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VEHICLE ELECTRIC POWER SIMULATOR FOR OPTIMIZING THE ELECTRIC CHARGING SYSTEM

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ABSTRACT–The vehicle electric power system, which consists of two major components: a generator and a battery, which have to provide numerous electrical and electronic systems with enough electrical energy. A detailed understanding of the characteristics of the electric power system, electrical load demands, and the driving environment such as road, season, and vehicle weight is required when the capacities of the generator and the battery are to be determined for a vehicle. An easy-to-use and inexpensive simulation program may be needed to avoid the over/under design problem of the electric power system. A vehicle electric power simulator is developed in this study. The simulator can be utilized to determine the optimal capacities of generators and batteries. To improve the expandability and easy usage of the simulation program, the program is organized in modular structures, and is run on a PC. Empirical electrical models of various generators and batteries, and the structure of the simulation program are presented. For executing the vehicle electric power simulator, data of engine speed profile and electric loads of a vehicle are required, and these data are obtained from real driving conditions. In order to improve the accuracy of the simulator, numerous driving data of a vehicle are logged and analyzed.

KEY WORDS : Electric power system, SOC (state-of-charge), Battery, Alternator

NOMENCLATURE

K_a : alternator constant
Ω : flux density
ω : rotator angular velocity
R_a : alternator internal resistance
V_a : alternator open circuit voltage
I_a : alternator maximum current
v_a : alternator terminal voltage
i_a : alternator terminal current
V_{OC} : battery open circuit voltage
C_O : battery over voltage capacitance
R_c : battery charging resistance
R_d : battery discharging resistance
R_b : battery internal resistance
v_b : battery terminal voltage
i_b : battery terminal current
C_{20} : 20 hour battery capacity
I_{20} : 20 hour battery current
C_D : discretized battery capacity
ΔC_D : changes of discretized battery capacity
n : peuker constant
η : charging efficiency
i_l : load current
R_l : load equivalent resistance

1. INTRODUCTION

The customer requirements and expectations are the driving force behind the increase in electrical power demand, and must be the strongest influence in determining future strategy. The minimum expectation is that the car will start and run reliably, even under certain conditions of abuse. This criteria should form the basis of any power system design, ensuring that any load demand imposed on the vehicle will not cause failure.

Many electric and electronic systems have been continuously added in vehicles to meet various regulations and customer demands over the last decade in these days. As a result, the demand of electric power has substantially increased. Furthermore the idle time fraction while the vehicle traveling has been increased owing to heavy urban traffic conditions. It becomes more important to design an electric power system which supplies sufficient power to various apparatuses to guarantee normal operations of them.

In order for the entire system to be reliable and trouble-free in any operating condition, it is necessary that the

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electric power output from a battery and an alternator should be matched with the remaining electrical loads as optimally as possible.

An improper decision of the capacity of electric power system, such as the alternator and battery, will cause serious problems in real driving conditions. For example, if the alternator capacity is designed too small, cold cranking problems and roadside breakdowns may occur. On the contrary, over-design of alternator capacity will degrade fuel economy due to vehicle weight and loss of propulsion power, and it will increase the cost of the vehicles.

When the capacities of the alternator and the battery are appropriately determined, many conditions should be considered, such as vehicle types, weather conditions, driving conditions, electrical load demands, and others. The electrical load demand varies depending upon the weather and driving conditions, and also the maximum output current of the alternator varies according to the engine speed in real driving conditions. Thus, an easy-to-use simulation program, which is called VEPS (Vehicle Electric Power Simulator), is developed to analyze and evaluate such complicated relations.

Firstly, the modeling procedures of major electric power systems of a vehicle and the simulation algorithm, which is developed for this study, are described.

Next, the characteristics of the VEPS are described in detail to demonstrate how easily this program can be used in an analysis of the electric power system of a vehicle.

Finally, some simulation results are explained to show how the changes in driving modes and design variables affect the power system.

