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Uncertainty when Testing Electric Vehicle Drive Trains

- Propagation of Measurement Uncertainty to Power (Loss), Efficiency and Energy Consumption -

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ABSTRACT: This paper discusses the relevance of precise measurements for the evaluation of the development and optimization process of the powertrain, or individual powertrain components, of electric vehicles in the context of measurement uncertainty (MU). It presents an innovative fiber-optic measurement technology that combines a sufficiently high bandwidth with a comparatively low MU. In addition to an introductory overview of the measurement technology used, the estimation of MU is examined in detail. In this context, the propagation of the MU of electrical measurands to relevant optimization parameters, such as active power, energy and efficiency, is analyzed. For this purpose, a time-discrete MU propagation is used, which considers the digital calculation algorithms implemented on modern power analyzers. In contrast to numerous established methods for estimating the MU of electrical power, energy and efficiency, this approach can also be used for non-sinusoidal voltages and currents, as they occur in converter-fed drives.

KEY WORDS: measurement uncertainty, electric power train, electric vehicle, efficiency, power, losses, energy, fiber-optic

1. INTRODUCTION

With the continuous worldwide growth in electromobility, the requirements for energy storage capacity and efficiency, as well as the resulting range of electric vehicles are also increasing. For this reason, efficiency is a central optimization criterion during the development process of a modern electric vehicle for maximizing its range. The development steps to be taken for this purpose, for example the use of suitable low-loss power converter and machine topologies, but also the optimization of the power converter control algorithms, are constantly being further developed and validated by measurements. For this reason, the correct interpretation of the measurement results is of utmost relevance for the quantitative evaluation of the development process and the assessment of development goals.

To meet these challenges, this paper presents a suitable fiber-optic measurement technology that combines a sufficiently high bandwidth[1,2] for measuring converter-fed drives with a comparatively low measurement uncertainty (MU). However, since every real measurement is associated with a certain MU, the transfer of the MU from electrical measured quantities to parameters calculated from them is derived in this context. For example, a MU of the measured voltages and currents propagates to a MU of the power and thus also of the energy consumption and ultimately of the range of a vehicle. The range of a vehicle is typically specified conservatively, considering the existing MU. If the MU of the measured quantities can be reduced, the specifiable range of this vehicle increases accordingly. This fact highlights the importance of measurement uncertainty in EV optimization. The reduction of MU can be achieved by a more detailed evaluation based on knowledge of the sensor properties and the measurement technology used. Therefore, the underlying signal processing algorithms of the power analyzer should be considered for the MU propagation. In this context, this paper presents a discrete-time MU estimation of power, efficiency that correctly accounts for the digital computation methods of these quantities on modern power analyzers.

2. MEASUREMENT OF THE ELECTRIC POWER TRAIN

2.1. Measurement Topology

Fig. 1 shows the basic system topology of an electric drive train together with a tailored, optimized measurement technology. The electric machine is supplied with power from a power source (e.g. battery) via a power converter. In order to measure essential optimization parameters such as efficiency or power loss, robust, reliable and highly precise measurement technology is required. In the case of converter-fed drives, the bandwidth of the sensors and the sampling rates of the measuring instruments must be sufficiently high to correctly measure the influence of the switching frequency[1,2]. On the other hand, the measurement results should have the lowest possible measurement uncertainty.

