Traction Permanent Magnet Synchronous Motor Torque Control with Flux Weakening

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Abstract. *The paper deals with analysis of dynamic behavior of a feedback flux weakening control of PMSM traction drive for light vehicles. The PMSM flux weakening is very important for traction drives. Two torque control structures were analyzed - pure feedback control and feedback control with prediction of the field producing current component. The principles, control structures, simulation and experimental results are given.*

Keywords

Permanent magnet synchronous motor, traction drive, torque control, magnetic flux weakening, vector control.

1. Introduction

Usage of permanent magnet synchronous motors (PMSMs) as traction motors is common in electric or hybrid road vehicles. For rail vehicles, PMSMs as traction motors are not widely used yet. Although the traction PMSM can bring many advantages, just a few prototypes of vehicles were built and tested as in [1], [2] and [3]. The next two new prototypes of rail vehicles with traction PMSMs were presented on InnoTrans fair in Berlin 2008 – Alstom AGV high speed train and Škoda Transportation low floor tram 15T “ForCity”.

Advantages of PMSM are well known. The greatest advantage is low volume of the PMSM in contrast with other types of motors. It makes possible a direct drive of wheels. On the other hand, the traction drive with PMSM has to meet special requirements typical for overhead line fed vehicles. The drives and specially their control should be robust to wide overhead line voltage tolerance (typically from -30 % to +20 %), voltage surges and input filter oscillations. These aspects may cause problems during flux weakening operation.

There are several reasons to use flux weakening operation of a traction drive. The typical reason is constant power operation in wide speed range and reaching nominal power during low speed (commonly 1/3 of maximum speed). The constant power region is described in traction diagram as hyperbolic curve; see curve A in Fig. 1 (F - traction force, M - torque, v - vehicle speed, n - motor speed). In the case of common traction motors like asynchronous or dc motors, it is possible to reach the constant power region using flux weakening. This is also possible for traction PMSM however problem with high back emf rises. A PMSM is permanently excited by permanent magnets. In the case of converter failure at speed close to the maximum speed, the back emf may rise up by 3 times. It may cause many problems especially in the case of common dc bus for more converters. A dc bus and a converter should be designed for this overvoltage indeed.

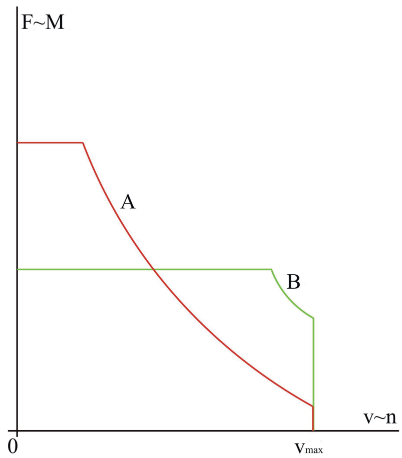

Fig. 1. Traction diagram (tractive force vs. velocity).

A high torque PMSM should be used to meet traction curve A. It leads to higher number of turns in stator windings. This is also disadvantage due to higher winding resistance which implies higher losses.

As it was mentioned earlier, a PMSM traction drive control should be robust. A flux weakening control is especially sensitive to voltage surges and high acceleration of drive (typically during wheel set skid).

The authors are interested in the field of PMSM control in the long term and also cooperate with industry sector in this field of research. This paper reassumes a previous paper [4].

2. Flux Weakening of PMSM

The flux weakening control of a traction drive is desirable. It is common for traction drives with asynchronous motors as well as for dc motors. Although it causes other problems, the flux weakening is unavoidable also for PMSM. A point of flux weakening is suppressing of back emf in high speed of drive. When the drive reaches nominal speed, a converter generates maximum voltage magnitude. Without flux weakening, the torque rapidly decreases to zero with increasing speed above the nominal speed and it can be even negative. This state of drive is very unstable and it is responsive to dc bus voltage surges. In fact, the drive is out of control in this state. It can happen also by low dc bus voltage. The flux weakening ensures correct control in the whole speed and voltage range.

There is only one way to reach flux weakening of PMSM. We can not reduce the permanent magnet flux directly. The flux weakening is possible by armature reaction, which reduces flux in air gap. The situation can be described by vector diagram shown in Fig. 2. The vector diagram shows voltage, current and flux values transformed to dq rotating reference frame. This reference frame is coupled with permanent magnet flux vector position. Speed of rotation is the same as speed of rotor (electrical synchronous speed ω). For variables' meaning, see Tab. 1.

