VIRTUAL E-MOTOR
AS A TOOL FOR THE DEVELOPMENT OF POWERTRAIN CONTROLLERS

The introduction of electric motors in powertrains provides many possibilities to influence the vehicle driveability using the inverter. The high dynamic response of electric motors can be put to use for the compensation of powertrain oscillations. Daimler and SET explains, that a "virtual e-motor" as Power-Hardware-in-the-Loop (PHIL) is an ideal tool for the test of such control strategies. However, the accuracy and precision of such a "virtual motor" is crucial for the success of such an implementation.

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NEW DIMENSION IN ELECTRICAL POWERTRAIN CONTROL

Oscillations in a powertrain are undesirable and, depending upon their intensity and frequency, they may be perceived by the vehicle driver and negatively affect the driving experience. Moreover, such oscillations in a powertrain increase wear. Issues such as these have high visibility at Daimler AG in Sindelfingen, where particularly electric and hybrid vehicles are faced with technical challenges. However, having electric motors present in the powertrain opens up completely new possibilities to dampen oscillations. They can be used as "compensation actuators", since their high dynamic torque response permits active powertrain damping. Algorithms can be developed that are superimposed over the normal engine/motor control.

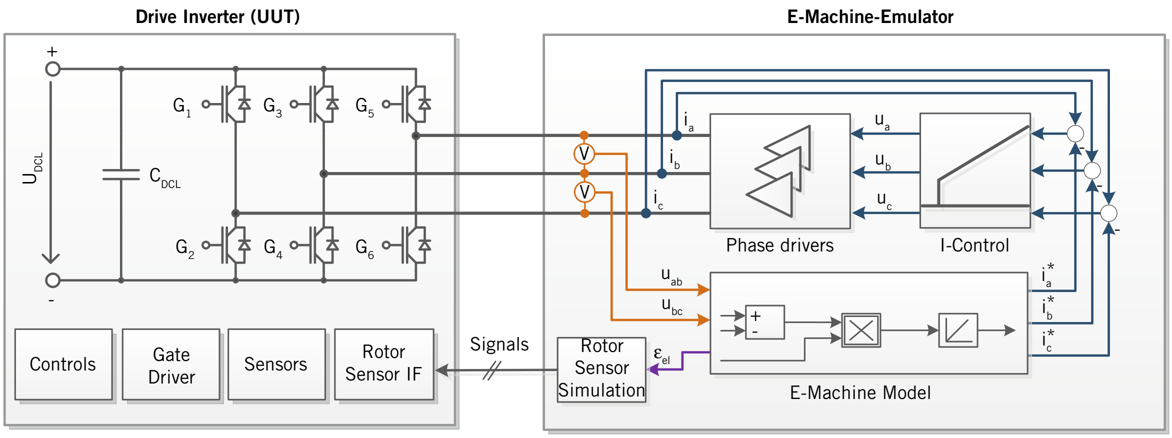
NEW TEST ENVIRONMENT IS REQUIRED

The basis for the development of such compensation controllers is a suitable test environment. In the development phase, on-road vehicle tests are not suitable due to their limitations and poor reproducibility. Rotating systems with dynamometers are also not able to reproduce the required dynamic speed range. The development team at Daimler AG decided therefore for a new approach using a virtual e-motor, a so-called e-motor emulator from SET Power Systems. The emulator permits tests to be run with the drive inverter at full electrical load, however without the mechanical limits a dynamometer set-up would impose. Since an e-motor emulator does not contribute mechanically, the real mechanical response of the powertrain can be simulated in realtime, whereby the phase connections of the e-motor inverter are emulated, ❶.

It can be assumed that a test rig utilising a load system presents "original" conditions to the e-motor, assuming that the correct e-motor is available. However, there is a drastic loss of "originality" of the whole test rig with regard to the dynamic response of speed and torque. The dynamometer including its control represents a second powertrain with high torque capacity, but with modest speed response. Thus a mechanical load system is not able to sufficiently reproduce the real characteristics of a vehicle powertrain. The use of e-motor emulators does, however, pose an important question: How accurately does the emulator reproduce the original e-motor on the electrical connections? Any compromises in the emulation accuracy would put the implementation of an emulator for the investigation of compensation controllers into question. A validation of the tool e-motor emulator must be prioritised.