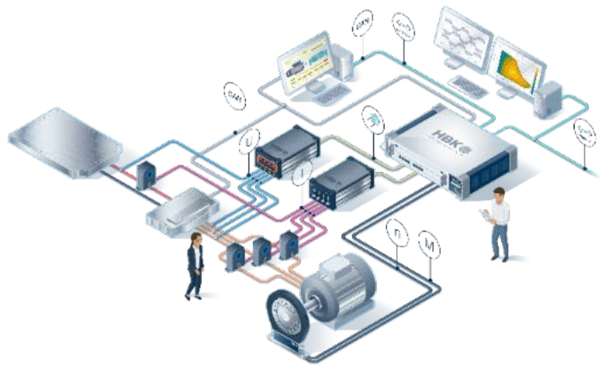

Fig. 1 Measurement Topology of an Electric Power Train

To fulfill these requirements, the measurement topology shown in Fig. 1 is used. The centrally located raw data acquisition system (power analyzer) measures all physical quantities that are relevant for optimizing the individual powertrain components and the entire powertrain in a time-synchronized manner. These include electrical quantities such as currents and voltages, but also the mechanical quantities of the drive shaft, i.e. speed, torque, as well as other system parameters, such as temperatures, accelerations, vibrations, acoustic signals and field buses, etc. Fiber optic probes are used to measure the electrical quantities. These are significantly more robust against unwanted EMC influences, especially in power converter operation. The fiber-optic galvanic isolation of the measuring system ensures a high level of personal and device protection, especially at high battery voltages and in the event of a fault. For long transmission paths, the signal propagation times are synchronized so that no unwanted phase shifts between individual signals occur.

In terms of current measurement, fluxgate compensation current transformers represent a very suitable compromise between sufficient bandwidth from DC to a few 100 kHz and, at the same time, a comparatively low MU. Compared to shunts, they have the great advantage that they are galvanically isolated from the circuit to be measured. Shunt measurements are often associated with common-mode interference, since very small differential voltages have to be measured on a very high and dynamically variable potential.

The measurement topology presented in Fig 1 can also be applied in an analogous approach to more complex and extensive applications, such as an electric vehicle, as shown in Fig. 2.

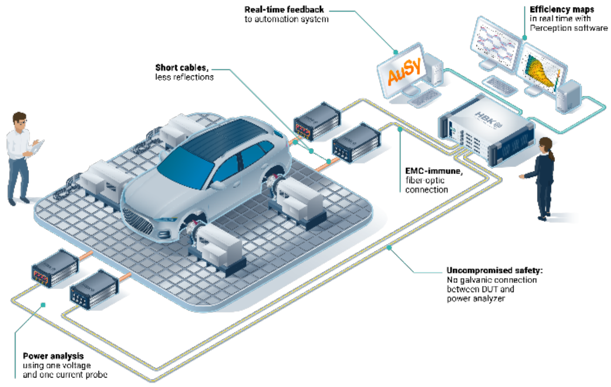

Fig. 2 Testing of an Electric Vehicle

2.2. Electric Power Measurement

Measuring the electrical power is essential for determining loss, energy, and efficiency of the power train components. The power exchange is calculated from the measured terminal voltages and conductor currents. The electrical system to be measured can be a two-wire system, for example the battery of a vehicle, or a multi-phase system, such as a three-phase machine as a drive. In general, from an electrical point of view, the generic n-wire system in Fig. 3 is therefore considered, where $n \geq 2$ corresponds to the number of conductors contributing to the energy transfer of system.

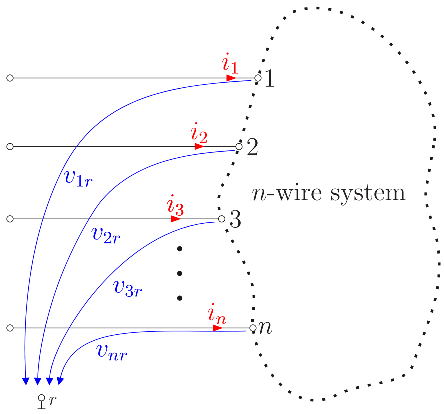

Fig. 3 Electrical n-wire system (based on [2] referring to [5,6])

It is well-known from standards[3,4] and scientific literature[5,6], that the instantaneous power $p(t)$ as a function of time t is given as the sum of products of a respective conductor current $i_\nu(t)$, with $\nu \in \{1, \dots, n\}$, and the associated phase voltage $v_{\nu r}(t)$ measured against an arbitrarily selectable common reference potential r.

$$p(t) = \sum_{\nu=1}^{n} v_{\nu r}(t) \cdot i_\nu(t) \qquad [1]$$

Integrating the instantaneous power within the time interval Δt, we obtain the related energy $e(t)$ transferred.

