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Modelling and simulation of vehicle electric power system

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Abstract

In recent years, the demand for an increased number of vehicle functions by legislation and customer expectations has introduced many electronic control systems and electrical driven units in vehicles and has resulted in steadily increasing electrical loads. Moreover, due to heavy urban traffic conditions, the idling time fraction has increased and reduced the power generation of the alternator. In the vehicle design phase, in order to avoid an over- or under-design problem of the electric power system, it is necessary to understand both the characteristics of each component of the vehicle electric power system and the interactions between the components. For this purpose, model and simulation algorithms of the vehicle power system are required.

In this study, the vehicle electric power system, which is mainly composed of a generator and battery, is modelled and evaluated. Among the various proposed battery models, two types are compared in terms of accuracy and ease-of-use. These two models are distinguished by the consideration of inrush current at the beginning of charging and discharging. In addition, a variable terminal voltage alternator model (VTVA model) is proposed, and is compared with a constant terminal voltage alternator model (CTVA model). Based on the major component model, a simulation algorithm is developed and used to perform a case study. Compared with real data from the vehicle, the simulation results of energy generation and consumption are comparable.

Keywords: Vehicle electric power system; Battery model; Alternator model

1. Introduction

In recent years, many electronic control systems and electrically-driven units in vehicles have been introduced. These systems have substantially increased electrical power consumption in vehicles. This trend requires electrical supply systems of larger capacity. The general demand for increased vehicle functions by legislation and customer expectations has resulted in a steadily increasing electrical load [1]. For example, electronic control units (ECUs) are relatively light loads but require a high-quality supply, and increase quiescent current demands. Systems such as braking and steering are now using electric actuation and require high integrity. Electrically heated catalysts (EHCs) require high power, perhaps of 1 min duration, at the same time as heavy starting loads [2,3].

Furthermore, the idle time fraction during vehicle operation has been increased due to the heavy urban traffic conditions, which reduces the power generation of the alternator. The electric power supply system of a modern vehicle has to supply sufficient electrical energy to numerous electrical and electronic systems. Vehicles need an efficient and highly reliable energy source of their own which must be available at all times. When the engine is running, the alternator becomes the on-board electricity generating plant, whereas, with the engine stopped, the battery is the vehicle's energy store. In order for the entire system to be reliable and trouble-free in any operating condition, it is necessary that the electric power output from the alternator and the battery should match the remaining electrical loads as optimally as possible. An improper decision regarding the capacity of the electric power system, such as that of the alternator and battery, will cause serious problems under actual driving conditions. For example, over-design of the alternator capacity will degrade fuel economy due to vehicle weight and loss of propulsion power, and will increase the cost of the vehicle. On the other hand, if the alternator capacity is too small, cold-cranking problems and road-side breakdowns may occur [2,4].

The vehicle electrical power system includes the alternator, battery, and electrical loads. With the increased requirement on modern cars for integrated, interactive vehicle sub-systems, the electrical power supply performance becomes more critical. 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 [2,3].

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Nomenclature

BWC	battery with capacitance
BWOC	battery without capacitance
CTVA	constant terminal voltage alternator
SOC	state-of-charge
VTVA	variable terminal voltage alternator
C_{20}	20 h battery capacity
C_b	battery overvoltage capacitance
C_n	net battery capacity
ΔC_n	changes of net battery capacity
i_a	alternator terminal current
i_b	battery terminal current
i_l	load current
I_{20}	20 h battery current
I_a	alternator maximum current
n	Peukert constant
R_a	alternator internal resistance
R_b	battery internal resistance
R_c	battery charging resistance
R_d	battery discharging resistance
R_l	load equivalent resistance
R_w	wire resistance
v_a	alternator terminal voltage
v_b	battery terminal voltage
V_a	alternator open-circuit voltage
V_b	battery open-circuit voltage
Greek letter	
η	charging efficiency

To determine the capacity of the alternator and the battery appropriately, many factors should be considered, such as vehicle type, weather conditions, driving conditions, and electrical load demands. In real driving conditions, the maximum output current of the alternator varies according to the engine rpm, and also the electrical load demand varies upon the weather and driving conditions. Thus, an easy-to-use model and simulation algorithm has to be developed to analyse and evaluate such complicated relations [5–8].

This paper describes modelling procedures for the major electric power systems of a vehicle, such as the battery and alternator. Equivalent circuit models of the vehicle electric power system are described in detail under both charging and discharging conditions, and a simulation algorithm is introduced. Finally, the simulation results are compared with experimental data.

2. Models of major components

To simulate the vehicle electric power system, the major electric systems should be modelled appropriately. As shown in Fig. 1, the electric system can be divided into three parts (battery, alternator, and electrical loads), and each part modelled as an equivalent circuit [19].

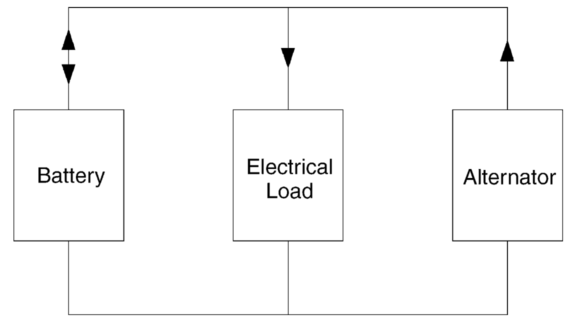

Fig. 1. Diagram of supply/demand of vehicle's electric power.

