EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

E-Motor Emulator –
Testing Power Electronics without Motor

S. Liebig, A. Schmitt, H. Hammerer

SET Power Systems, August-Braun-Str. 3, D-88239 Wangen i. Allgäu
sebastian.liebig@avl.com, alexander.schmitt@avl.com, horst.hammerer@avl.com

Abstract

In the past decade, inverter testing has become a very important and complex issue during inverter developments. State-of-the-art inverters, key components of electrical power trains, offer multiple functions, high reliability, fault tolerance and they must ensure a high level of functional safety. Especially automotive applications prove to be demanding due to their exceptionally high dynamic requirements, challenging mission profiles, harsh environment and special test cases such as the “curb stone edge” case with high currents and no speed. Conventional test methods such as motor test beds or passive RL-loads are not suitable to verify inverter functionalities in a sufficient manner. This paper presents a new and powerful inverter testing technology: the E-Motor Emulator – testing power electronics without an e-machine.

Keywords: inverter testing, E-motor emulator, motor emulation, e-machine, Power-HIL, motor test bench

1. Introduction

Fig. 1: Type of E-Motor Emulator.

One of the challenges in testing inverters is the wide range of different requirements, which have to be verified. Hardware-in-the-Loop (HIL) systems with e-machine simulation are an important method to verify the functionality of control algorithm [1] on signal level, but do not allow real power flow. Motor testbeds on the other hand allow real power flow and current control, however, fault scenarios as stipulated by ISO 26262 (e.g. short circuit between two phases), 0 Hz and high acceleration tests are not possible. Furthermore, there are several installation issues considering safety, mechanics and cooling involved. The E-Motor emulator, an all-in-one Power-HIL solution, meets the demands of all development-related tasks, verification on system level and end-of-line testing. On top of that it offers additional functionality such as easy change of motor parameters (even during operation) and monitoring / recording of all virtual model parameters. The EME behaves like a real e-machine, but without any restrictions regarding speed dynamics [2]. Continuous integration in simulation environment and development process is a further advantage, e.g. reuse of mission profile simulation data for test of inverter prototypes.

This paper presents an E-motor emulator with high power and current rating and excellent dynamic characteristic. Chapter 2 deals with the need for a high dynamic emulator and the subsequent necessary concept. Design and functionality of the emulator is described in chapter 3.Chapter 4 presents measurements at a serial product. Conclusions are stated in chapter 5.

2. P-HIL Concept

A precise P-HIL emulation requires a complete identical behaviour at the terminals of the PHIL test bench compared to the real machine. Therefore, the emulation converter has to apply a voltage at the coupling network very precise and with a minimal dead-time to ensure the correct current slopes of arbitrary machines within the coupling inductance. For this reason, the basic challenge of PHIL emulation is the calculation and generation of this voltage. Modern FPGAs and A/D-converters allow the calculation of the machine model including the counter voltage with sample rates of more than 3.125 MHz quasi continuous in real-time [3]. Indeed, the counter voltage generation is more challenging, especially for high power applications. The counter voltages are discontinuous functions since the current slopes depend on the clocked output voltages and are different in active as well as freewheeling states of the DUT. Moreover, the phase inductance of the coupling network can not correspond to the differential inductances of the machine due to iron saturation or the magnetic anisotropy of the rotor. For this reason, the emulation of the current slopes requires a converter topology that allows a high dynamic and very precise generation of the counter voltages. The modular multiphase converter and the associated modulation scheme offers such a dynamic and precise voltage generation.

3. Design and functionality

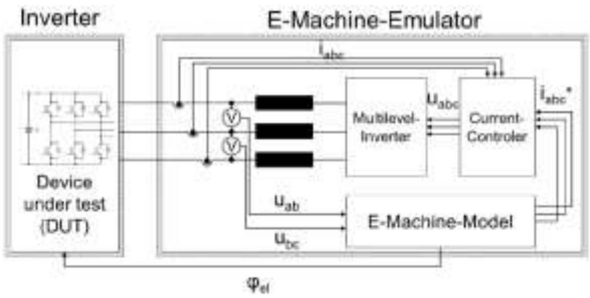

Fig. 2: Topology of E-motor Emulator hardware.

