Experimental Research of High-speed Electrical Motor Supercharger Dynamic Properties

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Abstract— This paper presents some specific issues of a high speed permanent magnet synchronous motor control used in a combustion engine supercharger system. A description of a method designed to limit the load angle of synchronous motor in high speed is given. Also experimental results in dynamic states are shown. In these states mainly acceleration times and energy intensity with correlation on motor current and field weakening were examined. Dynamic properties were tested for a power supply with both high and low internal resistance. The experimental setup description is given and test results for speed up to 42 000 RPM are shown.

INTRODUCTION

Combustion engine superchargers are normally powered with a turbine using combustion engine exhaust gases. This is a relatively simple solution but it has some drawbacks. One of them is the low dynamic as in the instant when the fuel supply is increased the turbine is unable to deliver the required torque to speed up the compressor.

An ideal solution of a supercharger propulsion system has to control the compressor based on instantaneous speed and supplied fuel. The optimized system dynamic has to correspond to the speed of changes of fuel and air supply.

Those desired properties can be achieved by a controlled electrical motor. The electrical motor equalizes in this case the turbine’s power fluctuations and increases system dynamic. The choice of optimal speed of both the propulsion system components makes it not desirable to place the turbine and electrical motor on the same shaft. A better solution is to place an additional smaller supercharger with electrical motor and compressor speed. This allows the choice of speed as a tradeoff between motor and compressor speed. Our main goal is a research in the field of hybrid supercharger system, mainly from control point of view.

For the hybrid supercharger a high speed permanent magnet synchronous motor (PMSM) was chosen. A frequency controlled feedback system is used. General information of such systems can be found in [1-4].

Some specific problems rise in the field of high speed PMSM control structures with required fast dynamic response. In PMSM high speed region flux weakening is used. This method uses a reactive stator current component to weaken the magnetic flux by causing a voltage drop on the longitudinal inductance acting against motor induced voltage.

For high speed the voltage drop on stator reactance is non negligibly increasing due to high stator frequency. Moreover it increases with increasing current. If a fast dynamic response is required a higher motor current is required too. For higher frequencies this causes a significant voltage drop on stator reactance causing a transition to flux weakening mode in lower speeds. To maintain stability it is however required to limit the total current and torque in this mode. For those reasons the speed increase in dynamic response of PMSM is not directly proportional to current increase in flux weakening mode. Another problem is that in the case of a high speed motor it is necessary to connect serial inductors filtering the current but at the same time also causing additional voltage drops.

This paper therefore also discusses the issues caused by torque limitation for a high speed PMSM in flux weakening mode and describes experimental results obtained with a high speed motor.

EXPERIMENTAL SETUP

For testing purposes an experiment setup was created, allowing measuring both static and dynamic properties of high speed PMSM. The experimental setup can be seen on Fig. 1 to 3. The dynamic response tests were done on two different PMSM. During the tests the motors were unloaded. First motor (PMSM 1) is coupled with a high speed dynamometer and has the following parameters: 2,9kW, 400V, 6,5A, 40 000min⁻¹, 0,7Nm. Second motor (PMSM 2) is a stand alone motor not coupled to a load. Its parameters are: 2 pole, 3,14kW, 400V, 11A, 25 000min⁻¹, 1,2Nm, max. 42 000min⁻¹. An experimental IGBT inverter with microprocessor controller and instantaneous PMSM rotor position measuring system was also designed for this purpose. Based on motor manufacturer recommendations the synchronous motor current ripple was decreased with serially connected inductors with inductance 2,4mH.

A two pole resolver is integrated into the PMSM. To measure the rotor position an electronic unit with 12 bit resolution providing 4096 positions per one revolution was developed. Detailed description can be found in [5]. Digital signal processor (DSP) controller was used during testing.
It is based on TMS320F2812 DSP. Switching frequency in the whole tested speed range from 0 to 42 000 RPM was 1 kHz and calculation frequency of the torque control structure 15 kHz.

THEORETICAL ANALYSIS OF TORQUE CONTROL

A low level torque feedback loop is required for high speed motor control. It is based on standard methods used for PMSM.

