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E-drive Component Tests Derived from Vehicle Master Test Cases in the SyrNemo Collaborative Research Project

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Abstract.

SyrNemo is a European collaborative research project that deals with the development of a highly integrated air-cooled next-generation E-drive (an E-drive consists of E-motor, inverter and controls) based on a Synchronous Reluctance Machine (SYRM). Its salient features are the use of ferrite magnets and a very high efficiency over a large operation range. Ultimately, any new E-drive component has to prove its viability in the vehicle where not only energy efficiency but also functional behaviour is checked. So the goal of the developer is to start the verification of E-drive components as early as possible. For that reason, relevant load cycles for E-drive testing are derived from vehicle driving cases. Vehicle driving functions are verified by so-called Master Test Cases that condense all possible driving manoeuvers into standardized sequences. On the E-drive level, these sequences can be boiled down to Test Primitives since many driving manoeuvers cause similar load patterns for the E-drive components. The most stressful Test Primitives can then be selected from simulations of different driving manoeuvres in vehicle models where the (electrical) load patterns of the components are determined. Because of the ease of simulation, it is relatively straightforward to find out the most demanding scenarios for the E-drive in terms of component ageing, for instance.

Key words

Electro-mobility, Green Cars Initiative, Synchronous Reluctance Machine, SyrNemo, driving cycle efficiency, rare earth independence, smart packaging, modular design, component testing.

1. SyrNemo Project Introduction

SyrNemo (cf. www.syrnemo.eu) is an innovative synchronous reluctance machine (SYRM) with higher power density and higher driving cycle efficiency at lower cost than state of the art permanent magnet (PM) synchronous machines.

The mass and volume specific power densities are increased by approximately 5%. This is achieved through an innovative magnetic reluctance rotor design with ferrite magnets. Hairpin windings (Fig. 1) are used to increase the slot fill factor to roughly 70 % from 40 to 50 % in the case of random windings.

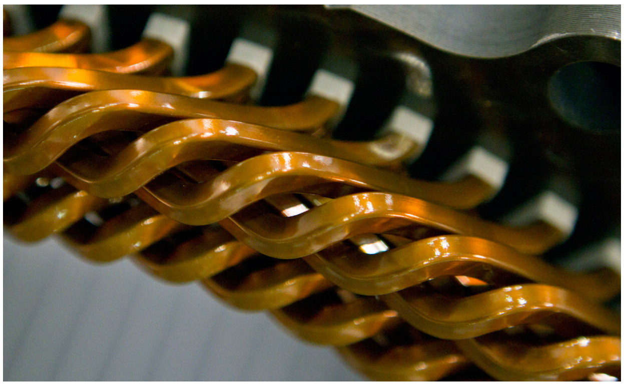


Fig. 1. Hairpin winding. Source: http://blog.caranddriver.com/we-build-the-chevy-spark-ev%E2%80%99s-ac-permanent-magnet-motor/.

The dependency on rare earth permanent magnets is eliminated by using ferrites for excitation. The proposed magnet circuit design can be seen in Fig. 2.

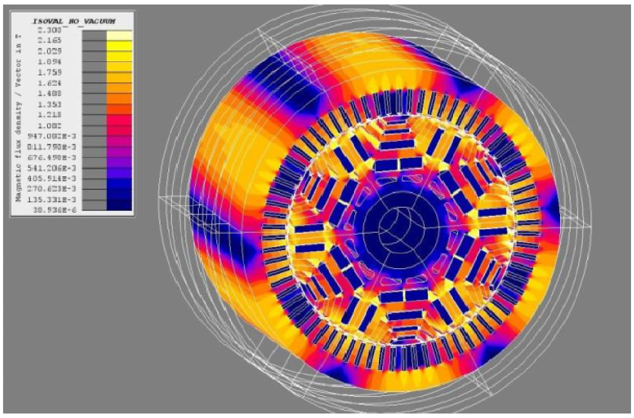


Fig. 2. SyrNemo SYRM FE-model. Source: SyrNemo project partners University of Hannover and CRF.

The proposed SYRM has a high efficiency over a wide range of speed and torque (Fig. 3). Therefore, the overall driving cycle efficiency of SYRM can be improved by 5–15% compared to Permanent Magnet excited Synchronous Machines (PMSMs).