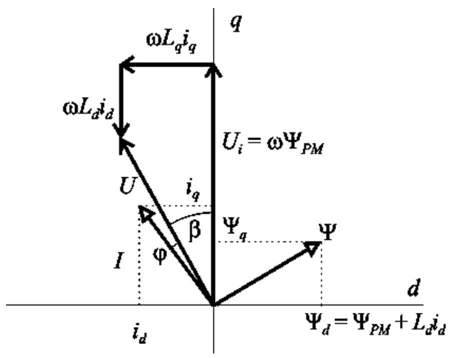

Fig. 2. Vector diagram of PMSM during flux weakening.

I	Phase current magnitude
i_d	Flux producing current component
i_q	Torque producing current component
I_{max}	Maximum current magnitude setpoint of I
L_d	Direct axis inductance
L_q	Quadrature axis inductance
M_i	Internal torque
R	Stator winding resistance
U	Phase voltage magnitude
u_d	Direct axis phase voltage component
U_{dc}	DC bus voltage
u_q	Quadrature axis phase voltage component
U_i	Induced voltage magnitude
U_{max}	Maximum phase voltage magnitude setpoint
U_{nom}	Nominal dc bus voltage
β	Loading angle
φ	Phase shift between current and voltage vectors
Ψ	Air gap flux
Ψ_d	Direct axis flux component
Ψ_q	Quadrature axis flux component
Ψ_{PM}	Permanent magnet flux
ω	Electrical angular velocity

Tab. 1. Nomenclature.

The back emf (induced voltage U_i) has effect in quadrature axis q. In the same axis, a voltage drop on inductance caused by i_d has effect, too. If a negative flux component current is set, the back emf will be suppressed by the voltage drop. This state is similar to an overexcited synchronous machine.

The aim of the flux weakening control is the optimal setting of i_d to reach the highest power and efficiency of a PMSM drive during flux weakening operation. There are many ways to flux weakening control realization. Some interesting solutions are given in papers [4]-[6]. Equations (1) and (2) represent voltage equation for stator windings specified to d, q components (p is the number of pole pairs).

$$\frac{d}{dt}i_d = \frac{1}{L_d}u_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}\omega i_q, \tag{1}$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}u_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}\omega i_q - \frac{\Psi_{PM}\omega}{L_q}, \tag{2}$$

$$M_i = 1{,}5p\left[\Psi_{PM}i_q + \left(L_d - L_q\right)i_d i_q\right]. \tag{3}$$

For i_d, we can derive using (1) and (2), (the R and the derivations are neglected):

$$i_d = \frac{\sqrt{U^2 - \left(\omega L_q i_q\right)^2} - \omega\Psi_{PM}}{\omega L_d}. \tag{4}$$

The (4) is solvable for:

$$U^2 - \left(\omega L_q i_q\right)^2 \geq 0. \tag{5}$$

We get an important condition by solving (5):

$$U \geq \omega L_q i_q. \tag{6}$$

In fact, the voltage drop caused by i_q is always lower than phase voltage, but this condition is important for flux weakening control to limit i_q setpoint. This is secondary limit for i_q setpoint. The i_q setpoint is primarily limited by maximum I. The PMSM design is important. If a PMSM is designed to meet traction curve A requirements, it will be probably necessary to use the secondary limit (due to higher inductance and resistance). In the case of a B curve designed PMSM (in Fig. 1), the secondary limit doesn't need to be used.

3. Control Algorithms

We analyzed two flux weakening control algorithms. Both of the controllers worked like front-end controllers for field oriented control (FOC) of PMSM. We used well

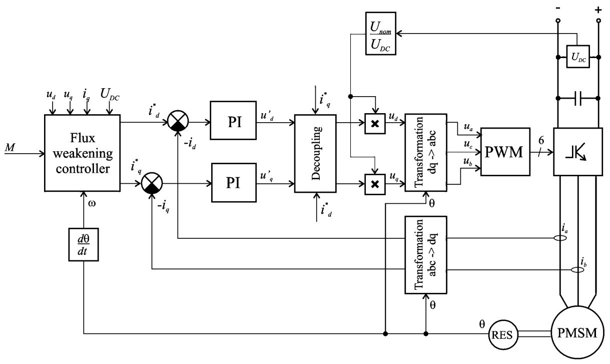

Fig. 3. Field oriented control with front-end flux weakening controller.

