Data Set Description: Torque Characteristics of a Permanent Magnet Motor - 74 Million Samples for Data-Driven Learning

Abstract—**A major part of the daily used electrical or mechanical energy is generated by electro-mechanical energy conversion. This energy conversion is mainly made possible by the use of electrical machines. In advanced drive-applications, these machines are usually operated in a controlled mode. To improve control performance, voltages and currents on the electrical side as well as angle/speed and torque on the mechanical side, are of interest. Typically, voltages and currents are measured. On the mechanical side angle/speed measurement is often applied and, with the exception of some special applications, torque measurement is not used at all. For these reasons, the torque must be estimated from the existing measured variables. To develop a torque estimator inspired by physical principles or machine learning (ML) methods a data set, consisting of about 74 million data points, was recorded at a test bench. Here, an automotive-typical permanent magnet synchronous motor (PMSM) was used. The measured signals are summarized in Tab. III and the details on how they have been experimentally obtained are explained in this paper.**

I. Introduction

A controlled electrical drive system includes an electrical machine, an inverter and a controller (Fig. 1). The inverter is a power electronic device with switchable semiconductors which converts the electric energy provided by the power supply from a two phase DC voltage to a three phase AC voltage with varying amplitude and frequency. This is required to operate the motor at different speeds with a certain torque generated. The motor converts electrical to mechanical energy and vice versa. However, at the end the motor is a passive system without any actuators and that is why the controller is only acting on the inverter switching states.

The controller is usually set up in a cascaded structure. The innermost cascade is represented by the current controller, followed by an open-loop torque controller. If the speed or position of the motor should be controlled, further cascades must be added. The torque controller is usually operated in open-loop mode since a torque sensor is not available in most applications (e.g. automotive and locomotive traction or automation). It selects a current operating point for a reference torque provided by a higher-level operating control, which is then transferred to the underlying closed-loop current controller as a reference. As a consequence, a precise model is needed that estimates the motor's torque in all operating points sufficiently well to ensure high performance (i.e. fast, efficient and accurate) torque control. During development phase of a new drive system, that torque model is usually identified based on experimental investigations on specially equipped laboratory test benches where such a torque measurement is available.

There are many different types of motors, which are preferred depending on the area of application. For recording this data set a permanent magnet synchronous motor (PMSM) was used as the electrical machine. This motor type is characterized by high power and torque density and is used, for example, as a drive machine for electrical vehicles.

The recorded data set allows to identify suitable torque models for PMSMs using different methods that can be compared.

The following sections describe the electrical drive system's basic operating principle (II) followed by an explanation of the experimental setup (III). The last section (IV) discusses how the data can be used to extract models for the torque characteristic.

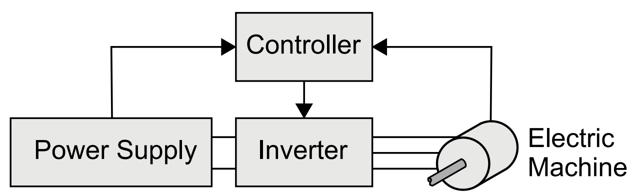

Fig. 1. Simplified structure of an electrical drive system

II. Operating Principle

Fig. 2 shows the components and their basic electrical models in more detail. The power supply can be seen as a voltage source having the voltage u_{DC}. The inverter consists of three switches (s_{a}, s_{b}, s_{c}) each having two possible switching states (1, 0). Thus, a total of eight different combinations of the switching states, yielding different voltages at the inverter terminals (a, b, c), are possible (Tab. I). These states are called elementary vectors $\boldsymbol{s}_n$ with n denoting the index of a vector. Usually the three phase AC currents $\boldsymbol{i}_{\mathrm{abc}} = \begin{bmatrix} i_{\mathrm{a}} & i_{\mathrm{b}} & i_{\mathrm{c}} \end{bmatrix}^{\mathrm{T}}$ are measured. In contrast, the voltages $\boldsymbol{u}_{\mathrm{abc}} = \begin{bmatrix} u_{\mathrm{a}} & u_{\mathrm{b}} & u_{\mathrm{c}} \end{bmatrix}^{\mathrm{T}}$ are calculated using the switching states and the measured supply voltage u_{DC}

$$\boldsymbol{u}_{\mathrm{abc}} = \frac{1}{3} u_{\mathrm{DC}} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} s_{\mathrm{a}} \\ s_{\mathrm{b}} \\ s_{\mathrm{c}} \end{bmatrix}. \qquad (1)$$

