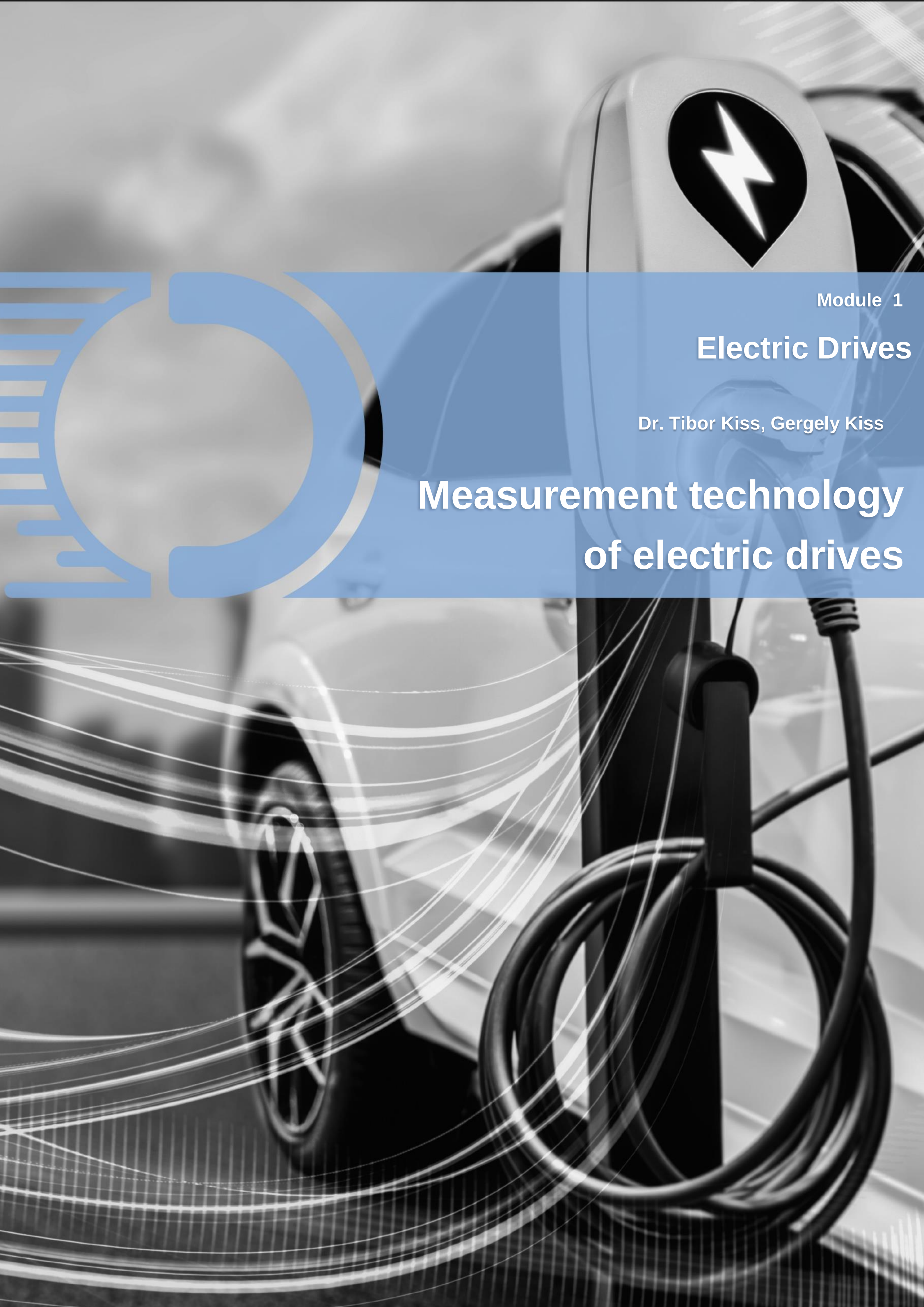

Module_1

Electric Drives

Dr. Tibor Kiss, Gergely Kiss

Measurement technology of electric drives

Module_1

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Measurement technology of electric drives

DRIVEN

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1. INTRODUCTION

In the past years the number of electric drives used in everyday applications has been increasing steadily. Traditional DC (Direct Current) motor drives are slowly becoming obsolete in almost any device due to the cost-friendly availability of AC (Alternating Current) motor drives and the advantages they offer. The ongoing electrification trend in the automotive industry pushes the development of new electric powertrains. Consequently, testing and validation of electric drive systems and e-motors is an emerging topic of high relevance.

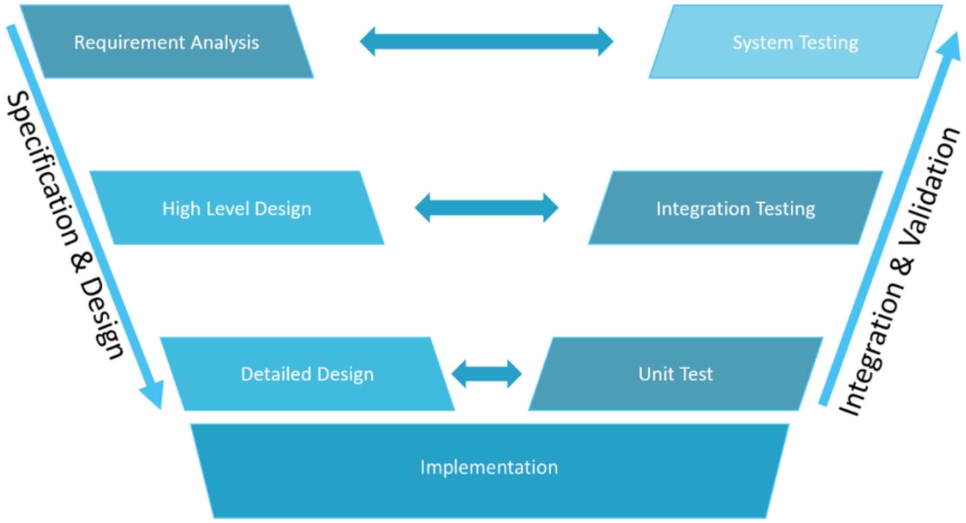
This brief booklet intends to provide a practical summary, and overview of the measurement technology of electric drives, with focus on the electric drives for automotive traction application in battery electric vehicles (BEVs). Rather than diving deep into the depths of measurement technology, the physics of electric machines or regulations and statistics the content remains on a “system level” to present the big picture of validation to the reader. A basic knowledge of the before mentioned subjects is however required to fully understand the concepts used here.

2. BACKGROUND OF PRODUCT DESIGN AND VALIDATION PROCESS

Modern industrial entities produce standardized components, equipment and software on a large scale and global scope. The different stages of the value creating process have been separated and are being optimized individually. Important steps, like design of a product, production and validation grew apart and are performed separately anywhere in the world. To bring order and structure to these distant parts, the industry implemented work instructions, process guidelines and fine-tuned them to increase success rate and reduce development costs. One of these process guidelines used by many today is the V-model.

The V-MODEL is an approach to guide the product development process in a structured way and can be visually represented as shown on Figure 1-1. On the left side of the V we see the requirements lining up, flowing and propagating from the highest level (system) towards the lowest details (components). The right side of the V shows the steps how the product is built up from the smallest components to the system level and it defines the correct tests on each level to ensure the components comply with the corresponding requirements on the left side. Thus, the V model is ensuring that product in development *1) is the right product for the given requirement and 2) the product is developed in the right way*. These two criteria are referred to as *1) validation*, i.e. the product fits to its real-life application and *2) verification*, i.e. the product is built up the correct way, according to legislation, norms, company standards.

A product's purpose, and how exactly it shall fulfill the purpose is documented in the so-called USER REQUIREMENTS SPECIFICATON (URS). The requirements ideally are directly coming from the product's end user (e.g., driver of a vehicle) and of course from legislation (safety standards of the target region). The fulfillment of the before mentioned requirements must be proven in the validation part of the development. This essentially means, that each requirement must have a corresponding testing step, which after execution and evaluation, tells the developer whether the product meets the requirement or not.



1-1. Figure The V-model [13]

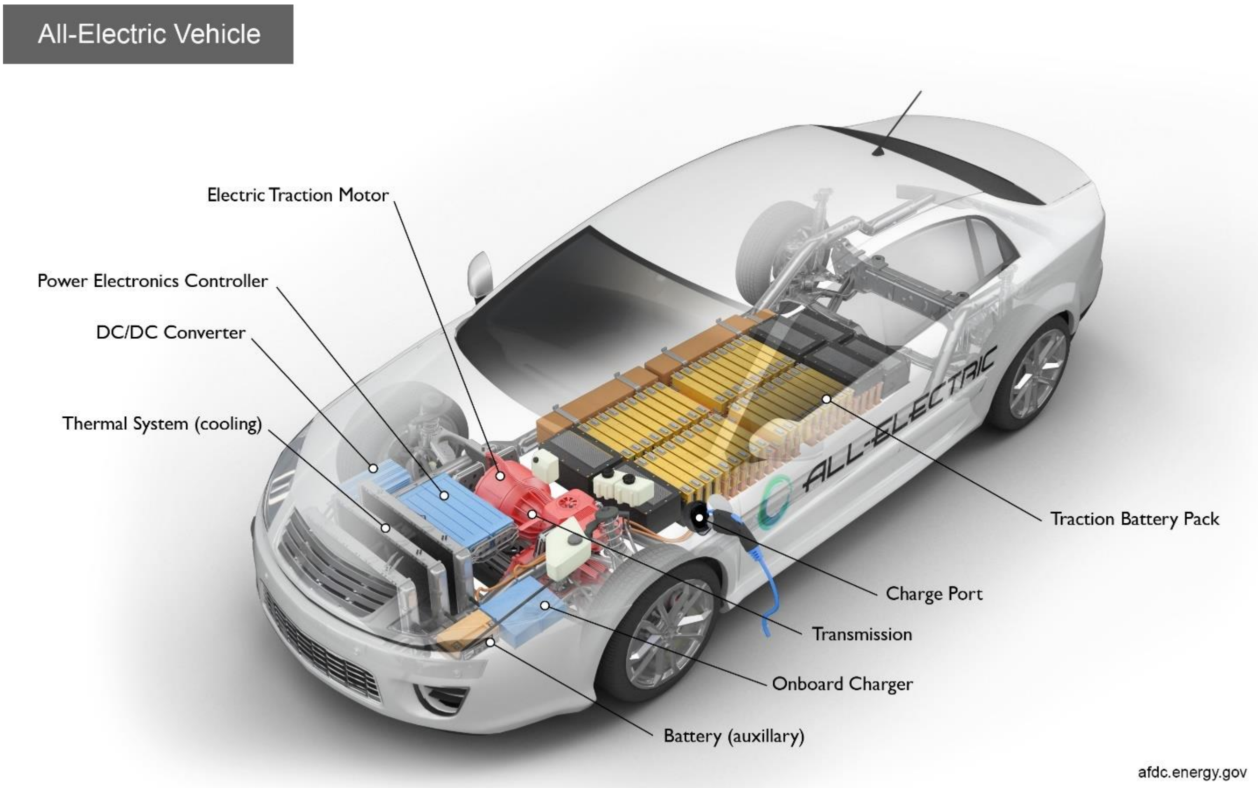
How strict the testing conditions are and how thorough the validation process is highly depending on the industry segment. In the automotive industry the validation process is highly regulated by industrial standards and norms. While some standards are mandatory and a matter of legislation, some are merely providing suggestions.

Besides the dry matter of legislation and fulfillment of end-user requirements the measurements of electric drives offer insight to plenty of interesting physical phenomena. In the complex system of an electric drive nearly each field of physics plays a significant role, with software and control design being the icing on the cake.

2.1 EXAMPLE OF REQUIREMENT: MAXIMUM WHEEL TORQUE

For this example, let us consider a passenger car powertrain development case. The manufacturer of the vehicle, an OEM (Original Equipment Manufacturer), wishes to develop a new BEV (Battery Electric Vehicle) for the European market. Let us assume the OEM already has a rough idea about the technical parameters of the new car, since from their previous combustion engine vehicles they have plenty of experience. They are also aware of the end-users', the drivers and passengers' requirements and legislation. Therefore they know the following information relevant to the example of max. wheel torque:

- *The car will be designed to use 205/55 R16 size tires (Figure 2-2).*
- *The car will have front wheel drive only.*
- *The vehicle needs to deliver its maximum torque and maximum power of 100 [kW] for a short time at 90 [km/h] velocity.*



2-1. Figure Layout of a Battery Electric Vehicle (BEV)

The Figure 2-1 shows an example of a BEV with a front wheel drive and the main components required for electric driving, storing energy, converting energy and re-charging.

Based on these boundary conditions and requirements the OEM's engineers calculated, that to meet these conditions the powertrain needs to deliver a minimum of **1260 [Nm]** in total, or **630 [Nm]** for each wheel on the front. This way a user level requirement has been propagated over the vehicle requirements to the requirement level of the electric powertrain.

$$\omega_{wheel} = 2\pi \cdot \frac{v_{car}\left[\frac{m}{s}\right]}{\pi D_{out,tire}[m]} = 2 \cdot \frac{\frac{90}{3.6}\left[\frac{m}{s}\right]}{0.632[m]} = 79.1\left[\frac{rad}{s}\right]$$

$$T_{wheel} = \frac{P_{mech}}{\omega_{wheel}} = 100\frac{[kW]}{79.1\left[\frac{rad}{s}\right]} = 1260\ [Nm]$$

2-2. Figure 205/55 R16 tire

In order to find out what this requirement means to the electric drive and finally the e-motor, we need to define (or design) the overlaying and parallel systems a little bit more in detail.

Let us start by fixing gear ratios between the wheel and the e-motor. For this example, let us assume the OEM would like to re-use the very same differential from its combustion engine vehicles, therefore this component is fixed. The reduction gear between the e-motor and the differential will be a stock part from one of the OEM's industrial suppliers, which is a tried out, cost effective part. The complete reduction ratio from e-motor to wheel over differential and reduction gear set is: **11.63**.

Based on this, we can calculate how much torque the e-motor must deliver in order to achieve the sum wheel torque of 1260 [Nm]

$$T_{e-motor} = \frac{T_{wheel}}{i} = \frac{1260[Nm]}{11.63} = 108\ [Nm]$$

The requirement specifies the speed as well.

$$\omega_{e-motor} = \omega_{wheel} \cdot i = 79.1 \left[\frac{rad}{s}\right] \cdot 11.63 = 919.93 \left[\frac{rad}{s}\right]$$

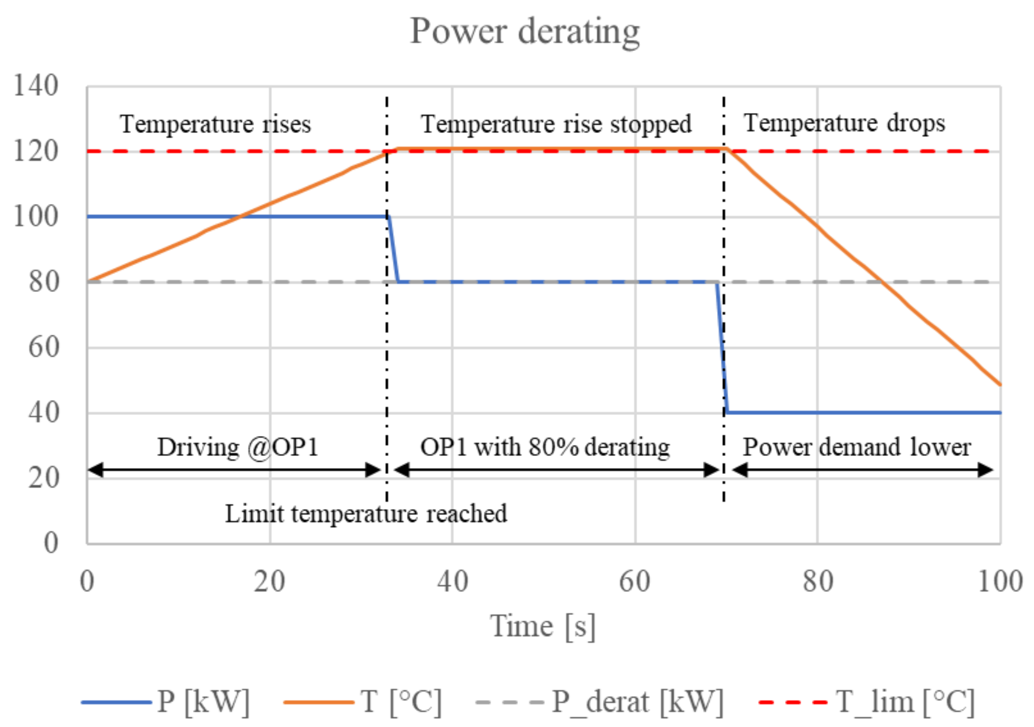
Which corresponds to **8784 [rpm]**. Now we obtained a OP (Operatio Point) requirement for the e-drive and the e-motor level:

- *OP1: speed = 8784 [rpm] and torque = 108 [Nm]*

2-1. Table Operation points

Requirement specification for design, points for validation and testing		
Point	Speed [rpm]	Torque [Nm]
OP1	8748	108
… OPn		

OP1 will be one of the corner stones for the electric drive design and point which must be tested during the product validation. It must be reached under any operational conditions unless the derating is in effect. Derating (Figure 2-3) means performance reduction due to reaching overload in temperature, battery voltage boundaries or entering to safety mode due to other vehicle components' errors.



2-3. Figure Example of a simple derating strategy allowing the maximum possible power e.g. during an acceleration period

OP1 of course, is just one of many operation points the electric drive must fulfill. Besides the operating points, there are numerous other requirements, physical boundary conditions and stresses the electric drive must comply with. At minimum the following boundary conditions must be fixed to support the design:

- *dimensions of the space dedicated for the electric drive,*
- *battery voltage of the HV battery e.g. 400 [V] nominal,*
- *maximum DC bus current,*
- *duration of OP1,*
- *available cooling type to take away heat from the electric drive (liquid / air).*

Let us fast forward in time and assume all these were defined and the e-motor, as well as the inverter, is already designed and ready for the first tests.

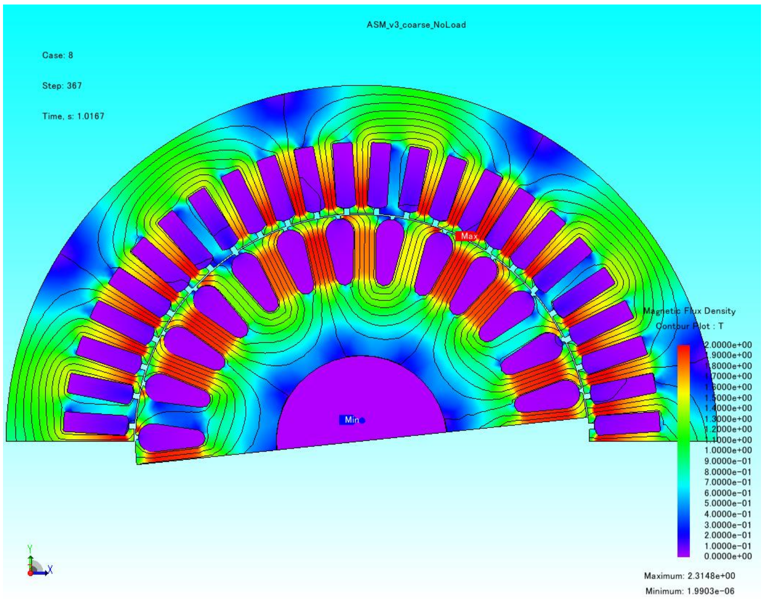
To verify whether the e-motor can deliver the required performance, it is usually mounted on an e-motor test bed. There it is electrically supplied by an ideal power source and mechanically connected to a large dynamometer (dyno), which is usually controlling the rotating speed. The dyno sets the mechanical speed and the ideal electrical power supply drives the e-motor sample with the exact current required to reach the target torque. Meanwhile the shaft torque is measured. Let us assume the e-motor delivered the required torque.

The inverter's fundamental purpose is supply the electric motor with current. Therefore, it must be able to maintain the desired current in stable way, otherwise the e-drive will not deliver the desired torque. Inverters can also be tested on a component level, where the e-motor is replaced either by a passive or an active electrical load. Active loads can be e-motor emulators, which can represent an e-motor's behavior in a realistic way. Let's assume that the inverter can reach the required phase currents under all conditions.

Therefore, we can conclude, that on the lowest level of the right side of the **V** the components can fulfill their specific requirement. The question arises: Is the validation process done? The short answer is *no*. Now with both parts of the electric drive available the integration work can finally start. To formulate it simple, *integration* is the process of "teaching" the inverter how to drive the e-motor under various conditions. It includes handling different driver inputs, driving scenarios, environmental condition changes, influence of other powertrain components. This is the way it can be ensured, that the electric drive will be able to perform e.g. OP1 "just as good" in all possible cases. In reality, the term "just as good" has a rather technical approach to it. The before mentioned requirements documentation also defines a certain tolerance range for its target values within which the performance is still acceptable. Which means every vehicle produced shall fall in the specified tolerance range, that ensures a steady user experience and compliance to norms.

In order to "teach" the inverter, the heart and brain of the electric drive, how to drive electric motor in the specific way, a series of integrations tests are carried out. It the frame of these the electric motor's performance is characterized based on measurements and often with the help of simulation tools. In fact, simulation based tools are sometime used to substitute certain testing phases. Of course, this is only possible, if the simulation models are already at a high maturity level and they have been validated and proven to be accurate enough multiple times during previous validation scenarios.

Figure 2-4 shows an electric machine simulation model, specifically an induction motor's no-load simulation. The goal in that case was to determine the machine's magnetizing inductance.



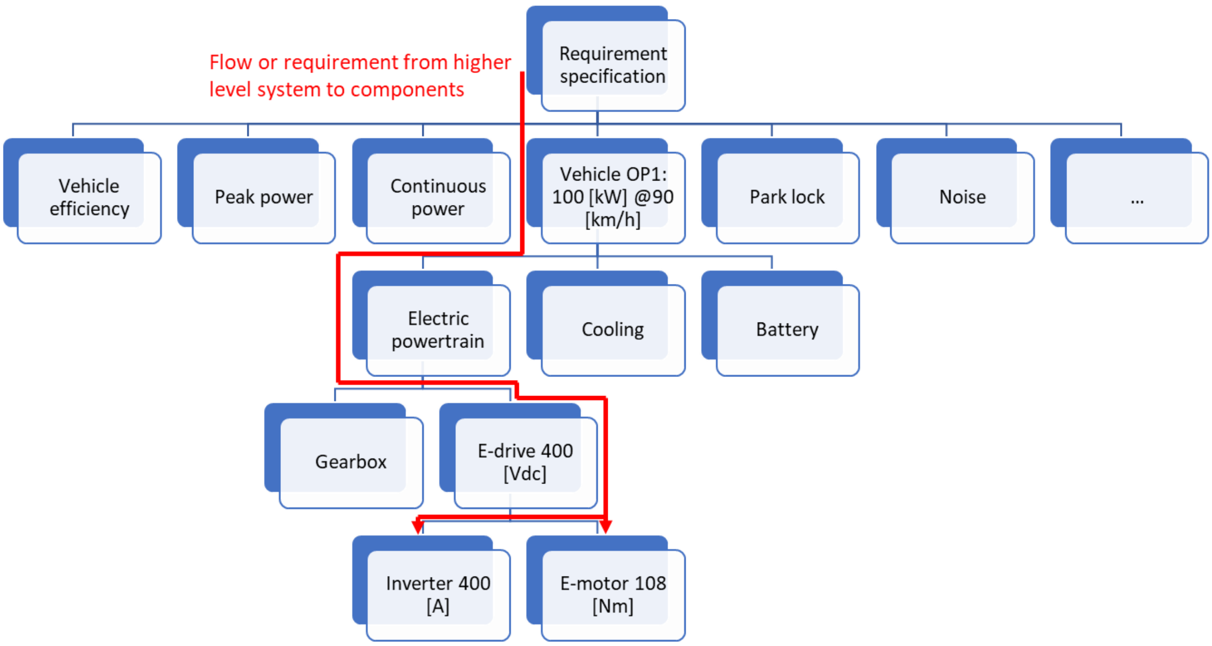
2-4. Figure Example of an electric machine simulation model, this case an induction motor's no-load simulation. The goal is to determine the machine's magnetizing inductance.

The integrations tests' purpose is to cover every possible operations condition and help calibrate and tune the electric drive system to meet demands in all defined conditions:

- *battery voltage levels, minimum, nominal and maximum,*
- *cooling conditions,*
- *thermal conditions.*

Based on the characterization the inverter and e-motor become one integrated system and the inverter shall be able to drive the e-motor with the desired accuracy, resulting in the fulfillment of the specified requirements on the electric drive level (Figure 2-5.).

Taking the next step towards top of the V model, the next integration level is electric axle, where the e-drive becomes integrated with the gearbox and differential. It is worth mentioning, that modern electric powertrains are becoming more and more integrated, which means that validating the components individually can be a challenging task. As an example: often, the cooling circuit is not complete without the gearbox housing, since the bearing in the gearbox may be cooled with same medium as the motor. In such cases usually special samples are made for the component validation step.



2-5. Figure Visualization of the flow of requirements. Note, that a single requirement influences and depends on many systems, not just one related to driving. E.g. cooling must be able to continuously take away the heat generated while in the stated continuous operation mode, the battery must as well be able to supply the required power continuously, while other requirement like for noise or EMC further refine how a specific OP must be performed.

Once the e-axle has been validated, it may be installed in an actual vehicle prototype, where the vehicle level validation and tuning can take place. Often the vehicle level is the first level, where every subsystem “meet each other” for the first time, therefore vehicle level integration is usually a challenging task. Due to its complexity and of course high costs, vehicle level testing is always the last step, when there is already enough confidence in the functional status of the subsystems and parts. However, this is still the last but necessary step, where the highest level requirements are validated and final vehicle calibration is performed.

3. TESTING CONSIDERATIONS

When properly built, an electric machine testing laboratory is a well-controlled area. However, it is not hazard-free. Taking an automotive electric powertrain laboratory as example, the main types of hazards are SAFETY, PHYSICAL and CHEMICAL.

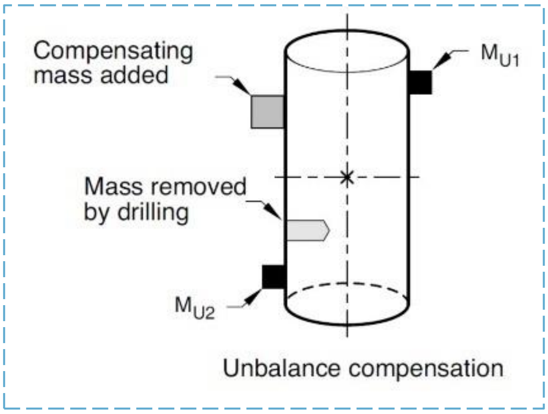
3.1 SAFETY

The test rigs operate at high voltage levels, thus for electrical preparations, reparations and maintenance high voltage certified personnel is required. Nowadays the usual voltage level of automotive electric powertrain validation laboratories reaches up to 1500 V. Special attention must be paid if the test setup contains high energy capacitors. Capacitors without a safety discharge circuit can maintain their charge for extended times even after the HV (High Voltage) supply has been shut down. The stored energy is more than enough to cause serios damage to health when touched by accident. While certified electric instrumentation cabinets and even most prototype UUTs (Unit Under Test) have an integrated capacitor discharge circuit modified test-setups, external devices, special HV circuitry may still have charged capacitor inside.

Both the UUT and test bed dynamometers draw high currents from the inverter and power cabinet through their cables, creating strong electro-magnetic fields around them. In a proper test-setup all power cables are supposed to be shielded due to the noise they can introduce to the environment and test results. However, this is just best practice, not a mandatory step. Magnetic fields cannot be completely shielded due to practical considerations. Therefore, the electro-magnetic shielding of cables only protects the environment from the high frequency field components. The so-called EMI (Electro-Magnetic Interference) not only effects the devices in the test cell but could potentially have negative impact on the function of pacemakers as well. Therefore, it is not advised for people with pacemaker to be in the direct vicinity of such test systems.

The new generation of electric drives are designed to reach outstanding power levels by extending the range of the rotation speed. Traction motors which spin up to **20.000 [rpm]** have become common. Therefore, the test beds for electric motors operate at and above that speed level. Consequently, special attention must be paid to the mechanical build of the test-setup. Dynamic balancing (Figure 3-1.) of the rotating parts is a must, and the process is regulated by guidelines. In any case no personnel shall be located perpendicularly along the rotating shaft, and all rotating parts must be covered by protective cover.

3-1. Figure Balancing [15]



Electric drives require lubrication for the moving mechanical parts and cooling media for their cooling systems. Most automotive traction drives use some form of a liquid cooling to take away the generated heat from the power electronics and from e-motor. The liquid cooling systems can fall into two categories based on the fluid used:

- *water or water-glycol cooling and*
- *oil cooling.*

Water-glycol mixtures for liquid cooling usually have distinctive color (red, blue, green) and are designed to maintain liquid form below sub-zero temperatures to higher operation temperatures, with freezing point below -40°C and boiling point over160°C. Oils in cooling systems are usually ATF (Automatic Transmission Fluid) oils, taken over from combustion engines. Care must be taken to avoid exceeding the boiling point of the coolants in order to avoid formation of fumes and vapor, especially in case of oil. The pressure and temperature of the cooling systems must be monitored all times. During test interruption one must always be careful touching surfaces, as they might be quite hot shortly after operation.

3.2 UNMANNED OPERATION

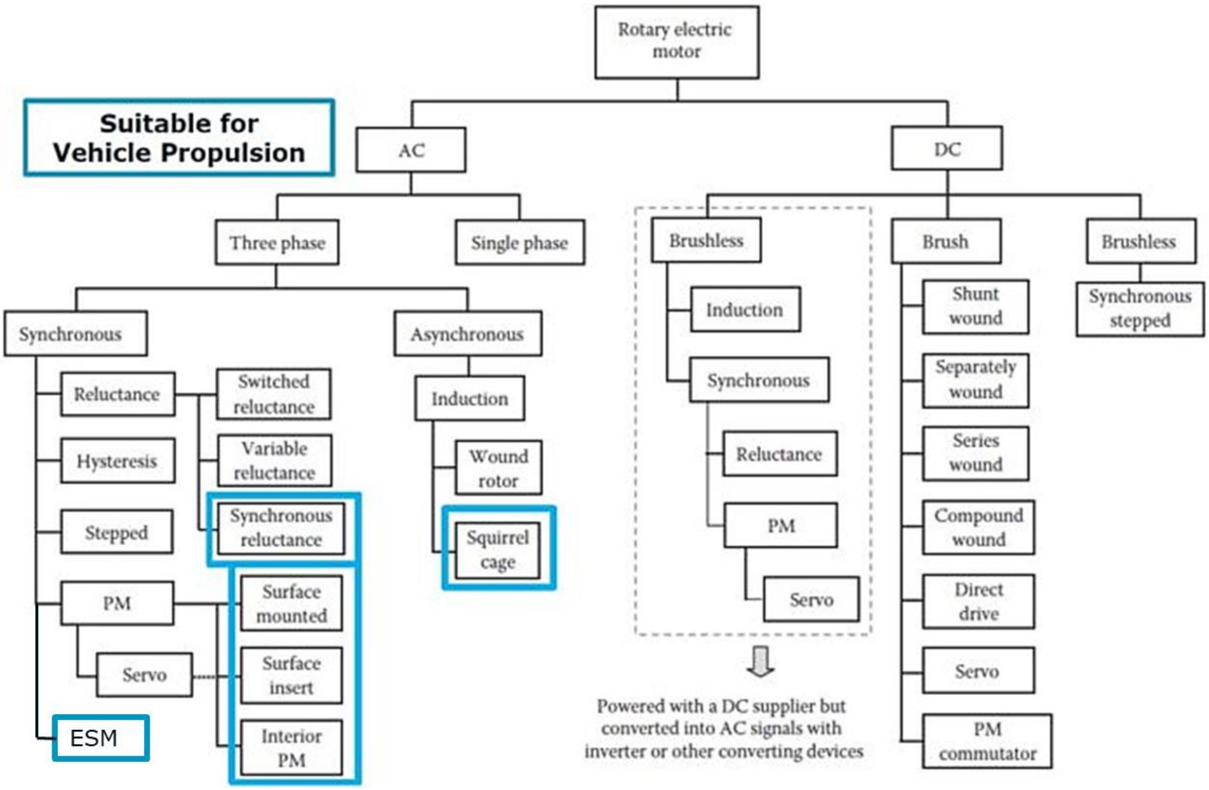
With the increasing number of tests which must performed in the validation process of an electric drive, automation of the testing has become a quite attractive option. A well designed and built test system can run unmanned, theoretically in 24/7 operation after the commissioning, i.e. after all the necessary preparations have been done by specialists. To achieve this, however, the test system must meet a number of requirements which guarantee the safe operation. Firstly, the test cell must be equipped with all the necessary safety equipment, detectors, fire extinguishers, alarms, relays, circuit brakers etc. which allow it to handle any situations. Second, it also needs to have a 24/7 remote surveillance, which can notify operators or safety personnel in case of malfunction. The operative part, i.e. running the desired test cases, is performed by a sophisticated test automation system, which has capabilities beyond a simple scheduler. The test automation will guard the test cycle, keep the UUT (Unit Under Test) and test equipment inside margins of safe operation. It will initiate cooldowns in case of overtemperatures and resume test once conditions are once again ideal.

