Application of an Auction based Automotive Power Network Management

Einsatz eines Auktionsbasierten Fahrzeug-Bordnetzmanagements

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Abstract — Due to the rising complexity and the demanded modularity for the automotive power network (APN), there is a growing need for a distributed and flexible automotive power network management. Recently, we presented a power management which incorporates auction theory in order to achieve distributed decision-making and to ensure scalability and fault tolerance. Thereby, the approach addresses modern APNs with multiple voltage levels and utilizes service-oriented architecture (SOA) for communication. This paper demonstrates the update mechanisms needed to facilitate a plug-and-play integration of new components and the application of customer preferences. We explain the steps regarding startup and update procedures in the SOA which enable the plug-and-play property of the proposed approach. Additionally, the possibility to introduce energy saving strategies is elaborated.

Zusammenfassung — Aufgrund der steigenden Komplexität und der geforderten Modularität von Fahrzeug-Bordnetzen gibt es einen wachsenden Bedarf für ein verteiltes und flexibles Bordnetzmanagment. Ein entsprechendes Bordnetzmanagement wurde kürzlich vom Autor vorgestellt. Dieses Bordnetzmanagement benutzt Auktionstheorie, um damit eine verteilte Entscheidungsfindung zu erreichen und Skalierbarkeit und Fehlertoleranz sicherzustellen. Das Verfahren ist für moderne Fahrzeugbordnetze mit mehreren Spannungsebenen ausgelegt und nutzt eine Service orientierte Archtiktur (SOA) zur Kommunikation. In dieser Arbeit werden die Update Mechanismen dargestellt, die zur Ermöglichung der Plug-and-Play Integration von neuen Komponenten und zur Anwendung von Nutzereinstellungen benötigt werden. Dazu werden die Schritte beim Start und die Vorgehensweise bei einem Update in der SOA erklärt, welche die Plug-and-Play Eigenschaft des Systems gewährleisten. Des Weiteren wird die Möglichkeit zur Integration von Energiesparstrategien beschrieben.

I. Introduction

The growing number of components in the automotive power network (APN) increases the vehicle complexity and confronts manufactures with great challenges [1], [2]. Furthermore, development cycles for software are shortening and the software level needs to be more flexible then ever to meet the need for customization [3]. On the other hand, environmental concerns and cost reduction call for a sustainable and comprehensive development of hardware systems [4]. Hence, update cycles for software and hardware domain are deviating. Additionally, the upgrade of vehicles with new hardware components, for instance regarding autonomous driving, calls for plug-and-play features of new components. The flexibility and modularity in the overall vehicle is guaranteed by a distributed design of the power management system. Therefore, we presented a power management shell (PMS) based on auction theory for modern vehicle topologies [5].

In Fig. 1 an exemplary modern APN with two voltage levels is shown. As a basis, the APN compromises the electric machine (EM) (48V Starter Generator), the energy storages (48V Battery, 12V Battery), the power electronics (PE) (DC/DC), and the wiring harness. For vehicles with (additional) electric propulsion, the loads powered by the APN are divided on the highest level into propulsive (EM) and nonpropulsive loads (48V Electrical Loads, 12V Electrical Loads). Thereby, the APN in Fig. 1 is usually applied to a hybrid electric vehicle (HEV) which uses the EM to boost driving operation and to regenerate energy by recuperation. Depending on the applied EM, the propulsion mostly poses the highest requirements in terms of absolute power consumption and power transients. The nonpropulsive loads differ in critical or safety-relevant components and comfort or hotel components [6]. A further load property for differentiation is the controllability. While some loads are continuously controllable by PE, others may only be switched in discrete steps. For further information about the APN and vehicle topologies we refer to [4].

Fig. 2 gives a simplified overview on the different management level within the control system of the APN [7]. Thereby, the PMS is the mid-level management which is embedded by the energy management shell (EMS) as the top level management and the power electronics shell (PES) on the bottom. The EMS determines the energy flows in the vehicle with respect to the different energy sources. Since the EMS plans the energy strategy, it has

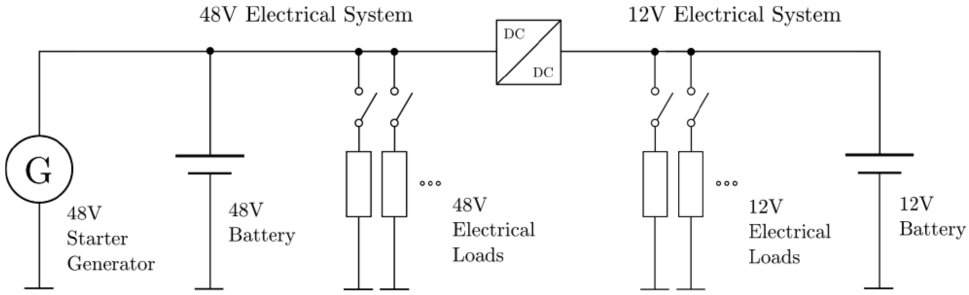

Fig. 1. Modern APN with two voltage levels and various subsystems.