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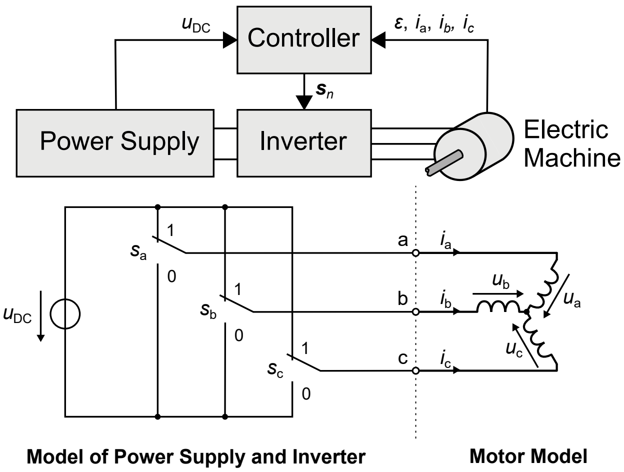

Fig. 2. Simplified electrical modeling of the drive system

TABLE I
INVERTER SWITCHING STATES

n	s_n		
	$s_{a,n}$	$s_{b,n}$	$s_{c,n}$
1	0	0	0
2	0	0	1
3	0	1	0
4	0	1	1
5	1	0	0
6	1	0	1
7	1	1	0
8	1	1	1

If the switching states are modulated / operated in a suitable sequence at a considerable high switching frequency, the inverter output is a three phase AC voltage with a certain average amplitude and average frequency (fundamental component of the voltage).

To simplify the description of the motor model, it is formulated in the so called dq-coordinate system. Here, the three-phase AC voltages/currents are transformed into two-phase DC voltages/currents with the following equation

$$\boldsymbol{x}_{\mathrm{dq}} = \frac{2}{3}\begin{bmatrix} \cos(\varepsilon_{\mathrm{el}}) & -\cos\left(\varepsilon_{\mathrm{el}}+\frac{\pi}{3}\right) & -\cos\left(\varepsilon_{\mathrm{el}}-\frac{\pi}{3}\right) \\ -\sin(\varepsilon_{\mathrm{el}}) & \sin\left(\varepsilon_{\mathrm{el}}+\frac{\pi}{3}\right) & \sin\left(\varepsilon_{\mathrm{el}}-\frac{\pi}{3}\right) \end{bmatrix} \boldsymbol{x}_{\mathrm{abc}}. \quad (2)$$

Looking from the feature engineering point of view, the transformation (2) applied to voltage and current signals is a standard procedure in electric drive modelling. The electrical rotation angle $\varepsilon_{\mathrm{el}}$ is linked with the measured mechanical rotation angle ε of the machine via the pole pair number $\varepsilon_{\mathrm{el}} = \varepsilon p$. If the arrangement of magnets and windings is repeated over the circumference of the machine, we speak of a multi-pole machine. The number of pole pairs describes, as a characteristic quantity, the number of rearranged windings and magnets.

