

A New Approach to Calorimetric Efficiency Measurements and Analysis of Electric Vehicle Drive Losses

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ABSTRACT

The development of battery electric vehicle drives comes along with comprehensive and time-consuming finite element methods and extensive measurement campaigns. The drive efficiency has drawn great attention from engineers and customers, because it influences the size of the drive, the cooling measures and the vehicle range.

Indirect efficiency acquisition accomplished by comparing inward and outward power, has a low accuracy which arises from a relatively small difference between inward and outward power of highly efficient drives. Therefore the indirect efficiency acquisition is insufficient to evaluate advanced development measures. This paper presents measurement and analysis methods developed within a collaborative research project, which aims at accelerating the development cycles of electrical drives by implementing and combining accuracy-improved Finite Element Simulations (FEM), extremely rapid Lumped Parameter Thermal Networks (LPTN) and a new efficiency measurement method with high accuracy. Findings of this project provide possibilities to optimize drive construction, material selection and control strategy.

The new approach of efficiency measurements is based on a direct loss measurement. Moreover, this approach adopts an innovative calorimetric measurement principle with the support of conventional dynamic measurement procedures: The calorimetric measurement principle yields to a high steady-state-accuracy; the conventional measurement identifies dynamic transitions.

This paper not only introduces highly precise measurement methods for evaluating heat dissipation of electric drives, but also new evaluation methods for the determination of internal power losses. An evaluation of test bench measurements is shown, in order to demonstrate the process of distinguishing different losses.

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INTRODUCTION

Limited energy resources, increase of environmental standards and high dependence on private cars encourage the development of alternative drives and fuels. Since many new concepts are based on electrical drives, it is necessary to develop new energy storage systems and highly efficient electrical drives.

The determinant of electric drives is its efficiency, not only because efficiency has a direct impact on the range and performance of electric cars, but also because a high efficiency plays a significant role in reducing harmful emissions.

Nowadays, the efficiency of permanent magnet synchronous motors is more than 90 % [1]. This factor restrains the further development as the room for improvement is limited. The central research and development issue is the reduction of parasitic energy loss which is difficult to analyze by means of physical and mathematical

approaches. Thus an iterative development method is adopted, which is supported by commonly accepted methods, such as finite element method and extensive measurement campaigns. In order to evaluate possible efficiency improvements in each developmental iteration cycle, operations in a test bench environment are necessary. Measurements need to be highly accurate since improvements are minimal. Therefore iterative development methods are extremely time-consuming and cost-intensive.

The collaborative research project "Procedure to Increase the Energy Efficiency of Electrical Drives" (VerfaS) aims to accelerate development cycles for electrical drives by implementing and combining accuracy-improved finite element simulations (FEM), rapid lumped parameter thermal networks (LPTN) and a new accurate efficiency measurement. The main problem of the current methods is a lack of precision, which mostly impedes iterative development approaches.

This paper dedicates to the development of new measurement instruments and evaluation methods. The calorimetric approach anticipates remarkable enhancements in terms of accuracy comparing with the conventional method. However, a shortcoming exists. Specifically, the measurements are indistinct because of the high thermal time constants of the test drive; hence the conventional method is indispensable to the detection of dynamic changes. Consequently, the new calorimetric method will be merged with the conventional method by means of a sensor fusion.

CALORIMETRIC LOSS MEASUREMENTS VERSUS INDIRECT LOSS MEASUREMENTS

This project is motivated by a common problem of the present test bench configurations, namely inaccurate efficiency measurements. The conventional way of efficiency determination compares the input and output power of the test machine. The input power of a motor-driven test machine can be evaluated on the basis of the modulated alternating current and voltage. The torque and rotational speed of the shaft have to be measured when evaluating the output power (see Figure 1).

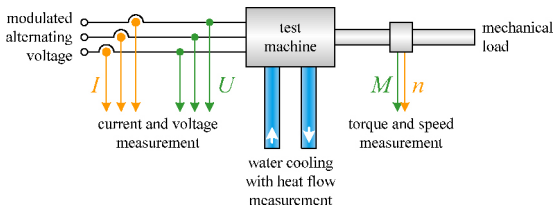


Figure 1. Test bench configuration for electric drives including calorimetric loss measurement.

Since the test machine's efficiency is very high, the values of input and output power have the same order of magnitude. However, the difference of these values indicates the energy losses and is thus of great developmental and research value.

