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3. Motor Control

In the third chapter, the overall control method of the Reluctance synchronous motor are presented. The overall structure and block diagram of the motor system are first introduced. The mathematical model of the controlled system (SynRm) in time-continuous and time-discrete form are than presented. Lastly, the current and torque controller are presented in detail.

3. 1 Overview of Motor control system

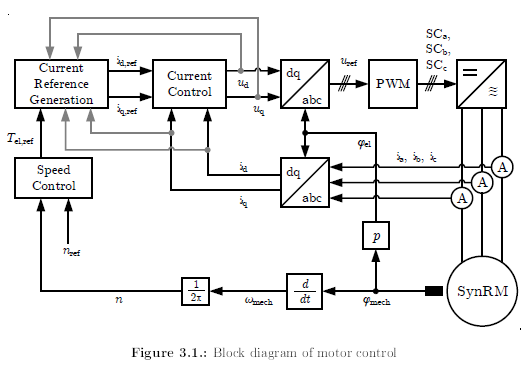
We introduce importance concept for the motor control system as well as commonly used technique for the facilitation of the design of our controller.

3.1.1 Field-oriented control

Field-oriented control (DE: Feldorientierte Regelung), or vector control is a control method that is widley adopted for the control of three-phase motors. The control of the motor is performed by controlling the stator current vector on the rotational dq Coordinate system, which is defined according to the magnetic field of the rotor. During steady-state condition of the motor, these two orthogonal current components, i.e i\_d and i\_q, are direct current signals, rather that alternating signals. This characteristic of the control value being constant in steady -state condition gives us great advantage in control of the systems. However, real-time computation for the inverse dq transformation and the dq transformation for the control value are required, since the SynRm is drived with three-phased AC-current. The inverse dq transformation is performed while giving the control command to the motor, as the dq transformation is performed during the sampling of the output of the motor.

3.1.2 Control Block diagram

Fig? shows the block diagram of the overall control of the motor system. The control of the motor is performed through a set of cascade controllers, where the Torque controller serve as the superposed controller and the current controller serve as the Subordinate controller. The current controller is a feedback controller as the Torque controller is an open loop controller that generate current setpoints with the use of preprogrammed data (Look-up-Tables). Details of the controller are presented in the following chapter.



The controlled system is composed of the SynRm and the three-phase inverter. As mentioned in the previous chapter, inverse dq-Transformation is performed on the output of the controller. Through PWM( pulse width modulation) methods, the resulting voltage signals on the a,b and c axis are interpreted into switching commands and are fed to the DC-linked inverter, which drives the SynRm with tree-phase AC-current. These current components on the a,b and c axis are then sampled and transformed back to d-q coordinate system as he feed-back signals of the current controller.

For the sake of generating correct current reference, the torque controller requires the information of the motor speed. This required signal is measured through time derivation of the motor rotation angle measured be the encoder, which is mounted on the shaft of the motor. The equation for electrical angle and rotation speed is presented in …

3.1.3 Parameter normalization

For the design of our controller systems and control parameters, the mathematical model introduced in chapter 2 should be consider. In this chapter, we define the normalized value for each electric and mechanical variable in Table ?

|  |  |  |
| --- | --- | --- |
| Synbol | Name | Value |
| I\_N | Normalized Current |  |
| U\_N | Normalized Voltage |  |
| M\_N | Normalized Torque |  |
| w\_N | Normalized Angular Frequency |  |

In this thesis, the maximum value for each parameter are chose as the moralization quantity.

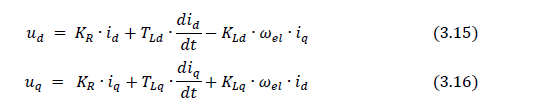
The normalization of the values are shown in equation? to equation ?

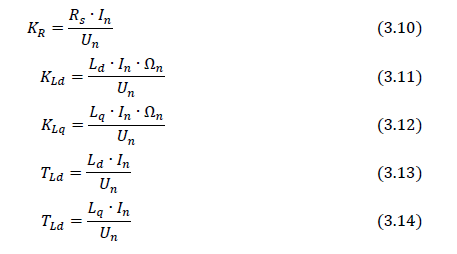
3.2 Synchronous reluctant motor

In this chapter, we define the Laplace representation in s-Domain and the block diagram of our controlled system based on normalization we defined in the previous chapter. Furthermore, a discrete representation of the motor equation should also be derived, since the controller of the motor should be a discrete time controller in order to be implemented on the test bench.