Methods for synchronous motor control are based on a transformed rectangular coordinate system in d,q axes and based on equation:

\[
M = 1.5 \cdot p \cdot (F_d \cdot i_q - F_q \cdot i_d) \quad (1)
\]

where \(F_d\) is the magnetic flux component in d axis, \(F_q\) is the magnetic flux component in q axis, \(i_d\) is stator current component in d axis, \(i_q\) is stator current component in q axis, \(p\) is number of motor pole pairs. If the d axis is identical to the magnetic flux source axis, i.e. rotor axis and if the motor is controlled to have a maximal torque creative component \(i_q\) (i.e. \(i_d = 0\)), equation (1) can be simplified to:

\[
M = 1.5 \cdot p \cdot F_q \cdot i_q \quad (2)
\]

where \(F_q\) is the motor magnetic flux. If the motor will have a negligible rotor magnetic non symmetry, i.e. the longitudinal and transversal rotor inductances are equal (\(L_d=L_q=L_1=L\)) equation (2) will be valid even for flux weakening mode where \(i_d \neq 0\). This is usually true for permanent magnet machines.

The armature interference given by \(i_d\) component is acting against the induced voltage in this mode and allows using the motor with an increasing speed while maintaining constant RMS stator power supply voltage.

\[
\begin{align*}
& \text{Fig. 1. Tested high speed motors: top - PMSM 1 – coupled with dynamometer, bottom PMSM 2.} \\
& \text{Fig. 2. Experimental IGBT inverter for high speed motor} \\
& \text{Fig. 3. Overall view of experimental setup} \\
& \text{Fig. 4. Phasor diagram of synchronous motor with torque control} \\
& \text{Fig. 5. Current components } i_d, i_q, \text{ reference voltages and speed(frequency) amplitudes for unloaded startup to 42 000 min} \\
& \text{Fig. 6. Startup without load angle } \beta \text{ limiting}
\end{align*}
\]
In field weakening mode the spatial stator current vector is ahead of the induced voltage. The general situation for field weakening mode is shown in a phasor diagram on fig. 4. In this figure $R_1$ is stator resistance, $U_{1s}$ stator voltage and $U_i$ induced voltage.

The basic feedback structure of the implemented controller is shown on fig. 7. It is a vector control structure with parallel controllers for current components $i_d$ and $i_q$. In a full magnetic flux mode current $i_q = 0$ and the spatial stator current vector is in q axis as can be seen on fig. 4. In a flux weakening mode the control structure creates a non zero $i_d$ current component. Its magnitude increases with increasing speed, increasing current and decreasing inverter input voltage $U_{DC}$. Calculation of required $i_d$ current component value is done by a feedback controller $\text{Reg } [U]$ and a predictive calculation block. This predictive block is predicting an optimal value $i_d^{**}$ from the instantaneous value of mechanical speed $\omega$ and from inverter input voltage $U_{DC}$. The resulting value of $i_d$ is given by adding the output value from the predictive block and feedback controller. In flux weakening mode this maintains a constant and maximal inverter RMS output voltage as can be seen on fig. 7.

The described high speed motor with the described control structure on fig. 7. was extensively tested both in unloaded and loaded state. A good control quality was achieved for speeds up to maximal speed 42 000 RPM. Experiment results for unloaded motor with maximal speed 40 000 min$^{-1}$ ($f = 700$ Hz) are shown on fig. 5. The desired current value for startup was set to $i_q = 5.7$ A. The maximal speed was achieved in time aprox. 1.5s and at the end of startup process the start of flux weakening mode where $i_d \neq 0$ is visible. A more detailed description of principles, experimental setup and tests of this high speed motor controller structure can be found in [6], [7], [8], [9].

In hybrid supercharger systems the key issue is the achievable acceleration of electric motor. A higher acceleration leads to higher required torque and to higher motor current. But higher current produces together with higher frequencies higher voltage drops on stator reactance and on reactance of serial filtering inductors.
In flux weakening mode where a constant and maximal inverter output voltage is maintained it is necessary to suppress more and more the induced voltage.

This is quite significant for higher currents and for a soft voltage source where with increasing speed voltage $U_{in}$ is dropping. In a phasor diagram on fig. 4 this will produce an increased phase angle between induced voltage $U_d$ and terminal voltage $U_1$. From synchronous motor theory it can be seen that this angle, called load angle $\beta$, has to be lower than 90°. If the controller structure will not limit this value, the controlled system will lose stability. The tested systems dynamic response and acceleration was limited by this problem.

