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42 V — an indication for changing requirements on the vehicle electrical system

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Abstract

The consumption of electrical energy by future cars is predicted to be in the range of several kW, exceeding that of today's cars approximately four-fold, even in the case of mid sized vehicles. To save fuel, new components and systems are under development, which will replace mechanical and hydraulic power by electrical power. The advantage of the new systems is that they consume power only in the case they are utilised. Some of them will be safety relevant. Additionally, comfort and convenience of future cars will be further increased. Most features are to be expected to be realised via electrical power. As a result, the complexity of vehicle electrical systems will be significantly increased. Two main measures will help to solve the issues: the development and implementation of an effective power management and the introduction of a new 42 V level. The paper gives an overview of the most important aspects of a modern energy management and explains intentions and values of the new 42 V draft standard. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The total system that is a vehicle is made up of a large number of individual functions, some of which are mechanically implemented, some mechanically/electronically and in many cases even simply electronically or using IT methods.

The need to further improve vehicles with regard to fuel consumption and pollutant emissions, while at the same time increasing ride comfort and safety, leads to a further increase in the energy requirement as a result of additional electrical loads [1]. The span of the average power, peak output and operating times of loads is further widened, and transient power requirements also contribute to the difficulty of providing stable operation of the vehicle electrical system. This leads to increasingly complicated vehicle electrical system conditions and stresses. This fact becomes increasingly important when used in safety-relevant systems, such as brake by wire.

Then there are loads that can only operate at higher voltages (xenon lights, heated windscreens), or which, because of their high power consumption (electric catalytic converter), are best operated at a higher supply voltage.

Logically, as the efficiency and effectiveness of the mechanical systems increases, the energy requirements of the vehicle electrical system must be proportionally reduced. To achieve this, in parallel with engine development, the electrical system, too, has to be redesigned and implemented using the latest technologies to improve its architecture and effectiveness.

When the Vehicle Electrical System Architecture Forum met for the first time at Sican GmbH (now SCI-WORX) in Hanover in April 1996, there were many doubts and reservations as to whether a 42 V powernet would ever be introduced. The viability, feasibility and even the sense were occasionally vehemently doubted. These doubts — if perhaps not all reservations — have now been virtually eliminated internationally. The 42 V powernet will come. The increasingly emerging technical and economic constraints are too great, as are the now undisputed advantages of electrical drives in comparison with mechanical and hydraulic drive systems: the reduction of (primary) energy consumption, simplification of recycling, easier installation, the elimination of moving parts, the reduction of mechanical linkages between the passenger cabin and the

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engine compartment, better utilisation of the advantages of microelectronics, programmability, etc. In view of the large number of publications on the subject, see for example [2–8], it seems almost superfluous to list them all again.

In the USA, the MIT/Industry Consortium was established in late 1995 [9]. This now has over 30 member companies from the manufacturing and supply industries, and concentrates on R&D for the 42 V powernet. At the individual meetings of the Forum in 1999, representatives from up to 15 different manufacturers and more than 50 supply companies took part.

As long ago as 1996, there was a tacit agreement with the MIT/Industry Consortium that the Vehicle Electrical System Architecture Forum should take on the definition of the outline conditions, not just because this more closely corresponded with the nature and the orientation of the Forum, but also because there was the justified assumption that this would be considerably easier in Europe than in the USA.

This paper describes the challenges of saving electrical energy and clarifies fundamental questions of diagnostics in the future vehicle electrical system as well as those relating to the introduction of energy management. Following on from that, there will be a discussion of standardisation of the 42 V powernet.

2. Consumption of electrical energy by motor vehicles

2.1. The optimisation of the electric/mechanical or mechanical/electric efficiency of electric components

In view of the fact that the percentage of energy required by electric consumers is currently only 10–15% of the entire energy that a car requires, car manufacturers and their suppliers have given little thought to the efficiency of alternators and to minimising the consumption of the electric consumers.

Nor is there any definition of the status of the automotive electrical system as an additional load on the combustion engine in the procedure for measuring a car's consumption of fuel. Here corresponding findings are needed concerning a car's average electric equipment in order to be able to realistically indicate its effective energy requirements, which is so interesting for consumers, that is measured in terms of litres of fuel per 100 km.

Geometrical dimensions, weight and the cost of the electric components used to be the optimisation parameters that attracted the main attention.

For example, if the three-phase alternator used in almost all European vehicles has an efficiency of between about 40% at full load and about 60% at low load, averaging out at about 50%, then this shows how much potential there is for reducing energy requirements simply through the generation of power.

For example, in a conventional 14 V system a saving equivalent to a weight of 167 kg is possible simply by improving the average efficiency of a 14 V, 120 A generator by 10% (from 50 to 60%) at an assumed current of $71.5\ \mathrm{A} = 0.60 I_{\max}$ corresponding to the equivalent, electric output/weight [1,10].

2.2. Adapting the supply voltages to the higher consumption requirements

2.2.1. The voltage of the electrical system

The change from the 6–7 V voltage to the 12–14 V voltage, which already took place in the 50s, was mainly the result of the higher consumption of the consumers connected up to the system. The high percentage of wasted energy and the avoidable costs for larger cross-sections in the wires were decisive arguments in favour of the change.

The number of electric components in cars and their power consumption persistently continues to grow. Consumers with a wattage of 1 kW and more are nothing unusual [11]. Thus, it comes as no surprise that the supply source needs to be readjusted to the increased requirements of the electric consumers.

If we classify the consumers according to their consumption, a range of up to 1 kW (corresponding to approximately 70 A) is still suitable for a supply voltage of 14 V. In the case this current will be exceeded, the consumers can only be supplied with electric power at unreasonably high losses. Large cross-sections in the wires also make trunks of wires stiff. They can no longer adapt to curved contours.

If we take the maximum current of approximately 70 A as a criterion for the class above, the 14 V supply, consumption requirements of up to 3 kW can be satisfied with a supply voltage which is three times larger, as is shown in the middle field in Fig. 1.

At present no electrical consumers are known whose wattage significantly exceeds these values. As a result it is not yet necessary to define and establish the question mark shown in the right field in Fig. 1.

2.3. Factors influencing the power consumption of the automotive electrical system

In order to permanently improve the power consumption of a car, it is first necessary to obtain an exact picture of the power sources and energy sinks.

Fig. 2 maps out the flow of energy, the size of the arrows also indicating the rough proportions of the individual forms of energy.