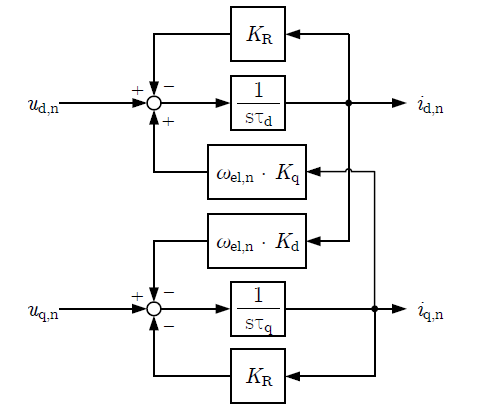
3.2.1 Model representation in s-domain

We start from the voltage equations in [equation number]. After normalization, we can derive the normalized voltage equation and its parameters in equation?





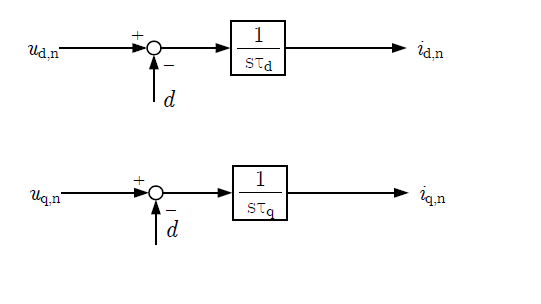
According to equation?, we are able to derive the block diagram representation of the motor in S-Domain, as shown in fig?



From the block diagram presented above, we can observe that the current of the d- and q-axis is cross-coupled***[literature num]***. Under high-velocity and high-dynamics operation, this characteristic can leads to deterioration in current control, since the cross-couple effect become more prominent with higher value of electric angular frequency. In some literature, a decoupling technique is adopted ***[literature num]***, where a decouple term is add into the output voltage value of the current controller to compensate the cross-coupling term of the motor.

For the design of our controllers, we can consider this cross-coupled term as disturbance and omit the signal for the sake of simplification. Also, the influence of resistance can be neglected. Thus, the simplified motor model can be view as an integrator with time constant T\_d and T\_q, as shown in equation?

The block diagram from fig? is reduced to the one in Fig?



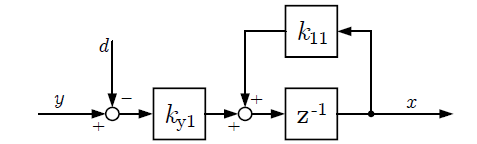
3.2.2 Model representation in z-domain

[reason for discrete time control: Reglungtechnik II Prof. Roth-Stielow]

[introduction to sampling time T\_A (Abtastzeit)]

In equation? , we modelled the motor as an integrator. Thus, equation? can be adopted, where z represents a delay for one time step.

The block diagram for the d-axis current is shown in fig ?



For the transfer function for the d-axis, the parameter k\_y1 and k11 can be derived using the following procedure shown in equation?

The same applies to the transfer function for the q-axis. Hence, we derived the transfer function for the motor in z-Domain as shown in equation?

