Construction of Highly-Accurate Simulation Model in Automobile's Power System

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Abstract: - In recent years, it is imperative to respond environmental problems and energy problems. Therefore, the automobile is required to improve fuel economy and develop environmentally-friendly know-how. Against the background of these, environmentally-friendly automobile is developed in the automaker. As a result, increasing electric technologies contribute promotion of electric loads in automobiles. These substantially increase electrical power consumption in automobiles. However, there is a limit of supplying electrical power generated by the alternator. Therefore, by understanding the behavior of electrical power, improvement of the stability of automobile's electrical power system and effective use of energy are expected.

The purpose of this study is construction of simulation model in the electrical power system of conventional automobile. The behavior of electrical power is measured by this simulation. Although the electrical power system of automobile has been estimated by experiment, it can be estimated by simulation. This simulation model includes power train model, alternator model, battery model and electric load model. Each model represents its own characteristic. This simulation model is simulated in a driving mode called 10-15 mode. And, the results are compared with measured results. In the result, this simulation model can provide high accuracy. The electrical power system can be evaluated by this simulation model without test runs.

Key-Words: - Automobile; Power system; Simulation; Power train; Alternator; Battery; SOC; Electric load

1 Introduction

In recent years, it is imperative to respond to environmental problems and energy problems. Therefore, the automobile is required to improve fuel economy and develop environmentally-friendly know-how. Against the background of these, environmentally-friendly automobile is developed in the automaker. As a result, the electric technologies are introduced and the electric loads in automobiles increase. These substantially increase electrical power consumption in automobile. However, there is a limit of supplying electrical power generated by the alternator. Therefore, by understanding the behavior of electrical power, improvement of the stability of automobile's power system and effective use of energy are expected [1-4].

Especially, the exhaust gas of commercial automobile is strictly regulated by legislation. Therefore, it is important problem that improvement in energy efficiency and fuel economy.

The purpose of this paper is construction of simulation model in the electrical power system of conventional automobile. The behavior of electrical power is measured by this simulation. This simulation model includes power train model, alternator model, battery model and electric load model. Each model represents its own characteristic.

This simulation model is based on previous research: 'Countermeasure for Stop Idling Policy for Automobile Power System', which discusses the simulation method of the automobile power supply system [1].

2 Power system of automobile

The electric and electronic equipments built into automobiles have increased. Therefore, many electronic control systems as well as lamp and windshield wipers are connected in the automobile. But, the elemental structure of automobile's electrical power system is the same as the structure of conventional automobile's electrical power system. The electrical power system of automobile is shown in Fig.1.

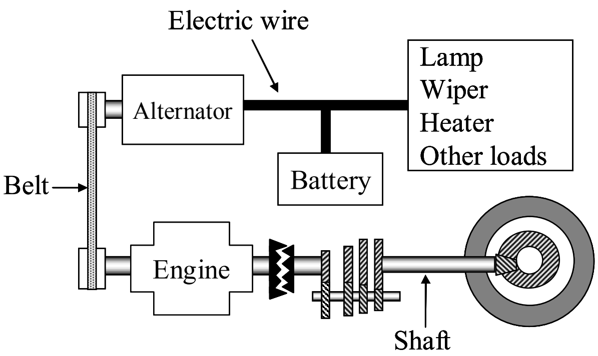

Fig.1 Power system of automobile

As shown in Fig.1, the electrical power system of automobile includes the power train, alternator, battery and electric load.

The power produced by engine is transmitted to the clutch. The clutch transmits or cuts the power. Then the power is transmitted to the transmission. The transmission changes vehicle speed by changing the gear. Then, the power is transmitted to the wheel, and the wheel rotate.

On the other hand, the power produced by engine is transmitted through the crankshaft and belt to the alternator. The alternator converts the mechanical energy into electrical energy, and it supplies the electrical power required by the other electrical devices. When the power generated by alternator is less than the power required by the other electrical devices, the battery supplies the shortage in the power to the devices. But, the alternator charges the battery while a normal cruising.

The alternator rotational speed changes because of the engine rotational speed changes every moment by the run situation. As a result, the generated voltage of alternator also changes. The regulator has the function of controlling the generated voltage of alternator, and the appropriate electrical power is supplied to the electrical devices and the battery [2,4].