The electric energy in a car generated by consumption of fuel is made up of the following factors:

$$\begin{aligned}\text{electrical energy} &= \text{efficiency of the electric components } (\eta)\\ &\quad \times \text{voltage of the electrical system } (U)\\ &\quad \times \text{current } (I) \times \text{period utilisation } (t)\end{aligned}$$

Thus, all the influential variables where changes must be made to minimise power consumption are known. In detail

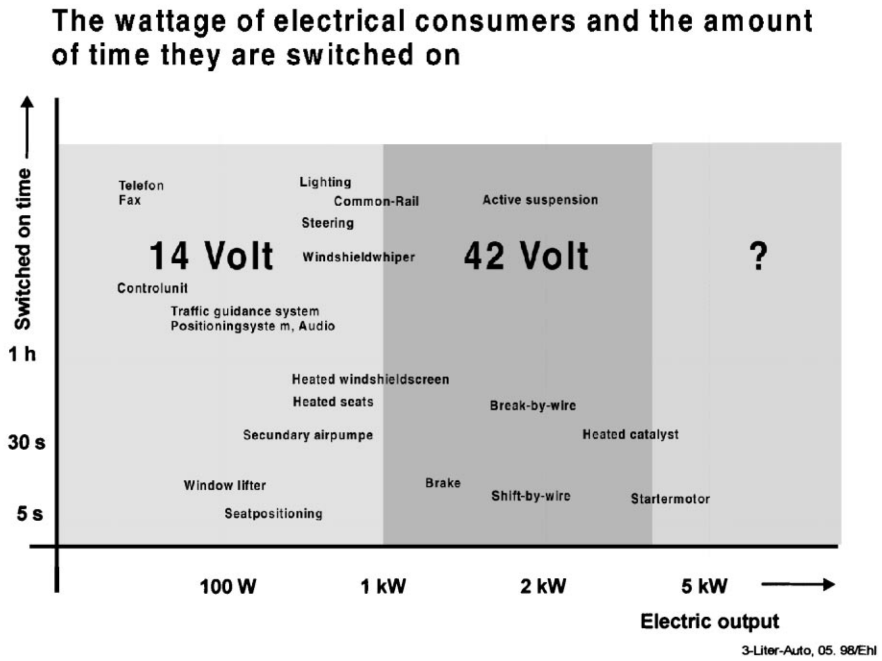

Fig. 1. The output of electric consumers and the amount of time they are switched on, now and in the future.

these are given below.

- The efficiency of the electric components in the automotive electrical system irrespective of voltage [12,13].
- The voltage to supply the consumers. Restrictions are imposed by the safety regulations for connectors and contacts and by the maximum voltage of micro-electronic components which is due to technology.
- The total amount of current which is determined by the power requirements of the consumers connected to the system.
- The period of time that the consumers are switched on, which is something that is decided by the motorist and which is also decisively influenced by the technical designer of the car.

3. Energy management

The final factor which influences the power consumption of the automotive electrical system is the timed switching on and off the individual electric components. As this goes hand in hand with a basic change in the existing electrical system, the restructuring of its architecture is inevitable.

In future, the output of energy generation components, which were previously dimensioned according to only simple criteria, must be controlled and regulated as needed by a management system for electric energy which intervenes horizontally in the many functions which work vertically. A management system which is also arranged horizontally in the system hierarchy is the multi-dimensional diagnosis. Although, its purpose is clearly different, an effective and

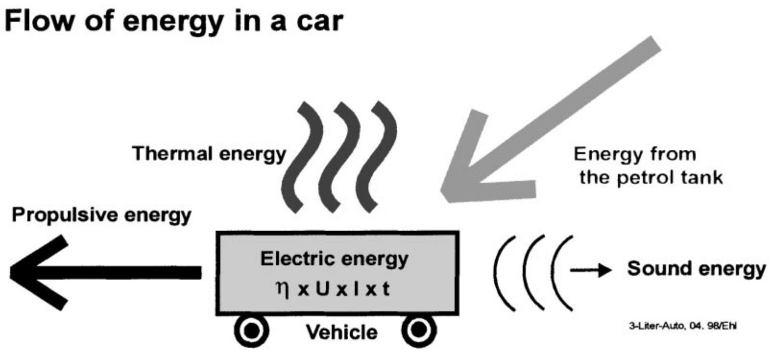

Fig. 2. The flow of energy in a car.

save energy management is only possible in combination with a multi-dimensional diagnosis.

3.1. Structure of vehicle mechanical/electronic systems

3.1.1. Vertical functions and their networking and inter-linkage

A necessary consequence of the step-by-step addition of mechanical/electronic functions to car equipment at very divergent rates of installation, is that each individual function has to be built up independently, autonomously and autarchically. It exists as an island and is surrounded by many other island functions. Because of this island status, multiple sensors and actuators are installed in vehicles to handle the same signals — even if the neighbouring function could provide the required signals.

From this background, the integration of individual functions, e.g. engine, gearbox and brake management, into a network level and the linkage of network levels of differing transfer speeds, — e.g. LOW-CAN, CAN and D2B — into network hierarchies is a revolutionary development step. The reasons for this are to be found in the attempts to seek technical and financial optimisation of car manufacture. Multiple utilisation of electrical components, such as sensors, a reduction of the amount of wiring, the associated increase in reliability, better utilisation of the installation space, band programming and the associated reduction of the plethora of variants, etc. are just some of the compelling arguments.

These principal relationships of networking and inter-linkage of individual functions in modern cars are presented in Fig. 3. Clearly discernible are the network levels A–D, structured according to transfer speeds and linked into a network hierarchy via gateways [14].

The diagram also shows the many parallel individual technical functions, originating from different internal or external development departments in the supply industry, which make up the total electrical system. The hardware/software functionality ratio (currently around 25:75%) is highlighted by the colour scheme.

For mechanical/electronic systems in vehicles, integration and inter-linkage into networks involves relinquishing the independent island principle. On the one hand, the introduction of defined gateways to the network achieves a certain level of standardisation of the network elements, and on the other, linkage via the network to other functions, together with support by their existence, favours progressive integration into the higher level total electrical system. Examples of this are the networking of engine and gearbox management into the drive train management (ASR) and networking of anti-blocking systems (ABS) and engine management into a pseudo four-wheel steering system. Obviously, the functionality exceeds that of the island functions, because a new functionality is added to the whole system.

Island functions and grouped island functions are subject to special criteria dependent on their purpose. They are therefore, also described as vertical functions hereafter.

3.1.2. System function or horizontal function

System functions carry out cross-sectional tasks horizontally across the individual technical functions. Examples of this are: energy management, diagnostics, the equal parts principle, the part numbers system, the quality strategy and the reliability concept.

However, these horizontally organised system functions frequently have only a virtual existence as rules, regulations or standard planning procedure. Implementation is by means of individual, non-separable functional elements introduced into the components and possibly an additional independent central component. One example is the diagnostic system. The diagnostic system comprises individual elements in each technical function, combined with an additional central diagnostics management function. To illustrate this, Fig. 3 must be supplemented as shown in Fig. 4

This diagram shows that data traffic between the elements of a system function is carried over the existing network

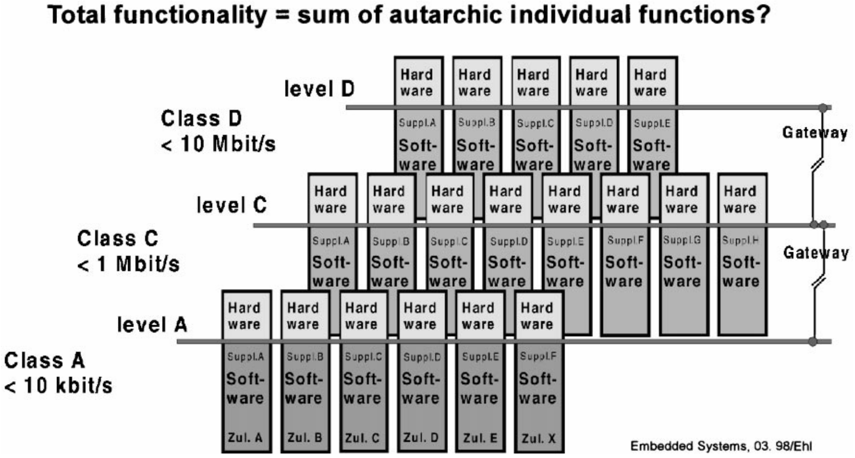

Fig. 3. Total functionality as a sum of autarchic individual functions.

