論文 Concept of Vehicle Electric Power Flow Management System (VEF)*

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Increasing electric loads in a vehicle causes over-discharge of a battery and drag torque due to an alternator. This paper gives a system concept of vehicle electric power flow management to solve these issues. Its primary function includes preserving electricity in a battery, stabilizing electric bus voltage, interfacing with vehicle torque control system, and improving fuel economy.

The key point to realize such a system is a unified structure. It offers 'Plug and Play' function for electric power management components. Newly developed Vehicle Electric Power Flow Management System (VEF) totally controls electric power flow in a vehicle. VEF contains an Electric Power Manager and its functional sub-systems, and controls them with the key parameter 'electric power'. The sub-system includes Generation, Storage, Conversion, and Distribution to the loads. While sum of power required by electric loads exceeds a capacity of Generation and discharge of Storage, some electric loads are forced to reduce. These loads are selected according to the sum of required electric power and priority based on the load operating conditions. As VEF has a unified structure, it can be extensively applied for newcomer generators, batteries and loads in various categories of vehicles.

VEF is evaluated with a test vehicle, and the results show that overall experiments are positive, including bus voltage stability and loads limitation with acceptable driver's feeling.

Key words : 'Plug and Play' function, Vehicle Electric Power Flow Management System, VEF, LPI, EEI, UML

1. INTRODUCTION

Electrical loads in a vehicle will be increased up to 2kW to 3kW in the future, because many auxiliary units will be driven by electricity, not by engine mechanical power nor by hydraulic power, and some amenity equipment such as seat heater, ventilated seat and steering heater will be spread.[1] As a design method of vehicle electric power supply is not well established, much adaptation would be required to optimize the power supply for such vehicles. Another point is that reliability of power supply will be strongly required, when x-by-wire and security systems are introduced in the vehicles. However, today's power supply design doesn't meet all of these requirements.

The purpose of this paper is a restructuring of the vehicle electric power system design for stable electric power supplies. Functions of power supply are categorized into one Electric Power Manager and four subsystems: Generation, Storage, Conversion, and Distribution to the loads. VEF is newly developed to combine these subsystems and to interface with other system controls by using a unified structure, which means 'Architecture for electric power control'. VEF concept shows the following features:

- 'Electric power' is selected as a key parameter to control VEF.
- Load Priority Index (LPI) is applied to preferentially distribute electricity to the important loads, when electricity is shortage.
- Electric Power Economy Index (EEI) is introduced for coordinating affordable power source to improve fuel economy.

2. PROBLEM ANALYSIS

A common control of today's electric power supply is structured based on a voltage feedback concept. A regulator of an alternator measures a bus voltage and compares it with reference value. An amount of electric power generation is feedback controlled so as to reduce the differences (**Fig. 1**). In this control structure, electric loads are treated as disturbances, and those electric loads withdraw electricity from the bus as much as they need at any time. This structure causes several problems as follows:

- Empty of battery: As electric loads are out of controls from the vehicle electric power supply system, battery discharges to be empty when the amount of generated power is smaller than that of load power.

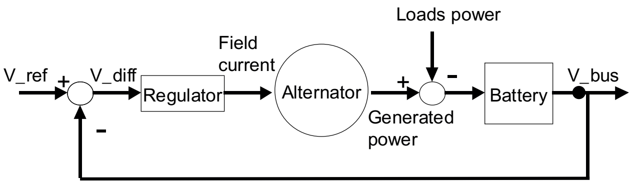

Fig. 1　A common control of electric power supply

- Bus voltage drop: As the same reason above, bus voltage will decrease when the amount of load power is large, and malfunctions occur in some loads.

- Drag torque: Because of the voltage feedback control, the amount of generated power equals that of load power. Therefore a torque used by the alternator to generate electricity changes widely according to the amount of load power. For example, 30 [Nm]- engine torque at idle speed is required when the amount of loads equals 2 [kW]. This value cannot be negligible compared to the maximum of the engine torque 100-150 [Nm].

- Shut down of important loads: As every load can withdraw electricity from the bus without distinction, important loads also stop working when the electricity is shortage. Concerning a reliability of electric power supply, an introduction of x-by-wire system raises problems.

