ZES ZIMMER
Precision Power Measurement

LMG600 Series Applications:

Traction inverter and its high frequency power losses in the electric drive train

v1.2

ZES ZIMMER – THE EXPERTS IN PRECISION POWER ANALYSIS

Efficiency measurement on traction inverters – Direct determination of high-frequency power losses using DualPath and Script Editor

The 2010s were a key decade for electromobility and its technology, marked by significant advances in research and development of semiconductor and materials science, as well as by subsidies, leading to increased market viability and attractiveness. This has now resulted in maximum drivetrain efficiency and correspondingly high vehicle's range. In particular, the main components of the electrified drivetrain of an electric vehicle (EV), such as the traction inverter and electric motor, must perform together optimally. Only this enables maximum conversion efficiency and optimal driving dynamics.

Manufacturers and system integrators face the challenge of optimizing the control of power semiconductors for the traction converter’s conversion process, tailored to the individual electric motor and the driving operating point. The aim is to ensure a consistently optimal energy balance across the driving profile. This with minimal impact on the mechanics (driving dynamics and acoustics). Additionally, this should occur bidirectionally in both ways of the energy flow (recuperation during the braking process).

Challenge for manufacturers and system integrators:

- High driving dynamics (controlled torque)
- High efficiency (bidirectional) (reflects range)
- Optimal acoustics (positive subjective noise rating)
- Low impact on mechanics (vibration)

Topics

- What are the components of a traction inverter’s power spectrum?
- How do these components individually affect the drive system and the motor?
- Why analyze HF power components in the spectrum separately?
- How do you measure the power at the inverter output?
- How do you separate and measure the HF power spectrum?
- What is the LMG600 DualPath architecture?
- Which parameters of a power analyzer must be considered?

However, the conversion process of a traction inverter is associated with various power loss mechanisms, in particular those that arise from the high-frequency (HF) switching processes of the power semiconductors. These losses are caused by control methods based on pulse width modulation (PWM). Resulting switching processes impose harmonics and high-frequency voltage and current components on the drive system, which do not contribute directly to generating turning momentum (torque), but cause power losses and affect the vehicle's electromagnetic environment. Some of these losses and loss mechanisms are listed below.

Typical losses and loss mechanisms due to HF components:

- Winding copper losses and iron core losses of the motor
- Leakage currents and associated insulation damage in the motor
- Switching losses and heat losses in the semiconductors in the inverter

In order to meet the above challenges for the drive system, the following solutions for optimization are available.

Solution for manufacturers and system integrators:

- Efficient control method of the traction inverter (vector control, space vector modulation)
- Variable switching frequency (depending on the operating point)
- Adaptive adjustment of the edge steepness (du/dt) of the PWM voltage

How can the effect of the above measures on optimized efficiency and driving dynamics of the drive system be verified?

This application note clarifies this question and describes in particular the procedure for directly determining the inverter-related high-frequency power losses of an electric drive train, hereafter an electric vehicle, using the LMG671 power analyzer.

Learnings

The separation and detailed analysis of the high-frequency power components are vitally important in order to verify and optimize the efficiency of the entire drive train. This is where our LMG671 power analyzer comes in. With its DualPath technology and measurement-cyclic execution of a code sequence from the integrated script editor, it enables the targeted and direct separation of the fundamental power from the high-frequency power components. This results in a significant reduction in data post-processing.

Wiring the LMG671 to the test object

A complete efficiency measurement on the electric drive train is usually performed by measuring the electrical power between the respective main components: high-voltage battery (HV battery), traction inverter and electric motor. A typical connection of the LMG671 in the current paths of the test setup is shown in Figure 1. The individual stages of the power measurement follow accordingly according to this connection shown. Finally, we measure the following:

Inverter

- Input power of the inverter (DC/DC input stage)
- Intermediate circuit power of the inverter (DC link circuit)
- Output power of the inverter (DC/AC output stage) / Input power of the electric machine

Motor

- Mechanical power of the electric machine (torque and speed sensor)