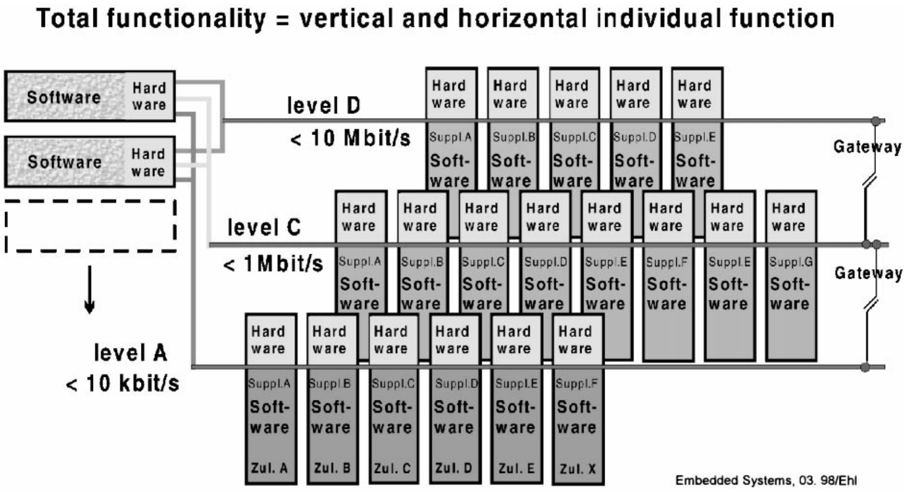

Fig. 4. Taking account of horizontally structured system functions.

levels, A, C and D. In particular cases, which generally have to be specifically justified, a separate horizontal integration can also be provided.

In the following, energy management and its arrangement in the matrix architecture is illustrated in detail as an example of system functionality of a modern vehicle. Multi-dimensional diagnostics (MDD) and horizontally overlapping system properties are localised in the matrix. These include, e.g. electro–magnetic compatibility (EMC), functional compatibility (FUC) and the reliability of the total system.

3.2. MDD

Conventional diagnostics essentially involve monitoring and controlling the mechanical hardware which is subject to wear. With an increasing number of functions, the warning and fault-search system shaped by the mechanical instrumentation develops into a system diagnostics facility which, as a central system function, additionally initiates and controls the structure, testing and possibly also the dismantling of the electrical system in the car (Fig. 5).

However, this assumes that an appropriate structure and control concept, which must be derived from the vehicle assembly sequence, already exists in the hardware and software in the ABS system control unit.

If, then, in addition to the diagnostics capability of each individual vertical function, there is a demand for an overlapping multi-dimensional horizontal diagnostics function, there have to be compelling reasons for the additional expense and complication. What are these?

- The task of the horizontal MDD system is to ensure that all vertical functions are evaluated and implemented according to the same criteria. This includes undertaking a graduated weighting according to the relevance of the

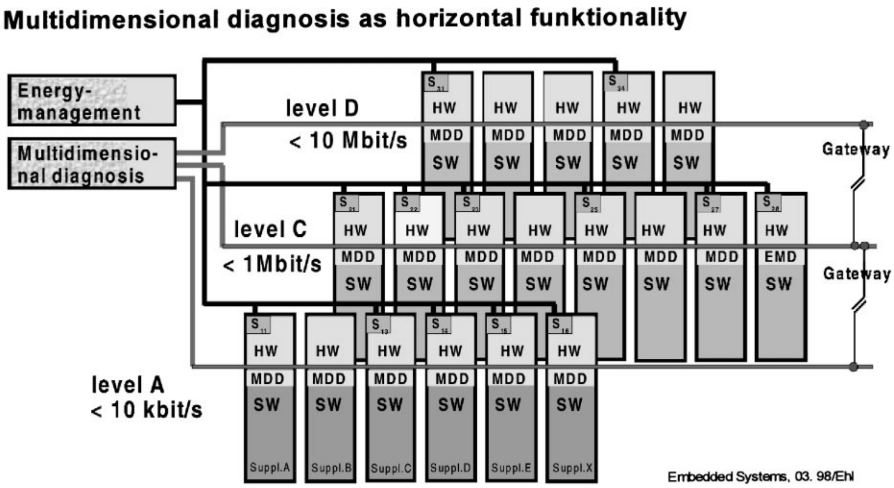

Fig. 5. MDD as a distributed horizontal function.

function from the perspective of the total system architect. So horizontal MDD is responsible for management of the diagnostics of the total system.

- With appropriate design, grouping vertical functions can create new vertical functions which do not always need a specific discrete control unit. For example, the interaction of engine management and the ABS system can produce a virtual four-wheel steering system. The MDD have to ensure that, as in the example given, the additional vertical functionality of the virtual four-wheel steering is monitored and any occurring faults indicated both as an individual system and in conjunction with the other system components.
- MDD has the additional objective of specifying a horizontal diagnostics proportion for the same-type areas (domains) defined by the reliability concept. An example of this would be the suspension domain, in which each of the vertical functions: ABS system, active suspension system, electronic stability programme, steer-by-wire, etc. has its own individual diagnostics function, but which require horizontal grouping jointly within the domain.

MDD is the only way of being able to give a guarantee in the future of having the ability to build up a large number of technical functions, such as the air conditioning system with around a dozen sensors and actuators, the electronic seat management system or a multi-airbag system, smoothly without any problems. Given the large number of technical functions, this is the precondition for the fault-free functioning of the end product, the car.

3.3. *Car reliability*

The increasing integration makes car reliability more and more into a system property. The functionality of each subsystem influences the reliability of the total system. Seen in this light, it is obvious that the property of reliability has to be designed for the car according to criteria which the car maker must specify in a uniform manner according to the relevance of the individual function for reliability.

3.3.1. *Vertical reliability*

In general, the electronics in a car are to be regarded as part of a master mechanical/electronic control circuit. This is characterised by a sensor field comprising a large number of individual sensors, an actuator field, which can be similarly widely branching, together with the programmable electronic control unit arranged between the two and which controls the hardware and software. The control circuit is completed by mechanical means (Fig. 6).

A system can be described as being 'reliable' only within the framework of the specified reliability criteria. The question of the limit of protection — how many possible correlated and non-correlated faults in a design have to be ameliorated by fuses — is something that can be decided and answered only by the relevant designer on the basis of the methods and technology available in each case.

