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Modeling of Lead-Acid Battery Bank in the Energy Storage Systems

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***Abstract*— The use of lead-acid batteries in large numbers and large size has many applications in industry. One of the most important applications, make a battery bank for energy storage systems. In an energy storage system, a large number of battery cells are parallel and series together and a load to feed. Behavior in a set of batteries is different from a single battery. In this paper, a novel model for modeling the battery bank in the energy storage system is presented. According to company data, Simulation results show that this model is corrected.**

***Keywords*— Energy storage system, Lead-acid battery, Battery bank, Charger, Charge and discharge curve.**

I. INTRODUCTION

Lead acid batteries due to the cheap price compared to other batteries and extend the range of available capacity are one of the best electrical energy storages. Using batteries in large number and scale as propulsion power of vehicles such as ships, submarines and electric vehicles is expanding. Energy storage systems in a wide range of applications such as uninterrupted power supply units (UPS), support systems, and uninterruptible power supply and also as propulsion system power supply locomotives, ships and electrical submarines have been used [1]. For example, the batteries which use in underwater vehicles are lead-acid batteries because of their advantages such as less cost of production, more diversity, more endurance during charging and discharging operation and proper electric efficiency. Lead-acid batteries have an appropriate cell voltage (2V/cell) and correspondingly high energy efficiency. The energy stored in a lead-acid battery is chemical energy which is converted to electrical energy [2]. Lead acid batteries, can be charge and discharged with high current [3]. The energy converted by chemical reaction (equation 1) is performed [4].

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \qquad (1)$$

In this paper, for modeling the battery from a modified model of lead-acid batteries used.

State-of-charge (SOC) is the capacity that remaining in a lead acid battery and it is considered as an important parameter of a battery. SOC can be estimated with the help of battery modeling [6]. Researchers, many models have been considered to represent the battery behavior. But in general, the battery is modeled by a voltage source and an internal resistance. In battery modeling, one changed model of previous lead-acid battery used. In addition for charging battery bank with 500AH (Ampere Hour) capacity which contains 220 batteries (each 2 volt) in series is used 31.5KVA, 50Hz and 380 volt diesel generator. The reason of selecting these kinds of battery and diesel generator are parameters and requirement information availability for simulating and comparison answers obtained possibilities. The information of the battery bank is obtained from the reference [5]. The results of simulations and comparison obtained data with battery manufacturing company's data, shows the modeling is correct.

II. BATTERY MODELING

For modeling the battery, a modified model is used. In most papers for modeling the battery from the variable voltage source and a fixed resistance used. The experimental results and catalogue battery manufacturers show this resistance is not constant but, the change in resistance is small and it can be assumed constant. In the energy storage system, due to the large number of series battery, regardless of these changes will be longer. Consequently, the effect of these changes should also be considered in the modeling. Lead-acid battery is having a 2 volt cells. The number of cells with respect to the voltage level is set. For example, to feed a 220 volt tree should be set Together 110 cells. After discharge the cell voltage decreases. This voltage reduction is in accordance with charge and discharge curves. To charge a battery bank, charging and discharging curves should be considered. One sample of these characteristics for some type of lead-acid batteries has been shown in figure 1. In the following diagrams, 'C' is battery capacitance per ampere hour and numbers have been shown on curves are discharging current. For example if the 12volts battery discharging with (I=0.05C) it discharges after 20 hours & (q=0) &(V=10.5).