4. ELECTRIC DRIVES

Electric drive testing is a complex topic. Electric drive units have multiple other functions, relevant to vehicle system, like mechanical park-lock actuation, DC/DC conversion, heating function etc. These are usually in the scope of an electric drive functional test. This booklet focuses on e-motor performance related parameters. Thus, electrical drive testing will be discussed in relevance to the e-motor and its integration to the inverter, together with controller and power electronics.

Many kinds of electric motors exist, as Figure 4-1. Shows. Vehicle traction applications require:

- *very high power density,*
- *good torque controllability,*
- *high efficiency over a wide speed and torque range and*
- *preferably low cost.*



4-1. Figure Family tree The family tree of electric rotating electric machines, highlighting the ones most suitable for vehicle propulsion [16]

The motor types, which fulfill the above requirements the best and therefore used for electric vehicles are the following machine types:

- *SRM (Synchronous Reluctance Machine),*
- *PMSM (Permanent Magnet Synchronous Machine),*

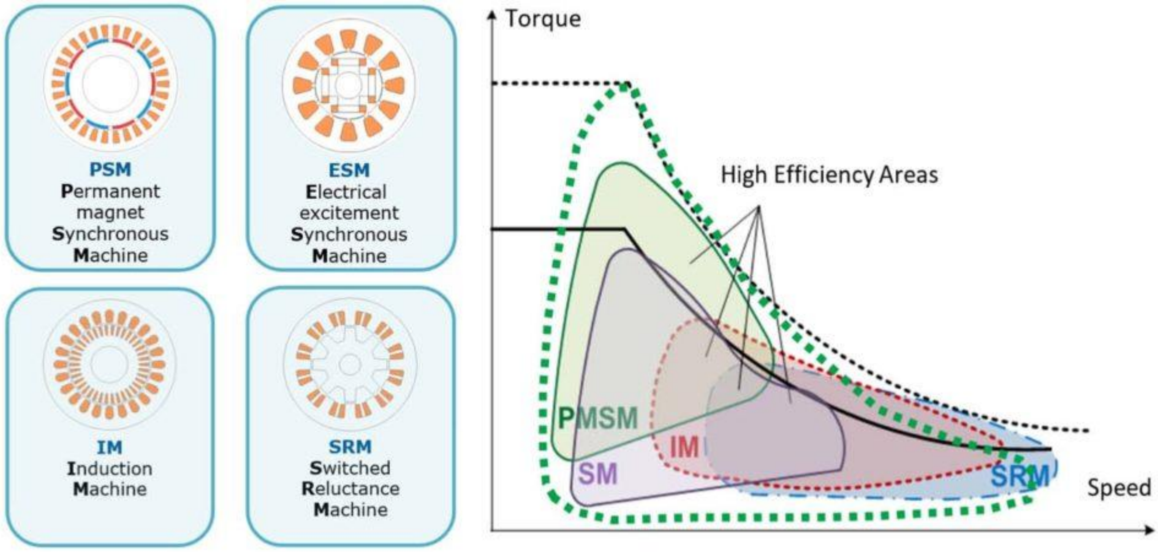
  - *Surface mounted,*
  - *Interior PM (IPMSM),*
- *ESM (Electrically excited Synchronous Machine),*
- *IM (Induction Machine) [squirrel cage].*

Of course, not all motors are equally well performing in all traction drive applications. Each motor type has its own characteristics, advantages and shortcomings. Depending on the specific operation range, or load profile, where the e-drive is used most of the time, Figure 4-2. can help choosing the best fitting e-motor for a target application.

PMSM, especially IPMSM motors have the best torque production capabilities due to the substantial air gap flux generated by the strong rare-earth magnets and sizable amount of reluctance torque. They unfortunately have relative high losses when operated at high speed, even at no-load, due to field weakening and core losses. Loss of control at high speed is also risky due to high short circuit currents.

IM or asynchronous machines (ASM) are often the cheapest alternatives. They offer robustness, tolerance towards high temperatures and practically zero core losses in no-load. Their drawback is the lower power factor and lower efficiency for the same power as the PMSM. Control tuning and achieving a precise torque control often takes more effort for these motors.

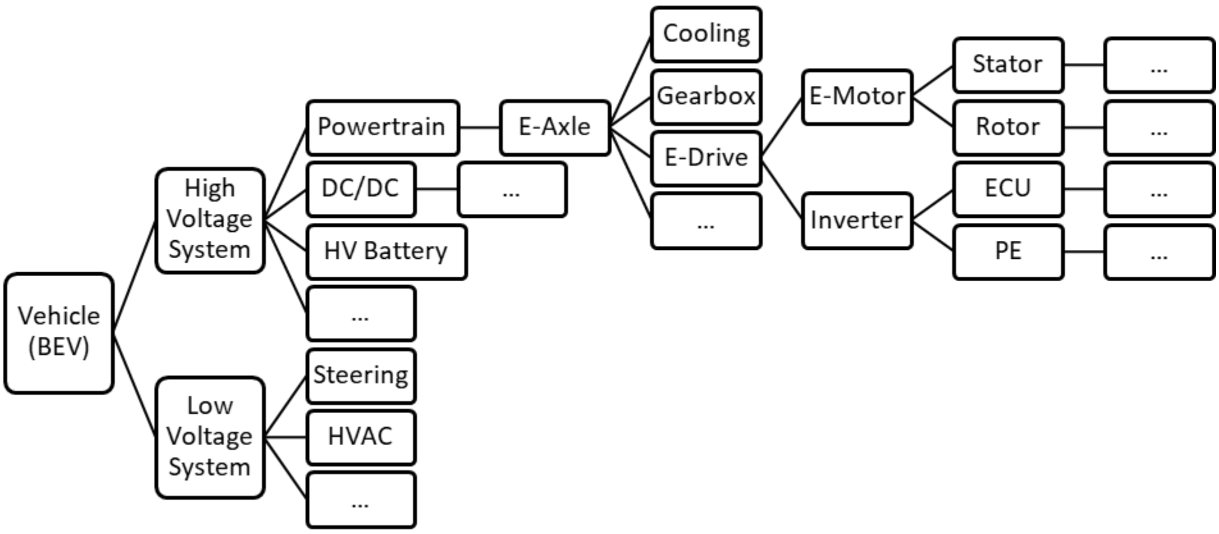
ESM motor type also deserve to be mentioned here. These motors require external current to flow through their rotor winding in order the create the rotor field. Supplying the rotor is a difficult task due to high rotation speeds, which also makes the rotor’s mechanical design a challenge. However, the power supply can be done either via slip rings or other contactless methods. Having an adjustable rotor current means one more degree of freedom: a directly adjustable rotor field. Thus, ESM when operated properly might have the best of both worlds: high torque at high efficiency when needed and low losses in no-load and high speed. The lack of costly rare-earth permanent magnets means a potentially cheaper design as well.



4-2. Figure Best efficiency operating areas of the most common electric motors in vehicle propulsion [16]

4.1 SCOPE OF THE TESTING: THE ELECTRIC DRIVE UNIT

The electric drive unit is a subsystem, which is responsible for providing torque, speed or position to the powertrain according to the demands it receives from the higher-level vehicle control unit. Its role in a non-automotive setting is quite similar, only its input demands originate from some other sources e.g. user control panels, computers etc.



4-3. Figure Scope of testing and where e-drive is positioned in the system. (HV: High Voltage, HVAC: Heating, Ventilation and Air Conditioning, ECU: Electric Control Unit, PE: Power Electronics)

The electric drive unit itself is a part of larger systems inside the BEV (Figure 4-3.). Its direct parent system is the e-axle. Most often the e-axle assembly (Figure 4-4.) is:

- *mounted to the vehicle chassis,*

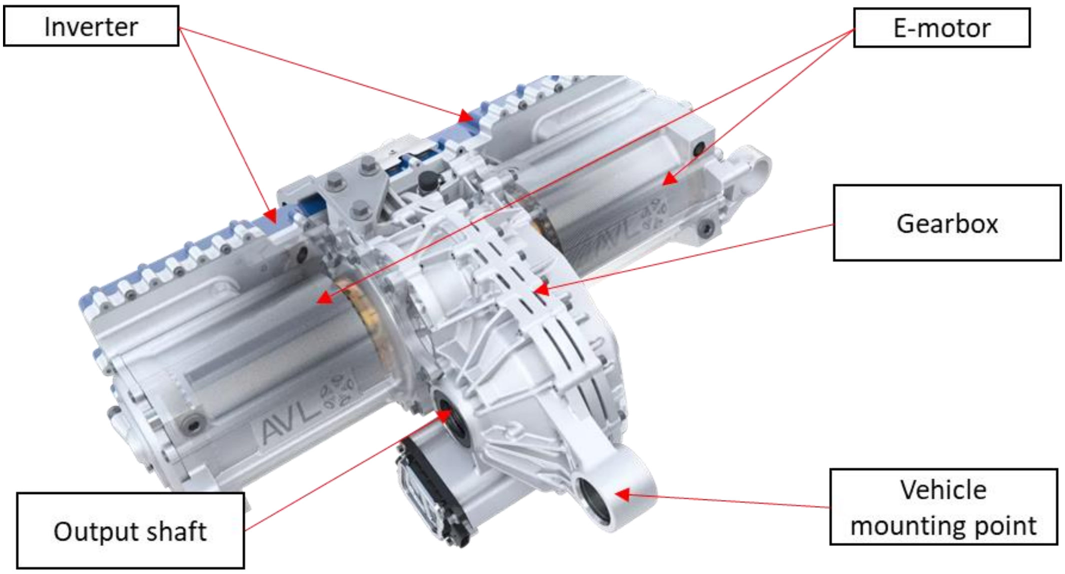
- *electrically connected to the high voltage battery where it receives electric power from,*
- *communicates with the vehicle control unit (VCU) receiving the demand signals and*
- *its mechanical power output is directly the side shafts, which are connected to the driven wheels.*

Therefore, the e-axle's output speed and torque must match the complete vehicle application. Rotational mechanical power is simply calculated as a product of mechanical torque and speed [rad/s].

$$P_m = \omega_m \cdot T_m$$

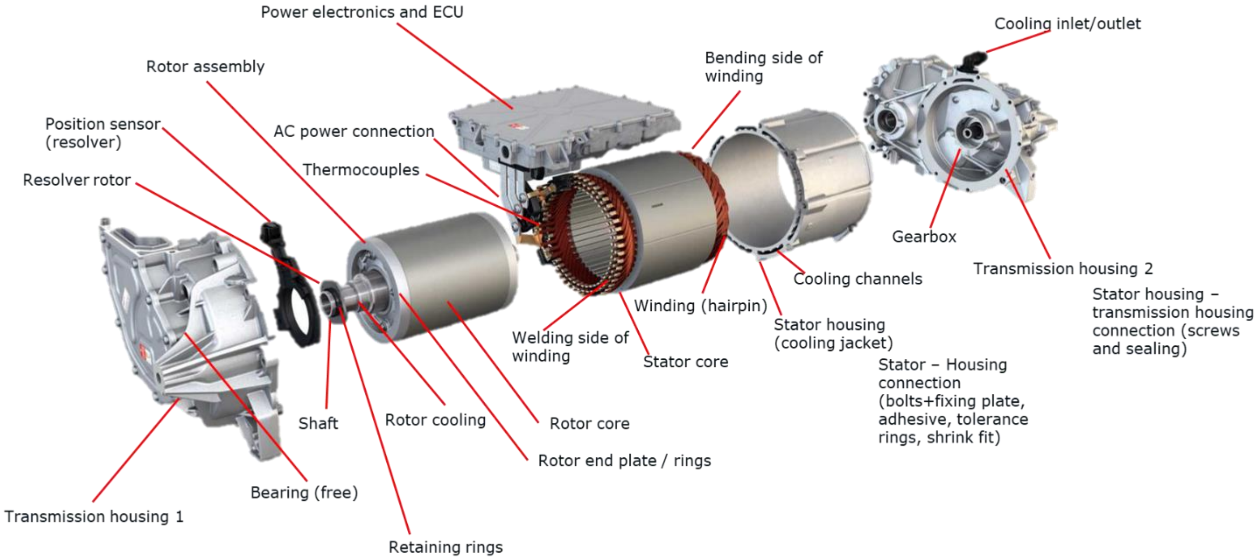
The mechanical power is balanced between speed and torque; therefore, it is possible to reach the same power either by increasing torque at reduced speed, or at lower torque but higher speed. In the design of electric motors high torque usually means oversized machine dimensions, bulky stator and shaft, heavy parts, and high losses at low power operation. Consequently, to increase power density, save material and make smaller, more light-weight components, e-motors are designed to reach target power by increased mechanical speeds. A speed reduction gearbox is mounted between the drive shaft and e-motors output shaft to reduce the e-motors mechanical output speed and increase the torque to the level which is required at the wheels. Usual total gear ratios range between 10 – 16. Note, that in case a differential is present, it often also represents a reduction gear. The total e-motor to wheel gear ratio will be the product of the gearbox's and differential's ratio.

Of course, there are different topologies, where the electric motor directly drives the wheels (hub motors), however these are still less common.



4-4. Figure E-Drive e-axle Electric axle with dual e-drives. No differential gear is used in this layout. [17]

Taking a deeper into the e-drive subsystem it becomes visible, that it is made of many subcomponents. On higher level, the electric drive can be described as a power converter, which turns electrical energy from e.g. a battery to mechanical energy, which moves a vehicle. The conversion process is reversible. Looking at a usual e-driver closer, one can notice, that in fact the power conversion from the battery to mechanical movement is dived into two parts. Since the electric motor requires alternating voltage and currents (AC) to establish a rotating field, which produces its torque and converts the electrical to mechanical power, the direct voltage and current (DC) of the battery must be converted into AC. The DC to AC conversion takes place in inverter, which is an electrical power converter. While this may seem like some cumbersome step, in reality the inverter is the key enabler for high performance variable speed drive applications. Figure 4-5. provides a more detail insight to the e-drive.



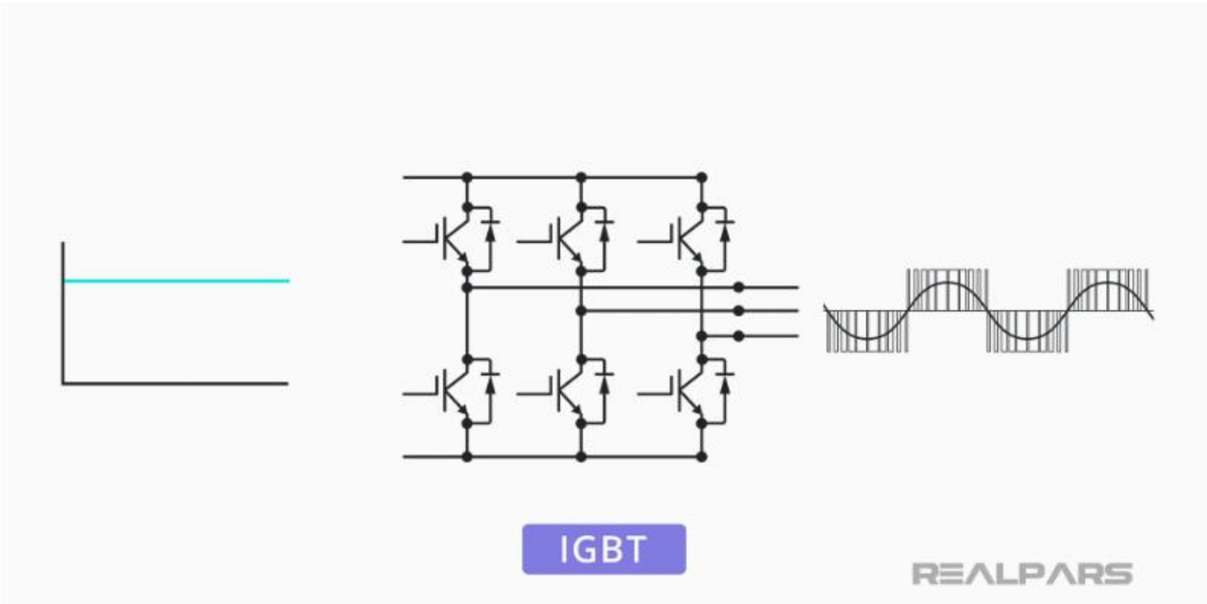
4-5. Figure E-Drive example The e-drive of the VW ID.3. It uses PMSM (Permanent Magnet Synchronous Machine) technology [18]

4.1.1 E-MOTOR

Inside the e-motor the stator and the rotor are the two parts which are responsible for the torque production and the electro-mechanical energy conversion, regardless of the machine type. The winding carries the AC currents and therefore must have relatively low ohmic resistance. High fill-factor windings, like hairpin, allow for high currents and good efficiency. High power density machines produce a lot of heat in a small volume, therefore natural cooling is not enough to keep them operational for longer periods of time. Different forms of liquid cooling either via water, oil or both are usually used to remove heat from the motor. The rotor position sensor is currently still a mandatory element in most electric powertrains, and it provides position and speed information to the inverter.

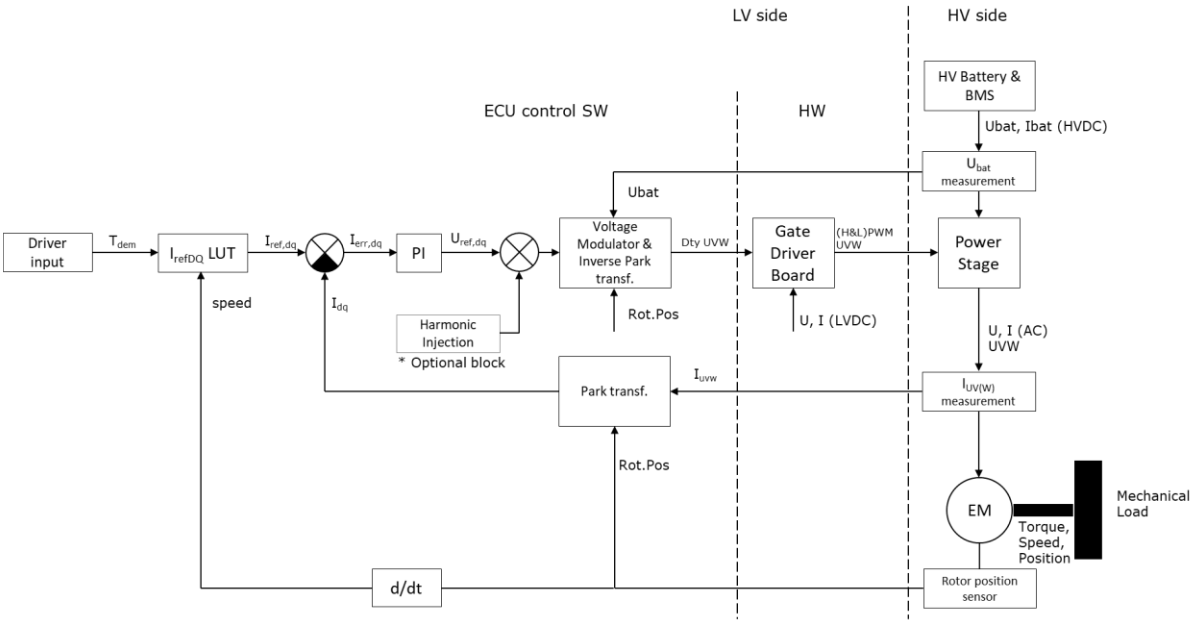
4.1.2 INVERTER

The inverter's task as already mentioned, is to convert the DC battery voltage to AC (and back) for the e-motor. Inverters do this by utilizing power electronic switching devices, like IGBTs, MOSFETs or SiC MOSFETs. The inverter is switching them on and off based on a modulation strategy and creates a modulated waveform. The most common modulation method is called Pulse Width Modulation (PWM) (Figure 4-6.). It has been established that, the inverter can turn its DC input to any desired AC frequency and amplitude on its output, only limited by the DC sources voltage level and current rating. When calibrated correctly, the modulated waveform's fundamental component is exactly the AC wave the e-motor needs. PWM modulation, as one might suspect already, creates a significant amount of harmonics. The e-motor current is filtered by the machine inductance, therefore high frequency components are usually damped enough to not disturb torque production. However, power electronic switching devices still create a significant amount of electromagnetic noise. Therefore, usually the entire e-drive together with the inverter is encapsulated in a shielded housing and any power cable running outside has its own shielding as well.



4-6. Figure Inverter convertering DC voltage to AC voltage using PWM

In order for the inverter to know, what kind of AC waveform the e-motor needs at any given moment to produce the required torque, the inverter needs a control algorithm and information about the actual state of the machine. This is achieved by the schematic shown on Figure 4-7.



4-7. Figure Field Oriented Control (FOC) inverter schematics (LUT: Look-Up Table, PI: Proportional Integral controller, EM: e-motor)

The inverter consists of the ECU, a gate driver board and the power electronics. The ECU is responsible for:

- *the communication, receiving demands, sending status messages and*
- *hosting application specific calibration data, look-up tables, derating functions*
- *processing input signals from measurements (currents, voltage, position, temperature…)*
- *failure handling and HW protection functions,*
- *running the real-time control software for current, torque, speed and position control*
- *in some cases running real-time machine models (ASM and sensor-less applications)*
- *determining the actual voltage set-points, duty cycles, for the PWM modulation and*
- *creating the gate driver signals for the gate driver.*

The gate driver:

- *galvanically isolates the ECU board from the HV side and*
- *it outputs a voltage which can turn the power semiconductors in PE on an off according to the ECU's demands under any load condition,*
- *implements dead-time or blanking time,*
- *provides protection for the semiconductors against overcurrent and*
- *defines the default semiconductor state while PWM is off.*

The power semiconductors must:

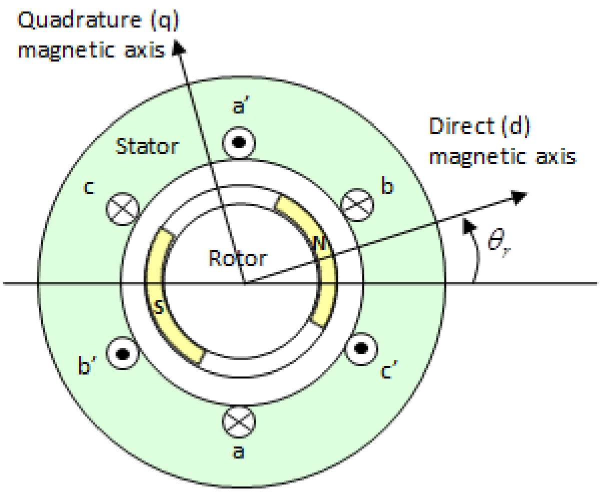
- *withstand the high voltage and current and transients during operation,*
- *provide a temperature signal which is related to its junction temperature to allow for thermal protection,*
- *ideally have very low conduction and low switching losses.*

When all the before mentioned parts perform their task correctly, the inverter can control the current of an electric machine.

4.1.3 PERMANENT MAGNET SYNCHRONOUS MOTORS IN THE DQ REFERENCE FRAME

In this booklet many of the machine parameters will be referred to in the direct-quadrature (DQ) reference frame of the machine. The DQ representation is transformed model based on and equivalent to the 3-phase machine model after applying Park's transformation. It enables FOC (Field Oriented Control), which is the most common motor control in modern electric drive applications.

The DQ model is based on a coordinate transformation which relies on an accurate and well-defined rotor position. The topic of rotor position will be discussed in more detail in the upcoming chapters. By definition the D direction of the motor is the axis of the rotor flux and position θ_r is zero, when the rotor flux's axis is aligned with the axis of first phase winding, e.g. winding **a** in Figure 4-8.



4-8. Figure The e-motor's D and Q directions. In case of PMSM, IPMSM and ESM motor's the rotor field is conveniently physically fixed to magnets or the excitation coil.

The e-motor's behavior can be approximately described with the following equations for the voltages:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - p\omega i_q L_q$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} - p\omega(i_d L_d + \Psi_{pm})$$

$$u_0 = R_s i_0 + L_0 \frac{di_0}{dt}$$

and for the electromagnetic torque:

$$T = \frac{3}{2} p\left(i_q\left(i_d L_d + \Psi_{pm}\right) - i_d i_q L_q\right)$$

Where:

- *ω is the rotor's mechanical rotation speed,*
- *p is the motor's pole pair number,*
- *L_d and L_q are the direct and quadrature inductances,*
- *R_s is the phase resistance.*

In practice normally i_0 = 0, therefore the u_0 equation can often be neglected.

The inductance and current terms together describe the established flux linkage by the stator winding:

$$\Psi_d = L_d i_d + \Psi_{PM}$$

$$\Psi_q = L_q i_q$$

The rotor's electrical speed is simply the product of the motor's pole pair number and the mechanical speed:

$$\omega_e = p \cdot \omega$$

In stationary operation, where the speed is stable and the i_d and i_q currents are constant, the derivative terms are zero: $L\frac{di}{dt} = 0$, and can also be neglected. During parameter testing this assumption is often used to make evaluation simpler.

4.1.4 MOTOR CONTROL

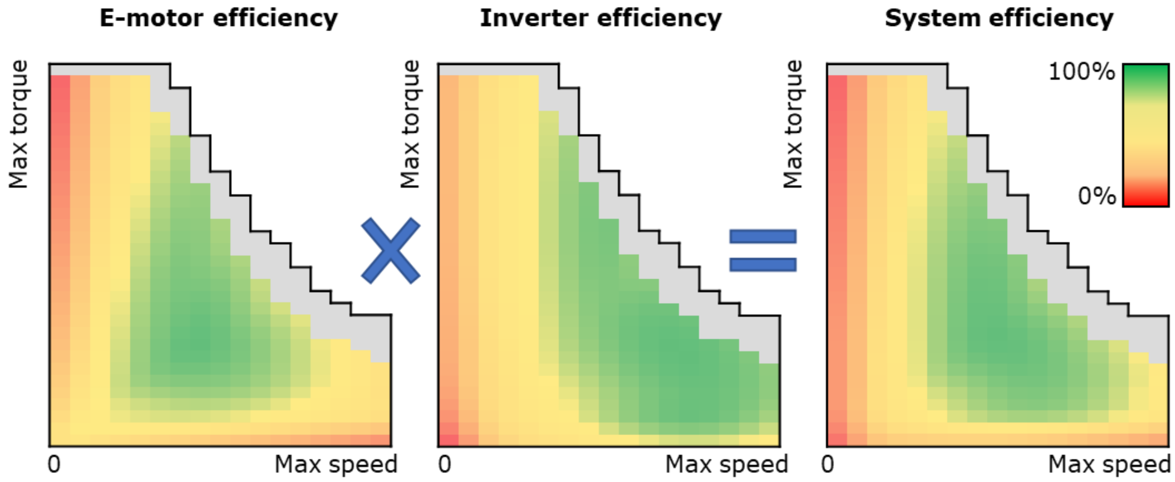
It has been established, that the inverter can control the current of an electric motor as needed. It is however not yet fixed, how exactly the desired torque is reached. Observing the simple torque equation, it is already visible, that same torque can be generated even by choosing different (i_d, i_q) currents. This gives the degrees of freedom to perform optimizations for different objectives.

Efficiency is a very important objective, which is easy to understand. By increasing the e-drive's efficiency the BEV's (Battery Electric Vehicle) range can be extended or at same range the size of battery required can be reduced. Both of which are attractive results.

An e-drive's efficiency is the combined efficiency of the inverter and the e-motor:

$$\eta_{edr} = \eta_{inv} \cdot \eta_{mot}$$

Unfortunately, the inverter and e-motor have high efficiencies under different kind of load conditions and drive parametrizations. Thus, the best system efficiency is usually reached in operation areas where they overlap or very good compromise is found, typically at medium speed and torque, which is often the rated continuous operation point of the vehicle, like cruising, as shown in Figure 4-9.



4-9. Figure Efficiency maps in motoring mode for e-motor, inverter and complete system

Due to the before mentioned reasons it makes sense to discuss the e-motor and inverter efficiency separately.

4.1.4.1 IPMSM OPERATION CURVES

Since current flowing in the machine will always cause ohmic losses, it is only logical to try and extract as much torque from the motor for the given current as possible. Maximizing output torque for the input current is a well-known strategy and is called *Maximum Torque Per Ampere (MTPA)*. Using the correct (i_d, i_q) current vector an optimal trajectory can be found, where the sum of synchronous torque, reluctance torque and minus the losses yields a maximum. Here the current limit of the e-motor is already reached and fully utilized to obtain the maximum torque. This is the *Constant Torque Control* shown in Figure 4-10. Theoretically, the maximum torque can be reached starting from stand-still and can be kept constant while speed increases.

While maintaining maximum torque and increasing the rotation speed, the next limitation is reached: the stator voltage limit. The stator voltage limitation depends on the high voltage DC (HVDC) supply of inverter. Inverters using FOC and Space Vector Modulation (SVM) or third harmonic injection can utilize the DC voltage well:

$$u_{max,ph} = \frac{u_{dc}}{\sqrt{3}}$$

Where $u_{max,ph}$ is the maximum linearly achievable phase voltage fundamental, peak (not rms). When the stator the stator phase voltage reaches this maximum, due to rising induced voltage and motor reactance, the inverter cannot drive more current into the e-motor, at least not while using the same (i_d, i_q) current vector. This is the start of the *Field Weakening Control*, also presented on Figure 4-10. In field weakening the inverter still can operate along the maximum possible current but torque drops.

