LEAD-ACID BATTERY STATE-OF-CHARGE ESTIMATION FOR INDUCTION MOTOR FORKLIFT TRUCKS

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Key words: lead-acid battery, secondary battery, state-of-charge, estimation, forklift trucks, pulse-width modulation, battery current reconstruction, induction motor

Abstract: While the automobile industry of electrically powered cars is still in its infancy, the industry vehicles, such as forklift trucks and other material handling equipment, have been in production for several decades. The use of electrically powered trucks imposes the problem of fuel-gauges, as they are not equipped with a reservoir enabling simple measurement of the fuel content. Knowing the battery state-of-charge is essential in preventing stranding and ensuring full-range exploitation of the battery power as well as informing the driver about the truck working hours time when battery charging should be done.

New electric trucks emerging in the market use AC motors for traction, necessitating phase current measurement. By using the existing hardware for phase current measurement, the battery current can be calculated thus reducing the cost of an additional hardware needed for battery current measurement. This paper addresses also the technique for correct battery current reconstruction from phase currents.

The paper presents two techniques enabling accurate estimation of the remaining battery capacity. During battery discharging, the ampere-hours taken from the battery are integrated and when the battery is not loaded, the open-circuit voltage measurement is made. A new technique to reduce the rest period needed to take the measurement of the open-circuit voltage is imposed to further improve the battery state of charge algorithm. Using both methods, i.e. the ampere-hours and open-circuit voltage, simplifies the overall state-of-charge estimation irrespectively of different battery sizes, battery ageing and temperature changes.

Ugotavljanje napolnjenosti svinčevih baterij v aplikacijah paletnih viličarjev s pogonom na indukcijski motor

Kjučne besede: svinčeva baterija, akumulator, stanje napolnjenosti, viličar, pulzno-širinska modulacija, rekonstrukcija baterijskega toka, izmenični motor

Izvleček: Medtem ko je avtomobilska industrija vozil na električni pogon še v povojih, je proizvodnja industrijskih vozil, kot so paletni viličarji in druga vozila za delo z blagom, v teku že več desetletij. Z uporabo električnih vozil se porodi problem merilnikov goriva, ker nimamo na vozilu rezervoarja, kjer bi lahko opravili preprosto meritev polnosti. Vedenje o napolnjenosti baterije je ključno, če nočemo, da nas vozilo pusti na cedilu, a da hkrati izkoristimo vso energijo, ki nam jo nudi akumulator. Poznavanje napolnjenosti baterije informira voznika o delovnih urah, ki jih električno vozilo še lahko opravi, in opozori, kdaj je potrebno baterijo napolniti.

Nova električna vozila, ki se pojavljajo na trgu, poganjajo motorji na izmenični pogon, kjer je za pravilno krmiljenje potrebno meriti fazne tokove. Z uporabo obstoječega elektronskega vezja za merjenje faznih tokov je možno izmeriti in izračunati baterijski tok. S tem se zmanjša strošek dodatnega elektronskega vezja, ki bi bil potreben za merjenje baterijskega toka. Ta članek predlaga metodo za pravilno rekonstrukcijo baterijskega toka iz merjenih faznih tokov.

Za točno ocenjevanje napolnjenosti baterije sta predstavljeni dve metodi. Med praznjenjem baterije se sešteva poraba amper ur in, ko baterija ni obremenjena, se opravi meritev napetosti odprtih sponk. Predstavljena je nova metoda za zmanjšanje potrebnega časa počitka baterije po uporabi, ki izboljšuje algoritem ugotavljanja napolnjenosti baterije. Uporaba obeh metod izboljšuje skupno oceno o napolnjenosti baterije in je neodvisna od kapacitete baterije, efekta staranja in temperaturnih sprememb.