The E-Motor Emulator is designed for inverters with a DC-link voltage as high as 1000 V and phase currents of 800 A_{rms}. The emulator must have much higher dynamics and significantly lower current ripples compared to the device under test ([4], [5], [6]). Low switching frequencies and hence low dynamics lead to very restricted emulation qualities [7]. Therefore, the emulators switching frequency is set to 800 kHz, the fundamental frequency of the phase currents can reach up to 5 kHz. This functionality covers a broad range of applications, including high-speed drives with more than 100.000 rpm.

The model is calculated in 320 ns, which equates an update rate of 3.125 MHz. This powerful signal processing unit enables detailed modeling of nonlinear motor characteristics. Furthermore, the model is able to change its parameters dependent on the position of rotor, i.e. flux vs. angle can be modelled with additional harmonics for instance.

The basic EME components are the multilevel inverter, coupling network at the output, current / voltage measurement and high performance FPGA for calculation of the PMSM or ASM model (Fig. 2). Fig. 3 depicts a typical PHIL test bench with unit under test, a battery emulator and the emulator itself with own DC-supply. Both battery emulator and EME supply are galvanically isolated to achieve similar conditions as in the real car, where the battery and the motor are floating against earth potential. The power flows in a circle, i.e. the 400 V_{ac} mains must provide the entire power loss only (about 20% of the inverter's output power). Due to that, it is possible to test 430 kW inverters with a conventional 125A grid supply only.

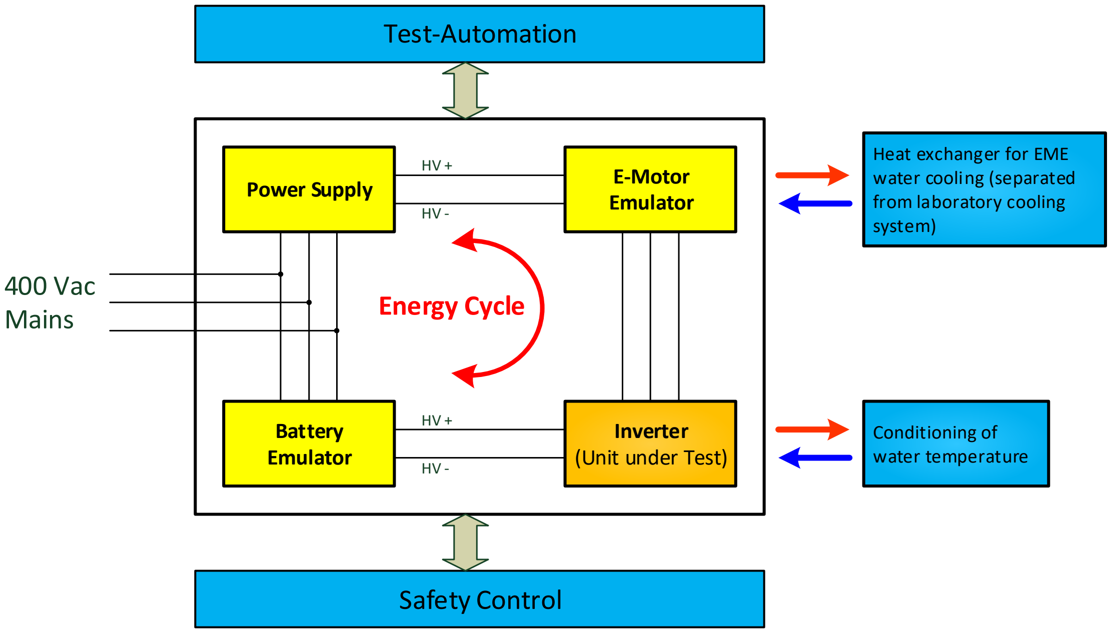

Fig. 3: Test setup with E-Motor Emulator.

4. Measurement results

The evaluation of the emulation quality of the phase currents is done through measurements with shorted emulator outputs, i.e. there is no test inverter connected. This enables an objective quality evaluation with lowest possible external influences. The phase currents are sampled and analysed through a Yokogawa power analyser in combination with LEM Ultrastab IT-1000 current transducers. The phase currents at 1 kHz and 5 kHz are depicted in Fig. 4 and Fig. 5. The emulation quality is excellent, which prove the low THD results in Fig. 6.