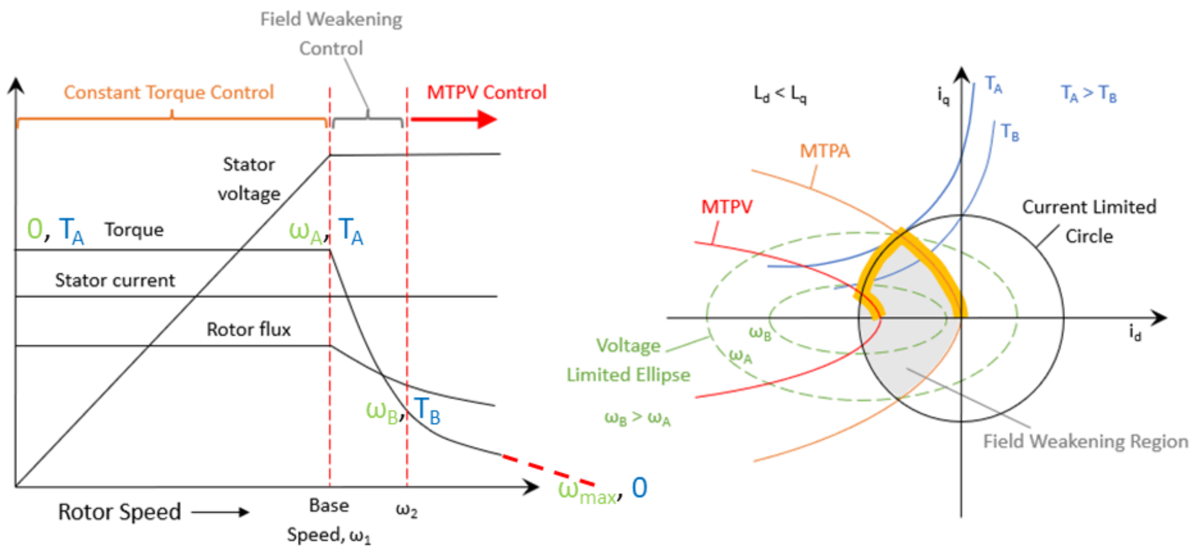


Figure a: IPMSM Characteristics for region highlighted in Figure b.

Figure b: Operating region for IPMSM

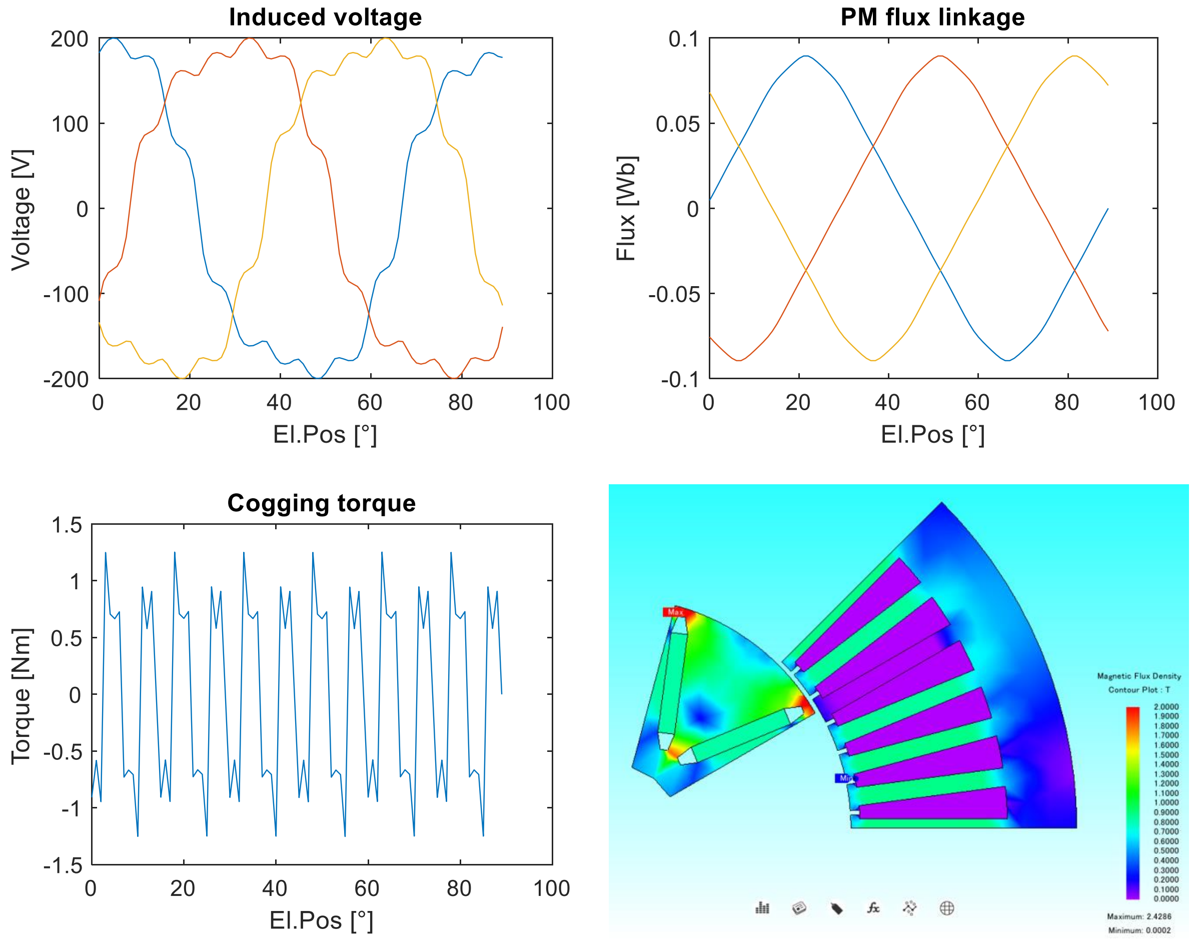
4-10. Figure IPMSM operation [19]

Depending on the supply voltage and e-motor design, the constant maximum current could be maintained over whole speed range. However, since the voltage has become the new limitation, it makes sense to utilize it as good as possible. Thus, another strategy is established: the *Maximum Torque Per Volt (MTPV)* control, which maximizes the torque output for the actual available voltage.

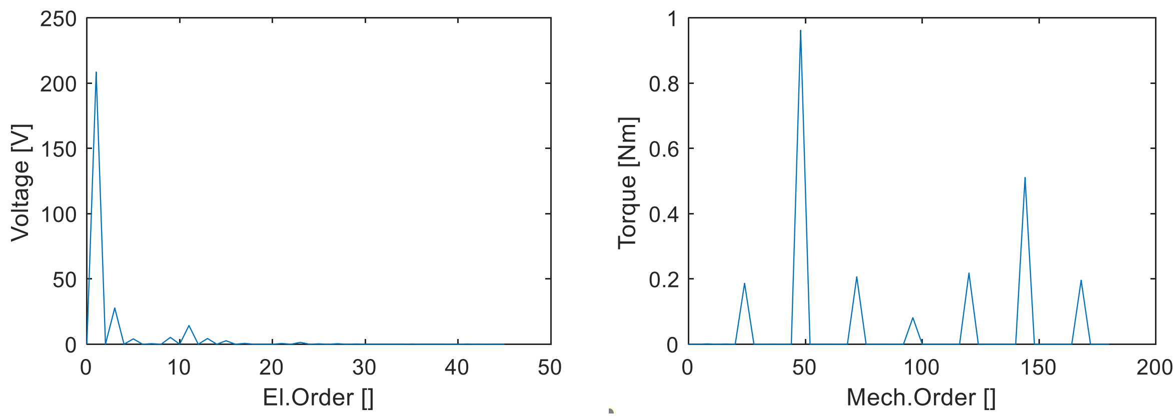
4.1.4.2 RIPPLE OF IPMSM

IPMSM e-motors are designed for high power densitiy and maximum utilization the material. Their magnetic circuit usually works at high levels of saturation and the windings are designed to establis the most amout of fundamental flux linkage. Consequently, IPMSM motors' behavior often show non-linear effects and significant harmonic distortion. It is a trade-off between smooth operation and high power densitiy. This topic is often assessed during motor design and later during drive optimization.

Below a short demonstration is presented of IPMSM behavior. In no-load operation (open circuit) the machine's induced voltage waveforms show a significant amount of harmonic content and due to slotting, no-load torque or cogging torque is also present (Figure 4-11.). Their spectrum in Figure 4-12. displays the usual harmonic orders. These harmonics in no-load already indicate a rough performance under currents.



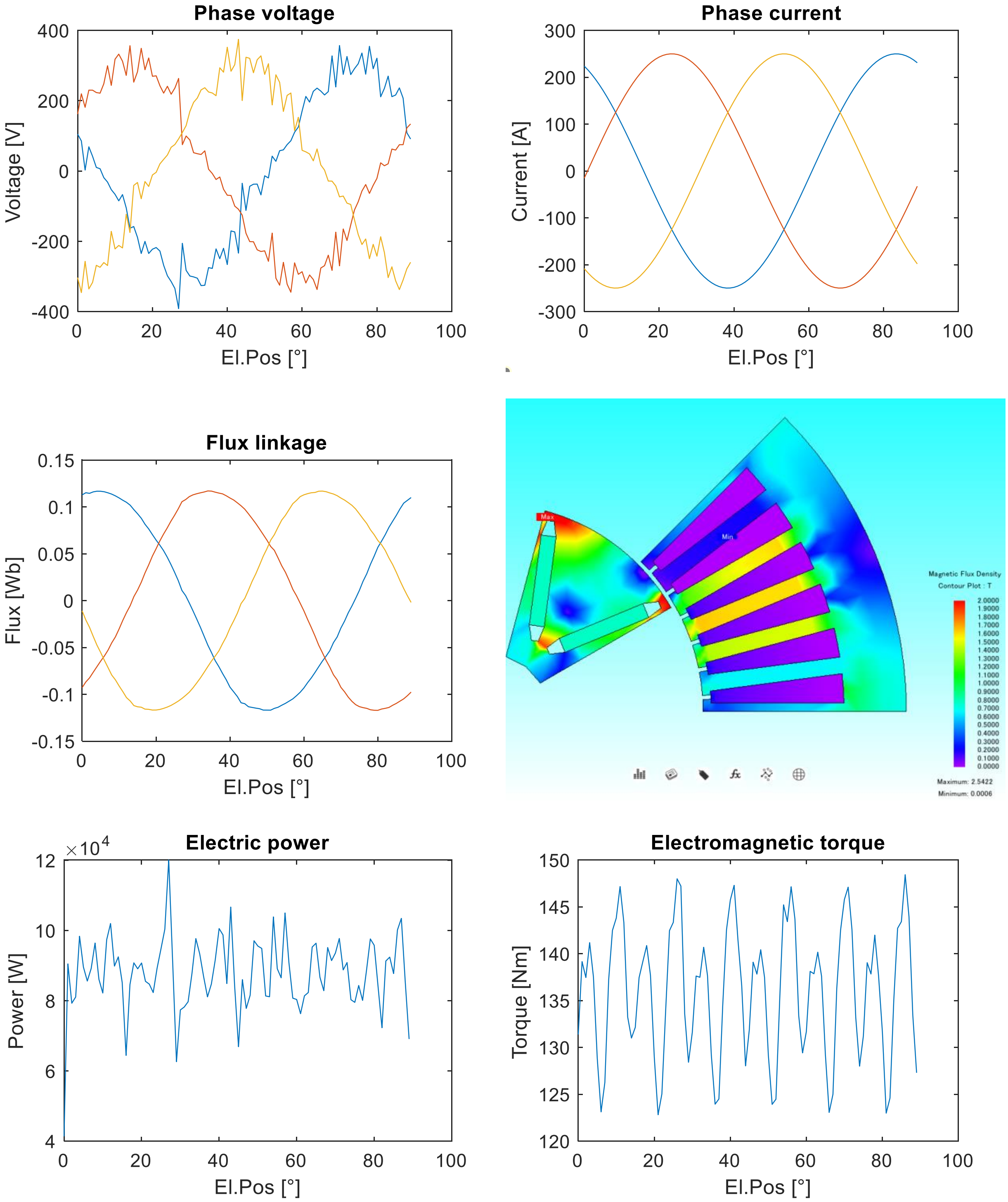
4-11. Figure IPMSM No-load operation



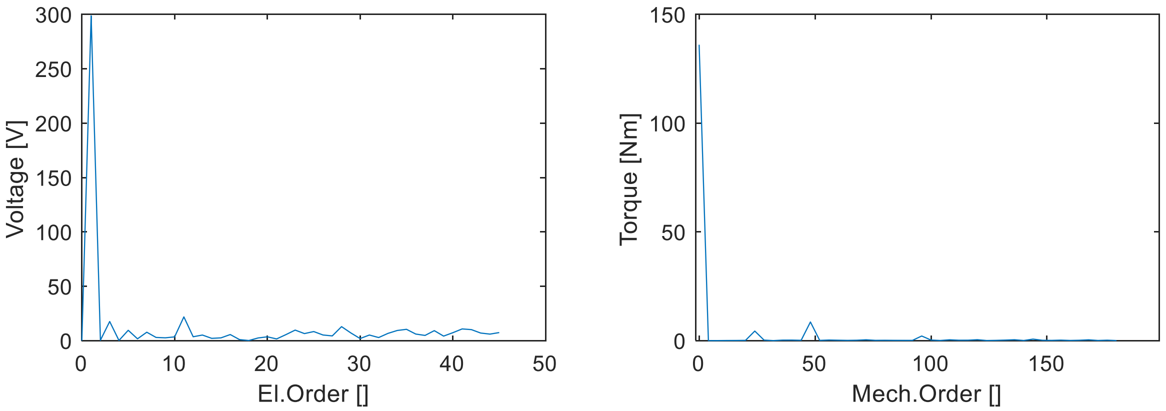
4-12. Figure IPMSM No-load voltage and torque spectrum

The machine under maximum torque operation, as expected, delivers a high amount of torque ripple, approximately 11% of the average torque (Figure 4-13. and Figure 4-14.).

These ripples might negatively impact the electric drive's acoustic performance or cause uncomfortable vibration and mechanical wear. Likewise, the electric power oscillation will increase losses in the electric transfer path and cause increased ageing in the DC-link capacitor and the battery and of course, electro-magnetic compatibility (EMC) issues. [9]



4-13. Figure IPMSM max torque operation



4-14. Figure IPMSM max torque spectrum of voltage and torque

Since the oscillation levels in the electrical power and torque both could be potentially unacceptable in the target application, they could be assessed by means of control tuning and optimization. The inverter normally has enough degrees of freedom to address and at least partially handle the problem.

Figure 4-13. shows a maximum efficiency case, as described in the IPMSM operation curves section. We also know, that by choosing a different (i_d, i_q) current vector, reaching the maximum torque might still be possible, but perhaps with slight deviations and at a lower efficiency. Different current vectors change distribution of the flux in the machine, alter the pattern of electromagnetic forces and might result in lower ripples. While this task can be done in simulation, it is quite often carried out during the calibration of the inverter and fine-tuning of the electric drive. The reason behind is, that simulation models are difficult to tune to such a high fidelity, where they can also accurately predict the high frequency behavior. Therefore, this part is further discussed in the testing sections.

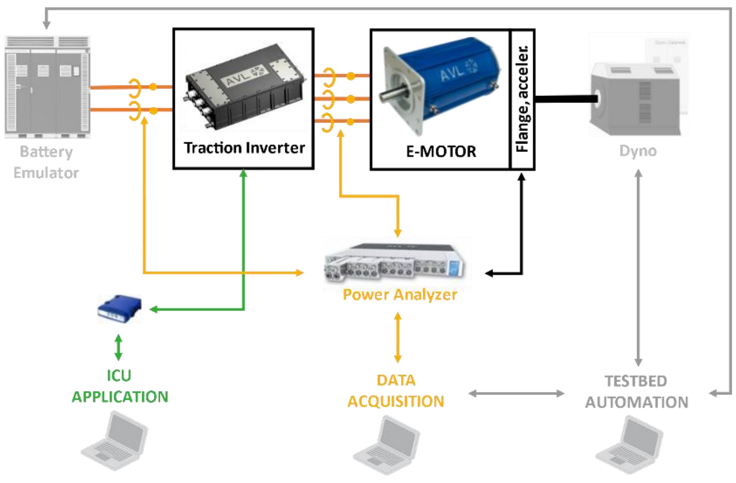
4.2 TEST BED LAYOUTS

The purpose of the test bed is to allow a high accuracy evaluation of the UUT. Therefore, the test bed is prepared to provide the ideal environment, in which the target parameters can be measured with ease.

4.2.1 E-MOTOR TEST BED

The e-motor test bed in its classical form consists of a load unit (dynamometer/dyno) with its own driving inverter (supply cabinet), some mechanical fixtures and adapters to couple the UUT to the dyno shaft, and an inverter which supplies, drives the UUT. This inverter is either the e-motor UUT's own dedicated application inverter "prototype" or a so called universal inverter, which is suitable for the purpose of the tests. Ideally the universal inverter is able to outperform the potential application inverter in terms of power and drive quality, not to limit the validation tests.

In e-motor testing, the UUT and the dyno are working against each other, while the mechanical, electrical and thermal quantities (torque, speed, current, voltage, temperatures etc.) are recorded by the measurement system as shown in Figure 4-15. In most cases the dyno is running in speed control mode and tries to ensure the most stable and smooth speed possible, while the UUT is free to switch between no-load, open-loop voltage control, current control and torque control, as the test requires.

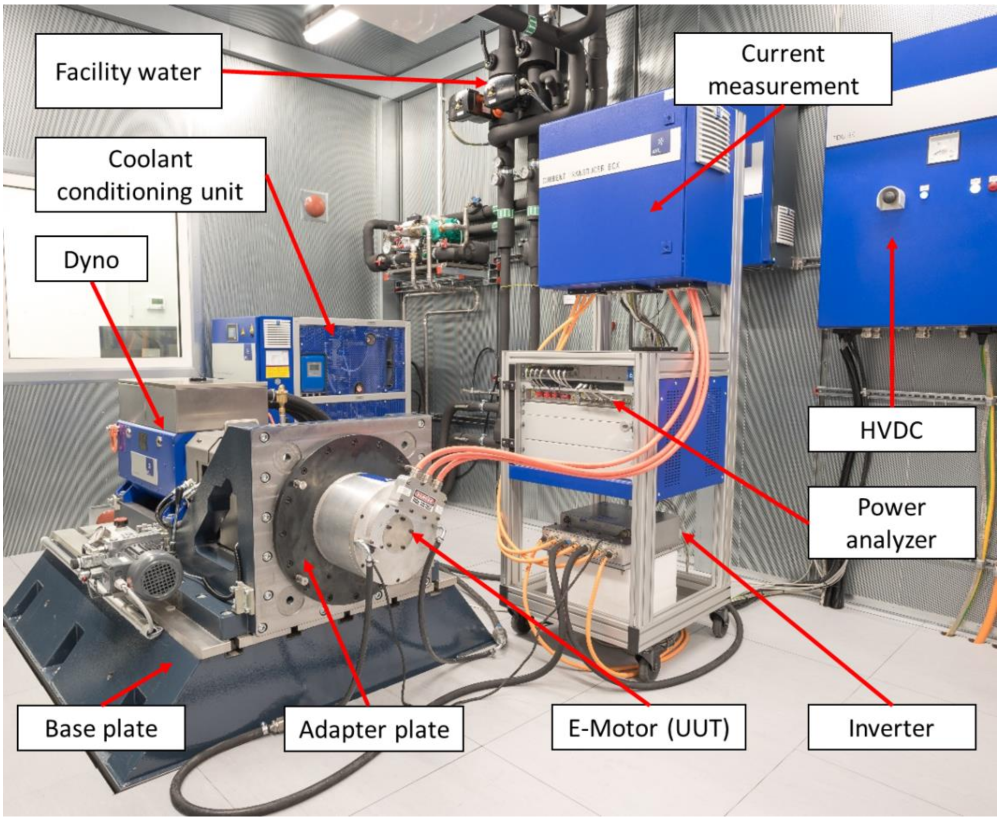


4-15. Figure E-motor test bed (TB) Schematic of e-motor test setup

In more detail the test bed components are followings:

- *Test cell: a dedicated space for the test equipment and UUT with all required safety installations.*
- *Test cell temperature conditioning: required to keep ambient condition for UUT and other equipment within limits and also for operators to allow entering the test cell.*

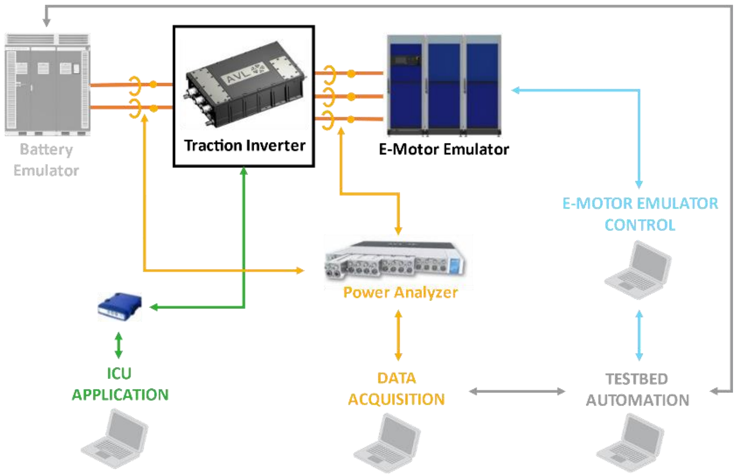
- *Base plate: provides a stable mechanical mounting point and due to its large mass decouples the test setup from environmental vibrations.*
- *Dynamometer: a powerful electric motor that provides ideal load conditions for the UUT, be it speed, torque or position.*
- *Dyno drive cabinet: is the inverter driving the dynamometer.*
- *Dyno cooling: removes excess heat from the dyno, ensuring temperature rise is below limits.*
- *Drive shaft: transmission of mechanical power.*
- *Torque measurement: usually placed as close to the UUT as possible.*
- *UUT mounting plate: a mechanical adapter which allows to mount the UUT (test sample) on the test bed.*
- *UUT (e-motor): the e-motor test sample*
- *UUT (inverter): either dedicated prototype or a universal inverter to drive the e-motor sample.*
- *UUT coolant conditioning: could be the UUTs own cooling system, but in prototype phase usually external cooling devices are attached to condition the inverter and e-motor to the desired temperatures.*
- *UUT DC supply cabinet (HVDC): the DC power supply which acts as source of sink for the UUT inverter, it can also perform battery emulation tasks.*
- *Sensors: temperature, flow rate, acceleration, voltage, current, etc.*
- *Measurement trolley: a simple trolley which houses a part of the sensors and data acquisition system, it can be placed near the UUT to reduce cable length.*
- *Data acquisition system: a system which collects all measured data in centralized way.*
- *Power analyzer: the device which measures electric and mechanical power in order to provide results which describe power conversion process.*



4-16. Figure An example of a test cell with an e-motor test bed installed. The setup shows the usually required devices for motor testing.

4.2.2 INVERTER TEST BED

Inverter test bed is an emerging type of test bed in e-drive applications, targeted to test, develop and validate the inverter component with all its functionalities. Naturally, here the UUT is the traction inverter itself. The inverter test bed does not have mechanical moving (rotating) components, since the e-motor is replaced by a high-quality power electronic device: the e-motor emulator. Based on its layout, presented in Figure 4-17. it is visible, that the overall functionality is similar, with exception of the moving parts.



4-17. Figure E-motor emulator

A good e-motor emulator works like an inverter, but at significantly higher speed. Its high-speed processing unit, usually FPGA (Field Programmable Gate Array) based, runs a simple or detailed electric motor model. The model is executed several times during a single UUT inverter switching period. Since the emulator operates significantly faster, it takes over the current control in the system. More precisely it sets the currents to same level, as the real e-motor would naturally have, at the given inverter voltage level and machine speed. The emulation of course extends to synthetizing a realistic position signal for the UUT inverter, as it is required for the control. Due to the speed of the emulation, the UUT inverter will operate the same way as if was driving a physical motor.

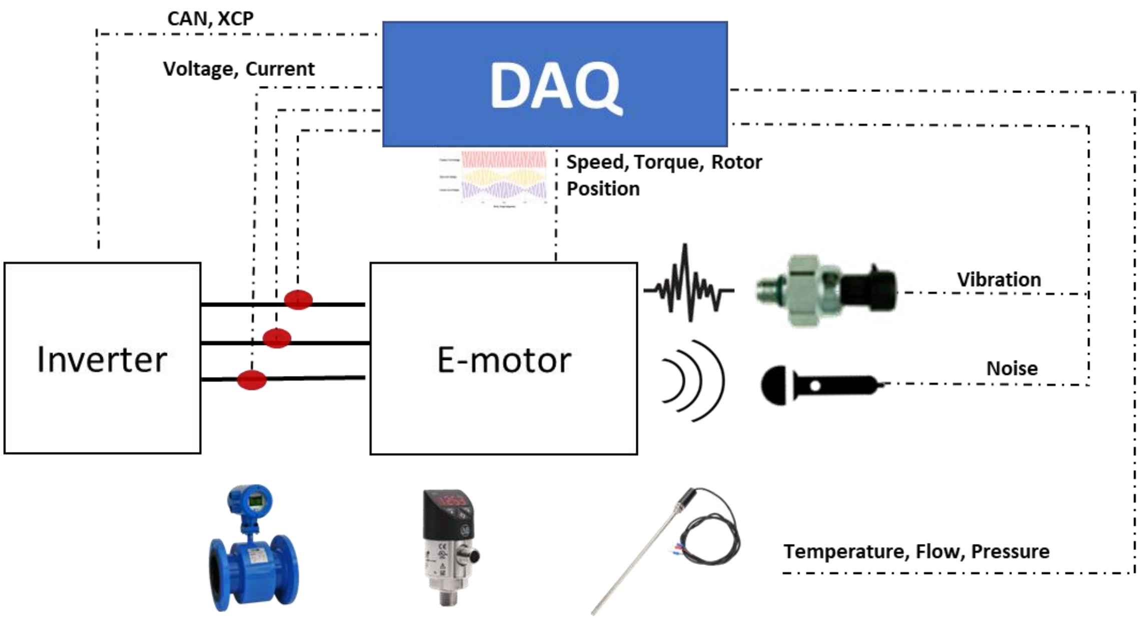
The advantage of an e-motor emulator is that inverter prototype validation becomes separated from the e-motor prototype, the footprint of the test bed is significantly smaller and it takes less effort to set up the tests, as no mechanical mounting is required. The repeatability of tests increase, as the emulator voids hardware variation of the e-motor.

The drawback is, that emulation only gets as good as good the model is parametrized. For example, the e-motor's thermal behavior due to self-heating and losses is usually slightly more complicated to represent in inverter testing.

4.3 DATA ACQUISITION

Electric drive systems are multi-physics devices, i.e. signals from different domains need to be considered in the evaluation their performance. Additionally to the UUT related quantities, the states of the testing environment's devices must be recorded as well. Signals and messages of different test system devices are all recorded, since in case of issues, they might help evaluate results or trace back problems. The most commonly measured quantities, signals are:

- *voltage,*
- *current,*
- *torque,*
- *force,*
- *acceleration,*
- *acoustic noise,*
- *speed,*
- *position,*
- *temperature,*
- *flow rate,*
- *pressure,*
- *digital messages on the communication bus (CAN).*



4-18 Figure Many types of signals from different sources are present during a measurement and must be measured simultaneously.

The first challenge for the data acquisition system is to collect all this signal at the same time. This isn't a straight-forward task, since, as the number of quantities already suggest, the amount of data is immense. Not only the amount but also the variety is quite large in which form the information and measurement signals are available. While some signals are present in the form of simple analog low voltage signals, some are already digitalized by the measurement sensor itself (e.g pressure, flow rate, torque…) and requires a completely different interface on the data acquisition device (Figure 4-18.). Therefore, often the recording is performed in a distributed manner, i.e. not every signal is recorded on the same device, but distributed to different modules, measuring cards.

Thus, we arrive at the second challenge: time synchronization. To obtain a meaningful dataset, the signals must share the same time-base, which means they must not be shifted compared to each other in time. Otherwise, the events in the measurement cannot form a consecutive chain, the cause and effect cannot be identified and the whole test becomes quite difficult to evaluate. For this reason, each signal or set of signals comes with a time-stamp, which is synchronized to a master device. This makes it possible to correlate electric DC to AC and mechanical power and e.g. allow to evaluate a transient overshoots, delays and inrush of power during a step torque change event aligned to CAN messages.

The data acquisition system's performance must match the goal of the tests being performed. The data acquisition must be able to record high quality data, which is good enough to judge the outcome of the validation test. This means, as a rule of thumb, the accuracy of the measurements must be at least 10 times better, than the smallest deviation which must be evaluated. For example, if at a certain operation point the maximum allowed torque deviation is 2 [Nm], then the measurement system must be able to resolve the signal in 0.2 [Nm] levels, of course with a nearly perfect repeatability.

Besides accuracy, sampling frequency is the next important topic. According to the *Nyquist-Shannon sampling theorem* the sampling frequency must be at least twice higher than the frequency of the measured signal:

$$f_{sampling} > 2 \cdot f_{signal}$$

In data acquisition this usually translates, that the sampling frequency must be at least twice as fast as the highest frequency harmonics which must be measured. While theoretically slightly higher than 2 times the frequency is enough, in practice usually 10 times higher frequency is used for sampling, otherwise only spectral evaluation if possible. Another consequence of the Nyquist-Shannon theorem is, that if the sampling frequency is lower than double the double of the signal's frequency aliasing happens. To avoid aliasing, the measured signals go through a low-pass filter before digital sampling or evaluation. The filter has a cut-off frequency well below ½ of sampling frequency and thus cuts off the high frequency parts, which would cause aliasing.

4.3.1 POWER MEASUREMENT

For correct power measurement the power analyzer must detect electrical periods and perform the calculations always over one or more complete periods, since RMS (Root Mean Square) value calculation of sinusoidal signals is only accurate that way. Power analyzers can perform period detection based on the filtered voltage, current or even position signals. If the period detection is working, the power analyzer can internally calculate the input DC, inverter AC and e-motor mechanical power using the equations in Table 4-1.

4-1. Table Power calculation

	Equations of power calculation
Inverter input power	$P_{ii} = U_{dc} * I_{dc}$
Average inverter input power	$P_{ii_{mean}} = U_{dc_{mean}} * I_{dc_{mean}}$
Inverter output power	$P_{io} = \frac{1}{T}\int_0^T u_{ac1}(t) * i_{ac1}(t)dt + \frac{1}{T}\int_0^T v_{ac2}(t) * i_{ac2}(t)dt + \frac{1}{T}\int_0^T v_{ac3}(t) * i_{ac3}(t)dt$
Fundamental inverter output power	$P_{io_{fund}} = \sqrt{3} * V_{io_{fund}} * I_{io_{fund}} * \cos\theta$

Motor input power	$$P_{mi} = P_{io} = \frac{1}{T}\int_0^T u_{ac1}(t) * i_{ac1}(t)dt + \frac{1}{T}\int_0^T v_{ac2}(t) * i_{ac2}(t)dt + \frac{1}{T}\int_0^T v_{ac3}(t) * i_{ac3}(t)dt$$
Motor output power	$$P_{mo} = \frac{2 * \pi}{60} * M * n$$

4.4 ELECTRIC MOTOR TESTING

4.4.1 BASELINE TESTS

E-motor testing starts by making sure, that the sample is physical fit before mounting it on the test bed. The minimum set of tests and checks are:

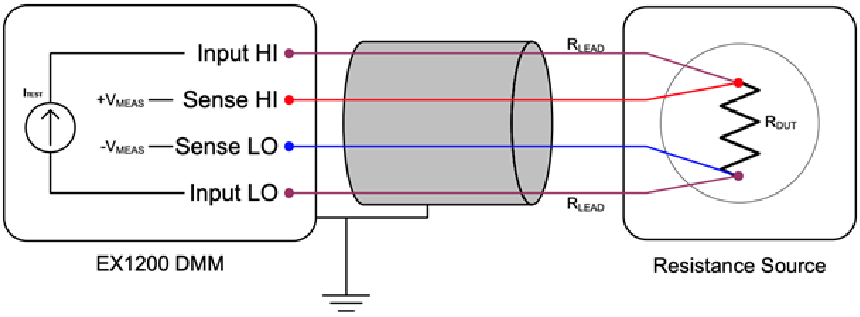
- *winding resistance test with a milliohm-meter (4 wire measurement method),*
- *winding-to-housing insulation test (e.g. impulse test),*
- *mechanical stress check of rotor,*
- *mechanical rotational check of the e-motor assembly,*
- *induced voltage test,*
- *tightness test of the coolant circuit (s), if possible on the e-motor level,*
- *visual check for any damage,*
- *position sensor check.*

4.4.1.1 STATOR WINDING PHASE RESISTANCE

It is extremely important to use a proper resistance measurement device, since normal e-motor's resistance is usually in the milli-Ohm range, where normal multimeters are unable to measure. A proper 4 wire device is needed (Figure 4-19.), with micro-Ohm range accuracy. Winding resistance shall match the motor's design specification, considering the actual temperature. It is equally important, that resistance values are symmetrical, with usually less than 1% asymmetry.