The electrical behavior of a PMSM in the dq-coordinate system can be described by the following voltage equation in component notation

$$u_{\mathrm{d}} = R i_{\mathrm{d}} + \frac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} L_{\mathrm{d}} - \psi_{\mathrm{q}}\omega_{\mathrm{el}} \quad (3)$$

$$u_{\mathrm{q}} = R i_{\mathrm{q}} + \frac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} L_{\mathrm{q}} + \psi_{\mathrm{d}}\omega_{\mathrm{el}} \quad (4)$$

or the circuit diagram (Fig. 3). Here, $\boldsymbol{i}_{\mathrm{dq}} = \begin{bmatrix} i_{\mathrm{d}} & i_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}}$ is the current, $\boldsymbol{u}_{\mathrm{dq}} = \begin{bmatrix} u_{\mathrm{d}} & u_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}}$ the voltage, $\boldsymbol{\psi}_{\mathrm{dq}} = \begin{bmatrix} \psi_{\mathrm{d}} & \psi_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}}$ the flux linkage, R the resistance, $L_{\mathrm{d/q}}$ the inductance in d/q-direction and ω_{el} the electrical angular velocity. Assuming a

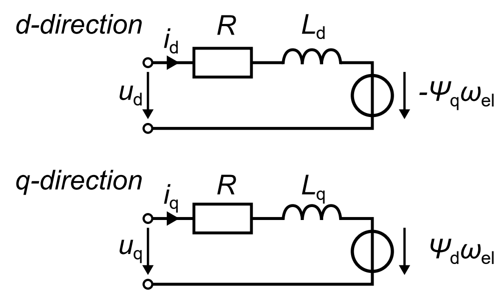

Fig. 3. Circuit diagram of a PMSM in the dq-coordinate system

linear magnetization, the flux linkage can be described by

$$\psi_{\mathrm{d}} = L_{\mathrm{d}} i_{\mathrm{d}} + \psi_{\mathrm{p}} \quad (5)$$

$$\psi_{\mathrm{q}} = L_{\mathrm{q}} i_{\mathrm{q}} \quad (6)$$

with the permanent magnet flux linkage parameter ψ_{p}. From a power balance on the electrical and mechanical side the torque can be derived

$$T = \frac{3}{2} p \left(\psi_{\mathrm{d}} i_{\mathrm{q}} - \psi_{\mathrm{q}} i_{\mathrm{d}}\right). \quad (7)$$

The above voltage, flux and torque equation form a very simple model of a PMSM which is very likely to predict the motor's torque only with significant residuals. A more detailed discussion of the operating principle and derivation of the formulas can be found in [2]. An enhanced motor model which includes magnetic saturation effects can be found in [3] [4].

III. EXPERIMENTAL SETUP

The following section briefly describes the test bench as well as the measured variables and their recording framework.

A. Devices under test

In Tab. II the most important test bench parameters are summarized. Fig. 4 shows the test bench with a transient recorder in the foreground and the used motor in the background.

B. Measurement framework

Input variables:
Since the dq-coordinate system, introduced in the previous section, is only a mathematical transformation, variables in this coordinate system cannot be measured directly. For this reason, the currents and voltages must be measured in the real-world abc-coordinate system. However, for later

TABLE II
TEST BENCH PARAMETERS

IPMSM	Brusa HSM16.17.12-C01	
Nominal power	P_{mech}	55 kW
Nominal speed	n_{mech}	$4000\,\text{min}^{-1}$
Nominal torque	T_{nom}	130 Nm
Pole pair number	p	3
Nominal phase current	I	170 A
Stator resistance	R	18 mΩ
Permanent magnet flux	ψ_{p}	68 mVs
Inverter	3×SKiiP 1242GB120-4D	
Typology	voltage source inverter 2-level, IGBT	
Inverter interlocking time	T_{i}	3.3 µs
Controller hardware	dSPACE	
Processor board	DS1006MC, 4 cores, 2.8 GHz	
Measurement devices		
Oscilloscope	Tektronix MSO58	
Current probes (zero-flux transducers)	3×Yokogawa, 500 A, 2 MHz	
Torque sensor	HBM, T10FS, 2 kN m	