An alternative emulation technology from another emulator supplier uses a fixed PWM pattern for the power semiconductors in the emulator's amplifier. A variable DC-link voltage of the emulator enables the current control at the emulator output. The THD and harmonics analysis shows that the presented control and hardware concept offer a significantly better performance (Fig. 6, Fig. 7).

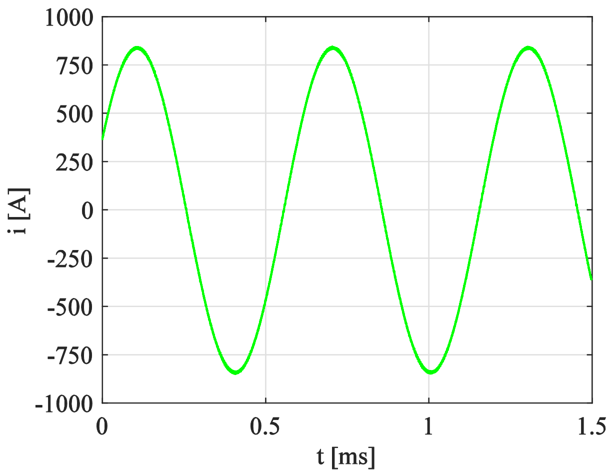

Fig. 4: Emulated phase current with 1,67 kHz fundamental frequency.

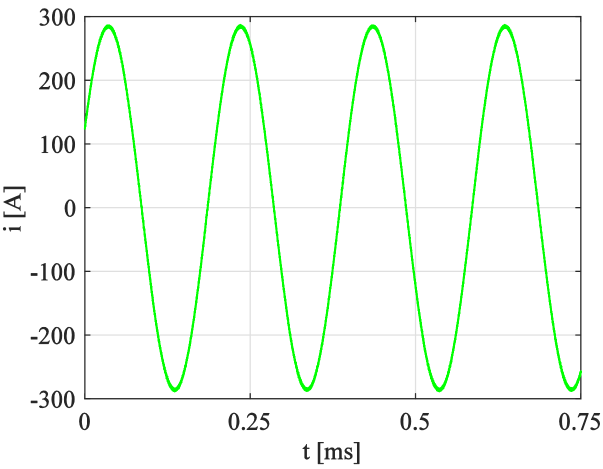

Fig. 5: Emulated phase current with 5 kHz fundamental frequency.

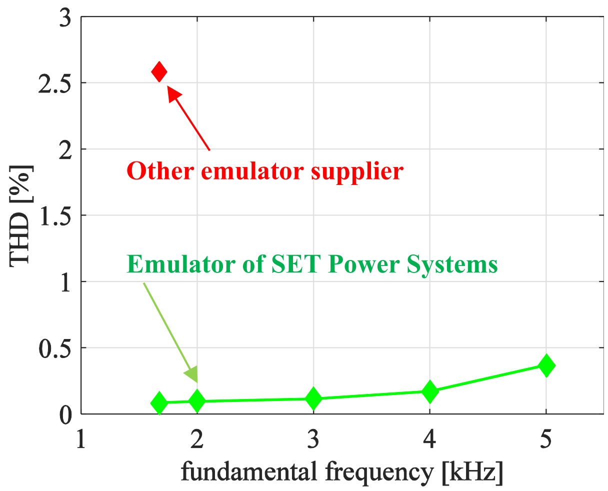

Fig. 6: THD of emulated phase current vs. fundamental frequency.

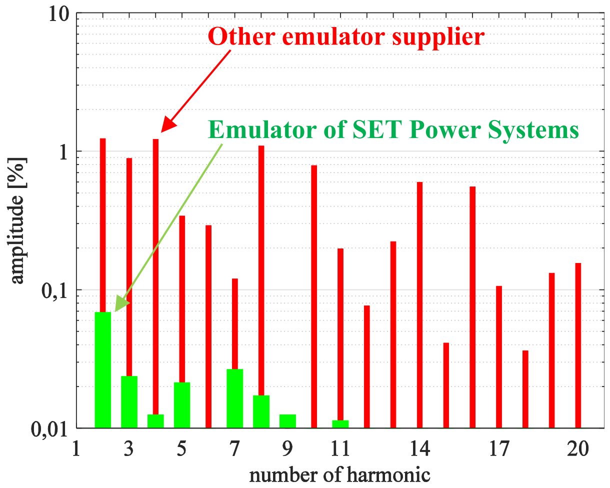

Fig. 7: Comparison of emulation quality by harmonic analysis between a SPS and another emulator supplier (shorted emulator outputs, 104 A_{rms} phase current with 1,67 kHz fundamental frequency).