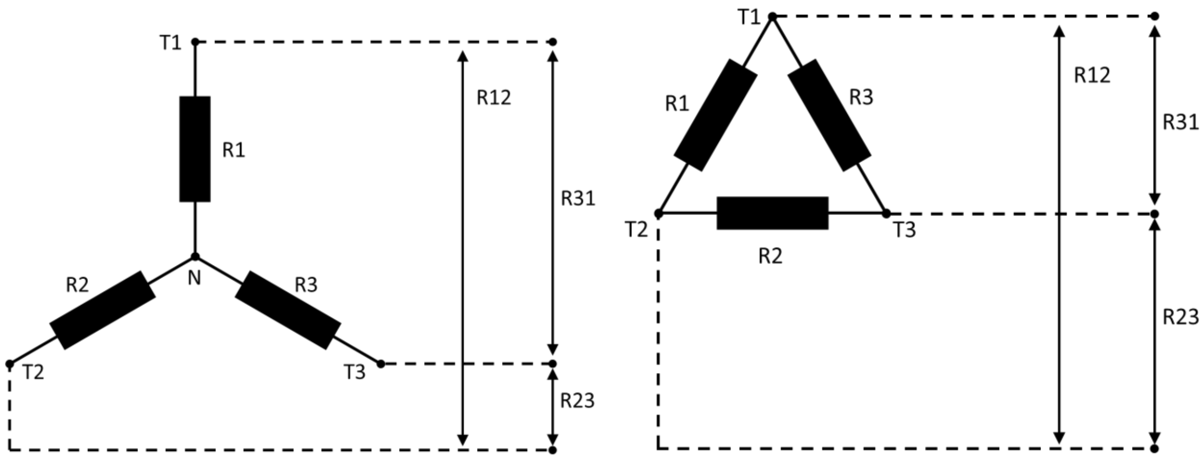
$$Asymm = \frac{\max(R_1, R_2, \dots, R_n) - \min(R_1, R_2, \dots, R_n)}{\text{mean}(R_1, R_2, \dots, R_n)} \cdot 100 < 1\%$$

In a usual 3-phase system n = 3.



4-19. Figure Schematic of a standard 4 wire resistance measurement [20]

The actual phase resistance often cannot be measured unless the winding is star connected (in other name wye connected) with access to the neutral. In VSD (Variable Speed Drive) application, i.e. where the e-motor is driven with an inverter the Neutral is very rarely accessible from the outside of the e-motor housing. The reason for this is, that the Neutral is a floating point, an in 2-level VSD it oscillates around 1/3 or the DC supply voltage due to zero-sequence voltage components of the switching electronics. For this reason, it is usually not desired to have it available.



4-20. Figure A winding in star (wye) connection layout (left) and in delta connection layout (right)

Consequently, when measuring resistance of STAR CONNECTED WINDING (Figure 4-20.) between the phase terminals the result (R_{12}, R_{23}, R_{31}) is the sum of the two phases. Repeating the measurement between all two terminals the individual phase resistances can be calculated.

$$R_{12} = R_1 + R_2$$

$$R_{23} = R_2 + R_3$$

$$R_{31} = R_3 + R_1$$

Solving this for R_1

$$R_1 = (R_{12} - R_2 + R_{31} - R_3)/2$$

and rearranging to the phase resistances:

$$R_1 = (R_{12} + R_{31} - R_{23})/2$$

$$R_2 = (R_{23} + R_{12} - R_{31})/2$$

$$R_3 = (R_{31} + R_{23} - R_{12})/2$$

This yields the equations for the phase resistance in a star connected 3-phase winding system. The set of equations to be solved in order to obtain a desired phase resistance can easily be understood based on the Figure 4-20.

Applying Ohm's reciprocal law to the DELTA CONNECTED WINDING it is straightforward to calculate the phase resistances from the measured values. Starting with the measured R_{12} value between terminal 1 and 2:

$$\frac{1}{R_{12}} = \frac{1}{R_1} + 1/(R_2 + R_3)$$

$$R_{12} = 1/(\frac{1}{R_1} + 1/(R_2 + R_3))$$

and extending the formulation to all 3 phases:

$$R_{12} = \frac{R_1(R_2 + R_3)}{R_1 + R_2 + R_3} = \frac{R_1R_2 + R_1R_3}{R_1 + R_2 + R_3}$$

$$R_{23} = \frac{R_2(R_1 + R_3)}{R_1 + R_2 + R_3}$$

$$R_{31} = \frac{R_3(R_2 + R_1)}{R_1 + R_2 + R_3}$$

$$R_1 = \frac{R_{12}(R_1 + R_2 + R_3)}{R_2 + R_3}$$

$$R_2 = \frac{R_{23}(R_1 + R_2 + R_3)}{R_1 + R_3}$$

$$R_3 = \frac{R_{31}(R_1 + R_2 + R_3)}{R_2 + R_1}$$

we finally obtain the values for the phase resistances:

$$R_1 = \frac{R_{12}^2 - 2\,R_{12}\,R_{23} - 2\,R_{12}\,R_{31} + R_{23}^2 - 2\,R_{23}\,R_{31} + R_{31}^2}{2\,(R_{12} - R_{23} - R_{31})}$$

$$R_2 = \frac{-R_{12}^2 + 2\,R_{12}\,R_{23} + 2\,R_{12}\,R_{31} - R_{23}^2 + 2\,R_{23}\,R_{31} - R_{31}^2}{2\,(R_{12} - R_{23} + R_{31})}$$

$$R_3 = \frac{-R_{12}^2 + 2\,R_{12}\,R_{23} + 2\,R_{12}\,R_{31} - R_{23}^2 + 2\,R_{23}\,R_{31} - R_{31}^2}{2\,(R_{12} + R_{23} - R_{31})}$$

Due to the parallel branches' effects, the formulation is slightly more complicated than in the start connected winding, however it still gives exact values.

Two very important notes must be made here:

1) *Based on resistance testing it is only possible to make conclusions on the complete winding, e.g. when parallel strands, coils are present which cannot be measured individually this measurement does not always have enough accuracy to detect a problem.*
2) *Since star and delta connected winding cannot be differentiated from each other just based on resistance testing, this information must come from the design side. Otherwise, the results cannot be compared to the design values.*

The stator phase resistance test provides a good opportunity to test any thermocouples which might have been integrated into the windings.

4.4.1.2 INSULATION RESISTANCE

Insulation resistance is measured between the winding terminal and e-motor housing with an appropriate insulation tester device. The practical rule to judge insulation resistance is that the winding must have at least *500 [Ohm] / 1 [V]* resistance for safe operation, which mean the motor shall have at least 500 [Ohm] insulation resistance for each Volts supplied by the power electronics, unless otherwise specified. E.g. the bare minimum insulation resistance of motor for maximum 400 [V] DC application is 200 [kOhm]. Normally insulation resistance of an e-motor is in the Mega- or Giga-Ohm range.

Using the two fundamental tests above it is already possible to make a conclusion on the winding's health. If the insulation values are well and the resistances are proven to be symmetrical it is highly likely, that the winding doesn't have short circuits in between layers, turns and the between wire and housing.

4-21. Figure Stator tester [21]

4.4.1.3 ROTOR OVERSPEED TEST

The e-motor's rotor must be able to endure high speeds and high rotational accelerations. This rises requirements for balancing, which means radial acceleration resulting from rotations must not exceed a certain limit threshold at any speed. The goodness of the balancing must meet the requirements of the application and the chosen mechanical supports (bearings). High rotation speed results in very significant mechanical stress levels in the rotor's steel structure (core), magnets (in case of PMSM (Permanent Magnet Synchronous Machine)) and field winding (in case of ESM (Externally Excited Synchronous Machine)). The mechanical overspeed testing takes place purely on the rotor level and is designed to test the rotor sub-assembly to its limits. It is often repeated on the e-motor and e-drive level as well after durability testing.

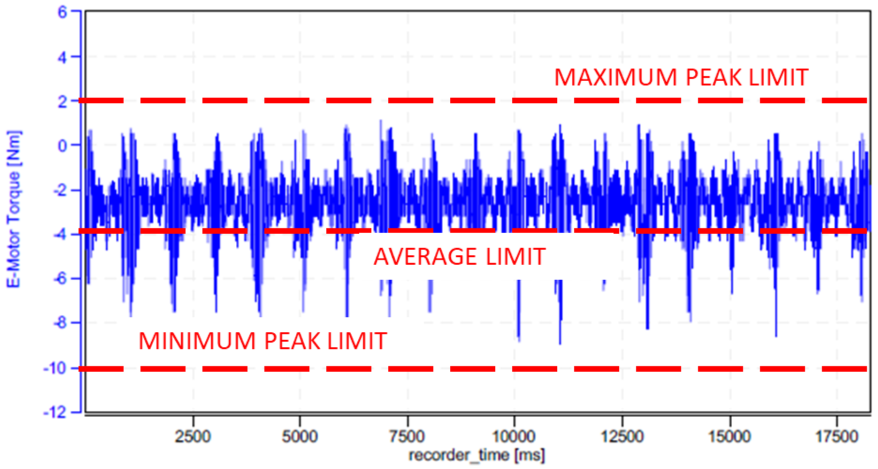
4.4.1.4 MECHANICAL ROTATION TEST

Once it has been proven, that the rotor itself can turn at required speed the e-motor can be assembled. On this level a final check is carried out, usually on a simplified test-bed setup, where some last tests are performed. The goal of these investigations is to see, whether the rotor assembly process was successful. Therefore, the e-motor is mounted on simple test station, which allows measurement of the shaft torque and at least the terminal voltages of the motor while driving the e-motor up to a certain speed. Such test stations are often referred to as EoL (End-of-Line) testers. For more meaningful and accurate result brand new e-motors require a short run-in sequence to overcome the initially higher friction torque of the bearings.

The mechanical no-load rotation test (Figure 4-22.) at minimum can show if the rotor can spin freely, without any excess drag torque resulting from:

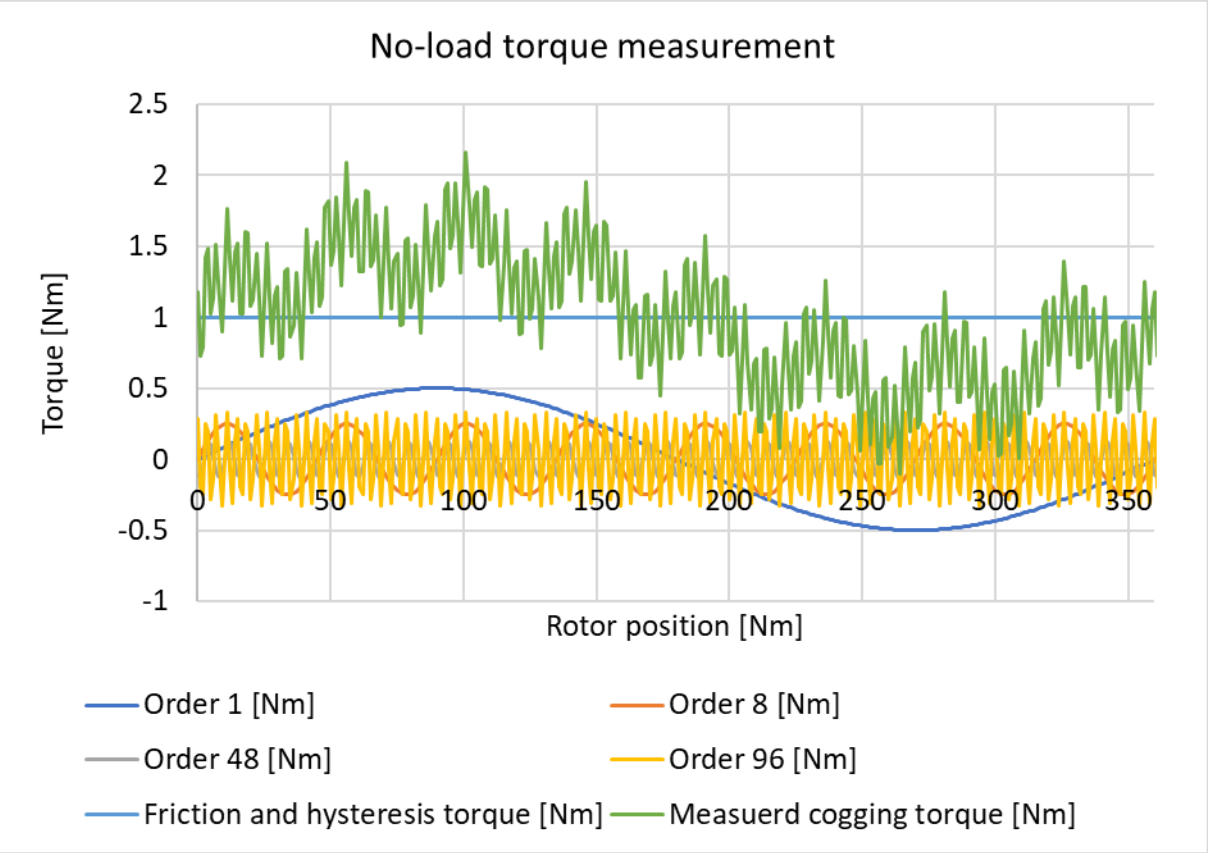
- *particles inside the air gap,*
- *winding short circuit caused during assembly,*
- *damaged bearing,*
- *friction between stator and rotor.*

In case the measured average and peak torque falls below the expected threshold the e-motor sample is okay to go.



4-22. Figure Example simple torque measurement, where the sample passed the limits set for its peak and average torque.

While making a conclusion regarding the previous questions a simple average (or mean) torque value could already be enough, some more sophisticated test devices allow for a more precise type of torque measurement. This case the test must be carried out at a very low, yet stable mechanical speed, ensured by the external driving motor. The no-load torque ripple, or *cogging torque* of an e-motor is reluctance type torque, which results from the saliency (non-uniformity of magnetic path resistances) inside the motor, depending on the rotor's actual position. In very basic level one could imagine as it comes from the alternation of teeth and slots facing the magnet. The cogging torque of an e-motor often contains valuable information about the quality of the assembly and uniformity of the parts. The low-speed test also allows to estimate the e-motor's mechanical friction and magnetic hysteresis losses (Figure 4-23.).



4-23. Figure Low speed no-load torque or cogging torque measurement example, showing the overall measurement and the torque components of an example 48/8 e-motor topology including a potential measurement setup's impact on the results in the form of a 1st mechanical order harmonic, which should not exist in a perfect setup.

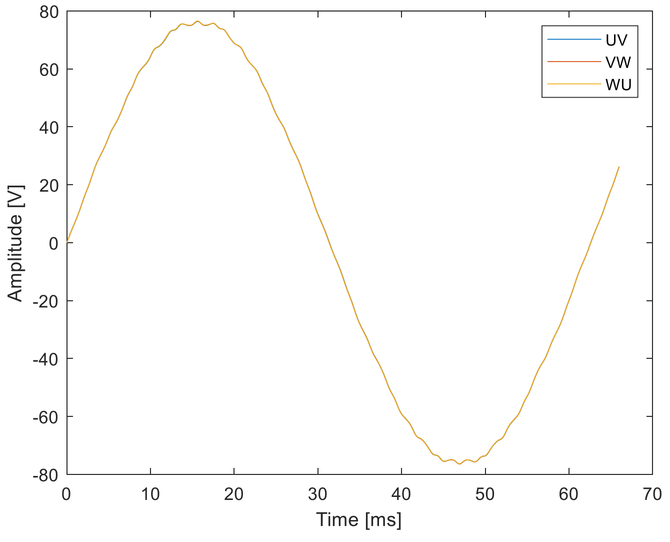
4.4.1.5 BASIC INDUCED VOLTAGE AND

Once the e-motor is already on a test station which can turn its shaft with an external drive, it makes sense to look at the motor's next fundamental property*: the induced voltage*. The induced voltage, also called BEMF (Back Electro-Motive Force), allows to make an overall diagnosis of the motor's magnetic circuit in no-load. It shows the amount magnetic flux links with the winding system, thus effectively telling whether all magnets inside the rotor are correctly magnetized and inserted and whether all (series connected) conductors of the winding are joined in the correct order.

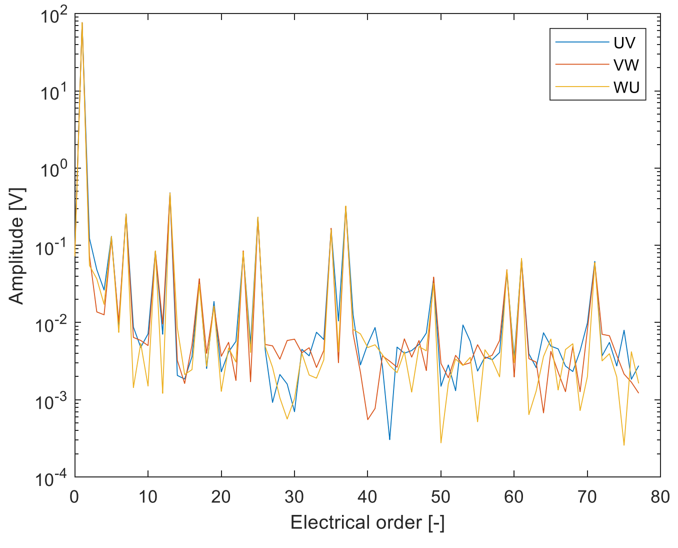
Since the operating point of the permanent magnets are temperate dependent, the motor's temperature must be considered if one wishes to quantitively judge the flux linkage.

Voltage symmetry and similarity of the waveforms, either based on time/position function or spectrum is extremely important (Figure 4-24. and Figure 4-25.). Asymmetries in the induced voltage mean either that either the tests or the evaluation were wrong, or the e-motor is badly produced and some of its parts which should be identical are completely different. Such motors shall not proceed to integration with an inverter. A practical asymmetry threshold when comparing voltage waveform fundamental waves is: *Asymm < 0.1% (Table 4-2.)*.

Of course, the threshold value depends on the measurement system as well. To enable a 0.1% asymmetry detection on a sample, the test system itself must have less than 0.01% asymmetry on a reference waveform. This is usually stated in the periodic calibration report of the equipment.



4-24. Figure Example of BEMF waveform, 3 phases overlay to expect differences.



4-25. Figure FFT overlay, careful: logarithmic Y axis and electrical order X axis, but shows that even low amplitude harmonics are almost identical between the 3 phases.

Phase shift is just as important as the amplitudes. Taking a look the 3 phase waveform or controlling the FFT based phase shift value is essential. Based on this the phase sequence of the motor can also be easily determined and can be compared to the design.

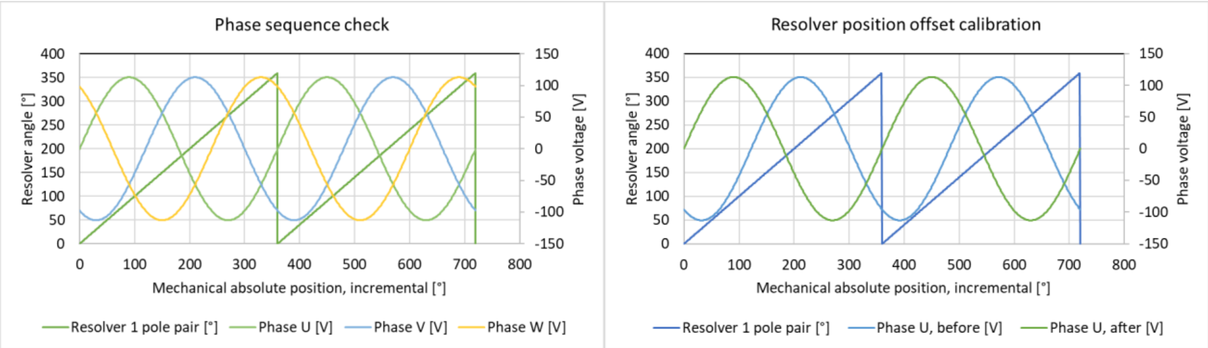
4-2. Table Example of good asymmetry values

avg UV [V]	avg VW [V]	avg WU [V]	Asymm %
76.313	76.351	76.328	0.05%

4.4.1.6 ROTOR POSITION SENSOR CHECK AND CALIBRATION

The role of the rotor positions sensor is to provide accurate, real-time information of the angular position of the e-motor's rotor to the inverter. The goal of this test is to verify that the integrated position sensor of the e-motor is working.

There are many control strategies which rely on position sensor and of course there are sensor-less application as well. Nowadays torque accuracy requirements are still difficult to meet without high resolution information of the rotor's position. Therefore, most of the automotive traction applications utilize some kind a position sensor. Field-oriented control (FOC), on which many PMSM e-drives rely, requires the presence of an absolute position sensor, like a resolver, hall-effect sensor, sin-cos encoder etc. In case of absolute type position sensors, it is necessary to calibrate the rotor position sensor's null-position to e-motor's magnetic axis (Figure 4-26.). Otherwise, the inverter cannot perform the most basic current control operations or overcome cross-coupling. This very essential step can be postponed to the validation test bed in case of prototype validation tests, however on production lines it is always carried out before or during the e-motor – inverter integration.

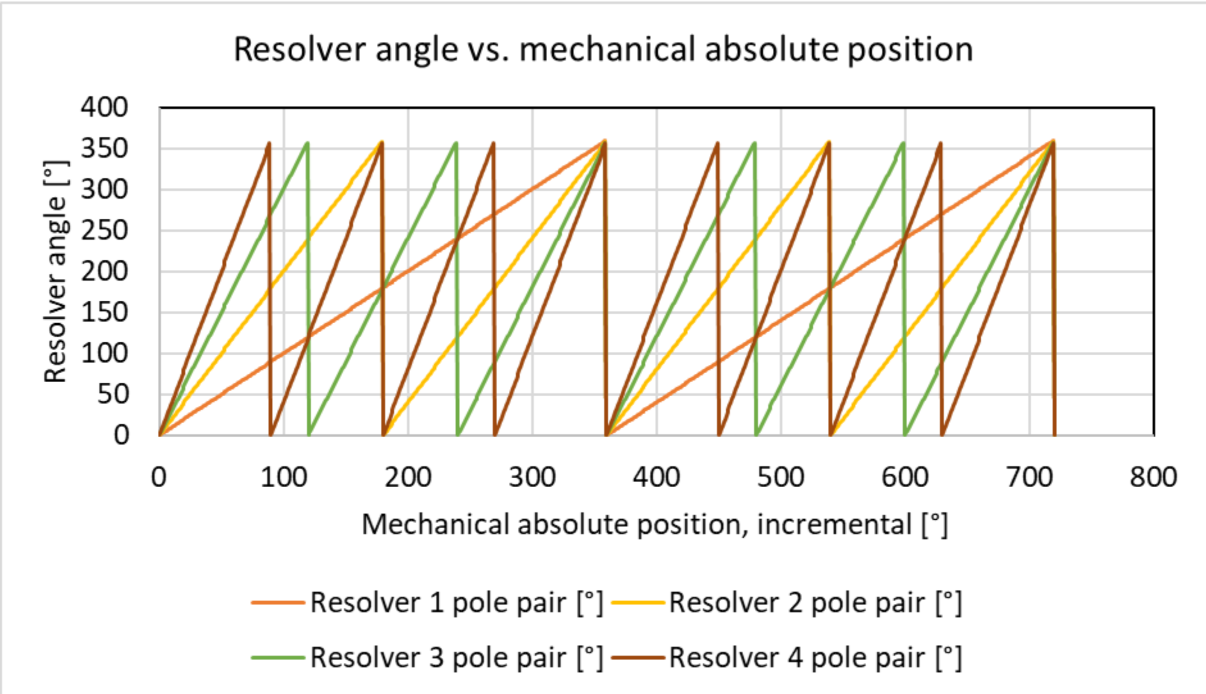


4-26. Figure The correct phase sequence of a motor with UVW winding layout and positive speed and b. showing an example how an electric motor controller is calibrated for FOC.

It is worth to note, that a resolver itself is tiny rotary machine as well. While it is an absolute position sensor, depending on its design the position signal it provides can be matching to the actual mechanical shaft position or it can be integer multiples of it. Just like an electric motor, resolvers can also have multiple pole pairs (Figure 4-27.). Multiple pole pair resolvers will show multiple times the actual mechanical shaft position (Figure 4-28.), i.e.

they make multiple periods over a single mechanical rotation. The pole pair number of the resolver should match the pole pair number of the electric motor. If that is not possible, the number of resolver pole pairs must be an integer fraction of the motor pole pair number, e.g. a one pole pair resolver can be paired with any number of electric motor pole pairs, while a 2 pole pair resolver works only with even number (2, 4, 8…) pole pair e-motors. For motor control this is quite useful to match resolver and e-motor pole pair numbers, because this way the position accuracy increases.

4-27. Figure Example of resolver with rotor and stator part, 4 pole pair, variable reluctance type from Tamagawa [22]



4-28. Figure Two mechanical turns and the corresponding resolver signal with different sensor pole numbers

4.4.2 PARAMETER TESTS

During the baseline tests we made sure, that e-motor sample is electrically and mechanically fit for the main test steps. The goal of parameter testing on the e-motor level is to learn all the essential properties, explore the required details of the electric motor. Such parameters, properties may cover requirements which must be validated and feedback may be required for the machine design loop. Some of the parameters are considered in a no-load case, to void influence of the power source:

- *phase resistance of the winding,*
- *fundamental and harmonic flux linkage with temperature dependency,*
- *no-load torque ripple (cogging torque),*
- *no-load acoustic behavior,*
- *no-load losses,*
- *short-circuit behavior (torque, impedance).*

However, many parameters are load dependent and cannot be evaluated without current, thus will also serve as the basis for e-drive integration, for example:

- *variable phase resistance,*
- *flux-linkage established by the winding at different current vectors,*
- *peak torque at max current,*
- *peak power at max current,*
- *power at voltage limitation,*
- *continuous performance at different coolant conditions,*
- *duration of peak performance and cool-down times,*
- *current overshoot in transient short circuit.*

Here those parameter tests will be covered, which are necessary for the e-motor – inverter integration and cannot always be ideally performed by the application inverter. With help of the parameter tests the e-drive operation curves described in Chapter 4.1.4 can be calculated. Although the inverter could and can calculate optimal current vector trajectories real-time, it is more convenient to pre-calculate the MTPA, field weakening and MTPV curves and feed them to the inverter as multi-dimensional look-up tables.

4.4.2.1 VARIABLE PHASE RESISTANCE

Ohmic resistance of a conducting parts changes depending on the temperature of the material and the frequency and amplitude of the currents flowing the conductors. This means, the phase resistance of the electric motor will depend on the actual operating conditions.

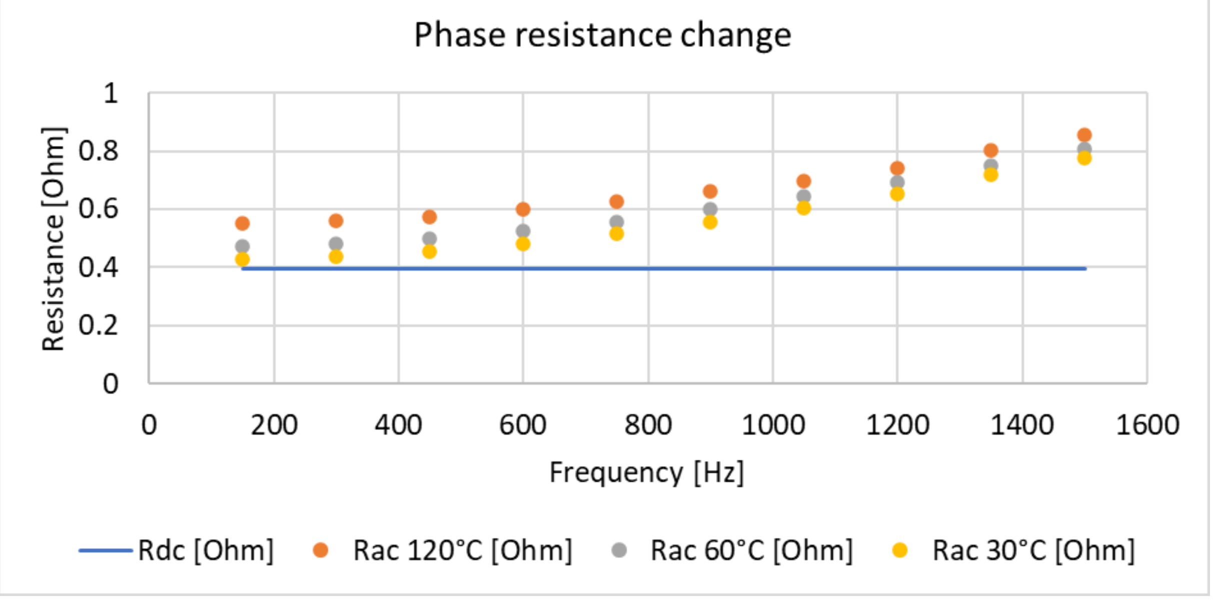
The ohmic resistance of usual conducting materials, like copper or aluminum changes proportional to the temperature:

$$R_1 = R_0(1 + (T_1 - T_0)\alpha)$$

Where R_1 is the new temperature due to change from T_0 to T_1 , R_0 is the resistance of the conductor at T_0 temperature and α is the temperature coefficient. Note, that temperatures should be used in [K] Kelvin.

Skin effect is a well-known phenomenon, where the current flowing in the conductor is pushed towards the conductor surface as the frequency increases due to eddy currents inside the material. This means, that at high frequencies the same current has to flow through a smaller cross section because the inner area of the conductor carries less current, which effectively translates to a resistance increase.

When conductors are placed near each other and surrounded by ferromagnetic material, like in the case of a conductors inside a stator slot, the current distribution in the conductors is affected by the total magnetic field. This is called the proximity effect, which is similar to the skin-effect, but it includes the influence of external magnetic fields. Typically, conductors in a winding suffer from this effect and will demonstrate phase resistance change depending on supply current conditions (amplitude, frequency, current phase angle). Sometimes this type of supply conditions dependent resistance is referred to as “AC Resistance” (Figure 4-29.). It must be noted, that depending on the measurement setup other type of losses, which are also interpreted as an ohmic resistance, may influence the results. Therefore, this test often takes place on a stator level only. Generally, figuring out how to separate the individual loss components in test results is field of study itself.



4-29. Figure An example of a AC resistance measurement at 3 different temperature levels and constant current, but varying frequency and the DC resistance at 20°C for reference. Note, how the resistance almost doubles compared to the initial level.

For motors, which have a significant AC resistance effect, thermal management needs to take this into account. Taking the Figure 4-29 as an example: under the same current, just the winding ohmic losses increase over 2 times between a low-speed driving and full speed. Under these circumstances the winding at high speed will overheat significantly faster than at low speed, even if the same current is flowing. Some simple thermal protection algorithms like I^2t, which is a current integral method, only takes care about the current over time, but does not consider that factors of losses might change themselves.