$$e(t) = \int_{t-\Delta t}^{t} p(\tau)\ \mathrm{d}\tau \qquad [2]$$

In the case of periodic signals in a steady state, so that $i_\nu(t+T) = i_\nu(t)$ and $v_{\nu r}(t+T) = v_{\nu r}(t)$, the active power is obtained as the mean value of the instantaneous power over the associated period T of the voltages and currents. The active power is therefore a measure of the average energy flow rate per period:

$$P = \frac{1}{T}\int_{t-\mathrm{T}}^{t} p(\tau)\ \mathrm{d}\tau \qquad [3]$$

The efficiency η of a system is defined as the ratio of the active power output P_{out} to the active power input P_{in}:

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \qquad [4]$$

The power loss P_{loss} is given by:

$$P_{\mathrm{loss}} = P_{\mathrm{in}} - P_{\mathrm{out}} \qquad [5]$$

The parameters in equations [1] to [5] are essential for characterizing the effectiveness of all components of the electric powertrain and for the efficiency of the electric vehicle. When optimizing a powertrain during the development process of a vehicle, it is therefore essential to know the MU of the individual parameters in order to evaluate the development progress and the achievement of the development goals and specifications.

3. MU OF RELEVANT SYSTEM PARAMETERS

3.1. Continuous-time MU Propagation

Assuming that the time-dependent MUs of the n phase voltages $u(v_{\nu r}(t))$ and the n phase currents $u(i_\nu(t))$, as well as the MU of the period $u(T)$ are known from datasheets or calibration certificates, the propagated MU of the active power is estimated by the Gaussian MU propagation(7):

$$u(P) = \sqrt{\begin{aligned}&\sum_{\nu=1}^{n}\left[\frac{\partial P}{\partial v_{\nu r}(t)}\cdot u\big(v_{\nu r}(t)\big)\right]^2 + \cdots \\ &+\sum_{\nu=1}^{n}\left[\frac{\partial P}{\partial i_\nu(t)}\cdot u\big(i_\nu(t)\big)\right]^2 + \cdots \\ &\qquad\left[\frac{\partial P}{\partial T}\cdot u(T)\right]^2\end{aligned}} \qquad [6]$$

Based on [1], [3] and [6], we obtain the partial derivative of the active power with respect to the m-th terminal voltage

$$\frac{\partial P}{\partial v_{mr}(t)} = \frac{\partial}{\partial v_{mr}(t)}\left\{\frac{1}{T}\int_{t-T}^{t}\sum_{\nu=1}^{n} v_{\nu r}(\tau) i_\nu(\tau)\ \mathrm{d}\tau\right\} \qquad [7]$$

and the partial derivative of the active power with respect to the m-th conductor current:

$$\frac{\partial P}{\partial i_m(t)} = \frac{\partial}{\partial i_m(t)}\left\{\frac{1}{T}\int_{t-T}^{t}\sum_{\nu=1}^{n} v_{\nu r}(\tau) i_\nu(\tau)\ \mathrm{d}\tau\right\} \qquad [8]$$

Since in [7] and [8] both the respective differential $\partial v_{mr}(t)$ or $\partial i_m(t)$ and the upper and lower limit of the integral depend on the time t, the order of differentiation and integration generally cannot be interchanged. However, [7] and [8] can be significantly simplified in the context of the time-discrete formulation in the following subsection 3.2, see [17] and [18].

