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Prognostics and Health Monitoring of Lead Acid Battery

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ABSTRACT

The ever-increasing number of electrical loads in the commercial vehicle emphasizes the significance of lead acid battery used for starting and the powering of electrical systems in a commercial vehicle. In order to monitor the health of the battery, parameters SOC (State of Charge) and SOH (State of Heath) are introduced. The existing methods to calculate these parameters use impedance monitoring based approach which requires an expensive current sensor. This paper describes a smart algorithm and the experimental verification of the algorithm that uses only voltage values for predicting the failure of the battery.The voltage waveforms during a cranking event is studied by the ECU (Engine Control Unit) and the health of the battery is determined based on it. A parameter, SOH measure is obtained from the algorithm and the value of this parameter reduces with increase in life of the battery. If the value of the SOH measure reduces below a threshold, then the failure of the battery is predicted before the actual failure.The algorithm is validated with the help of real time data obtained from the vehicles. This method of calculating the SOH is resourceful and cost-effective as it exploits the data that's already available in the ECU namely battery voltage and ambient temperature. Thus, it does not warrant an addition of sensor to the system in place.

KEYWORDS: Lead acid battery; ECU (Engine Control Unit); SOH; Prognostic; Engine cranking.

Introduction

Lead acid batteries have become a reliable technology through the years and is widespread among all industries. The ability to supply high discharge currents and the simplicity in design makes lead acid batteries best suitable for automotive SLI (Starting, Lighting and Ignition) application. At the time of starting the vehicle, lead acid battery powers the starter motor and after the engine is cranked, the alternator charges the battery as per the demand from the system. The anode and cathode are Lead (Pb) and Lead oxide (PbO_2) respectively and Sulphuric acid (H_2SO_4) is used as an electrolyte. While discharging the battery, lead sulphate ($PbSO_4$) is obtained with H_2O as byproduct and during charging lead sulphate thus formed is reduced to lead and lead oxide. The chemical reaction for discharging and charging is explained in equation 1 and equation 2 respectively.

$$\boldsymbol{Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_20} \quad \text{.....(1)}$$

$$\boldsymbol{2PbSO_4 + 2H_20 \rightarrow Pb + PbO_2 + 2H_2SO_4} \quad \text{.....(2)}$$

Failure modes and Lead acid Battery Aging

The average life of a commercial vehicle battery is 1-2 years[1]. The health of the battery is affected by many factors with distress to the material being the foremost one. Continuous deterioration of health of the battery leads to its failure. The major failure modes of the lead acid battery include positive grid corrosion as an effect of overcharging and operating in increased temperature. This leads to the increase in the internal resistance and decrease in the discharge voltage[3].

Hastened charging and discharging and prolonged discharged periods result in formation of $PbSO_4$ crystals on the cathode[3]. Oxidation of cathode reduces the capacity of the battery. Other failure modes of the lead acid battery include loss of electrolyte, short circuits and porous anode and cathode.

Thus, undesirable chemical responses cause a reduction in the health of the battery with the effects of these responses being irreversible[3].

Parameters for Monitoring Battery Health

In order to monitor the health of the batteries, accurate monitoring of battery parameters is essential. The battery parameters aid us in knowing the current state of the battery that in turn assists us in prognosis of the battery failure. Important battery parameters used for this algorithm are State of Charge (SOC) and State of Health (SOH)[7].