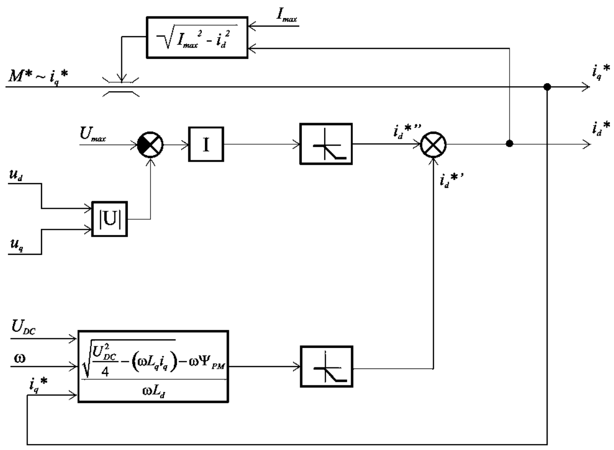

Fig. 4. Flux weakening control enhanced by prediction of id.

known FOC control structure enhanced by a decoupling block and dc bus voltage correction (Fig. 3).

The decoupling block improves dynamics of the FOC during transient effects. The decoupling is based on induced voltage and voltage drops in both control loops. The voltage correction ensures robustness to dc bus voltage changes.

As mentioned earlier, two flux weakening controllers were analyzed. The first of them uses pure feedback control. The second one is also feedback based but a predicted value of i_d is added to controller output. The prediction is based on (4).

Fig. 4 shows the structure of the controller with the prediction of i_d. The controller observes desired voltage vector component u_d and u_q and computes magnitude of the voltage vector. A followed control loop keeps constant desired voltage magnitude by setting the i_d setpoint. An integrator with antiwind-up limitation is used like the controller. The antiwind-up limits integrator output from $-i_d$ to 0. To avoid overcurrent, the limiting block sets constraints for i_q setpoint.

A disadvantage of the algorithm without prediction of i_d is low dynamics which can make problems during transient effects. Higher dynamics of the control can be reached by higher gain of the integrator but the high gain of the integrator leads to unstable behavior. The philosophy of the second controller is prediction of i_d and correction of the predicted value by the feedback controller. Therefore sufficient dynamics can be reached with lower gain of the integrator and also the behavior is stable during transient effects. The prediction uses (4).

4. Simulation Results

The Matlab Simulink application was used for simulations. A mathematical model of the drive corresponds to real drive, see Section 5.

5. Experimental Results

Experiments have been carried out using a special stand with a 58 kW traction PMSM. The stand consists of PMSM, tram wheel and "continuous" rail. The PMSM is a prototype for low floor trams. PMSM parameters: nominal power 58 kW, nominal torque 852 Nm, nominal speed 650 rpm, nominal phase current 122 A and number of poles 44. Model parameters: R = 0.08723 Ω, $L_d = L_q$ = 0.8 mH, Ψ = 0.167 Wb. Surface mounted NdBFe magnets are used in PMSM. Advantage of these magnets is inductance up to 1.2 T, but theirs disadvantage is corrosion. The PMSM was designed to meet B curve requirements. The stand was loaded by an asynchronous motor. The engine has parameters as follows: nominal power 55 kW, nominal voltage 380 V and nominal speed 589 rpm.

An IGBT inverter was used for feeding of PMSM. For control, a DSP TMS320F2812 by Texas Instruments was used. Maximum operation speed of drive was up to nominal speed of the motor to avoid dangerous overvoltage in dc bus during faults of inverter at speeds higher than nominal. To reach flux weakening operation, the maximum voltage threshold for flux weakening was 75 %. Also the torque rate was limited during the steps for safety reasons. To reach a dc bus voltage change during torque setpoint steps, a front-end resistor of 2 Ω was used.

Experimental conditions were: converter switching frequency 5 kHz, nominal dc bus voltage 560 V, dead times 2 μs.

For the construction of workplace the high requirements of construction had to be taken into consideration from viewpoint of EMC according to [7]. The reason is cooperation of the controlling and measuring microprocessor circuit. The power part is a strong source of interference because inverter with PWM generates voltage pulses with hundreds of V/μs. Satisfactory elimination of all parasitic signals caused by the operation of power electronic converters was reached by compliance to requirements of workplace construction from viewpoint of EMC (particularly shielding of power and signal conductors, filtering of network currents, galvanic separation and site layout).