To calculate the derivative of the active power P with respect to the period T, we use the following analytical relations. First, we consider that the instantaneous power in [1] does not depend on the selection of the averaging interval for the active power calculation in [3], so that $\partial p(\tau)/\partial T = 0$. If the period were not detected correctly by the power analyzer, the averaging in [3] would be carried out over a wrong integration interval, but the actual period of the voltages and currents would not change. Furthermore, the time t at which the averaging is carried out is freely selectable and thus independent of the integration interval T, so that $\partial t/\partial T = 0$. We continue to consider the product rule, $\frac{\mathrm{d}}{\mathrm{d}x}[u(x)\cdot v(x)] = \frac{\mathrm{d}u(x)}{\mathrm{d}x}\cdot v(x) + \frac{\mathrm{d}v(x)}{\mathrm{d}x}\cdot u(x)$, see (8), the Leibniz integral rule for parameter integrals, $\frac{\mathrm{d}}{\mathrm{d}y}\left(\int_{a(y)}^{b(y)} f(x,y)\ \mathrm{d}x\right) = \int_{a(x)}^{b(x)}\frac{\partial f(x,y)}{\partial y}\ \mathrm{d}x + \frac{\partial b(y)}{\partial y}\cdot f(b(x),y) - \frac{\partial a(y)}{\partial y}\cdot f(a(x),y)$, see (8), and the periodicity of the instantaneous power $p(t-T) = p(t)$ assumed in the context of active power calculation. With all that we obtain:

$$\begin{aligned}\frac{\partial P}{\partial T} &= \frac{\partial}{\partial T}\left\{\frac{1}{T}\int_{t-T}^{t} p(\tau)\ \mathrm{d}\tau\right\} \\ &= \underbrace{-\frac{1}{T^2}\int_{t-T}^{t} p(\tau)\ \mathrm{d}\tau}_{=-\frac{1}{T}\cdot P} + \frac{1}{T}\cdot\frac{\partial}{\partial T}\left\{\int_{t-T}^{t} p(\tau)\ \mathrm{d}\tau\right\} \\ &= -\frac{P}{T} + \frac{1}{T}\left[\int_{t-T}^{t}\underbrace{\frac{\partial p(\tau)}{\partial T}}_{=0}\ \mathrm{d}\tau + \frac{\partial t}{\partial T}\cdot p(t) \right. \\ &\qquad\qquad \left. - \frac{\partial(t-T)}{\partial T}p(t-T)\right] \\ &= \frac{1}{T}\left[\underbrace{\frac{\partial t}{\partial T}}_{=0}[p(t)-p(t-T)] + \underbrace{\frac{\partial T}{\partial T}}_{=1}p(t-T) - P\right] \\ &= \frac{1}{T}[p(t-T) - P] = \frac{1}{T}[p(t) - P]\end{aligned} \qquad [9]$$

Theoretically, equations [6] to [9] allow the continuous-time estimation of the MU of the active power based on the time-dependent waveforms of the measured voltages and currents, their period and the corresponding uncertainties. In practice, however, the analytical expressions of these signals are typically unknown. Furthermore, the power calculation in DAQs/power analyzers is based on time-discrete samples of the measured signals.

The calculation of the MU of the energy in [2] is carried out in an analogous way to the active power from [3], i.e. analogous to equations [6] to [9]:

$$u(e(t)) = \sqrt{\begin{array}{l}\sum_{\nu=1}^{n}\left[\frac{\partial e(t)}{\partial v_{\nu r}(t)}\cdot u\big(v_{\nu r}(t)\big)\right]^2+\cdots \\ +\sum_{\nu=1}^{n}\left[\frac{\partial e(t)}{\partial i_{\nu}(t)}\cdot u\big(i_{\nu}(t)\big)\right]^2+\cdots \\ \left[\frac{\partial e(t)}{\partial \Delta t}\cdot u(\Delta t)\right]^2\end{array}} \quad [10]$$

$$\frac{\partial e(t)}{\partial v_{\nu r}(t)} = \frac{\partial}{\partial v_{mr}(t)}\left\{\int_{t-\Delta t}^{t}\sum_{\nu=1}^{n} v_{\nu r}(\tau) i_{\nu}(\tau)\,\mathrm{d}\tau\right\} \quad [11]$$

$$\frac{\partial e(t)}{\partial i_{\nu}(t)} = \frac{\partial}{\partial i_{\nu}(t)}\left\{\int_{t-\Delta t}^{t}\sum_{\nu=1}^{n} v_{\nu r}(\tau) i_{\nu}(\tau)\,\mathrm{d}\tau\right\} \quad [12]$$