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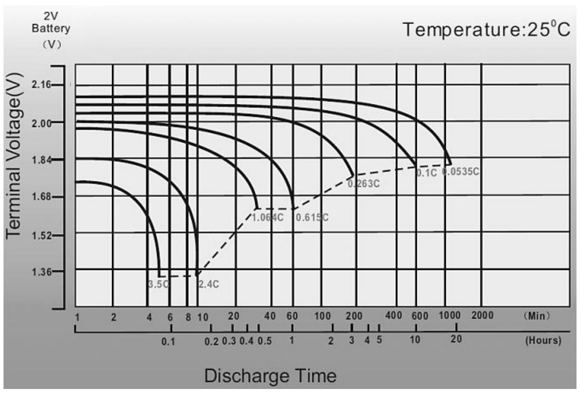

Fig. 1 Discharge curves of real battery [5]

Some references represent the models which described batteries dynamic behavior [6] [7] [8]. Battery model should track charging and discharging curves precisely. Representing model in [3] is static model with constant parameters that predict charge and discharge curves with one level of accuracy. The static voltage on battery (q), battery current (I_{batt}), state of charge (SOC), internal voltage (E_{in}) and terminal voltage (V_{batt}) equations represent as follow:

$$I_{batt} = \frac{dq}{dt} \tag{2}$$

$$SOC = 100\frac{q}{Q} \tag{3}$$

$$E_{in} = E_0 - K\left(\frac{Q}{Q-q}\right) + Ae^{-Bq} \tag{4}$$

$$V_{batt} = E_{in} - R_{batt}I_{batt} \tag{5}$$

In these equations Q, E0, K, A, and B are constant which depend on battery type. The integral of current obtains the charges with the number between low limit of zero and high limit which determines by battery capacitance (Q). Fig. 2 shows the model of battery in simulation. In Figure 4, both voltage and resistance values are variable and are a function of the SOC. Voltage dependence of the SOC is determined by charge and discharge curves. Also, the battery internal resistance curve is given by the battery manufacturer.

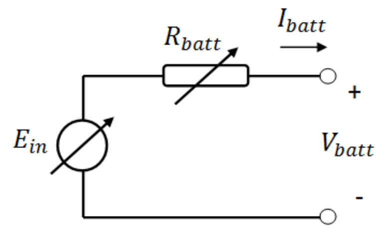

Fig. 2 Suggested Battery model

Fig. 3 represents the resistance curve of battery which is the function of charging status. As is known, with the battery charging, its internal resistance is reduced. This non-linear curve is dependent on SOC and has been considered in the modeling of this article. Other environmental parameters affected in the model the batteries. Parameters such as temperature, pressure, and battery age, but usually assumed to be standard conditions for the batteries and therefore these parameters are not considered for simplification.

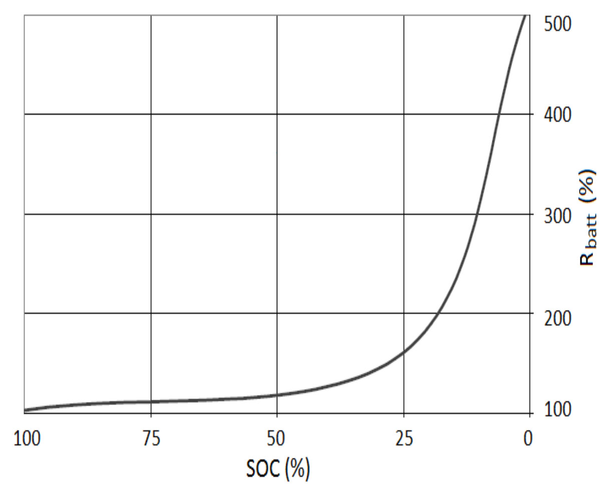

Fig. 3 Resistance curve based on the battery charge status

III. BATTERY CHARGING

Mainly lead-acid batteries are charged in three ways:

- Constant Voltage,
- Constant Current,
- Combination of constant current and constant voltage

In Combination of constant current and constant voltage, first method is used in beginning of the process and second method is used in end process.