1 Introduction

All vehicles used today in the field have limited power sources, which consequently limit its operational hours. To ensure their proper operation, enough energy to power them, has to be made available in the system. Whether this energy is directly measurable or not, the driver has to be informed by some means of the actual energy still in the vehicle. Drivers of combustion-engine driven vehicles are accustomed to checking the gas gauge so as to estimate operational hours the vehicle can run. Measurement of the remaining gasoline available in the vehicle is simply a measurement of the level of fluid in the tank. The gauge usually shows the level as a portion of the full tank. On the other hand, electrically powered vehicles lack this simplicity of the fuel gauge and determination of the available energy in the battery pack is quite an ample task. In majority of cases industrial vehicles are powered by secondary lead-acid batteries addressed in this paper. This type of the batteries has been a successful commercial commodity for more than a century. The reasons for this wide use are mostly their low price, simple manufacturing and good performance and life cycle characteristics /3/. In the same way, the fuel gauges show the percentages of the tank fullness and the battery state-of-charge indicators show the percentage of the remaining battery capacity. This helps the driver to estimate how long the vehicle will operate and when charging of the battery is necessary. The accuracy of these indicators is essential in preventing stranding and ensuring full-range exploitation of the battery power. The battery state-of-charge (SOC) is a complex non-linear function of the discharge current, ambient temperature, battery age and other parameters /4/. In practice, direct measurement of some of these parameters is either impossible or too expensive. There are several practical methods available to monitor lead-acid batteries. All of them use one or more measurement data to estimate the remaining capacity in the battery. Most of the methods implemented in the market use either the simple open-voltage /6/ or coulometric method (ampere-hour measurement) or a combination of the two /5/. Other techniques are specific gravity, voltage under load /2/ and various battery model-based methods /1/, /7/. The specific gravity method directly indicates SOC by showing the acid concentration in the electrolyte transformed during discharge.

The method presented in this paper is a combination of the open-circuit and ampere-hours measurement /4/. A monitoring technique based on the open-circuit voltage, which was originally used in the forklift truck, is improved with battery current measurement. An improved technique drastically reducing the stabilizing time of the battery voltage is developed to predict the open-circuit voltage. The proposed algorithm optimizes the overall accuracy due to the constant measurement of ampere-hours drawn from the battery. At the same time, it adapts to different operating conditions, battery ageing and quality of battery service. Battery-powered material-handling trucks use different types of the traction motors. In the past, mainly separately excited DC motors were used. Today, with new technologies evolving and fast signal processors availability, induction traction motors are widely used. For control purposes, phase currents of the AC induction motors have to be known. To reduce the cost and additional hardware for battery current measurement, the paper describes techniques to reconstruct the battery current of the induction motor from the measured phase currents /8/. All high power devices on the electric truck contribute to the total energy consumption and have to be taken into account. The main truck controller collects these data and computes the total battery current.

2 Battery capacity

The term battery capacity describes the amount of usable energy stored in the battery. There are several principles to define it. The theoretical capacity is the total power that can be drawn from a battery. This value depends on the amount of the electrolyte and not on the material in the plates of a new battery /3/. The electrolyte in the lead-acid battery is a solution of sulphuric acid and water. This concentration is defined as a specific gravity, a measure of density, which is the ratio of the mass of the mixture of sulphuric acid and water to pure water. The relationship between the state-of-charge and specific gravity is linear as shown in Figure 1 /3/.

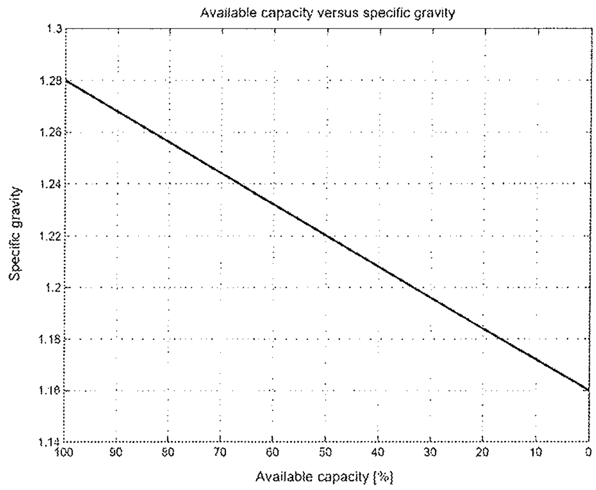

Figure 1. Relationship between the available capacity and specific gravity for a typical traction secondary lead-acid battery

The usable capacity defines the ampere-hours available in the battery at a certain discharge rate. A battery rated at 400 Ah at C/5 rated current means that the battery can be discharged at 80 amperes in 5 hours. This capacity varies depending on the discharge current. The above battery discharged at 200A will last only 1.6 hour, giving only 320Ah. Peukert /9/ empirically defined the relationship between the available capacity *Ca* and the discharge current I as:

$$C_a = KI^{n-1} \tag{1}$$

where constants n and K depend on the temperature, concentration of the electrolyte, and the structure of lead-acid batteries. It should be noted that the usable capacity does not take the recuperation effect into account, because it is derived under continuous, constant current discharge conditions /4/. This means that with intermittent rest periods between discharges, the electrolyte has more time to diffuse and thus increases the total capacity of the battery. Since the usable capacity is defined as practical capacity, most commercially available battery indicators show usable capacity. The recommended usable capacity is generally only 80% of the rated usable capacity to insure the maximum battery life /3/.

