

A New Approach to the Test, Assessment and Optimization of Robust Electrical Distribution Systems

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ABSTRACT

Both the electrical portion of the powertrain and the rising number of auxiliary systems will considerably increase the electrical power requirements in future vehicles. In addition, multiple voltage supply levels will enhance the complexity of the electrical distribution system (EDS), while strict cost, weight, packaging, and safety constraints must be upheld, posing serious design challenges in terms of robustness, reliability and energy efficiency.

Currently, a self-contained integral test or evaluation of the EDS is normally not applied. For such a purpose, quantitative quality criteria are introduced here which allow a comparative assessment of an EDS by addressing the dynamic and static stability of the supply voltage, the reliability of the fusing system, and the ability to provide the required electrical power.

The presented approach uses both precisely-defined test scenarios and a comprehensive EDS test bench. It is based on a hardware-in-the-loop (HiL) system with an extensive measurement set-up allowing the determination of the quality criteria mentioned above. Thus, thorough investigations into the impact of the dimensioning of EDS components as well as of new architectures can be conducted. In addition, a quantitative performance benchmarking and the identification of functional risks or of potentials for optimization are possible. The paper presents the theoretical description and initial experimental data, followed by a discussion of the next steps, for instance the application of the method to simulation, as well as a look at future possibilities.

CITATION: Brabetz, L., Ayeb, M., Jilwan, G., Graebel, P. et al., "A New Approach to the Test, Assessment and Optimization of Robust Electrical Distribution Systems," *SAE Int. J. Mater. Manf.* 6(3):2013, doi:10.4271/2013-01-0396.

INTRODUCTION

The electrical part of the powertrain, the rising number of electrical functions, and the conversion of mechanical or hydraulic systems into mechatronic devices will considerably increase the electrical power and energy requirements of future vehicles. In addition, multiple voltage supply levels will increase the complexity of the electrical distribution system (EDS), while strict cost, weight and packaging constraints must be upheld. Furthermore, the functionality of a significant part of future electrical systems is highly safety-critical, e.g. standards such as ISO 26262 must be applied. Thus, the design of an EDS faces serious challenges in terms of robustness, reliability, and energy efficiency.

Currently, testing and validation are based on test conditions defined mostly by the specifications of particular electrical subsystems. A self-contained integral test or evaluation [1,2,3] of the EDS is normally not applied and singular tests, e.g. for critical test cases, yield simple go/no-go results. In this paper, quantitative quality criteria are defined which allow a systematic and comparative

assessment of the performance and robustness of an EDS. They address the dynamic and static stability of the supply voltage, the reliability of the fusing system, and the ability to provide the required electrical power.

The presented approach uses both precisely-defined test scenarios and a comprehensive EDS test bench which is based on a hardware-in-the-loop (HiL) system. Thus, any test condition can be implemented, repeated and documented, whereby an extensive measurement set-up and data-processing system allows analysis using the quality criteria mentioned above. The results enable thorough investigations into the effect of the dimensioning of generator, battery, and EDS components, of the topology of the EDS, of the control strategy applied, and of the benefits of additional components such as DC/DC converters or storage devices [4]. Furthermore, they allow the comparison of the performance of various already-existing EDSs, as well as an appropriate benchmarking. The robustness is evaluated either by identifying functional risks or by detecting potentials for optimization. In addition to the theoretical description, the

paper presents initial experimental data, results for a given EDS, and a comparison of technical optimization measures, followed by a discussion of the next steps as well as a look at future potentials, for instance the application of the method to simulation.

QUALITY CRITERIA

The following criteria and respective visualizations are proposed to evaluate, summarize and present the vast amount of measurement or simulation data in an intuitive and comparable form. Although the formal description might look complex, the underlying ideas are quite simple and the implementation within a simulation or data acquisition environment is straightforward. As already mentioned, results are valid and comparable only with respect to a given test scenario.

Voltage Stability

The first group of criteria addresses voltage stability. It can be applied to the overall supply voltage, e.g. at the battery positive pole to describe the behavior of the complete EDS, or to the voltage at component level, e.g. at components especially sensitive to voltage variations. Three criteria are defined in order to address the voltage behavior in the time- and frequency domains (Tables 1, 2 and 3).