For example, in a particular test scenario, the test machine has an electrical input power of $P_{el}=50$ kW an efficiency of $\eta=96\%$ and a mechanical output power of $P_{mech}=48$ kW. Therefore, the losses are $P_{loss}=2$ kW. Our assumption is that the losses can be decreased by 100 W, which has to be accurately proven on a test bench. It is obvious that the change of 100 W is easier to be detected in the loss measurements with a full range of 2 kW instead of the mechanical power measurement with a full range of 48 kW.

The same conclusion can be drawn from a propagation of uncertainty. The determination of the efficiency in engine-operation is described in the conventional way:

$$\eta = \frac{P_{mech}}{P_{el}} \quad (1)$$

The absolute uncertainty $\Delta\eta$ of the conventionally examined efficiency η has to be calculated depending on the relative uncertainties u_{Pel} and u_{Pmech} of input power P_{el} and output power P_{mech} . According to the error propagation formula [2], this is achieved by the following equation:

$$\Delta\eta = \sqrt{\left(\frac{\partial\eta}{\partial P_{el}} \cdot u_{Pel} P_{el}\right)^2 + \left(\frac{\partial\eta}{\partial P_{mech}} \cdot u_{Pmech} P_{mech}\right)^2} = \sqrt{u_{Pel}^2 + u_{Pmech}^2} \cdot \eta \quad (2)$$

This equation shows that the relative uncertainty of the efficiency measurement is the root-mean-square of the relative input and output measurement uncertainties.

In contrast, the new approach measures the losses directly; in engine-operation the determination of the efficiency can be described as follows:

$$\eta' = 1 - \frac{P_{loss}}{P_{el}} \quad (3)$$

The absolute uncertainty $\Delta\eta'$ of the new efficiency measurement can be calculated based on the relative uncertainties u_{Pel} and u_{Ploss} of input power P_{el} and losses P_{loss} :

$$\Delta\eta' = \sqrt{\left(\frac{\partial\eta'}{\partial P_{el}} \cdot u_{Pel} P_{el}\right)^2 + \left(\frac{\partial\eta'}{\partial P_{loss}} \cdot u_{Ploss} P_{loss}\right)^2} = \sqrt{u_{Pel}^2 + u_{Ploss}^2} \cdot (1 - \eta') \quad (4)$$

Equation (3) and (4) show the error propagation for measuring the losses and the inward power in engine-operation. The new approach can also be used to determine the efficiency from the losses and the outward power. This results in the following equation in engine-operation:

$$\eta'' = \frac{P_{mech}}{P_{mech} + P_{loss}} \quad (5)$$

The related absolute uncertainty $\Delta\eta''$ can be calculated based on the relative uncertainties u_{Pmech} and u_{Ploss} of outward power P_{mech} and losses P_{loss} :

$$\Delta\eta'' = \sqrt{\left(\frac{\partial\eta''}{\partial P_{mech}} \cdot u_{Pmech} P_{mech}\right)^2 + \left(\frac{\partial\eta''}{\partial P_{loss}} \cdot u_{Ploss} P_{loss}\right)^2} = \sqrt{u_{Pmech}^2 + u_{Ploss}^2} \cdot \eta'' \cdot (1 - \eta'') \quad (6)$$

The comparison of equation (2), (4) and (6) indicates an evident benefit of the new approach over the conventional approach. The absolute uncertainty of the new method is the root-mean-square of the individual uncertainties, which is weighted with either $(1-\eta')$ or $(1-\eta'')\eta''$ while the absolute uncertainty of the conventional efficiency measurement is the root-mean-square of the individual uncertainties, which is weighted with η . The new method shows a significant improvement within the efficiency range of 80 % to 100 % (see Figure 2).

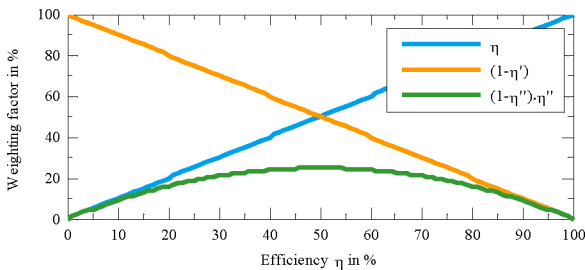


Figure 2. Weighting factors for different measurement principles.