3 Battery SOC measurement

In a certain way SOC differs from the usable capacity showing the percentage of the available total capacity rather than indicating the amount of ampere-hours available from a cell. As already mentioned above, there exist several measuring techniques to estimate the battery SOC /6/.

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1) specific gravity measurement, 2) open-circuit voltage measurement, 3) battery voltage under load measurement, 4) ampere-hours measurement, and other combinations of these four basic techniques. The specific gravity measurement method is impractical for real applications, since the battery has to be opened and rested for several hours after use.

3.1 Open circuit voltage method

The open-circuit voltage of a secondary lead-acid battery is directly related to the battery SOC. This method is particularly suitable for automated battery monitoring since it enables to measure the voltage directly from the battery terminals and no special sensors are required. The nominal voltage of the lead-acid cell is 2V. The open-circuit voltage is a direct function of the electrolyte concentration, ranging from 2.125V for a cell with 1.28 of the specific gravity to 2.05 V with 1.21 of the specific gravity /6/. The open-circuit voltage depends also on temperature of the electrolyte but the temperature coefficient is about 0.2mV/C and can be neglected in real applications where operating conditions do not change for more than 50 °C, which is less than 1% of the total battery capacity. Thus, the relationship between the open-circuit voltage and specific gravity is linear within the usable battery capacity range. The battery open-circuit voltage being linearly dependent on specific gravity, which is a direct SOC indicator, the state-of-charge can be defined by the ratio of difference of actual open-circuit voltage V_{OCV} to empty battery open-circuit voltage V_{empty}, to difference of full battery open-circuit voltage V_{full} to empty battery open-circuit voltage V_{empty}:

$$SOC_{OCV} = \frac{\hat{V}_{OCV} - V_{empty}}{V_{full} - V_{empty}} \qquad (2)$$

The open-circuit voltage must stabilize before a reliable measurement can be made. This stabilization process can take from 30 minutes to several hours depending on battery design, former discharge current and SOC.

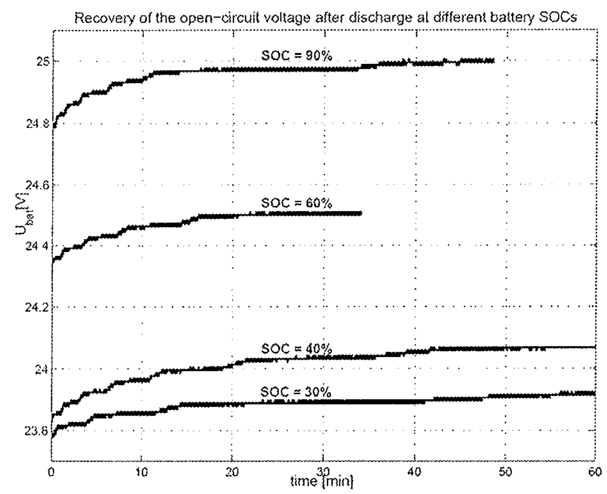

Figure 2. Recovery of the open-circuit voltage at different battery SOCs

Figure 2 shows a typical recovery process of the battery open-circuit voltage at different SOCs.

Estimating the open-circuit voltage shortly after the load has been disconnected from the battery can solve the problem of the long stabilization period after each discharge cycle. A period of 7 minutes was established as appropriate by the method presented in /4/. The proposed method is based on experimentally determined time required by the battery voltage to fully stabilize. Interpreting this time in a logarithmic scale, very constant values were obtained for different types of batteries and discharge rates prior to the recovery process. Since 7-minute period of rest can be quite long for some truck drivers, the time needed to calculate the open-circuit voltage should be reduced. To have it further reduced, the proposed method takes into account the current battery SOC of the battery and the battery current prior to the recovery process.