The distribution form describes the accumulated time at which the voltage is within a given voltage interval (Table 1). As the various operating voltage ranges are unequally critical to the proper functioning of the loads (Fig.1), the introduction of a weighting function $g(u)$ allows the calculation of a quality factor G_V (Eq.1). The exponent k is required to enhance the impact of small but essential values of n_μ . A high G_V value is critical. Finally, the box plot voltages u_Q (Eq.2) characterize the distribution form whereas u_{Q+} and u_{Q-} give the critical boundary voltages.

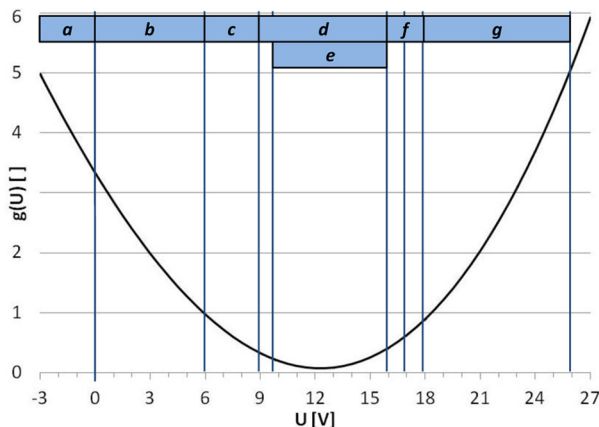


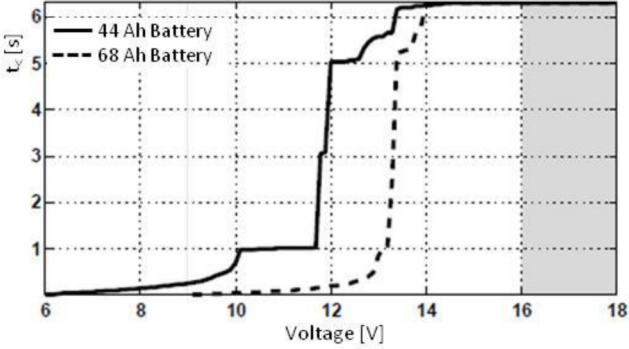
Figure 1. Supply voltage ranges and weighting function $g(u)$, (a) inverse polarity, not allowed, (b(g)) no or limited function, (c) allowed voltage range during motor start, (d)(e) operating voltage range at engine off and on, and (f) allowed operating range for limited time period

Table 1. Voltage stability criterion: time domain (1)

Criterion	Voltage stability, time domain (1)	
Visualization	Histogram	Accumulated time within a voltage interval
	Box Plot	Median and Quantiles
Quality Factors	G_V	Quantifies the stability of the voltage with respect to the specified operating ranges
	u_{Qmed} u_{Q1}, u_{Q2}	Median and quantiles to describe the distribution
	u_{Q-}, u_{Q+}	Minimum and maximum voltages passed for 1% of n
Equations $u_{min} : u_{max}$: Voltage range m : Number of intervals n_{tot} : Number of consecutive measurements g_μ : Weighting function $\Delta_U = \frac{u_{max} - u_{min}}{m}$, $\mu \in \{1 \dots m\}$, $u_\mu = u_{min} + (\mu - 1) \Delta_U$ $n_\mu = n_\mu([u_\mu, u_\mu + \Delta_U])$, $n_{tot} = \sum_{\mu=1}^m n_\mu$, $\tilde{n}_\mu = \frac{n_\mu}{n_{tot}} \cdot 100\%$		
Quality Factor: $G_V = \sum_{\mu=1}^m \tilde{n}_\mu^k g_\mu$, $k = 1/3$ (1)		
Box Plot: $u_{Q1} : \sum_{\mu=1}^{Q1} \tilde{n}_\mu = 25\%$, $u_{Med} : \sum_{\mu=1}^{Med} \tilde{n}_\mu = 50\%$, $u_{Q2} : \sum_{\mu=1}^{Q2} \tilde{n}_\mu = 75\%$ $u_{Q-} : \sum_{\mu=1}^{Q-} \tilde{n}_\mu = 1\%$, $u_{Q+} : \sum_{\mu=1}^{Q+} \tilde{n}_\mu = 99\%$ (2)		

In most cases, the required information is the maximum uninterrupted time period at which the voltage was under or above a given level. This issue is addressed by the second criterion with quality factors and visualization given in Table 2.