In summary characterizing the ohmic resistance's change is a necessary step to setup the e-drive's thermal protection strategy.

4.4.2.2 INDUCED VOLTAGE AND PERMANENT MAGNET FLUX

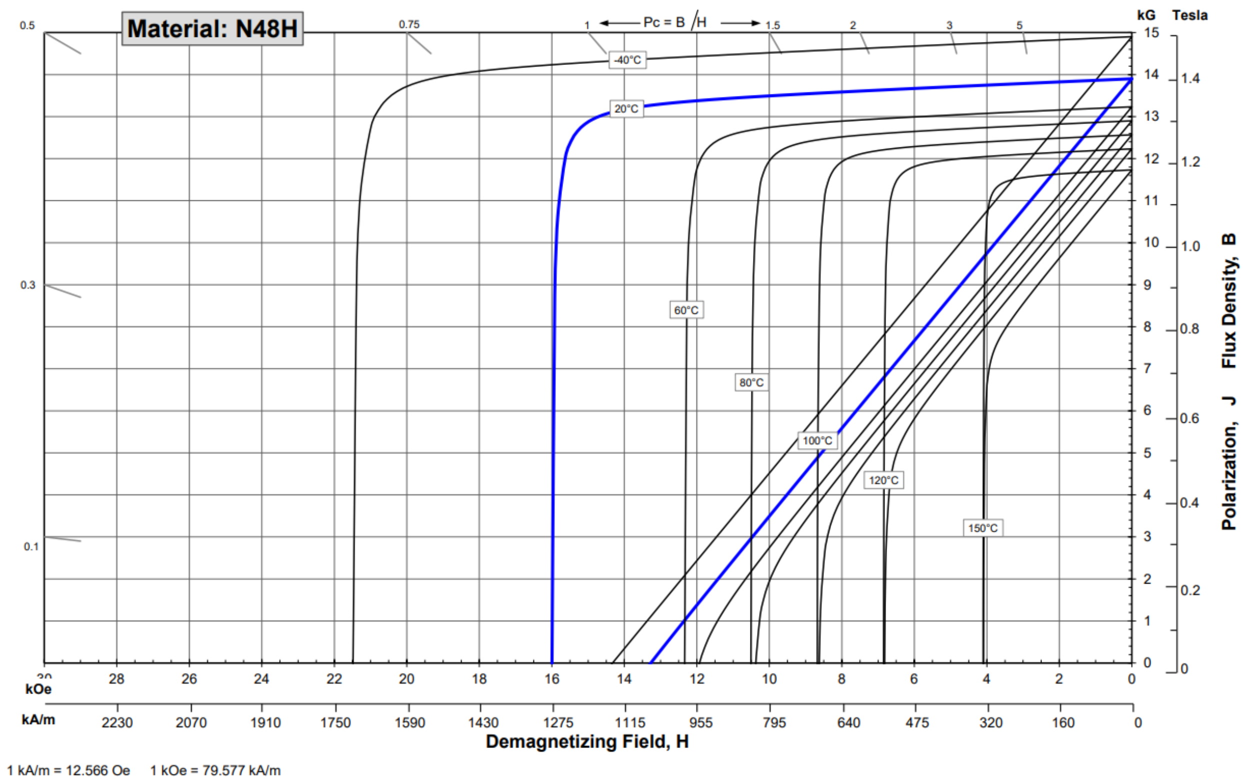
In case of permanent magnet motor (PMSM or IPMSM) or a motor with an excitation coil on its rotor the machine's rotor produces the air gap flux. The most convenient way to obtain the flux linkage established by the permanent magnets or the excitation coil is to run induced voltage measurements. Since permanent magnet flux is highly temperature dependent, the measurement must be carried out at multiple, but at least 2 temperature levels (Figure 4-30.).

The permanent magnet flux linkage's fundamental can be obtained from the voltage fundamental in a stationary, no-load, operation by:

$$\Psi_{pm,fund} = \frac{u_{i,fund}}{\omega_e}$$

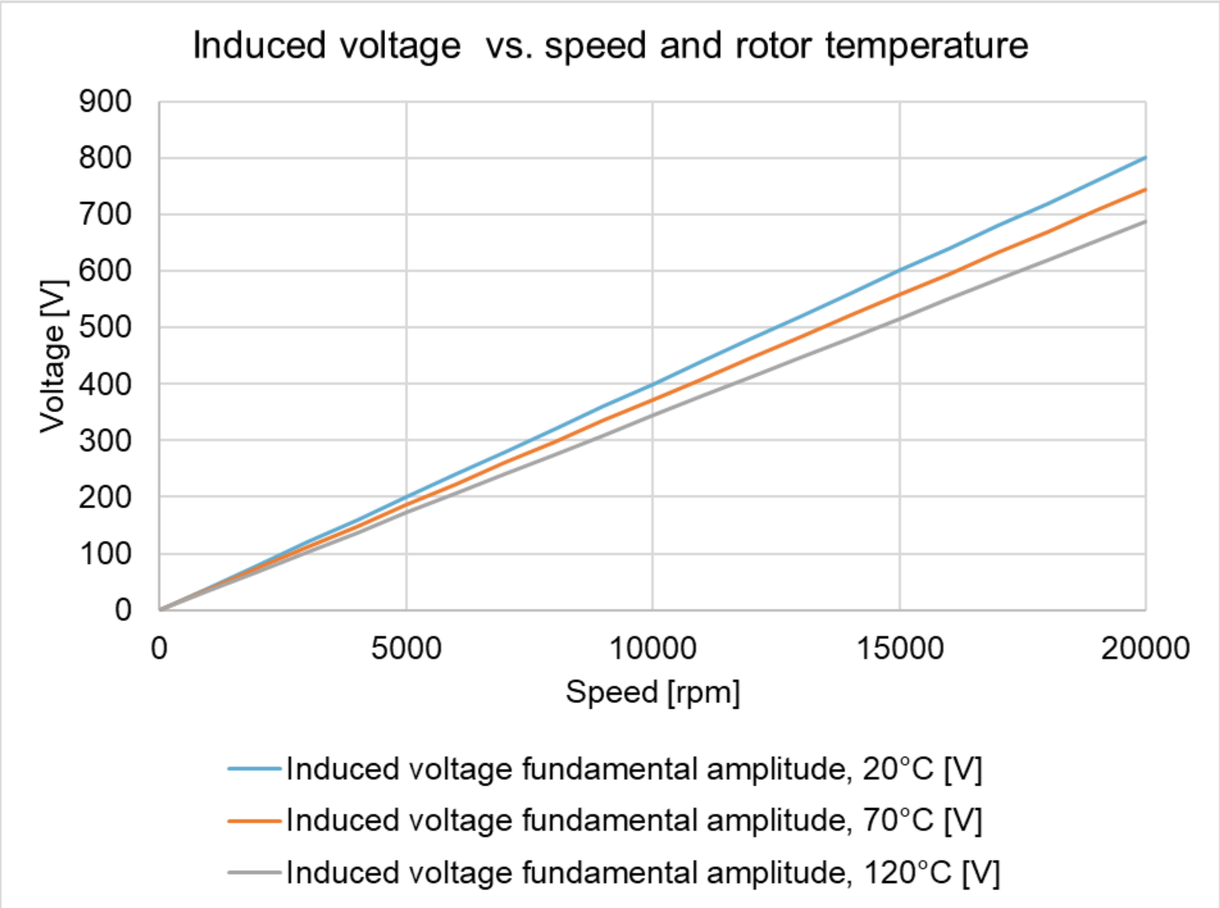
The flux linkage and the induced voltage are linearly proportional, which makes it easy to. The equation works for harmonics as well, but the electrical speed must be scaled appropriately.

The induced voltage's change due to temperature influence is normally linear (Figure 4-31.), since the range where electric motors operate and where tests are carried out fall in the linear behavior range of the permanent magnet materials (in case of rare-earth). Induced voltage variation therefore could also be approximately calculated if the magnet material's temperature coefficient [%/K] is known.



4-30. Figure BH curves of permanent magnet [23]

Electric motors are however assemblies which include several “parasitic” gaps besides the main air gap due mechanical tolerances. As a result, the induced voltage’s temperature dependency, or temperature coefficient, will not necessarily be the same as the magnet material’s.



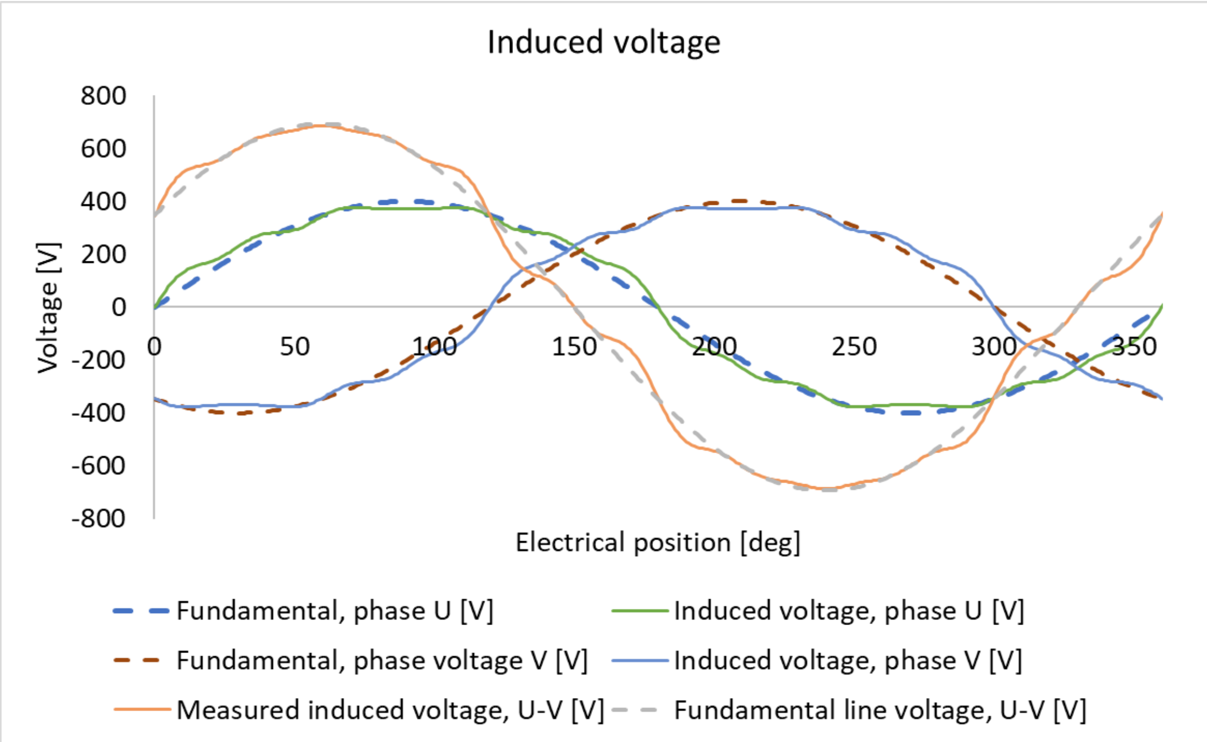
4-31. BEMF vs T and rpm example of an e-motor.

Similarly to the resistance tests, induced voltage can usually be measured only between phase terminals, which means the motor's actual phase voltage cannot be measured unless the neutral point of the winding is accessible. This means, that the zero-sequence components of the voltage waveform, like the 3^{rd} harmonic and its multiples, cannot be measured without the neutral. Therefore, even though the phase voltages can be calculated based on the measured phase-to-phase of line voltages, part of the information is lost.

The induced voltage waveform can carry information on the magnetic saturation levels inside the electric machine. Generally speaking, a higher harmonic content of the induced voltage, likely means a higher magnetic saturation in the machine. However, this cannot be taken as rule of thumb, since the induced voltage and its harmonic content will be heavily influenced, on purpose, by the machine designer, by:

- *winding layout,*
- *stator geometry (tooth and slot shape),*
- *rotor pole geometry,*
- *magnet geometry and*
- *skewing.*

Figure 4-32. shows an example of a measured line voltage and the corresponding phase voltages. The harmonic distortion in the example is slightly exaggerated for the sake of demonstration, however many high power-density electric motos display similar harmonic content. The dashed line indicates the fundamental component.

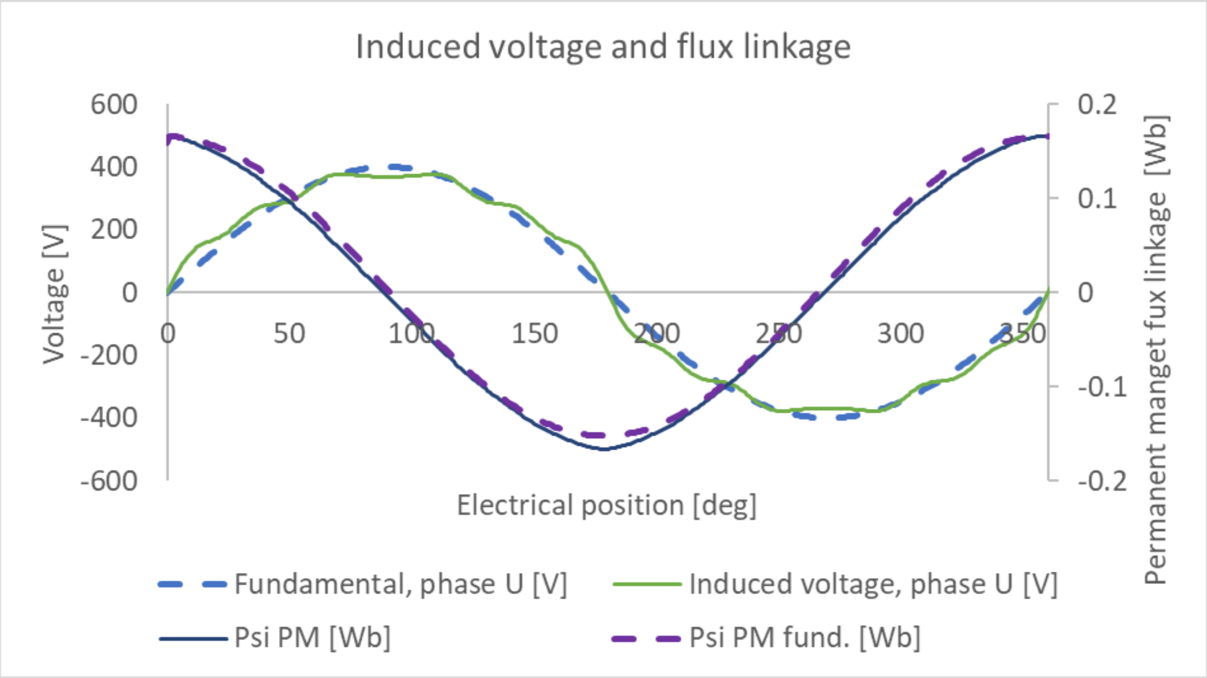


4-32. Figure Line voltage measurement and the corresponding phase voltages, indicating fundamentals. The corresponding line voltage and phase voltage are 30° shifted from each other.

As it was already established, the induced voltage of a PMSM electric motor strongly correlates to the flux linkage established by the permanent magnets. In a no-load case their relationship is described by Faraday's law of induction:

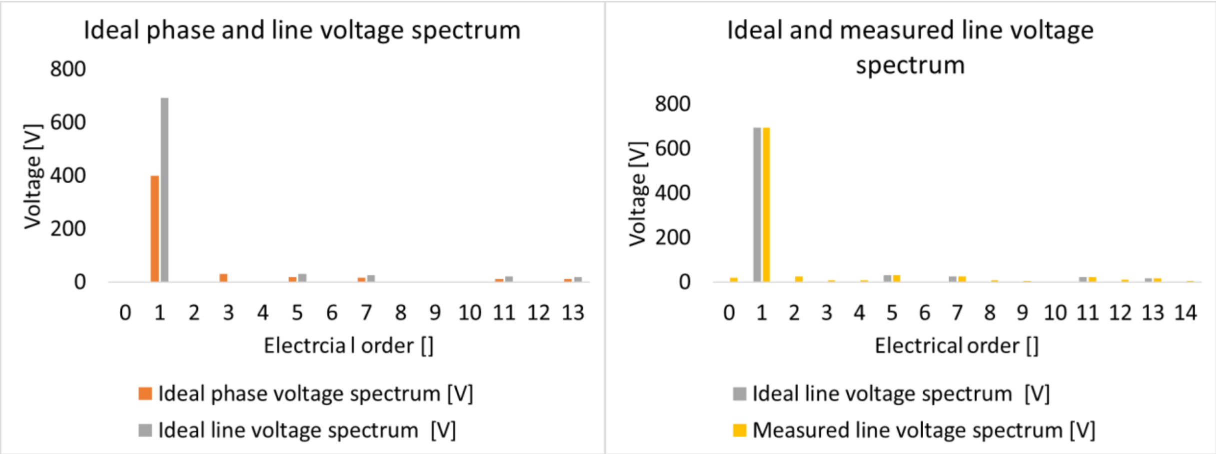
$$U_{BEMF}(t) = -\frac{d\Psi_{PM}}{dt}$$

Therefore, the permanent magnet flux linkage ψ_{PM} can be calculated using a simple integration as shown in Figure 4-33. The permanent magnet flux linkage ψ_{PM} is a main contributor in torque production, determining it correctly is essential for the parametrization of electric drives.



4-33. Figure BEMF and flux waveforms

Another useful way to visualize the induced voltage is by applying an FFT over a complete period. This way an order spectrum is obtained (Figure 4-34.), which a quite common tool for evaluation.



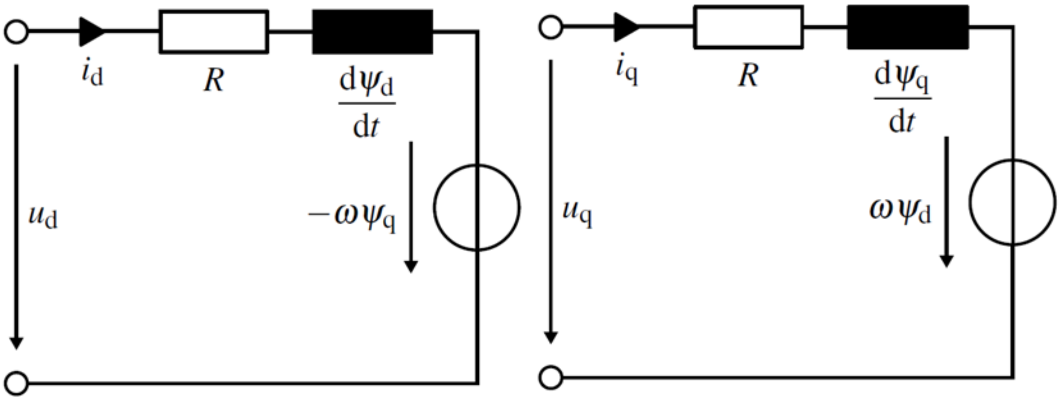
4-34. Figure BEMF spectrum

Neither the ideal or the measured line voltage contains, or should contain 3rd harmonics if the motor is in a good condition. If the measurement is taken with a non-constant speed, i.e. the dyno speed had low frequency oscillations or speed was simply changing during the measured period, sidebands will appear in the order spectrum. Such sidebands are measurement artifacts and unfortunately sometimes they can influence the evaluation results.

4.4.2.3 FLUX LINKAGE AND INDUCTANCES

Flux linkage is an essential parameter for electric drives. During a flux linkage measurement, the whole operation range of the e-drive is covered by (i_d, i_q) current vector pairs in order to map the D and Q direction inductances and flux linkages, which are essential for setting up a good motor control. While flux linkages naturally are available from simulation models as well, the parameter identification test is necessary to, first, validate the simulation models, secondly to increase the accuracy.

Using the DQ motor model, the machine can be described with two equivalent circuit models as shown in Figure 4-35.



4-35. Figure The PMSM's D and Q equivalent circuit.

As already described in a previous chapter, in stationary operation, where the derivative terms can be neglected, the motor voltages take the following form:

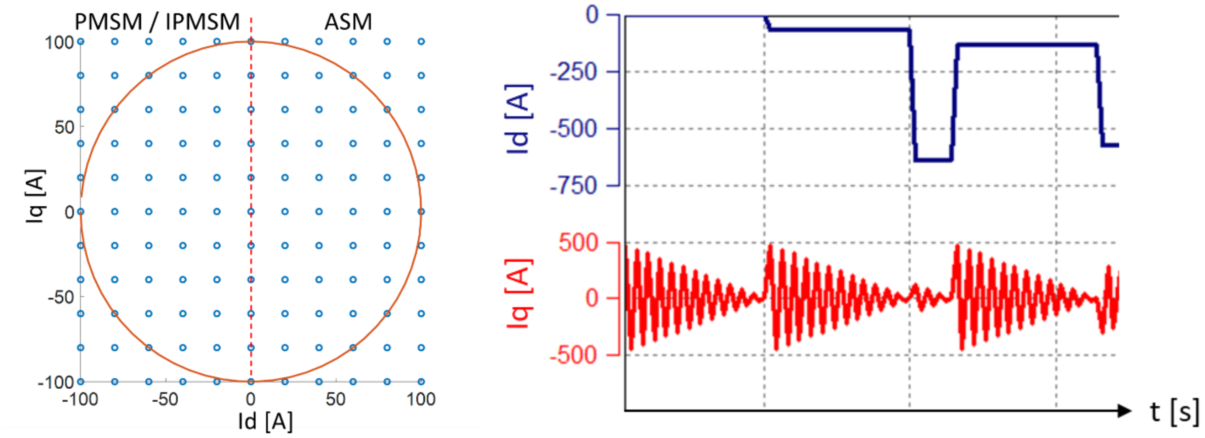
$$u_d = R_s i_d - \omega_e \Psi_q$$

$$u_q = R_s i_q + \omega_e \Psi_d$$

The resulting parameters are functions of the current vector:

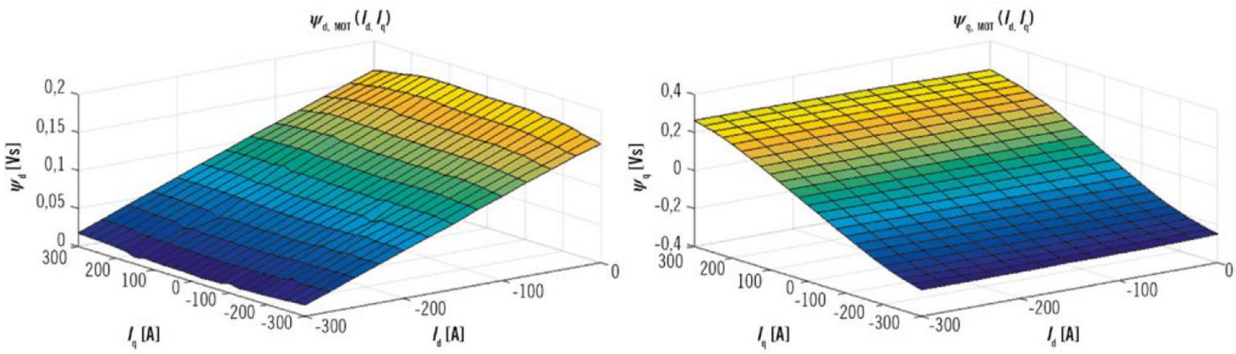
$$\psi_d(i_d, i_q), \psi_q(i_d, i_q); L_d(i_d, i_q), L_q(i_d, i_q)$$

Based on the equations it is easy to conclude, that previous information of the phase resistance is needed in order to compensate for resistive influence.



4-36. Figure Id and Iq current vector grid (left) and test execution shown in time domain (right)

Figure 4-36. shows an example for PMSM and ASM motor types and an example of the test's actual run with applying all the (i_d, i_q) operation points to the motor. The orange circle represents the current limit of the motor which shall not be exceeded. The test runs on a fixed, usually low, speed and sweeps through the pre-defined (i_d, i_q) combinations.

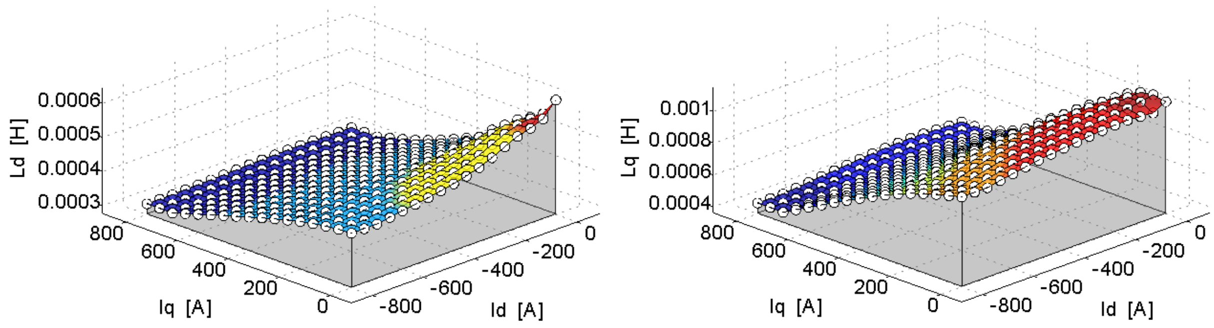


4-37. Figure Flux tables resulting from the identification measurements.

The fundamental fluxes (Figure 4-37.) are calculated based on voltage and L_d and L_q (Figure 4-38) in stationary operation can be calculated based on the equations:

$$L_q = \frac{R_s i_d - u_d}{\omega_e \cdot i_q}$$

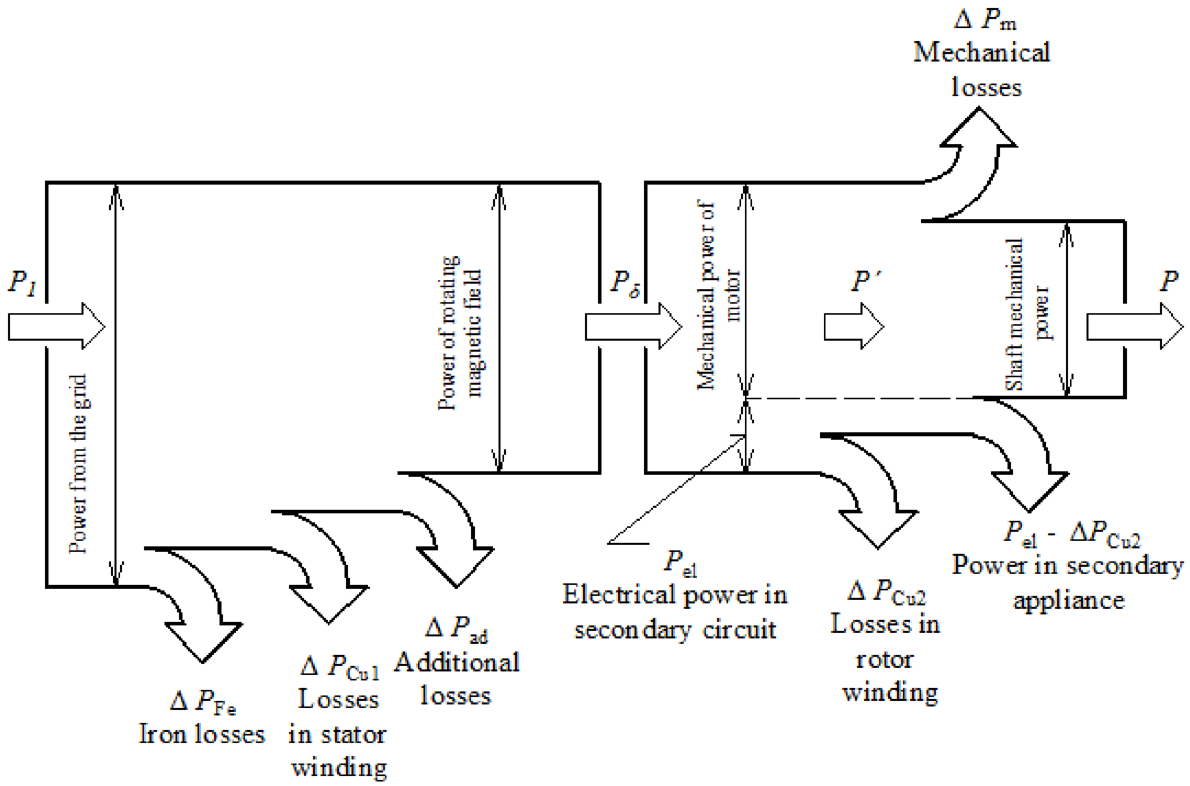
$$L_d = \frac{R_s i_q - u_q + \omega_e \Psi_{PM}}{\omega_e \cdot i_d}$$



4-38. Figure LdLq inductance maps example, in motor mode only

As the equations show ψ_{PM} is needed to compensate for the flux, which is not established by the Id current, but the permanent magnets.

Usually, during the flux linkage mapping measurements the motor torque is measured as well. Therefore the function of the torque in terms (i_d, i_q) is identified as well in the process *T = f(id, iq).* It must be noted, that the torque measured in this step is not going to accurately represent the motor behavior, since it lacks the speed dependency. Electric motors will exhibit increasing losses together with increasing mechanical speeds with components shown in Fig Losses.



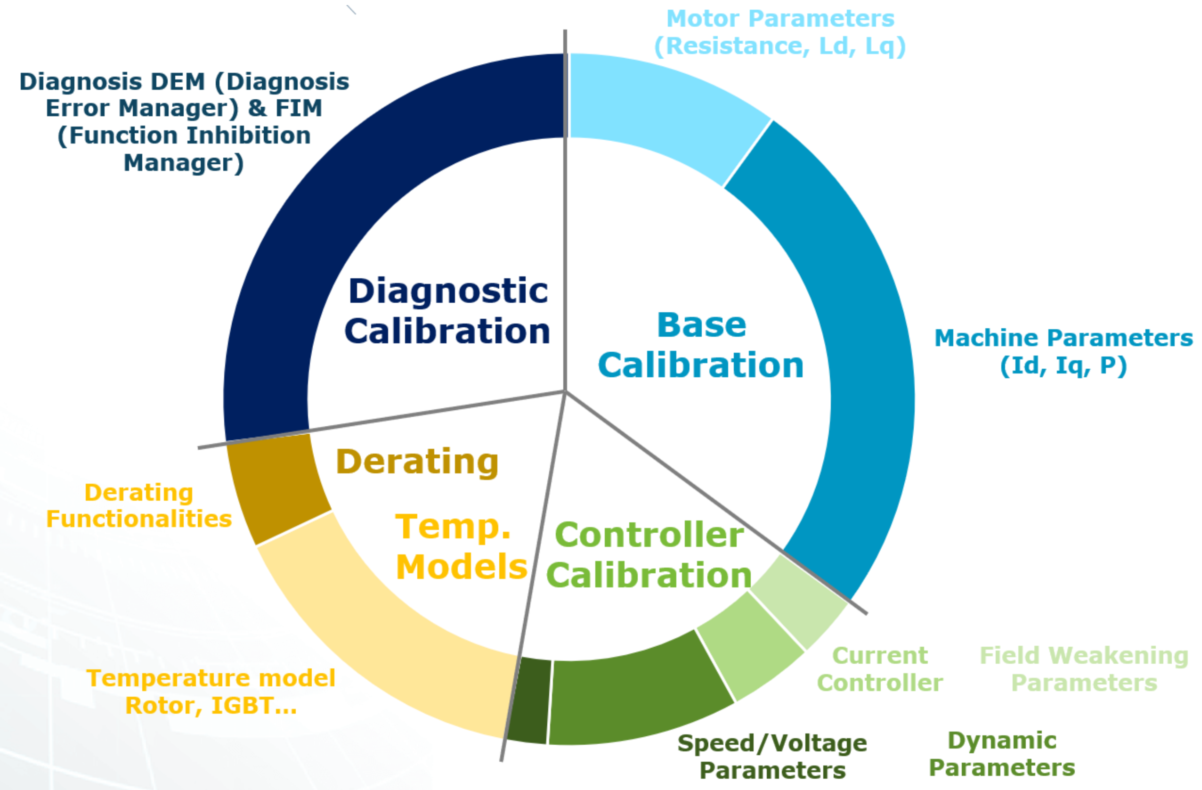
4-39. Figure Overview of losses in an e-motor from the input terminals, through the stator and air gap towards the shaft [24]

4.5 ELECTRIC DRIVE TESTING

Once the electric motor has been thoroughly measured and its parameters have been identified the validation and set-up process of an electric drive is approximately 33% ready as Figure 4-40. shows. All the required machine parameters are known allowing to create the starting calibration of the inverter. As described in the *Section 4.1.3* the inverter needs the following parameters for accurate and dynamic control:

- POLE PAIR NUMBER, *this one* IS ESSENTIAL,
- *permanent magnet flux linkage,*
- *Ld and Lq inductances.*

Due to the non-liner behavior of most these parameters (pole pair number does not change of course), instead of scalar values, 1D or rather 2D look-up tables are used as shown before.