THE YARDSTICK FOR AN E-MOTOR EMULATOR IS THE ACCURACY OF EMULATION

Since an emulator must reproduce the behaviour of the e-motor, the quality of emulation, meaning the deviation of emulated current and voltage when compared to real motors, is of crucial importance. Deviations at this level lead to errors in simulated torque. As the speed of the virtual motor increases, so too does the importance of the emulator electronics performance (calculation and control speed, synchronicity of field and rotor position, etc.). Of particular importance here is the motor model employed by the emulator. Standard models have limited performance, such as the linear PMSM model (synchronous motor with permanent magnets). A disadvantage of a linear model, for example, is that the saturation effect in the motor plating and magnetic flux harmonics in the air gap are ignored. For this reason, the emulator uses an alternative, flux-based motor model, ❷, that overcomes these limitations.
This flux-based model requires extensive configuration in order to be able to describe exactly the interactions and nonlinear dependencies in the e-motor. This data can be acquired by an electrical mapping of the original e-motor, processed by mathematical algorithms to bring the data into a form suitable for loading into the emulator models. This results in a very precise, virtual motor that behaves at the electrical connections as the original motor would. Alternatively, an FEM analysis based on the motor construction data can be used to acquire the necessary data. Data that has been generated using these methods do result in certain deviations from reality; however, there is a huge advantage in terms of time. While a new prototype motor may not be available for over six months, the emulator can be con-



❶ Functional principle of the e-motor emulator

figured with the data, so that “overnight”, the new motor is available as an emulation and can be connected and used for tests and controller design immediately. Temporary solutions are not required and the setting up of additional models and HIL rigs can be avoided. The developer can immediately begin testing on the virtual motor with the drive inverter and the control technology in safety.

FLEXIBILITY IN MODEL REFINEMENT

In order to be able to take advantage of the simpler parameter configuration of the linear model compared to the flux-based model, the e-motor emulator can be switched between both model variants, ❸. This gives the system user the ability to get up and running very quickly using a simple linear model. The system can be switched over to a far more precise flux-based model at a later stage, once an existing motor has been mapped, or when data derived from FEM are available.

DATA GENERATION FROM A REAL MOTOR

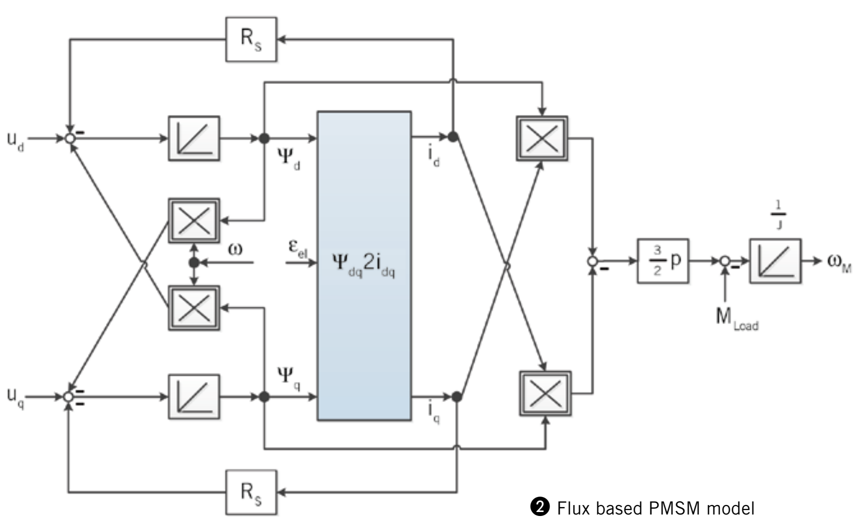
In order to be able to use the exact data of an e-motor, it must first be mapped. These three-dimensional maps describe the characteristics of the motor, including non-linear behaviour and harmonics. This set of maps provides a simple-to-trace sequence for the use of an e-motor emulator based on measured data, or alternatively, based on FEM data. The most precise data is obtained by mapping the original e-motor. A detailed description of the model data generation process and validation of an e-motor emulator can be found in [1].