Table 2. Voltage stability criterion: time domain (2)

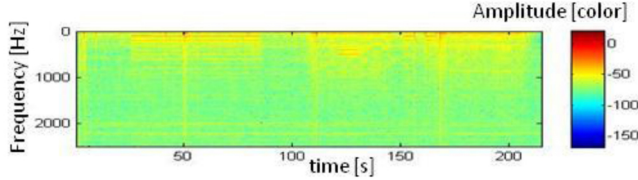
Criterion	Voltage stability, time domain (2)	
Visualization	Histogram	Maximum uninterrupted time below or above a given voltage level
		
Quality Factors	$t_{<9V}$ $t_{>16V}$	Maximum uninterrupted time below 9V or above 16V
Equations	$t \in [t_a, t_b] \quad , \quad t_b \geq t_a$ $t_{<}(u_\mu) = \max \{t_b - t_a \mid u(t_a) = u(t_b) = u_\mu \wedge u(t) \leq u_\mu\}$ $t_{>}(u_\mu) = \max \{t_b - t_a \mid u(t_a) = u(t_b) = u_\mu \wedge u(t) \geq u_\mu\}$ Quality Factors: $t_{<}(9V) \quad , \quad t_{>}(16V) \quad (3)$	

The third stability criterion describes the spectrum distribution of a sliding interval $[t, t+\tau]$ using FFT. Although the frequency range here is considerably below the level required for EMC/EMI investigations, it is still very useful for the diagnosis of the EDS and the identification of a distortion source, as well as to assess the quality of the supply voltage. The proposed quality factor is the distortion factor because it is a well-known quantity and interpretation is simple.

Fusing Concept

The fusing concept has a very important impact on the layout of the EDS, the dimensioning of the wiring, and the safety of operation. The functions are that (a) a faulty circuit is switched off before further damage occurs and (b) that there is no interruption during proper operation. The opposing boundary condition is to keep the nominal fuse values as small as possible in order to avoid overdimensioning. Thus, an ideal EDS must ensure the functionality mentioned above by using the smallest fuse values possible. Hence, for every fuse a quality factor G_f is calculated which is above 1 if the fuse value is too small and is 0 if it is too high. Finally, the quality factor G_{f0} of the entire EDS is defined simply as the percentage of suitable fuses (Table 4).

Table 3. Voltage stability criterion: frequency domain

Criterion	Voltage stability, frequency domain	
Visualization	Spectra	Frequency-spectrum versus time, amplitudes expressed as colors
		
Quality Factor	G_ω	Harmonic distortion
Equations	τ : Duration of time interval $2n$: Number of measurements within interval Δ_t : Time between measurements U_k : Amplitude of harmonics $\Delta_t = \frac{\tau}{2n-1} \quad , \quad k \in \{0 \dots 2n-1\}$ $U_k = \sum_{v=0}^{2n-1} u(t+v\Delta_t) e^{-\frac{2\pi j k v}{2n}} \quad (\text{FFT})$ Quality factor G_ω (harmonic distortion): $G_\omega(t, t+\tau) = \sqrt{\frac{1}{\sum_{k=0}^{2n-1} U_k^2} \sum_{k=1}^{2n-1} U_k^2} \quad (4)$	

The proposed evaluation uses a straightforward fuse model that is based on an energy balance as follows:

$$\Delta_f = T_f - T_{amb} \quad , \quad \Delta_f G_f = I_0^2 R_E (1 + \beta \Delta_f) \quad (5)$$

with T_f and T_{amb} the fuse- and ambient temperatures, R_E the electrical resistance, β its temperature coefficient and G_f the thermal conductance. Under the simplified assumption that above a specific current I_0 the temperature difference Δ_f is constant due to the melting of the fuse, and that an energy E_{melt} is necessary for the interruption, one gets

$$E_{melt} = R_E (1 + \beta \Delta_f) \int_0^{t_f} (I^2 - I_0^2) dt \quad (6)$$

with tripping time t_f . Fig. 2 shows that specified and calculated t_f/I values, e.g. for ATO fuses, are in good accordance. In addition, one finds (Fig.3) that the specific value $E_{melt}/(I + \beta \Delta_f)$ can be described as a function of I_0 :

$$\frac{E_{melt}}{R_E (1 + \beta \Delta_f)} = \gamma \left(\frac{I_0}{1A} \right)^\alpha \quad , \quad \gamma = 0,421 A^2 s \quad , \quad I_0 = 1,24 I_N \quad , \quad \alpha = 2,3 \quad (7)$$

where I_N is the nominal fuse current. Thus equations (6) and (7) describe a semi-empirical model which can be used for the quality factor G_f as defined in Eq. 5. As an example, Fig.