3 Modeling

The electrical power system of automobile is divided into four elements, which are compounded from the power train, alternator, battery and electric load, and it is modeled. The electric circuit of automobile is calculated from these four elements, and the simulation model of automobile's electrical power system is constructed. This model is simulated using MATLAM/SIMULINK.

3.1 Power train

The mechanism of a driving unit from an engine to wheels is called a power train. The power generation of the alternator is affected not only by the electrical power system but also by the mechanical system. Therefore, modeling of a power train is required.

In the power train model, the engine rotational speed is calculated from the vehicle speed. In other words, the gear position is automatically decided by vehicle speed, and the engine rotational speed is calculated and output.

3.1.1 Driving mode

In this paper, 10-15 mode is used for the simulation of electrical power system. In Japan, this driving mode is often officially used to measure the fuel cost. This driving mode represents an average driving mode in urban area. Fig.2 shows the vehicle speed variation of 10-15 mode.

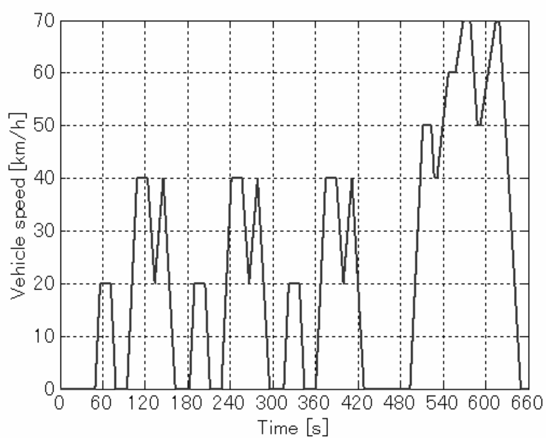

Fig.2 Vehicle speed variation of 10-15 mode

3.1.2 Gear change characteristic

The gear position is automatically decided from the vehicle speed. However, even at same speed, the gear position is different due to the condition of acceleration or deceleration. Therefore, the gear change characteristic is modeled by considering the vehicle speed and acceleration. In this paper, the transmission has 5 steps. Fig.3 shows the flowchart of gear change characteristic.

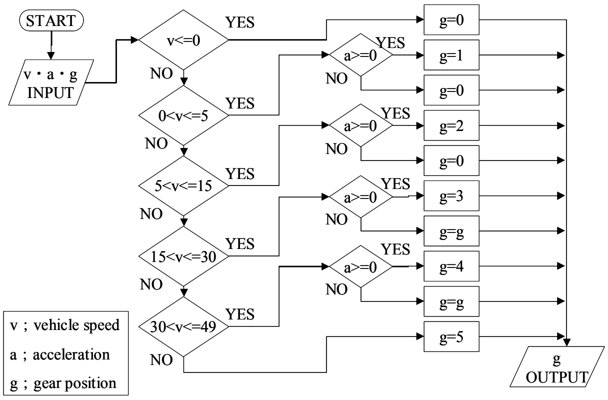

Fig.3 Flowchart of gear change characteristic

3.1.3 Calculation of engine rotational speed

As shown in Eq.(1), the engine rotational speed e_r[rpm] is calculated from the vehicle speed v[km/h], transmission ratio t_r and constant K. The transmission ratio is decided from the gear position. The constant K depends on the final reduction ratio and size of wheels. In this paper, the constant K is 34.2.

$$e_r = v \times t_r \times K \quad \cdots\cdots (1)$$

3.2 Alternator

An alternator is the power generation device which consists of a three-phase synchronous generator, a rectifier unit and a voltage regulator [6]. Fig.4 shows maximum output current of a typical 24V-60A alternator. As shown in Fig.4, the alternator has two characteristics, which are hot condition and cold condition. Maximum output current of the cold condition is larger than that of the hot condition. The reason is that the rotor coil resistance increases by heat and the field current decreases. So the magnetic flux density decreases and the power generation current also decreases. Normally, an alternator is driven under hot environment [2]. So in this paper, the maximum output current of hot condition is analyzed. In this paper, a 24V-50A alternator is used. Fig.5 shows maximum output current of hot condition of a typical 24V-50A alternator. In Fig.5, the alternator begins generating electricity from 900[rpm]. And the maximum output current is saturated with 46[A]. The alternator is driven by the engine, so the alternator rotational speed is dominated by the engine rotational speed. The pulley ratio from the engine to the alternator is about 2.0 to 2.5. For example, when the engine rotational speed is 600[rpm], the alternator rotational speed is 1500[rpm]. The pulley ratio is different according to the type of vehicle. In this paper, the pulley ratio is 2.1875. Regarding the formulation of alternator characteristic based on Fig.5, in Eq.(2), $f(r)$[A] is maximum output current where r[rpm] is alternator rotational speed.