3.3.2. *Horizontal reliability*

If all vertical individual functions fulfil their separately defined reliability concepts and the assumption can be made that reliability can be guaranteed during the product life under the specified technological conditions, then this certainly raises the question of what exactly the horizontal reliability concept is, what it is responsible for and what it must perform?

- The task of the horizontal reliability concept is to ensure that all vertical functions are evaluated and implemented according to the same criteria. This includes undertaking a graduated weighting according to the relevance of the function from the perspective of the total system architect. So the horizontal reliability concept is responsible for proportionality of the individual vertical reliability concepts of the total system.

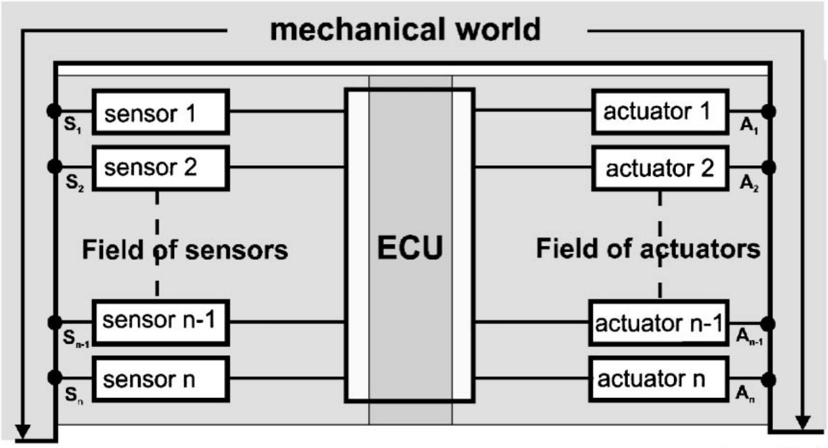

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Fig. 6. Electronic part of a mechanical/electronic control circuit.

- With appropriate design, grouping vertical functions can create new vertical functions. The horizontal reliability concept has to ensure that the additional vertical functionality, both as an individual system and in conjunction with the overall system, cannot generate any hazardous conditions.
- The area of responsibility of a horizontal reliability concept also encompasses all those cases which do not originate from reliability-relevant functions, but which can nevertheless adversely affect the reliability of the total system.
- For example, a reliability concept of a vertical function must not assume that a short circuit in a different vertical function will result in the common supply voltage failing. If however — for any reasons whatsoever — a probability should exist of this occurring, the reliability concept for the total system must provide for appropriate countermeasures.

This problem takes on great significance, in particular following the introduction of the additional 42 V power supply.

3.4. Reasons for horizontal electric energy management

To obtain maximum efficiency from the components for the generation, storage and distribution of electrical energy, which to date have been dimensioned according to simple design criteria, these will in future have to be controlled by a horizontally arranged energy management system This particularly includes the alternator, battery and powernet.

Fig. 7 shows the fundamental architecture of a horizontally integrated energy management structure with the corresponding horizontal networking.

Logically, the components for energy generation, storage and distribution, together with the high-power loads, must be equipped with S_{xy} switches and networked with the horizontally arranged energy management system. It is as yet not possible to make any generally valid statement as to whether this network should be fulfilled by existing bus systems or should be provided separately. However, because of the safety relevance of the energy supply for the entire electrical system, it is very probable that the flow of energy management information to the relevant network components will be separated from the vertical networking, such as CAN, D2B, via its own network level.

It is also discernible from the schematic diagram that the energy management system is a distributed horizontally acting system due to the electronic switching S_{xy} installed in the individual vertical control units. Its fundamental structure and above all the software-based strategy of time-switching of high-power electric components has to be developed by the car makers and specified for the remaining components of the electrical system.

The structural fusion of the energy management system with the crossbar switch used on modern vehicles (central electrical system) as a radial hub of the powernet suggests itself as an obvious development. Developing this as an electronic system will allow further quality improvements to be made.

These include:

- the replacement of electro–mechanical relays by power electronic components,
- electronic fuses with individual software-definable cut-off behaviour,
- connection to the car information network,
- control of the relevant condition variables of the powernet supply by intervention at the energy generation stage,
- control of the energy requirement by priority-dependent switching of the electric loads, etc.

The following properties of every vertical function must be optimised.

- The efficiency of the electrical components in the powernet independently of the powernet voltage.

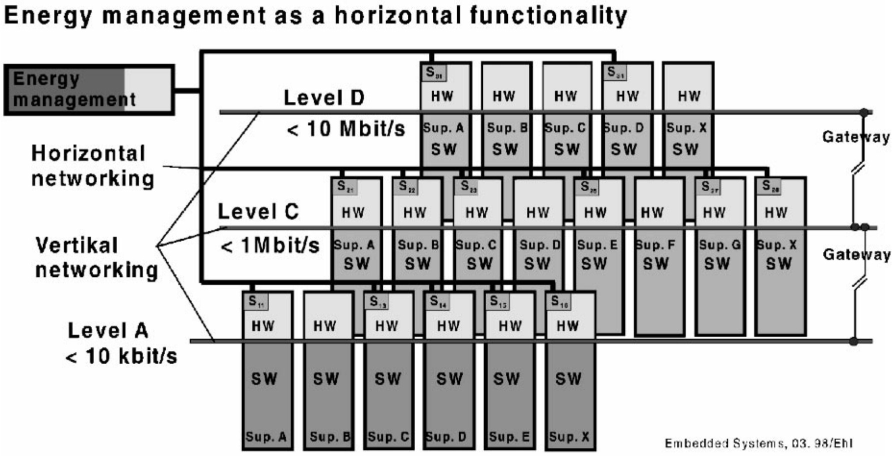

Fig. 7. The basic architecture of an energy management system.

- The current requirement of each vertical function, which when aggregated determines the power requirement of the energy generation device.

The horizontal electricity management system also covers the following responsibilities.

- Determination of an optimal powernet voltage to feed all loads. Protection specifications for plug and pin connectors and contacts and technologically-based limit voltages of microelectronics sub-assemblies can be seen as imposing certain restrictions.
- Determination of the switch-on time of electric components according to priority and duration, selected by the user of the vehicle and decisively also by the designer of the car.
- Ensuring the time compatibility of all switching measures in the powernet in order to eliminate critical or reliability-relevant conflicts, respectively [9].

4. Standardisation of the 42 V powernet

4.1. Review

The foregoing chapters clearly point out the many chances offered by the introduction of the new vehicle electrical system, but also the great challenges. From the beginning, the people involved were aware of the fact, that only if internationally accepted basic requirements are available as soon as possible, the development of systems and components for the 42 V net would be economically feasible.

At a very early stage at the end of 1996, the Forum resolved to define a standard for the new powernet, with unanimity that the attempt had to be made to do this on the international level and obtain as high a level of acceptance as possible.

The project was then presented by Sican to FAKRA (the DIN standards committee for road vehicles) and at the end of 1997 recognised by VDA as being worthy of standardisation. In 1998, the 'Work Group Standardisation' (WGS), made up of members of the Forum, commenced its work under the direction of Sican. From April 1999, the project has received direct financial support from the VDA on the understanding that a draft standard be submitted within 1 year.