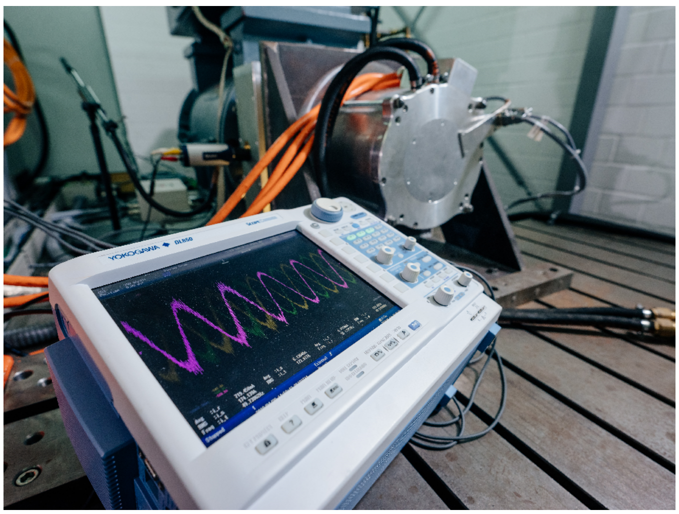

Fig. 4. Test bench with the used PMSM in the background

investigations, variables in the dq-coordinate system are preferred due to the simpler model description of the motor. To transform the variables from the abc to the dq-coordinate system, the rotor angle must also be measured. The voltages and currents were recorded with an oscilloscope and a sampling rate of 1 MHz. The electrical rotor angle ε_{el} as well as the voltage of the power supply u_{DC} were recorded using the control system's analog digital converters (ADCs) with a sampling frequency of 20 kHz. In addition the index of the inverter's elementary vector $\boldsymbol{s}_n$, which was active between two sampling points, is attached. Furthermore the measurement data of the control system ADCs were upsampled to a frequency of 1 MHz, so that calculations can now be executed on the 1 MHz grid.

Data set coverage:
In principle, only reference values in the left i_{d}-i_{q} half-plane are given to the current controller of a PMSM. Moreover, the length of the current vector must not exceed a certain value. Otherwise, there is a risk of thermal overload or destruction of the motor. In order to cover the entire operating range in the current plane, the physical quantities were recorded at 74 stationary operating points with a measuring time for each operating point of 0.5 s (Fig. 5). Although the current controller is in steady state and the speed no longer changes, a high-frequency so-called current ripple can still be detected. This can be explained by the switching operation principle of the inverter.

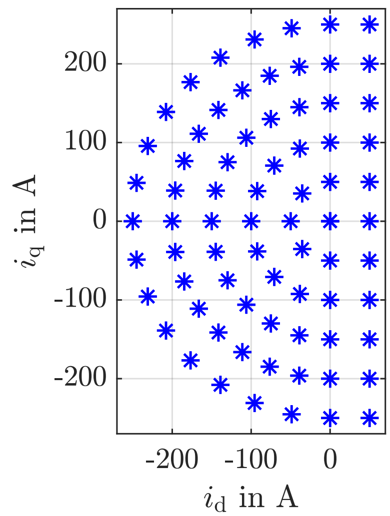

Fig. 5. Equidistant operating points in the left i_{d}-i_{q} half-plane

Many torque estimation methods are based on the induced voltage of the flux linkage. This induced voltage is directly proportional to the speed and, therefore, fails when the speed tends to zero. For this reason the operating points were recorded for a low speed of $120\,\text{min}^{-1}$ and a medium speed of $2000\,\text{min}^{-1}$ to investigate the speed-dependency of any possible estimation method.

Torque measurement setup:
Usually torque estimation methods are supposed to estimate the electro-magnetically produced torque of the motor in the air gap between rotor and stator. To validate the estimation methods, the torque estimates are compared with torque measurements. Typically, the torque of the motor shaft is measured by torque transducers. However, by assuming the equivalence of electro-magnetically produced torque and measured mechanical torque, systematic errors are made. On the one hand, AC components of the electro-magnetically produced torque are damped by the mass inertia of the motor shaft or distorted by mechanical resonance frequencies. On the other hand, the DC component is biased by bearing friction and drag.