- Fuel economy degradation: The amount of generated power normally equals that of load power at any time. This means that electric power is going to be generated even though efficiencies of the engine and alternator are worse. In such a case, more fuel is required to generate electricity and fuel economy deteriorates.

3. CONCEPT OF POWER SYSTEM RESTRUCTURING

The problems above are caused by the fact that power supply controls only power generation as a supply side and doesn't control load power. Therefore, loads, which mean a demand side, should also be considered to restructure the power supply system. The whole power system is restructured with VEF, whose function is categorized into one Electric Power Manager and four subsystems: Generation, Storage, Conversion, and Distribution to the loads. 'Electric power' is selected as a key parameter to control Electric Power Manager and its subsystems (**Fig. 2**). This idea comes from 'Torque' based control, which becomes popular among powertrain control and vehicle dynamic control.[2)3)]

Furthermore, as a target scope of the electric power control will be wider and an importance of power control will be raised, its software size will be increased, and it'll take more time to maintain and modify the software. Therefore, at the beginning of VEF development, an architecture that leads object oriented software structure has been developed for reusing software, improving maintainability and so on.

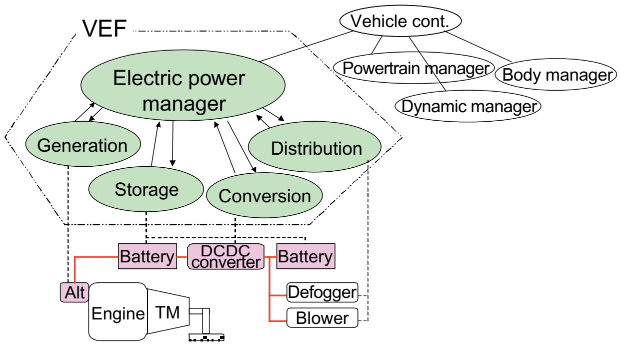

Fig. 2　VEF and related control systems

4. DESIGN

4.1 Requirements

At the first step to restructure the electric power control, requirements for the power system have been analyzed with UML (Unified Modeling Language).[3) 4) 5)] **Figure 3** shows a use case diagram of UML. Main customers of the power system are electric loads, driver, engine, vehicle and regeneration.

These customer's requirements are then broken down into the power system functions as shown in **Fig. 4**. Electric Power Manager combines the subsystems to realize these functions. Features of these control functions are bus voltage stabilization based on battery charge/discharge power limitation, electric power distribution based on LPI and power source coordination based on EEI.