Electrical loads can be modelled as equivalent resistance, which varies according to the ON/OFF status of each load. Since the alternator and the battery have electrically complicated characteristics, however, they cannot be modelled as simple components. Among the various modelling methods of the alternator and the battery, an empirical approach is adopted because of its simplicity and relative accuracy.

2.1. Battery

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

Battery characteristics are determined by the internal chemical reactions, and these reactions are affected by the ambient temperature, the state-of-charge (SOC), the charge–discharge rate, and charge–discharge history. Thus, it is not easy to predict the charge–discharge current and changes in the SOC of the battery. The current flowing into the battery is determined by the charging voltage and the internal impedance of the battery [18].

Typical charging and discharging currents are shown in Fig. 2. In this test, it is assumed that the battery is charged at a constant voltage and then discharged under a constant load. At the beginning of charging, a very large inrush current flows, and immediately after that, the current decreases very sharply. Then, the charging current decreases smoothly.

Various modelling methods have been proposed up to now [9]. These can be divided into electrochemical methods and electrical equivalent circuit methods [13–15]. The electrochemical model usually gives 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 in this study because it is relatively accurate and efficient.

Batteries can be described in terms of two equivalent circuit models, as shown in Fig. 3. These two models are

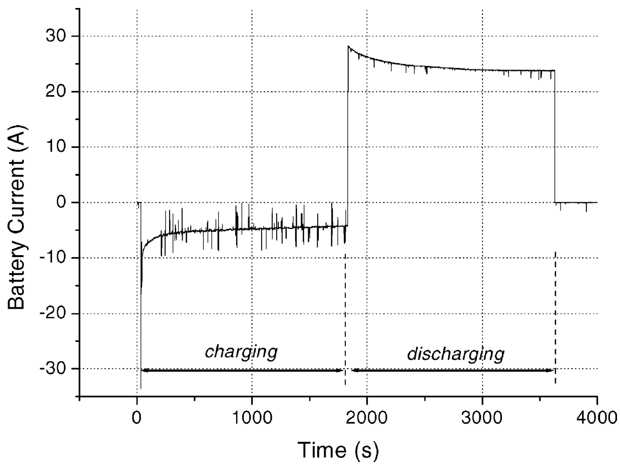

Fig. 2. Typical charging and discharging current of battery.

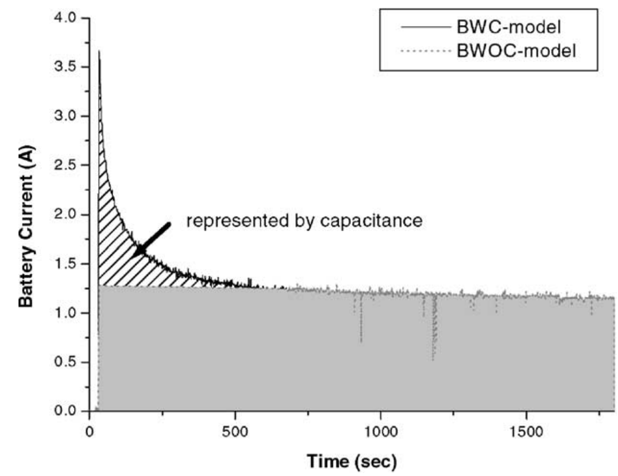

Fig. 4. Charging current when $v_b = 12.55$ V.

classified by the consideration of inrush current at the beginning of charging or discharging. The battery model with capacitance (BWC-model) represents the inrush current by a capacitance (C_b) and a resistance (R_c or R_d) [10,11], but battery model without capacitance (BWOC-model) ignores it [12]. The BWC-model shows more accurate results but it requires four parameters (C_b, R_c, R_d, and R_b) to be identified. Furthermore, it is necessary to identify overvoltage capacitance (C_b), a time-consuming procedure, which represents the time constant of the inrush current. On the other hand, the BWOC-model has only two parameters (R_c, and R_d), and does not need such a lengthy procedure as the BWC-model.

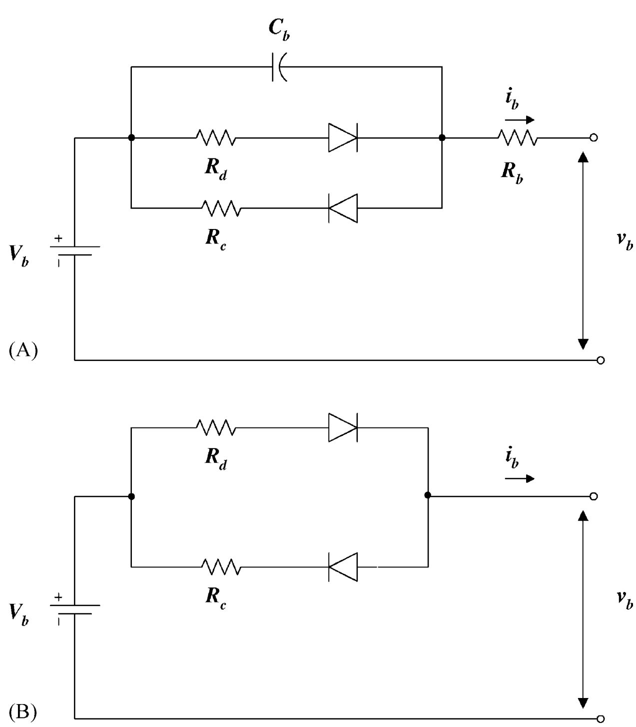

Fig. 3. Equivalent circuit model of a battery: (A) BWC model (B) BWOC model.

