

Steady State Torque Optimal Operating Point Control for Wound Rotor Synchronous Motors

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Abstract – This paper discusses steady state optimal control of the motor from the maximum torque point of view. The motor behavior is researched with a vector control supply in the full speed range. The optimal considerations are compared with a behavior of the classical control structures such as the unity power factor strategy.

Keywords–optimal operating point; wound rotor synchronous motor; maximum torque per ampere; maximum torque per flux; unity power factor

I. INTRODUCTION

The wound rotor synchronous machine (WRSM) became more frequentative during recent years due to the price increase of the permanent magnets, which are exclusively made by China. Another reason for the employment can be the pressure of the market system to innovate products with DC machine for regulated medium voltage drives. The drives operate with several megawatts of power so that the maximal effective using of energy is required. In order to achieve the optimality, the maximum torque operating point of the motor is sought and is set through the d, q-axis stator currents and rotor field current as features [1]. Furthermore, the utilization of damper winding was considered and was avoided due to additional torque ripples and power losses.

In accordance with the torque equation (1), the reluctance torque cannot be utilized from the saturation reason [2]. The wound rotor has higher inductance in the d-axis than the q-axis $L_{sd} > L_{sq}$ (In the d-axis, the salient pole iron of the rotor has higher magnetic conductivity than the air gap in the q-axis), therefore the positive d-axis current has to be used for the reluctance utilization for the increasing of the total moment. As the surface permanent magnet synchronous motors (PMSMs) are controlled [3], [4], [5] the first idea how to optimally operate these wound motor is to keep the d-axis stator current to be zero up to the base speed, but it usually was not common even thirty years ago [6], [7], [8], [9]. The most utilized strategy is to orient the vector control on stator or magnetic flux linkage, where the field rotor current is higher than nominal and the d-axis stator current is negative. For right orientation, the mathematical motor model with parameters is used. The several known strategies use different approaches. The simplest methods operate with current flux model in d, q rotor reference frame coordinates as [9]. The next utilizes the voltage motor model as the core of the phase lock

loop estimator, see [10], where several adjustable filters are used for elimination of the DC drift at the back electromotive force. It solves the estimated flux fluctuation in the transition states. The paper [6] shows combined observer with the current and voltage mathematical models, where the current model corrects the input voltage of the voltage model. It solves the problem of the voltage model in the low speeds. Finally, the advanced solutions utilize a state observer as [7], which contains the voltage equations of the motor for determination of the stator flux linkage by the integration and the correction feedback uses the current model. This solution is presented as the stable observer for whole speed range of the rolling mill drive. Otherwise, the d, q rotor reference frame can be used without any mathematical model or flux linkage estimator but the optimal operating points demonstrate nonzero d-axis current (For the flux oriented control, the d_v-axis current in the flux reference frame is kept zero up to the base speed) even up to the base speed. In the field weakening area, the rotor current decreasing to zero with the increase of the speed is considered. It is partially truth. The rotor current is slightly reduced, but not proportionally to the rotor speed. More dramatically, the d-axis stator current is lowered. Since the rotor reference frame is used (the frame angle is given from the position sensor), the challenge of the rightness flux linkage estimation is shifted to the generating of the rotor and stator current demands.

This contribution features the simulation study of the vector controlled motor with emphasis to the maximum torque. The results are compared with the classical approaches and discussed. Consequently, the simulations are verified on the developed laboratory prototype.

II. THEORETICAL FOUNDATION

A. Mathematical analysis

The fundamental considerations are made from the following torque equation:

$$T = k_p p_p [\psi_f i_{sq} + (L_{sd} - L_{sq}) i_{sq} i_{sd}] \quad (1)$$

, where

T Electromagnetic torque,

k_p Park's transformation constant,

p_p	Number of pole pairs,
ψ_f	Rotor field flux linkage,
i_f	Rotor field excitation current (recalculated on the stator side),
i_{sd}, i_{sq}	d, q-axis components of stator current vector,
L_{sd}, L_{sq}	d, q-axis stator inductances.