2. THE VEHICLE ELECTRIC POWER SYSTEM MODEL

In order to supply the electric power, vehicles need an efficient and highly reliable source of energy of their own which must always be available at any time. When the engine is running, the alternator becomes the on-board electricity generating plant, whereas, either when the engine stopped or when the alternator's output power is insufficient, the battery is the vehicles energy storage.

To simulate the vehicle electric power system, the major electric systems of a vehicle should be modeled appropriately. As shown in Figure 1, the electric system can be divided into three parts (battery, alternator, and electrical loads), and each part is modeled as an equivalent circuit.

The electrical power system is not just a collection of isolated components. The various loads consume power, the alternator provides it, and the battery buffers and stores it. There will be a high degree of component interaction during operation and, therefore, there should also be a high degree of interaction during the design stages.

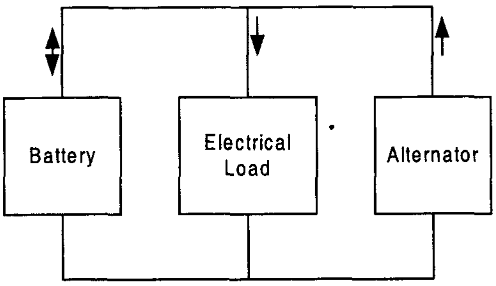

Figure 1. Diagram of supply/demand of vehicle electric power.

2.1. Electrical Load Model

Electrical loads can be modeled as equivalent resistance, which varies according to the ON/OFF status of each load. However, since the alternator and the battery show the complicated characteristics electrically, they cannot be modeled as simple components as electric load. Among various modeling methods of the alternator and the battery, an empirical modeling method is employed in this study because it is relatively simple and accurate.

2.2 Alternator Model

In general, the alternators are composed of an AC generator, rectifier, and voltage regulator. The voltage generated from AC generator can be obtained as follows.

$$V_a = K_a \Omega \omega \tag{1}$$

But, the regulator, which is connected the terminal of the AC generator, regulates the terminal voltage of the alternator at the constant value. In general, the alternator can be modeled as an constant voltage source when the power of the alternator is enough to supply the current to the load. Alternators are coupled with the engine by a pulley. Owing to the constant pulley ratio between the alternator and the engine, the alternator operates at greatly different speeds. So, the generated energy of the alternator heavily depends on the engine rpm.

In Figure 2, the maximum available output current of the alternator at a variety of different speeds is shown by the characteristic curve.

The alternator can be modeled according to the maximum available current, e.g. the short circuit current (I_a). As shown in Figure 3, if the alternator maximum current is smaller than the load current (i_l) needed by the electrical devices, the alternator is modeled as a constant current source with maximum current. In the other case, the alternator is modeled as a constant voltage source.

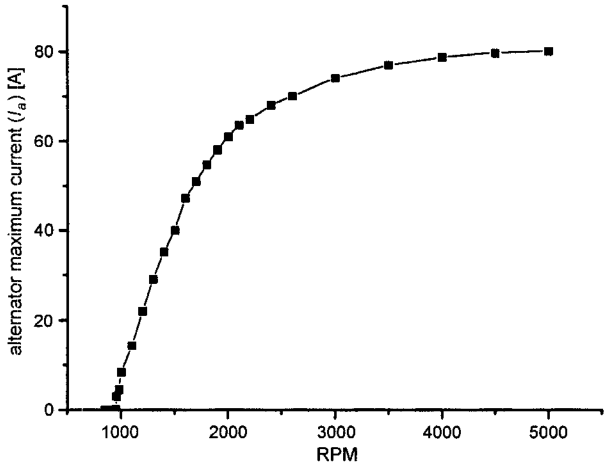

Figure 2. Typical characteristic curve of an alternator.