Both the objectives of international acceptance and keeping to the timetable, were achieved. For a considerable time now, development work has been going on world-wide to the specifications of the draft standard. With only 12 meetings of the WGS, of which 7 took place between April 1999 and March 2000, the draft was completed in German and English (for submission as an ISO standard) and submitted to FAKRA.[3] Three essential factors which supported this success are as follows.

- The desire and the necessity to significantly accelerate the development of standards.
- The support of the WGS by VDA and FAKRA as a group working independently of DIN. This allowed international participation. PSA and Renault regularly take part in the meetings.
- But the most important factor was that, for what was probably the first time ever in the history of the automotive industry, the Vehicle Electrical System Architecture Forum made and makes possible a free and intensive exchange of experience and opinion from experts of virtually all involved companies. This was accomplished by the work of the MIT/Industry Consortium.

It is not possible at this point to discuss every single detail. The following deliberations therefore go into the basic ideas and most important definitions underlying the draft standard.

4.2. Intentions of the standardisation

The first point to clarify is why only "14" and "42 V" are discussed in the context of the new powernet. These are the voltages (rounded) which the loads actually 'see' when the engine is running. But the main reason is that no definite technology was intended to be specified by the new standard. The 12 V and correspondingly 36 V, however, are the nominal voltages of traditional lead–acid batteries. But there are now other interesting technologies from the point of view of energy storage [15], which can provide different rated voltages. In addition, the term "42 V powernet" (also: "PowerNet") has become established around the world. No one any longer asks about battery voltages.

The WGS and the Forum have successfully defended their case, against some strong opposition from the standardisation committees, for retaining the term "42 V" in the title. It was therefore worded as follows.

Road vehicles — Conditions for electric and electronic equipment for a 42 V powernet

Part 1: General; Part 2: Electrical Loads

Other specifications of certain technologies, such as the vehicle electrical system architecture, should be avoided. Both intentions are specifically noted in the foreword to the draft standard and at other necessary points.

> *Extract from the foreword:*
> *'The objective of this paper is to standardise the voltages by establishing permitted voltage levels and test procedures for the loads, without prescribing specific technical solutions. It is not in the scope of this document to specify a certain battery technology. Therefore, any terms related to the lead acid battery are avoided in the title. In the case any definition specific for the lead acid battery is given in Part 1 and Part 2, appropriate comments are included'.*

It is a platitude to state that early standardisation makes a very significant contribution to development certainty. The

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[3] WGS/WD 02/2000-1, -2, the drafts are available free of charge at www.sci-worx.com, click "Partner".

difficulty arising here, however, was that various technical aspects (at least at this time) cannot be included, because they simply are not known. You are 'standardising the future'.

The participants had recognised this, but also the enormous advantages that the process offered, are given below.

- An 'incomplete standard' is better than none, if it contributes to defining generally accepted economically viable and technically feasible basic requirements (see above). But what is 'incomplete'? A standard is a kind of diplomatic compromise. Everything else is a matter of specification.
- Little 'consideration' need be taken of existing components and systems, so the standardising body is relatively independent.
- A very important factor was that this offered a unique opportunity of eliminating the inadequacies of the existing 14 V electrical system, while at the same time including both the advantages of semiconductor technology and its limitations at an early stage.

The general new conceptual approach is one of considering the system as a whole. A basic principle of the draft standard is therefore the originator principle: interference has to be eliminated where it occurs. These measures ensure that the maximum voltage on the 42 V powernet is limited to 58 V for a maximum duration of 400 ms.

In terms of semiconductor technology and microelectronics, most people immediately think of microprocessors, but forget that a large proportion of vehicle electronics consists of power electronics and mixed-signal ASICs. Wherever analogue semiconductor elements are used, the actual problem is not the voltage, but the current. Increasing the operating voltage allows currents to be reduced, leading to a significant reduction in area — and, in semiconductor technology terms, that means a significant reduction in costs [16]. The restriction of the permissible voltages in the powernet has a further effect — that of the possibility of using standard processing of semiconductors while avoiding expensive protection circuits. This will open up new ways of using microelectronics and semiconductor components in vehicles.

Originally, an attempt was made to base the draft standard on [17], including new definitions for the 14 V powernet and EMC.The first intention was quickly abandoned, although, here, too, it would be desirable to make the requirement less stringent. But it was and is not to be expected that existing 14 V components will be changed.

The second project was initially retained. The first draft, submitted to members of the Forum for discussion in late 1998, was therefore still heavily orientated to DIN 40839, or respectively, ISO 7637. Once drafts of new standards on the 14 V vehicle electrical system (ISO/WD 16750 and E DIN 72300) became accessible to the WGS and the Forum in mid-1999, the resolution was made to adjust to these drafts and not to include the EMC definitions.

The justification for this is that it could in future make sense to merge the standards. In addition, to avoid irritations, the 'classic' division into EMC standards and standards on voltage values should be retained. It is apparent that architecture plays a key role in the case of a 14 V/42 V dual-voltage electrical system [18,19]. However, this is greatly dependent on the vehicle type and is for the most part an unknown quantity.

4.3. Definitions of the draft standard

Part 1 of the draft contains general definitions and definitions of terms and will therefore not be discussed here.

Practically every definition included in the draft is the result of intensive co-ordination activities, not only at the Vehicle Electrical System Architecture Forum and in the WGS, but also in collaboration with the MIT/Industry Consortium.

4.3.1. Static voltages

In the draft, the 42 V powernet voltage is paraphrased by the term, 'working voltage'. This was necessary, because in international and national standards (which are all based on the rated voltage of the lead–acid battery, see above), the term, 'powernet voltage', does not exist, whereas the term, 'working voltage', has been introduced.

In summary, the definitions of the static voltages in Section 4.1, Part 2 of the draft are as given in the Addendum, extraction 1.

The individual values will be dealt with in greater detail further below. At this point, reference is simply made to some following special features.

- The index 'PN' of the symbol for the working voltage stands for the term, 'powernet'.
- Paragraph 2 defines the measuring point at the inputs of the device being tested. As a result, other influences, e.g. the wire resistance, are not taken into account. The interpretation is therefore unambiguous.
- In contrast to standards for the 14 V system, the maximum operating voltage, is defined including ripple. This provides a safeguard to ensure that transients, such as generator ripple, which are permanently present in the powernet, may not exceed 50 V (except in exceptional circumstances). On this basis, it was necessary to define an effective static voltage, which all systems/components must comply with.
- For reasons already discussed, no specification of the battery voltage is included.

The specification of the maximum static voltages is consequently as given in the Addendum, extraction 2.

In all specifications, it is important to distinguish between the standardised values and the corresponding test. The definitions in accordance with Section 4.3.3 of the draft are a good example of this. The test specifications are always a compromise between the best possible depiction of reality and the realisation of the test.