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In constant voltage method, constant voltage which is slightly more than the rated voltage, applied to battery. In this case, the charge current may be is too high in the beginning of the process and cause to reduce the battery life. In constant current method, battery charges with constant current which is selected in the range between 0.05C and 3C. Selected constant current depends on charge process speed which is needed. In the combination method, first battery charges with constant current and then charges with constant voltage. If the constant current value and constant voltage value are selected properly, this charging method can be optimum in term of adaptive objective function. Obviously combination method required more complex control structure. Fortunately lead-acid batteries are less sensitive than charging current in compared with other batteries. Due to low price of lead-acid batteries in compared with others, these batteries are charging with one of three methods unwary. In this paper battery charging simulation has been done with constant current method.

IV. SIMULATION RESULTS

The simulated battery bank contains 220 lead-acid batteries which are connected in series. The capacity of each of them is the Q=500Ah and nominal voltage of total of them is 440 volts. The resistance of each battery in a complete charging state is R_{fc} =0.006mΩ. The constant parameter of equation 4 is achieved as E0=488.7, K=24.2 and A=B=0 by predicting charging and discharging curves in figure 4. Simulated charging and discharging curves have been shown in figure 4.

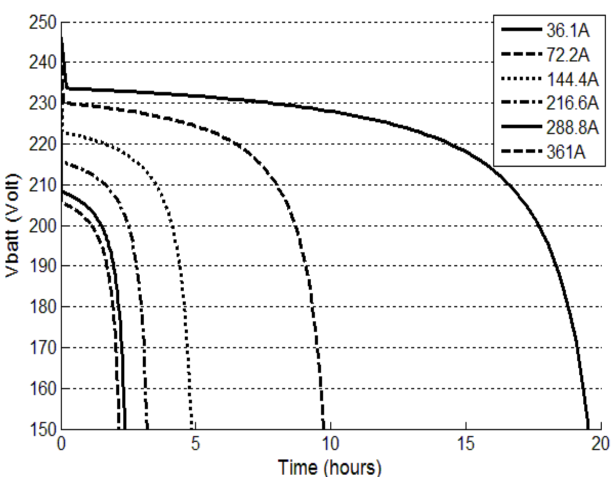

Fig. 4 Charging and discharging curves of the battery bank

Figure 9 shows a real curve of coefficient of internal resistance of the battery and predicted one. The real curve has been shown with filled circle which is plotted by testing in the laboratory. The value of internal resistance of the battery is equal to resistance of battery in a fully charged state multiplied by the coefficient of internal resistance ($R_{batt} = R_{f\,c} \times K_r$). As is clear value of internal resistance of battery in discharged state is 4 times greater than its value in a fully charged state. For demonstrating the effect of this change in resistance and error caused by that it's enough if this value is multiplied by the number of batteries, the resistance of each battery and charging current.

According to the curve in figure 3, coefficient of internal resistance R_{batt} versus state of charge SOC can be predicted by polynomial function. Regarding to the curve in figure 3 minimum degree of function for fitting is 3. Appropriate degree of predicted function of internal resistance of battery curve is 5 because of model accuracy and simplicity. This curve fitting is done by MATLAB. The third and fifth degrees of predicted functions are plotted in figure 5.

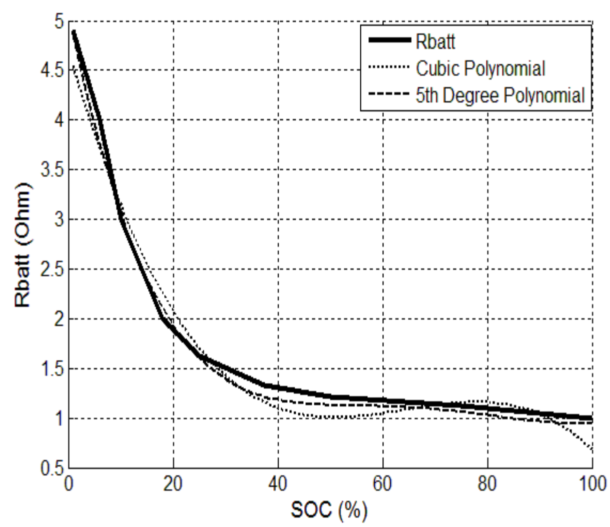

Fig. 5 the predicted curves for R_{batt} curve

The effective value of error and total mean square errors of these fitted functions have been shown in table 1. The equation 6 shows the coefficients related to fifth degrees fitted function.

