Lead-acid Battery State Sensor ～Development of Battery Full Charge Detection Technique With Internal Resistance～

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ABSTRACT After we succeeded in launching the lead-acid battery state sensor as the only one supplier in Japan, we have been making our best effort in improving the accuracy to gain more market share. From the viewpoint of controlling the automotive fuel efficiency and securing the reliability of the automotive power source, we think that it is definitely most important to detect the battery charge rate (SOC = State of Charge). It is necessary to combine several different elemental techniques to improve the estimated accuracy of the SOC. One of the typical ones among these techniques is the full charge detection. Its purpose is to detect that the battery reaches almost full charging state and set the SOC at the point as Full-Charge 100% to be the starting point from there on. Therefore, this accuracy will influence the whole estimated accuracy from there on. We have developed our original full charge detection technique applied from our original detection index "resistance ratio" which is based on the combination of the internal resistance increasing at charging and our battery equivalent circuit model learning technique from the pulse discharge. And we have succeeded in improving the SOC detection accuracy. Here, we are going to report the outline of our success mentioned above.

1. INTRODUCTION

Recently in the automobiles, the power source has been required to be more reliable, as more and more electrical and electronic components are adopted and the optimum fuel efficiency control is getting common as well. It is also getting common to equip with the lead-acid battery state sensor which monitors the state of an automotive battery to secure its reliability. We, as the only one supplier of this lead-acid battery state sensor in Japan, launched our first Battery State Sensor (BSS) in 2012 and have already shipped more than 10 million in the cumulative total until now. In near future, a major change is expected in the structure of the overall power source system because higher quality of the power source is required for the automatic driving. And the market scale of lead-acid battery state sensors is expected to continue growing. Along with the growing market, we are making our best effort in improving the performance of BSS to be more competitive to gain more market share. Figure 1 shows an example of our products.

It is the most fundamental function required to the BSS to estimate the charged rate (SOC=State of Charge) at any point in time against the full charge capacity. The improvement of the accuracy and reliability of this function against the current level is always demanded because it is not only the index of the power supply ability of the battery at this point but also the basic information applied to the optimal fuel efficiency control of a vehicle represented by the start-stop control. It is necessary to combine several different elemental techniques to realize the improvement of accuracy. One of the very important ones among these techniques is the full charge detection which detects that the battery reaches almost full charge state. It plays not only to improve the SOC estimation accuracy but also to cancel the accumulated estimation errors to secure the stable power supply ability by detecting signs of the battery approaching its full charge state to switch the SOC to 100% or the value of Full Charge 100% which seems more certain. The full charge detection is very important because it influences the SOC estimation accuracy. And almost every company makes efforts in constructing the optimal detection logic of it as well.

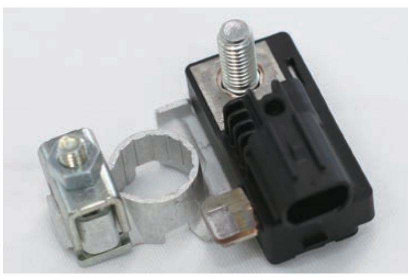

Figure 1 Battery state sensor (made by FAS).

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We found out that a battery had such characteristic as the internal resistance at charging increased when approaching the full charge state and focused on it. Further, we combined it with our original battery equivalent circuit model[1] learning technique by pulse discharging to design our original detection index "resistance ratio". We have developed such technique as to maintain the accuracy by applying it even for any battery of different sizes or made by different manufacturers. In addition, we have developed the correction technique against main outer error factors in the detection together with it and have succeeded in developing the logic as well to maintain the accuracy in the practical range of automotive environment.

2. SOC ESTIMATION AND FULL CHARGE DETECTION

Unfortunately, it is impossible to measure the SOC (=the amount rate of electricity charged in a battery) directly in an actual vehicle. Therefore, it is necessary to estimate it by calculation with the BSS based on the information of current, voltage and temperature which can be directly measured under the automotive environment. This is the most important function required to the BSS. There are two important pillars for the estimating calculations: one is the calculation of the change of SOC based on the amount of electricity in and out of a battery and the other is the calculation of SOC based on the stable Open Circuit Voltage (OCV) which has a linear relation with the SOC of a lead-acid battery[2]. However, we have to solve some problems to secure the accuracy in a lead-acid battery equipped in an actual vehicle. First, as for the current integration, the error of full charged capacity is cumulated when converting the amount of electricity in and out to the percentage of SOC. The full charged capacity is decreasing little by little with the deterioration of the battery and it becomes an obstacle to secure the SOC accuracy. Equation (1) shows the relation between the SOC and the full charged capacity.