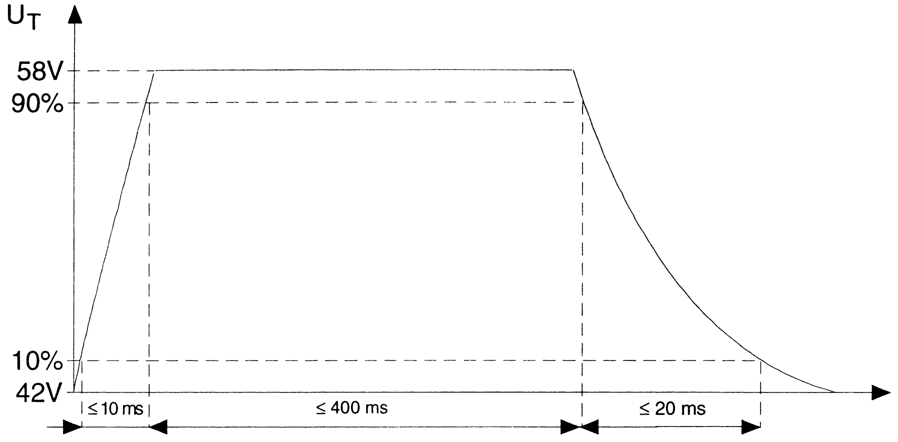

Fig. A1. Slope of the test pulse for $U_{\text{max, dyn}}$. This figure corresponds to Fig. 4, WGS/WD 03/2000-2.

The definition of a maximum of 48 V effective voltage naturally includes the fact that even 'genuine' static voltages may not exceed this value. The motive for the 48 V is not only the lead acid battery, but also to enable energy recuperation, eg. via regenerative braking.

Sentence 3 in Section 4.3.1 in the Addendum permits a lower effective value than 48 V, where agreement is reached. There was intensive discussion on this. It was shown, however, that if this value was fixed, it would be likely to lead to significantly increased costs of traditional generators, as these generally have a relatively high ripple proportion. It could also be said that this sentence was inserted 'for the protection' of suppliers. Priority is given to compliance with 50 V including ripple. If the manufacturer cannot accept increased costs, this opens the way to permitting a lower effective voltage with the disadvantage of a somewhat slower recharging of the battery. The problem in any case does not arise for modern crankshaft-starter generators. They have a significantly lower ripple proportion [20].

A new feature, which is not included in ISO/WD 16750-2 and E DIN 72300-2, is the implementation of frequency-dependent damping to be fixed in the specification of the device being tested. This became necessary because the economical electrolytic capacitors, which are frequently used for protection of electronic components, would not have been able to comply with the definition.

4.3.2. Overvoltages/dynamic voltages

The important — because most far-reaching — specifications of the draft are those relating to the maximum overvoltages and the permitted emissions (Addendum, extraction 3).

The specification of the maximum static overvoltage can, in principle, be omitted, and is actually only a precautionary measure against the demand for a higher voltage for jump starting.

The maximum dynamic overvoltage, as specified here, forms the basis of the 'originator principle'. Anyone in the know will notice that the character of the test pulse is the same as that defined to date in DIN 40839 and ISO 7637 (load dump) except that it is limited here to 58 V, see Fig. A1, i.e. the requirement for protective circuits in the 42 V powernet are lower than in the traditional vehicle electrical system. The reason for this limitation has been adequately discussed above. Of course, this specification caused extremely lively discussion, since many suppliers and manufacturers forecast a significant increase in costs. But in the final analysis, it was recognised that a single component, such as the generator in this case, cannot determine the requirements of the entire system. The same applies to other transmitters of high-energy interference pulses.

Practically at the last minute, the definitions on limitation of emissions were inserted, with the wording according to the Addendum, extraction 4.

The people involved in the standardisation were naturally aware that this was encroaching onto EMC territory. However, as the draft standard did not contain any further specifications on emissions, with the exception of load dump protection, it became clear that it could not guarantee the voltages. On the traditional vehicle electrical system, the situation is different, because the relevant EMC standards exist.

A similar set of arguments led to Section 4.6.2 (see Addendum). At first glance, the first paragraph in particular may appear unusual in a standard. And it is. But it was found necessary to explicitly refer to new EMC standards required for the 42 V powernet. In this way it was hoped to accelerate standardisation in this area.

4.3.3. Voltage drops

Let us leave operating and overvoltages and turn now to voltage drops. In this area, specifications were included for slow voltage drops and rises, such as occur with a slow discharging and re-charging battery, and for short voltage drops (triggering of a fuse) as well as for testing the reset behaviour. These specifications and tests are included, appropriately adapted, on the basis of those contained in ISO/WD 16750-2 and E DIN 72300-2. This was another area which initially aroused controversial debate at the

Forum. The main argument of the opponents was that it was not a good idea to transfer all the inadequacies of the old vehicle electrical system to the new powernet through the route of standardisation. However, since these definitions will certainly be included in the above-mentioned standards, it was finally decided to accept these in an adapted form.

The definition of the extremely important start pulse needed a good deal more work and discussion, because this is where the determinant influences on the battery and systems and components relevant to starting and safety are set down. Following intensive debate and repeated revision, agreement was finally reached on the specification in Section 4.8.3 of the draft (see Addendum, extraction 5).

In the 'General' section, the minimum starting voltage is fixed at 21 V including starter ripple. That was not always the case. Initially, the definition referred (appropriately) to the 'effective value', i.e. a lower voltage was permissible with a minimum ripple level.

A debate is currently underway about the adoption of a test pulse in ISO/WD 16750 which, in contrast to DIN 40839, explicitly includes the starter ripple. The background to this is that problems for electronic systems may occur if the starter ripple causes the voltage to drop below 5 V — the operating voltage of many electronic systems — during cranking. The question was raised as to whether this new test pulse (adapted) should be included as an alternative in the draft standard for the 42 V powernet. Consultation with experts established that this problem was not relevant for them in the 42 V powernet. The WGS therefore saw no necessity in defining a test pulse including ripple, as the test procedure should not be over-complicated. At the same time, this meant that the requirements on systems and components relevant to starting and safety could be reduced.

The minimum starting voltage (21 V) was initially specified at 25 V [17]. This had to be reduced to the values specified in Table 2, due to the current exclusive use of lead–acid batteries. The best power match is achieved at half the rated voltage. The battery manufacturers would have liked to have seen 18V. However, studies showed that the specifications set out in the table represent a good compromise: when the starting process is initialised, the optimum power match is allowed. During the starting process, 21 V is still very close to the maximum output of the lead–acid battery. Because of the characteristic curves of lead–acid batteries, the previously defined 25 V for the minimum starting voltage would have required an increase in the capacity.

The table includes no information on battery voltage and the designation U_0 was introduced in the graphic for the upper voltage level. It is defined in Section 3.3.3, Part 1 of the draft (see Section 3.3.3., WGS/WD 03/2000/1).

3.3.3 Supply voltage U_0

Maximum voltage supplied by the battery to the powernet. This voltage may differ depending on battery technology.