The EME not only models the fundamental frequency and back-EMF, but emulates exactly the current ripples depending on motor inductance and inverters switching frequency. Another quality criteria is the emulation accuracy regarding the back-EMF, since the emulator is able to reproduce a back-EMF with non-linearities and harmonics. Fig. 8 shows a comparison between measured back-EMF from an E-motor and emulated back-EMF. The spectrum proves the high emulation accuracy.

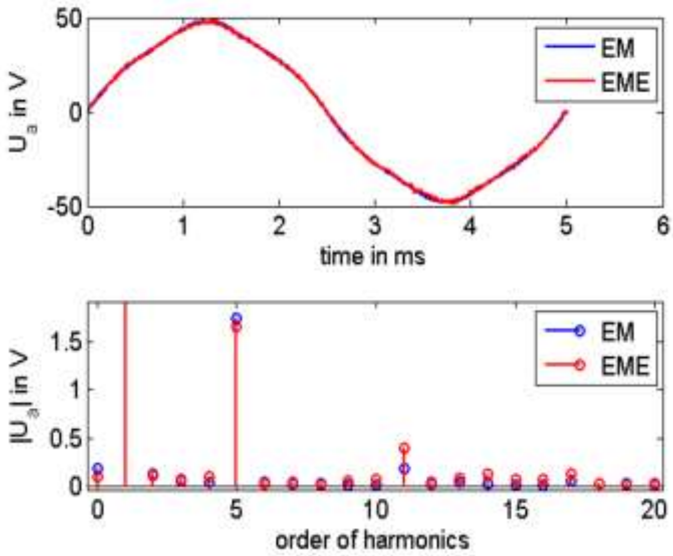

Fig. 8: Comparison of measured and emulated non-linear back-EMF (picture taken from [1]).

Fig. 9 depicts a high current motor start-up emulation. This occurs e.g. at the curbstone edge case, where the car demands high torque at zero speed. An emulator enables the execution of this complicated test case in a simple manner and under reproducible conditions and high freedom in parameterization. Furthermore, the emulator allows the use of any load characteristics, independent from their complexity. The current and frequency steps in Fig. 10 and Fig. 11 prove the high dynamic quality of the presented emulator.

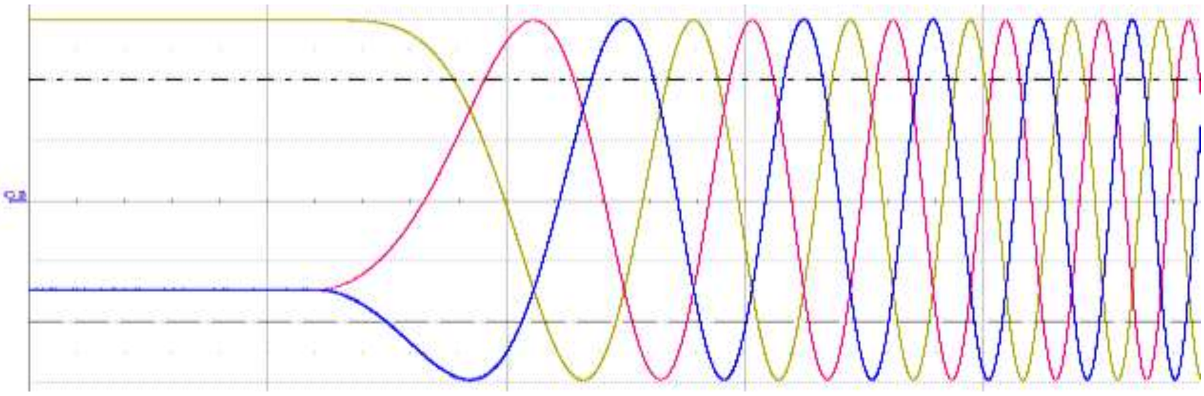

Fig. 9: Emulation of motor start-up from zero to 1 Hz with high currents (possible application: simulation of curbstone edge case).