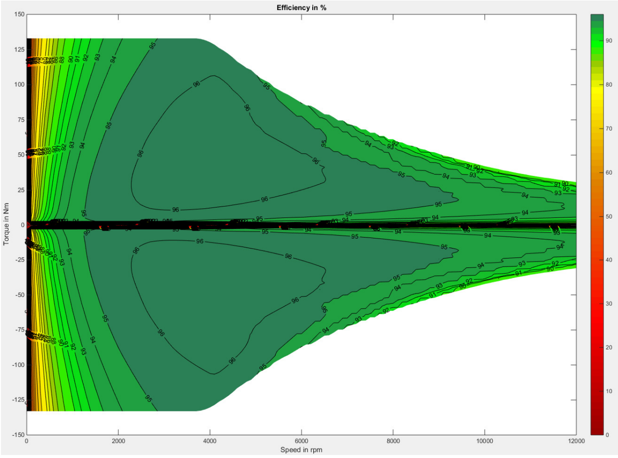


Fig. 3. SyrNemo SYRM efficiency map. Source: SyrNemo project partner University of Hannover.

The control of the drive is optimized to achieve the maximum possible efficiency in each operating point incorporating the stator winding temperature.

Synchronous reluctance machines have obtained renewed interest during the last years, cf. [1]. The proposed SYRM is a very promising candidate for being the next generation electric motor of full electric vehicles. For increased overall energy efficiency and cost effectiveness, inverter, Motor Control Unit (MCU) and SYRM are integrated into an air-cooled housing (Fig. 4). In that case, the expensive wiring harness between inverter and E-motor can be replaced by bus bars. Air cooling reduces production costs by eliminating cooling jacket, coolant pumps and pipes. The required fan for overcoming low-speed situations is a comparably inexpensive component.

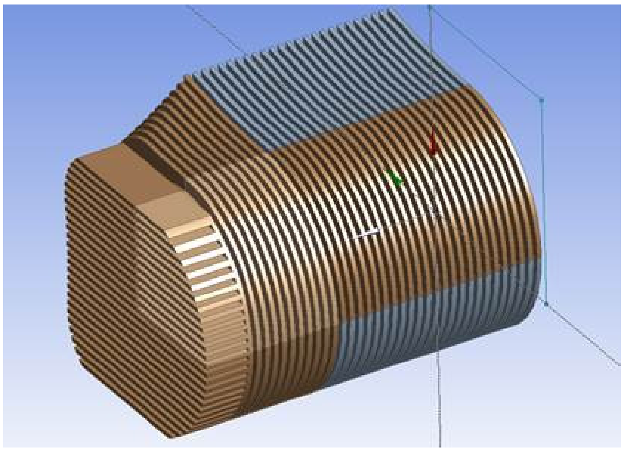


Fig. 4. Air cooled SyrNemo E-drive unit comprising SYRM and inverter. Source: SyrNemo project partner AIT.

2. Component Testing

The continuous strive for environmentally more benign transportation has led to invigorated interest in electric propulsion. A review of recent literature ([2]-[6]) has shown that the topic of electric component reliability and durability has attracted considerable effort during the last years.

A. Component and Sub-System Testing

The fitness for use of an E-drive component in a vehicle is assessed on various levels. Performance testing of individual components (i.e. E-machine alone) is done according to standards. Tests for efficiency and IP-class are often conducted according to the sub-sections of IEC 60034, for instance, cf. Table I.

Power train sub-systems, such as the E-drive comprising E-motor, inverter and controls, are not covered by standards but by requirement (RQ) documents. For ease of compilation of such documents, carmaker associations have created quasi-standards that are considered as best practise for ensuring E-drive performance, durability, and HV-safety, to name but a few. Well known examples for such tests are the High Temperature Operating Endurance (HTOE) and the Powered Thermal Cycle Endurance (PTCE) tests.

Table I. –Test methods for component and sub-system testing.