$$\begin{aligned}\frac{\partial e(t)}{\partial \Delta t} &= \frac{\partial}{\partial \Delta t}\left\{\int_{t-\Delta t}^{t} p(\tau)\,\mathrm{d}\tau\right\} \\ &= \int_{t-\Delta t}^{t}\underbrace{\frac{\partial p(\tau)}{\partial \Delta t}}_{=0}\mathrm{d}\tau + \frac{\partial t}{\partial \Delta t}\cdot p(t) \\ &\qquad -\frac{\partial(t-\Delta t)}{\partial \Delta t}p(t-\Delta t) \\ &= \underbrace{\frac{\partial t}{\partial \Delta t}}_{=0}[p(t)-p(t-\Delta t)] + \underbrace{\frac{\partial \Delta t}{\partial \Delta t}}_{=1}p(t-\Delta t) \\ &= p(t-\Delta t)\end{aligned} \quad [13]$$

Finally, in this section, we consider the MU of the efficiency defined in [4], again using Gaussian uncertainty propagation based on the MUs of the input and output active power $u(P_{\mathrm{in}})$ and $u(P_{\mathrm{out}})$:

$$\begin{aligned}u(\eta) &= \sqrt{\left[\frac{\partial \eta}{\partial P_{\mathrm{out}}}\cdot u(P_{\mathrm{out}})\right]^2 + \left[\frac{\partial \eta}{\partial P_{\mathrm{in}}}\cdot u(P_{\mathrm{in}})\right]^2} \\ &= \sqrt{\left[\frac{u(P_{\mathrm{out}})}{P_{\mathrm{in}}}\right]^2 + \left[\frac{P_{\mathrm{out}}\cdot u(P_{\mathrm{in}})}{P_{\mathrm{in}}^2}\right]^2}\end{aligned} \quad [14]$$

3.2. Discrete-time MU Propagation

On the basis of the results of the previous section, the general calculation rule for estimating the MU of electrical power, energy and efficiency are derived. Considering that the measurands are sampled at multiple integers $k \in \mathbb{Z}$ of the sample time T_{s}, with regard to Fig. 3, we obtain sampled values of the terminal voltages $v_{\nu r}(t = kT_{\mathrm{s}}) = v_{\nu rk}$ and conductor currents $i_{\nu}(t = kT_{\mathrm{s}}) = i_{\nu k}$. Thus, we obtain time-discrete samples of the instantaneous power in [1]:

$$p_k = \sum_{\nu=1}^{n} v_{\nu rk}\cdot i_{\nu k} \quad [15]$$

We further assume that the period T of the voltages and currents is a multiple integer $N \in \mathbb{N}$ of the sample time T_{s}, so that $T = NT_{\mathrm{s}}$. To derive a discrete-time representation of the active power $P_k \approx P$ from [3], we approximate the integration by applying right-hand rectangle method (Riemann sum)[8], where the time infinitesimal is substituted by the finite sampling time $\mathrm{d}\tau \approx T_{\mathrm{s}}$ and additionally [15] is taken into account.

$$\begin{aligned}P_k &= \frac{1}{NT_{\mathrm{s}}}\cdot\sum_{\kappa=k-N+1}^{k} p_\kappa\cdot T_{\mathrm{s}} = \frac{1}{N}\sum_{\mu=k-N+1}^{k} p_\kappa \\ &= \frac{1}{N}\sum_{\kappa=k-N+1}^{k}\sum_{\nu=1}^{n} v_{\nu r\kappa}\cdot i_{\nu\kappa}\end{aligned} \quad [16]$$