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TABLE I
FITNESS PROFILE OF PREDICTED FUNCTIONS

Fitted function	Effective error value	Total mean square errors
Third degree	0.2932	0.2422
Fifth degree	0.1449	0.0629

$$R_{batt} = R_{fc} \times [(-7.51\times10^{-10})SOC^5 + (4.18\times10^{-7})SOC^4 + (-7.9\times10^{-5})SOC^3 + (67\times10^{-4})SOC^2 + (-0.265)SOC + 5.128] \quad (6)$$

R_{fc} is resistance fully charged. Figure 4 shows the coefficient batteries curve during the charging process.

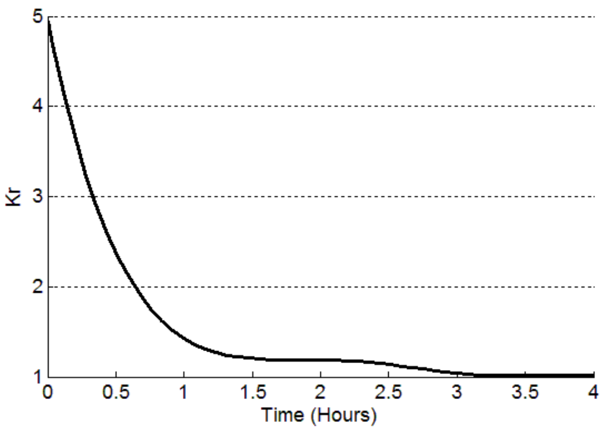

Fig. 6 Internal resistance of the battery bank

In figure 7 to 13, the charging process for the proposed model has been done. Figures 7 and 8 relating to the charging current is constant. Figure 7 voltage and figure 8 shows the battery bank charging. In this section, the constant current charge is equal to 0.1 C considered.

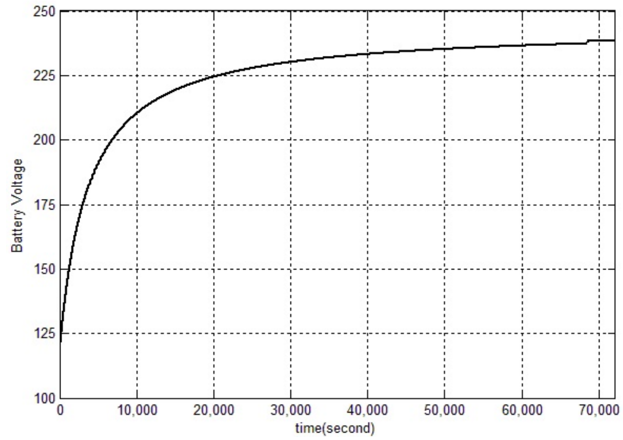

Fig. 7 Voltage of the battery bank

Battery voltage to the gassing voltage increases. After a jump start battery bank voltage gas that the charge should be stopped at this time. Subsequently, the voltage of the battery bank has a jump at this time should be to stop the charging process. Because extra charging battery caused the reduce battery life. As is clear in Figure 8, the initial charge of the battery bank is assumed 5%.

