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The benefits of advanced methodologies in battery electric vehicle development and validation

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Executive Summary

The development of forward-looking drive systems in the e-drive sector is picking up speed again. On the one hand, developers must reinvent themselves to survive global competition. On the other hand, system and calibration engineers face constant challenges to cope with the enormous workload of increasing test requirements, software updates, and test components across the most diverse test environments [1].

The development of an electrical drive has it center in simulation. It is enabled by the nature of the electrical drive in combination with the possibilities that are offered in the simulation tools today. Still there is still a need to validate and improve the results on a testbed.

To ensure high testing efficiency and reduce the calibration and optimization efforts for the Unit Under Test (UUT), a new testing approach has been implemented as the new standard.

1 Challenges in the E- Drive development and application

The global E Drive market is highly competitive, and a worldwide supplier needs to differentiate its offering to be successful [2], [3]. Besides satisfying the functional and safety requirements needed to enter the market, a supplier needs to calibrate and optimize the E-Drive systems for additional requirements like:

- Torque precision, mandatory for a robust current control and vehicle drivability calibration
- Efficiency of the entire Electric Drive Unit, mandatory to increase range of the EV
- Efficiency of each single component (Inverter, E-Motor)
- NVH (Noise Vibration Harshness), mandatory to comply with comfort and durability

1.1 Complexity and Effort

The typical base calibration of an electric drive unit (EDU) as shown in Figure 1 includes a long list of pre-calibration and calibration tasks, each with detailed reports. For the sake of this presentation, we consider the EDU to consist of an Insulated Gate Bipolar Transistor (IGBT) inverter paired with an Internal Permanent Synchronous Motor (IPMSM).

For every Inverter Control Unit (ICU) variant the calibration engineer starts with a list of pre-calibration tests, such as angle calibration, induced EMF measurement, Motor Parameter identification, Controller characterization etc. Each of these activities need to be done at specific operating conditions, and safety boundaries which the engineer must constantly monitor during test execution.

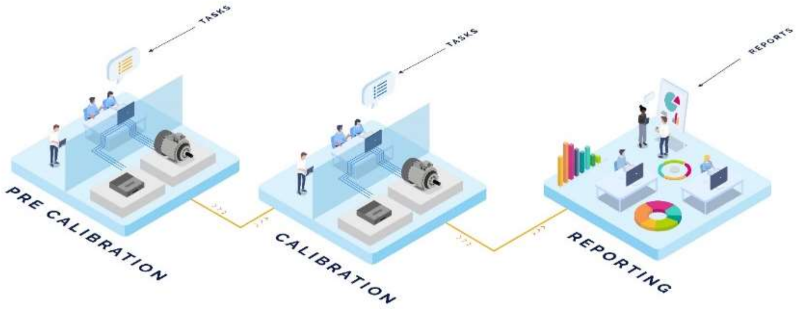

Figure 1: Base Calibration of an E-Drive Variant

2 Inverter parameter optimization at an E-Drive testbed

2.1 Testing Environment

To implement test standardization and complete automation of testing, a new tool chain topology has been introduced for test creation, execution, and result evaluation as shown in Figure 2 .