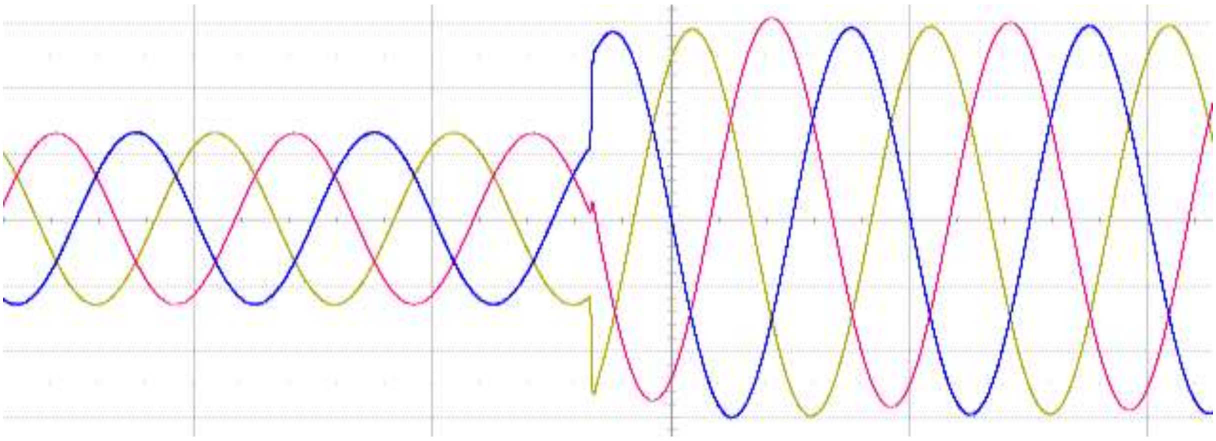

Fig. 10: Current step at 1 kHz fundamental frequency, which proves the high dynamic performance.

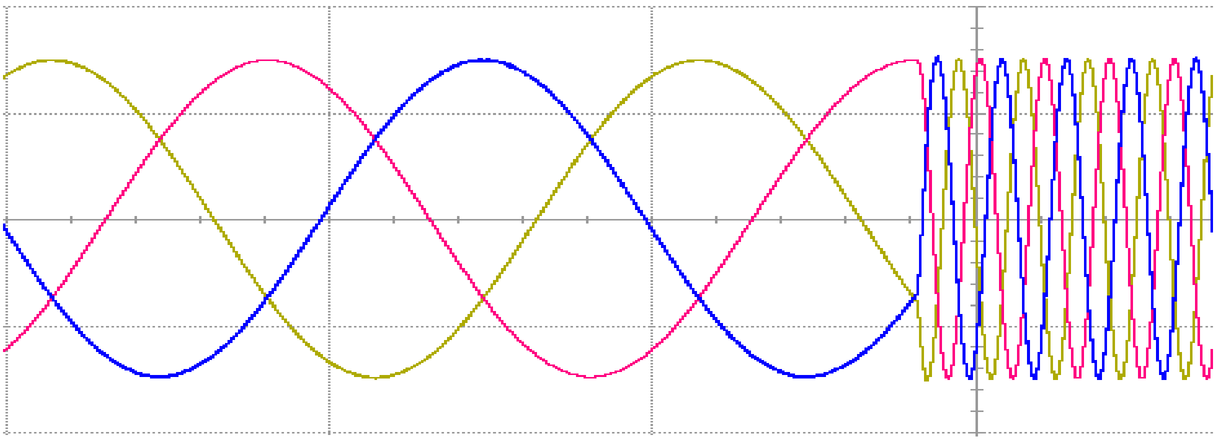

Fig. 11: Frequency step from 100 Hz to 1 kHz.

5. Conclusion

This paper presents a powerful E-motor emulator with high dynamic behaviour and high accuracy of output voltage and phase current generation. This results in very precisely E-motor emulation with back-EMF, power flow, current ripples and flux harmonics. The measurement results prove the high emulation quality, which offers very low THDs in the range of 0.1 to 0,4% at fundamental frequencies up to 5 kHz. Furthermore, the presented emulator technology copes with the requirements regarding emulation of three or six phase permanent-magnet synchronous machines with nonlinear magnetics as well as asynchronous machines.