Testing according to International Standards • IEC 60034 provides a compilation of standards for the performance testing of electrical machines, for instance.
Testing according to Requirements and Quasi-Standards (Examples) • High Temperature Operating Endurance (HTOE): The lifetime of the E-motors shall be proven by operating the E-machine at high (coolant, winding) temperature with high continuous load. • Powered Thermal Cycle Endurance (PTCE): For varying ambient and coolant temperatures, the lifetime of the E-motor shall be proven by cold starts and pulsed power. The aim is to achieve high temperature gradients by high E-motor currents. The effectiveness of the cooling method shall be demonstrated by activating coolant flow during the load pulses. • High / Low Temperature Storage Tests: Cooling effectiveness shall remain sufficient when the E-machine is operated after the storage tests.

On the other end of the spectrum, functional vehicle testing ensures the proper working of vehicle functions, such as recuperation in the case of a hybrid or electric vehicle, and the transitions between functions. These tests are generally not covered by standards or quasi-standards but they are derived from vehicle RQs. Vehicle RQs have to be covered by RQs on powertrain (PT) level. Consequently, powertrain tests can be derived from PT requirements. Furthermore, sub-system and component tests can be derived from sub-system and component RQs, respectively. As one might imagine, the amount of such derived tests might become prohibitively high due to the many possible variants. For that reason, it becomes mandatory to detect similarities between the many component load patterns derived from vehicle RQs via PT, sub-system and component RQs. These component load patterns are called Test Primitives (TPs). Since TPs resulting from various vehicle test cases usually cause different stress on component level, it suffices to consider the test primitives with the highest resulting component stress. Such a stress must be an equivalent one taking the absolute stress values and their relative frequency into account. For example, a modest stress level can lead to significant component ageing when its rate of occurrence is sufficiently high.

B. Obtaining Test Primitives from Vehicle Functional Testing

As mentioned in the last paragraph, a component or sub-system TP is a sequence of load states that is occurs in a similar way for different driving manoeuvers. Driving manoeuvers are realized by the available vehicle functions in different vehicle states. Vehicle functions are tested during the vehicle functional tests where all functions and all allowed transitions between the functions are tried out. Although the E-drive components are involved in different vehicle functions at different vehicle states, their trajectories in the torque-speed map are often similar. In a hybrid car for instance, Electric Acceleration forward and Electric Boost, will exhibit related torque and speed profiles. These two cases will be characterised by a brisk speed increase combined with quite high torque peaks, albeit, for a relatively short period of time. The introduction of TPs leads to a reduction of functional component or sub-system tests by an order of magnitude compared to testing all variants induced by the vehicle functions and their transitions.

Fig. 5 shows the basis of vehicle functional testing. Every driving function (e.g. Electric Creep or Conventional Creep) can be translated into a manoeuver (e.g. Creep forward or Creep reverse) combined with a vehicle state (e.g. Pure Electric). The states are selected by the driver via mode switches.

For every function and every transition between functions, a corresponding test has to be made on vehicle level. It can be figured out that the load patterns of the E-drive components will have similarities for different manoeuvres leading to the E-drive TPs mentioned above.