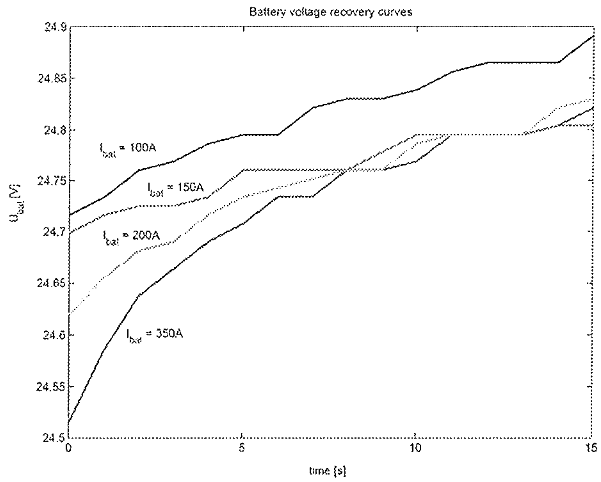

Figure 3. Battery open-circuit voltage recovery curves after different battery current loads

The higher current, before the rest period takes place, has a strong impact on the recovery curve of the open-circuit voltage as it can be seen from Figure 3. Taking this into account, the asymptote of the recovery curve can be adapted. The dependency was found to be linearly related to the current. At the same time, the total ampere-hours drawn from the battery after the last rest period affect the recovery curve, since with greater loads the battery takes more time to stabilize than with smaller loads.

3.2 Ampere-hour method

Under-load measurement of the battery current and integrating it over the time constitutes the ampere-hours measurement method. This method is widely used since it is simple to implement and gives satisfactory results for constant-load states conditions. The coulometric measurement gives a continuous indication of the battery ampere-hours and by knowing the battery capacity the current battery

SOC_{Ah} can be calculated by the ratio /1/ of the actual battery capacity $C_a - \int I_{bat} dt$ to total battery capacity C_a:

$$SOC_{Ah} = 1 - \frac{\int I_{bat} dt}{C_a} \qquad (3)$$

This technique provides a relatively accurate SOC indication, but is prone to the accumulation error resulting from inaccurate current measurement and other factors that are not taken into account. In its most basic form, the battery capacity is assumed to be constant, but in reality the capacity varies with the discharge current, type of discharge, battery age and temperature. As these effects are not taken into account, this method can be regarded as accurate only for short time lasting states. Its second drawback is that the total battery capacity has to be known. To neglect the lack of knowledge of the battery capacity, the proposed method uses the open-circuit voltage result SOC_{OCV} and ampere-hours consumed C_{meas} to estimate the total battery capacity $\hat{C}_a$ (4).

$$\hat{C}_a = \frac{C_{meas}}{SOC_{OCV}} \qquad (4)$$

Each of the techniques discussed above has its own drawbacks. However, by combining the open-circuits voltage and ampere-hours measurement, it is possible to get very accurate results. The ampere-hours measurement is used

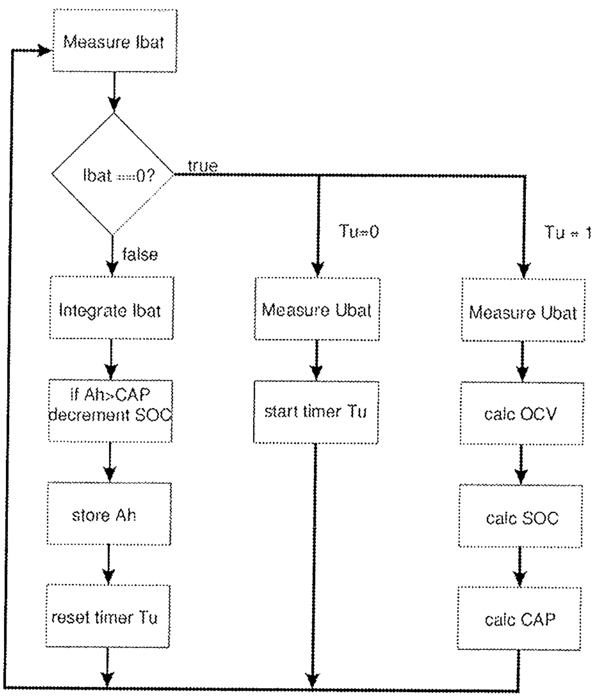

Figure 4. Measurement algorithm scheme

when the truck is operating and current is drawn from the battery. This informs the driver of the current ampere- hours consumption. When the truck is at rest and no power is drawn from the battery for long enough periods, the open-circuit voltage measurement takes place and estimates the battery SOC (Figure 4). On the basis of SOC calculated from the open-circuit voltage, the total battery capacity correction is made (4), which influences the ampere-hours SOC estimation (3).