$$f(r) = 46\left(1 - e^{-\frac{r-900}{1000}}\right) \quad \cdots\cdots (2)$$

Fig.6 is the graph of Eq.(2), where $f(r)$ is output current and r is alternator rotational speed.

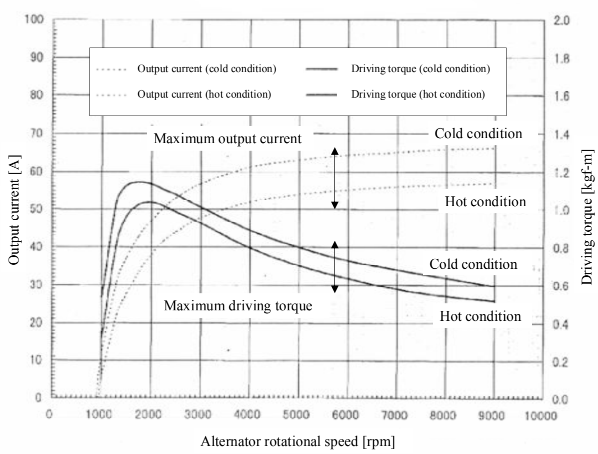

Fig.4 Alternator output characteristic (24V-60A)

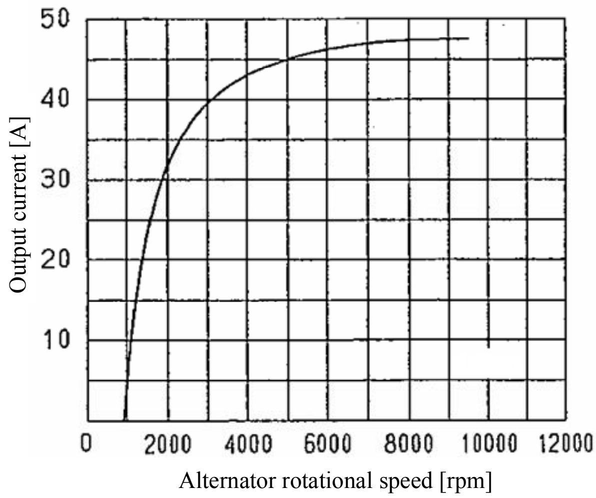

Fig.5 Alternator output characteristic (24V-50A)

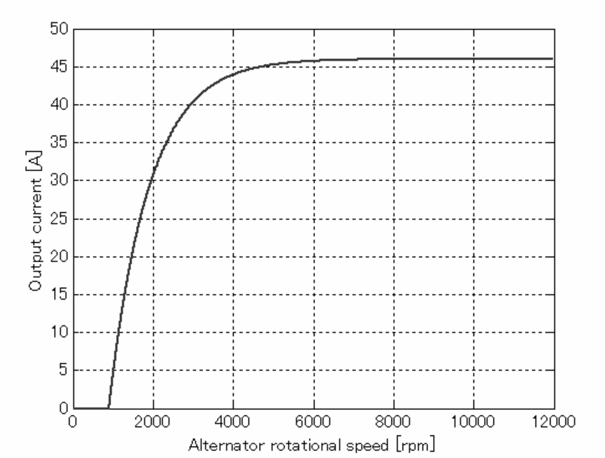

Fig.6 Alternator model characteristic

The electromotive force of alternator is kept at about 28[V] by the regulator. However, the terminal voltage of alternator decreases as the output current of alternator increases. Fig.7 shows the measured result of voltage droop characteristic. In Fig.7, the rotational speed is the engine rotational speed. The terminal voltage of alternator decreases following constant slope. Therefore, the resulting alternator internal resistance is 0.0324[Ω]. If the output current of alternator reaches the maximum output current, the terminal voltage of alternator droops down. In this paper, the voltage droop characteristic is modeled by adding equivalent alternator internal resistance.