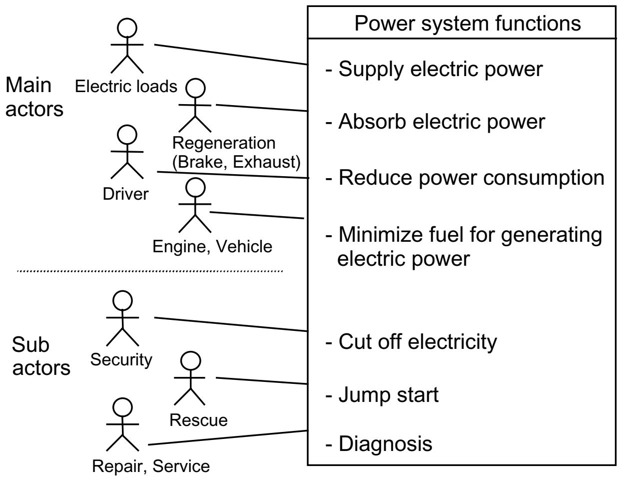

Fig. 3　Use case diagram

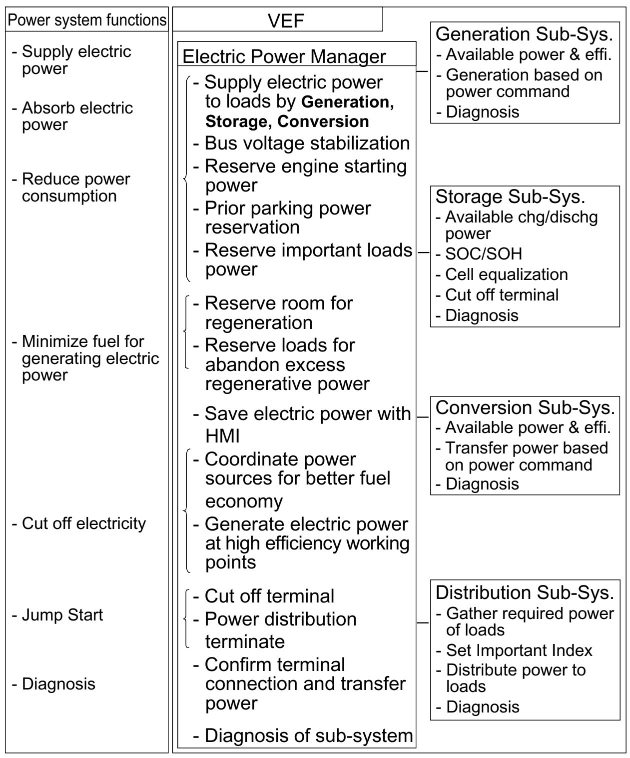

Fig. 4　Power system functions

4.2　Features

4.2.1　Bus voltage stabilization

Bus voltage is clumped with a terminal voltage of the battery, and its terminal voltage is changed according to charge/discharge electric power of the battery at the moment. Therefore, quantity of charge/discharge of the battery is set to be a control parameter to maintain bus voltage in a certain level. When a target voltage range is given to Storage subsystem, available charge and discharge of power are to be calculated.

These limits of electric power are treated as the available power of the battery at the moment. The left figure of **Fig. 5** shows a relationship between a battery charge/discharge power and battery terminal voltage. For example when a lower limit of the bus voltage is given, maximum battery dischargeable power to keep the bus voltage above lower limit is defined according to the battery characteristics. The right figure of **Fig. 5** shows an electric power balance of supply and demand side. Available supply power is defined as a sum of the battery dischargeable power and the generation power. If sum of loads power overcomes the available supply power, then the loads should be limited to maintain the bus voltage. Detailed control strategy of load limitation will be shown in the next section.

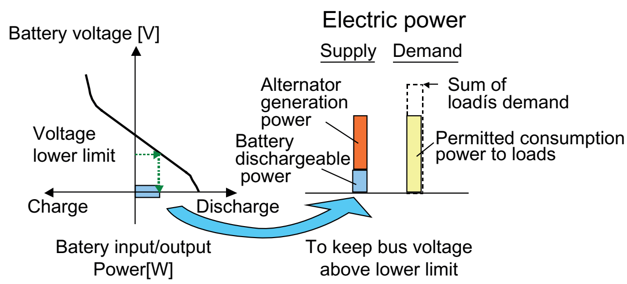

Fig. 5　Bus voltage stabilization

Electric Power Manager controls Generation and Distribution subsystem so as to keep charge/discharge of the battery within these limits. These limits are also changed according to a state of charge (SOC), a state of health (SOH) and a temperature of the battery. As these values are changed slowly, the bus voltage can be stabilized.

4.2.2　Electric power distribution (Demand control)

Electric power distribution is integrated in VEF to limit loads power for stabilizing the bus voltage, reserving electricity for important loads, saving energy for eco-driver and so on. Firstly, required power of the loads and their LPI (Load Priority Index) are gathered in the Distribution subsystem (**Fig. 6**). When Generation subsystem reaches upper limit of the electricity supply, the total permitted power to loads is forced to reduce by Electric Power Manager. Then Distribution subsystem distributes electric power to each load according to LPI. LPI is normalized between zero and one. As important loads such as x-by-wire system have higher LPI, electric power is distributed to these loads preferentially and minimize malfunction of such important loads. Usually high power loads and important loads have their own controllers, it can be realized to gather information of required power and LPI from the controllers through vehicle information network, and force to reduce its power according to the permitted distributed power that Distribution subsystem commands.