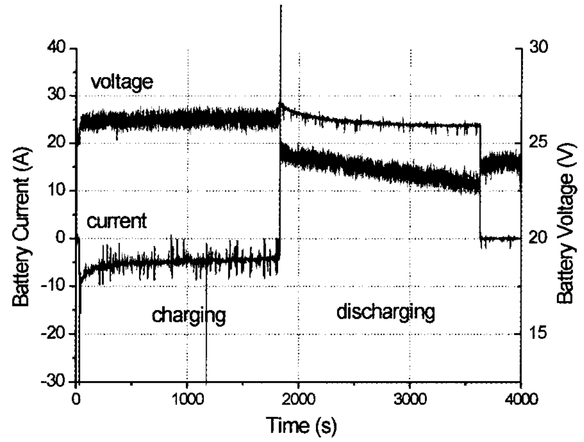

Figure 4. Typical charging/discharging characteristics of battery.

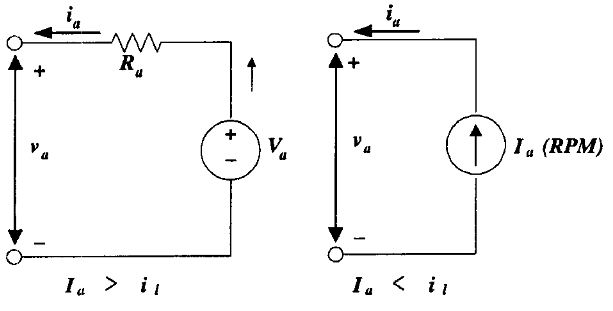

Figure 3. Alternator model.

2.3. Battery Model

Within the vehicle electrical system, the battery acts as the chemical storage device for the electrical energy generated by the alternator. It must be able to supply high currents for cold cranking briefly, and to supply some or all the currents required by other systems for a limited period (idle or engine is not running). In vehicles, lead-sulfuric acid batteries are generally used.

Battery characteristics are determined by the internal chemical reactions, and these internal chemical reactions are affected by the ambient temperature, the SOC, the charging-discharging rate, and charging-discharging history. Thus, it is not easy to predict the charging-discharging current and the changes of the SOC.

Modeling methods of the battery can be divided into the electro-chemical method and the electrical equivalent circuit method. The electro-chemical method usually shows more accurate results, but it is more difficult to model, and it takes much more time to simulate. Therefore, the electrical equivalent circuit model is adopted.

The current flowing into the battery is determined by the charging voltage and the internal impedance of the battery. The internal impedance is affected by active polarization, concentration polarization, and internal resistance.

Figure 4 shows the typical charging and discharging patterns of a battery. At the beginning of the charging, a very large in-rush current flows, and immediately after that, the current decreases very sharply because of the active polarization. And then the charging current decreases smoothly due to the concentration polarization.

Theses battery characteristics can be modeled as shown in Figure 5. Open circuit voltage (V_{OC}) is a function of the specific gravity of sulfur and temperature, and can be obtained by the Nernst Equation. In-rush current, which appears at the beginning of charging, can be represented by the capacitor (C_O) and internal resistances (R_c, R_d, R_b). The current variation depending on the SOC can be modeled as charging internal resistance (R_c) and discharging internal resistance (R_d) which are functions of the SOC. Figures 6 and 7 show the internal resistance of a battery, which is acquired by an experimental modeling procedure.

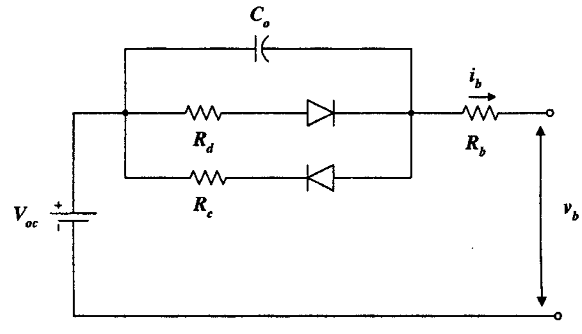

Figure 5. Equivalent circuit model of a battery.