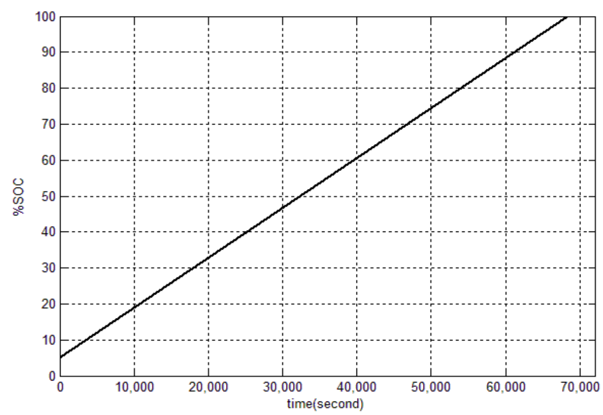

Fig. 8 SOC of the battery bank

Figures 9 and 10 relating to the charging voltage is constant. Figure 9 current and figure 10 shows the battery bank charging. In this section, the constant voltage charge is equal to 238 volt.

EXPLORING RESEARCH AND INNOVATIONS

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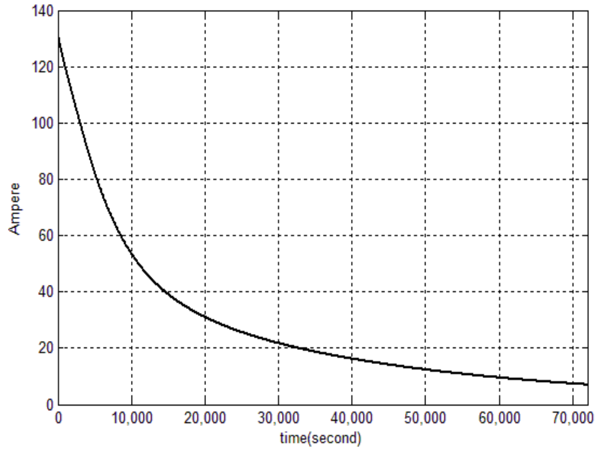

Fig. 9 Current of the battery bank

In Figure 9, it is clear that the constant voltage charging method, as the current decreases exponentially.

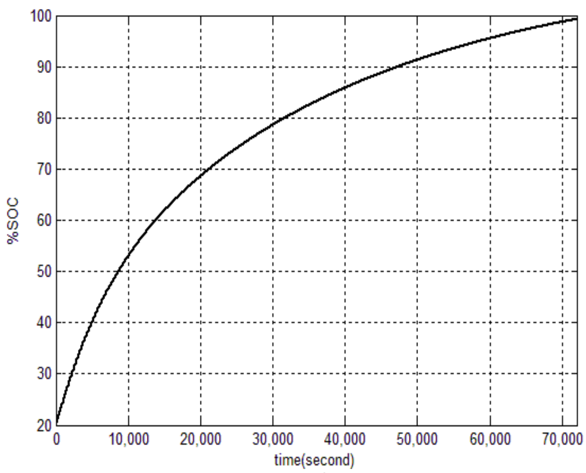

Fig. 10 SOC of the battery bank

Figures 11 to 13, the combination of constant current - constant voltage is shown. In this way, the batteries are recharged with a constant current and after reaching the rated voltage, with voltage higher than rated voltage (slightly more) are charged. Figure 11 the charge current, Figure 12 state of charge and Figure 13 shows the voltage at the battery bank. This method is actually a combination of the two previous methods, which has more benefits compared to they are.