4 Battery current reconstruction

The forklift truck is a material-handling vehicle powered by a lead-acid battery. The whole system is composed of several electrical devices. The main truck controller is a four-phase inverter controlling an induction motor and DC pump. besides this, it handles the system logic and drives all hydraulic components. The electrically powered aided steering (EPAS) is a separate device controlling a permanent magnet motor, tiller card is a driver command board and graphic display is the system output device informing the driver of the system status. Only the main truck controller and EPAS system are the major power consumption devices and their current has to be taken into account. Since EPAS is a separate device, the information of its current load is sent to the main truck controller through a system communication channel.

In order to correctly calculate the ampere-hours drawn from the battery, an accurate current measurement unit is needed. This usually involves shunt resistor measurement or more sophisticated equipment such as toroidal coils and Hall sensors. Both techniques require expensive electronic parts that have to be added to the system. Furthermore, it complicates the electrical wiring of the truck, which adds an additional cost to the truck. Since the main truck controller already measures the current of the traction induction motor and the current drawn by the DC pump motor, it can calculate also the battery current. The hydraulic pump is a PWM driven serial excited DC motor, so its current can be calculated from the measured DC motor current flowing in the phase i_{phase}. By knowing the applied frequency $1/T_{period}$ and duty cycle T_{on} of PWM modulation, also the battery current I_{DC} can be reconstructed by:

$$I_{DC} = i_{phase} \frac{T_{on}}{T_{period}} \qquad (5)$$

More problems arise in the case of traction motor battery current reconstruction. The traction motor is a three-phase symmetrically wounded induction motor driven by a three-phase voltage source inverter (Figure 5). It is possible to

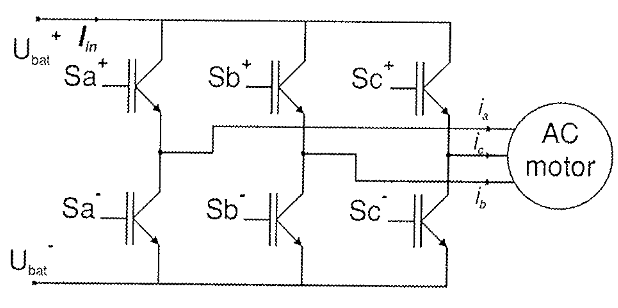

Figure 5. Three-phase inverter

calculate the current drawn from the battery by knowing the phase currents and the switching state of the three-phase inverter. Due to the discrete nature of the output phase voltage, only seven distinct voltage vectors can be generated. Each voltage vector within the sequence corresponds to the state of the VSI power switches. These states determine the way in which phase currents are mirrored by the dc-link current (Table 1).

$I_{in} = 0$	(Sa, Sb, Sc) = (0,0,0)
$I_{in} = i_a$	(Sa, Sb, Sc) = (1,0,0)
$I_{in} = -i_a$	(Sa, Sb, Sc) = (0,1,1)
$I_{in} = i_b$	(Sa, Sb, Sc) = (0,1,0)
$I_{in} = 0$	(Sa, Sb, Sc) = (0,0,0)
$I_{in} = i_a$	(Sa, Sb, Sc) = (1,0,0)
$I_{in} = -i_a$	(Sa, Sb, Sc) = (0,1,1)
$I_{in} = i_b$	(Sa, Sb, Sc) = (0,1,0)

