad^{-1}$]	c_f	Friction coefficient [-]
ω	Angular velocity – mechanical [$rad.s^{-1}$]	ρ_{air}	Air density [kgm^3]
ω_r	Angular velocity – electrical [$rad.s^{-1}$]	r	Rotor diameter [m]
$K_{air\_friction}$	Coefficient of air friction [$N.m.s.rad^{-1}$]	l	Rotor length [m]
C_m, α, β	Steinmetz equation material constants [-]	i_α, i_β	α, β component current [A]
B_{mat_m}	Peak flux density [T]	v_α, v_β	α, β component voltage [V]
P_{core}	Stator core power loss [W]	i_u, i_v, i_w	u, v, w component current [A]
δ	Torque angle [rad]	M	ΣΔ filter decimation ratio [-]
τ	Time constant [s]	$f_{\Sigma\Delta}$	ΣΔ filter modulation frequency [Hz]
T_N	Nominal torque [Nm]	k_I, k_P	PI controller setting
T_L	Load torque [Nm]	P(t)	Park transform
H (jω)	Frequency response	L{}	Laplace transform

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Curriculum vitae

University and scientific carrier:

- 2003, Ing., Faculty of Mechanical Engineering, Czech Technical University in Prague, branch of Instrumentation and Control Engineering
- 2008, Ph.D., Faculty of Mechanical Engineering, Czech Technical University in Prague, branch Control and System Engineering

Professional carrier:

- 2003 - present, Division of Electrical Engineering, Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague

Study stays:

- 2006 – (4 months) –Laboratoire de Mécanique Appliquée, Université de Franche-Comté, Besançon, France

Supervised diploma theses: 9

Text books: 1 + 1 electronic book

Scientific work:

Articles in journals: 6

Papers on international conferences: 37 (13 in Web of science, 16 in Scopus)

Citations: 2 citations in WoS, 1 in IEEE xplore + 3 others

Papers on local conferences: 27

Program committees: member of 2 committees on IEEE conferences, **chair** of Modeling and Control special session on 2 additional IEEE conferences

Obtained utility designs: 4

Obtained patents: 2

Additional patent applications: 1x CZ, 1 US patent, 1 Russian patent