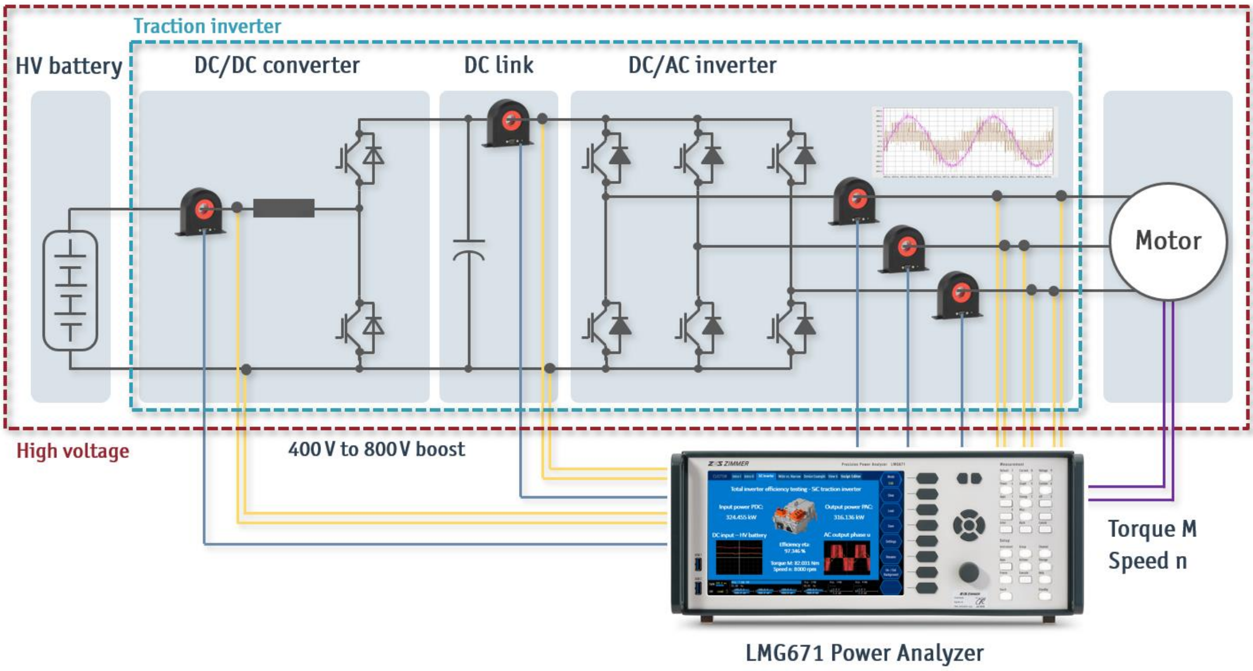

Figure 1: Wiring of the LMG671 power analyzer to the electric drive train test setup

The measurement of currents in their signal form, frequency and phase, both on the DC and AC side of the inverter, requires high accuracy, linearity and stability. Current sensors with minimal phase errors are essential, particularly at the inverter output and fundamental frequencies of up to 1000 Hz. Precision current transducers of our PCT series should be used here, such as the PCT600[1], which are also supplied directly from the LMG671 using Plug'n'Measure[2].