Table 1. Inverter states and line currents

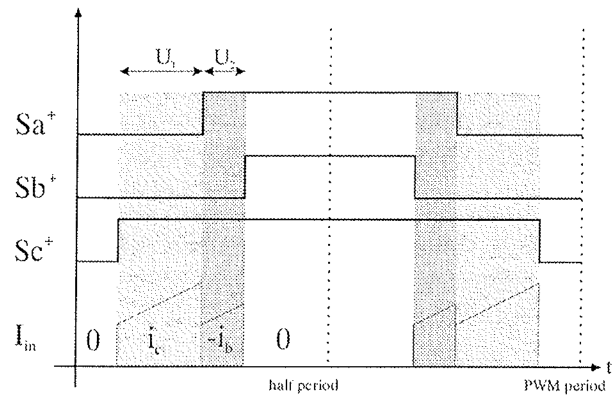

Figure 6. Signals controlling the upper transistors in a three-phase inverter

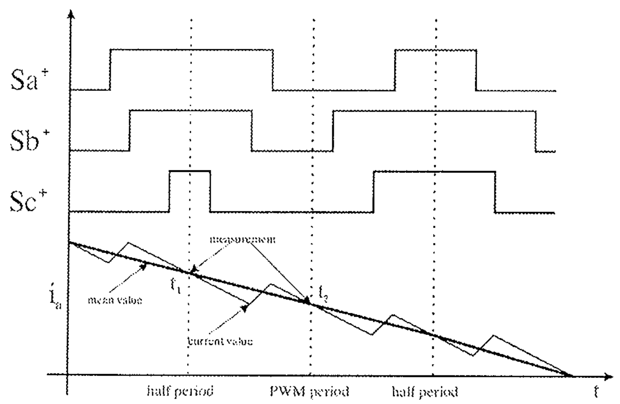

Figure 7. Correct measurement of phase currents in symmetric PWM

A signal processor placed on the main controller board drives the phase inverter and does all on board calculations for induction motor control. The VSI state is known at any time in the workflow. The same processor measures also induction motor phase currents. To avoid measurement errors due to the ripple current caused by PWM modulation of the sinusoidal phase current, symmetrical PWM modulation is implemented. The measurement of the phase current takes place at a half period when all upper transistors are switched on and at periods where all lower transistors are switched on and there is no battery current flowing into the inverter (Figure 6). The average phase current is calculated based on two measurements at times t1 and t2 (Figure 7).

In each sampling period, the correct sector has to be determined and the length of the U1 and U2 stator voltages has to be calculated (Figure 6). Determining the actual sector the inverter is in; the correct direction of the line current can be defined. When this is known, the average battery current can be calculated for that period:

$$\bar{I}_{in} = \frac{i_{phase1}(Sa,Sb,Sc)\cdot U_1 + i_{phase1}(Sa,Sb,Sc)\cdot U_2}{T_{half\_period}} \quad (6)$$

The sampling frequency of phase currents for battery current reconstruction is 50Hz.

5 Measurement results

In order to evaluate the proposed method of the battery SOC estimation algorithm, several measurements were made in field. They were carried out on a forklift truck powered by a 24V lead-acid battery manufactured by Fiamm (12 cells, 375Ah at C/5). The battery was fully charged before each discharge cycle with a laboratory charger. The cycle tests were done under various working conditions. The truck was accelerating, decelerating, lifting load and driving on different slopes to match normal operating conditions.