4-40. Figure Diagram showing the distribution of efforts spent on specific times during validation and integration

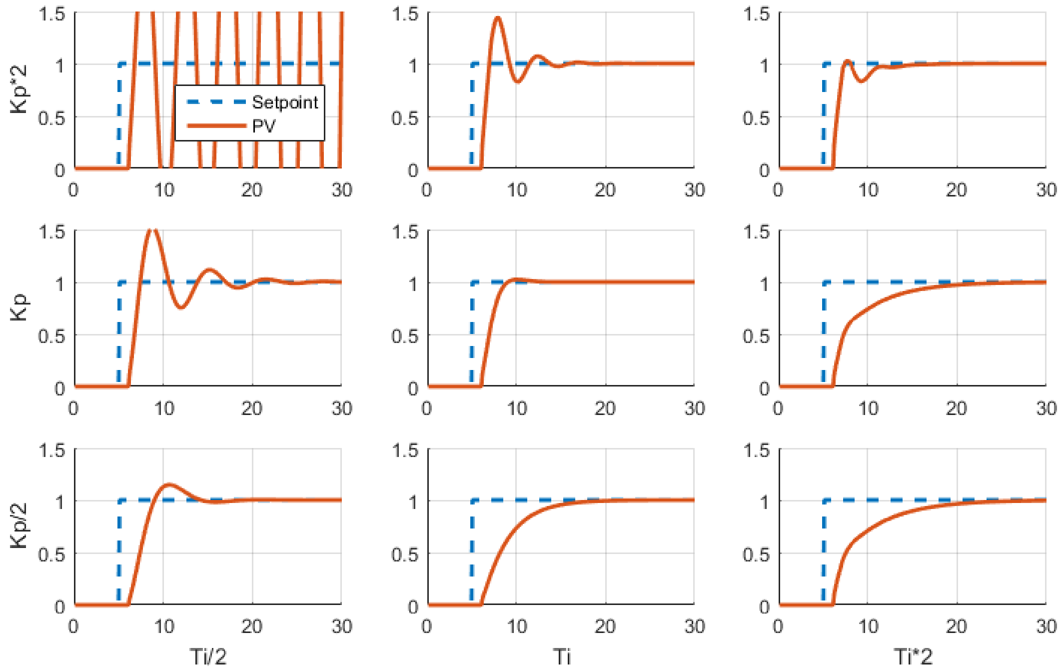
The very first part of the integration after the electrical connection of the e-motor to the inverter is to flash the *rotor position sensor's offset value* in the inverter software. The procedure is described in the *Section 4.4.1.6*. Practically, once the FOC control SW knows the motors pole pair number and the position sensor is calibrated, the inverter can drive the motor with specific currents defined as (i_d, i_q) with low dynamics.

4.5.1 CURRENT CONTROLLER OPTIMIZATION

Very likely, with the initial (or default) PI controller settings the currents will not reach their target value optimally (see Figure 4-41.). Normally during the tuning, the behavior in the middle of the Figure 4-41. is the target. Ideally the current controller needs to be tuned to overcome the motor's electrical time constant T_e, to reach fast current response.

$$\tau_e = L/R$$

Since current is directly proportional to the developed electromagnetic torque, the current step response is a key parameter to tune in electric drives. The difficulty arises from the fact, that the motor's parameters are current dependent, therefore a single, globally optimal PI tuning value usually does not exist. In order to achieve a good current response different operation points the P and I gains are look-up tables. The controller gains change depending on the actual desired operating point and sometimes even other boundary conditions like PWM frequency and DC voltage. The control tuning process during the electric drive integration is an essential step, since usually parasitic effects of cabling and sample deviations make it difficult to use purely simulation based tuning values.



4-41. Figure PI tuning, influence of changing the P (Kp) and I (Ti) gains of the controller [25]

After the basic PI tuning, where the inverter is tuned in a way, that it can reach any current set-point optimally with its PI controller the inverter is ready to go with its pre-uploaded look-up tables.

While the operating tables obtained from e-motor testing are already providing information on the optimal e-motor efficiency, the complete electric drive system's efficiency may not be optimal yet. As it was already demonstrated in Figure 4-9., the inverter efficiency plays an equally significant role. Also, the initial parameter tables do not necessarily include electric motor losses, therefore torque accuracy based on the initial parameter tests at fix speed can be suboptimal.

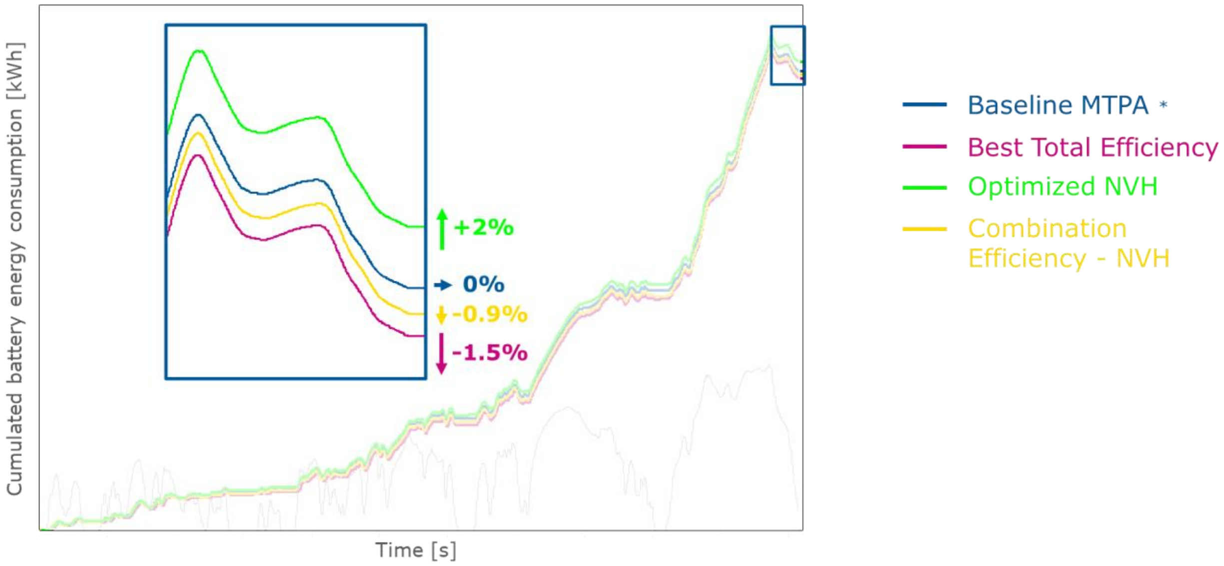
Due to these reasons during the electric drive integration additional tests are done to calibrate and tune the electric drive as a system. Efficiency is only one of the targets. An electric drive usually must fulfill different objectives as well, like:

- *system efficiency,*
- *NVH (Noise Vibration Harshness),*
- *torque ripple,*
- *EMC.*

Traction inverters offer a wide range of parameters, variables and flexibly configurable functions, which can be tuned individually like:

- *PI controller gains,*
- *switching frequency,*
- *modulation method,*
- *current vector,*
- *harmonic injection.*

All the targets cannot be fulfilled completely at the same time or by the same settings, as they often are opposing each other. It means, that the either the inverter can switch between different optimal driving strategies, depending on the actual goal (efficiency, NVH, current THD, etc…), or it can use a trade-off between the different targets. The electric drive integration and calibration testing is supported by various tools which enable modeling the cost function, be it efficiency, noise or other indicator and find the optimal parameters settings in the multidimensional space of variations. Figure 4-42. shows an example of the impact of different inverter parameter tunings on efficiency and NVH and the resulting best compromise.



4-42. Figure Optimization based on energy consumption over a drive cycle

Since the inverter offers many parameters which all influence the e-drive's behavior it has become unpractical to tune all of them manually. Additionally, the number of measurements needed, to fill up look-up tables with a "brute-force" method, by measuring every possible combination yields just too many measurements and high effort.

If one would approach the problem the classical way using a full-factorial method, in order to measure e.g. the torque as function of I_d, I_q currents and PWM frequency with just 10 different values each, the total amount of measurements would be:

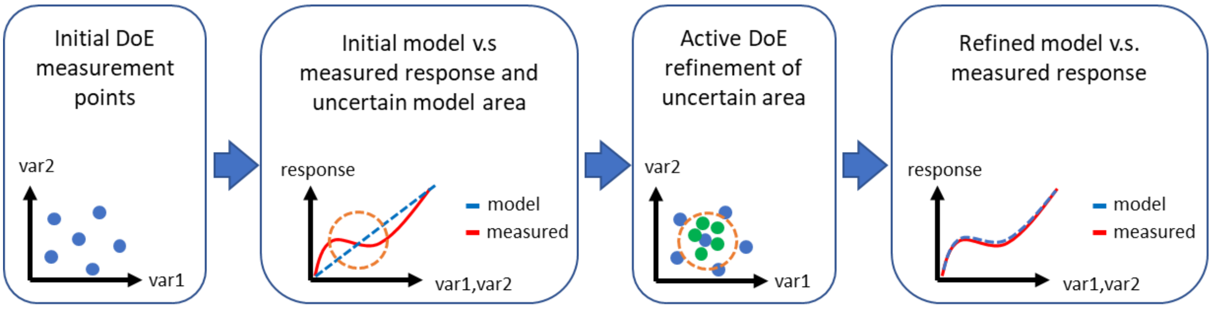
$$N = k_{id} \cdot k_{iq} \cdot k_{pwm} = 10 \cdot 10 \cdot 10 = 10^3 = 1000$$

A thousand measurements can take a long time to complete. Instead, automatic test bed controlling tools supporting DoE (Design of Experiment) methods are gaining popularity. DoE covers multiple methods of experiment design. In a nutshell, DoE's goal is to reduce the number of measurements required to accurately capture the behavior of a response (like torque) as a function of variations (i.e. Id, Iq and PWM frequency). Even more sophisticated tools actively model the response function during the test and compare it to the actual measured values.

$$T_{model} = f(Id, Iq, PWM)$$

$$model\ error = T_{model} - T_{measured}$$

Where the model error is too high, the measurement control increases the amount of measurement point around it, thus improving the model accuracy. This method is called Active DoE and the process is shown in Figure 4-43. In practice Active DoE yields as good results as a full factorial analysis at significantly reduced testing time.



4-43. Figure Active DoE

Now we have seen, how different target functions, responses can be modeled based on variations in measurement results. The next step is the optimization itself. The goal is to find the variable combination(s) which lead to the desired value of the target function. Figure 4-44. shows, how the inverter parameter variations influence the e-drives performance parameters, like torque, losses, and current harmonics. In this approach each target (or response) becomes a function of the chosen variation parameters. For example, the loss written as the function of the (i_d, i_q) current vector, the mechanical speed and the inverter's PWM frequency is:

$$P_{loss} = f(Id, Iq, rpm, PWM)$$

Similarly, the current THD is:

$$THD = f(Id, Iq, rpm, PWM)$$

Such functions are built using multi-dimensional "curve fitting" and shown on Figure 4-44.

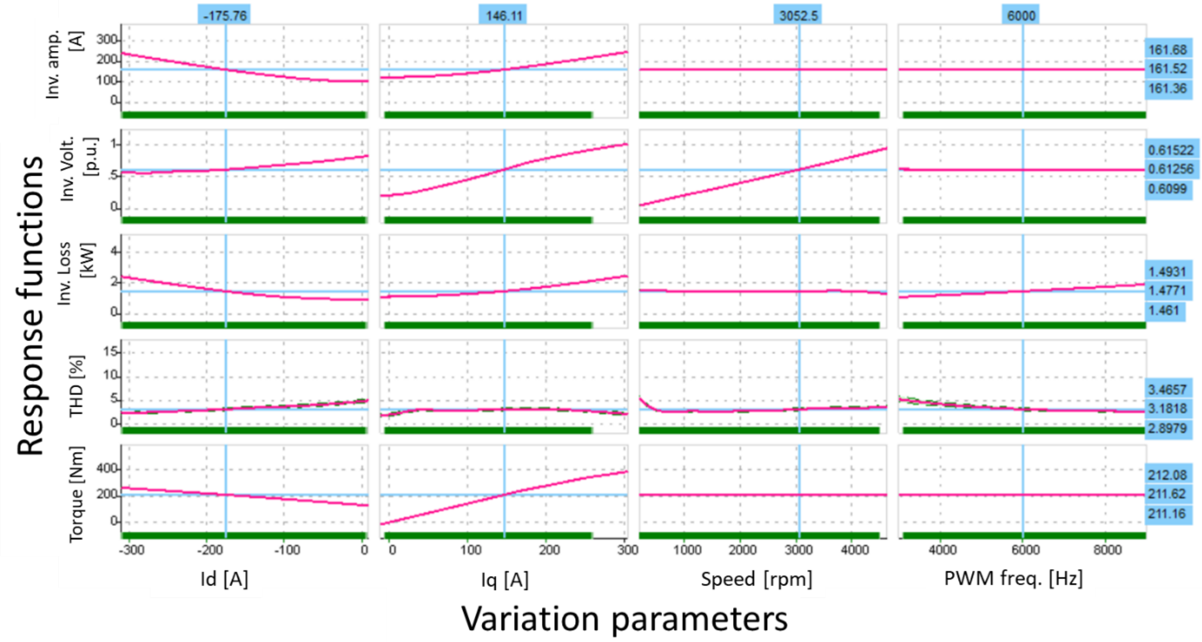
The optimizer's task is usually to find the minimum of the response functions (of course, the response function must also be defined accordingly), such as:

$$\min(P_{loss})$$

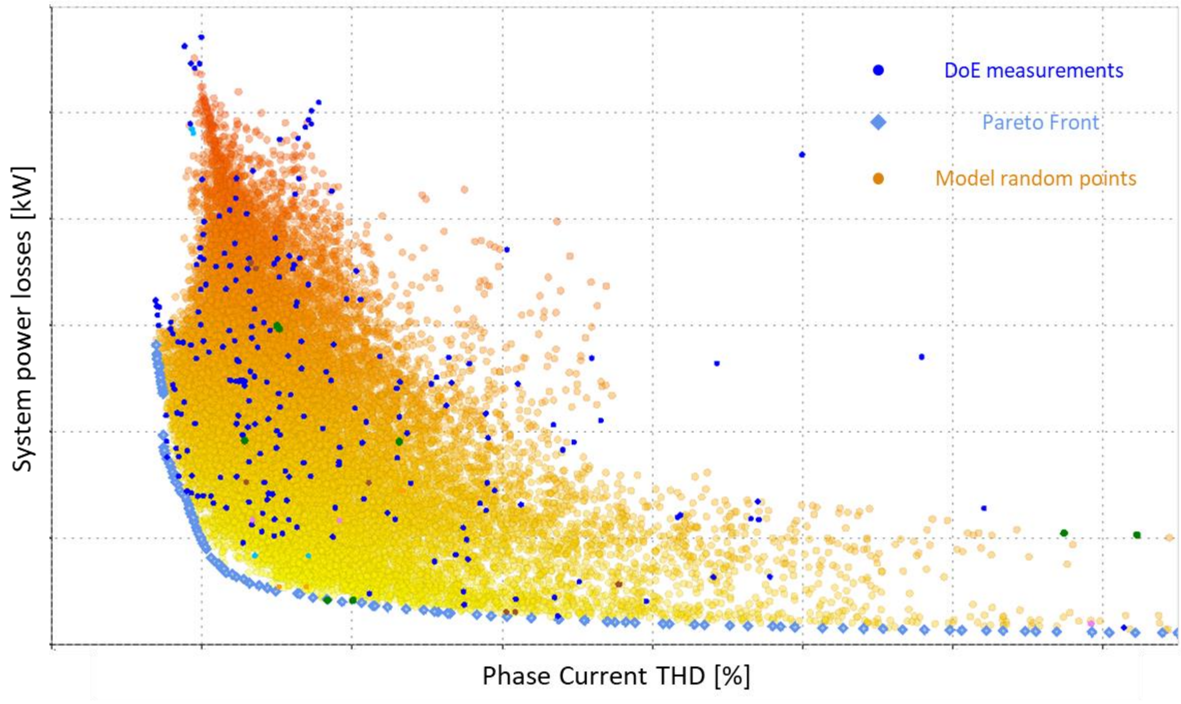
and

$$\min(THD)$$

That is, to find the (Id, Iq, rpm, PWM) parameter values, where both the losses and the THD are minimal. That is how we obtain the so-called Pareto front shown on Figure 4-45. We can observe, how minimizing the losses eventually leads to a rapidly increasing current distortion, which is in close relationship with EMC behavior. At the same time reducing current harmonics costs power, as approaching the THD minimum goes hand in hand with the increase of losses. We can conclude that on one hand, *it only makes sense reduce losses until the current quality is still acceptable* and on the other hand, *to improve current quality unnecessarily will just negatively impact the system efficiency*.



4-44. Figure Variation and modeling



4-45. Figure Pareto front, and how to find the best trade-off between multiple objectives of an optimization.

4.5.2 PEAK PERFORMANCE TESTS

Electric drives usually feature a rather high overloading capability. This is also referred to as the peak characteristic, and it is an operation mode, which cannot be continuously maintained. The duration is depending on the electric machine and power electronics design, the actual coolant and ambient temperatures and, of course, the actual temperature of the components resulting from previous operation.

The goal of peak performance testing of electrical drives is to measure the available maximum torque and power under different boundary conditions, such as speed, DC voltage, coolant temperature and flow rate, ambient temperature, etc. Additionally, thermal aspects of high-power operation can be evaluated at the same time. The tests will clearly show under different conditions which component reaches its thermal limit first, thus limiting the operation time and triggering derating. Of course, the UUT needs special preparation in terms of installed temperature sensors. Sensors are usually mounted in the following locations:

- *stator winding head,*
- *stator slot,*
- *coolant inlet and outlet (all coolant liquids),*
- *stator housing,*
- *rotor (either slip ring telemetry or other contactless solution),*
- *bearing,*
- *inverter power electronics (junction temperature measurement usually integrated to the power semiconductors and usable via the gate driver IC),*
- *various points on the electric drive's housing,*
- *ambient temperature.*

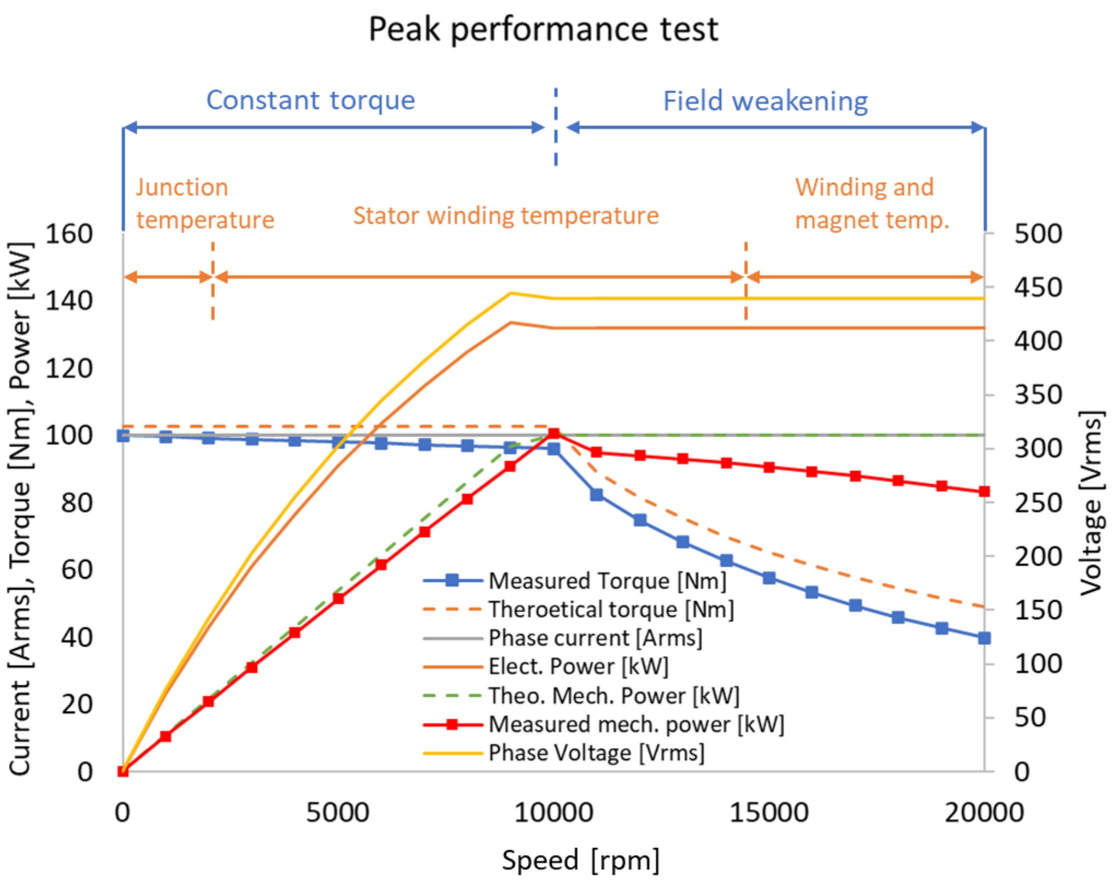
Often, these results can be used to determine operational limits of the electric drive at peak performance or to establish and calibrate thermal models, which will help protecting the unit from overheating in the final application.

As the efficiency maps (Figure 4-9.) already suggest the losses generated during operation are not always split between the inverter and e-motor the same way. The inverter conduction losses can be higher during low-speed operation due to the peak current flowing for extend duration. The extreme example is stand-still mode. The power semiconductor's junction volume is rather small; therefore it heats up very fast. Torque in standstill is often limited due to this reason.

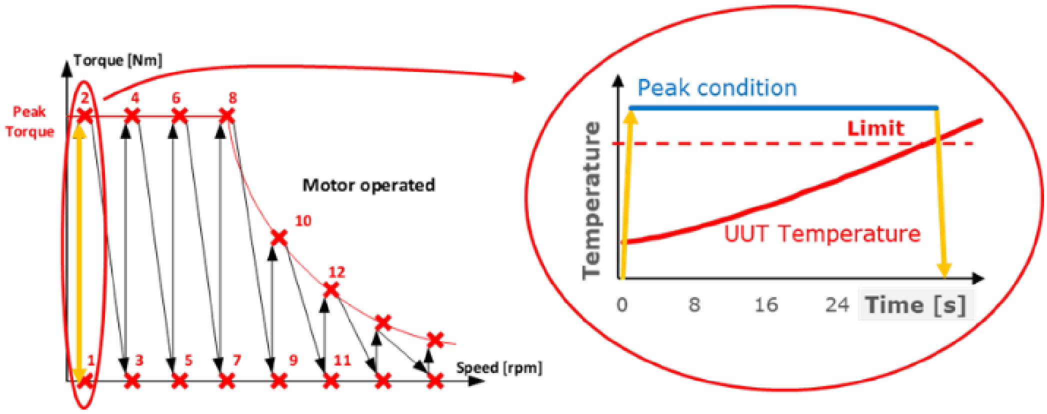
Phase currents cause ohmic losses in the stator winding, thus heating it up. High power density electric drives with liquid cooling are often designed to reach peak torque and power at current densities over 30 [A/mm^2]. This high current density cannot be maintained continuously as even liquid cooling cannot dissipate the heat fast enough to keep the temperatures below the thermal limit of the winding's insulation. Also, a considerable portion of the winding, the winding head, hangs out of the stator and often is not cooled directly. Outside the stator the liquid cooling does not take effect. Thus, at peak power winding temperature rises rapidly and usually reaches a thermal limit within fraction of a minute.

Magnet temperature in peak power operation usually isn't a bottleneck since the rotor's thermal response is slower than the winding's. However, it cannot be excluded. At higher rotational speeds the eddy current losses rise exponentially. In high-speed peak power operation current waveforms often deteriorate from pure sine due to limited inverter frequency. The excess current harmonic resulting from worse current control also add to the magnets eddy current losses. This can lead to increased magnet temperatures, which together with a large demagnetizing field can cause irreversible polarization loss.

Figure 4-46. shows an example of a peak performance measurement done with constant current control and voltage limitation. The indicated theoretical torque and power curves are results of the pure e-motor equations, which do not take losses into account. Consequently, the measured torque and power deviates from the theoretical as speed dependent losses increase. During the test the maximum torque is demanded from the inverter, which was already calibrated for torque control after the controller optimization. The peak power is maintained until the temperature limit is reached. Afterwards a cooldown period follows before the next operating point (Figure 4-47.).



4-46. Figure Example of a peak performance measurement at constant phase current indication the usual possible thermal limit factors.



4-47. Figure Peak performance tests involve cool-down periods between OPs and are run in a sequence.

4.5.3 CONTINUOUS LOAD TESTS

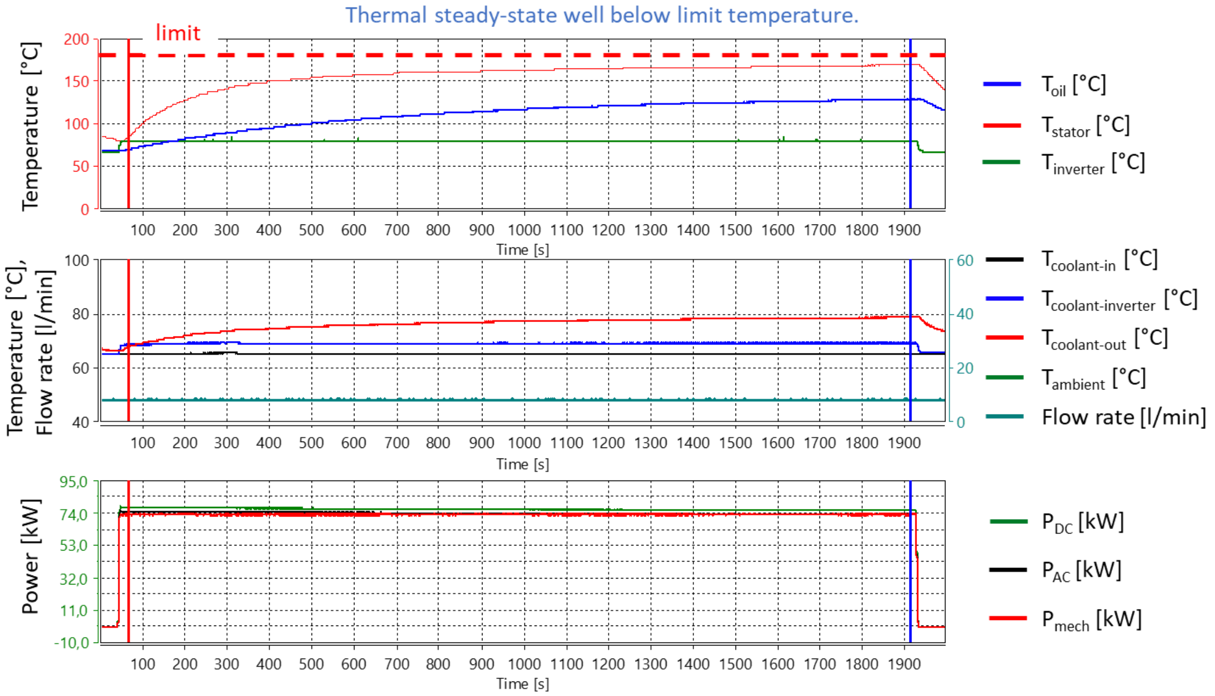
The definition of continuous operation, or the S1 continuous duty, is that the electric drive can maintain the operation point long enough for the motor temperatures to reach a steady-state value (i.e. below or equal to limits). During the continuous load tests the goal is to check, whether the pre-defined continuous load operating points reach a steady-state temperature value below the limits. That means, during continuous operation neither inverter temperature, stator temperature, magnet temperature or any other temperature limit shall not be exceeded [26].

The other objective is, to derive parameters for thermal calibration of the drive unit. As shown in Figure 4-20. thermal calibration is one of largest part of the drive calibration. This is mainly due to amount of time needed to reach steady-state temperatures, both under load and in cool-down. Test automation systems can help to find the limit of the continuous operation via testing. The test system can monitor the temperatures during the tests and step-by-step increase the torque demand of the electric drive. After applying a new demand, the system waits until the steady-state is reached (Figure 4-49.), and if the temperature is within the tolerance, defined around the limit temperature, the limit point is found. Then the automation can go to the next rotation speed or even change other boundary conditions as well, like coolant flow rate, temperature etc.

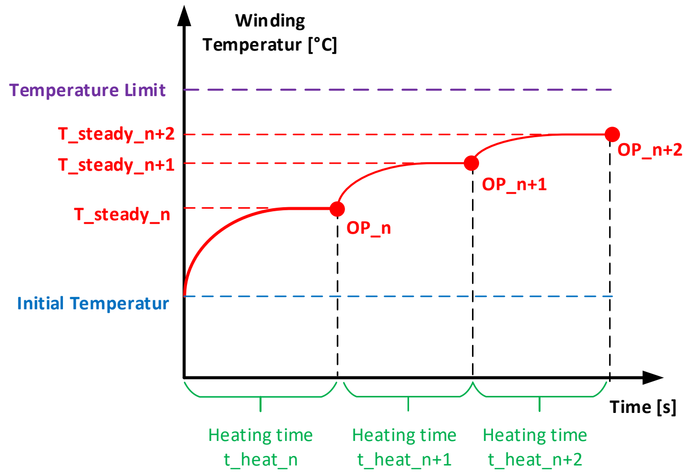
To summarize continuous load testing falls into two main categories of different objectives:

- *To* CONFIRM E-DRIVE THERMAL BEHAVIOR*: apply a pre-defined operation point at pre-defined boundary conditions, e.g. an OP from the requirements specification and run the OP for the specified time. Monitor temperature during the test and evaluate results. If no overtemperature occurred, then the UUT is OK. If temperature limits are reached during test, the unit could be faulty and the root-cause of the problem must be found. Figure 4-48. shows an example of a test of this kind.*
- *To* FIND CONTINUOUS LOAD LIMITS*: run automated or manual test sequence, to find the maximum load for each required condition by adjusting the load until the*

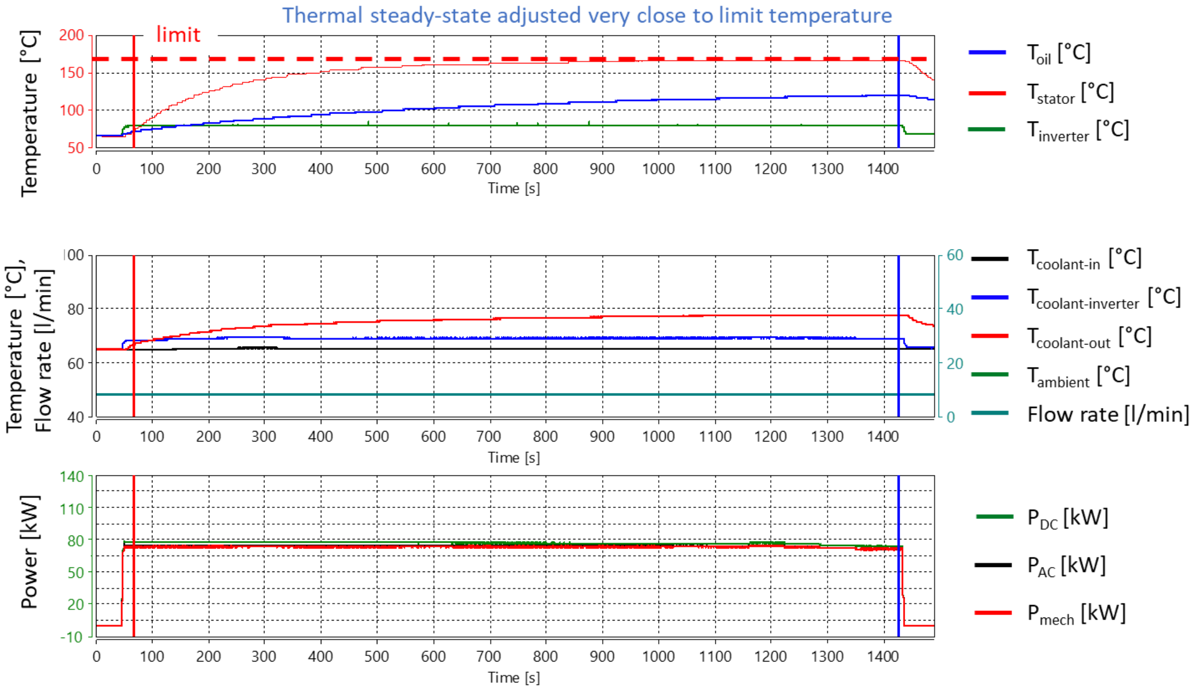
stead-state temperatures reach the thermal limits of the e-drive. Figure 4-50. shows an example for this type of test.