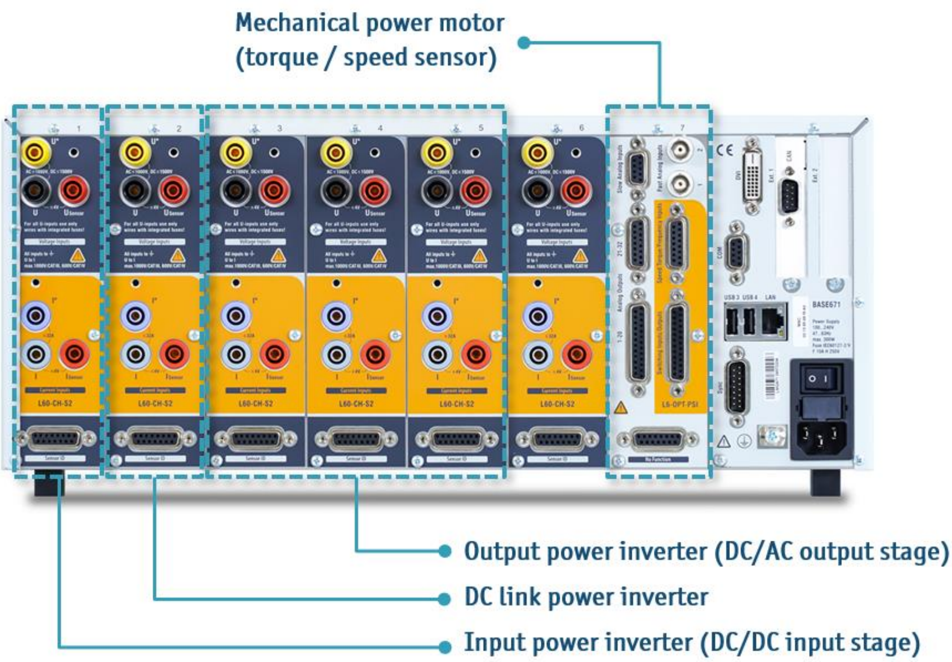

Figure 2: Wiring and grouping of the LMG671 measuring channels

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[1] PCT600 current transducers offer highly accurate current measurement of up to 600 Arms (1000 Apeak) at DC - 500 kHz. More at: https://www.zes.com/en/Products/Sensors/PCT

[2] Plug'n'Measure facilitates direct supply of the sensor and supplements the automatic setting of the scaling factor and the measuring ranges by means of sensor information exchange with the measuring device. For more information, see “Features” under: https://www.zes.com/en/Products/Precision-Power-Analyzers/LMG671

Learnings

With its 7 available slots, the LMG671 facilitates modular equipment with up to 7 power measurement channels (type A/B/C/S) and up to 2 process signal interfaces (PSI - One PSI occupies one slot). In this way, all important measuring points in the electric drive train of an electric vehicle, from the high-voltage battery to the traction inverter output respectively the electric motor, can be wired to and evaluated on a single device. A complete power and efficiency analysis is therefore possible with a single LMG671 power analyzer.

DualPath parameterization of the LMG671

Typical for our LMG600 device family is the powerful GROUP menu, in which the targeted application-specific parameterization of the power analyzer for the processing of the measurement signals happens. As a result, plausible and precise measurements can be carried out. Focusing on the measurement of the inverter-related electric power, the most important steps and settings are:

- Grouping[3] of the power measurement channels as per Figure 2
- Selection of the measuring range and setting of the optimal range mode (S-channel specific: AC, DC) per group
- Synchronization of the individual groups
- Connection including, if necessary, the applicable sample value conversion (star-delta-wiring in a 3-phase system)
- Filter for signal processing and conditioning for integrated measured values and calculation of the harmonics
- Processing for simultaneous narrowband and wideband measurement of the electrical signals

In particular, the last point listed above, Processing, is of high significance here, since the DualPath technology of the LMG600 series in the corresponding mode (see marking in Figure 3) enables the separation of the fundamental, narrowband and wideband power as intended in this application.

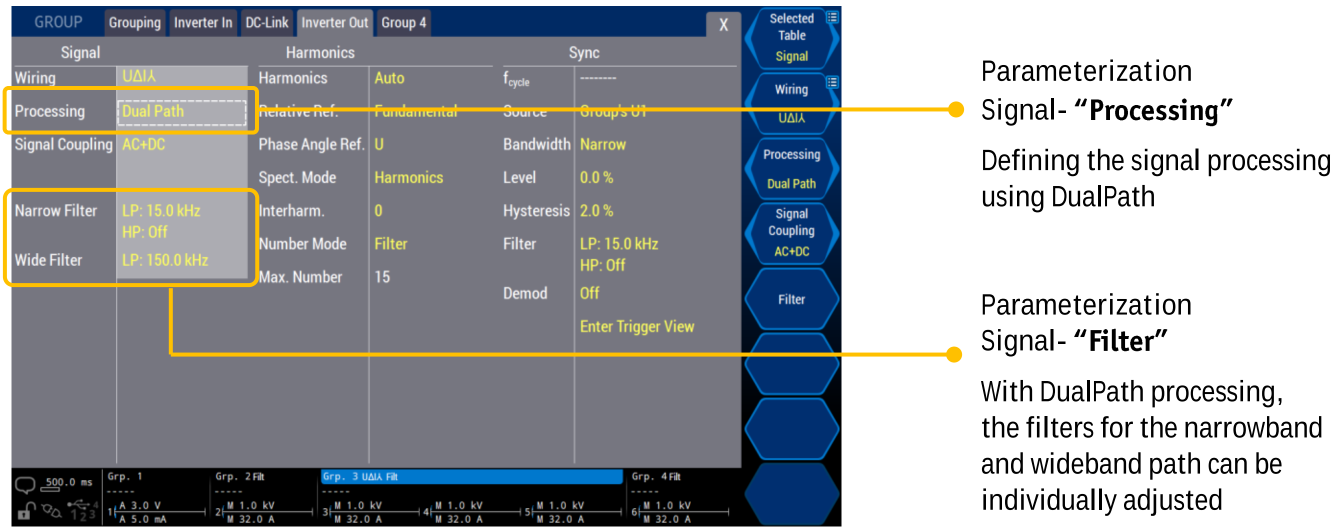

Figure 3: LMG671 GROUP menu for parameterizing the signal processing

[3] Grouping the measuring channels provides group-independent synchronization, direct wiring-dependent sample value computation (i.e. star-delta conversion) and direct calculation of the collective total values.