4.3.4. Reverse polarity and short circuit protection

Particularly hotly debated topics were those of protection against reverse-polarity connection and short-circuiting. While reverse-polarity connection of a 12 V battery is unpleasant, on a 36 V battery it can produce extremely dangerous situations. But it is also important to prevent reverse-polarity connection between, e.g. a 12 and 36 V battery. Partly for that reason, many participants continue to demand the use of two batteries, one in the 14 V system and one in the 42 V system. A further reason is jump starting, which should also be possible between a 14 and 42 V vehicle. A simple solution to the problem is the introduction of form-fitting plugs and battery terminals, which have to be designed in such a way as to completely exclude contact with the terminal if an incorrect plug is used. However, these questions are a matter for a new battery standard. Indeed, a working party has been set up, made up of members of the MIT/Industry Consortium, with the objective of introducing an international draft standard on this subject by the end of this year (details: http://auto.mit.edu/consortium, Button: battery termination).

Devices being tested for the traditional vehicle electrical system have to be subjected to a negative voltage of −14 V for 60 s. The object of this draft standard was to define less stringent conditions in the event of reverse-polarity connection. Agreement was very quickly reached in the Vehicle Electrical System Architecture Forum that no permanent negative voltages should be permitted and that instead, reverse-polarity protection should be demanded for the 42 V powernet. In this way, costs can be reduced, particularly for electronic components and systems, e.g. ECUs. Tests by the semiconductor manufacturers and system suppliers, and enquiries by relevant companies led to the definitions set out in Section 4.9 of the draft (see Addendum, extraction 6).

The specified voltage value and the duration of the test pulse include an additional safety margin. Section 4.9.3 (see Addendum) explicitly refers to reverse-polarity protection, consciously leaving matters of design and type open.

A great deal of time was necessary to arrive at the definitions for short-circuit protection. It could have been left at simply including requirements for the 42 V system, which would have considerably simplified work. However, this was rejected, because the prevailing opinion was that the 14 V system could not be entirely ignored in the draft, as 'downwards compatibility' should be guaranteed on a dual-voltage vehicle electrical system.

The greatest difficulty occurs if a short-circuit is applied between 14 and 42 V systems, e.g. through the wiring [19]. Experts from fuse manufacturers, cable harness suppliers and manufacturers were asked to give their opinions on this, or invited to meetings of the working party. The subject was given top priority at the Forum on 16 March 2000, where five contributions were presented by different companies. Detailed proposals were drawn up and submitted to the working party. However, this clearly shows that uniform standardisation is practically impossible. The dependence on the architecture (i.e. the wiring routing) and the relevant protection strategy is much too great in this case. The manufacturers pointed out that preventing short circuits was, in the final analysis, their responsibility. They are confident that the problem can be solved using tried and tested methods. As a result, the definitions and recommendations for the draft standard are set out in Section 4.10 of the draft as given in the Addendum, extraction 7.

Section 4.10.1 and 4.10.2 (see Addendum) only partially correspond to the provisions in ISO/WD 16750-2, because they do not include a test definition. This was rejected by the WGS on the grounds that testing short-circuit resistance was part of the specification of systems and components. Additionally, the test procedure specified in the above-mentioned standard is based on traditional melt type fuses. However, it cannot be excluded that other types of fuses will be used in vehicles in the future.

Section 4.10.3 (see Addendum) shall create a relationship to the 14 V system. The decision was facilitated by the expected reduction of the maximum voltage in the 14 V system to 24 V. The final sentence of Section 4.10.3.2 is intended to point out that action still needs to be taken on this matter. Whether an overvoltage protection actually becomes necessary at a later date, is a matter for debate. It is conceivable that this kind of component could be avoided.

4.3.5. EMC

The matter of EMC has already been touched upon. Existing standards are quoted in the draft, but it is also pointed out that their applicability has still not been secured, e.g. as is the case in Section 4.13 of the draft (Addendum, extraction 8).

4.3.6. Other definitions

Further definitions of the draft refer to dielectric strength and insulation resistance. These apply equally to components in the 14 V system and those in the 42 V system and have been adopted from ISO/WD 16750-2, or E DIN 72300-2. The same applies to mechanical, climatic, thermal and chemical stresses, which are specified in parts 3–5 of the above-mentioned draft standards and are therefore only cited.

5. Concluding remarks

The standardisation of the 42 V powernet has shown that with early preparation and inter-disciplinary and international co-operation (which was and is actually practised at the Forum), together with the bundling of activities, such as communication, prepara- tion of meetings, reporting on an international level, production of detailed minutes, etc. by a neutral partner (in this case Sican), consensual solutions can certainly be achieved in a short time. It should be emphasised that only in a few exceptions were the members of the WGS pro- fessionally involved with standardisation activities. The financial support by the VDA should also be stressed, as this enabled Sican to operate with the necessary intensity in an alien environment for the company. The members of the Forum also deserve special mention — particularly those who were there at the birth — whose commitment made a decisive contribution to the success of the 42 V powernet. The work of the Forum is not yet finished. Many aspects of the new powernet are still to be discussed and taken on to generally accepted conclusions.

Addendum — Extraction from the Draft Standard

The definitions given here are original extractions of the draft standard submitted to FAKRA and ISO. In the meantime, some wordings may have changed due to editorial work of FAKRA and ISO. To the authors knowledge, no technical content has been so far subject to changes.

Extraction 1

4.1 Voltage definitions for the 42 V powernet

Operating voltages and test voltages in the 42 V powernet shall be in accordance with Table 1.

The voltages shall be applied at the electric/electronic equipment/component terminals.

Extraction 2

4.3 Maximum operating voltage and effective value

4.3.1 General

Maximum operating voltage $U_{\text{op, max}}$ in a 42 V vehicle electrical system. Peak value of the voltage including ripple,

Table 1
Voltages in the 42 V powernet

Code	Operating voltage				Operating conditions for equipment/components
	Working voltage of the powernet U_{PN} (V)	Maximum operating voltage $U_{\text{op, max}}$ (V)	Effective value of maximum operating voltage $U_{\text{eff-op, max}}$ (V)	Minimum operating voltage $U_{\text{op, min}}$ (V)	
L	42	50[a]	48	21[b]	Full functionality during starting
M	42	50[a]	48	30	Full functionality with engine off
N	42	50[a]	48	30	Full functionality with engine on

[a] Including ripple.

[b] Plus starting profile.

irrespective of the transient format and the frequency range if not otherwise specified.

The minimum frequency is 50 Hz.

The effective value is $U_{\text{eff-op, max}}$. Upon agreement, $U_{\text{eff-op, max}}$ may be below 48 V.

4.3.2 Values

$U_{\text{eff-op, max}} \leq 48$ V
$U_{\text{op, max}} \leq 50$ V (including ripple)

4.3.3 Test

Connect the device under test. Heat the device under test in a hot air oven to $T_{\max}$ minus 20°C. Apply the following test to all applicable inputs of the device under test:

$U_{\text{op, max}} = 50$ V (including ripple)
$U_{\text{eff-op, max}} = 48$ V (root mean square)
$U_{\text{PP}} = (4–1)$ V, depending on frequency
$U_T = U_{\text{DC}} + 1/2U_{\text{PP}}\sin(\omega t)$
$f_T = 50$ Hz to 20 kHz
Internal resistance ≤ 100 mΩ
Type of wobble: sawtooth, linear
Wobble duration = 60 s
Test duration = 5 sweeps

A frequency dependent damping of U_{PP} shall be applied as given in the specification of the device under test.