The torque is dependent on all three currents i_{sd} , i_{sq} , i_f . The first part of the equation with the field flux linkage is called main torque part and the second part is known as the reluctance torque part. As the state of the art shows, the application of the positive i_{sd} current is unusable due to saturation effect. The classical strategy is to overexcite the machine as is shown in the next Fig. 1.

The higher field flux linkage than nominal is applied through the rotor current. The nominal magnetic flux linkage in the air gap of the machine is ensured by the negative d-axis current. The only one assumption has to be assured, that the main torque increase is higher than the reluctance part decrease. Consequently, the optimal operating point is given by higher than nominal field current, negative d-axis current and adequate q-axis current. Up to the base speed, the usable area of the operating points is limited only by the maximum stator and rotor current. In the field weakening area, see Fig. 2, the ellipses of the minimal performance field weak are the second limitation rule. In comparison with the PMSMs, this elliptic area is smaller with the speed increase as well, but shifted on the d-axis by the changing of the rotor current, because the d-axis center is given by:

$$-\psi_f / L_{sd} = -L_{md} i_f / L_{sd} \quad (2)$$

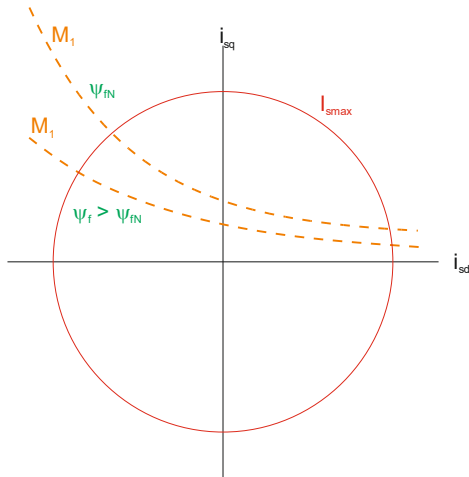


Figure 1. d,q-axis current diagram for different field flux linkage up to the base speed

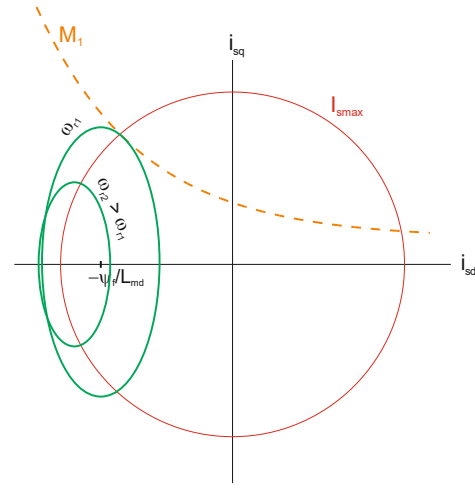


Figure 2. d,q-axis current diagram for different speeds in the field weakening range

B. Simulation study

For the determination of the optimal operating points for the maximal torque values, the simulation has been made by Cartesian vector control in current loop with depth modulation controller (input: modulation depth, demand: 1, output: demanded d-axis current) during really slow transient effect under sinusoidal wave supply and constant voltage in converter dc-link. The detailed description of the vector control is featured in Fig. 4 and [11]. It is method how the optimal field current can be determined without relatively complex mathematics. The rotor current and flux controller can be used for the simple vector control for the machine, which is operated on the maximum torque values without any mathematical model.

The results are featured in Fig. 3 and 5. The slow transient is always depicted for constant speed and changing of the three current in accordance with the limitation rules. The Fig. 3 shows almost constant rotor current. Truthfully for the laboratory machine, the optimal rotor current is constant for all speeds, because the rotor-stator linkage changes. The final value of the rotor current refers to limit shift of the ellipse center to the maximal stator current. The next Fig. 5 refers the benefits of the optimal control. The torque for any speed is higher in comparison with the zero d-axis current control. Even for two maximal speeds, the feasible torque for zero d-axis is zero. It refers the wider speed range with the optimal control.