To determine which model is more appropriate in the vehicle electric power system model, total charge and inrush current charge have been analysed, as shown in Figs. 4 and 5. A 90 A h battery is charged at 12.55 and 13.5 V, respectively. In these figures, the hatched area represents the amount of charge induced by the inrush current. The inrush current charges become 0.05 Ah (0.054% of 90 Ah) and 0.06 Ah (0.068% of 90 Ah) at 12.55 and 13.5 V charging, respectively. The total amount of inrush current charge increases as the supply voltage increases, but the ratio of inrush current charge to total charge decreases. Similar effects also appear at the beginning of discharging although the charges are not the same as those when charging. Therefore, the inrush current effect can be ignored in the model for the whole vehicle electric power system. As a result, the BWOC-model is used in this study.

The open-circuit voltage of the battery, V_b, is a function of the relative density of sulphuric acid and the temperature. It can be obtained from the Nernst Equation. The variation of current on the SOC can be modelled as R_c and R_d which are

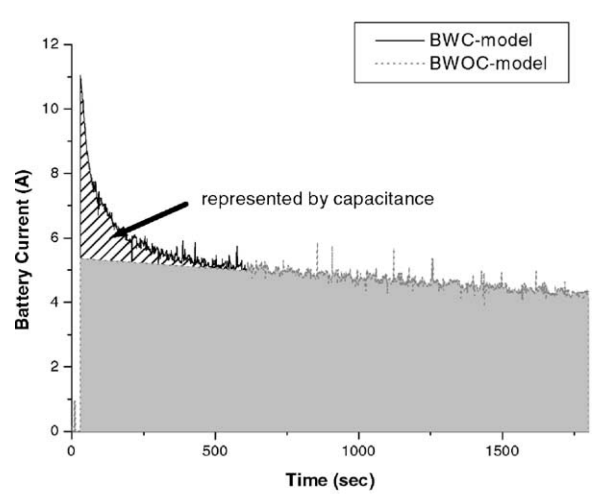

Fig. 5. Charging current when $v_b = 13.5$ V.

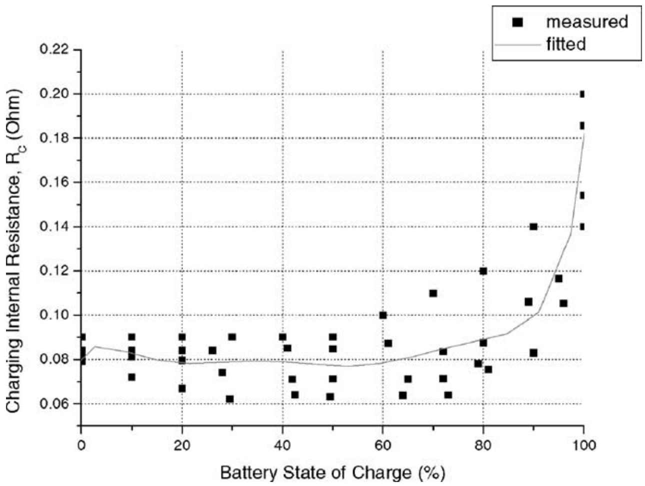

Fig. 6. Charging internal resistance (R_c).

functions of the SOC. The relationship between these two parameters and the SOC is shown in Figs. 6 and 7.

2.2. Alternator

When the engine is running, the alternator supplies the electrical power required by the other electrical devices. In general, alternators are composed of an ac generator, a rectifier, and a voltage regulator. The output current of the alternator at a variety of different speeds is shown by a characteristic curve. Alternators are coupled to the engine via a pulley. Due to the constant pulley ratio between the alternator and the engine, the alternator operates at greatly different speeds [16,17,19].

The alternator can be modelled according to the maximum available current. If the alternator maximum current is greater than the load current needed by the electrical devices, the alternator is modelled as a constant-voltage source. By contrast, if the alternator maximum current is

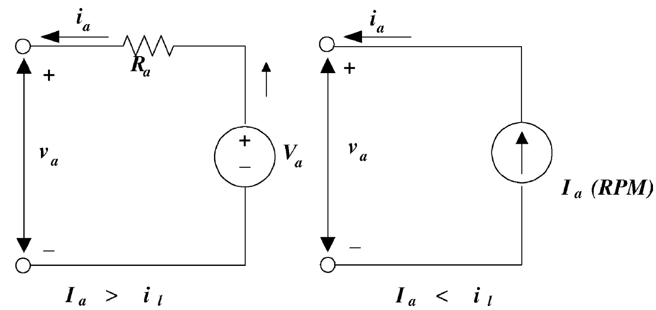

Fig. 8. Constant terminal voltage alternator (CTVA) model.

smaller than the load current, the alternator is modelled as a current source.