U_{DC} must be set to ensure that the above values are observed. This test pulse must not be applied to the battery.

Extraction 3

4.5 Overvoltage

4.5.1 Maximum static overvoltage

Even in the case of jump start, the maximum operating voltage $U_{\text{eff-op, max}}$ defined in Section 4.3.2 shall not be exceeded.

4.5.2 Maximum dynamic overvoltage

4.5.2.1 General

Maximum dynamic overvoltage $U_{\text{max, dyn}}$ for high-energy pulses in a 42 V vehicle electrical system (currently load dump). Limit voltage for load dump protection (LDP) at the generator.

The LDP must be designed to ensure the value of $U_{\text{op, max}}$ and $U_{\text{max, dyn}}$. The tolerance of the LDP shall be agreed upon between vehicle manufacturer and supplier.

4.5.2.2 Values

The following mandatory values apply for $U_{\text{max, dyn}}$:

$U_{\text{max, dyn}} \leq 58$ V
$t_S \leq 400$ ms

4.5.2.3 Test

Connect the device under test. Apply one test pulse to all applicable inputs of the device under test.

The nature of the required test pulse is shown in Fig. A1.

Extraction 4

4.6 Emissions

4.6.1 High energy pulses

No load shall produce an overvoltage exceeding $U_{\text{op, max}}$ as defined in Section 4.3.2.

4.6.2 Low energy pulses

Emission levels of electric/electronic components of the 42 V powernet and their measurement shall be in accordance with a new standard to be prepared. Temporarily, the pulse definitions given in Sections 4.6.1 and 4.6.2, ISO 7637-1 and DIN 40839 Part 1, superimposed to the voltages defined in Section 4.1 and 4.5.2 of WGS/WD 03/2000-2, apply with severity class III according to Table 2, ISO 7637-1 and DIN 40839 Part 1, respectively.

Measurements shall be according to Section 3.3, ISO 7637-1 and Section 3.2, DIN 40839 Part 1. The shunt resistor R_{s1} shall be 120 Ω.

Extraction 5

4.8.3 Starting profile

4.8.3.1 General

The minimum start voltage U_{start} is the lowest threshold for the permitted operating voltage at startup. It represents a minimum value including a possible ripple at startup.

4.8.3.2 Test

Apply the test pulse as specified in Fig. A2 to all relevant inputs of the device under test. The following diagram and table show the values of the test pulse.

The voltages are applied at the terminals of the device under test, if not otherwise specified.

Table 2
Voltage profile of the starting pulse[a]

$U_{\min}$ (V)	U_{start} (V)	t_r (ms)	t_6 (ms)	t_7 (ms)	t_8 (ms)	t_f (ms)
18	21	5	15	50	500–20 000	100

[a] See Section 3.3.3, Part 1.

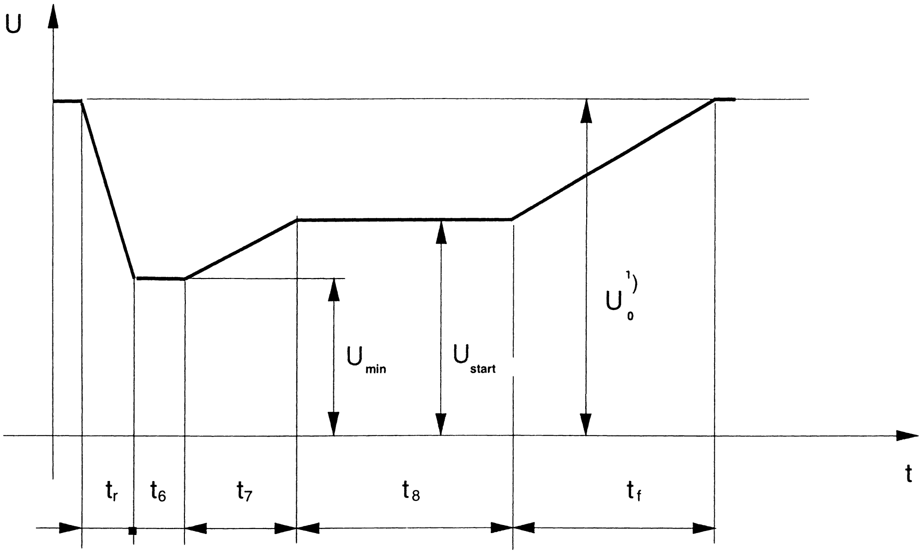

Fig. A2. Profile of the starting pulse. This figure corresponds to Fig. 7, WGS/WD 03/2000-2.

Extraction 6

4.9 Reversed voltage

4.9.1 Purpose

Aim of this test is to check the resistance of the device under test against the connection of a reversed battery in case of using an auxiliary starting device.

4.9.2 Test

Apply a negative voltage to all relevant inputs of the device under test. Values:
$U_T = -2$ V
$t \leq 100$ ms
$R_i \geq 1$ mΩ

4.9.3 Reverse polarity protection

In order to cope with the values defined in Section 4.9.2s, the implementation of a reverse polarity protection is recommended for the 42 V powernet. Design and test to be agreed upon between supplier and manufacturer.

Extraction 7

4.10 Short circuit protection

4.10.1 Electronic equipment in the 42 V powernet

Inputs and outputs (without load circuits) of electronic equipment in the 42 V powernet shall have a short circuit protection against U_{PN} and ground (with active and inactive outputs, without voltage supply and/or with ground) as given in the specification of the device under test.

4.10.1.1 Requirement

Functional status as defined in Part 1 of the standard shall be given in the specification of the device under test.

4.10.2 Load circuits in the 42 V powernet

All outputs shall withstand the currents as ensured by the corresponding protection. Values shall be given in the specification of the device under test.

4.10.2.1 Requirement

Functional status as defined in Part 1 of the standard shall be given in the specification of the device under test.

4.10.3 Short circuit from 42 V to other voltages

4.10.3.1 General

The short circuit protection and testing of electric/electronic equipment supplied with voltages differing from 42 V shall be as given in the specification of the device under test.

4.10.3.2 14 V/42 V dual voltage electrical system

The inclusion of an overvoltage protection in the 14 V system is recommended for a vehicle designed for a 14 V/ 42 V dual voltage electrical system. The maximum overvoltage protection level shall not exceed the maximum voltage level defined for the 14 V system (e.g. jump start).

For starting aid, a secure method must be developed.

4.10.3.3 Requirement

Functional status as defined in Part 1 of this standard shall be given in the specification of the device under test.

Extraction 8

4.13 Electromagnetic compatibility

The following EMC specifications are listed for reference. Performance measurements based on these specifications are not the requirements of this standard, if not otherwise specifed.

- ISO 7637-1, -2, -3
- ISO 11451-1, -2, -3, -5
- ISO 11452-1, -2, -3, -5, -6, -7
- CISPR 25
- CISPR 12
- ISO 10605

The applicability of this standards to the 42 V powernet is still under discussion and investigation.

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