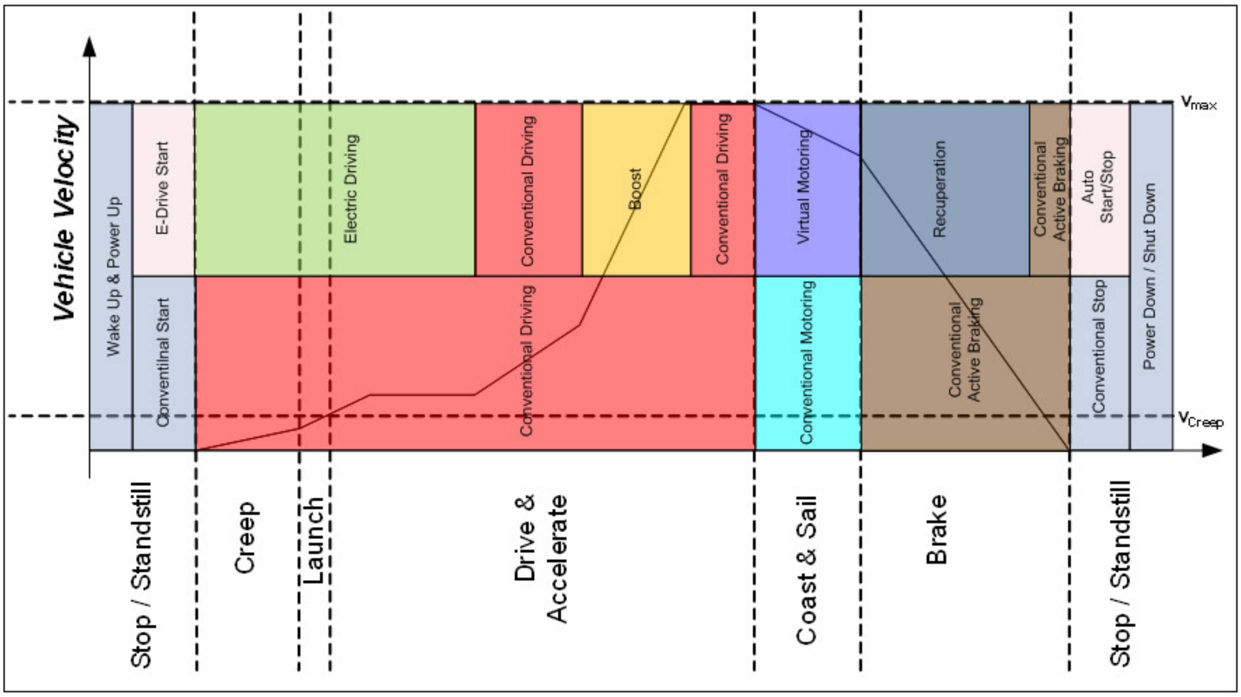
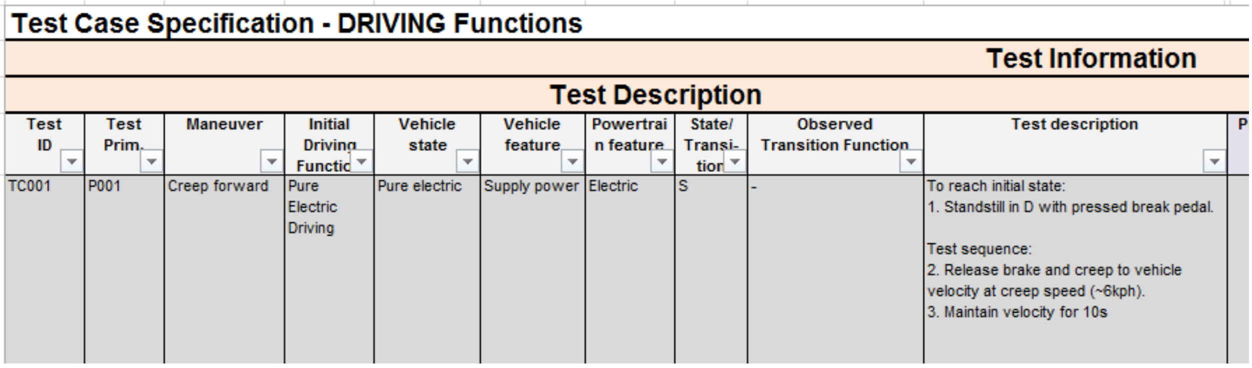


Fig. 5. Standard driving patterns and vehicle functions.

Obviously, the graphical representation (cf. Fig. 5) of driving manoeuvers is not sufficient for accurately describing functional tests. Therefore, test sequences are defined where pre- and post-conditions as well as the test sequences themselves are provided step by step. Fig. 6 gives an impression of a file containing test cases for vehicle testing. Of course, for component testing on a test bed, this approach is too time-consuming because for a P2 hybrid architecture, e.g., roughly 300 basic test cases for states and state to state transitions have to be conducted on vehicle level. On a test bed, only a small fraction of the data traffic inside the vehicle is provided by the tested components. The bigger share had to be simulated which is a magnificent task. When there are parameter variations planned as well, the number of tests can enormously increase. Consequently, the number of tests is generally kept as low as possible by utilizing the so-called Master Test Cases only.

A basic test case prior to any parameter variation is called a Master Test Case (MTC). Testing only MTCs results in the smallest test set that still covers the whole vehicle functionality.