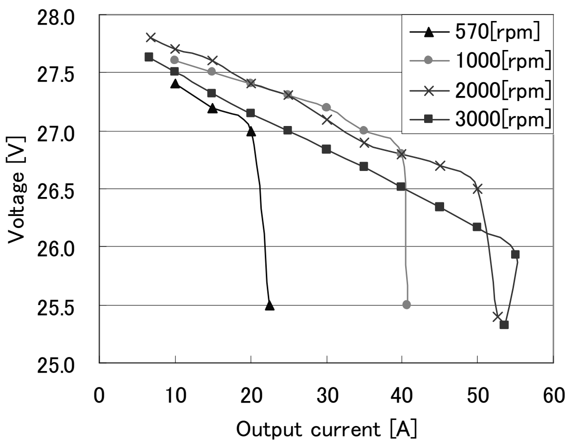

Fig.7 Measured result of voltage droop characteristic

3.3 Battery

The battery is an electrical storage device. It stores electrical energy generated by an alternator as chemical energy. And, it has the function that discharge by converting the chemical energy into the electrical energy as required. The battery is classified into many different types according to how to store the chemical energy. In automobiles, lead-acid battery is generally used [7,8].

The battery voltage varies by the state of charge (SOC), the ambient temperature, the charge-discharge rate and charge-discharge history [3,9-11]. In this paper, the battery model characteristic shown in Fig.8 is used. It represents the simple characteristic of battery, and the battery electromotive force depends on SOC. The SOC is defined by Eq.(3)

$$\mathrm{SOC} = \frac{\text{Remaining capacity [Ah]}}{\text{Full charged capacity [Ah]}} \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

The battery is full charged state when SOC = 1. The SOC decreases if the battery is discharged, and the SOC increases if the battery is charged. In this paper, the SOC is calculated by Eq.(4) [12].

$$\mathrm{SOC} = \mathrm{SOC}_{\mathrm{ini}} - \frac{1}{\mathrm{C}} \int_0^t I_b \, dt \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where I_b is the battery current, and the discharge current is positive value, $\mathrm{SOC}_{\mathrm{ini}}$ is the initial value, C is the total of electrical charge calculated from the battery capacity.

In this paper, the battery capacity is 52[Ah] and the initial SOC is 1.0.

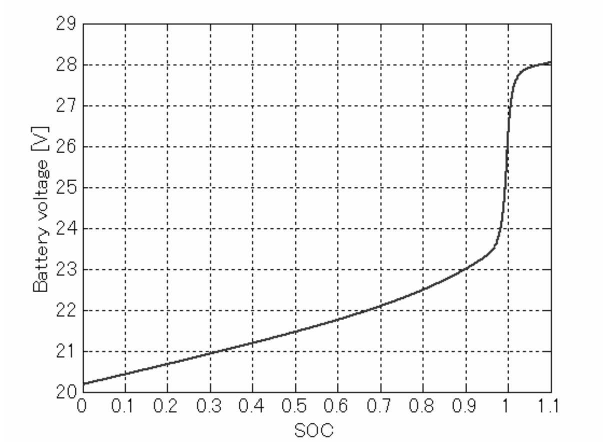

Fig.8 Battery model characteristic

3.4 Electric load

There are several electric equipments in the commercial vehicle. For example, those include lights, an air conditioner, and electric control systems. In this paper, those are modeled as equivalent resistance. The electric loads as shown in Table 1 are used in this simulation. R_1 is 1[Ω], which represents an interior lamp, an air conditioner, and a refrigerator on carrier.

R_1 is connected at all the time. R_2 represents the stoplight, and it is connected during deceleration and stop. R_3 represents the engine starter, and it is connected for three seconds before engine starting.

Table 1 Specification of electric equipment

R_1 (lights + air conditioner)	1[Ω], 580[W]
R_2 (stoplight)	15.4[Ω], 37.4[W]
R_3 (engine starter)	0.045[Ω], 5700[W]

3.5 Electric circuit of automobile

Fig.9 shows the electric circuit of automobile. It can be divided into three parts which are a battery, an alternator and electric loads. Each part is modeled as an equivalent circuit. Table 2 is symbols in Fig.9. In Fig.9, the electric circuit of automobile is numerically analyzed using a node equation with an admittance matrix.