State of Charge determines the remaining capacity of the battery and this is expressed in percentage (%). If nominal capacity of the battery is the amount of charge that can be stored in the battery, then SOC is defined as

ABBREVIATIONS: SOC – State of Charge; SOH – State of Health; ECU – Engine Control Unit; BCU – Body Control Unit; SLI – Starting, Lighting and Ignition; OCV – Open Circuit Voltage; CAN – Controller Area Network the ratio of the battery's current capacity to the battery's nominal capacity.

$$SOC = \frac{Current\ capacity\ of\ the\ battery}{Nominal\ capacity\ of\ the\ battery} \times 100 \qquad .....(3)$$

State of Health is a parameter that defines the present condition of the battery compared to its perfect conditions. It is defined as the ratio of nominal capacity of the battery to the rated capacity of the battery. It is also expressed in terms of percentage and a fresh battery has a hundred percent SOH.

$$SOH = \frac{Nominal\ capacity\ of\ the\ battery}{Rated\ capacity\ of\ the\ battery} \times 100 \qquad .....(4)$$

Voltage Waveforms during Engine Cranking

A typical voltage waveform at the time of cranking can be seen in figure 1. The values shown are taken in a 184kW engine that is cranked with the help of a 24V, 6.5kW starter motor. The ambient temperature during the measurement was 33°C. It can be seen that the battery voltage reduces at the time of cranking as it supplies power to the starter motor. Once the engine is cranked, the alternator coupled with the engine switches ON and hence the battery voltage recovers to a nominal value.

At the time of cranking, the battery displays an ohmic behavior as the current values are proportional to the voltage values. Hence, the battery can be modelled as shown in figure 2 in a simpler manner as compared to Thevenin's battery model having double layer capacitor and change transfer resistance.

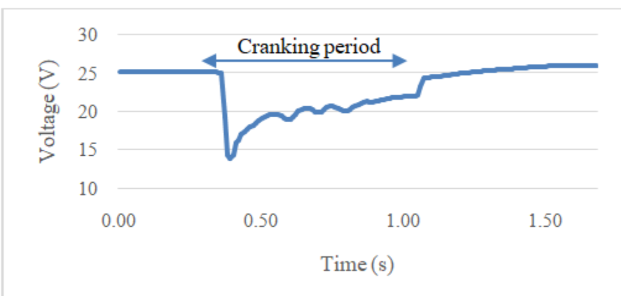

Fig. 1. Typical voltage waveform of a commercial vehicle at the time of cranking.

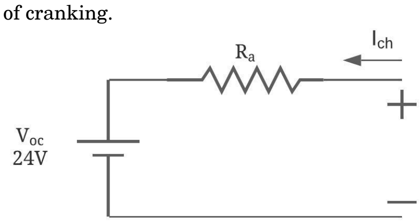

Fig. 2. Ohmic model of the lead acid battery.

In Figure 2, V_{oc} represents the open circuit voltage of the battery which is approximately 24V for commercial vehicles. R_a and I_{ch} denotes the ohmic resistance and direction of the charging current respectively.

Need for the Work

The implementation of this algorithm serves the customer in numerous ways in terms of downtime and monitory benefits. When the life of the battery degrades beyond a limit, the vehicle does not start as it does not have the ability to power the starter motor. The service life of the battery expires without any warning to the customer. Using this algorithm, the user is notified before the actual failure and hence the battery changeover downtime is reduced.

When the vehicle is in operation with an unhealthy battery, the electrical loads have an impact on them. Major electronic components in the vehicle such as ECU, BCU (Body Control Unit), sensor and electrical loads might malfunction because of an unhealthy battery which leads to inadmissible consequences such asreduced life span and overheating[2].

Theory

The outline of the proposed algorithm is represented in figure 3. The algorithm begins by detection of a cranking event. Once the cranking event is detected, battery failure prediction analysis is initiated in the ECU. The voltage waveforms of the battery voltage during the cranking event is analyzed and two valley voltages V_a and V_b are obtained.The first two local minima in the cranking voltage waveform are voltages V_a and V_b. The voltage before the cranking event is measured as open circuit voltage V_{oc}. The value of V_{oc} helps in the calculation of SOC measure. If the value of SOC measure is above 60%, SOH measure is calculated.