Test Case Specification - DRIVING Functions

Test Information

Test Description

Test ID	Test Prim.	Maneuver	Initial Driving Functio	Vehicle state	Vehicle feature	Powertrain feature	State/ Transition	Observed Transition Function	Test description	P
TC001	P001	Creep forward	Pure Electric Driving	Pure electric	Supply power	Electric	S	-	To reach initial state: 1. Standstill in D with pressed break pedal. Test sequence: 2. Release brake and creep to vehicle velocity at creep speed (~6kph). 3. Maintain velocity for 10s	

Fig. 6. Translation of standard driving patterns to master test cases.

For the sake of legibility, Fig. 6 cannot show the whole test specification. For that reason, an example of a functional vehicle test (Table II for the test description, Fig. 7 for the expected powertrain and vehicle reactions) is provided in the sequel:

Table II. – Functional vehicle test description - Recuperation at de-coupled engine

Initialization Phase:	*Main Test:*
• Wake Up / Power Up sequence • Enable Pure Electric Driving feature • Engage gear lever position D, release brake pedal and apply acceleration pedal. • Accelerate vehicle to speed 30 km/h • Maintain speed of 30 km/h for approx. 5 s • System Reaction / Pre-Requisite for main test: System Wake Up and Hybrid System ready and HV > 60 V, engine running and vehicle driving with velocity @ 30 km/h.	• Release acceleration pedal, after approx. 2 s apply brake pedal • System Reaction: ○ Engine torque= 0 Nm (Engine stopped, separation clutch C0 opened) ○ E-drive Unit supports with negative torque to fulfil Powertrain torque demand ○ After braking: Powertrain torque demand = E-drive torque ○ HV Battery: in charging mode *Final Phase:* • (Smoothly) brake to standstill and initiate Power Down / Shut Down

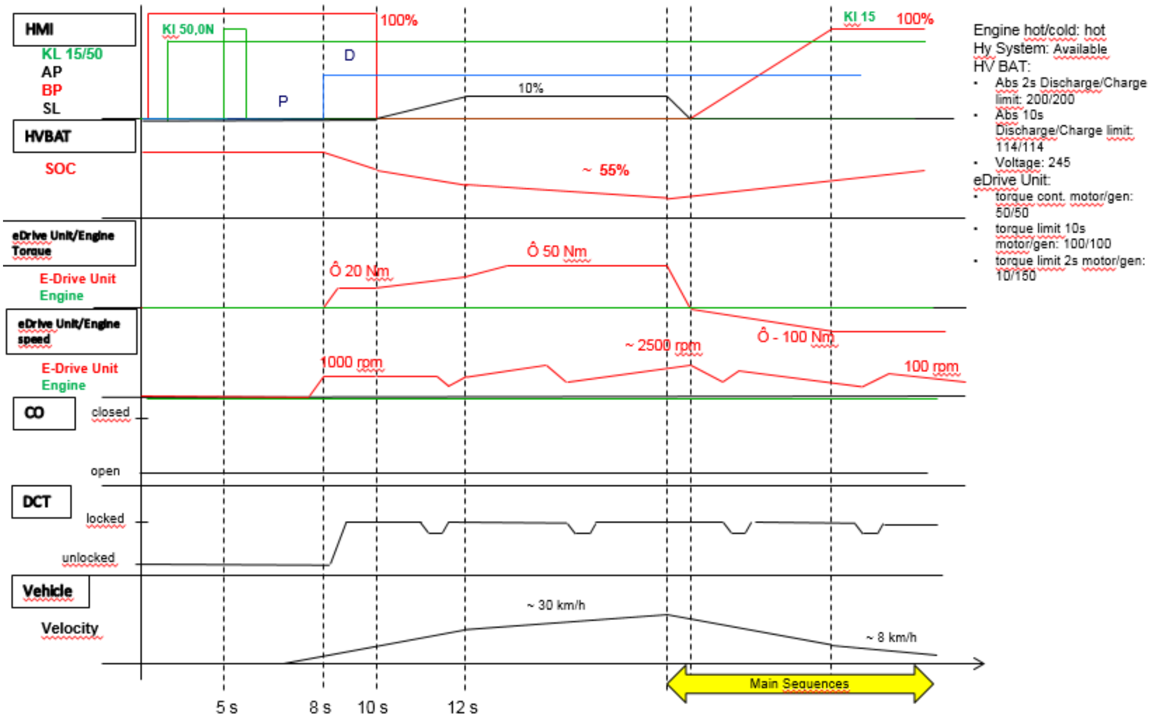


Fig. 7. Functional vehicle test - Recuperation at de-coupled engine.