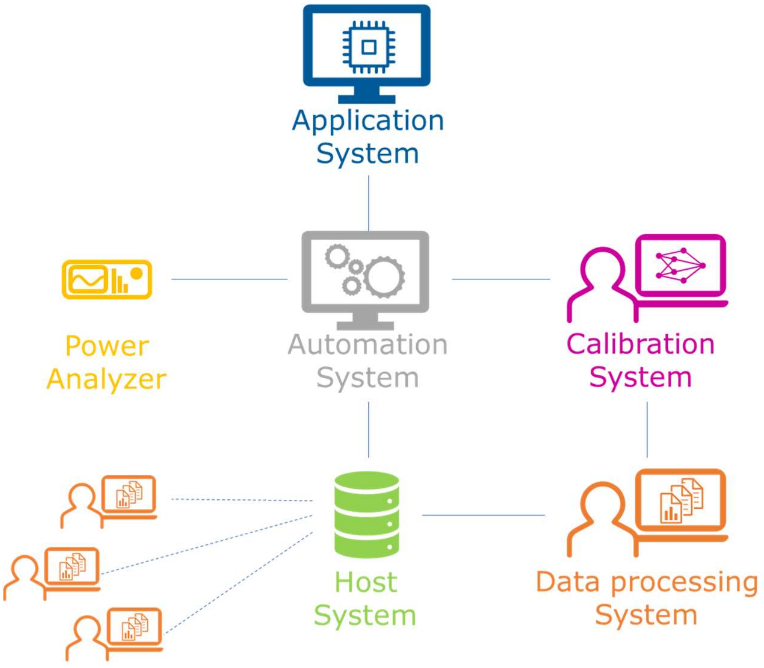

Figure 2: New Tool chain topology

The strength of this tool chain topology is that every relevant software at the E-Drive testbench is interfaced with each other to allow seamless transfer of commands and data.

The automation software is central hub communicating with all the other software tools. The calibration engineer can vary Inverter Control Unit (ICU) parameters via the calibration system. Thanks to the communication between the application system and the automation system, the changes are effective in the Inverter Control Unit.

All the data is stored in a host system by the automation system, making it easily accessible by the calibration engineers locally as well as globally.

The automation system is communicating with the power analyser and the application system to collect all the data in a structured way and storing it in the host in a consistent manner.

The calibration software system is responsible for controlling the calibration and optimization task. In it the calibration engineer can:

- Parametrize the variation channel list using a Full Factorial list or a Design of Experiment (DoE List).
- Define Safety limits.
- Define Stabilization Criteria.
- Define sequence to initiate UUT start up, shut down, heat up or cool down.
- Define measurement lists
- Define recorders to record measurements for analysis & report generation
- Execute data postprocessing scripts and generate automatic reports.

The calibration software communicates with the automation software to control the test execution. This well-connected and systematic tool chain was implemented across global locations to support our test standardization.

2.2 Standard Templates for Tests

The first step is to introduce standardization in the creation of the tests, in the data collection and data processing. The goal is reducing the time spent by testing and design engineers on managing data gathering locally and worldwide and giving them more time to focus on the final optimization targets.

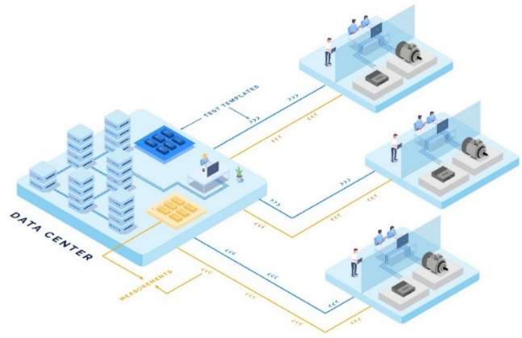

Figure 3: Standard test templates and measurement data maintained and stored at a central host

Test scenarios are now developed using standard templates which are maintained and updated centrally. In the development of E-Drives, most tests have a similar workflow, with minor modifications depending on the target of the tests and the UUT. The calibration process has the following benefits from a central defined and standardized template [4]:

- Safety Limits, Online formulas, automation scripts and measurement lists can be setup once and reused between tests. The engineer does not need to recheck them for every test.
- UUT controller relevant parameters are kept standard to avoid influencing the test results with subjective decisions.
- Testbed or UUT start up or safe shut down sequences, UUT stabilization sequence, special sequence of tasks for cooling down or heating up the UUT etc can be defined once and re used between tests.

2.3 New development methodology

For the use case, an E-Drive with a IGBT (Insulated Gate Bipolar Transistors) 3-phase inverter coupled with a IPMSM (Interior Permanent Magnet Synchronous Machine) with 4 pole pairs and 48 stator slots was the Unit Under Test (UUT). The initial dataset was provided by analytical calculations performed in simulation. The testbed was used to validate the initial dataset and thereafter for ICU application optimization.

2.3.1 First Step: E-Drive Optimization on E-Motor Testbed

The initial dataset was provided by analytical calculations performed in simulation. The testbed was used to validate the initial dataset and thereafter for ICU application optimization.