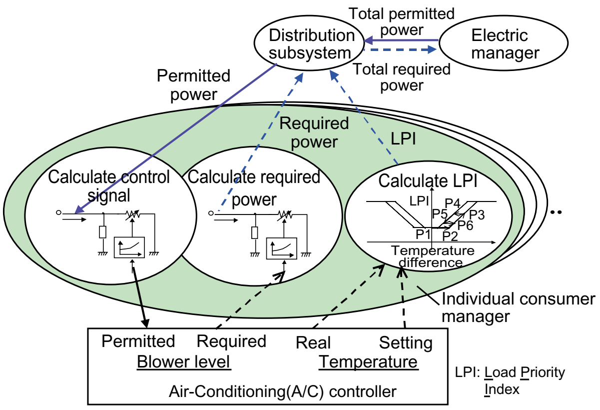

Fig. 6　Distribution subsystem

During the load power limitation, electric power is distributed to each load periodically to avoid stopping certain loads in a long run. For example, a defogger and a mirror heater are distributed electric power alternately. This changeover is also base on LPI. For example, LPI of feed forward-controlled-load such as defogger is changed periodically, and LPI of feedback-controlled-load such as an air conditioning system is changed according to its recent performance. When a difference between target temperature and real temperature is large, LPI is set to be high, and vice versa. As LPI is changed according to time and load performance, electric power can be distributed to each load to avoid stopping certain loads in a long run.

4.2.3　Power source coordination (Supply control)

As there are a lot of power source in a vehicle such as power generation with an alternator, battery discharge and power transfer from another bus with DCDC converter, power source coordinate method based on EEI (Electric power Economy Index) has been developed (**Fig. 7**). EEI is a fuel economy index for unit electric power, and its unit is [g/kWh]. For example, EEI of power generation with the alternator is calculated based on an engine fuel economy and an efficiency of the alternator. It varies according to the engine working points. EEI of battery discharge is calculated based on a charge history. If the battery is charged with economical EEI of power generation, EEI of battery will also be economical, especially when regenerative braking electricity is charged.

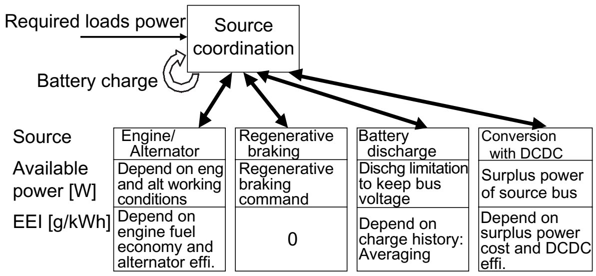

Fig. 7　Power source coordinator and EEI

An available power of each power source is also informed with each subsystem. For example, an availability of power generation is calculated based on an available torque of the engine and an available torque of the alternator at a present engine revolution number. If a drag torque by the alternator wants to be avoidable in a vehicle maximum acceleration, the available torque of the engine is set to be small. Then power generation becomes small, and the drag torque will also be small.

The power coordination works as follows. When the total required power of the loads is smaller than the amount of available power source, power sources with economical EEI are selected in due order. In case the amount of available power source is not enough, Electric Power Manager selects all power sources and reduces the total permitted power to Distribution subsystem.

4.3　Restructuring of the vehicle electric power system with VEF

The above functions are combined through the key parameter ‘electric power’ so as to make a generation and distribution commands. A schematic figure of VEF is shown in **Fig. 8**. The important functions such as the bus voltage stabilization, the power distribution and the source coordination are arranged firstly, and others are followed. As interfaces between Electric Power Manager and its subsystem are defined, subsystems are easily substituted and added. For example, a newcomer load such as a steering heater will be easily added with the common interfaces of ‘Required Power’, ‘LPI’ and ‘Permitted Power’. This structure offers ‘Plug and Play’ function.