$$SOC = (\text{the amount of electricity charged / full charged capacity}) \times 100 \quad (1)$$

Next, as for the linear relation between a lead-acid battery and the stable OCV, we can say, first of all, that it is difficult to measure the stable OCV accurately under the actual automotive environment. It is caused by the condition of a battery that either charge or discharge current is always flowing to and from it during the actual operation of a vehicle and the over voltage is added to it. It is almost impossible to measure the stable OCV directly except for such a case of a weekend driver because a long inactive time without any current flowing is necessary until the over voltage has dissipated. We have already developed our original technique[3),4)] to estimate the stable OCV based on the dissipation process of the over voltage and succeeded in reducing the SOC estimation error. But we have not solved the error perfectly, yet. As the value of SOC against the voltage varies in each individual battery, it is practically impossible to equip a battery sensor with the relation logic adapted to each individual battery mounted in a vehicle. This individual difference generates the SOC estimation error. Further, along with using a battery, the relation may change from the initial condition caused by the influence of changes in the concentration and the deterioration of its electrolyte.

It is a general method to secure the stable performance of the power source under restrictions on the accuracy that the SOC is switched to the value of 100% or Full-Charge 100% at the point when detecting the full charge condition of SOC around 100% and setting this as the starting point and that the calculation & control is carried out to control the SOC within a certain range based on the starting point. And in addition to the method mentioned above, in order to maintain the accuracy of SOC estimation, the OCV-SOC relation is matched to fit a mounted battery with making use of the function of the full charge detection to control the individual difference between the stable OCV and the linear relation and those errors generated by changes caused by the deterioration.

3. CONTENTS OF DEVELOPED TECHNIQUE

3.1 Full Charge Detection With Applying the "Resistance Ratio"

As mentioned above, the full charge detection of a battery has been applied ever since, and the behavior of current during charging has been mainly applied to it as a specific technique. Figure 2 shows an example of the relation between the SOC and the charging current of four batteries different in sizes and made by different makers when charging under the same condition with no influence from any disturbance.

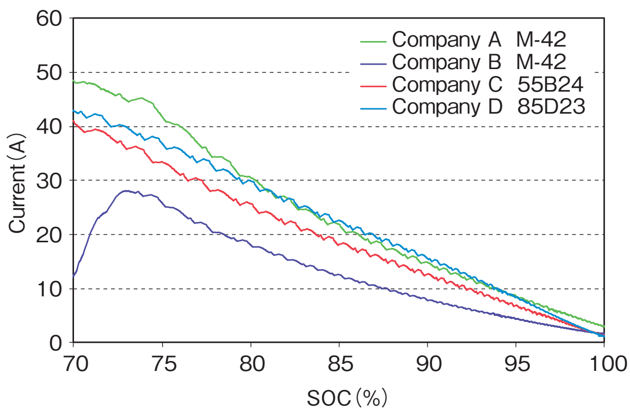

Figure 2 Relation between the charging current and the SOC.

As shown in Figure 2, the charging current of a battery is decreasing along with the progress of the charge and the increase of SOC. The detection techniques to use the decrease of current as an index are most generally and frequently applied. On the other hand, as shown in Figure 2, it is difficult to set a clear threshold, because the curve of decreasing current following the increasing SOC slopes very gently down to zero. And when setting the same current threshold, such a case was known that there was a large difference in the relation of the charging current and the SOC even if the sizes of batteries were the same. An example shown in Figure 2 shows actual gaps between each SOC as large as 93% to 98% when setting the threshold current at 5 A. Naturally enough, the error becomes much larger when considering the influence of disturbance. Therefore, it is estimated that highly accurate detection of the full charge cannot be realized with only setting a simple threshold on the current value.

At first, we tried to use the resistance at charging as an index to improve the accuracy of detection mentioned above. Equation (2) shows our way of thinking of the resistance at charge *R_charge*.

$$R\_charge = \Delta V / I \qquad (2)$$

ΔV : Difference between the charging voltage and the open circuit voltage
I : Charging current

There is a merit to adopt the resistance as an index as the detection sensitivity is improved and as easy setting of the threshold is realized because the resistance value is highly increased in the shape of a hyperbolic curve along with the decrease of current as the current is a denominator of the equation.