DualPath describes the simultaneous sampling (two A/D converter principle) and processing of the measurement signal as a narrow and broadband spectrum, both in the current and voltage path of a measurement channel, see Figure 4.

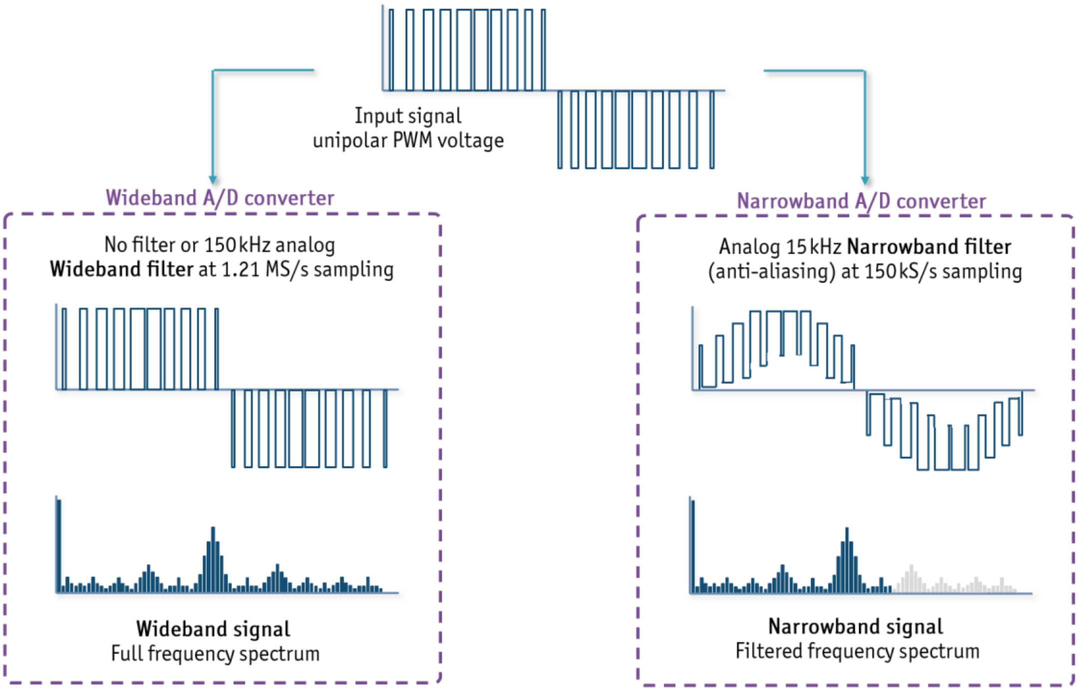

Figure 4: Schematic representation of the LMG600 series DualPath signal processing

The pulse-width modulated voltage signal, in Figure 4 the output voltage of the inverter which has already been converted from delta to star voltage, is now further processed using DualPath in two bandwidths to calculate the measured values, here the narrow and wideband signal. The LMG671 also offers the exclusive fundamental frequency values by integrated Fast Fourier Transformation (FFT) as an additional 3rd bandwidth.

The same DualPath processing occurs simultaneously for the current signal. This ultimately results in equivalent bandwidths for the power signal. The resulting trio of bandwidths offers the following power spectra at the inverter output for further detailed analysis and measured value processing:

- Full power spectrum up to the 150 kHz corner frequency of the wideband filter[4] or unfiltered (utilizing the 10 MHz analog bandwidth of the S-channel)
- Aliasing-free power spectrum up to the 15 kHz corner frequency of the narrowband filter
- Fundamental power from the Fast Fourier Transformation applied to the aliasing-free power signal of the narrowband path

Note

Calculating the harmonics and ultimately the fundamental power using FFT generally occurs over a defined time window or a defined number of signal periods. Power measuring devices may have different time windows for the FFT and cyclic update rate (integration interval) of the integrated measured values. With the LMG671, uniformity and thus increased stability can be created in a targeted and low-effort manner. More information on this can be found in the LMG600 user manual or via our application support.