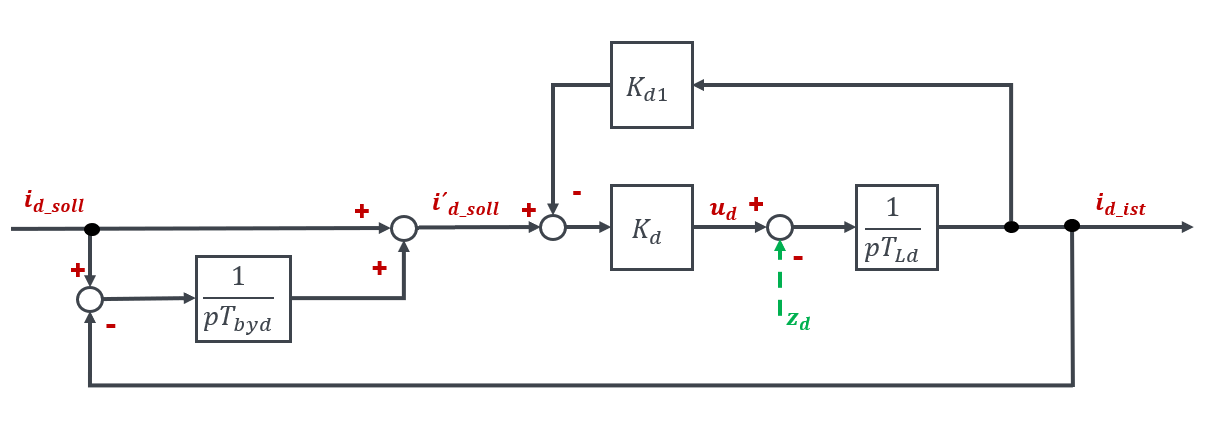
3.3 Current Controller

This chapter present the current controller both in time-continuous form and time-discrete form.

3.3.1 Time-continuous current controller

With the simplified model we derived from equation? as our controlled system, we first design the controller in continuous time and calculate the control parameters for the desired characteristic. For the system transfer function on the d- and q-axis are the same, we only consider the d-axis in this chapter. The parameters for the q-ais can be derived with the same procedure.

Fig ? shows the block diagram of the current controller. The controller consist of a status controller (DE : Zustandregler) and a Bypass integrator (DE:Bypass-I-Regler). The former is a simple feedback controller that has the controller parameter Kd1 and Kd. The latter is a Bypass integrator (DE:Bypass-I-Regler). As discussed in previous chapter, we defined the cross-coupled terms between the d,q-axis as disturbance z, which are proportional to motor speed. The effect of this disturbance on the system become prominent at higher speed. The Bypass integrator is hence implemented and has the function of eliminate the system disturbance and maintain system stability.

****

From the block diagram, we can derive the overall system transfer function as equation ?

Our desired system transfer function is a first order system (PT1-Glied) as shown in equation? The parameter Kwd represent the gain value of the system and the parameter T\_eld is electric time constant of the system.

We use the pole-zero cancellation technique to reduce the transfer function in equation? from 2-order system t 1-order system.

From equation?, we are able to derive the control parameter k\_d and K\_d1 based on the design parameter T\_eld and T\_byd.

For the design of our system, we choose the parameters for the d- and q- axis in Table?

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | d-axis | | | q-axis | | |
| parameter |  |  |  |  |  |  |
| value | 1 |  |  | 1 |  |  |

The

[System response plot]

The smaller the bypass time constant, the quicker the disturbance converges to 0.

3.3.2 Time-discrete current controller

For the implementation of our control system on the controllers and test bench, the current controller should be time-discrete. We use the same control structure as in time-continuous controller. The control block diagram is shown in fig?

We can fist look at the bypass integrator. In time-continuous current controller, the bypass integrator is as shown in equation?

After transform the y into z domain, we can derive the bypass integrator in time-discrete from.

From fig?, we can derive the transfer function in equation?

Similar to continuous controller design procedure, we have to first find our desired transfer function. We start from the transfer function in s-Domain shown in equation?. The pole of the continuous control system can be derived from equation?, as shown in ?

Then, the continuous pole s\_p can be transferred to the discrete pole z\_p with the z-transformation.

The derived time-discrete pole is used in out desired transfer function in z-Domain. As shown in equation?, we define the desired characteristics of the system as a fist order system.

Using pole-zero cancellation, we can reduce the system to first order system.

we can thus obtain the parameter k\_d and k\_d1 in relation of ky1, k11, and k\_by

3.3.3 Anti-windup

Since there is a maximum operational voltage limit on the inverter, the output of the current controller has to be limited by a maximum value in order not to damage the inverter during operation. The voltage limitation is shown in equation[?][?]

A voltage limiter is placed at the output of the status controller to restricted the total voltage u\_s of the system. The output of the voltage limiter can be described in equation?

Usually when a large step change in the current command is given, the total output voltage of the status controller exceeds the voltage limit and leads to the saturation of the output at the maximum value. During these cases, a windup phenomenon often occurs, where the integral state of the controller accumulates control errors while still in saturation, leading to a large overshoot, long settling times, and an unstable response. ***[literature anti-windup]***

Anti-windup control method is often implemented to suppress this problem. The Anti-windup controller compares the output variable from the status controller and from the voltage limiter. In case of a difference between the two occurs, the anti-windup controller modified the input command into a realizable command to prevent the windup phenomenon and to restore the consistency of the integral state. For our research, a robust anti-windup system is particularly important, since the current controller operates constantly close to voltage limit in the field-weakening region.