4-48. Figure Continuous load, pre-defined operation point run for 30 minutes.



4-49. Figure Continuous performance measurement to find the maximum allowed load.



4-50. Figure CLOR tests, thermal steady-state found by actively adjusting the power output of the drive.

4.5.4 DRIVING CYCLES

To evaluate how an electric drive performs over realistic, but still uniform, repeatable conditions, driving cycles were defined. These cycles supposed to represent an average usage in a specific region. NEDC (New European Driving Cycle) is composed of two parts: ECE-15 (Urban Driving Cycle), repeated 4 times, is plotted from 0 s to 780 s; EUDC cycle is plotted from 780 [s] to 1180 [s] as shown in Figure 4-51. WLTP (Worldwide harmonized Light vehicles Test Procedure) is a global standard for determining pollutant and energy consumption for light vehicles. In practice NEDC is used most often in Europe.

Driving cycles are defined for complete vehicles. On an e-motor test bed naturally we might see different power consumption levels. The results are still useful however, since they provide an average performance utilizing mostly the nominal operation area of the electric drive and are useful to comparison of UUTs and optimization.

The evaluation for electric drives is straightforward. The measured electric power system input and mechanical output powers are integrated. Thus, we obtain the complete supplied energy and the mechanical work and the efficiency of the conversion process can be calculated.

Total energy input from the battery:

$$E_{DC} = \int P_{DC} dt$$

Total energy output of the inverter to the e-motor:

$$E_{AC} = \int P_{AC} dt$$

Mechanical work output of the electric drive:

$$W_{mech} = \int P_{mech} dt$$

System efficiency over the cycle:

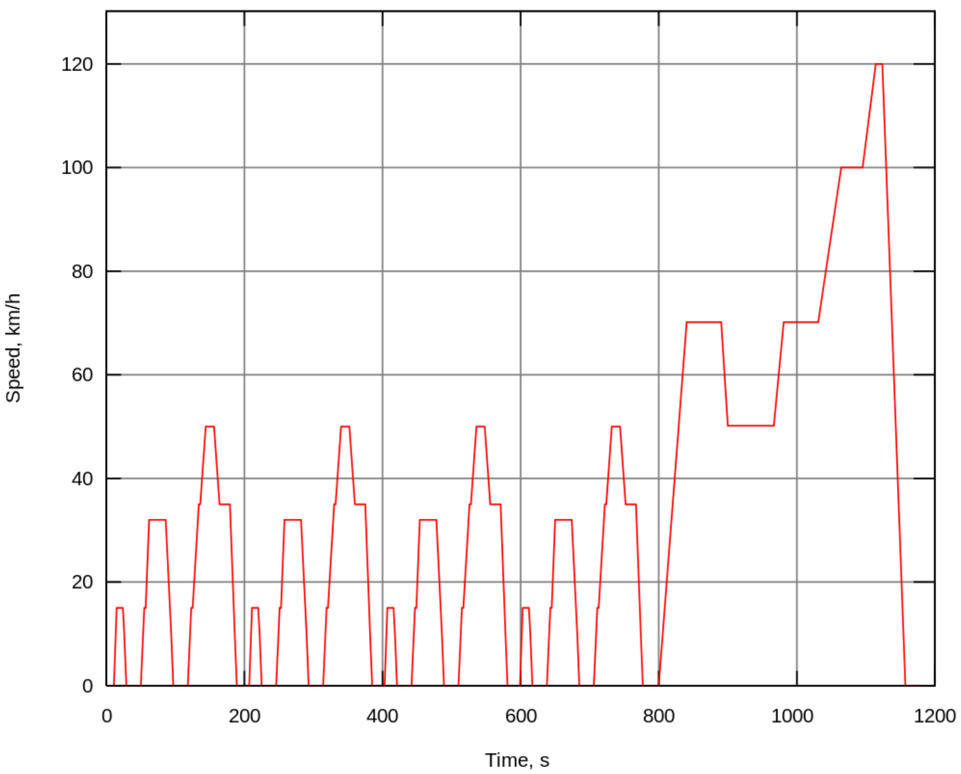
$$\eta_{sys} = \frac{W_{mech}}{E_{DC}}$$

Inverter efficiency:

$$\eta_{inv} = E_{AC}/E_{DC}$$

Motor efficiency:

$$\eta_{mot} = W_{mech}/E_{AC}$$



4-51. Figure NEDC driving cycle [27]

4.5.5 NVH TESTING

Every moving component is a potential source of vibrations and noise, which can be disturbing for the user or problematic for the application. The topic of NVH (Noise Vibration Harshness) can be dived into parts. First, there are mechanical vibrations, which are harmful and could potentially increase wear of parts, resulting in less reliability or substandard performance. Second, from the human user's point of view harsh noises and vibrations can cause discomfort and substandard user experience.

Mechanical vibrations propagate via transfer paths through solid materials, liquids, and gases. In order to reduce the perceived vibration and noise at the output, either the source must emit less disturbance or the transfer path carrying the disturbing vibrations and noise towards to the investigated location or user (driver) must be changed. The mounting of the source needs to be improved in a way, that it blocks or absorbs more of the noise from the source. For example, in conventional cars with combustion engines, which traditionally are not silent power sources, vibrations are reduced by decoupling the combustion engine from the chassis. The engine is mounted to the chassis via rubber engine mounts, which effectively dampen the vibrations coming from the engine. An engine emits noise as well, since it has many adequate surfaces to couple via air. The noise levels are reduced by noise absorbing mats and panels mounted inside the engine compartment. The passenger compartment has of course even more layers of noise insulation to ensure acceptable noise levels inside.

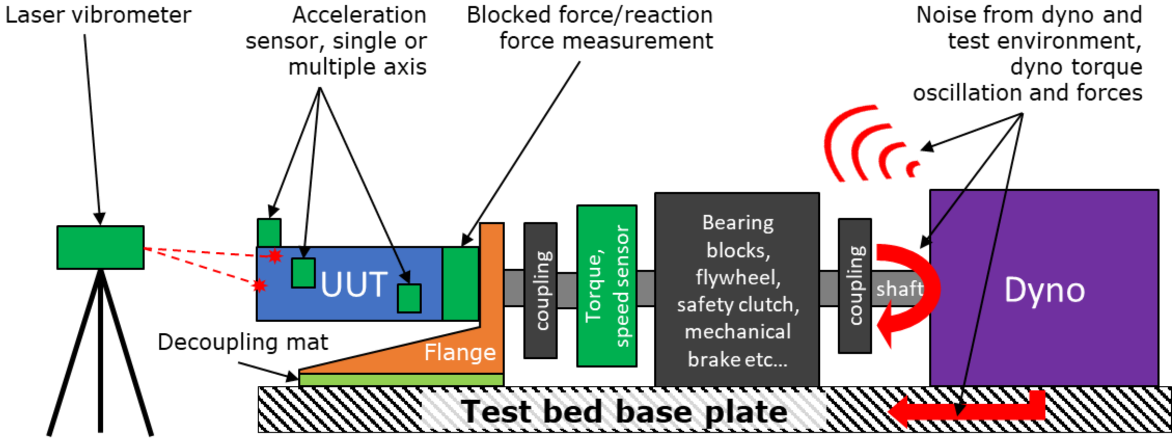
While electric drives in general operate considerably more silent than combustion engines with equivalent power, NVH testing of electric drives has become emerging trend. Even though the acoustic behavior and acceptance testing is still carried out on complete vehicle level, front-loading to component level, like electric drive is becoming increasingly common. The explanation to this controversy is, that it is significantly less effort to implement changes early in the development process, then in its final steps.

When measuring the NVH behavior of a test sample, it is essential to isolate the UUT from its surroundings, since it will influence the results. The measurement focus is the UUT, the only source of vibrations and noise of interest. Depending on the scope of testing and measurement method different test setups must be considered. A classical e-motor test bed has various elements which can introduce disturbances to the test results:

- *fans and cooling units,*
- *gearbox,*
- *bearing blocks and couplings and*
- *the dynamometer.*

These parts usually have stiff, well conducting, path through the shaft, flanges and the baseplate towards the UUT, where their influence can deteriorate the test results.

Nevertheless, a number of measurements can still be performed on the e-motor test bed in case the UUT flange offers some level of mechanical vibration decoupling and the dyno runs significantly smoother than the UUT as shown in Figure 4-52. Induction motor dynos coupled with flywheels can provide good enough performance. The sensor types yielding useful result on a simple e-motor test bed are usually acceleration sensors based on piezoelectric principle.

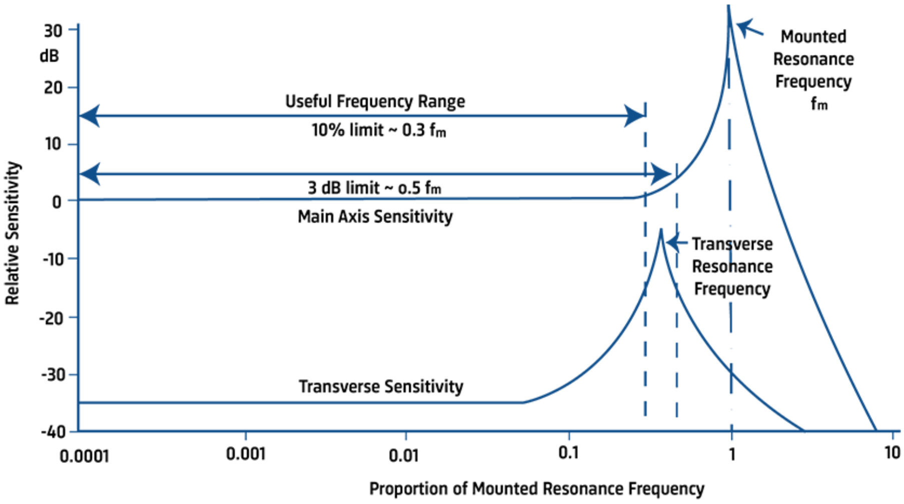


4-52. Figure NVH test on an e-motor test bed, torque oscillations and surface accelerations, blocked force, structure borne noise considered

While the measured quantities are often accelerations (or rather, the voltage proportional to the accelerations) in acoustics, especially airborne noise measurements, the most commonly used unit is *A-weighted decibels [dBA]*. A-weighting is defined in the standard *IEC 61672:2003* and it takes into consideration the special aspects of human sound perception, e.g. the fact, that human hearing is less sensitive at low audio frequencies.

The installed accelerometers, like on Figure 4-53., sensor must be mounted on the measured surface of the UUT. The accelerometer itself might have single or multiple axes of measurement possibility depending on its internal design. Thus, it can allow the measurement of the normal and tangential accelerations of a target surface. Such acceleration sensors are often placed near source of the mechanical vibration, like near stator of an electric motor, over large surfaces, gearboxes and beside the fixed bearing of the shaft. They are used for limit monitoring as well to indicate instabilities in the setup e.g. due to bearing damage. The type and quality of the mechanical mounting, connection of the sensor to the surface has a significant impact on the measured acceleration. The ideal frequency characteristic (Figure 4-54.) specified by the manufacturer is only valid under ideal mounding conditions. The sensor own mass must also be considered for small parts as it may influence the resonance frequency (or the overall transfer function of the part).

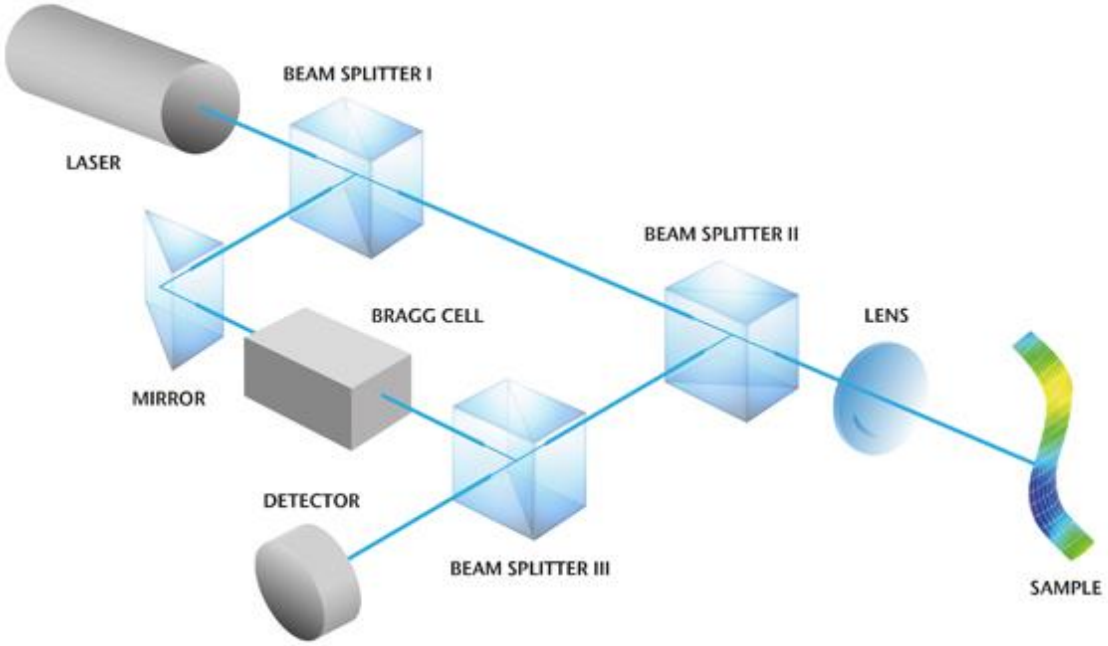
4-53. Figure Acceleration sensor [29]



4-54. Figure Accelerometer frequency response [29]

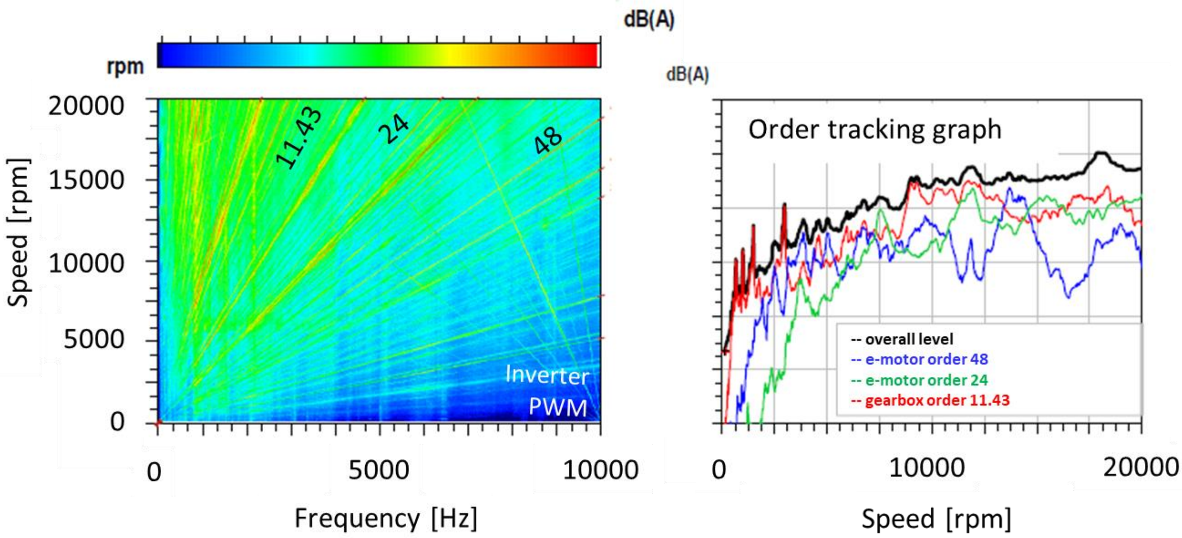
Another, mechanically more constrained way of acceleration measurement is a method referred to as blocked force measurement. Blocked force measurements measure the reaction force between the e-motor housing and the mounting flange. It is a relatively stiff connection since the piezoelectric sensors used are mechanically stiff themselves. An advantage of this method is that the UUT to sensor connection is well defined. If multiple sensing elements are present and their distance from the rotational axis is well known, the dynamic torque can also be calculated.

Both beforementioned methods relies on mechanical contact to the measured sample. Laser Doppler vibrometers offer a contactless method to measure surface displacement up GHz frequency range. Since the measurement itself doesn’t influence the sample, it is also suitable for small parts (Figure 4-55.).



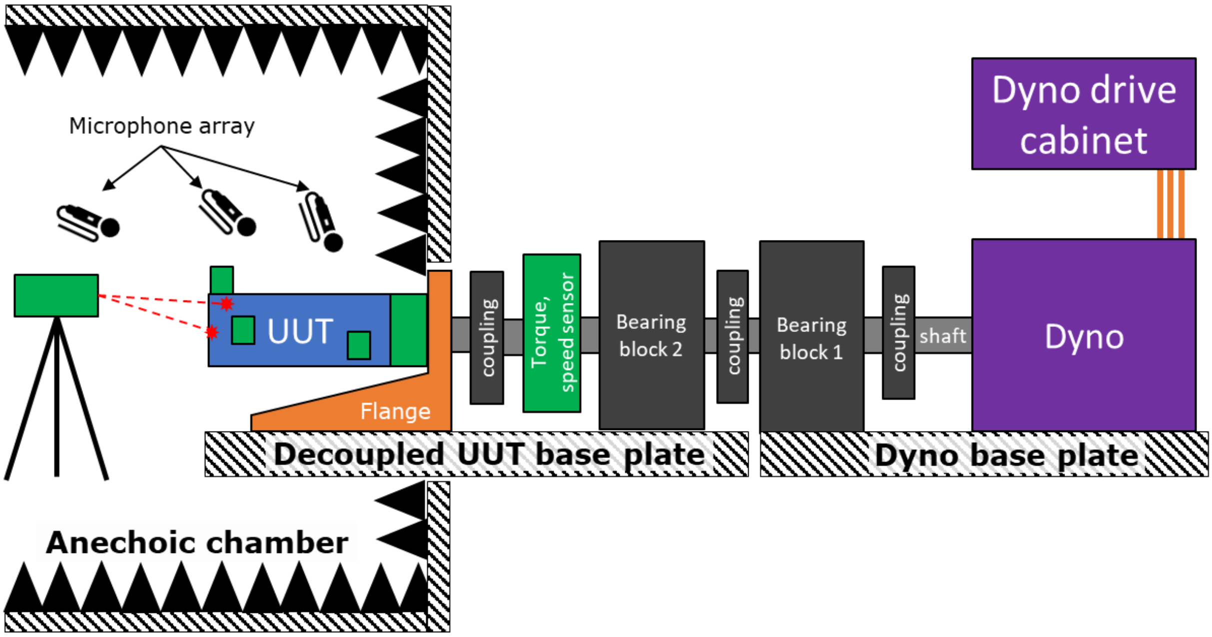
4-55. Figure Laser Doppler Vibrometer [30]

NHV measurements are usually displayed on Campbell diagrams where the engineer can more-or-less easily identify dominant orders, resonances. Order tracking graphs can show in more detail how a specific order's amplitude changes over the investigated speed range as shown in Figure 4-56.

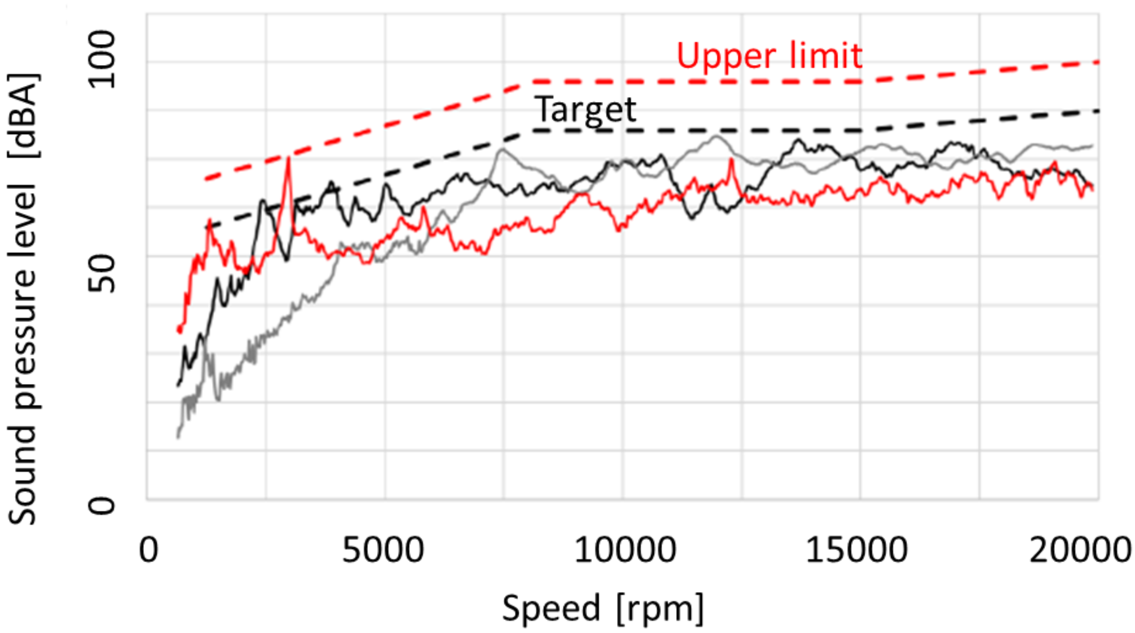


4-56. Figure Example e-motor acceleration measurement with Campbell-diagram and order tracking graph.

Airborne noise cannot be accurately measured on a classical e-motor test bed, since it is an inherently noisy environment. Airborne noise can only be measured in some form of an anechoic chamber, which isolates the test area from external noise and vibration and provides echo-free testing space. For this reason, special measuring rooms are built which are mechanically decoupled from the load unit, placed outside the chamber (Figure 4-57.). Microphones are placed in the required distance, 1 meter spherical placement is standard, and measurement results are evaluated in a similar fashion as before (Figure 4-58.).



4-57. Figure NVH testing in anechoic chamber for measurement with microphones



4-58. Figure Airborne noise graph

4.5.6 EMC TESTING

EMC (Electromagnetic Compatibility) testing is the measurement of e-motor and inverter electromagnetic noise emissions under different load and operating conditions. Besides the emissions, the UUT's immunity towards external disturbances is tested as well in the so called susceptibility tests. The testing procedure is described in the standards *IEC CISPR 25 and ISO 11452*. CISPR stands for *Comité international spécial des perturbations radioélectriques*. Type of electromagnetic noise components are differentiated based on their propagation paths:

- *conducted and*
- *radiated electromagnetic noise.*

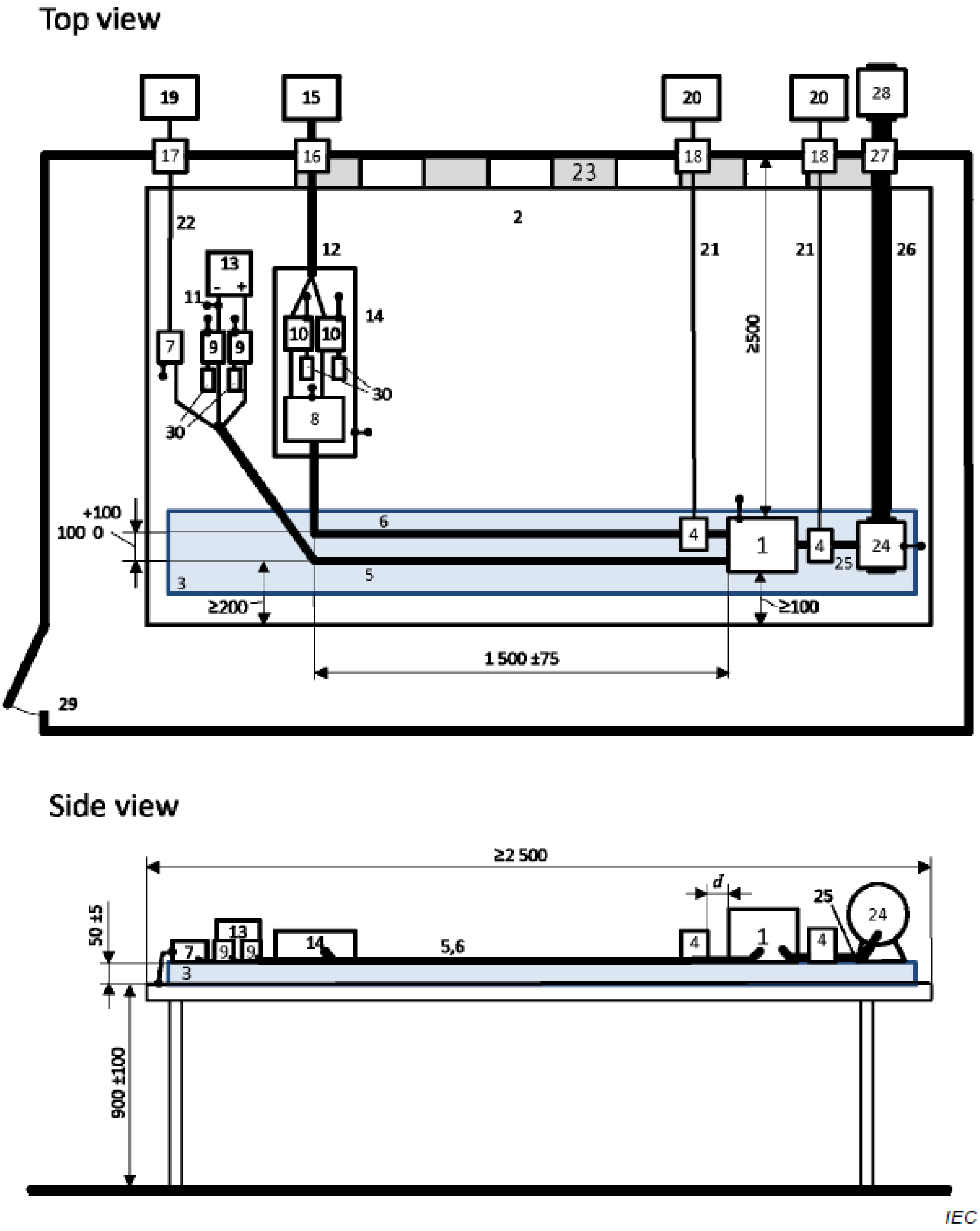
Conducted noise travels along the cables, wires, busbars, and other electrically conductive paths. Practically, conducted EMC is high frequency current harmonics. They are usually evaluated between 150 [kHz] and 30 [MHz] frequency, above which they are not dominant. The range can be adapted for the specific application. Radiated electromagnetic noise is electromagnetic field corresponding to displacement currents, emissions of the UUT that can interfere with wireless devices.

The importance of EMC measurements comes from the fact, that modern devices are almost exclusively switching devices. This includes not just the traction part of e.g. an electric vehicle, but all other actuators like power steering, DC/DC converter, on-board charger, pumps and fans. Shielding is mandatory, however switching power electronics still can emit electromagnetic disturbance, which might negatively influence other components performance. Conducted noise can disturb sensitive signals, like the position signal of an FOC controlled drive and cause unexpected behavior. Radiated noise can disturb communication of wireless devices. Therefore, each component has certain EMC requirements it needs to fulfill. Both conducted and radiated emissions must fall below an application specific limit.