And as a corrective action against the error in the current behavior at charging caused by individual difference of each battery, we tried to combine the charging resistance with the internal resistance gained from the equivalent circuit model learning technique by the pulse discharge which is a feature of our BSS. An example of the equivalent circuit model of a lead-acid battery is shown in Figure 3.

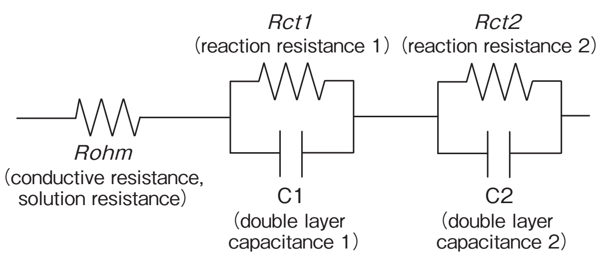

Figure 3 An example of the equivalent circuit model.

One of the great pillars for our lead-acid battery state detection technique is to learn the equivalent circuit models including every resistant element in a battery by carrying out the pulse discharge during an idle period of a vehicle and the state of battery is estimated based on this learnt information[5]. As the pulse discharge internal resistance during an idle period of a vehicle is reflecting the size of battery, the difference of the designed internal resistance value, and the changes caused by the deterioration, we thought that the influence caused by the individual difference of batteries could be improved if correcting the resistance value at charging with the information of internal resistance measured by the pulse discharge. As a result of examination, we designed our original index, that is the resistance ratio = *R_ratio* and adopted it. Our way of thinking of the resistance ratio (*R_ratio)* is shown in Equation (3).

$$R\_ratio = f\,(R\_charge,\ Rohm,\ Rct1) \qquad (3)$$

"f" is a function to calculate "*R_ratio*", and "*Rohm*" and "*Rct1*" learnt by the pulse discharge and the charge current resistance "*R_charge*" are given to the "f" as its input. As shown in Figure 3, *Rohm* reflects the conductive resistance of a mounted battery and *Rct1* reflects the reaction resistance at the pulse discharge. The relation between the resistance ratio *R_ratio* and the SOC calculated by the optimized equation and coefficients is shown in Figure 4.

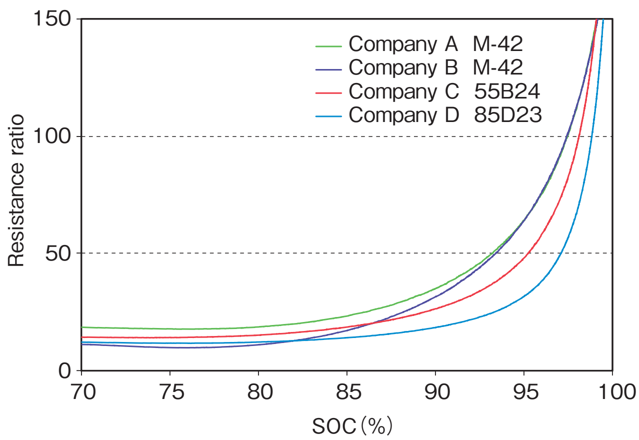

Figure 4 Relation between *R_ratio* and SOC.

When setting 120 as a threshold of the resistance ratio at which the average period required until detecting the full charge from start of charging is as same level as that in case of the detection at current 5 A shown in Figure 2, the range of actual SOC was as small as 97% to 98%, that is, the estimation error has become only one fifth of that in the case of applying a simple current value as an index. In this way we have realized the detection at a high sensitivity but with little influence from the individual difference of batteries.

3.2 Influencing Factors to the Full Charge Detection

The relation curves shown in Figure 4 above are the results after charging under the same condition. However, the relation between the resistance ratio and the SOC may change depending on the difference in the actual operating environment. The difference will be major factors to cause disturbance errors. There are three major factors as mentioned bellow.

1) Temperature
2) SOC at initial charging
3) Charging voltage

The result of each influence is explained as follows.

Figure 5 shows an example of the relation between the resistance ratio and the SOC based on the various temperature levels when other conditions than temperature (SOC at initial charging = 70%, charging current = 14.4 V) are fixed.