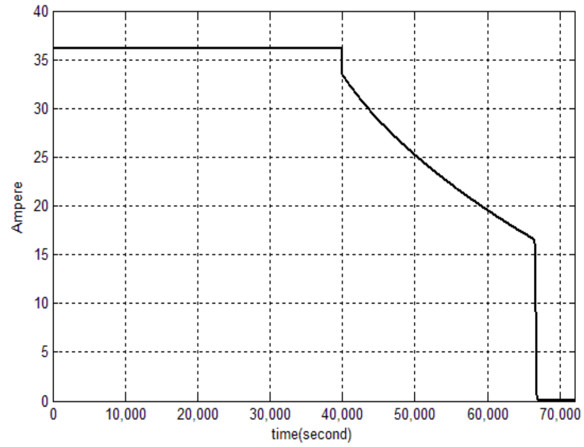

Fig. 11 Current of the battery bank

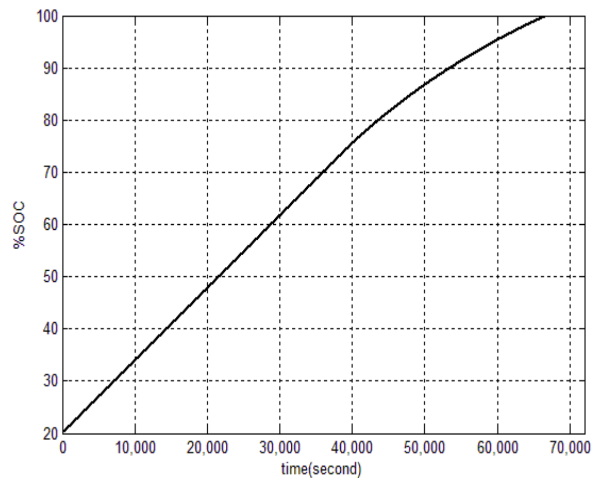

Fig. 12 SOC of the battery bank

In Figure 12 the initial state of charge the battery bank, 20% is assumed. From the Figures 4 and 8, can be understood that voltage for charging the battery bank, 5 and 20% respectively, 125 and 213 volts and they are quite in accordance with the battery manufacturer Curves.

In Figure 14, curves are provided by the manufacturer that the battery is fully in accordance with simulation results.

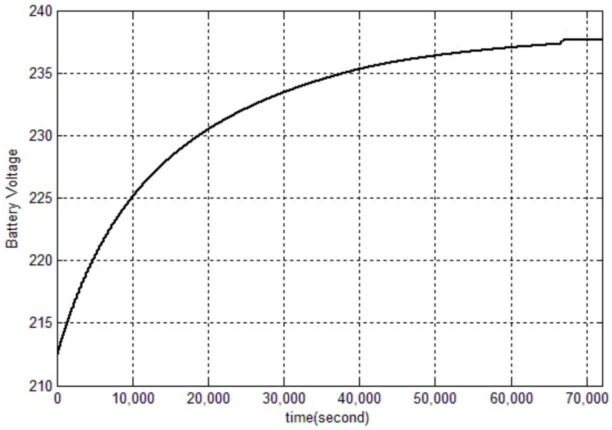

Fig. 14 Voltage of the battery bank

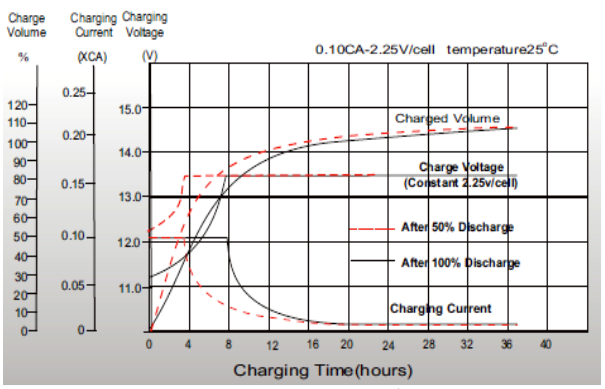

Fig. 15 Current, voltage and SOC curve of the actual battery bank [7]

V. CONCLUSION

In this paper a new modeling was performed for a lead acid battery bank in the energy storage system. In most modeling related Lead-acid batteries, internal resistance, considered to be fixed. In an energy storage system, a huge bank of batteries may be composed from the large number (About several hundred batteries) of batteries. In this case, the fixed internal resistance of batteries is something wrong. Hence, in this paper for modeling the battery bank, this resistance is considered a variable. Internal resistance of the battery depends on the state of charge that in modeling, the battery manufacturer's data, has been considered. Simulation results and conform it to battery manufacturer's catalogue, Represents the correctness the modeling has been presented.

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