[4] Any interference in the measurement setup that are in range of the several 100 kHz or MHz and could negatively affect the overall power measurement is avoided by selecting the analog 150 kHz wideband filter.

Learnings

The LMG671 with its DualPath technology enables the user to measure the inverter output power, simultaneously and separately for the fundamental frequency (aliasing-free) of the narrowband path and for the wideband or full spectrum. This forms the basis for directly calculating the inverter-related high-frequency spectrum.

Contrary to the double consecutive measurement of the individual power spectra, the user benefits by halving the test duration, significantly reducing the thermal and mechanical stress on the test object and maintaining the same test conditions.

By ideally parameterizing the harmonic calculation, the measurement of the aliasing-free fundamental frequency values can be optimized in terms of their stability, compared to the cyclic integration interval for the measured values, and precision.

Analysis of inverter-related high-frequency power losses

After the DualPath processing has been parameterized, the integrated script editor[5] enables the HF power respectively the HF power loss component of the traction inverter to be determined using mathematical calculations. The difference between the measured wideband and fundamental power is typically calculated as in the following formula, whereby this is based on the active power component.

$$P_{hf} \cong P_{wide} - P_{fund}$$

high-frequency power — wideband power — fundamental power

This formula is finally written and installed in the LMG600 script editor, see Figure 5.

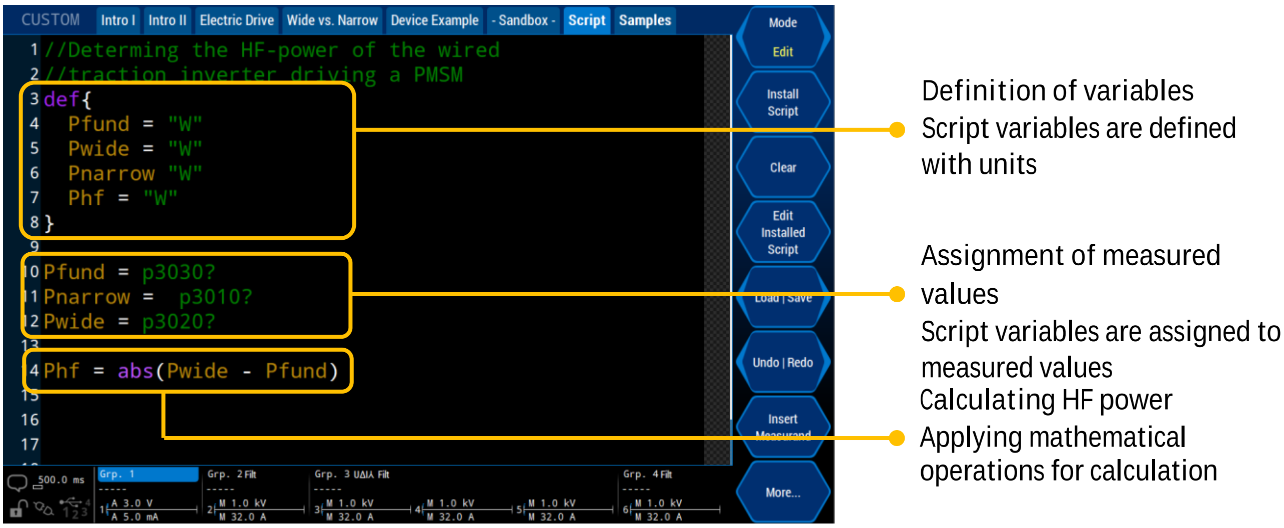

Figure 5: Script editor for calculating high frequency power losses at the converter output

Finally, in the application scenario on an electrified drive train, as here of an electric vehicle, all three electric powers can be measured and evaluated in a time-efficient and highly accurate manner for specific operating points, i.e. at constant speed and different torques, and even for bidirectional operation, i.e. acceleration operation and regenerative braking operation (recuperation via back EMF), see Diagram 1. By having the measurement supplemented with