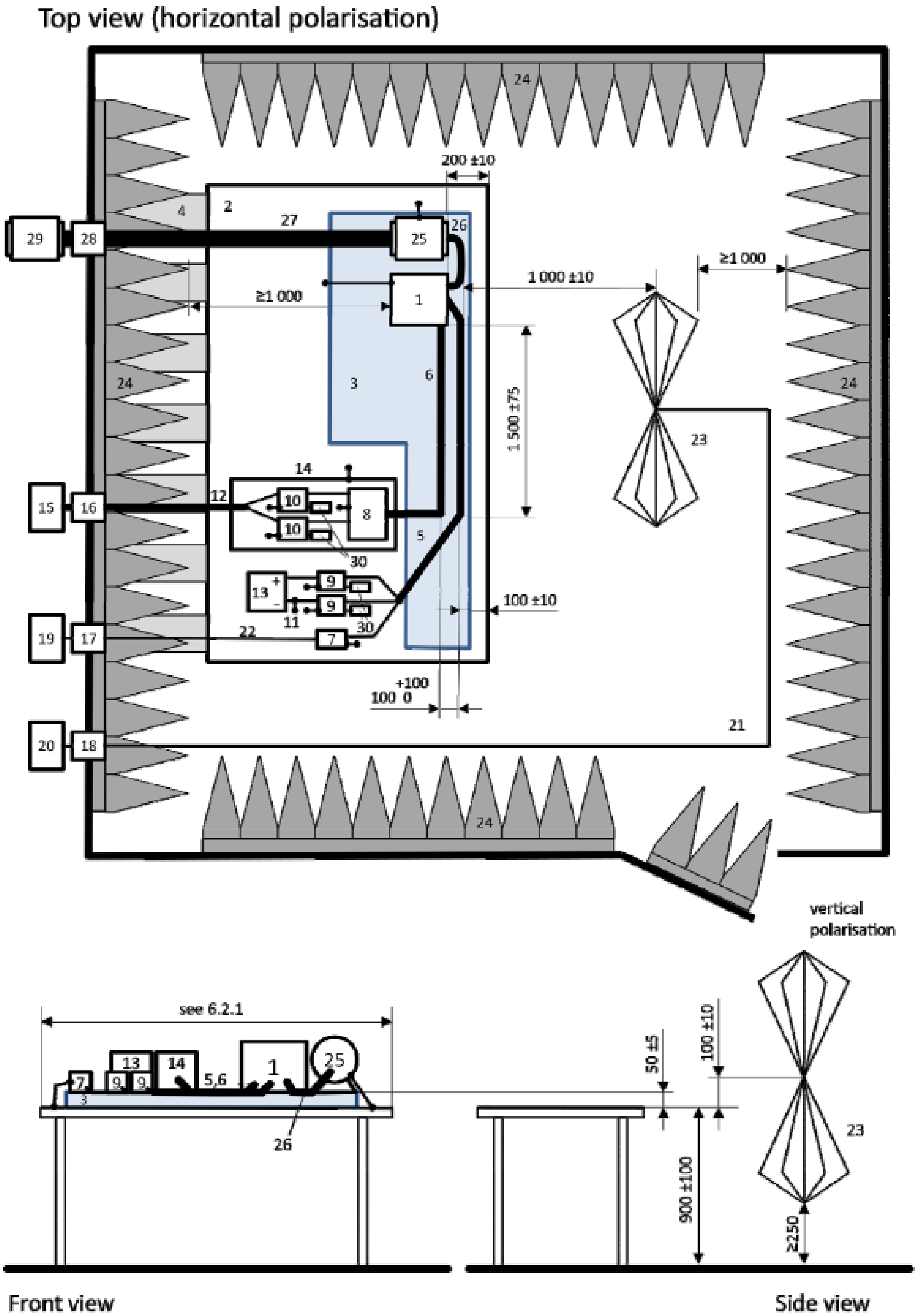
Of course, final EMC behavior is evaluated on the complete vehicle, however testing is often done on the e-drive level too. Figure 4-60. shows the standard setup for *radiated emission* measurements of electric drives. *Conducted EMC* measurement can be carried out in the same chamber as well if current probes are installed, however it is not necessary. As shown in Figure 4-59., for conducted noise measurements only a shielded enclosure is needed, absorption wall cover is not required. While the default setup is defined with a physical e-motor, emulation is also possible. The test environment's concept is very similar to the anechoic chamber setup known from NVH testing. It is defined in a way to eliminate external noise sources and cancel reflections inside the testing chamber. This includes separation of the load machine (dyno) and its cabinet from the testing area. To ensure comparable results between different test chambers and UUTs the setup's components, cable lengths, impedances, antenna distances and types, ground plane area and properties are well specified. The setup usually contains a LISN (Line Impedance Stabilization Network) or AN (Artificial Network) which is a device that provides uniform impedance to perform the conducted EMC measurements. Beside that it fulfills a filtering function which eliminates frequency components from the measured signal which are not interesting for the conducted EMC. Radiated EMC tests (Figure 4-60.) are carried out using different antenna types, fitting for the measured frequency range listed in Table 4-3.

4-3. Table Antenna types

Frequency Band	**Antenna Type**
150 kHz–30 MHz	1 m vertical monopole
30 MHz–200 MHz	Biconical
200 MHz–1000 MHz	Log-periodic
1000 MHz–1500 MHz	Horn or log-periodic



4-59. Figure CISPR 25 Conducted EMC test, the test setup with current probes.


Top view (horizontal polarisation)
vertical polarisation
see 6.2.1
Front view
Side view
200 ±10
1 000 ±10
≥1 000
1 500 ±75
100 ±10
+100
100 0
50 ±5
100 ±10
900 ±100
≥250

4-60. Figure CISPR 25 Radiated EMC test, an example of radiated emission test setup measurement with biconical antenna for EUTs with shielded power supply systems with electric motor attached to the bench.

Where:

1 EUT
2 Reference ground plane
3 Low relative permittivity support (εr ≤ 1,4) thickness 50 mm (a non-conductive support can be used for the electric motor)
4 Ground straps (see 6.2.1)
5 LV harness
6 HV lines (HV+, HV−)
7 LV load simulator
8 Impedance matching network (optional)
9 LV AN
10 HV AN
11 LV supply lines
12 HV supply lines
13 LV power supply 12 V / 24 V / 48 V (should be placed on the reference ground plane)
14 Additional shielded box
15 HV power supply (should be shielded if placed inside the ALSE)
16 Power line filter
17 Fibre optic feed through
18 Bulk head connector
19 Stimulating and monitoring system
20 Measuring instrument
21 High quality coaxial cable e.g. double shielded (50 Ω)
22 Optical fibre
23 Biconical antenna
24 RF absorber material
25 Electric motor
26 Three phase motor supply lines
27 Mechanical connection (e.g. non-conductive)
28 Filtered mechanical bearing
29 Brake or propulsion motor
30 50 Ω load

Figure 4-61. shows a real-life example of a EMC measurement chamber. It must be noted, that radiated EMC measurements are extremely sensitive to antenna placements and positional deviations in the setup can cause significant change in the results.

4-61. Figure AVL EMC test setup

4.6 ELECTRIC MOTOR FAILURE MODES

Finally, a few words about the failure modes of electric motors. Electric motors are subject to sever sources of stress, which continuously degrades their properties and this, over a longer period of time leads to an operation failure. The main stress categories and type of wear are the followings [11]:

ENVIRONMENTAL
- *moisture*
- *chemical*
- *abrasion*
- *foreign objects*

ELECTRICAL
- *dielectric*
- *tracking*
- *corona*
- *transients*

MECHANICAL
- *coil movement*
- *rotor strike*
- *miscellaneous*

THERMAL
- *aging*
- *overloading*
- *cycling*

4.6.1 STATOR FAILURES

A typical failure mode of stator occurs at the winding, as it is subject to high temperatures as well as high electrical fields. The inter-turn short circuit of the winding is more common for induction motors, however other motor types are affected as well, and it usually occurs:

- *between turns of one phase,*
- *between turns of two phases,*
- *between turns of all phases,*
- *between winding conductors and the stator core.*

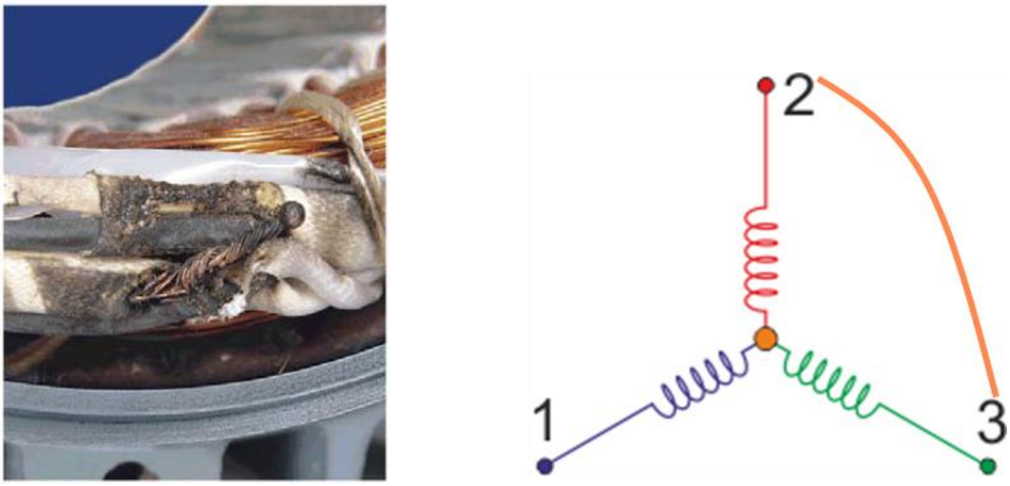
The causes of inter-turn short circuits are [11]:

- *voltage transients,*
- *reflection resulting from cable connection between motors and ac (e.g. PWM) drives,*
- *long cable connections between a motor and an ac drive can induce motor over voltages.*

4.6.1.1 EXAMPLES: STATOR FAILURES [12]

Short circuit at the leads (Figure 4-62.):

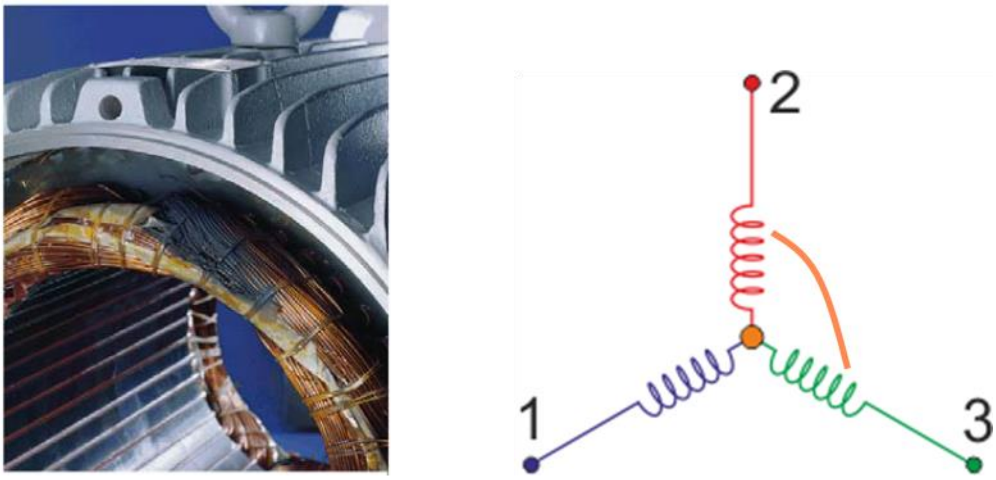
- *The winding is short-circuited through the lead sleeving (insulation) over the end winding.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge.*



4-62. Figure Short circuit at the leads [12]

Short circuit between phases (Figure 4-63.).

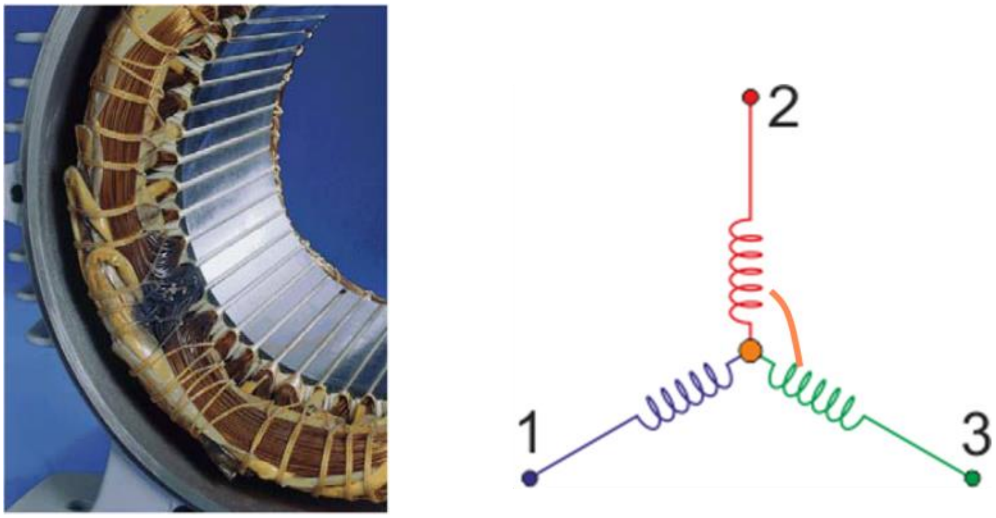
- *The winding is short-circuited through the enameled wire insulation and phase separator (if any) in the end winding.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge.*



4-63. Figure Short circuit between phases [12]

Inter-turn short circuits are due to voltage transients (Figure 4-64.).

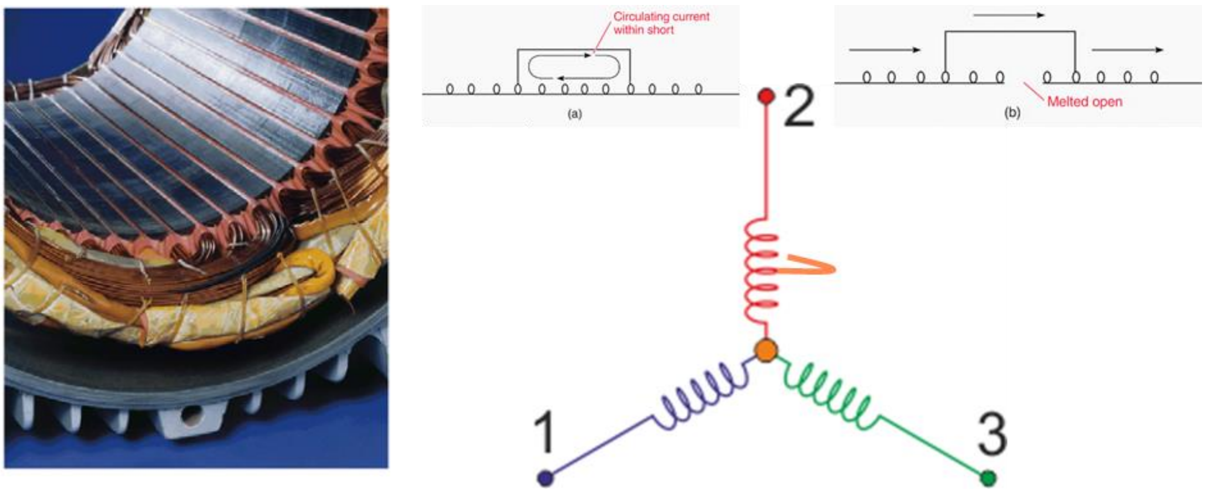
- *The winding is short-circuited through the enameled wire insulation and phase separator (if any) in the end winding.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge.*



4-64. Figure Inter-turn short circuits [12]

Inter-turn short circuits between turns of the same phase (Figure 4-65.).

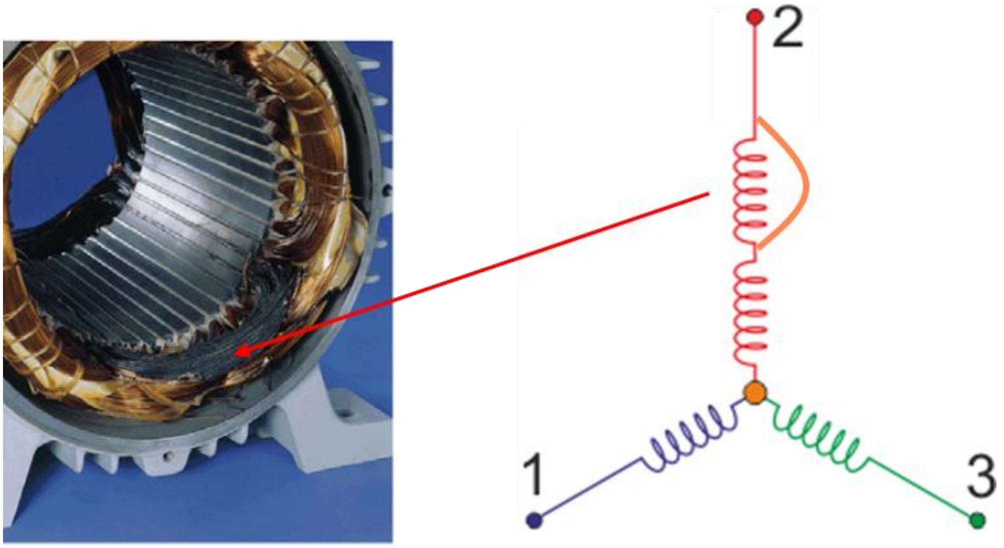
- *The winding is short-circuited through the enameled wire insulation layers between turns.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge (transients), e.g. related to long AC cables and PWM inverter drive.*



4-65. Figure Inter-turn short circuits between turns of the same phase [12]

Short circuited winding (Figure 4-66).

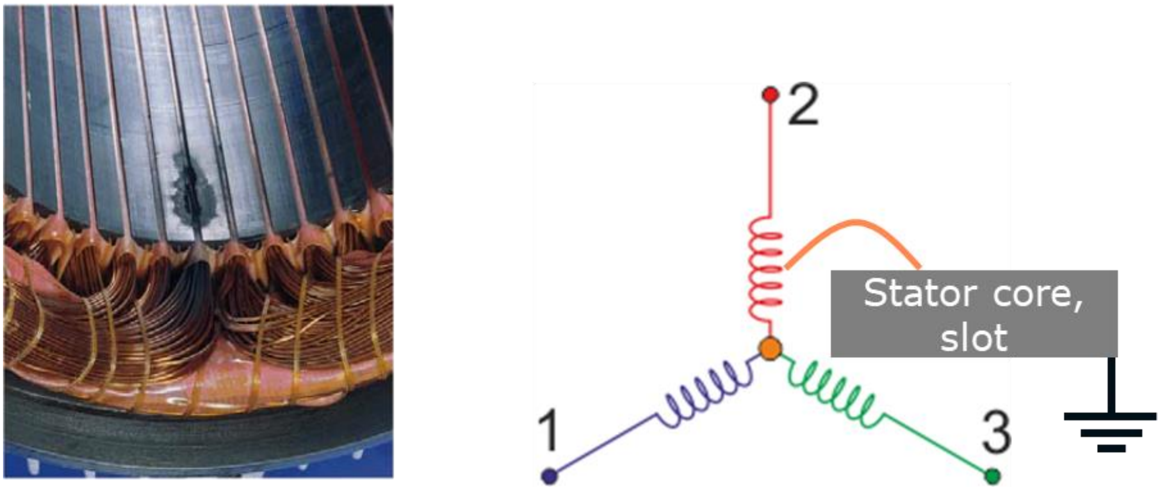
- *The winding is short-circuited through the enameled wire insulation and phase separator (if any) in the end winding.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge.*



4-66. Short circuited winding [12]

Short circuits between winding and stator core inside the stator slot (Figure 4-67).

- *The winding is short-circuited through the enameled wire insulation and the slot insulation.*
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge. The slot could be damaged by mechanical grinding of the rotor, and the insulation could be thermally degraded due to increased heating by the eddy currents.*

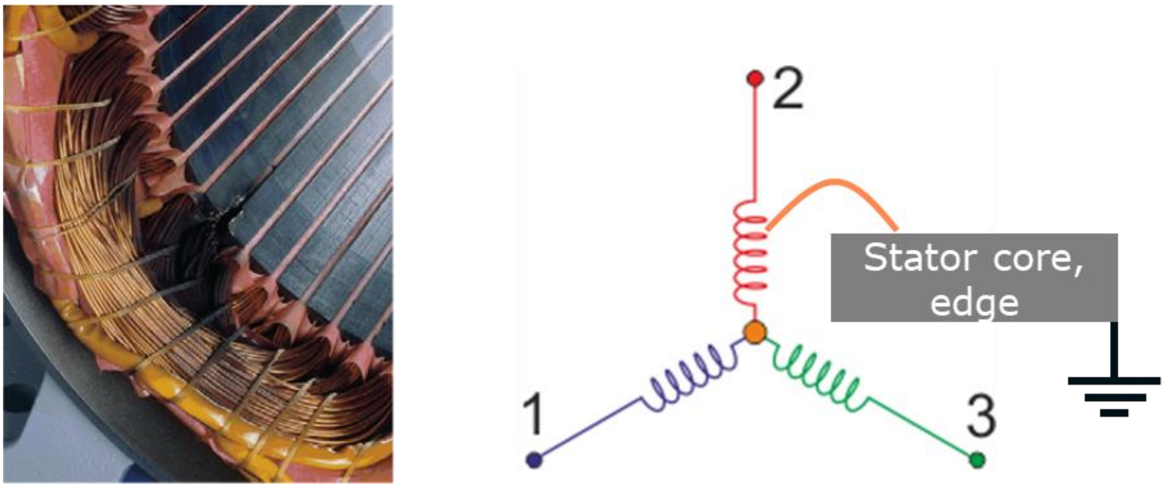


4-67. Figure Short circuits between winding and stator core inside the stator slot

Short circuits between winding and stator core at the edge of the stator slot (Figure 4-68).

- *The winding is short-circuited through the enameled wire insulation and the slot insulation.*

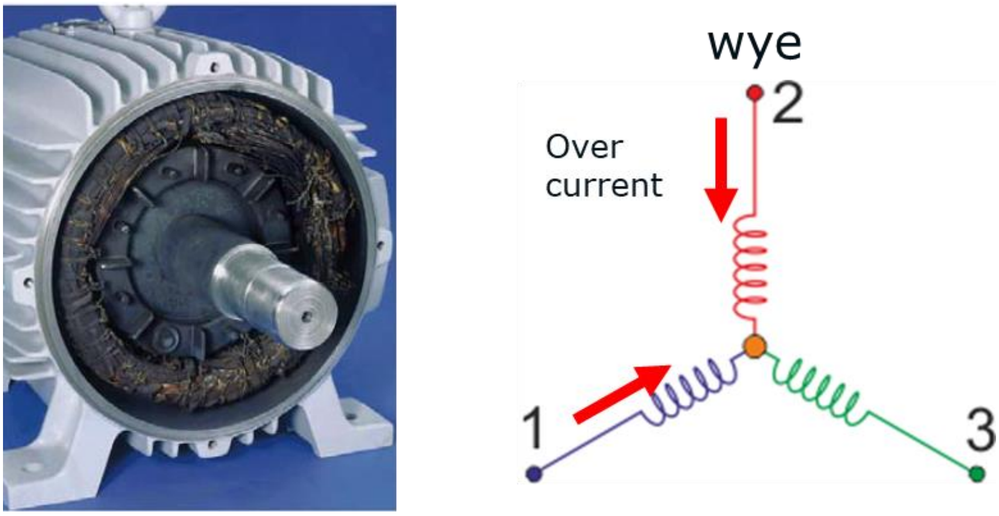
- *This type of insulation failure is typically caused by contaminants, abrasion, vibration or voltage surge.*



4-68. Figure Short circuits between winding and stator core [12]

Burned wire insulation due to long term over-current (Figure 4-69).

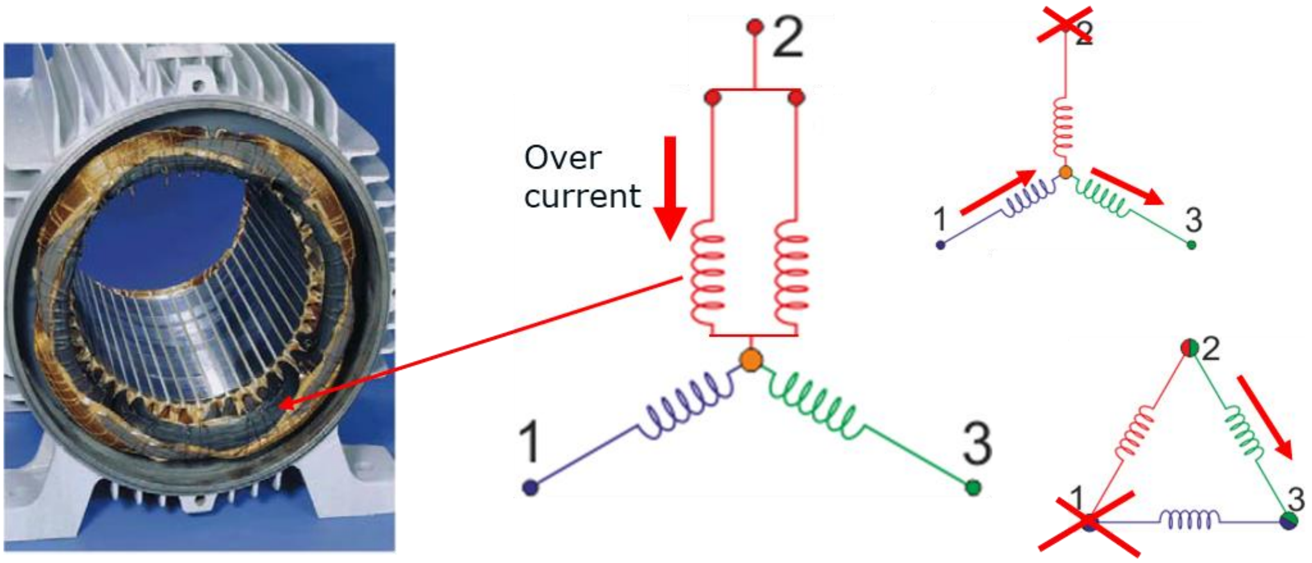
The motor is operated outside of temperature limits for an extended period until winding fails.



4-69. Figure Burned wire insulation due to long term over-current [12]

Single-phase/coil-group failure due to un-balanced currents (Figure 4-70.).

- *A single phase or coil-group fails due to over-current for an extended period.*
- *Reason could be*
- *failure on input side (UVW),*
- *an open circuit in a parallel coil group.*



4-70. Figure Single-phase/coil-group failure due to un-balanced currents [12]

4.6.2 ROTOR FAILURES [11]

The rotor of an electric motor experiences the following type of stresses:

- *thermal,*
- *electromagnetic,*
- *residual,*
- *dynamic,*
- *mechanical,*
- *environmental.*

There are influencing factors, which affect the wear caused by stresses [11]:

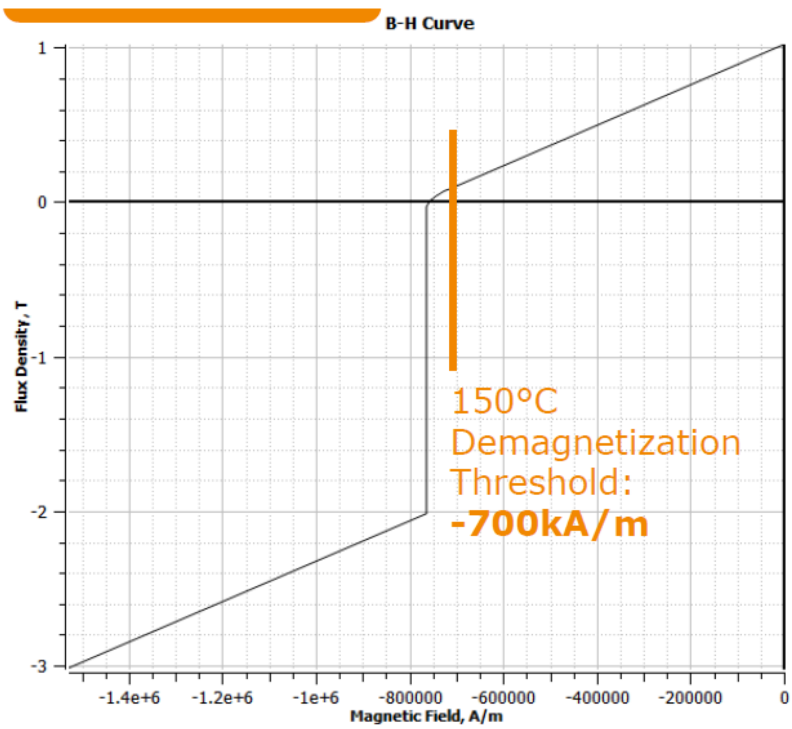
- *working torque,*
- *unbalanced dynamic force,*
- *torsional vibration and transient torques,*
- *residual forces from casting, welding, machining and fits (radial, axial, other),*
- *magnetic force caused by slot leakage flux vibrating at twice the frequency of rotor current (squirrel cage induction motor only),*
- *magnetic force caused by air-gap eccentricity,*
- *centrifugal force,*
- *thermal stress caused by end-ring heating,*
- *thermal stress caused by temperature differential in bar during start (skin effect) (squirrel cage induction motor or cage dampener motor only),*
- *thermal stress caused by axial bar growth,*
- *axial force caused by skewing the rotor bar.*

Eccentricity is always present to some extent. How well it is handled depends on the application's expected operation speeds. The fundamental cases of eccentricity are:

- *Rotor's outer diamter is eccentric to the axis of rotation.*
- *Stator bore is eccentric.*
- *Rotor and stator are round but do not have the same axis of rotation.*
- *Rotor and shaft are round but do not have the same axis.*
- *Any combination of the above is applicable.*

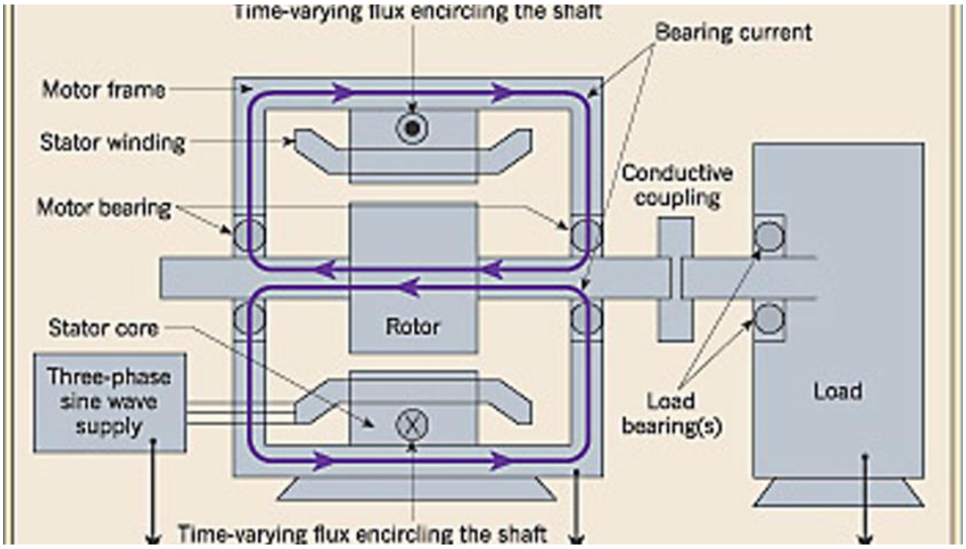
If the rotor is not centered in the air gap, the magnetic forces acting on it are unbalanced, resulting in a non-zero total force acting on the rotor. Ideally the opposing magnetic forces should balance each other. Note, that the winding can produce unbalanced forces as well, e.g. in case of failure of winding or even the failure of the inverter. Unbalanced forces will bend the rotor and can cause the rotor to collide with the stator and/or the winding. At higher rotational speeds the rotating movement always acts in way to pull the shaft into the center.

Permanent magnet rotors feature a special kind of failure mode, called demagnetization. Demagnetization means, the magnets inside the rotor suffer an irreversible loss of polarization. The cause can be temperature, high demagnetizing filed, mechanical impact and stress. Usually, a combination of the these is required to demagnetize a high grade rare-earth permanent magnet in an IPMSM. Figure 4-71. demonstrates the safety limit of a magnet, higher demagnetizing fields at 150°C will cause irreversible loss of polarization.

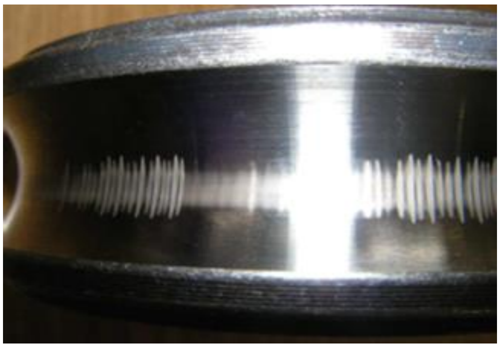


4-71. Figure Demagnetization curve and limit field of a permanent magnet.

Another critical part of rotating machines is the bearing. Bearing design and choosing the correct one for the application is not a straightforward task. Here only a single failure mode is introduced, which is related to the electromagnetic focus of this booklet. Bearing currents occur due to non-symmetrical stator flux as shown in Figure 4-72 or build-up of electrical charge. Given a well conducting electrical path, such as the electric motor's housing, even a low amount of non-symmetric stator flux can induce current through the bearings. The current degrades rolling surfaces and reduces bearing life-time. One type of wear is demonstrated on Figure 4-73. Bearing currents can be avoided by increasing the resistance of the path through the bearing. Commonly used techniques are to use non-conductive ball-bearing or use isolating coating. The rotor shall not be isolated on both sides, as that leads to build-up of electrical charge, which leads to sparking. Should the rotor be isolated on both sides a carbon brush with slip-ring provide an alternative route for the charges.



4-72. Figure Bearing currents



4-73. Figure Damaged bearing rolling surface

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Module_1

Electric Drives

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Measurement technology

of electric drives

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