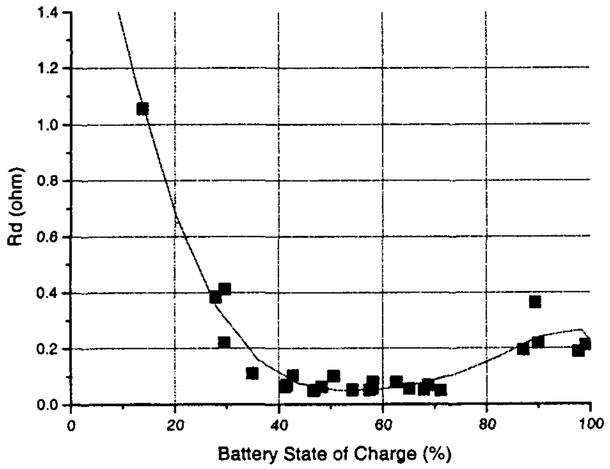

Figure 6. Discharging resistance (R_d) of a battery.

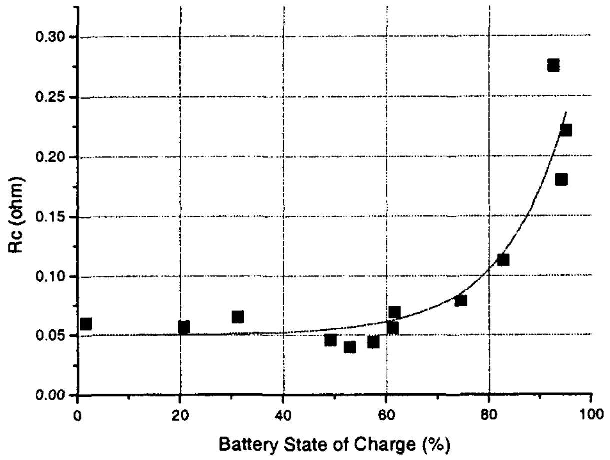

Figure 7. Charging resistance (R_c) of a battery.

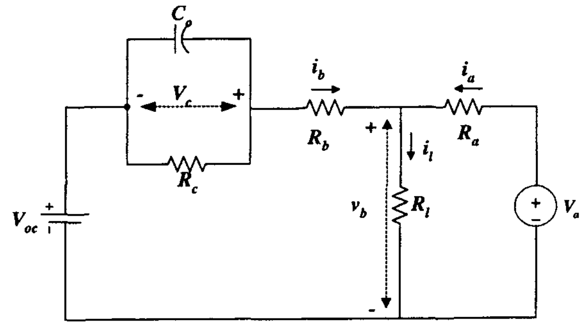

Figure 8. Equivalent circuit model (Charging).

2.4. Simulation Algorithm

Figure 8 and 9 is the equivalent circuit model of the vehicle electric power system. To simulate the continuous-time equivalent circuit model, Euler method is used in discretization. In each time step, the battery current is calculated based on the engine rpm profile, the electrical load current profile, and the battery and alternator models which are established by the users. After the determination of the battery current, the change of the battery capacity (ΔC_D) is calculated. The changes of SOC (ΔSOC) are calculated by the battery current and the present SOC.

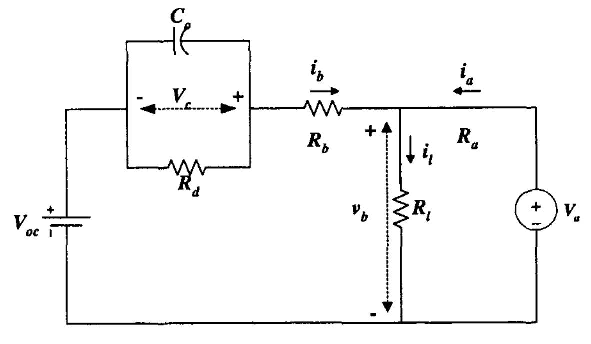

Figure 9. Equivalent circuit model (Discharging).