update cycles in the range of seconds. The PMS coordinates the power flows based on the energy strategy and the current availability of power. Hence, the PMS is of high importance in phases of exorbitant power demand. The PES is responsible for the control of the actual power flows and the stabilization of demanded voltage levels.

In the following Section 2, we introduce the proposed power management approach which makes use of SOA as the communication paradigm to facilitate modularity and fault-tolerance [5]. In order to achieve the plug-and-play property, the proposed algorithm for the PMS based on auction theory is extended by an update mechanism. Subsequently, we discuss options for energy saving strategies within the APN and argue the capability of the approach in Section 3.

II. Power Management based on Auction Theory

The proposed algorithm for the PMS is based on the unified pricing auction (UPA) [8] and builds the foundation for the underlying voltage stabilization by the PES (see Fig. 2). A detailed description of the algorithm which extends the initial ideas in [9] and [10] is elaborated in [5]. The basic idea is to calculate the supply and demand in the APN with regard to the current price for power p. Thereby, the price p is determined by the capability of the suppliers, for instance the EM, and the current demand of the power consuming components.

A. Basic Algorithm

To balance the provided and demanded power in the APN, the different components communicate with a central auctioneer which accumulates both sides and calculates the price p for the next time step k (see Fig. 3). The algorithm starts with an initial price p_{init} and is repeated for every time step k with the previous market clearing price $\text{MCP}(k-1)$. For a smooth calculation, the price-to-power functions (PPFs) are designed monotonically increasing for the suppliers and monotonically decreasing for the consumers. Furthermore, for monotonic PPFs, an intersection between supply and consumption is guaranteed

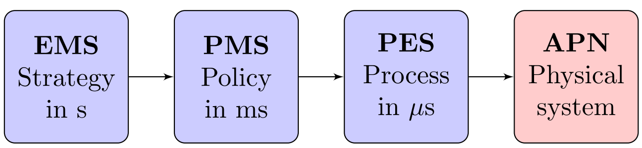

Fig. 2. Management levels in APNs adapted from [7].

[10]. In case of various voltage levels which is common in modern cars, the dc/dc-converter limitations in terms of power transfer $P_{\text{PE,lim}}$ between the voltage levels $\mathbb{V}$ have to be taken into account. Thus, an individual price adaptation mechanism is needed. If the limit of a PE in the PES is exceeded, the voltage level price p^j in the supplied voltage level $\mathbb{V}_j$ is adapted accordingly. Thereby, the individual sum of supply and consumption in $\mathbb{V}_j$ needs to be calculated. If the sum is below the PE limitation, the individual market price adaption for p^j is terminated. The adjustment for the voltage levels is proceeded until all the PE limitations are met.

The stability and scalability of the suggested auction procedure for the PMS is ensured by the price ranges for the individual design of the PPFs (see Table I). The maximum market price $p_{\max}$ is set to 10. Since the market price is expected to be positive, the resulting price range is $p \in [0, 10]$. Table I lists the price intervals and the abstract interpretation regarding the component behavior. The plug-and-play property of the power management algorithm relies on the compliance of these mandatory boundaries.

For Δp_{rec}, the EM is or has recently been in recuperation mode. In order to convert as much kinetic energy as possible, the various systems and comfort components are asked to consume extra power. Thereby, more energy is converted or the battery charging current is reduced which overcomes the limitations of the PE and the battery storages or mitigates the strain on the battery [11]. If the APN is not able to consume or store the provided electric power ($p = 0$), the EM will reduce the recuperation and braking moment is shifted to alternative braking systems. In the optimal range Δp_{opt}, the operation of the subsystems is optimized regarding energy efficiency and comfort of the driver and the passengers. In the following price range Δp_{red}, the components referring to comfort functionalities are demanded to reduce their power consumption. Hence, the power is mainly balanced by demand reduction. The last price range Δp_{crit} depicts the critical APN state. In Δp_{crit}, all comfort systems are switched off and the APN operates in emergency mode. Thus, only safety-relevant systems are supplied which ensures a safe driving operation and the possibility to safely stop the car if necessary.