[5] The LMG600 script editor includes a variety of possible mathematical operations, use of integrated functions, writing entire program sequences including common conditional queries (if-else) and loops (for, do-while), in style of well-known programming languages as Python. Further information: https://www.zes.com/en/Service/Downloads/Documents/Brochures

additional torque, speed and eventually mechanical power measurement, the high-frequency power (losses) can likewise be calculated with below following formula from the motor's power losses, as visualized in Diagram 2.

$$P_{hf} \cong P_{lm\_wide} - P_{lm\_fund}$$

high-frequency power losses   wideband motor power losses   motor fundamental power losses

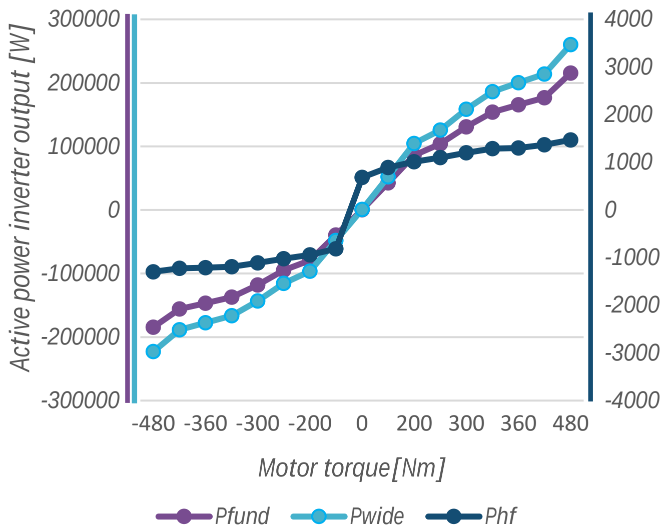

Diagram 1: Active inverter output power at 4000 rpm, bidirectional traction inverter on synchronous machine

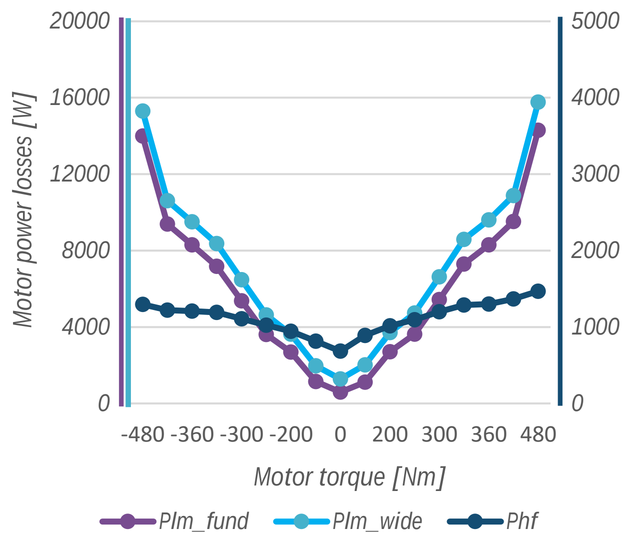

Diagram 2: Motor power losses at 4000 rpm, bidirectional traction inverter on synchronous machine

For the application itself, the LMG671 also offers the specific creation and display of a measurement menu customized to its requirements, which allows the direct reading and cross-checking of the measured values and signal waveforms during testing at the operating point reached. This is shown as an example in Figure 6. Scope signals can also be substituted or supplemented by plot diagrams in order to observe the thermal settling of the test object for the operating point to be verified.