For given sample based MUs of the measurands $u(v_{\nu rk})$, $u(i_{\nu k})$ we obtain the following partial derivatives:

$$\begin{aligned}\frac{\partial P_k}{\partial v_{mrh}} &= \frac{\partial}{\partial v_{mrh}}\left\{\frac{1}{N}\sum_{\kappa=k-N+1}^{k}\sum_{\nu=1}^{n} v_{\nu r\kappa}\cdot i_{\nu\kappa}\right\} \\ &= \frac{1}{N}\sum_{\kappa=k-N+1}^{k}\sum_{\nu=1}^{n}\frac{\partial}{\partial v_{mrh}} v_{\nu r\kappa}\cdot i_{\nu\kappa} = \frac{1}{N}\cdot i_{mh}\end{aligned} \quad [17]$$

$$\begin{aligned}\frac{\partial P_k}{\partial i_{mh}} &= \frac{\partial}{\partial i_{mh}}\left\{\frac{1}{N}\sum_{\kappa=k-N+1}^{k}\sum_{\nu=1}^{n} v_{\nu r\kappa}\cdot i_{\nu\kappa}\right\} \\ &= \frac{1}{N}\sum_{\kappa=k-N+1}^{k}\sum_{\nu=1}^{n}\frac{\partial}{\partial i_{mh}} v_{\nu r\kappa}\cdot i_{\nu\kappa} = \frac{1}{N}\cdot v_{mrh}\end{aligned} \quad [18]$$

Based on the previous assumption $T = NT_{\mathrm{s}}$, we derive we derive $\frac{\partial T}{\partial N} = T_{\mathrm{s}} \Longrightarrow \partial N = \frac{1}{T_{\mathrm{s}}}\partial T$, resulting in $\frac{\partial P_k}{\partial N} = T_{\mathrm{s}}\frac{\partial P_k}{\partial T}$. With respect to [9], we obtain:

$$\frac{\partial P_k}{\partial N} = T_{\mathrm{s}}\frac{\partial P_k}{\partial T} = \frac{T_{\mathrm{s}}}{NT_{\mathrm{s}}}[p_k - P_k] = \frac{1}{N}[p_k - P_k] \quad [19]$$

In analogy to the continuous time representation of the MU in [6], the discrete time representation of the MU of discrete active power calculation in [16] is given by:

$$u(P_k) = \sqrt{\begin{array}{c} \displaystyle\sum_{\kappa=k-N+1}^{k} \sum_{\nu=1}^{n} \left[\frac{\partial P_\kappa}{\partial v_{\nu r\kappa}} \cdot u(v_{\nu r\kappa})\right]^2 + \cdots \\ \displaystyle \ldots + \sum_{\kappa=k-N+1}^{k} \sum_{\nu=1}^{n} \left[\frac{\partial P_\kappa}{\partial i_{\nu\kappa}} \cdot u(i_{\nu\kappa})\right]^2 + \cdots \\ \displaystyle \ldots + \left[\frac{\partial P_\kappa}{\partial N} \cdot u(N)\right]^2 \end{array}} \qquad [20]$$

Inserting [17] to [18] into [19], we obtain the MU of the discrete-time calculation of active power:

$$u(P_k) = \frac{1}{N} \cdot \sqrt{\begin{array}{c} \displaystyle\sum_{\kappa=k-N+1}^{k} \sum_{\nu=1}^{n} [i_{\nu\kappa} \cdot u(v_{\nu r\kappa})]^2 + \cdots \\ \displaystyle \ldots + \sum_{\kappa=k-N+1}^{k} \sum_{\nu=1}^{n} [v_{\nu r\kappa} \cdot u(i_{\nu\kappa})]^2 + \cdots \\ \ldots + [(p_\kappa - P_k) \cdot u(N)]^2 \end{array}} \qquad [21]$$

In order to estimate the MU of the energy from [2], we further assume that the time interval Δt is a multiple integer $M \in \mathbb{N}$ of the sample time T_s, so that $\Delta t = MT_s$. To derive a discrete-time representation of the active power $e_k \approx e(kT_s)$ from [2], we approximate the integration by again applying right-hand rectangle method (Riemann sum)(8), where the time infinitesimal is substituted by the finite sampling time $d\tau \approx T_s$ and additionally [15] is taken into account.