Two electrical equivalent circuit models for the alternator are used in this study. One is a constant terminal voltage alternator model (CTVA model) [8], and the other is a variable terminal voltage alternator model (VTVA model). The CTVA model (Fig. 8) assumes that the alternator terminal voltage is always the rated voltage. Therefore, the alternator operates as a constant-voltage source when the battery is charged. In addition, the alternator works as the constant-current source which is dependent on the alternator speed while discharging. In the CTVA model, the charge/discharge critical point is invariable at a constant alternator speed.

On the other hand, the VTVA model (Fig. 9), which is proposed in this study, assumes that the alternator voltage is dependent on the state of the electrical load and battery. As shown in Fig. 10, the actual alternator maximum current varies according to the alternator speed and the terminal voltage.

Consequently, in the case of battery charge, an alternator can be modelled as a series circuit of an internal resistance and an independent voltage source. On the other hand, in the case of battery discharge, an alternator can be modelled as a

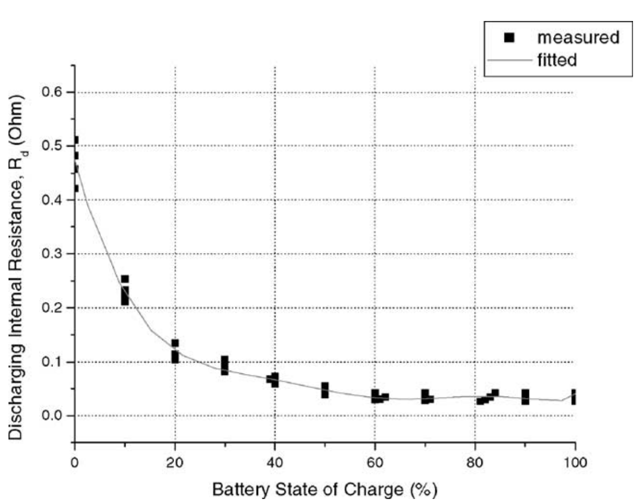

Fig. 7. Discharging internal resistance (R_d).

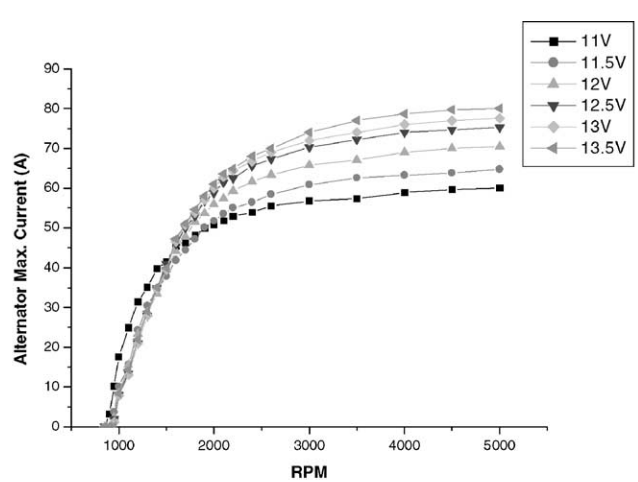

Fig. 9. Alternator maximum current at different terminal voltages.

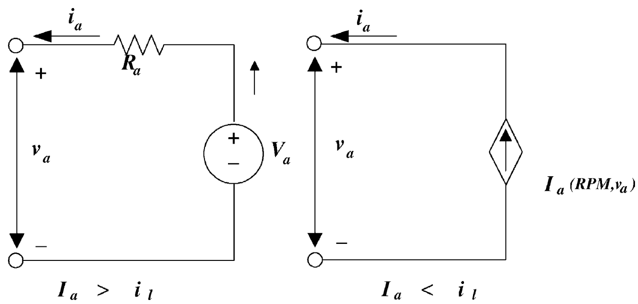

Fig. 10. Variable terminal voltage alternator (VTVA) model.

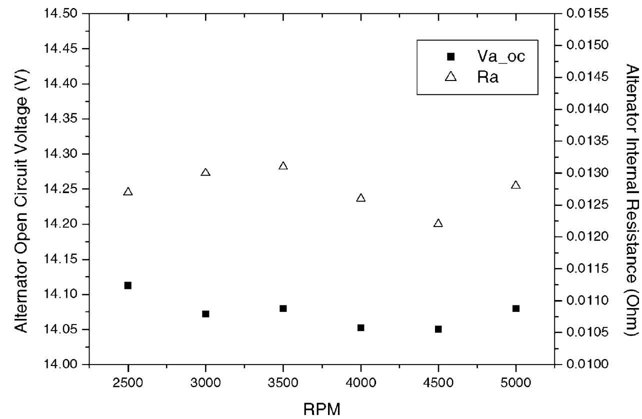

Fig. 12. Open-circuit voltage and internal resistance of alternator.

dependent current source, which is a function of alternator speed and the terminal voltage. While the battery is being discharged, the voltage regulator becomes a short circuit, and the alternator becomes a three-phase, synchronous, self-excited generator. Thus, if the alternator terminal voltage drops due to the heavy electric load, this decreases the excitation current of the excitation winding. As a result, the maximum current decreases according to the voltage drop of the terminal voltage, as shown in Fig. 9. When the load current is smaller than the alternator maximum current (e.g. in the case of battery charge), the alternator terminal voltage depends on the load current. In addition, the switching of the voltage regulator, the conduction loss in the diode bridge rectifier, and the resistance of the armature winding all affect the alternator terminal voltage. So, by using the voltage drop, the alternator internal resistance and the alternator open-circuit voltage can be estimated.