In case of charging, e.g. the alternator maximum current is greater than the load current, the battery charging current is determined by the difference between the alternator maximum current and the load current or by the SOC of the battery.

$$i_b = Max\left(i_l - I_a,\ -\frac{V_c}{R_c} - C_o\dot{V}_c\right) \tag{2}$$

All the charges are not stored in the battery, because some energy is dissipated in the form of heat. So, the charging efficiency should be considered as shown in the following equations.

$$\Delta C_D = \frac{-i_b\Delta t}{3600}\eta \tag{3}$$

$$\Delta SOC_k = \frac{\Delta C_D}{C_{Dk\text{-}1}}(1 - SOC_{k\text{-}1}) \tag{4}$$

In case of discharging, the battery supplies the current conjunction with the alternator by discharging the stored energy.

$$i_b = i_l - I_a \tag{5}$$

In the case of discharging, by simple calculations, the equation of ΔSOC can be obtained as follows based on Peukerts battery model.

$$i_b^n t = \text{constant} \tag{6}$$

$$\Delta SOC_k = \frac{i_b\Delta t}{3600C_{20}}\left(\frac{i_b}{I_{20}}\right)^{n\text{-}1} \tag{7}$$

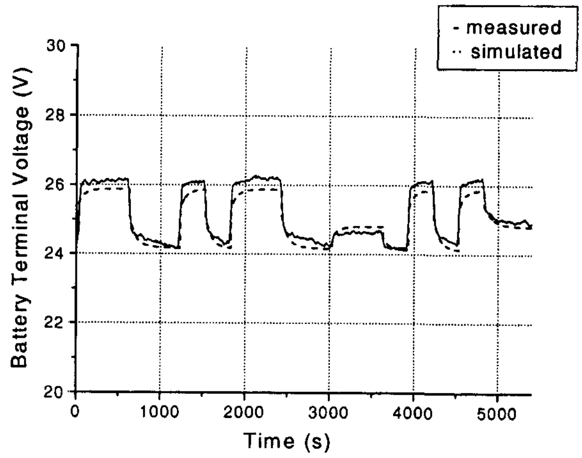

Figure 10. Comparison between simulation and measurement of a battery terminal voltage.

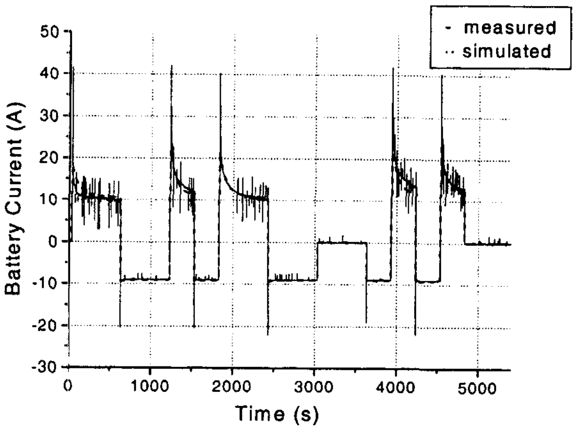

Figure 11. Comparison between simulation and measurement of a battery current.

2.5. Model Validation

Figure 10 and 11 show the terminal voltage and current of simulation and measurement. Two lead-acid batteries are connected in series, and the charging and discharging process are repeated. The charging voltage was 26.5 volts, and load current was about 10 amperes when the battery was discharged. The initial SOC of the batteries was about 74 percent. The measured data and the simulated data are closely correlated.