B. Customization of Price-to-Power Functions

The suggested price ranges shape the underlying rules for the individual PPFs. Thereby, every component has its

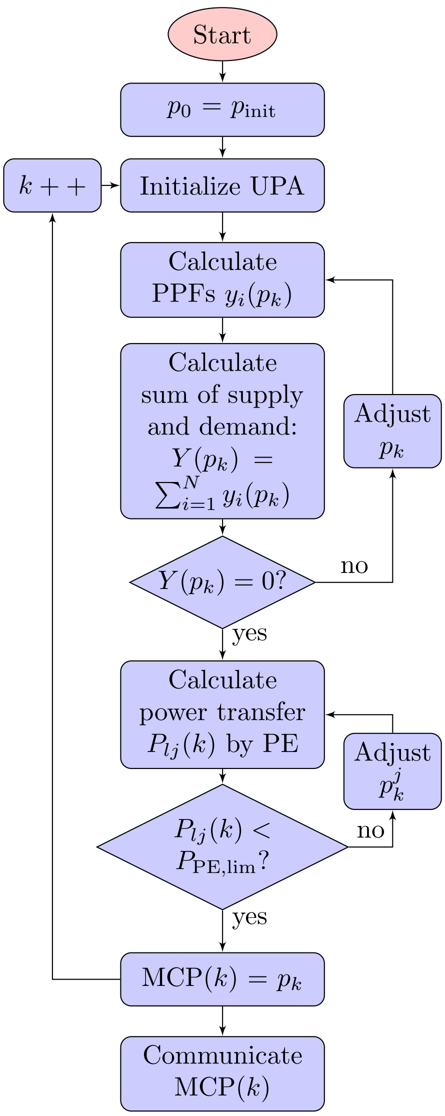

Fig. 3. Modular PMS based on UPA with the adaption for multiple voltage levels $\mathbb{V}_j$ and the consideration of PE limitations $P_{\text{PE,lim}}$.

own PPF which takes into account the individual component states and maybe the driver's or passengers' preferences. However, the price ranges in Table I describe mandatory specifications for every PPF which are important in particular for emergency situations. The plug-and-play feature for new components is ensured by considering these underlying rules in the individual PPF design.

The behavior in certain price levels depends on the general functionality of the component and the user preferences. An example for a PPF of a supplier system in the

TABLE I. Price ranges and component behavior as mandatory specifications for the PPF design in order to achieve the plug-and-play property of the overall algorithm.

Range	Variable	Interpretation
$[0, 2]$	Δp_{rec}	Recuperation mode
$(2, 6]$	Δp_{opt}	Adaptive power supply
$(6, 8]$	Δp_{red}	Reduced comfort
$(8, 10]$	Δp_{crit}	Critical APN status

APN is demonstrated in Fig. 4. Since the battery is a storage system, it acts as supplier or consumer depending on the internal states and the state of the power network. Here, the state of charge (SOC) is the most important state regarding the general functionality. As shown in Fig. 4, the battery PPF accounts for the necessity of charging when the SOC is low and offers power to the APN for a higher SOC. With regard to the boundaries, the battery is only a power supplier (SOC = 1) or a power consumer (SOC = 0), respectively.

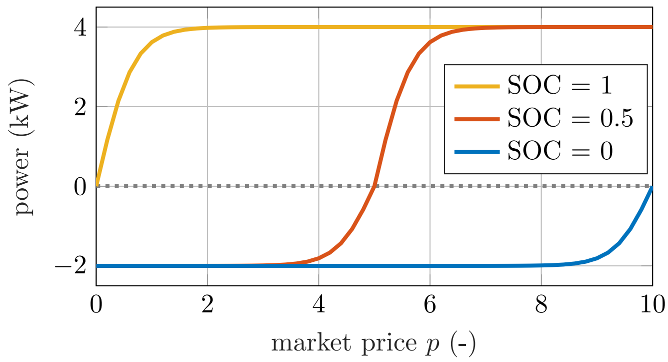

Fig. 4. PPF customization for the battery with different SOC levels.

The seat heating is a comfort component which has a flexible power consumption due to the heat capacity of the seats. If the available power in the APN is restricted, the seat heating could be switched off in order to reduce the consumed power. On the other hand, for recuperation phases, the seat heating is able to consume additional power. Both operations are possible without comfort reduction for the passengers since the heat capacity of the seat prevents the seat temperature from leaving the comfort zone around the set point in the short term. An exemplary design of the seat heating PPF is visualized in Fig. 5. As the seat heating system is a power consumer with discrete power steps, the power control causes more challenges to the auction mechanism [10]. To achieve a smooth market price calculation, the depicted seat heating PPF comprises linear transitions between the discrete power level steps and a hysteresis to prevent iterated switching (see the blue lines in Fig. 5). In general, the exemplary seat heating system consists of three power levels. For the recuperation phase which offers extra power, the highest seat heating level is chosen. The power level of the mid-term market price range refers to the level which is set by the passenger. If the price p exceeds the price limit p_{red}, the power level is reduced.