The alternator terminal voltage is measured according to various load currents and alternator speeds. The alternator current ranges from zero to maximum value at a constant alternator speed. A first-order polynomial is fitted to the data of a constant alternator speed, as shown in Fig. 11. The slope of the fitted line represents the alternator internal resistance, and the y-intercept of this line provides estimation of the open-circuit voltage. The internal resistance and the alternator open-circuit voltage at various alternator speeds are shown in Fig. 12. Both parameters are nearly constant over the wide range of alternator speeds due to the operation of the regulator.

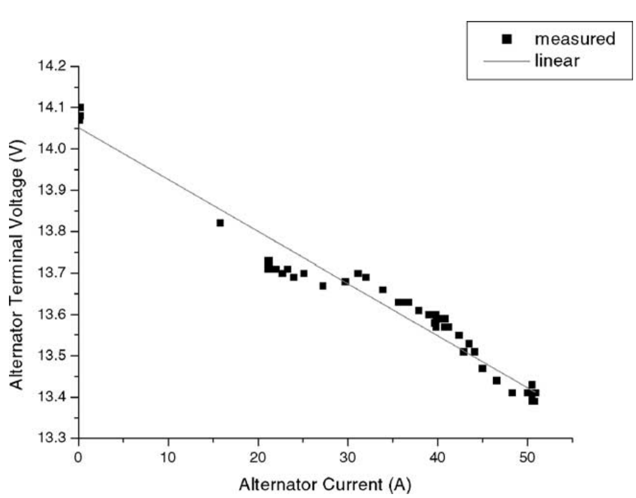

Fig. 11. Test result at 4000 rpm.

3. Simulation algorithm and equivalent circuit model

In each time step, the battery current is calculated through the engine rpm profile, the electrical load current profile, and the vehicle electric power system model. Changes in the SOC are calculated from the battery current and the present SOC. The conceptual flowchart of the simulation algorithm is shown in Fig. 13.

In the following discussion, the VTVA model is used as an example in an equivalent-circuit model, but the CTVA model could be used in the same manner.

3.1. Discharging mode

The equivalent circuit model for discharging is shown in Fig. 14. If the maximum current output of an alternator, which is determined by the engine rpm in the driving mode, is smaller than the load current, the battery supplies the current in conjunction with the alternator by discharging the stored energy, i.e.

$$i_b = i_l - i_a \tag{1}$$

After determination of the battery current, the change in SOC of the battery is calculated according to Peukert's SOC model. The Peukert relationship states that the product of the constant-current discharge time t and the discharge current i_b to the power n is constant, i.e.

$$i_b^n t = \text{constant} \tag{2}$$

Using this relationship, the battery ampere-hour capacity, C_b, at some discharge current, i_b, can be related to a known discharge rate, C_{20}, by:

$$C_b = C_{20}\left(\frac{I_{20}}{i_b}\right)^{(n-1)} \tag{3}$$

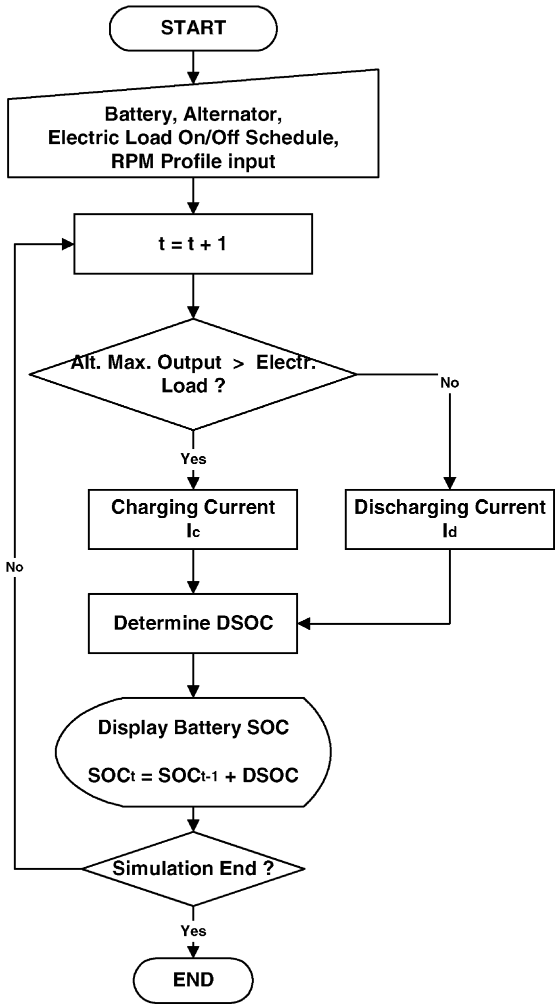

Fig. 13. Flowchart of simulation algorithm.