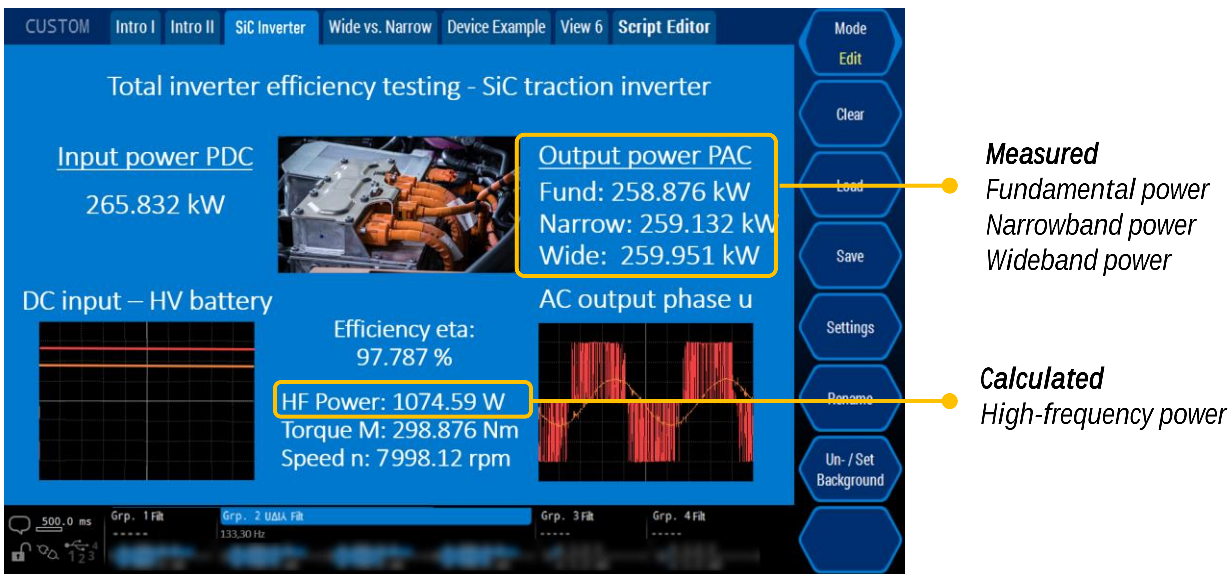

Figure 6: LMG600 CUSTOM menu for the power efficiency testing application of a SiC[6] traction inverter

Further derived measurements

Complete efficiency analysis of the entire drive train

The separation of the wideband power spectrum for separate analysis of the fundamental and HF power is part of a comprehensive efficiency measurement on an electric drive train. The LMG671 is optimally developed for this application.

The measurement is supplemented by the acquisition of either analog or frequency signals (encoder or resolver signals) from torque and speed sensors via the power analyzer's process signal interface (PSI) - we receive a direct measurement of the torque, the speed and, as a result, the mechanical power of the motor. If we measure on a synchronous motor (e.g. permanent magnet synchronous motor), the LMG671 also offers the measurement of the Id, Iq and I0 current components for the verification of the field-oriented control.

When connecting according to Figure 1 and Figure 2, it furthermore ensures a complete measurement of the power conversion efficiency with the highest accuracy and reliability. Here, a customer-specific measurement menu as illustrated in Figure 6 could also be created or requested from our technical experts.

If the complete efficiency measurement on the drive is carried out using dependencies of the speed and torque, we obtain, as an example, in the first step at constant torque, the efficiency curve in Diagram 3. In further torque-speed-combination-measurements, we get the so-called efficiency map for certain operating quadrants, as shown in Figure 7 for the first quadrant (forward acceleration/ driving).

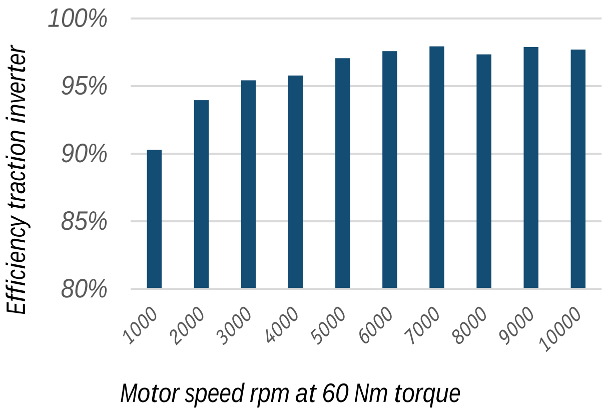

Diagram 3: Efficiency of the traction converter at variable speed and constant torque

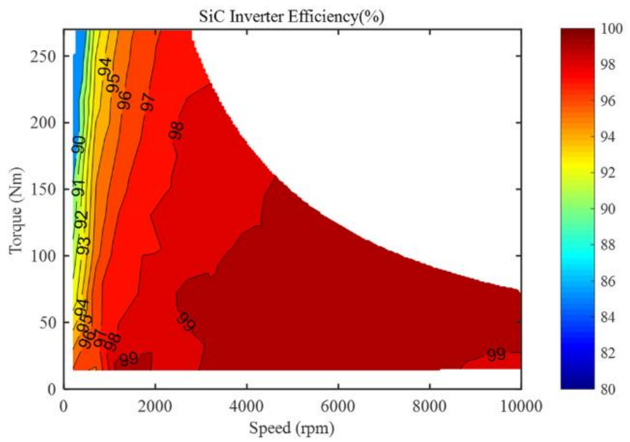

Figure 7: Efficiency map of a SiC inverter, (Su, et al., 2022)