The partly contradictory optimization targets were to:

- Maximize efficiency, especially system efficiency, given by the multiplication of the inverter and the E-Motor efficiency: for the same mechanical power output, minimize the battery energy consumption.
- E-machine NVH performance
    - Minimize structure borne NVH for higher comfort and lower acoustic emissions: measured with an accelerometer sensor positioned at the rear stator housing.

The ICU parameters varied over the entire speed range of the machine were:

- Phase currents Id (direct) and Iq (quadrature)
- IGBT switching frequency
- Pulse Width Modulation (PWM) strategy, Continuous (CPWM) and Discontinuous (DPWM)

A detailed investigation of three operating points was chosen to illustrate the optimization process. Starting with an analysis of the losses of the inverter, the E-Motor and of the combined system.

- At 1500rpm 300Nm, CPWM comes with higher inverter losses as expected but on the motor side the losses are lower than with DPWM. At a system level, the lowest losses are achieved with CPWM at a low switching frequency.
- At 2500rpm 300Nm, it is questionable which modulation is more beneficial. DPWM still comes with higher losses in the motor, even if it less compared to the previous operating point. The system losses are comparable if optimal values of Id and switching frequency are considered.
- • At 3000rpm 300Nm, the differences in motor losses are neglectable and the lower inverter losses of DPWM remains as the only differences on a system level. Up to 0.3kW battery power reduction can be achieved with DPWM compared to CPWM.

The analysis so far was only considering the losses of the E-Drive. With the models of the additional KPIs, a multi-objective optimization can be performed with the purpose to minimize NVH and the system losses at the same time. In Figure 4 the trade-off plots between the system losses and the fluctuating torque is displayed for the three operating points.

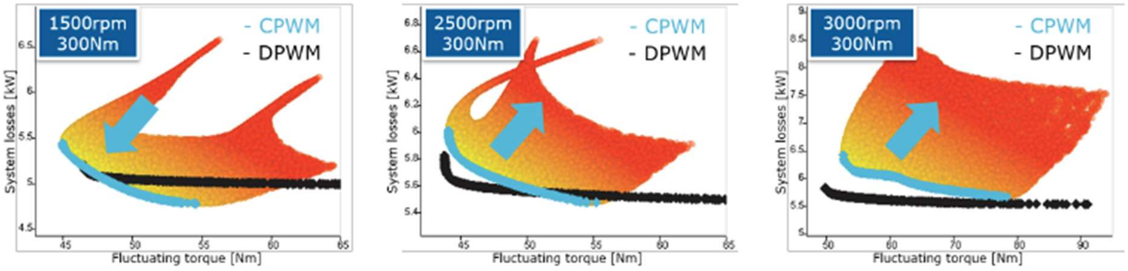

Figure 4: Trade-off between System Losses and Fluctuating Torque

- At 1500rpm, CPWM has a better trade-off compared to DPWM: For a given level of fluctuating torque, it is achieved with lower system losses compared to DPWM.
- At 2500rpm, the trade-off curves of CPWM and DPWM are crossing each other. Whether the one or the other is preferred depends on the optimization target.

- At 3000rpm there is a clear benefit in using DPWM. Both losses and fluctuating torque are always beneficial compared to CPWM.

A Design of Experiments (DoE) methodology using machine learning (Active DoE) was used to reduce the test burden using an interactive statistically distributed test plan. The measured data was used to train empirical models for the optimization task, using the variation parameters as input and the KPIs as responses.

Two different ICU application optimization concepts range were evaluated in detail:

- Best system efficiency
- Best NVH performance

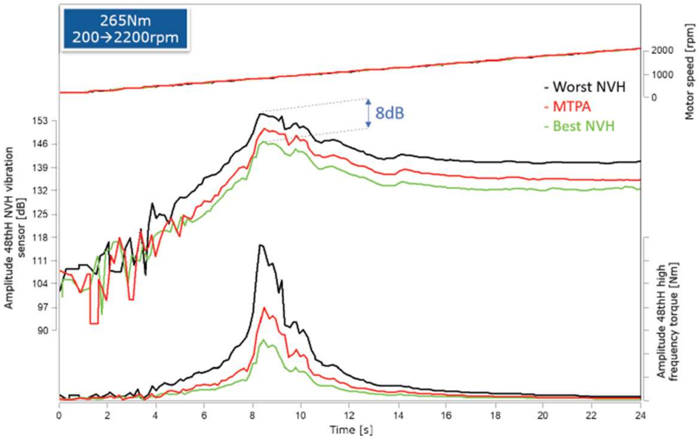

Figure 5: ICU parametrization influence on NVH

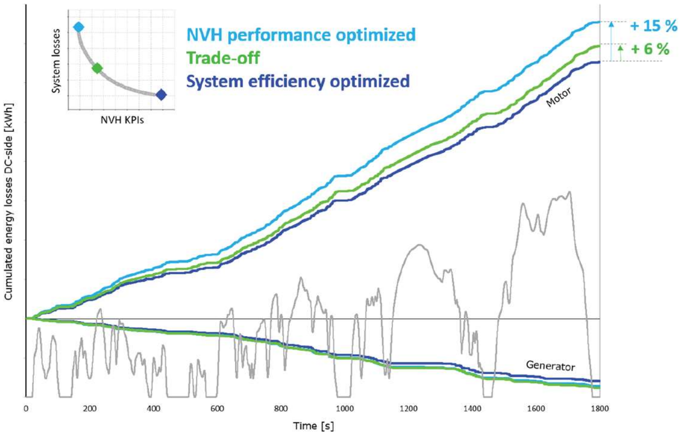

Figure 6: Comparison of cumulated losses with different ICU applications

Comparing the two application concepts revealed that a NVH-optimal parametrization has a cost in terms of efficiency. Performing a WLTC cycle with the best NVH performance dataset increases the cumulated losses in motor operation with 15% compared to the best system efficiency dataset as seen in Figure 6. [1]

The model-based optimization method also allows to find a trade-off between the two optimizations. A third optimization was performed with improved NVH at a limited cost in increased system losses.

The method described does not want to suggest which optimization is the best one: it is dependent on the applications and on the defined targets. The method supports the application engineer to find the right trade-off for the ICU application, improving NVH with the minimum negative influence of the system efficiency. The selected trade-off is fully transparent to other engineers as well as management and can be re-balanced if needed, without having to return to the testbed to collect new data.

2.3.2 Next level: Fine Optimization on Anechoic testbed After SOP

Once the E-Drive Unit / E-Drive System or even the Vehicle is at SOP level, the hardware and the base calibration of the ICU Paramters will be fixed and modifications are usually not possible or very time and cost intensive. Nevertheless, it may occur that a bad NVH behaviour is discovered with negative impacts on the durability of the E-Drive unit.. At this stage of the Vehicle development it is clear that we cannot alter the efficiency of the fixed E-Drive configuration and Software.
The remaining option is to to introduce additional advance control strategy such as harmonic current injection to selectively reduce mechanical harmonics that are responsible for torque ripples and further reduce the discovered NVH behaviour.:

Testing Environment

The measurement would be done on Anechoic testbed (see Figure 7) with a high dynamic torque transducer flange, capable to measure high harmonics also at high speed.

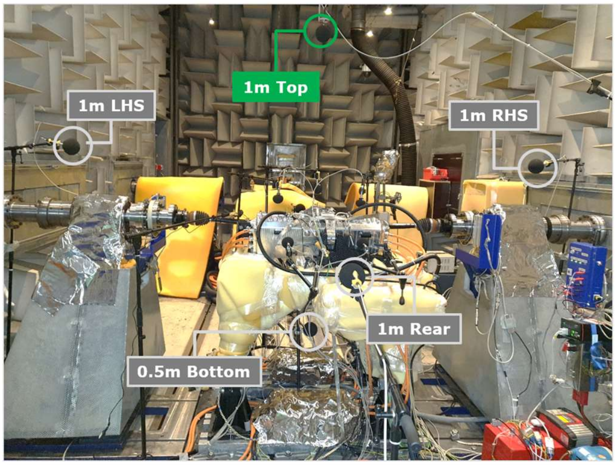

Figure 7: Example of standard airborne noise measurement set-up with 1m microphones

Task:

- Calibrate 6fe harmonic current injection (amplitude & phase) to actively reduce the problematic mechanical harmonics measured in the airborne noise
- Validate reduction of sound pressure level (SPL) for dynamic speed/load points