The torque measurement for this dataset was determined using a torque transducer based on strain gauges. Since the torque estimator should not learn any mechanical resonance frequencies or damping, the AC-component of the measured torque was eliminated by averaging. However, this also has the

TABLE III
VARIABLES CONTAINED IN THE DATA SET

Variable	Unit	Description	Data type	Classification	Recording device	Notes
time	s	measured time	single	inputs	scope	
i_a	A	measured a-current	single		scope	
i_b	A	measured b-current	single		scope	
i_c	A	measured c-current	single		scope	
u_a	V	measured a-voltage	single		scope	
u_b	V	measured b-voltage	single		scope	
u_c	V	measured c-voltage	single		scope	
ε_{el}	rad	measured electrical angle	single		control system ADCs	upsampled to 1 MHz
u_{DC}	V	measured supply voltage	single		control system ADCs	upsampled to 1 MHz
$\boldsymbol{s}_n$	–	elementary vector	single		control system ADCs	upsampled to 1 MHz
T	Nm	measured mean torque	single	target	control system ADCs	averaged per operating point

consequence that no angle-dependent electromagnetic effects can be learned.

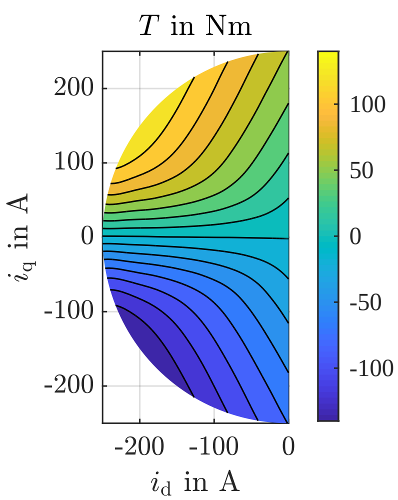

Fig. 6. Measured torque at a speed of $120\,\mathrm{min}^{-1}$

Summary of the measurement setup:
The properties of the measured variables are summarized in Tab. III. The data set contains three comma-separated values (CSV) files. Two files correspond to the concatenated time series of the 74 operating points for $120\,\mathrm{min}^{-1}$ and $2000\,\mathrm{min}^{-1}$ respectively. These time series include the other measured variables, except the torque. The remaining file contains the mean torque values belonging to the operating points and the two speeds.

IV. POSSIBLE APPROACHES FOR MODEL EXTRACTION

The torque characteristic can be identified using different approaches on the basis of the data set. The identification techniques can be classified into ML methods and methods, which are physically motivated and based on model equations. In addition, hybrid methods can be mentioned as a combination of both categories.

A. Machine learning methods

With the help of ML methods (e.g. artificial neural networks (ANNs)), models can be trained which estimate the torque as a function of the input variables. No expert knowledge is required here. However, the trained models cannot be generalized to other electric motors. This is a big disadvantage because for other electric motors complex test bench measurements with torque sensors have to be recorded too.

B. Physically-inspired methods

Physically motivated methods are based on modeling approaches of the electric drive train derived from first-order physical principles. These models contain parameters (e.g. inductances, resistances, ...), which are usually taken from the data sheet or extracted from the nameplate. On the one hand, these procedures typically do not cover parasitic effects and often come with parameter deviations. These can result in significant estimation errors. But on the other hand, these models are based on general equations and, therefore, there is no need for extensive torque measurements on a test bench as it is the case with ML methods. For physically-inspired methods, the measured torque contained in the data set is not needed to train the models. Here, the measured torque is used only to quantify the estimation error and for the validation of the models.

C. Hybrid methods

Hybrid methods could be a possibility to utilize the advantages of ML and physically motivated methods. Here, the model structure (e.g. regressors or features) of a data-driven approach has to be chosen in such a way that the identified parameters can be physically interpreted. Here, a special case is the empirical parameter identification within the above mentioned physically-inspired models which is typically known as grey-box identification.

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