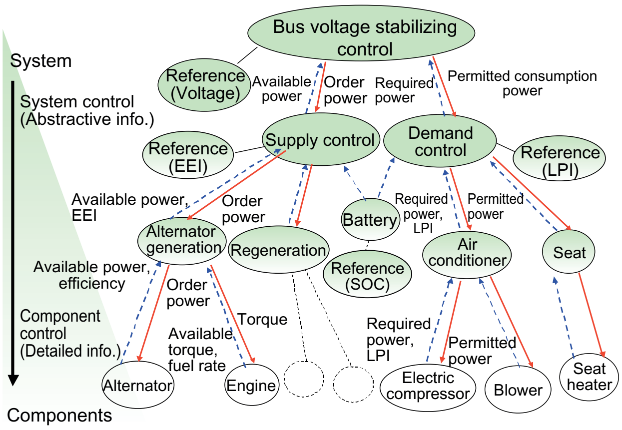

Fig. 8　Schematic figure of VEF

In addition, the software structure of VEF itself is based on 'class' and each function is divided into these classes. As the interface and a responsibility scope of each function is clearly defined, it's easy to reuse software when it is implemented into another vehicle and some options are added. **Figure 9** shows an object diagram of VEF.

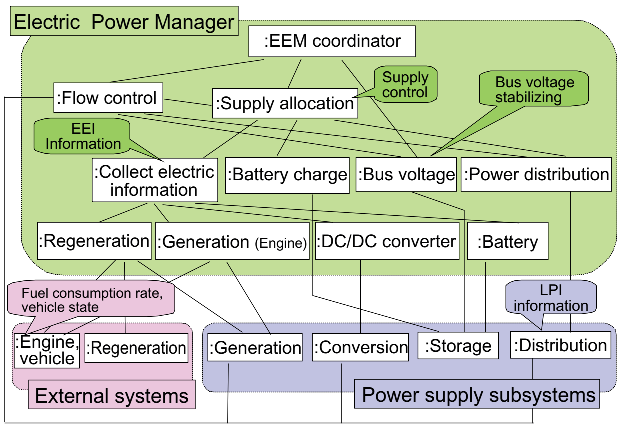

Fig. 9　Object diagram of VEF

5. RESULT

Distribution is one of the most important functions of VEF, because this part has been treated as disturbance in a common power supply and there has been no control structure as a subsystem of VEF. Therefore, this distribution function is firstly developed and evaluated with a test vehicle and a rapid prototyping system based on MATLAB/Simulink.

Figure 10 shows the power control performance. A thick solid line indicates the total required load power, and a thin solid line indicates the total permitted power calculated in Electric Power Manager. As the total permitted power equals that of required power within 25 second, a real power indicated with the dot line equals the required power. After 25 second, the total permitted power becomes smaller than that of required power, and the real power follows the total permitted power. The difference between the real power and the permitted power is within 50W.

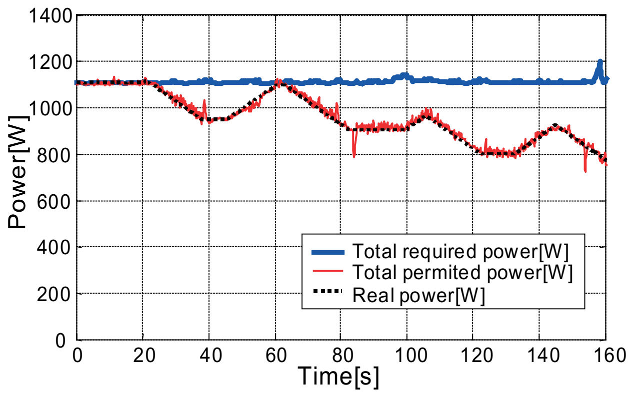

Fig. 10　Power control performance

Next, the bus voltage stability is evaluated with and without Distribution subsystem. The upper picture of **Fig. 11** shows that without Distribution subsystem the big voltage drop occurs when the amount of loads is large. The lower picture shows that the voltage drop is avoided by using the permitted power limitation, which is one of the VEF function.

Figure 12 shows that the electric power is distributed to each load periodically. A defogger and an electric fan are driven alternately with variable LPI to avoid stopping certain loads in a long run. In addition, a sensory analysis is concluded that more than 80% of experimental subjects accept 400W power reduction with LPI (**Fig. 13**). A condition of the test is that the alternator generates 800W at an engine idling revolution and the total required power is 1200W. If this situation continues, the battery will be empty within 75minutes. As Distribution subsystem limits the real distributed power to 800W, battery charge can be kept.