VALIDATION – BETTER THAN THE ORIGINAL

At first sight this statement may appear to be a contradiction, an original cannot be improved. However, if production tolerances are taken into account, users may ask themselves “which” original they are currently testing. By using representative comparative measurements [1], the results from the e-motor emulator from SET Power Systems GmbH were found to deviate from the real motor in the range of a few percent, which is considerably lower than the production tolerance for a typical electric motor. This means that the emulator describes the numerical characteristics of the motor practically perfectly and is not subject to the usual motor tolerances. There is thus nothing to preclude the application of this emulation approach to tasks such as motor control verification, inverter endurance testing or efficiency optimisation.

INVESTIGATION OF ACTIVE DAMPING USING E-MOTOR EMULATION

The e-motor emulator provided by SET Power Systems GmbH was used by Daimler AG in the passenger car research group to test and calibrate drive inverters. The target vehicle was a Mercedes-Benz E 300 BlueTEC Hybrid – a vehicle with a hybrid powertrain. This configuration permits the e-motor, which is located at the transmission input, to be decoupled from the combustion engine using a wet clutch, whereby a pure electric traction mode is possible. ❹, shows the hybrid powertrain



❷ Flux based PMSM model

with the corresponding high voltage components.

As a result of the e-motor location, intermediate states with open clutch and transmission in neutral are possible, which can cause very high speed gradients. These rapid changes in speed must be represented on the test bed, for example, in order to be able to validate the stability of the current controller. Conventional load test beds cannot faithfully reproduce the rapid speed changes due to their inherent high inertia of the load machine, or dynamometer. A further characteristic of the P2-hybrid powertrain is its tendency to produce rotary oscillations. The e-motor, in comparison to a conventional powertrain, has a high moment of inertia, which then forms a dual mass oscillator with the drive shafts, which includes spring and damper elements, ❺. The drive shafts, being the most compliant elements in the powertrain, are susceptible to perceptible oscillations. The resulting resonant frequencies are low in frequency and represent a loss of comfort for the vehicle driver. In order to guarantee high driveability and comfort, the high torque response of the e-motor is used to actively damp the oscillations.

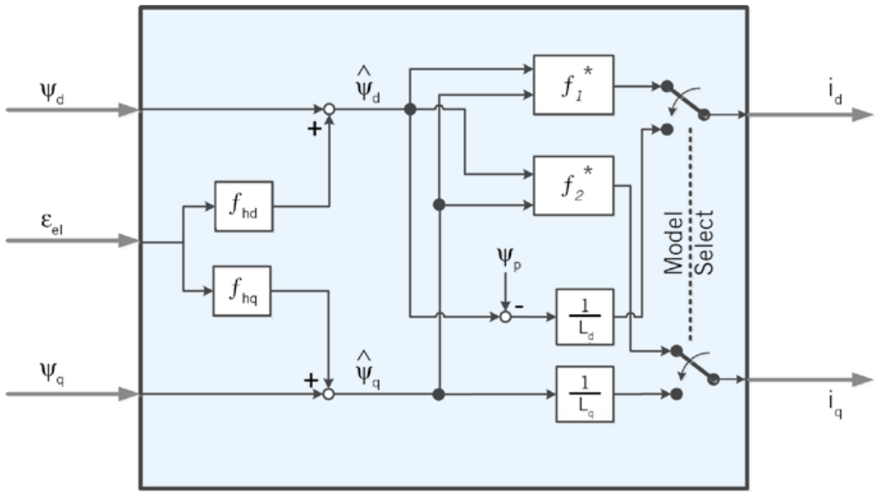
Conventional load test beds using dynamometers rapidly hit their limits when attempting to simulate powertrain oscillations due to their high moment of inertia. This is where an e-motor emulator offers a considerable advantage, since the mechanical elements of the system are only simulated and do not limit the dynamic speed response. The powertrain oscillations can be represented by the following differential equation:

EQ. 1	$J_{EM}\ddot{\varphi}_{EM} = M_{EM} - \frac{c_{sw}}{\ddot{u}^2}(\varphi_{EM} - \varphi_{Rad}\ddot{u}) - \frac{d_{sw}}{\ddot{u}^2}(\dot{\varphi}_{EM} - \dot{\varphi}_{Rad}\ddot{u})$ $\frac{J_{Fzg}}{\ddot{u}^2}\ddot{\varphi}_{Rad}\ddot{u} = \frac{c_{sw}}{\ddot{u}^2}(\varphi_{EM} - \varphi_{Rad}\ddot{u}) + \frac{d_{sw}}{\ddot{u}^2}(\dot{\varphi}_{EM} - \dot{\varphi}_{Rad}\ddot{u}) - \frac{M_{last}}{\ddot{u}}$

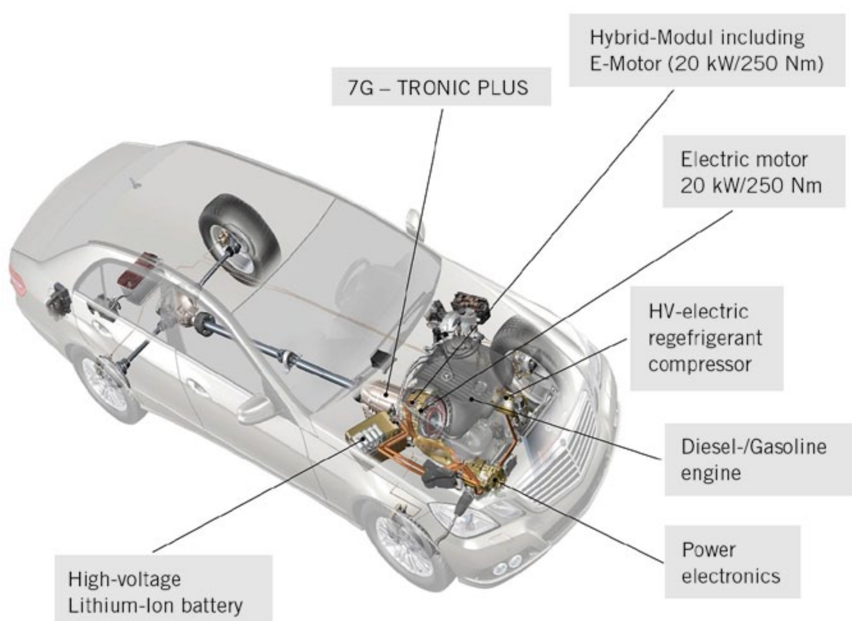
Neglecting the mass of the drive shafts and the transmission, the inertias of the vehicle J_{Fzg} and the e-motor J_{EM} have a major impact. The spring constant c_{sw} and the damping factor d_{sw} are determined by the mechanical configuration of the drive shafts. The damping of the system is naturally low, since friction losses must be minimised. The total system damping can be increased by introducing additional torque via the e-motor leading to increased driving comfort:

EQ. 2	$M_{EM}^{Damp} = -K_p(\dot{\varphi}_{EM} - \dot{\varphi}_{Rad}\ddot{u})$

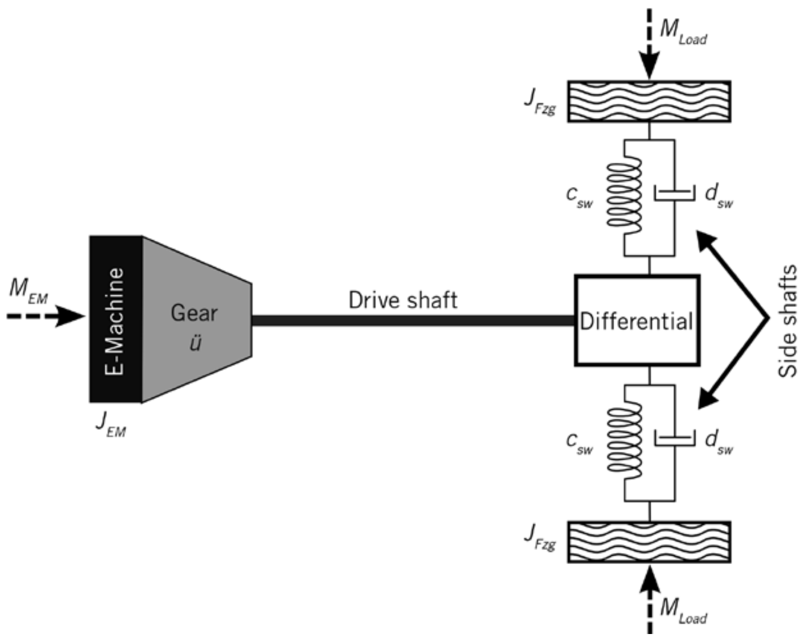
In order to test and to calibrate the software components for active damping, the e-motor emulator was connected with a powertrain model that ran on a realtime platform. This system can generate realistic load profiles that occur in the real world. Up until now, the investigation of active damping functions was only really possible in the vehicle, but can now be carried out in a reproducible manner on an e-motor emulator system. ❻ shows a test, recorded once with and



❸ Flux-block in the model with switching possibility



❹ Mercedes-Benz E 300 blue TEC hybrid powertrain



❺ Schematic representation of the spring-mass-damper system in the powertrain

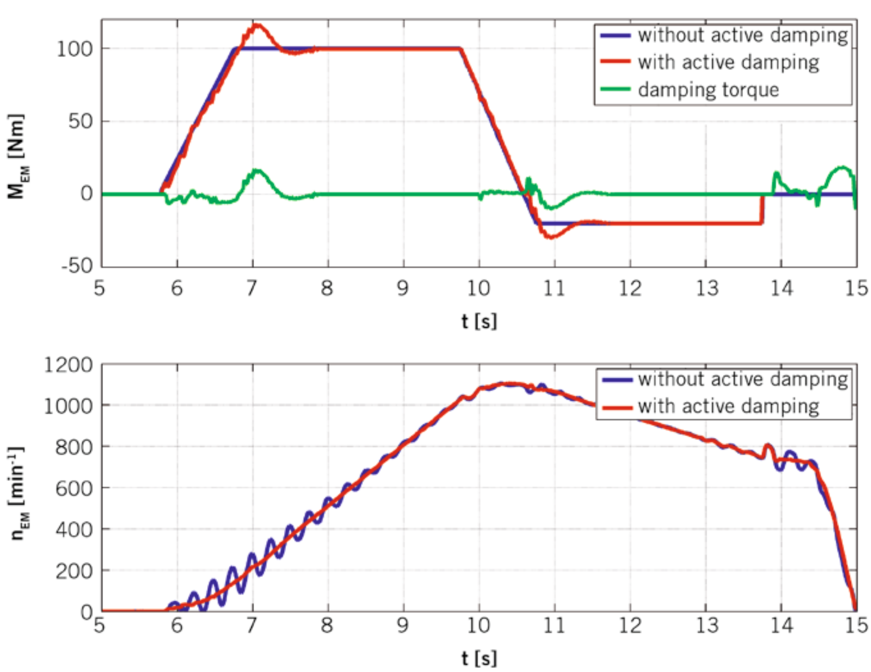
once without active damping. The effect of the active damping provided by the e-motor can be seen on the speed trace.

SUMMARY

Engineers working in the field of drive inverter development now have the possibility of running system tests in a laboratory environment, reproducibly and under power, thus enabling them to systematically optimise control algorithms. The number of vehicle tests required can be drastically reduced, which reduces costs and development times. The precise simulation of the e-motor by using a flux-based model makes close-to-reality testing possible even with high speed gradients. This approach also opens up new possibilities such as the ability to compare the efficiency of various control strategies, or the application of representative motor load for endurance investigations.

REFERENCE

[1] Uebener, S.; Böcker,J.: Application of an Electric Machine Emulator for Drive Inverter Tests within the Development of Electric Drives, European Electric Vehicle Congress, Brüssel, 2012, www.set-powersys.de



❻ Investigation of active damping on an e-motor emulator