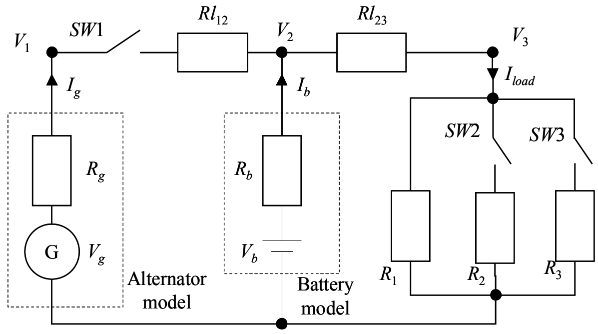

Fig.9 Electric circuit of automobile

Table 2 Symbols in electric circuit of automobile

V_g	alternator electromotive force
V_b	battery electromotive force
V_1	alternator terminal voltage
V_2	battery terminal voltage
V_3	load terminal voltage
I_g	alternator current
I_b	battery current
I_{load}	load current
R_g	alternator internal resistance
R_b	battery internal resistance
R_1, R_2, R_3	load equivalent resistance
Rl_{12}, Rl_{23}	line resistance
$SW1$	reverse flow prevention device
$SW2$, $SW3$	load switch

4 Simulation model validation

The simulation model is validated by comparing simulation results with actual running data. In simulation results and actual running data, driving mode is 10-15 made, the battery capacity is 52[Ah]. In this simulation, the initial SOC is 1.0, the electrical loads are R_1 and R_2.

Simulation results are shown as follows. Fig.10 shows voltage fluctuation, Fig.11 is current fluctuation, and Fig.12 is SOC fluctuation. And, Fig.13 is voltage fluctuation of the measured result, Fig.14 is current fluctuation of the measured result.

In Fig.10, V_1 is the largest, and V_2 is less than V_1 by line voltage drop of Rl_{12}, and V_3 is less than V_2 by line voltage drop of Rl_{23}. As compared with Fig.10 and Fig.13, the two voltage waveforms show similar behavior.

As compared with Fig.11 and Fig.14, the each waveform shows similar behavior. The discharge current is positive value in battery current I_b. When the automobile idles, the electrical power generated by the alternator decreases, and the battery supplies the shortage in the electrical power to the electric loads. But the power generated by the alternator increases when running, and the alternator supplies electrical power to the battery and electric loads. Therefore, the load current I_{load} is relatively constant. The waveform in Fig.14 oscillates because of use of hazard indicator.

Fig.12 shows SOC fluctuation. The initial SOC is 1.0. The SOC decreases to 0.996 after cruising. Therefore, the quantity of electric discharge is more than that of charge in the battery.

To obtain the precision of this simulation model, it is required that the transient dynamics characterization and charge-discharge behavior of battery should be modeled in detail.

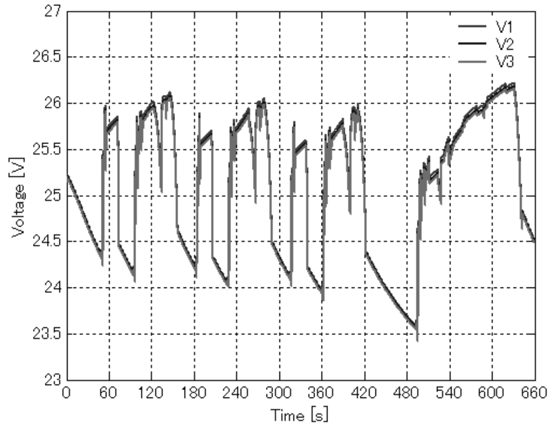

Fig.10 Voltage fluctuation (simulation result)