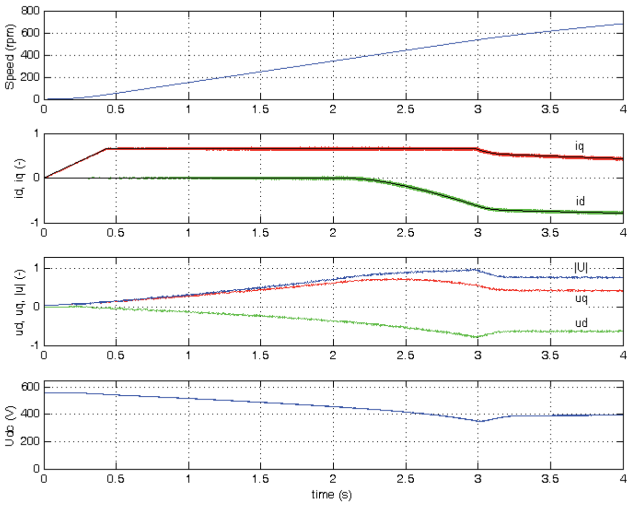

Fig. 5. No-load start of the drive, feedback controller, lower integrator gain (simulation) – obvious voltage overshoot at transition to weakening mode.

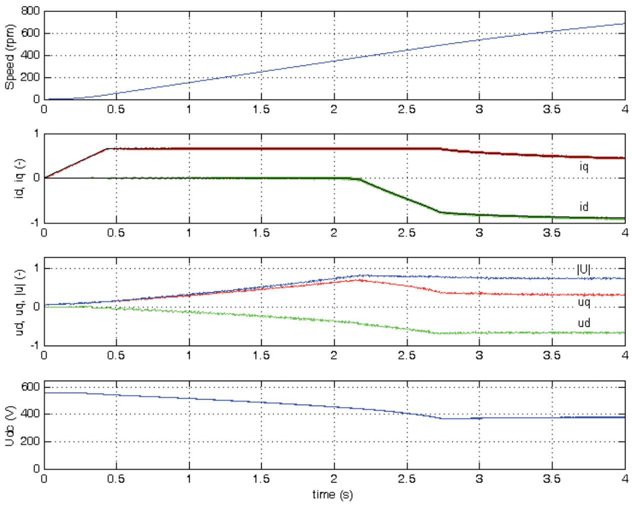

Fig. 6. No-load start of the drive, feedback controller with prediction, lower integrator gain (simulation) – without voltage overshoot at transition.

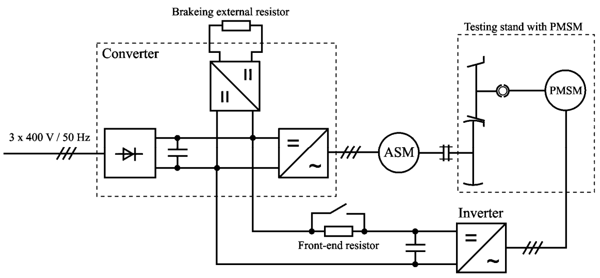

Fig. 7. Testing set-up.

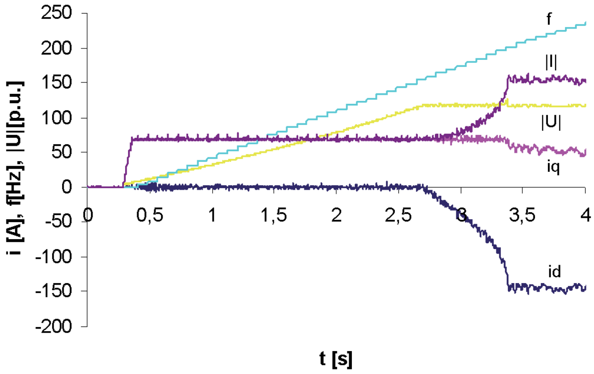

Fig. 8. No-load start of the drive, feedback controller, higher integrator gain (experiment).

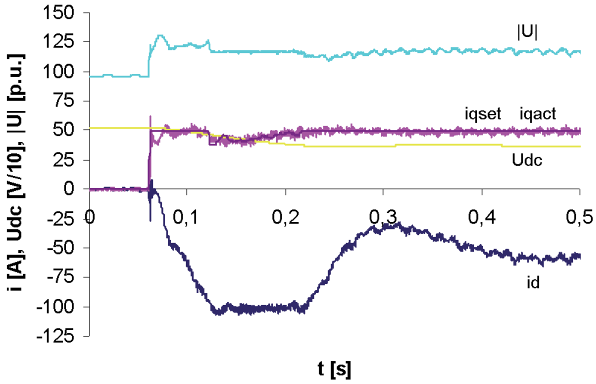

Fig. 9. Setpoint step and dc bus voltage drop – feedback controller, higher integrator gain (experiment).