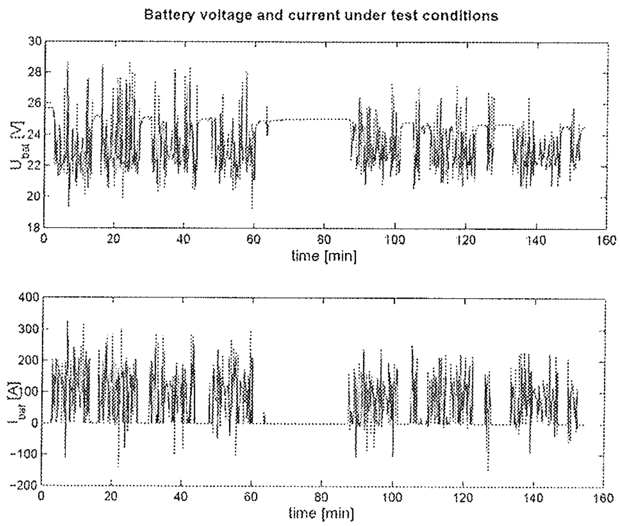

Figure 8. Battery current and voltage under test conditions

Thus, the battery was not discharged at a constant but at a time-varying rate (Figure8). During discharge, the ampere-hours were measured with a BRUSA BCM 400 ampere meter and logged every 10 minutes. At the same time, the estimated SOC based on ampere-hours calculated within the main truck controller were logged on a laptop computer connected to the main truck controller over a serial communication interface. The measured ampere-hours were then compared to ampere-hours calculated by the truck main controller. As can be seen in Figure 9, the accumulation error increases at the end of the discharge cycle, where the error between the measured and calculated ampere-hours rises to 2%. These results show reliability due to the known battery capacity and quite new battery pack used in the test. In old batteries, this error can increase, since they can no longer provide the rated capacity. In a separate discharge cycle open-circuit voltage estimation tests were made. After each discharge cycle, the battery was put to rest to fully stabilize in order to measure the actual open-circuit voltage (Table 2). After each 5% of discharge, a rest period of two hours took place to allow for correct measurement of the open-circuit voltage. As demonstrated in graphs 9 and 10, the proposed technique of the SOC measurement gives very satisfying results, as the error between the actual and estimated SOC never exceeds 5% (Figure 10). To provide for a comparison, values obtained with the old algorithm are plotted in Figure 10. As it can be seen, by using the new algorithm, accuracy is improved by more than 15% compared to the old one. This is mainly due to continuous measurement of battery consumption in terms of ampere-hours drawn form the battery.

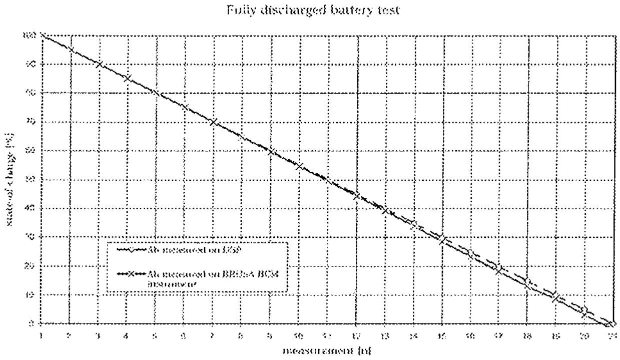

Figure 9. SOC measurement results based on Ah measurement

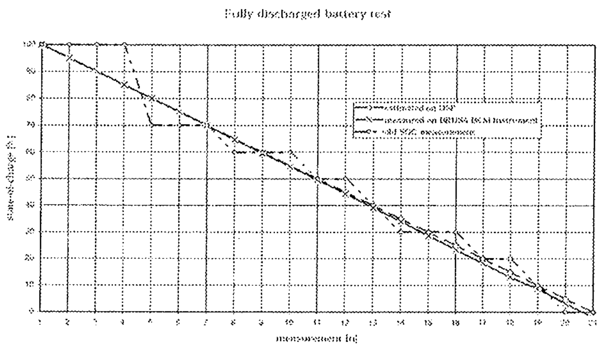

Figure 10. SOC measurement results improvements

Estimated Voltage	Estimated SOC	Error
23,78	0,19	0,01
23,74	0,172	-0,008
23,78	0,19	0,01
23,85	0,225	0,045
23,74	0,172	-0,008
23,75	0,175	-0,005
25,25	0,925	0,035
25,21	0,907	0,018
25,14	0,872	-0,018
25,14	0,872	-0,018
25,25	0,925	0,035

Table 2. Estimated open circuit voltage after different loads were disconnected from the battery at 18% and 89% of actual SOC respectively.

6 Conclusion

This paper addresses issues related to the battery SOC estimation of lead-acid powered forklift trucks. It shows that the use of the coulometric method for calculating SOC allows continuous monitoring of the battery pack also when the truck is running. Combining this method with the open-circuit voltage method improves the overall accuracy as shown by the obtained measurement results. The proposed open-circuit voltage estimation method shortens the time needed to accurately calculate the battery SOC and provides more flexibility to the truck driver and truck work-cycle performance. Its additional advantages are that there is no need for the battery capacity to be known, its age is not important, and the ambient operating conditions are not restrictive. Other fields of use are in solar modules, repeaters, and other remote equipment.

The paper also describes a simple technique to reconstruct the battery DC current from three-phase induction motor currents. It gives very good results and reduces the cost of additional hardware needed for accurate battery current measurement.

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Prispelo (Arrived): 09. 01. 2006; Sprejeto (Accepted): 30. 01. 2006