$$e_k = \sum_{\kappa=k-M+1}^{k} p_\kappa \cdot T_s = T_s \cdot \sum_{\kappa=k-M+1}^{k} \sum_{\nu=1}^{n} v_{\nu r\kappa} \cdot i_{\nu\kappa} \qquad [22]$$

For given sample based MUs of the measurands $u(v_{\nu rk})$, $u(i_{\nu k})$ we obtain the following partial derivatives in analogy to [17] and [18]:

$$\frac{\partial e_k}{\partial v_{mrh}} = T_s \cdot i_{mh} \qquad [23]$$

$$\frac{\partial e_k}{\partial i_{mh}} = T_s \cdot v_{mrh} \qquad [24]$$

Based on the previous assumption $\Delta t = MT_s$, we derive we derive $\frac{\partial \Delta t}{\partial M} = T_s \Longrightarrow \partial M = \frac{1}{T_s} \partial \Delta t$, resulting in $\frac{\partial e_k}{\partial M} = T_s \frac{\partial e_k}{\partial \Delta t}$. With respect to [13], we obtain:

$$\frac{\partial e_k}{\partial M} = T_s \frac{\partial e_k}{\partial \Delta t} = T_s \cdot p_{k-M} \qquad [25]$$

In analogy to the continuous time representation of the MU in [10], the discrete time representation of the MU of discrete energy calculation is given by:

$$u(e_k) = \sqrt{\begin{array}{c} \displaystyle\sum_{\kappa=k-M+1}^{k} \sum_{\nu=1}^{n} \left[\frac{\partial e_\kappa}{\partial v_{\nu r\kappa}} \cdot u(v_{\nu r\kappa})\right]^2 + \cdots \\ \displaystyle \ldots + \sum_{\kappa=k-M+1}^{k} \sum_{\nu=1}^{n} \left[\frac{\partial e_\kappa}{\partial i_{\nu\kappa}} \cdot u(i_{\nu\kappa})\right]^2 + \cdots \\ \displaystyle \ldots + \left[\frac{\partial e_\kappa}{\partial M} \cdot u(M)\right]^2 \end{array}} \qquad [26]$$

Inserting [23] to [25] into [26], we obtain the MU of the discrete-time calculation of energy:

$$u(e_k) = T_s \cdot \sqrt{\begin{array}{c} \displaystyle\sum_{\kappa=k-M+1}^{k} \sum_{\nu=1}^{n} [i_{\nu\kappa} \cdot u(v_{\nu r\kappa})]^2 + \cdots \\ \displaystyle \ldots + \sum_{\kappa=k-M+1}^{k} \sum_{\nu=1}^{n} [v_{\nu r\kappa} \cdot u(i_{\nu\kappa})]^2 + \cdots \\ \ldots + [p_{k-M} \cdot u(N)]^2 \end{array}} \qquad [27]$$

The MU of the efficiency is calculated based on the MUs of discrete output and input active power $u(P_{\mathrm{out}k})$ and $u(P_{\mathrm{in}k})$, which might in in turn be calculated by [21] in case of an electric system, for example power converter:

$$\begin{aligned} u(\eta_k) &= \sqrt{\left[\frac{\partial \eta_k}{\partial P_{\mathrm{out}k}} \cdot u(P_{\mathrm{out}k})\right]^2 + \left[\frac{\partial \eta}{\partial P_{\mathrm{in}k}} \cdot u(P_{\mathrm{in}k})\right]^2} \\ &= \sqrt{\left[\frac{u(P_{\mathrm{out}k})}{P_{\mathrm{in}k}}\right]^2 + \left[\frac{P_{\mathrm{out}k} \cdot u(P_{\mathrm{in}k})}{P_{\mathrm{in}k}^2}\right]^2} \end{aligned} \qquad [28]$$

Of course, [21] can also be applied if, for example, one of the power quantities in an electrical machine is an averaged mechanical power. In this case, the mechanical power can be estimated in the same way as the electrical power, but using the measured speed and torque values and its MUs.