3. DEVELOPMENT OF VEHICLE ELECTRIC POWER SIMULATOR

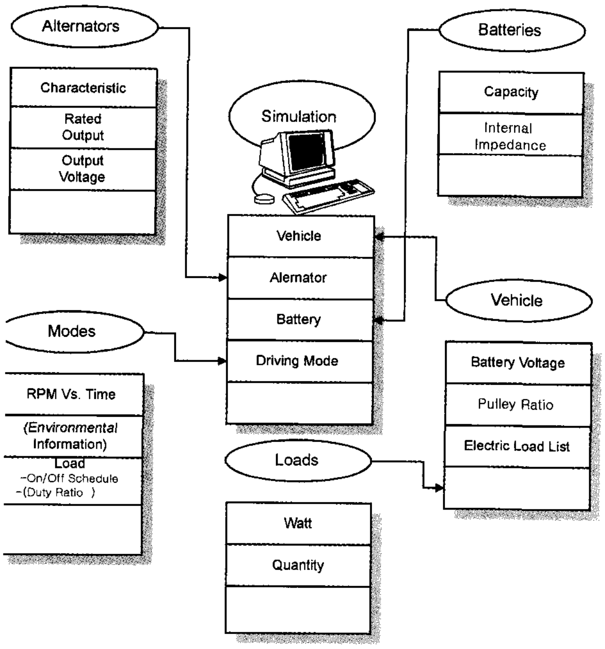

Figure 12. Data structure of VEPS.

The VEPS program is developed with Microsoft Excel as a user interface. Model information of alternators, batteries, and other electrical loads is managed through an Excel worksheet. The simulation algorithm is implemented by functions of Excel and Visual Basic, and simulation results are displayed in the forms of sheets and charts of Excel.

3.1. Data Structure

Figure 12 shows the data structure of VEPS. Data of each component (e.g. vehicle, alternator, battery, and loads) is manipulated in component files. This component file constitutes a major database of VEPS.

Mode file contains driving mode information, such as rpm profile and each load's on/off schedule.

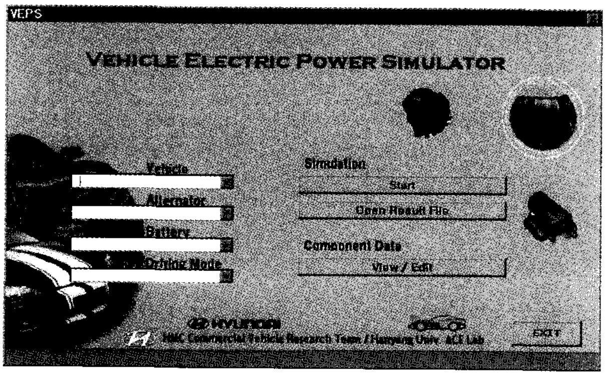

Figure 13. Main window of VEPS.

3.2. Basic Operation

All the functions of VEPS are easily accessed through the main window of VEPS (Figure 13). Selecting the list boxes in the left corner can configure each component, and the power system is simulated based upon the information of components and driving modes.

3.3. Update of Component Database

In order to update the component database, each component has its own input window, which is classified according to the component's characteristics. A user can update his/her own component database by means of the input function of various components.

3.4. Simulation Results Display

Upon the completion of the simulation, a new workbook of Excel is created, and a summary window, which displays important information, appears at the top of the screen. The user can identify the major simulation components, the statistical data, and the changes of the SOC of the battery. More detailed information is shown in work sheets of the result workbook in various formats.

4. DRIVING TESTS

Since alternator output and electrical load heavily depend on the driving condition, it is necessary to acquire real driving patterns to create test modes. Two bus courses in the City of Seoul are selected as test courses, and 56 driving tests are conducted during seven days.

Major analysis results of driving tests are shown in Figure 14 and Figure 15.

5. SIMULATION

When the vehicle electric power system is designed, the system engineers should determine the alternator capacity, battery capacity. And because an alternator is coupled with an engine by a pulley, engine rpm and pulley ratio, e.g. the ratio of an alternator pulley to an engine pulley, should be considered.

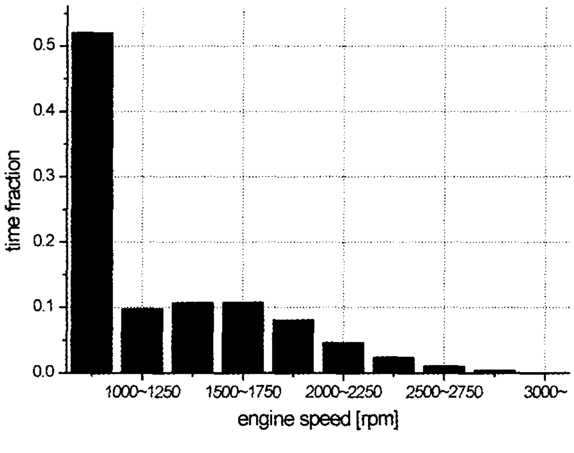

Figure 14. Distribution of engine rpm of driving tests.