C. Component Functional Testing

In the field of E-motor insulation life prediction, the variety of stresses seen by the insulation and the many possibilities of small but acceptable defects leads to a considerable complexity. This situation is aggravated by the many operational profiles encountered in vehicle usage and the plethora of potential contaminations. Due to that complexity, a deterministic estimation of insulation life cannot be given.

However, a specific probability how large a percentage of all E-motors of a certain type could survive under a given load profile is an urgent desiderate. For that reason, the main influencing factors of ageing have to be captured, such as electrical and thermal stress. By Arrhenius' formula, the temperature influence can be approximated. Combined with a voltage stress formula, the simplest multi-factor approach is conceived. In addition to such static descriptions, thermal gradients – or even thermal shock – pose a considerable problem for the mechanical endurance of insulation layers or of inverter bonding. In very exposed environments, such as vehicles and wind power, temperature jumps can dramatically reduce the life span of an insulation system. A similar effect can be attributed to severe vibrations.

By the increased application of oil cooled windings, new problems have arisen. Whereas new oil can even improve insulation life by the suppression of partial discharge, aged oil often contains reaction products such as acids. In automotive applications, the oil can also contain tiny metal parts from abrasion in transmissions.

Approaches in multi-factor stress analysis have not led to unified models independent of manufacturers or even base configurations of the insulation system. So the only way that remains is to test the insulation system in the ambiance and under the conditions it was developed for. That does not only include the ambient conditions, such as temperatures, humidity, contaminants but also electrical and mechanical conditions. If the controller and the inverter is known, then it should be used during the test as well since insulation ageing heavily depends on the voltage gradients caused by the inverter's switching pattern. The same is true for vibration levels and thermal conditions. Component temperatures are not only influenced by ambient but predominantly by their operational regime, i.e. the driving cycle of the vehicle.

A result of a vehicle simulation based on a given driving cycle yielding component stress and ageing can be seen in Fig. 8. Besides longitudinal vehicle dynamics, a simple hybrid controller is implemented that translates the torque requests of the driver into a torque distribution between Internal Combustion Engine (ICE), E-drive and mechanical brakes. Amongst other influencing factors, such as component de-rating, the torque distribution is mainly controlled by the State of Charge (SoC) of the HV battery.

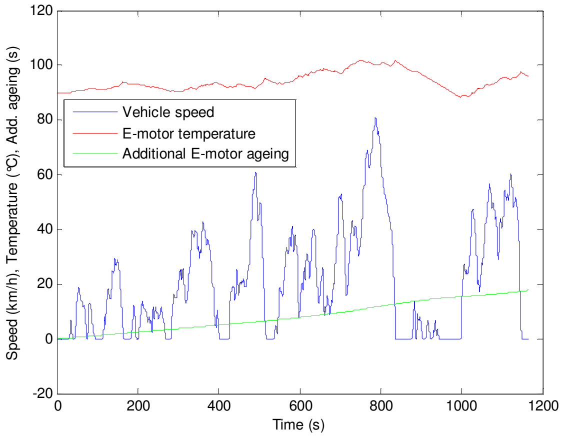


Fig. 8. Vehicle driving pattern influencing E-motor ageing.

From the torque-speed profile of the E-motor, a resulting current-voltage profile is determined via the E-drive controllers. Thermal models of HV battery, inverter, cooling system, and E-motor yield the component temperatures and the respective de-rating factors. Temperature and temperature gradients as well as voltage levels and inverter switching frequency, if variable, give estimations for the components' loss of life during the investigated driving event.

3. From Master Test Cases to Component Tests

By taking driving cycles and component ageing into account, several important findings for E-drive component testing were obtained in the SyrNemo project. First, the inclusion of component ageing models in behavioural vehicle models gives insight how driving patterns affect components' longevity.