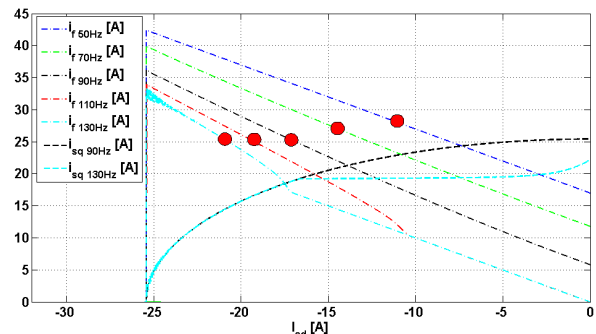


Figure 3. Current graphs for different stator frequency

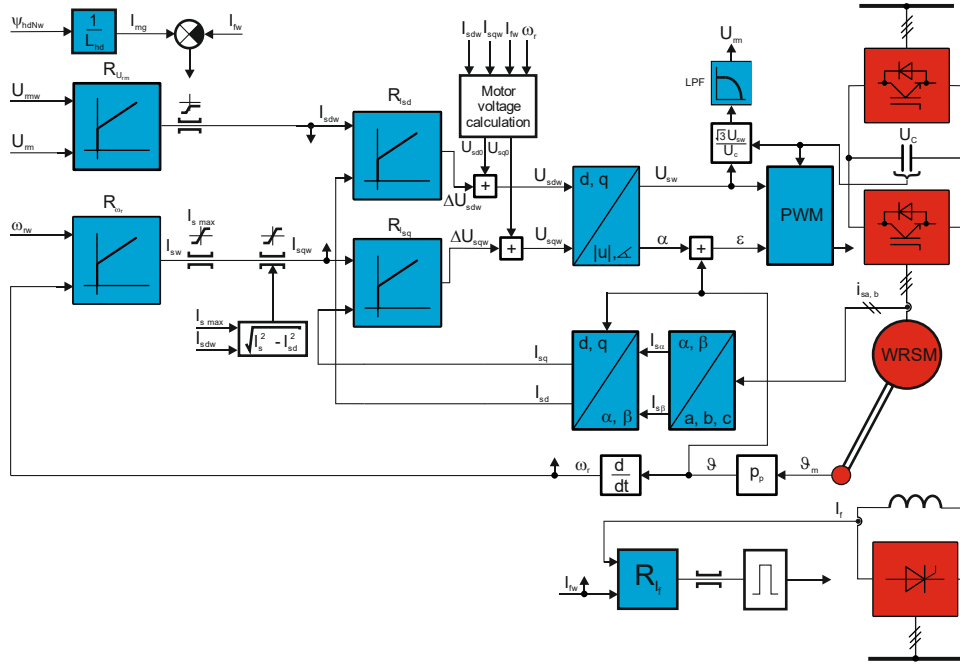


Figure 4. Vector control in Cartesian coordinates

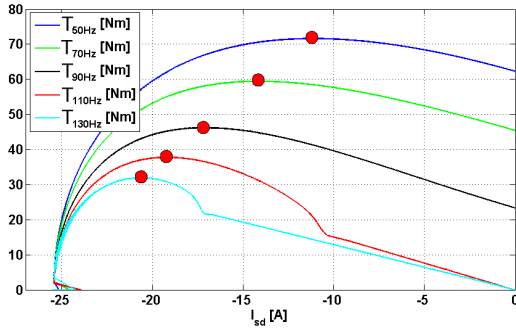


Figure 5. Torque graphs for different stator frequency

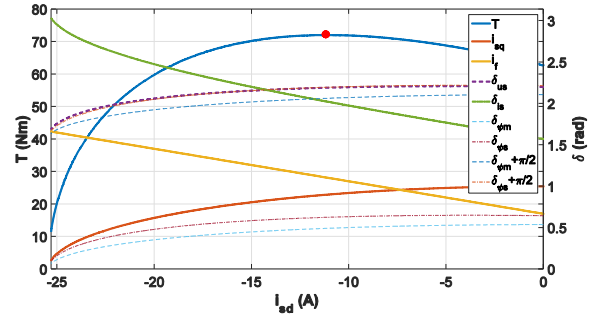


Figure 6. Torque, current and angle graphs for stator frequency $f_s = 50\text{Hz}$

In reaction on common questions about the comparison of the optimal strategy and the classical approach to control the motor in reference frame tied to stator or magnetic flux linkage, thus to keep the outer or inner unity power factor, the same slow transients has been depicted see Fig. 6 and 7.