The block diagram in fig? illustrate the current controller, voltage limiter and the anti-windup controller. AS shown in the block diagram, the difference between the value at the input and output is multiplied with a gain factor and subtracted to the input signal of the integrator.



**[like this, but time-discrete, output of the limiter with ‘ ]**

Based on the block diagram above, we can calculate the transfer function of the Anti-windup structure on the d-axis. As shown in equation?, the transfer function is a first -order system.

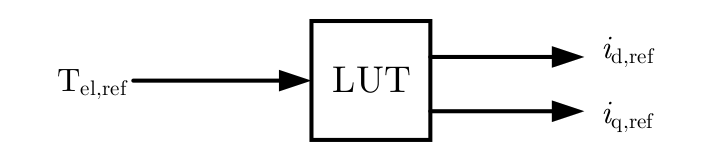
For the derivation of , the desired transfer function has to be first determined. We assume the continuous time transfer function is the one in equation?. We can then derive the discrete pole in equation?.

With the desired transfer function in discrete time, we can derive in relation to , and .

3.3.4 Voltage Limiter

3.5 Torque controller

In the cascade structure of the motor controller, the Torque controller serve as the superposed controller and generate reference points for the current vector on d-q coordinate System. Unlike the feedback control method used in current controller, the current reference point is generated with a per-determined data set, which is implemented as “Look-up Tables (LUT)”, as shown in fig?. In convention, torque control of the motor is performed through this offline technique, where the optimized operating points for every torque value in the whole speed range are stored in the controller beforehand, so that online calculation for is not needed. The calculation of these optimized data sets is gathered and calculated with the 2D inductance table of Ld and Lq with respect to current id and iq, which is measured on a test bench. ***[find source]***



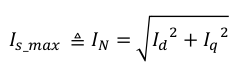
According to equation? Due to the induced voltage (back EMF) that proportional to the rotational speed, the utilized voltage of the motor reaches the voltage limit at a certain speed. We call this corner speed (DE: Eckdrehzahl). Hence, we divide the operation range of the motor to basic speed region and Field-weakening region

For the two different speed regions, several operating methods are proposed for the optimized operating point of the current vector. The following paragraphs present these operating methods in detail.

3.4.1 Torque curve, Current limit circle, Voltage limit hyperbole

We introduce in this paragraph important visualization technique on the 2D plain of id and iq. This graph will be constantly reference in the following chapters, since it plays a integral part in the design of our control strategy.

Equation? Shows the condition for maximum operable current on the d- ,and q-axis.



As we can infer in this equation, Is\_max(Id,Iq) has the shape of a circle on the id,iq plain as shown in fig?. The current vector should always be inside this circle, so that the maximum current is not exceeded.

Equation? Shows the equation of the Torque as a function of Id and Iq.

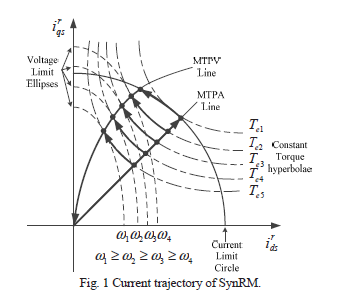
M\_soll =K\_m.(Ld-Lq)IdIq

When Ld and Lq is fixed across the id iq plain, the M\_soll (Id,Iq) should be a linear line across the id iq plain. However, if we consider saturation effect of the inductance across id iq plain, equation? Should be rewrite to equaiton?. M\_soll (Id,Iq) thus has th shape of a curve, as shown in fig?.