C. Communication, Startup, and Update Mechanism

The general decision about communication approaches based on SOA for the implementation of the distributed power management is explained in [5]. In this contribution, the event-based communication which collects all the information within the central market place is further elaborated and extended with an update mechanism. With the knowledge about the PPFs and the system states, the central auctioneer has the necessary information to directly calculate the MCP (see Fig. 3).

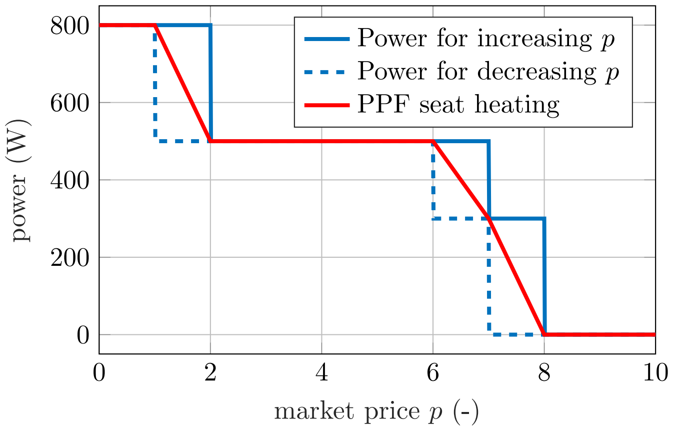

Fig. 5. The seat heating PPF in red and the actual power levels with hysteresis in blue for an increasing p (solid line) and for a decreasing p (dashed line).

For each change regarding the PPFs or the internal states of the components, the central auctioneer has to be informed. Particularly, the internal states need to be updated regularly since they dynamically change during operation. For a smooth behavior in terms of power balancing, the different components with switching behavior, for example seat heating, blowers, or wipers, need to be coordinated. Otherwise, due to the hysteresis, the difference between the calculation for the UPA algorithm and the actual power demand would grow with the number of switching components. Therefore, the price ranges Δp_{rec} and Δp_{red} in which the switching occurs are divided in sections corresponding to the number of power steps. Furthermore, the power difference between the steps could be considered in the update mechanism so that the power reduction is even in the intervals. A major factor in the update process for the sectioning are the user preferences. Thereby, the allocation of the sections correlates with the priority of the components. If a component in the APN is ranked with a higher priority, it will be switched off later and vice versa. Hence, the driver is able to customize the behavior of the power management with regard to the individual preferences. The update mechanism for the hysteresis is performed whenever a component changes its behavior, for instance if a passenger selects a new step for the seat heating. New components in the APN are automatically considered in this procedure.

D. Energy Efficiency and Energy Saving

In general, energy efficiency is a task on the component level. Thereby, the individual component or system in the APN should be designed to fulfill its tasks with a minimum effort regarding communication, computation, and power consumption [4]. As an example, the electrification of the heating ventilation and air conditioning (HVAC) system leads to various improvements in terms of component efficiency and adds flexibility to the APN [11]. Additionally, the electrification enables further possibilities on the system level, for instance the start-stop mechanism which facilitates the vehicle to stop the traction motor(s) in a waiting phase without stopping the HVAC. The utilization of extra energy in phases of recuperation which makes use of the flexible loads is another possibility that is already considered in the proposed algorithm (see Δp_{rec} in Table I). Here, the prediction of the future driving situation offers further potentials for optimization on component and on system level [11].

However, energy savings make only sense if the driver or passenger preferences are taken into account. Thus, driver and passengers should get useful hints for energy saving settings within the customizable preferences. Whereas, an artificial restriction of power in the APN in order to switch off comfort components which is suggested in [10] only results in dissatisfied customers in the long run.

III. Conclusion

Modularity and flexibility are important factors for modern vehicles which are enabled by the proposed power management algorithm based on auction theory [5]. Thereby, we explain the basic algorithm design and the customization in terms of adaptable PPFs which take into account the internal states and the driver preferences. To achieve the plug-and-play feature regarding the inclusion of new components, a suitable startup procedure and an update mechanism for components with switching behavior is elaborated. The update mechanism which allocates the power steps of the switching components for smooth load reduction is applied regularly during operation. Furthermore, we present different strategies for energy efficiency and energy savings which are partly considered in the proposed algorithm or could lead to further improvements.

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