The battery SOC depends on the net discharge ampere-hours according to:

$$\mathrm{SOC} = 1 - \left(\frac{C_n}{C_b}\right) \tag{4}$$

where $C_n = i_b t$ is the discharge ampere-hours at rate i_b, and t is the discharge time in hours. Unfortunately, during a driving cycle, the discharge rate is not constant but varies from one time interval to another. Consequently, the SOC equation must be modified to give the charge occurring during a computational time interval of Δt seconds. For the kth time interval, this gives

$$\Delta\mathrm{SOC}_k = -\frac{\Delta C_{n,k}}{C_b} = -\frac{i_b \Delta t}{3600\, C_{20}} \frac{1}{C_b} = -\frac{i_b \Delta t}{3600\, C_{20}} \left(\frac{i_b}{I_{20}}\right)^{n-1} \tag{5}$$

with the net SOC at the end of that time interval being:

$$\mathrm{SOC}_k = \mathrm{SOC}_{k-1} + \Delta\mathrm{SOC}_k \tag{6}$$

and the net discharged ampere-hours being:

$$C_{n,k} = C_{n,k-1} + \Delta C_{n,k} \tag{7}$$

3.2. Charging mode

The equivalent circuit model for charging is given in Fig. 15. When the alternator current is sufficient for the electrical loads, the battery is charged. In this case, 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.e.

$$i_b = \max\left(i_l - I_a, \frac{V_b - v_b}{R_c}\right) \tag{8}$$

In the case of charging, all the charges are not stored in the battery, i.e. because some energy is dissipated in the form of heat. So, the charging efficiency η should be considered. During the charging process, a constant charge efficiency is assumed such that the incremental ampere-hours become:

$$\Delta C_n = \frac{i_b \Delta t}{3600} \eta \tag{9}$$

Assuming constant-efficiency charging, the change in SOC is given by

$$\Delta\mathrm{SOC}_k = \frac{\Delta C_n}{C_{n,k-1}} (1 - \mathrm{SOC}_{k-1}) \tag{10}$$

And the net SOC and ampere-hours are given by the same equations as the discharging case, respectively.

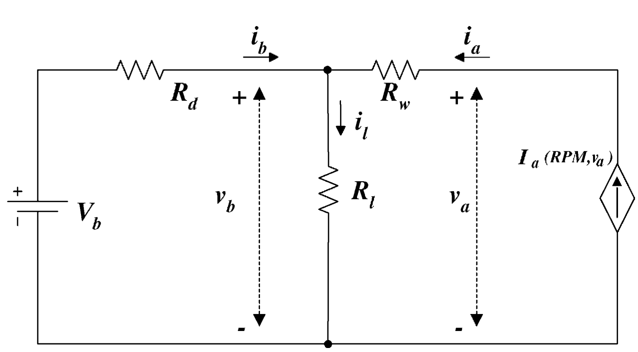

Fig. 14. Equivalent circuit model (discharging).

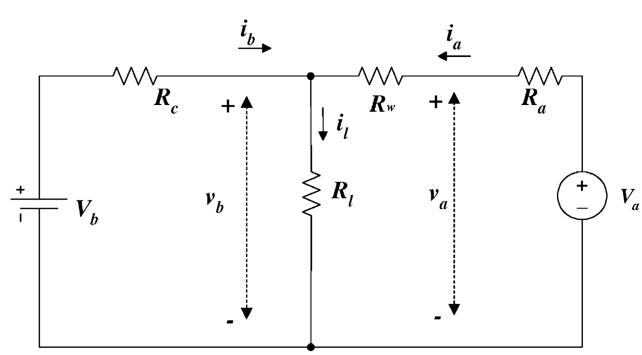

Fig. 15. Equivalent circuit model (charging).

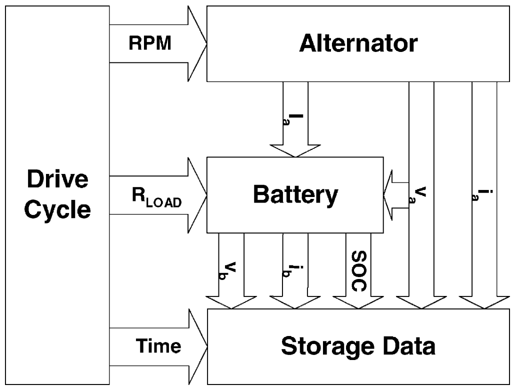

Fig. 16. Structure of simulation.

4. Structure of simulation program

The vehicle electric power system simulation (Fig. 16) is developed with the simulation program MATLAB/SIMULINK. This program is based on individual component models, and analyses vehicle electric power flow on a second time basis of a specified driving cycle. Component parameters are saved in M-files, so the simulation program can manage various models of components.

An upper level schematic of the vehicle electric power simulator (VEPS) routine is shown in Fig. 17. A drive cycle, which consists of the alternator speed and electric load resistance, provides the basic data. The alternator speed is used by the alternator sub-system (Fig. 18), and the electric load resistance is used by the battery sub-system (Fig. 19). The alternator block provides the alternator maximum current and terminal voltage to the battery block. The battery block calculates the battery terminal voltage, power, current, and SOC using the alternator maximum current, terminal voltage, and load resistance.