Fig. 5 shows experimental results without loss of stability but without load angle limiting. To achieve higher desired values of torque creative component $i_q$ and to achieve higher total accelerations the load angle limiting block has to be added. It limits the current component $i_q$ when load angle $\beta = 90°$. This decreases the available torque but allows the system to maintain stability and continue the acceleration but with a lower acceleration.

Fig. 6 shows experimental results with PMSM 1 without load angle $\beta$ limiting and where a value over 90° was achieved. The inverter was powered from a soft voltage source. This can be seen from negative $u_q$ values of the power supply voltage phasor $U_1$. Symbol $[U]$ denotes in fig. 6 the amplitude of inverter input voltage calculated by the Pythagoras formula from components $u_d$ and $u_q$.

LOAD ANGLE LIMITING IN FLUX WEAKENING MODE

The controller structure has to limit the $i_q$ stator current component as not to achieve load angle $\beta > 90°$. Also over current protection is required. Therefore also current amplitude has to be limited. The $i_q$ current limiter on fig. 7 calculates the maximal current based on values of $i_q$ and $\beta$. A lower value from those two results is taken.

For high speed motors PMSM 1 and PMSM 2 the $i_q$ limit caused by load angle $\beta$ maximal value is more common.

The implemented method for $i_q$ stator current component limiting is based on phasor diagram on fig. 8 where stator resistance $R_s$ is neglected.

From calculation efficiency point of view and calculation precision and based on the $\tan$ function properties the load angle limiting is done by calculation of angle $\alpha$ according to equation:

$$\tan \alpha = \frac{U_i - \omega L_i q}{\omega L_i d} = \frac{\omega F_f - \omega L_i d}{\omega L_i q}$$

where $U_i$ is the induced voltage, $L_i$ stator inductivity, $F_f$ permanent magnet magnetic flux and $\omega$ stator voltage angular speed.

By simplification an equation for maximal $i_q$ current value for a given $\alpha_{MIN}$ is obtained. It can be seen that $\beta=90°$ corresponds to $\alpha=0°$:

$$i_{qMAX} = \frac{L}{\tan \alpha_{MIN}}$$

Fig. 12 Motor startup without load angle $\beta$ limiter – low internal resistance power supply
Based on the form of \( \tan \gamma \) function and for reasons of some robustness against imprecision and non-linearity caused by changes of inductance \( L \), the value of \( \gamma_{MIN}=21 \) was chosen. This corresponds to limiting \( \beta \) to 69° and to lower torque of about 7% from the state where \( \beta=90° \). There is no feedback control of load angle \( \beta \) when this limiting is activated. The calculation is based only on analytical calculation of mathematical model of motor and motor parameters. For this reason there is some imprecision for limiting angle \( \alpha \) calculation in the range from 16° to 26° for a desired value of 21°. \( \tan \gamma_{MIN} = 0.4 \). This causes torque fluctuations for about ±3%. For this application however this does not pose a problem.

Fig. 9 and Fig. 10 show waveforms for PMSM1 for an unloaded motor and load angle \( \beta \) limiting set to \( \gamma_{MIN} = 0.4 \), i.e. \( \alpha_{MIN} \approx 21° \). Fig.9 shows components of voltage \( u_{\alpha} \) and \( u_{\beta} \) and it can be compared with fig. 6. Fig. 10 shows the waveform of \( \tan \alpha \) with a desired value 0.4 in limiting mode.

For better readability motor speed is shown in Hz. From those figures also a function of \( i_q \) component limiter can be clearly seen. The waveforms were measured with a soft power supply – a single phase bridge diode rectifier with filtering capacitor. Due to the limiter block the motor could be started with higher initial current and startup time was significantly limited compared to fig.5 without limiter.

Fig. 11 shows waveforms for PMSM1 for unloaded startup. The inverter was in this case powered with a low internal resistance power supply. It was a three phase bridge diode rectifier and it can be compared with fig. 6. Fig. 10 shows the waveform of \( \tan \alpha \) with a desired value 0.4 in limiting mode.

For better readability motor speed is shown in Hz. From those figures also a function of \( i_q \) component limiter can be clearly seen. The waveforms were measured with a soft power supply – a single phase bridge diode rectifier with filtering capacitor. Due to the limiter block the motor could be started with higher initial current and startup time was significantly limited compared to fig.5 without limiter.