Since testing in the vehicle takes place at the end of a development cycle, any problems found at that stage are very costly to sort out. Moreover, a component running into de-rating for temperature reasons is seen as a severe drawback in the drivability assessment of a vehicle. Generally, the Hybrid Control Unit (HCU) or the Vehicle Control Unit (VCU) should always be in full control of the components' performance. De-rating should only be a protective action in the case of emergency which is not to happen during normal operation.

For those reasons, the powertrain developer would like to start the components' lifetime assessment much earlier. In the best case, this process should begin when the components are being selected via energy efficiency calculations and the underlying (real world) driving scenarios are getting known. However, for estimating characteristic loading of E-drive components, simple but sufficiently aggressive driving manoeuvers are sufficient, such as a brisk pure electric acceleration.

For pure electric driving - a simple load case where all the propulsion torque is provided by the E-motor – a possible speed pattern of the E-machine is depicted in

Fig. 9. The rather abrupt speed variations are caused by the gear shift function of the vehicle.

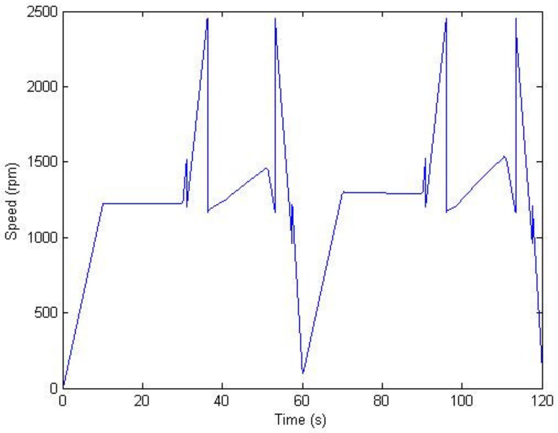


Fig. 9. E-motor speed during electric drive test.

The resulting E-motor temperature increase is shown in Fig. 10 for a start at room temperature. Since stator winding temperature is one of the major influencing factors of insulation ageing, the most damaging load scenarios can be picked from the simulations and used for physical testing.

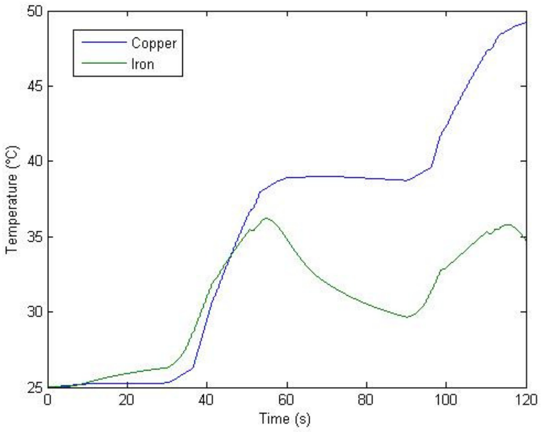


Fig. 10. E-motor temperatures during electric drive test.

Taking another step, designed experiments (DoE) can be used to derive maximally damaging tests for the components based on vehicle dynamics. Future test of E-drive components will not only take static load and ambient conditions into account. They will mimic the situation in the vehicle as close as possible, for example on Power Train test beds. By AVL's Load Matrix™ approach, the tests can be limited to the most significant load conditions thus achieving optimal test acceleration while keeping focused on the factors determining durability and reliability.

4. Conclusion

Stress encountered in E-drive components of electric or hybrid electric vehicles depends very much on the driving cycles to be expected in the target vehicle. Testing the components in the vehicle takes place at a relatively late stage in an electrification project. Therefore, a method for deriving E-drive load patterns for earlier testing would be desirable. From the driving manoeuvers during vehicle Master Test Cases, E-drive Test Primitives can be obtained. Simulating these vehicle driving manoeuvers with a suitable model comprising the E-drive components yields an estimation of the relative severity of each Test Primitive. Using the most demanding tests according to the statistically expected vehicle usage can give a comparably fast first check of the components' performance and longevity in the vehicle.

Acknowledgement

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