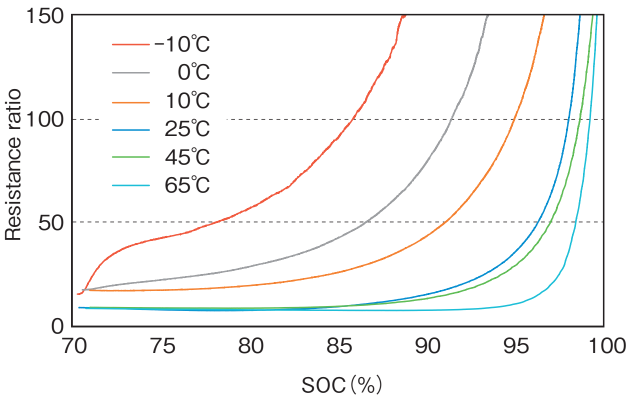

Figure 5 Difference of the relation between the resistance ratio and the SOC caused by the different temperature.

Figure 5 explains that the lower the temperature becomes, at the lower SOC the resistance ratio tends to increase. When assuming the threshold is 120, there is a gap of 87% to 99% in SOC at –10°C to +65°C even if the sensitivity and the accuracy are improved by using the resistance ratio. Therefore, no full charge detection can be correct unless the proper SOC value shall be set in accordance with the temperature when the temperature varies.

As shown in Figure 6, lower the SOC at initial charging becomes, at the lower SOC the resistance ratio increases. When setting the threshold at 120 and assuming the SOC at initial charging = 30% which will occur extremely seldom in an actual vehicle, there will be the gap of 73% to 99% in the SOC at detection. Therefore, no full charge detection can be correct unless the proper SOC value shall be set in accordance with the SOC at initial charging when it varies as well as the temperature.

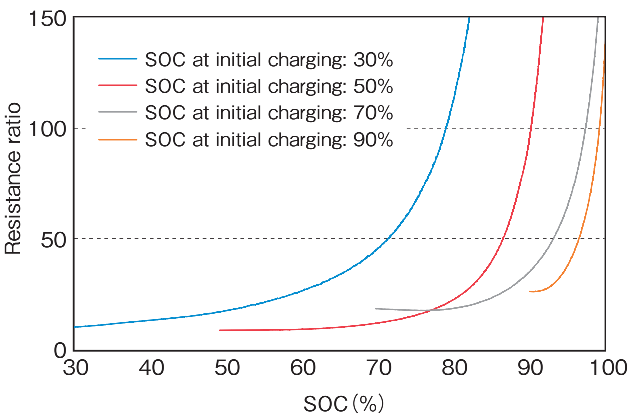

Figure 6 Difference of the relation between the resistance ratio and the SOC caused by difference of SOC at initial charging.

Next, Figure 7 shows an example of the relation between the resistance ratio and the SOC based on the various charging voltage levels when other conditions than charging voltage (temperature=0°C, SOC at initial charging=70%) are fixed.

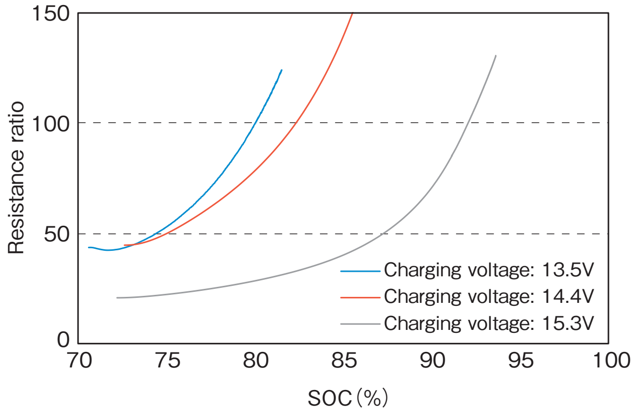

Figure 7 Difference of the relation between the resistance ratio and the SOC caused by difference of charging voltage.

As shown in Figure 7, the lower the charging becomes, at the lower SOC the resistance ratio increases. When setting the threshold at 120 and assuming the charging voltage as 13.5 V to 15.3 V, the range of SOC at detection is 82% to 95%. Therefore, it explains that no full charge detection can be correct unless the proper SOC value shall be set in accordance with the charging voltage when it varies as well as either the temperature or the SOC at initial charging.

As mentioned above, our originally designed resistance ratio is successful in realizing the high accuracy against batteries various in their sizes and manufactures when charged under the same condition. However, it is necessary to add proper correction by considering the error factors caused by disturbance, those are 1) temperature, 2) SOC at initial charging and 3) charging voltage in order to maintain the accuracy even if the condition varies under the actual automotive environment.

3.3 Counter Measures Against the Influencing Factors

We have adopted such logic against those three error factors mentioned in the former chapter, that carries out the calculation fundamentally based on our way shown in Equation (4) below.