Fig. 12 shows waveforms for PMSM1 powered from a low internal resistance power supply and for a low desired value of current component \( i_q \) where load angle \( \beta \) limiting will not occur.

Fig. 13 and fig. 14 show waveforms for PMSM2 with the highest tested acceleration. Value of \( \tan \gamma_{MIN} \) was set to 0.25, the inverter was powered from a low internal resistance power supply. As can be seen from Fig. 14 there is a relation between individual current component and its absolute value. Also it is visible that when limiting of load angle \( \beta \) and \( i_q \) current component occurs this produces \(|I|\) limiting too.

### Dynamic and Energetic Motor Properties

During experiments with high speed motor startup time for an unloaded motor to 42 000 RPM was measured. This was done for various values of \( i_q \) current component and for a high and low internal resistance power supply. In range where flux weakening is not used, the motor dynamic torque is proportional to requested value of \( i_q \) current component and with increasing \( i_q \) the startup time reduces significantly. After the transition to flux weakening mode it is necessary to limit also the load angle \( \beta \) and this will limit also \( i_q \) current component. The requested \( i_q \) current component value will no longer affect acceleration. The higher the requested value of \( i_q \) is, the higher the motor current is and the higher are voltage drops on serial inductors and on motor inductance. This reduces motor speed where load angle \( \beta \) limiting starts. This limits partially the influence of higher startup current.

Fig. 15 shows waveforms of startup time for PMSM1 and PMSM2 in unloaded state. Described dependency UDC 1 was obtained for a high internal resistance power supply and those described as UDC 2 for a low internal resistance power supply. Startup times for PMSM1 are longer as this is a motor with a higher moment of inertia and higher mechanical loses. From this figure it can also be seen that a higher internal resistance of the power supply causes longer startup times as a sooner transition to load angle \( \beta \) limiting is required. Fig. 16 show the dependence of energy required for startup based on various values of \( i_q \). The required energy was measured for PMSM2 by integrating the product of input current and voltage on the inverter input before the filtering capacitor with a voltage and current probe and a storage oscilloscope.
It can be seen that there is not a significant trend in the dependence and fluctuations are caused by imprecision of measurement. The average energy required for unloaded motor startup is 1400 J.

To calculate the ratio of energy used to increase the motor's kinetic energy to energy taken from the power supply on the inverter input, it was first necessary to calculate motor’s moment of inertia.

Motor’s moment of inertia was calculated from a motor startup on fig. 15. In this experiment where the motor was powered with a constant current without field weakening speed 440 Hz (26 400 min⁻¹) was reached in 0,24 s. The startup current was 11A, this corresponds to torque 1,2Nm. Considering the relatively high current and torque, mechanical losses were neglected in the calculations.

Moment of inertia is

$$ J = M \frac{\Delta \theta}{\Delta \omega_m} = 1,2 \frac{0,24}{2\pi 440} = 0,000104 km^2 $$

Kinetic energy of motor for speed 4 200 000 min⁻¹ is:

$$ E_k = \frac{1}{2} J \omega_m^2 = \frac{1}{2} \frac{0,000104 \cdot (2\pi 700)²}{2} = 1005 J $$

Average efficiency of energy conversion to mechanical energy calculated from average power supply conversion is:

$$ \eta = \frac{E_k}{E} = \frac{1005}{1400} = 0,72 $$

Fig. 16 Dependence of energy required for PMSM2 unloaded startup on requested value of \( i_q \)

Fig. 17 Dependence of energy conversion efficiency \( \eta \) for dynamic motor startup on \( i_q \) current component – motor PMSM 2

Fig. 17 shows dependence of energy conversion efficiency \( \eta \) for dynamic motor startup on \( i_q \) current component – motor PMSM 2. It can be seen that the variance is probably caused only by uncertainties of measurement and the efficiency is constant around 70%. The efficiency was measured for PMSM2 without a dynamometer where a maximal amount of electrical energy was transferred to mechanical energy.

CONCLUSIONS

The designed controller structure for PMSM torque control with load angle \( \beta \) limiting show very good results for fast transient states. According to fig. 13 the motor can startup to speed 42 000 RPM in approximately 490 ms. High acceleration was achieved due to higher possible PMSM2 current \( I_n = 11 A \).

ACKNOWLEDGMENT

This research was supported by Czech ministry of education research grant No. 1M0568.

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