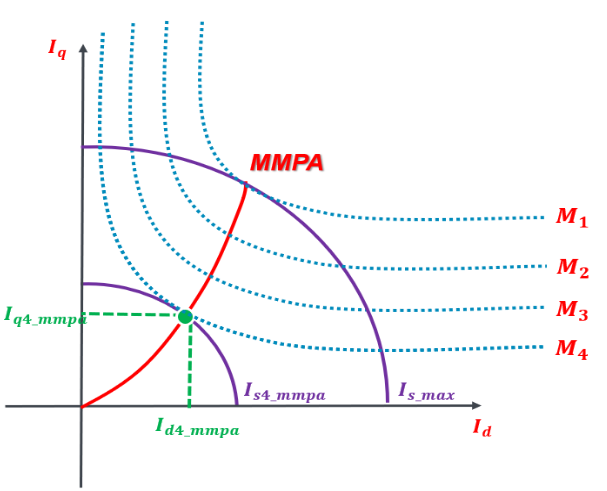
[why is voltage limit a hyperbole]

With higher rotational speed, the voltage limit hyperbole becomes smaller, thus limiting the operation range and the current vector.



3.4.2 Basic speed region

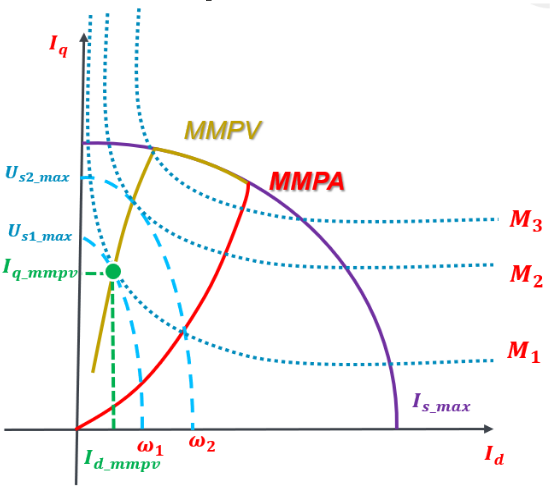
In the basic speed region, the optimized operating point in id-iq plain is characterized by the “maximum Torque per Ampere” curve (MTPA). The MTPA curve represents the operating points that generate the maximum torque value with the same total current Is used. The Torque value along the MTPA curve varies form 0 to the maximum Torque, which is the point where MTPA curve and the current limit connects. As shown in Fig? , the MTPA curve is characterized as the tangent points of the Torque curve and the current circle.



3.4.3 Field weakening region

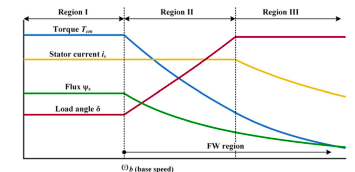
With increasing speed, the voltage limit hyperbole shrinks. As corner speed of the motor is reached, the voltage limit hyperbole intersect the current limit on the highest point on MTPA curve. For motor speed higher than the corner speed, the motor can no longer maintain maximum Torque,and the operating point have to decrease it id value and increase the iq value, while maintain operation with maximum current, I\_max. This trajectory of operation points is called “Maximum Ampere” (MA), which correspond to the current limit curve. As shown in fig?, the generated torque decrease while maintaining maximum current.

With even higher rotational speed, the induced voltage is so strong that operation with maximum current is no longer possible. Both the current on the d- and q- axis have to decrease in order to maintain operation with the maximum voltage. The trajectory followed in this region is called “Maximun Torque per Voltage”(MTPV). The MTPV is characterized as the tangent points of the Torque curve and the voltage hyperbole, as shwon on fig?. The output torque value continuous to drop, until the maximum operable speed is reached.



[show hyperbole \omega \_eck, MA and MTPV]

With the torque command equals to the maximum Torque, and a motor speed form 0 to N\_max, we are able to acquire the M-N relation ,as shown in Fig? The operation of the motor follows the operation trajectory MTPA,MA and MTPV presented in this chapter.



[show three region]

3.4.4 Overall control structure

The generation of the current reference in the torque controller is an off-line technique, where per-determined data set for optimized current vector according to Torque and speed is stored as an Look-up-Table and used during motor operation. Fig ? Show the block diagram of the Torque controller.

Three LUTs are used in torque controller. The Torque command is first limited by the M-n Table according to the current motor speed to prevent operation outside the operable region. The current reference point are than generated based on the Torque command using either the LUT for MTPA or MTPV and MA, determining on whether the motor is in basic speed or field-weakening region.

Literature

Decoupled dq-axis Current Control for PMLSM based on Variable-Gain Adaptive Internal Model

Anti-windup Robust Controller Considering Motor Dynamics For Speed Servo System