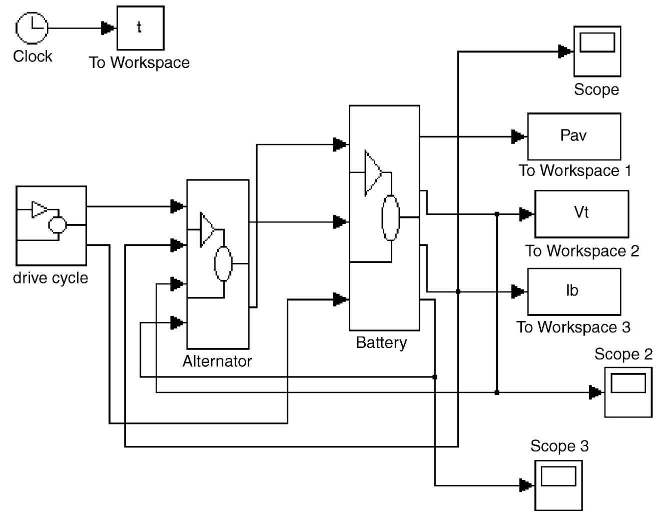

Fig. 17. SIMULINK block diagram of VEPS.

5. Model validation

Several tests have been performed to validate the model. The battery used in these tests, is the Solite CMF60, the rated voltage of the test alternator is 13.5 V, and the rated output current is 75 A. All tests are run at a constant alternator speed of 3000 rpm.

To compare the accuracy of the two alternator models(VTVA model and CTVA model), first a charging and discharging driving cycle was examined using a 81.6% charged battery, and the two equivalent circuit models were simulated. These results are shown in Figs. 20 and 21. As described previously the two alternator models show different characteristics in the discharging phase, and this is verified by the simulation. The VTVA model shows more accurate results than the CTVA model.

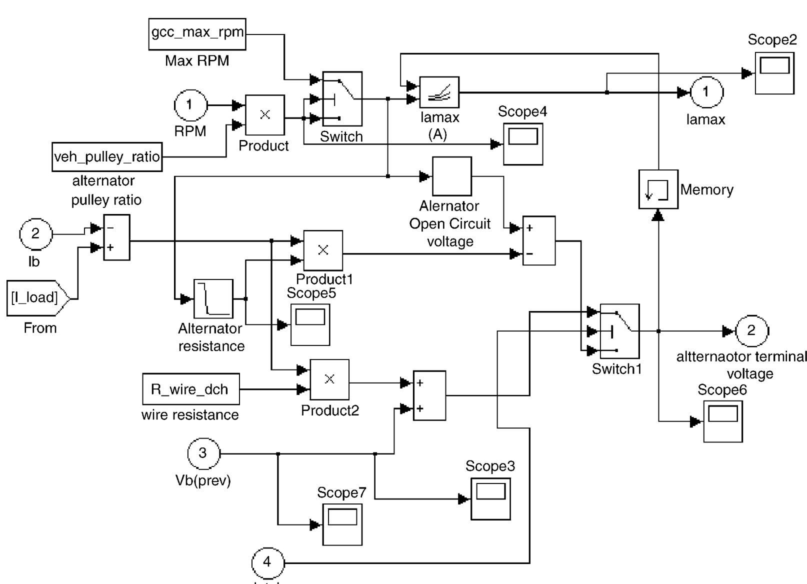

Fig. 18. Alternator model in VEPS.

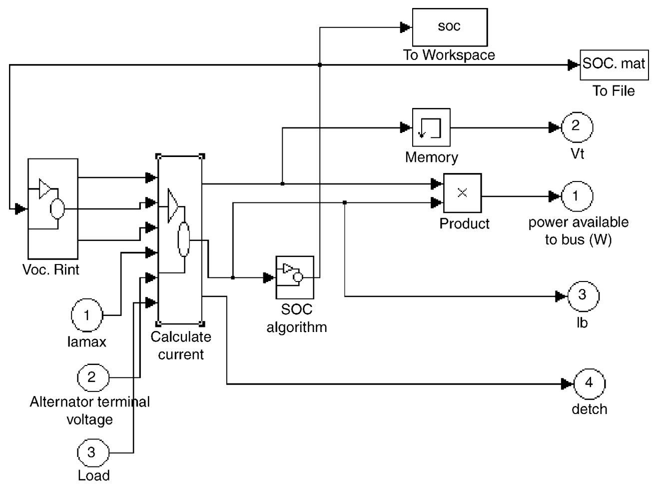

Fig. 19. Battery model in VEPS.

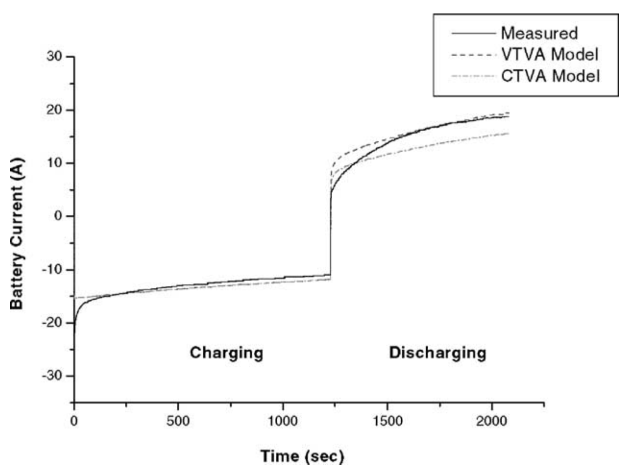

Fig. 20. Comparison between VTVA model and CTVA model (battery current).