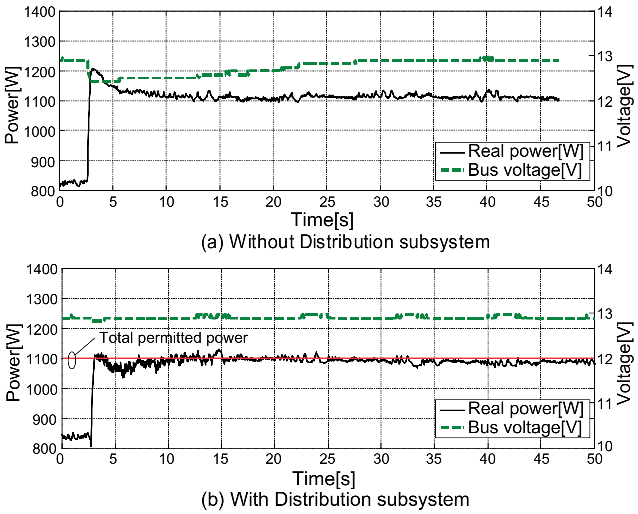

Fig. 11 Power limitation and bus voltage

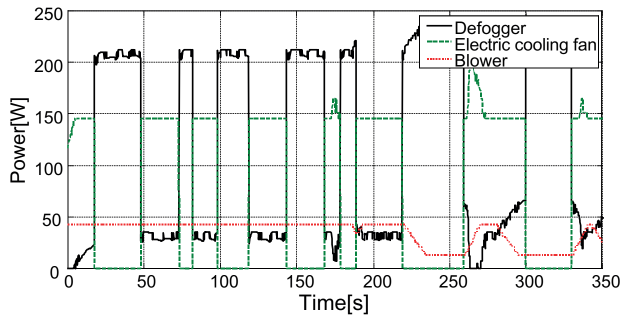

Fig. 12 Power distribution to loads

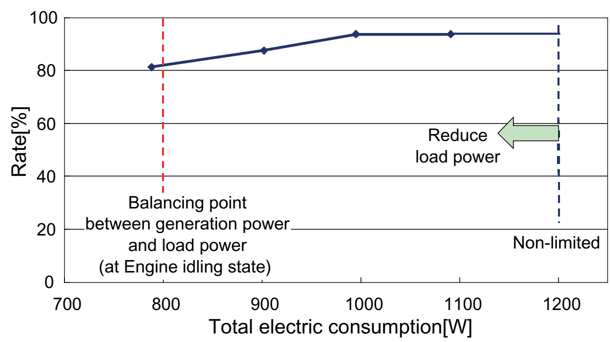

Fig. 13 Sensory analysis of distribution subsystem

The above four results confirm that Distribution subsystem offers bus voltage stability and preferential power supply according to LPI with acceptable feelings.

6. CONCLUSION

The restructuring of the vehicle electric power system is designed with newly developed VEF. Functions of the power system are categorized into one Electric Power Manager and four subsystems: Generation, Storage, Conversion, and Distribution to the loads. VEF combines these subsystems based on the key parameter 'electric power' and interfaces with vehicle system controls. VEF offers priority power distribution to the important loads with Load Priority Index (LPI) and improves fuel economy by coordinating the power source with Electric Power Economy Index (EEI). As this software structure is based on the object oriented 'class', it can offer 'Plug & Play' and it will be easy to reuse in other vehicles.

As distribution is newly built on power supply control and this part is one of the most important functions of VEF, this distribution function is evaluated with the test vehicle. The results show that the power control with LPI is positive, including bus voltage stability and loads limitation with acceptable feeling, and foresees that whole VEF will function. All functions are now being programmed in the test vehicle to evaluate especially EEI function. In the future with high electric power consumption, VEF will play a key roll to construct the vehicle electric power supply systems.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

VEF: Vehicle Electric Power Flow Management System

LPI: Load Priority Index

EEI: Electric Power Economy Index

UML: Unified Modeling Language

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