Full charged SOC = g (R_ratio, temperature, SOC at initial charging, charging voltage) (4)

"g" is a function to calculate the SOC when detecting the full charge, and each of the error factors, temperature, the SOC at initial charging and the charge voltage are input to the "g" as well as the resistance ratio R_ratio as its input. Those three error factors were explained one by one in Figure 5 to Figure 7 shown above. However, influence caused by each error factor is actually not independent but affected each other. The degree of influence may change linked with the change of other conditions, while there are no changes in the trend of individual influence. Therefore, the actual equation becomes very complex. Our fundamental way of thinking is explained based on an example of our corrective action against the influence of charging voltage adopted at the last.

In Figure 8 shown below, the estimation error when estimated in the range of temperature from −10 to +65°C and the SOC at initial charging=70 to 90% based on the equation which has already included the countermeasure against the influence caused by the SOC at initial charging and is based on the assumption that the charging voltage is fixed at 14.4 V. As it can be estimated from the trend shown in Figure 7, the actual SOC tends to be lower than the estimated value when charging at low temperature and it looks like as if a positive error is added on the estimated value.

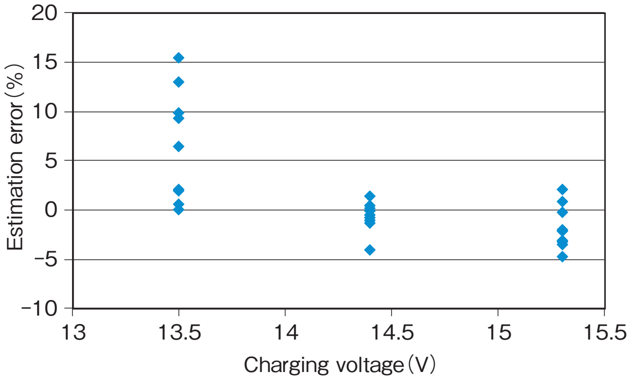

Figure 8 Error of the full charge detection when ignoring the charging voltage.

The degree of errors varies because the degree of influence caused by the charging voltage varies depending on the other conditions mentioned above. Typical trend of the influence to the SOC at the full charge detection is shown in Figure 9.

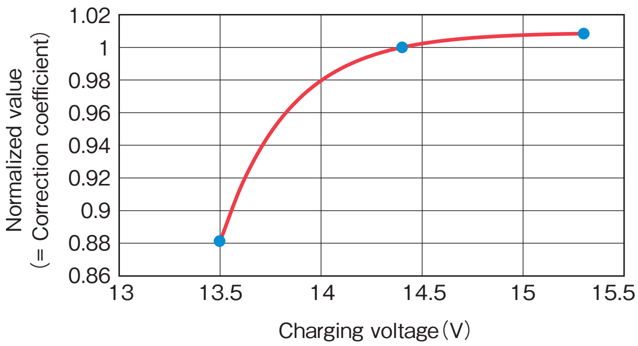

Figure 9 Normalized SOC at full charge detection against various charging voltage.

Those dots shown in Figure 9 are the relative values of averaged SOC actually measured when detecting the full charge of a battery under a single resistance ratio and normalized in order to set the charging voltage 14.4 V as the standard value 1. The curve plotted over the actually measured dots is the output of the function to which the charging voltage is entered as its input. If applying this function, the predicted relative value at any charging voltage can be calculated based on the value at 14.4 V charging. Using it as the correction coefficient, the estimated SOC adopted on the assumption that the charging voltage is 14.4 V can be corrected to be the estimated SOC corresponding to the actual charging voltage.

Our basic thought on the correction against the influence of charging voltage is mentioned above. However, the absolute value will change with keeping the trend shown in Figure 9 when the condition varies, although the temperature and the SOC at initial charging are fixed at a certain condition. In order to make it able to consider the difference in the degree of influence on the charging voltage caused by temperature and the SOC at initial charging, it is necessary to calculate the correction coefficient by the 4-dimensional function to which the charging voltage, temperature and the SOC at initial charging are entered as its input after carrying out the same analysis as shown in Figure 9 under many conditions and investigating the relation of the coefficient against temperature and the SOC at initial charging to replace the coefficient of the function which calculates the correction coefficient for the influence of charging voltage to the function of temperature and the SOC at initial charging. As it is difficult to visualize a complete 4-dimensional function, an example of SOC at initial charging=70%, a 3-dimensional curved surface of correction coefficient against charging voltage and temperature is shown below in Figure 10.