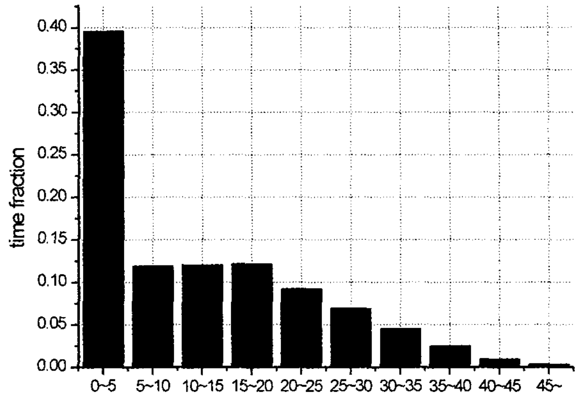

Figure 15. Distribution of bus speed of driving tests.

By using VEPS, various simulations are performed based upon the real data of rpm and speed of the vehicle that are acquired through the driving tests.

Firstly, simulations of various driving modes are conducted to analyze the dependence on the driving modes. Secondly, simulations of various alternator capacity, battery capacity, and pulley ratio are performed to evaluate the effects of these design variables.

5.1. Changes of Driving Modes

Among the driving tests, three driving data (fast, moderate, slow) are selected in one course in this simulation. As the mode names represent, fast mode has the shortest travel time, and the slow mode takes the longest travel time. A rainy summer night load condition is assumed, and vehicle components are configured by referring to the real data of a city bus from Hyundai Motor Company.

Table 1 shows the simulation results for SOC and normalized SOC based upon the real test-driving data

Table 1. Simulation results based upon various driving modes.

Mode	Ave. load (A)	Idle time frac. (%)	Ave. engine speed (RPM)	Charging time frac. (%)	ΔSOC (%)	Normalized ΔSOC (1 hour)
Fast	50.5	34	1286	74	+2.5	+6.6
Mod.	49.7	46	1043	63	+1.5	+2.8
Slow	48.6	52	1030	54	+1.5	+2.3

such as the engine rpm and the electrical load.

Since generally the running engine speed is higher than the idle engine speed, if the idle time fraction is small, the battery is likely to be charged. The simulation results show this trend. Since the course fast has the lowest fraction of the idle time and the highest engine speed compared with two other slower modes, the largest increment of SOC is expected, and these simulations prove it.

5.2. Changes of Alternator/Pulley Ratio

The simulations are performed by altering alternator capacity, battery capacity, and pulley ratio. A real 30 minute-driving RPM data and a high load current profile are used in all simulations.