These two considerations concerning the difference between efficiency measurement principles are supported by an extended propagation of uncertainty based on standard measuring chains on electrical drive test benches. Three high performance current transducers (e.g. IT 700-S) convert input currents into smaller values. Shaft speed and torque are transformed into voltages by using a combined speed-/torquemeter (e.g. GIF FLFM1eS). These values together with the three phase alternating voltage are measured and analyzed by a precision power analyzer (e.g. Yokogawa WT3000). The power analyzer determines input power, output power and efficiency of the test machine.

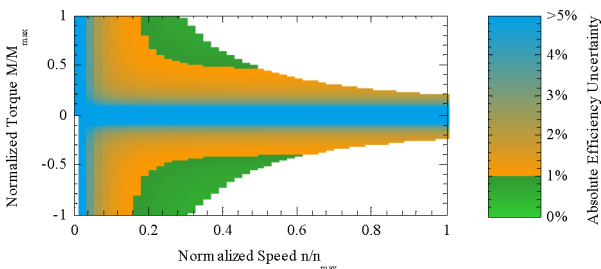


Figure 3. Uncertainty of conventional efficiency measurements.

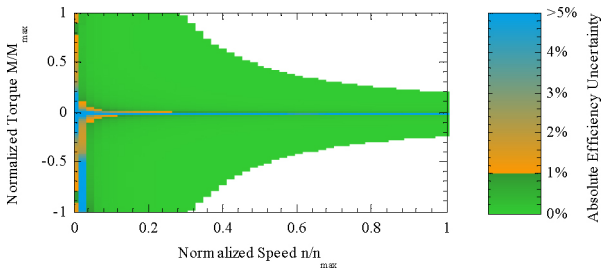


Figure 4. Uncertainty of calorimetric efficiency measurements.

This measuring chain and simulation results of losses in any actual drive stage conclude the charts of the absolute efficiency uncertainty in Figure 3 and Figure 5. Figure 3 presents the operating modes with inaccurate efficiency measurements; inaccuracy occurs mainly for small torque or small shaft speed. These working points are important

for daily use of a car since during start-up a high torque at low speed is needed and when driving straight ahead a low torque at varying speed is required.

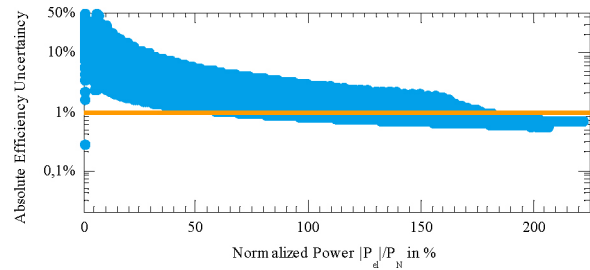


Figure 5. Uncertainty of conventional efficiency measurements depending on the electric power.

Unlike the conventional efficiency measurement, the new approach is based on a heat flow measurement and the known electrical power measurement. Because of the individual measurement uncertainties, the combination of electrical power measurement and calorimetric loss measurement promotes a higher accuracy than the combination of mechanic power measurement and calorimetric loss measurement. The accuracy of the heat flow measurement is estimated according to existing measurement devices (see Table 1). The new measuring chain leads to a far lower uncertainty as one can see from Figure 4 and Figure 6.

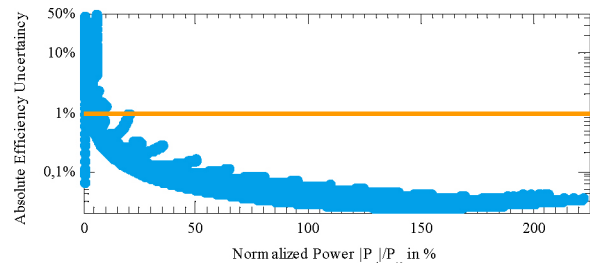


Figure 6. Uncertainty of calorimetric efficiency measurements depending on the electric power.

The comparison of Figure 5 and Figure 6 illustrates that the accuracy can be dramatically enhanced by the new method. In the conventional efficiency measurement, uncertainties are usually greater than 1 %, whereas high uncertainties are only found when the electrical power is less than 5 kW in the calorimetric efficiency measurement.

Furthermore, the average uncertainty of the conventional measurement is approximately 4 %, while the average uncertainty of the calorimetric method is approximately 0.5 %. Last but not least, one should notice again that these uncertainties are given in absolute values.

Table 1. Assumed accuracy for heat flow measurement.

Measurement	Input range	Zero point stability	Deviation from the measurement
Mass flow	3... 10 kg min ⁻¹	10.7 g min ⁻¹	0.1 %
Temperature difference	0... 20 K	20 mK	0.1 %