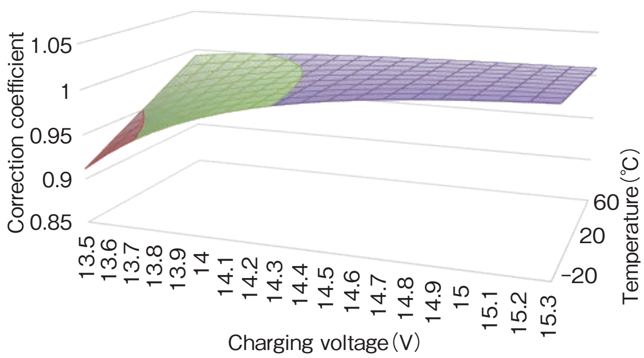

Figure 10 A 3-dimensional curved surface of correction coefficient vs. charging voltage and temperature.

Our way to correct the influence of charging voltage has been already mentioned above. That of the temperature is about the same and that of the SOC at initial charging is as well. Integrating all of those mentioned above, the equation (4) is finally completed. Using the equation (4) which even includes correcting the influence of charging voltage, we have improved the errors shown in Figure 8 to be those shown in Figure 11 below.

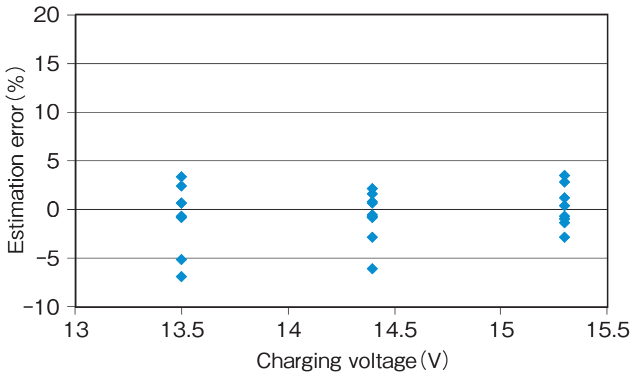

Figure 11 Error of the estimated full charge when considering the charging voltage.

The full charge detection with the maximum error range from +3.35% to −6.03% has been realized by our theoretical calculation based on our evaluation data tested on a total of 18 batteries of various models in the range of the battery temperature=−10°C to +65°C, the SOC at initial charging=70% or more, and the charging voltage =13.5 V to 15.3 V.

4. CONCLUSION

As mentioned above, as a result of that we have made use of the merit of our equivalent circuit model learning technique based on our original pulse charging method to introduce our original index “resistance ratio” and that we have combined the correction techniques against the three disturbance factors at the full charge detection such as 1) temperature, 2) SOC at initial charging and 3) charging voltage, we have succeeded in the development of the highly accurate full charge detection technique which is stable in the practical range of the temperature, the SOC at initial charging and the charging voltage. However, on the other hand, in the actual automotive environment, we have no such stable charging as that in our assumed environment where our logic was adopted and there are not only the charging voltage switched step by step but also busy switching between charging and discharging. As a matter of fact, in our logic loaded on an actual vehicle, the weighted averaging process was added to secure the equivalent accuracy based on the current data and the voltage data typical in an actual vehicle. Even though, a guard function is equipped to bypass the processing when it is judged as difficult to maintain the accuracy. Further, it is required to continue improving the logic to be freer from any restriction and easier to use.

And in our full charge detection, it is required to add no less than a certain quantity of charging to reach the threshold. In general, the nearer the threshold is set to SOC = 100% strictly, the higher the accuracy of SOC at the detection can be. But on the other hand, the longer period is required to continue charging. We have already improved this problem with introducing our original index resistance ratio. However, as there is an infinite variety of how to use a vehicle. It is applicable to have a very accurate estimation with setting the strict threshold in such a vehicle like a taxi as is expected to have a long operating time almost every day. But on the other hand, in such a vehicle as is used only for dairy shopping, the function falls into such condition that it seldom works. As a matter of course, it is preferable to set the threshold reached in a short time from the viewpoint of frequency of functional operation, but such detection is meaningless since it cannot maintain the required accuracy. To make appropriate responses to the problem mentioned above, it is necessary to be able to judge objectively the accuracy against the range and the probability of securing the functional operation based on not only our logic but also statistical data about the operation time of vehicles driving all over the world as the background.

Furthermore, the full charge detection technique is one of the elemental techniques to realize the SOC estimation. The final target is to secure the accuracy of the SOC estimation. It is necessary to make well-balanced improvement of the accuracy of other related techniques further and to develop such techniques as to make car manufacturers of our customers happy as well.

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