Firstly, the difference between constant torque speed region and field weakening rang is evident. Up to the base speed (Fig. 6. $f_s = 50\text{Hz}$), the optimal operating point almost corresponds with the inner unity power factor. Whereas in the field weakening, the optimum agrees with the outer unity power factor see Fig. 7. The control oriented only on one flux linkage is not able to optimally operate under the whole speed range.

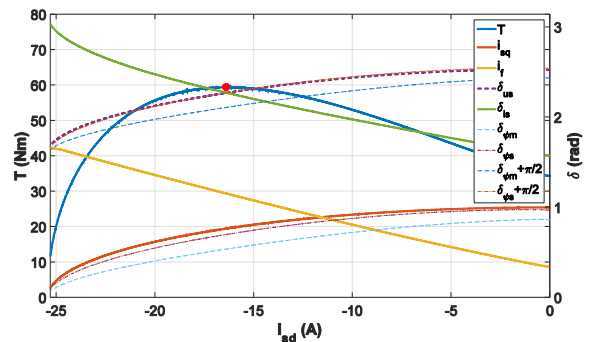


Figure 7. Torque, current and angle graphs for stator frequency $f_s = 70\text{Hz}$

III. EXPERIMENTAL TESTS

The optimal control has been verified on the developed laboratory stand as specifies the next parameter table and motor depiction.

TABLE I. MOTOR PARAMETERS

Stator phase resistance	$R_s = 0.28 \Omega$
Rotor resistance on rotor side	$R_r = 6 \Omega$
d-axis stator inductance	$L_{sd} = 60 \text{ mH}$
q-axis stator inductance	$L_{sq} = 25 \text{ mH}$
Rotor rectifier input voltage	$U_{rec} = 80 \text{ Vrms}$
Number of pole pairs	$p_p = 2$
Nominal stator current	$I_{sN} = 18 \text{ Arms}$
Nominal rotor current	$I_{rN} = 2 \text{ A}$
Converter dc-link voltage	$U_{cN} = 700 \text{ V}$
Maximal modulation depth	$U_{rmw} = 0.2$



Figure 8. Laboratory WRSM with salient poles – 10kW

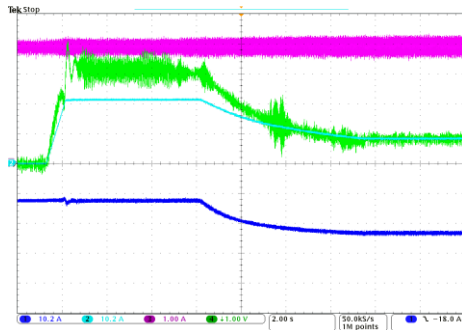


Figure 9. Speed up - Optimal control, $f_s = 0 - 30\text{Hz}$: Ch1: d-axis current I_{sd} [10.2A/div], Ch2: q-axis current I_{sq} [10.2A/div], Ch3: field current I_f [8.66A/div], Ch4: motor torque T [20Nm/div]

The verification has been made by sensing of the motor torque and changing with the motor currents to find the torque maximum consistently with the simulation transients. From these tests, the optimal rotor current has been determined and used as demand for the vector control. Consequently, the drive speed up is shown in the Fig. 9. Real control operates with higher constant rotor current and lower torque than has been theoretically simulated. It refers to necessity to improve model of the motor. The comparison of any unity power factor control has not been made practically from the same reason, because the precise parameters are needed for the appropriate flux model and unity power factor cannot be precisely measured due to pulse wide modulated stator voltage and further the control variety is really small for this design of machine even in the simulations.

IV. CONCLUSIONS

The main objective of this contribution is to answer on the question: Is a unity power factor control the same as the optimal maximum torque strategy? The answer is No, but for many drives the difference can be neglected. The more significant difference occurs for the lower loads (torques) of the motor, whose characteristics are theme for the future research.

This paper features mainly the simulation study, which is partly verified on the laboratory rig.

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