After the engine starts, the algorithm proceeds for further evaluation. Calculation of SOH measure involves inputs from various directions. From voltages V_a, V_b, ambient temperature and the SOC measure, the value of SOH measure is calculated. If the value of the SOH measure is less than the threshold value, the battery is identified to be unhealthy and the driver or the fleet manager is notified with the help of tell-tale on a possibility of battery failure. This notification can be in the form of tell-tale in the driver cabin or via telematics unit to the electronic devices. In case of a healthy battery i.e. SOH measure is greater than the threshold value, the algorithm returns to the beginning.

The battery voltage values are available and are monitored by the ECU. Thus, it can be seen that the algorithm involves inputs from the ECU and does not require an addition of a sensor to the system in place.

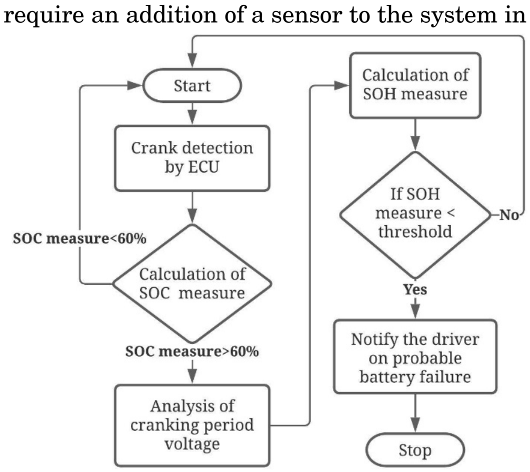

Fig. 3. Algorithm overview and flowchart for calculating SOH measure.

Calculation of SOC measure

Open circuit voltage (OCV) is defined as the potential difference between two terminals when no load is connected across them i.e. no electric current flows between the terminals. The open circuit voltage of the lead acid battery helps in the calculation of SOC. When the vehicle is not operational, the current drawn from the battery is in terms of milliampere (mA) and hence it is disregarded for the calculation of OCV.

The proportional relationship between the lead acid cell voltage and the concentration of the sulphuric acid is well reputable. According to lead acid battery chemistry, a relationship between specific gravity of the electrolyte and SOC of the battery[2]. Linking both relationships, the correlation between OCV and the SOC of the 24V auto-motive SLI lead acid batteries is established in table 1.

TABLE 1

Relationship between SOC, specific gravity of sulphuric acid and Open Circuit Voltage.

State of Charge (%)	S.G.	Open Circuit Voltage (V)
100	1.265	25.1
75	1.225	24.4
50	1.190	23.5
25	1.155	22.2
0	1.120	19.5

Methodology

ECU monitors the battery voltage at the frequency of 200 Hz which implies the time period of data sampling is 5 ms. In order to eliminate the noise out, moving average of two data samples is calculated for the algorithm. When there is a brief drop in the battery voltage of greater than 5 V, a cranking event is detected. Post detection of a cranking event, two consecutive local minima are obtained and are denoted as V_a and V_b. Mathematically, these values are obtained if consecutive data samples follows the following conditions.

$$V1 - V2 > 10\ mV \quad \text{.....(5)}$$

$$V2 - V3 > 10\ mV \quad \text{.....(6)}$$

$$V4 - V3 > 10\ mV \quad \text{.....(7)}$$

$$V5 - V4 > 10\ mV \quad \text{.....(8)}$$

In equation (5), (6), (7) and (8) V1, V2, V3, V4 and V5 represent five consecutive data samples. If the consecutive data samples follow this algorithm, V3 is taken as V_a and on further execution of the same conditions, V_b is calculated. The conditions for a cranking event are checked with an actual commercial vehicle and it is represented in figure 4. From the figure, the value of V_a can be calculated as 13.94 V.

Calculation of SOH Measure

The calculation of SOH measure involves values of Va and Vb from the cranking voltage analysis, open circuit voltage and the ambient temperature. The difference between the open circuit voltage and the value of Va is termed as dV1. Similarly, the difference between Va and Vb is termed as dV2. In figure 5, the illustration of open circuit voltage, Va, Vb, dV1 and dV2 are shown in a cranking waveform data taken from an actual commercial vehicle.