Learnings

The comprehensive measurement of the entire electric drive train during development for system optimization, subsequent type testing and specification is the world of the LMG671. From the high-voltage battery to the electric motor, in the testing scenario of an electric vehicle, the measurement and verification of the entire or intermediate (single converter stages individually tested) efficiency is enabled with the highest precision (verifiable by calibration), the most precise signal synchronization, gapless and continuous sampling, even during bidirectional operation of the test object. Ultimately, this comprehensive measurement paves the way for the required representation and analytical assessment and evaluation of the drive efficiency depending on the dynamics of speed and torque, i.e. efficiency map, in single or continuous test.

[6] SiC – Silicon Carbide

Testing the input and output waveform of the inverter

Sometimes the devil is in the details and a further detailed analysis based on raw data of the measured signals, beyond the numerical analysis of the electrical power and efficiency, can shed some light on the matter.

- Recording and qualitative evaluation of the inverter signals with special signal analysis software LMG600 SampleVision at up to 1.21 MS/s sample stream
- Qualitative investigation of atypical or unwanted signal peaks
- Investigation of the frequency spectrum up to 600 kHz for a specified time interval

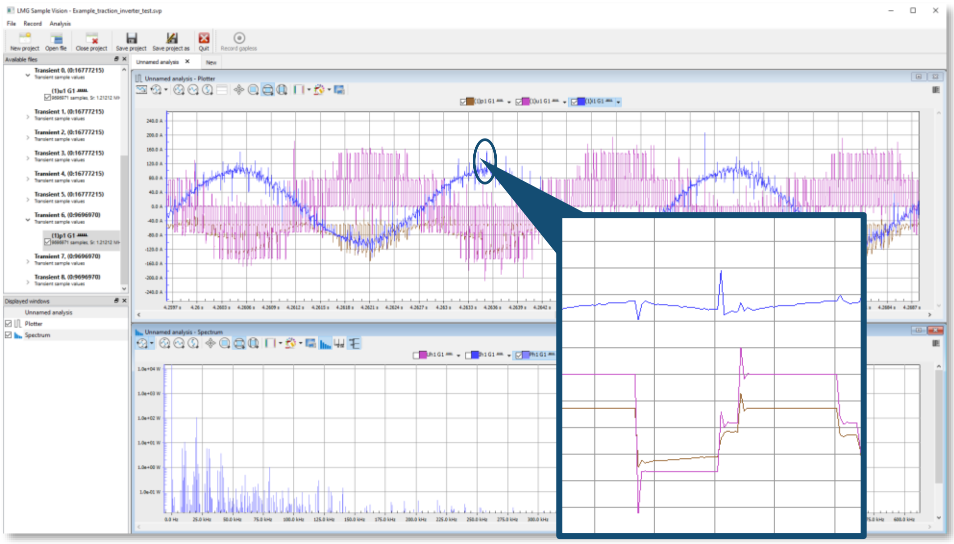

Figure 8: Analysis of the inverter signals with the LMG600 SampleVision waveform analysis software

Optimization potential of the switching behavior, such as:

- Adjust the switching time: Soft switching
- Snubber circuits: Implementing RLC circuits in the commutation path to compensate or smooth the transient peaks
- Adjust the gate resistor: Increase/decrease resistance value at the switch-on and switch-off time (e.g. at SiC-MOSFETs)

Learnings

The analysis of the signal sample values at the highest possible resolution of 1.21 MS/s enables the qualitative assessment of the signal waveforms at the inverter output during the precise power and efficiency measurement. Peaks in the signals can already indicate oscillations in the switching processes, which reduce efficiency and additionally stress the motor winding insulation. There is potential for optimizing the switching behavior here, such as specifically adjusting the switching time, implementing snubber circuits, adjusting the gate resistance (e.g. for SiC MOSFETs) at the switch-on and switch-off times. More detailed investigations of these optimization options can be supplemented by quantitative analysis using ultra-fast oscilloscopes.

References

Su, H., Zhang, L., Meng, D., Li, Y., Han, N., & Xia, Y. (2022, September 24). *Modeling and Evaluation of SiC Inverters for EV Applications.* Retrieved from MDPI: https://www.mdpi.com/1996-1073/15/19/7025

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