Testing Methodology:

With a similar method to the E-Drive Optimization on E-Motor Testbed, the step show on Figure 8 would be applied:

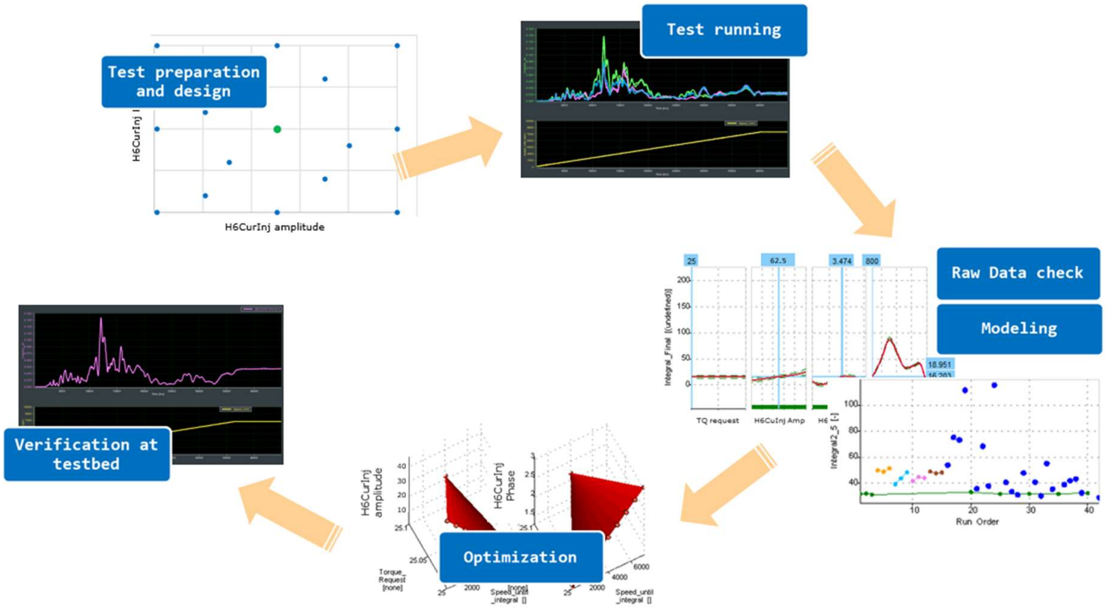

Figure 8: Testing methodology

Comparing the optimum found via our methodology with the base sound pressure level (SPL) of the 24th Order reveal a gain of up to 15DB improvement as visible on Figure 9 and 10.