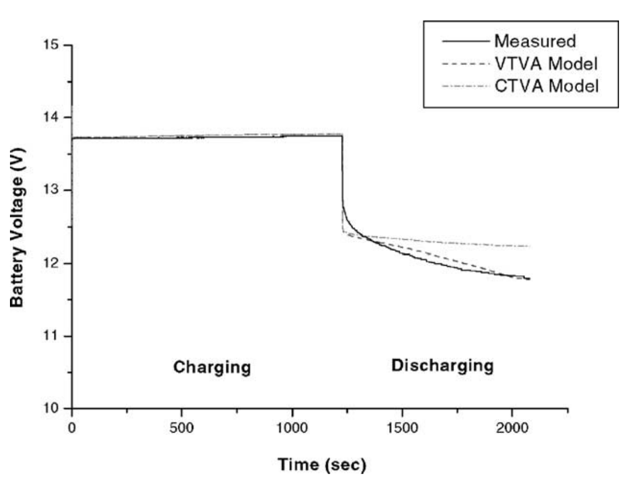

Fig. 21. Comparison between VTVA model and CTVA model (battery voltage).

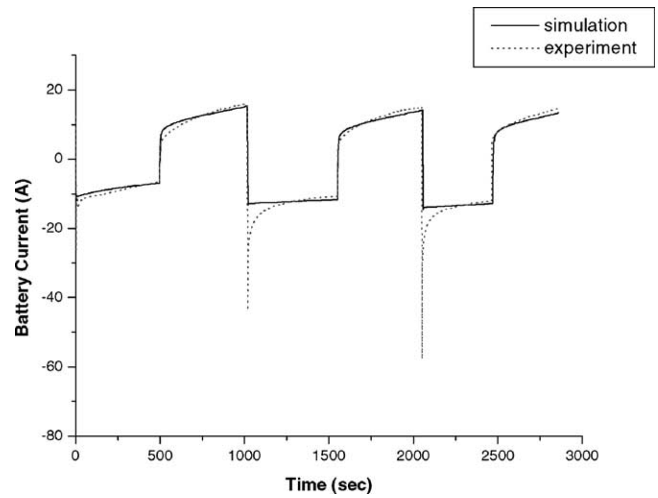

Fig. 22. Validation of model using repeated charging–discharging mode (battery current).

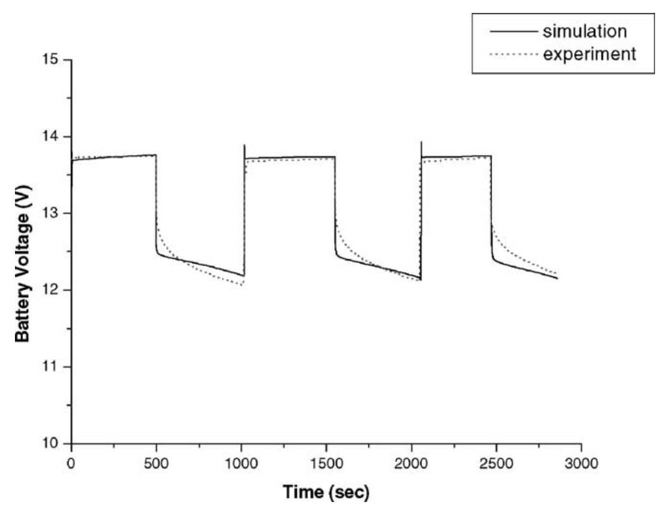

Fig. 23. Validation of model using repeated charging–discharging mode (battery voltage).

Table 1
Comparison of SOC

	Initial SOC (%)	Final SOC (%)	Change of SOC (%)
Simulation	90	84.51	−5.49
Experiment	90	84.68	−5.32

A comparison between the measured and simulated results with the VTVA model are shown in Figs. 22 and 23 and Table 1, for a run in a repeated charging/discharging mode when the initial SOC is 90.1%. The measured data and the simulated data are in close agreement.

6. Conclusions

The introduction of an increased number of electrical systems in vehicles has led to higher electrical loads while traffic conditions around the world are causing an increased amount of vehicle idling and the subsequent reduction of power that may be generated by the alternator. Therefore, a real-time PC-based simulation program which can analyse the characteristics of the individual vehicular electrical components as well as the interaction between the components will assist optimisation of the design of the electrical power system. Models and simulation algorithms which represent the vehicle electric power system must be prescribed for such a program.

In this study, two battery models are compared in terms of accuracy and ease-of-use for simulations. The BWC-model shows more accurate results, but it takes a longer to identify the model parameters. On the other hand, the BWOC-model is relatively simple, and is therefore preferable in the vehicle electric power system model.

Also, a more precise alternator model, the VTVA model, is developed. The VTVA model takes into account the effect that the alternator maximum current decreases as the terminal voltage drops. Compared with the CTVA model, the VTVA model reflects the varying terminal voltage and shows more accurate results.

Based on models for the components, the vehicle electric power system model and the simulation algorithm are developed. This model is composed of an alternator, a battery, and other electrical loads. The model accurately depicts the performance of vehicle electric power flows.

The VEPS, which has adopted the mathematical models described above, has been developed. The VEPS can be used as a useful design tool to determine appropriate capacities of an alternator and a battery for a vehicle in the design phase by analysing the electric power system dynamically. During the simulation using real vehicle data for engine rpm and electrical load, the VEPS provides useful information, such as the power flow of major components, and the battery SOC.

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