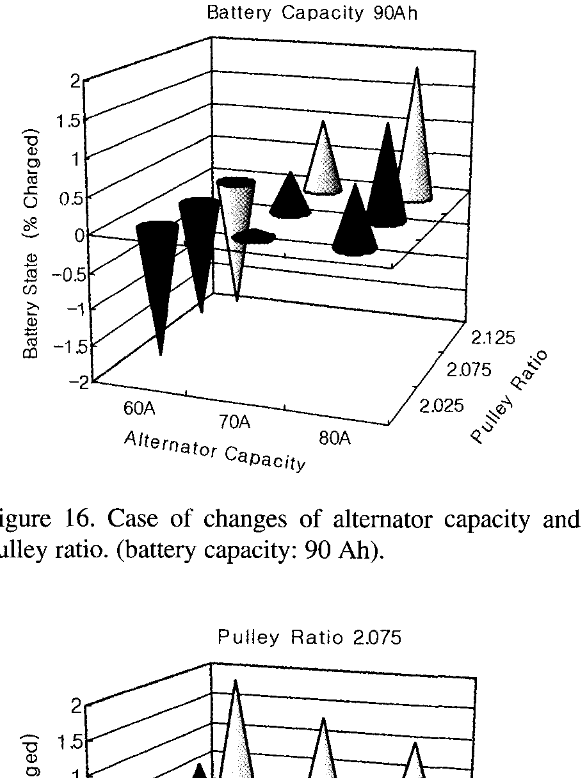

Figure 16. Case of changes of alternator capacity and pulley ratio. (battery capacity: 90 Ah).

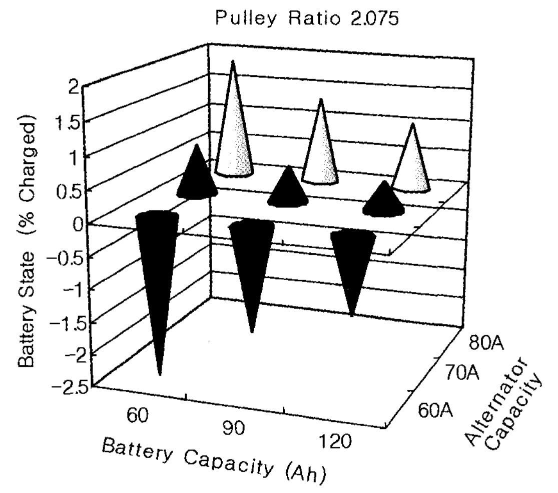

Figure 17. Case of changes of battery capacity and alternator capacity. (pulley ratio: 2.075).

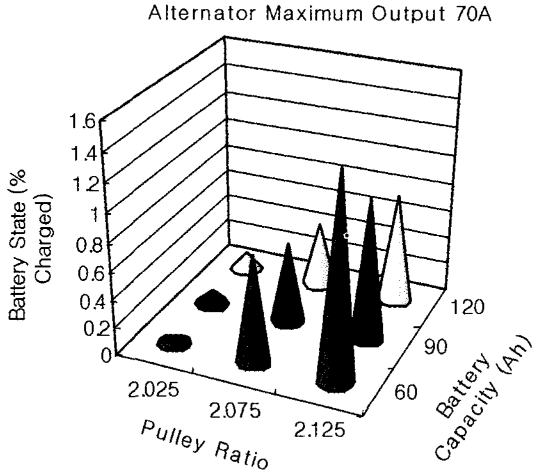

Figure 18. Case of changes of pulley ratio and battery capacity. (alternator capacity: 70A).

In Figure 16, the battery capacity is set to 90 ampere-hours, and the alternator capacity and pulley ratio are changed. This shows that the proper alternator maximum output current is 70 ampere, and the pulley ratio is 2.025, because the battery is still slightly charged.

In Figure 17, the pulley ratio is set to 2.075, and the alternator capacity and battery capacity are altered. As it can be expected, if the battery capacity is small, the alternator capacity affects the SOC greatly.

Lastly, the alternator capacity is set to 70A, and the simulations are performed by changing the battery capacity and pulley ratio. If the pulley ratio is large and battery capacity is small, battery SOC increases very much (Figure 18).

6. CONCLUSION

For simulating the vehicle charging and discharging electric systems dynamically, an electric power simulation program, called Vehicle Electric Power Simulator (VEPS), is developed.

Electrical equivalent circuit model for simulating the vehicle electric power system is presented. This model is composed of alternator, battery, and other electrical loads. This model is relatively simple and accurately depicts the performance of vehicle electric power flows.

During the simulation using the real vehicle data of engine rpm and electrical load, VEPS depicts the relationship among the electric components and provides useful information such as the battery state-of-charge.

VEPS can analyze the electric power charging and discharging system dynamically, and can be used as a useful design tool to determine appropriate capacities of an alternator and a battery for a vehicle during the design phase.

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