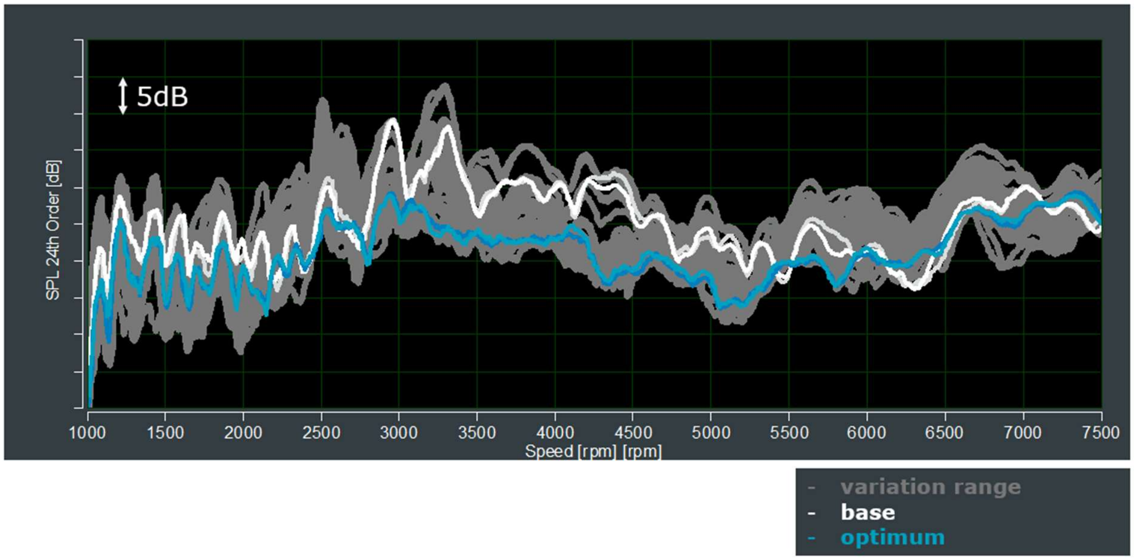

Figure 9: Low Torque – SPL 24th Order before/after

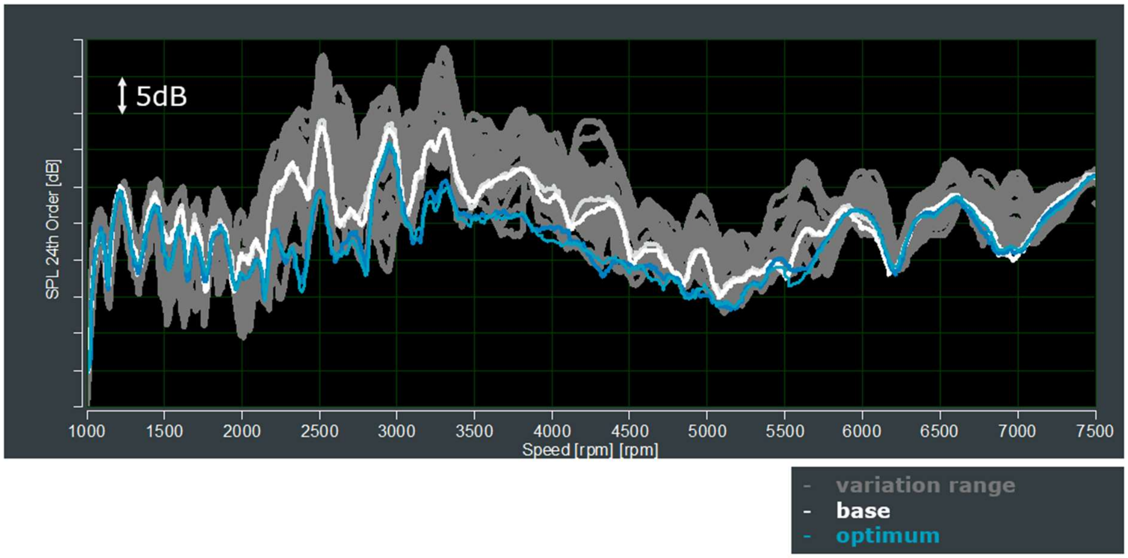

Figure 10: High Torque - SPL 24th Order before/after

This gain in the low speed/low torque area is critical since this is where the vehicle will be operated often. Further, the durability of the drivetrain is positively impacted by these improvements.

Additionally to the NVH gain, it is important to realize that this result could be achieve in a much reduce testing time compare to a standard methodology (up to 60% gain).

3 Conclusion

One of the biggest challenges for E-Drive development is to be fast to the market. It is a new technology, in a new market, in a crowded business. The question is how E-Drives can be developed for the shortest possible time to market. Consequently, innovative methods and new testing environments must be continuously explored for reaching higher development speed.
It has been shown how an innovative development methodology applied at an E-Drive testbed and Anechoic testbed offers a powerful solution. This new methodology maximizes the system efficiency while also fulfilling comfort criteria (NVH) by optimizing the inverter control unit application.

References

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Presenter Biography

Morgan LE COSSEC studied electrical engineering and started at AVL in 2005 as an application engineer for Advance Testing Methodologies on TestBeds. He has more than 10 years of experience in powertrain development, holding various roles within AVL. In 2011, he became Global Business Development Manager for Calibration Technologies, helping to introduce model-based technologies to accelerate the calibration process. In 2018, he was appointed Global Business Development Manager for Smart Calibration and Virtual Testing, extending his responsibilities to AVL's entire virtual testing portfolio. New applications of virtualization for battery electric vehicles and advanced hybrid powertrains as well as the industrialization of virtual testbeds for early and advanced testing were the main innovation achievements.