Main fields of application are development and end-of-line tests. It is possible to reuse mission profiles from the design process in order to test the inverter and directly compare the simulated and real behaviour. The EME has various advantages: no rotating parts, no maintenance, low safety requirements, high flexibility regarding motor model parameters and emulation of fault scenarios or parameter tolerances. Furthermore, some special test cases such as the curbstone edge case can be emulated in a very comfortable and reproducible manner with high flexibility in parameterization. However, there is one important challenge: the emulator needs motor parameters, which have to be acquired from FEM calculations or motor measurements.

6. References

[1] S. Uebener and J. Böcker, "Application of an electric machine emulator for drive inverter tests within the development of electric drives," *EEVC Brussels, Belgium,* pp. 19-22, November 2012.

[2] H. Hammerer and D. Strauss, "E-Maschinen-Emulator kontra rotierendem Prüfstand," *ATZelektronik 7,* p. 192–197, 2012.

[3] A. Schmitt, J. Richter, U. Jurkewitz and M. Braun, “FPGA-based real-time simulation of nonlinear permanent magnet synchronous machines for power hardware-in-the-loop emulation systems,” *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society,* pp. 3763-3769, October 2014.

[4] S. Trabelsi, "Umrichterprüfung mit Hardware-in-the-Loop und Einsatz einer neuartigen schnellen oberschwingungsarmen Leistungsendstufe," *PHD thesis, ISSN 9783183364213,* 2004.

[5] S. Grubic, B. Amlang and W. Schumacher, "A high-performance electronic hardware-in-the-loop drive - Load simulation using a linear inverter," *IEEE Transactions on Industrial Electronics, 57(4),* pp. 1208 - 1216, December 2009.

[6] A. Schmitt, “Hochdynamische Power Hardware-in-the-Loop Emulation hochausgenutzter Synchronmaschinen mit einem Modularen-Multiphasen-Multilevel Umrichter,” *Disseration,* 2017.

[7] M. F. Oettmeier, “Stator-Flux-Oriented control and real-time emulation techniques for permanent-magent synchronous machines,” *Dissertation,* 2013.

[8] B. Cebulski and M. Thom, "Power-HiL-Simulation von Elektroantrieben für Hybridfahrzeuge," *Internationaler ETG-Kongress,* 2007.

7. Authors

Dr. Sebastian Liebig is responsible for several projects at SET Power Systems GmbH (SPS), which is part of the AVL Group and a leading global supplier of inverter testing systems. Prior to joining SPS, he worked for Liebherr-Elektronik as power electronics engineer and project manager. In parallel, Sebastian worked at his PhD-thesis in the field of AC/DC topologies for aerospace applications. For his work, he was granted in 2011 the best paper award of the international conference PCIM in Nuremberg. Sebastian graduated 2014 at the Institute of Prof. Josef Lutz (Technical University of Chemnitz, Germany).

Dr. Alexander Schmitt is responsible for system design at SET Power Systems GmbH (SPS), which is part of the AVL Group and a leading global supplier of inverter testing systems. Prior to joining SPS, Alexander worked at the Institute of Electrical Engineering (ETI) which is located at the Karlsruhe Institute of Technology (KIT). He received his PhD degree from the KIT in 2017 for his thesis about the high dynamic power hardware-in-the-loop emulation of nonlinear permanent magnet synchronous machines with a modular multiphase multilevel converter.

Horst Hammerer is Co-Founder & CEO of SET Power Systems GmbH, part of the AVL Group and a leading global supplier of inverter testing systems. He has been involved in aerospace, test systems and power electronics for more than 30 years. Prior to founding his own company, Horst developed and designed new testing strategies at Liebherr-Aerospace. In 2008 he was granted an innovation award for successfully introducing a P-HiL component to test A380 CPCS computers, resulting in a joint venture between his private enterprise and the AVL List GmbH. He is passionate about enhancing and redefining testing methods for more meaningful results, focusing on the transfer of aerospace testing methods to e-mobility. His visions and innovative approaches to technological thinking make him a welcome speaker at conferences and universities. Horst studied in both Germany and the UK and holds a degree in communication engineering from the University of Applied Sciences Ulm.