Ambient temperature plays an important role in calculating the SOH measure. Having same values of SOH measure for the same battery operating at different temperatures might mislead the user on battery failure prediction. From ambient temperature, a new parameter, V_{temp} is calculated from table 2.

It should be noted that the values in the table are given for a 24V commercial vehicle battery and the value of V_{temp} can be increased or decreased proportionally based on the nominal voltage of the battery considered.

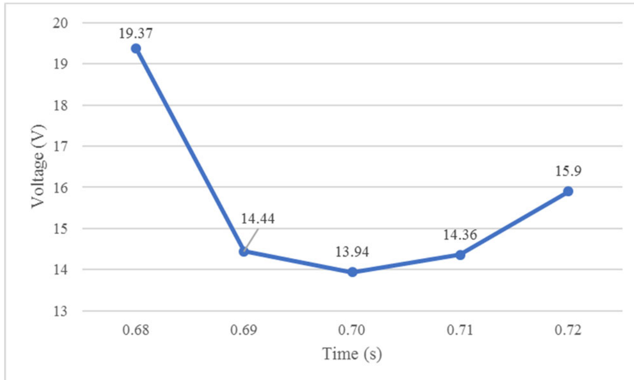

Fig. 4. Calculation of local minima voltage V_a.

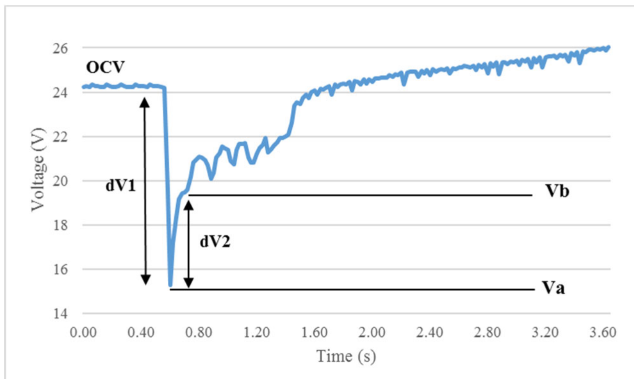

Fig. 5. Illustration of the parameters used for the algorithm.

TABLE 2

Relationship between ambient temperature and Vtemp.

T (°C)	-30	-20	-10	0	10	20	30	40
Vtemp (V)	0	0.1	0.2	0.4	0.6	0.8	0.8	0.8

The next parameter that gets introduced in the algorithm is Vdiff. This parameter is calculated from the values of dV1. The value of dV1 is about 6 V for a healthy battery and if it gets excessively more than that value, then the battery is considered unhealthy, irrespective of the battery's recovery performance. The values of Vdiff for different values of dV1 are given in table 3.

TABLE 3

Relationship between dV1 and Vdiff.

dV1 (V)	2	4	6	8	10
Vdiff (V)	-0.16	-0.09	-0.02	0.05	0.12

Similar to the previous relationships, Vdiff values for intermittent values of dV1 can be calculated with a regression equation. Finally, SOH measure parameter is calculated with the help of equation (9). The parameters, Vtemp and Vdiff are added together and the difference between dV2 and the sum is calculated for obtaining SOH measure.

$$\boldsymbol{SOH\ metric} = \boldsymbol{dV2} - (\boldsymbol{Vtemp} + \boldsymbol{Vdiff}) \qquad .....(9)$$

If the value of the SOH metric is positive, the battery is considered to be healthy and in case of a negative SOH metric, the battery is considered to be unhealthy and the hence the driver or the fleet manager is notified.

Results

The algorithm for monitoring the SOH of the lead acid battery has been verified in a commercial vehicle and the comparison betweenan old and a new battery are discussed herewith. The commercial vehicle used for the verification is a truck having a lead acid battery of 24V nominal voltage. The major parameter used for this algorithm is the battery voltage which is already available in the ECU at the rate of 200Hz.