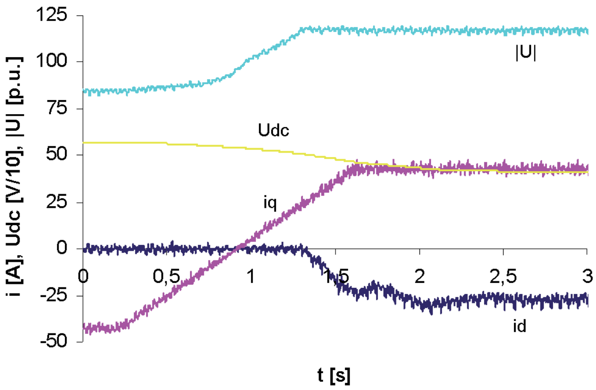

Fig. 10. Setpoint generator – motor change and flux weakening – feedback controller, higher integrator gain (experiment).

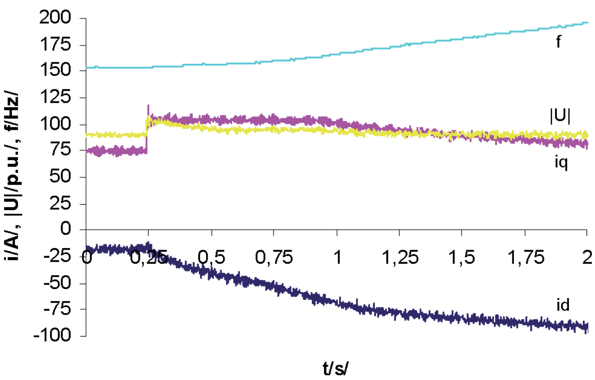

Fig. 11. Wheel skid, current limitation and flux weakening – feedback controller, higher integrator gain (experiment).

6. Conclusions

The main aim of the paper is analysis of dynamic behavior of the drive using feedback based flux weakening control. Two control structures were tested. The first of them was a pure feedback control and the second one was feedback control with added prediction of the i_d. The tests were performed on the mathematical model and also on a real PMSM drive.

The simulations show the prediction of the i_d improves the dynamic behavior of the drive (compare Fig. 5 and Fig. 6). A higher setting of integrator gain may cause oscillations of i_d and i_q during hard torque setpoint steps. Although the prediction brings improvement, the pure feedback control of the particular type of PMSM reaches good dynamic behavior, too. The negative effect of the pure feedback control could be avoided by torque setpoint rate limitation which is necessary to limit increase of acceleration anyway. The high integrator gain causes no problem during high acceleration of the drive.

The experimental results correspond with simulation results instead of results of the feedback control with prediction. Due to high inaccuracy of the i_d prediction, effects of the prediction were negligible. The inaccuracy was caused by equation (4) which is derived from linear model of a PMSM (1) - (3). Also a resistance of the phase winding is neglected. Nevertheless the simulation results showed the advantages of the prediction, however the accurate prediction has to be chosen (e.g. look-up table based).

The pure feedback control with lower integrator gain reaches low dynamics which causes desired phase voltage magnitude overshoots over 1 p.u. (In fact, the desired voltage is desired duty cycle of PWM). The inverter can not generate output voltage higher than 1 p.u., thus the drive is out of control for a moment. These states should be avoided for the reason of reliability of the traction drive. The higher integrator gain causes oscillations of the i_d during transient effect mostly caused by setpoint steps, see Fig. 9. The oscillations of the i_d in the figures are partially caused by mechanical system with flexible clutch between PMSM and loading engine. The higher gain causes no problem during high acceleration of the drive (Fig. 8. and Fig. 11.).

This work can be used as one part of background for analysis of traction drive with PMSM influence on the supply network. Drive influence on the network in various modes (i.e. motor/generator mode, low/high speed, weakening mode, steady state/transient effect) is researched from the viewpoint of EMC. Limitation possibilities of the drive negative effects are researched at the level of models and experiments both from the viewpoint of electric drive parameters choice (i.e. especially input filter) and from the viewpoint of semiconductor converter control strategy (i.e. switching frequency, dead time, PWM algorithm, feedback control) as well.

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