4. SPECIAL CASE: MU OF DC POWER OF A 2-POLE

In this section, we consider the application of the general rule from [21] to a two-terminal network with ideal DC signals as depicted in Fig. 4.

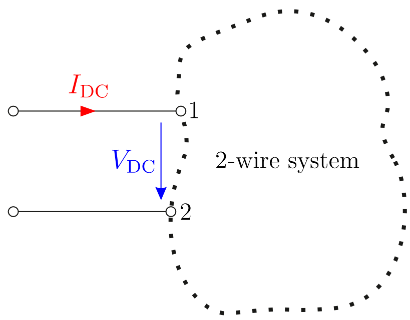

Fig. 4 Ideal DC 2-wire system

As is known from the literature(6), the instantaneous power transfer of this two-terminal network is obtained from [15] with $n = 2$ and $i_{2k} = -i_{1k}$ as $p_k = v_{1rk} \cdot i_{1k} + v_{2rk} \cdot i_{2k} = v_{12k} \cdot i_{1k}$. Since the ideal DC case is considered in Fig. 4, this results in the instantaneous power $p_k = v_{12k} \cdot i_{1k} = V_{\mathrm{DC}k} \cdot I_{\mathrm{DC}k}$. From [17], we derive:

$$u(P_k) = \frac{1}{N} \cdot \sqrt{\begin{array}{l} \sum\limits_{\kappa=k-N+1}^{k} [I_{\mathrm{DC}\kappa} \cdot u(V_{\mathrm{DC}\kappa})]^2 + \cdots \\ \dots + \sum\limits_{\kappa=k-N+1}^{k} [V_{\mathrm{DC}\kappa} \cdot u(I_{\mathrm{DC}\kappa})]^2 + \cdots \\ \dots + [(p_k - P_k) \cdot u(N)]^2 \end{array}} \quad [29]$$

We assume that in the DC case all samples of voltage and current are equal (neglecting the influence of MU for the ideal consideration), so that $V_{\mathrm{DC}k} = V_{\mathrm{DC}}$ and $I_{\mathrm{DC}k} = I_{\mathrm{DC}}$. Furthermore, the instantaneous power p_k is constant and thus equivalent to its mean value, the active power P_k, so that $p_k - P_k = 0$ regardless of the averaging interval or the number of samples N used for averaging. Furthermore, we assume that in the ideal DC case and under constant ambient conditions, e.g. constant ambient temperature, the MUs of the DC quantities are the same at each sampling time, i.e. $u(V_{\mathrm{DC}k}) = u(V_{\mathrm{DC}})$ and $u(I_{\mathrm{DC}k}) = u(I_{\mathrm{DC}})$. These idealized assumptions allow us to simplify [29] to estimate the MU of the active power of a two-terminal network in the ideal DC case:

$$u(P_k) = \frac{1}{\sqrt{N}} \cdot \sqrt{[I_{\mathrm{DC}} \cdot u(V_{\mathrm{DC}})]^2 + [V_{\mathrm{DC}} \cdot u(I_{\mathrm{DC}})]^2} \quad [30]$$

Equation [23] confirms the well-known relation, that averaging a DC signal over N samples reduces the MU of the result by a factor of $\frac{1}{\sqrt{N}}$ compared to no averaging.

5. CONCLUSIONS

This paper describes the importance of test and measurement equipment and technologies when optimizing an electric vehicle powertrain. Based on the fundamental system topology, typical requirements for the measurement technology are presented. It is analytically demonstrated how the MU of the measured variables propagates to the MU of relevant system parameters calculated from the measured variables, such as active power, energy and efficiency. A method is chosen that correctly takes into account the digital calculation algorithms of modern power measurement devices. Many established methods for estimating the MU are only applicable under ideal conditions, for example for sinusoidal or DC quantities. The innovative approach of this paper also allows for the consideration of non-sinusoidal AC quantities (and DC), as they occur at the output of a power converter. The major challenge and continuous optimization in the practical application of the presented method involves the calibration processes for determining the uncertainty of individual samples of voltages and currents.

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