The cranking waveform of a new and an old battery are represented in the figure (6) and (7) respectively. The old battery has been in the vehicle for approximately one lakh kilometers of operation. It can be seen that the OCV of both the batteries are above 24V and hence the SOC of the batteries are over 60 % as per table (1).

Parameters V_a and V_b i.e. the local minima are obtained as per the equations (5), (6), (7) and (8) and from those values, dV1 and dV2 are calculated. Using look-up tables (2) and (3), Vtemp and Vdiff are achieved and finally using equation (9), SOH measure parameter is realized.

From table (4), the SOH measure of the old battery that has run one lakh kilometers is considerably lesser than the SOH measure of the new battery. On further usage of the old battery, the SOH metric would further reduce and reach the threshold. This happens due to the reduction in the recovery local minima voltage, Vb if the value of Va holds same. Similarly, the trials were done using new and old batteries and the results obtained are in conformance to the algorithm established.

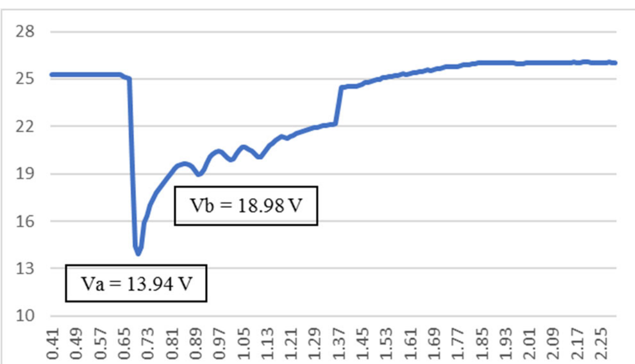

Fig. 6(a). Cranking waveform of a new battery.

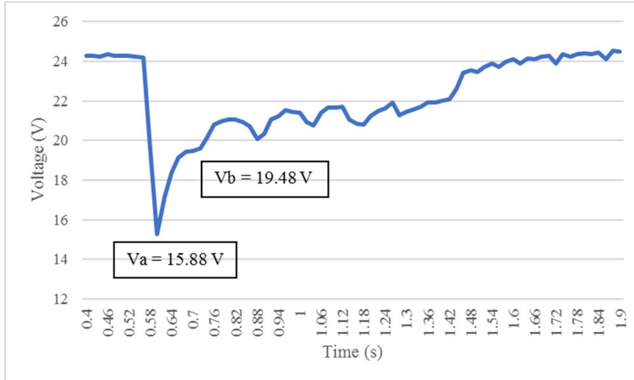

Fig. 6 (b). Cranking waveform of an old battery.

TABLE 4

Calculation of SOH measure

Parameters	New Battery	Old Battery
Va (V)	13.94	15.88
Vb (V)	18.98	19.48
OCV (V)	25.26	24.19
dV1 (V)	11.32	8.31
dV2 (V)	5.04	3.60
Ambient Temperature (° C)	33	33
Vtemp (V)	0.8	0.8
Vdiff (V)	0.24	0.052
SOH measure	4	2.75

Conclusions and Future work

SOH monitoring and prognosis of lead acid batteries are becoming highly significant because of its applications and reliability concerns. This paper best describes the outline of an algorithm that predicts the failure of the lead acid battery with available data from the ECU without having an additional sensor in place and the devised algorithm was proved with data from a commercial vehicle. The sampling rate for the required data is already available with the ECU. Hence the battery potential can be measured in this sample rate during cranking and SOH measure can be computed inside ECU. Though the threshold for SOH measure is zero as per theory, an apt cutoff for SOH measure will be narrowed down based on experimental investigation.

The practical results taken in a commercial truck also show an accordance to the algorithm and prove that the algorithm is effective in predicting the failure of the lead acid batteries. More data from actual vehicles can improve the algorithm in all perspectives to make it more reliable for the end user. With constructive additions to the algorithm on temperature dependencyand analysis of cranking waveforms, the accuracy in predicting the failure of the lead acid batteries will increase and become more dependable.

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