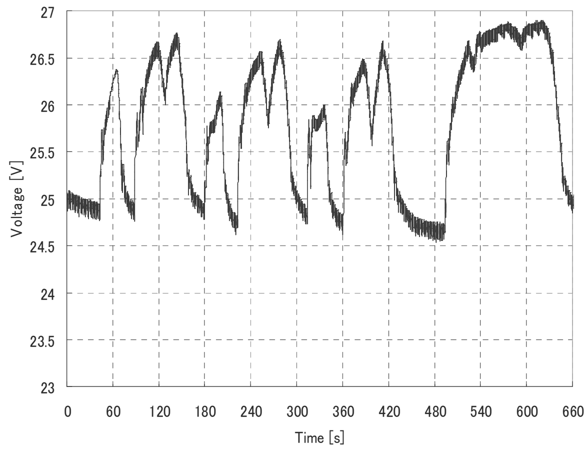

Fig.13 Voltage fluctuation (measured result)

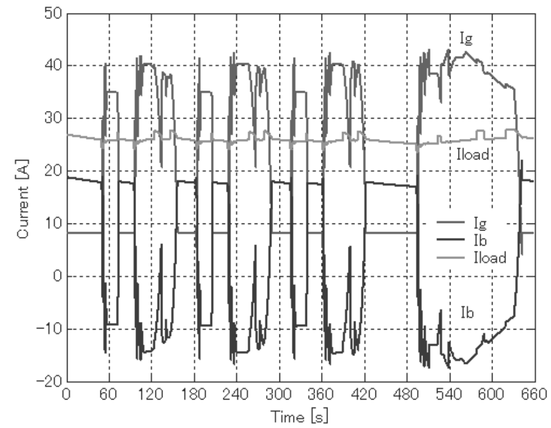

Fig.11 Current fluctuation (simulation result)

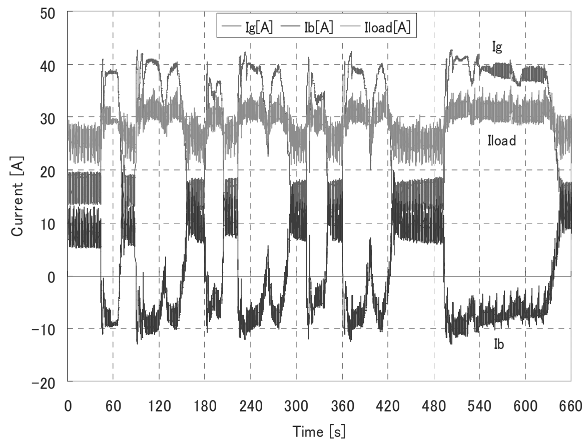

Fig.14 Current fluctuation (measured result)

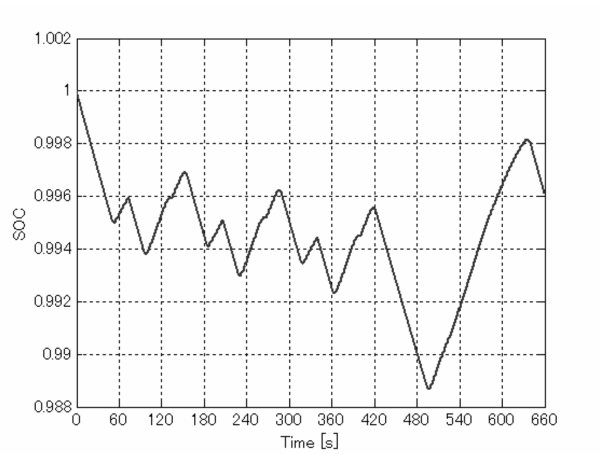

Fig.12 SOC fluctuation (simulation result)

5 Conclusion

Increasing electric technologies contribute promotion of electric loads in automobiles. They substantially increase electrical power consumption in automobiles. However, there is a limit of supplying electrical power generated by the alternator. Therefore, by understanding the behavior of electrical power, improvement of the stability of automobile's electrical power system and effective use of energy are expected.

In this paper, the behavior of electrical power is measured by simulation. The electrical power system of automobile is divided into four elements, those are the power train, alternator, battery and electric load, which are modeled and discussed in this paper.

The behavior of electrical power in 10-15 mode can be depicted by this simulation model. And this simulation model can provide high accuracy.

The electrical power system in the various driving modes can be evaluated by inputting the various driving modes. Therefore, the electrical power system can be evaluated by this simulation model without test runs. In the future, this simulation model can be served for the evaluation of energy management method of the automobiles such as hybrid automobile and electric automobile.

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