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Failures analysis and improvement lifetime of lead acid battery in different applications

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***Abstract*—This paper reviews the failures analysis and improvement lifetime of flooded lead acid battery in different applications among them uninterruptible power supplies, renewable energy and traction applications. In fact, the performances and lifetime of battery are important parts in these energy systems. Over time, the performances of lead acid battery are deteriorated and caused the limit of the service life. In this context, the authors propose an approach to identify the critical failure modes of lead acid battery according to the application duty cycle. The knowledge acquired on these battery degradation modes allow properly propose some recommendations as ways for eliminating or reducing the identified failure modes for each application. These recommendations based on the improvement of manufacturing process and incorporation an appropriate charge cycle. The appropriate charge cycle is based on the multistep current profile that reduces the degradation of battery by ensuring the full state of charge and avoiding the overcharge risks.**

***Keywords*—lead acid battery; failure mode; lifetime; charge cycle; manufacturing;**

I. INTRODUCTION

Lead acid battery is the main source of electrical energy storage with a wide range of applications such as uninterruptible power supplies, renewable energy and traction applications. In renewable energy applications, lead acid batteries are used to address the problems of the electric power in terms of stability, quality and dependability [1]. Similarly, the quality and stability problems of a grid in uninterruptible power supplies can be processed by the connection of lead acid batteries [2]. Concerning the traction applications, the advent of vehicle "more electric" or hybrid contributes to the uses of lead acid batteries for provide all or part of the energy requirements depending on the rate of hybridization and mission of the vehicle [3].

The use of lead acid battery in different applications poses a problem related to the degradation of their performances and the limit of the service life [4,5]. These reasons make the lead acid battery as the weak link and the most expensive component of the system. The main objective of this paper is to analysis the failure modes of the lead acid battery and improves their lifetime in different applications. In this context, the different applications of flooded lead acid battery are firstly studied. Then, the critical failure modes of the lead acid battery for different applications are discussed. In the third part, the author proposes corrective actions during the manufacturing process and during lead acid battery operation to reduce their degradation and extend service life according to the duty cycle. In this context, an appropriate charge cycle is developed that ensures the full state of charge and protects against the overcharging risks.

II. DIFFERENT APPLICATIONS OF FLOODED LEAD ACID BATTERIES

The flooded lead acid batteries can be classified according to the application types in the following main categories: stationary battery, renewable energy storage battery and traction battery. Each of these applications of lead acid battery has its own distinctive duty cycle that presents in this section.

The stationary battery used in uninterruptible power supplies (UPS) systems ensures the supply electrical of sensitive loads in case of power supply failure such as: power cuts, short interruptions voltage and voltage drop, micro power cuts, overvoltage, etc. In this case, the battery provides power from a few seconds to one hour through a DC/AC converter. In normal operation, the battery is continuously charged from the grid through an AC/DC converter until the full state of charge in order to immediately intervene in case of grid failure. The classic way of maintaining the full state of charge is the "floating": by imposing on the battery a higher voltage than the open circuit voltage [2].

In the renewable energy applications, the fluctuating energy problems can be solved by connecting lead acid batteries that provide or absorb a power. In case of high output power of source, the renewable energy is transferred through a DC/DC converter controlled by MPPT to supply the load and charge the battery. When the output power of the source is insufficient, the battery supplied the power to the load until the maximum discharge capacity is reached [6].

Among the traction applications, lead acid batteries are widely used in hybrid electric vehicle. A hybrid electric

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vehicle comprises two propulsion members; an electric engine and an internal combustion engine. The energy storage devices associates to these two engines are: electrical energy storage (battery) and fossil energy storage (fuel tank). The development of hybrid vehicle provides the functions such as stop-start, Zero Emission, boosting and regenerative braking. The regeneration of braking is a means for recovering part of the kinetic energy of the vehicle through the alternator mode of the electric machine in order to charging the lead acid battery. This energy can also be used for other functions such as boost mode. In this application, the battery operates under high rate partial state of charge (HRPSOC) rather than from a fully charged condition. In fact, the battery cannot supply the required starting current when the state of charge (SOC) is low and it cannot accept charge efficiently either for high SOC [7]. In stop-and-go function, the engine is stopped each time the vehicle is stopped, and is restarted when the accelerator is pressed again. The "Zero Emission" mode is used in the start-up phases of the vehicle, the electric engine can completely replace the internal combustion engine for propelling the vehicle at low speed by using the battery [1].

III. Research Of Critical Causes Of Flooded Lead Acid Battery Degradation By Causal Tree

The use of the flooded lead acid battery in uninterruptible power supplies, renewable energy and traction applications is in fact the weak point of the system because of the gradual degradation of performance and the limit of their lifetime. The main degradation modes of flooded lead acid battery are stratification of electrolyte, sulphating of electrodes, corrosion phenomena, non cohesion of active mass and loss of electrical connection [4,8].

The sulphating of the electrode indicates the growth of lead sulphate crystals ($PbSO_4$) in size. This creation of large crystals reduces the amount of active mass available and thus the available capacity. In other hand, the non uniform distribution of electrolyte concentration creates a stratification of electrolyte wherein the acid is frequently more collected at the bottom of the battery. The stratification of electrolyte leads to reduce the battery capacity by concentrating the chemical reaction to specific parts of the electrodes [4].

The corrosion is the destruction of the metal under the action of the environment that caused by the dehydration phenomenon. This phenomenon appears when the level of electrolyte is too low that makes the electrodes in contact with the air and oxidizes [8].

The degradation of active mass and shedding create the non cohesion of active mass. The degradation of active mass is a process where the loosening of the active mass particles resulting in a loss of electronic conductivity. However, the shedding is a mechanical loosening of the active mass and the rest of the electrode.

The loss of electrical connection is caused by the vibration which produces fatigue failure, particularly between the cast on strap and pillar post. This failure is due to insufficient penetration of molten metal at the joint [9].

Some of the factors associated with these failure modes are related to fabrication process and operating conditions. The deficiency of battery capacity in the manufacturing process is accompanied by the low quality of paste, grid, and electrolyte, pasting, curing and drying process, formation, finishing [10]. The non cohesion of active mass can be refers to low quality of paste, pasting, curing and drying process. In addition, the low quality of the plate formation and the low quality of paste can contribute to the sulphating phenomenon. The low quality of grid and the low quality of the plate formation promotes the corrosion of the electrode and the low quality of the electrolyte facilitates the stratification phenomena during lead acid battery operation. However, the loss of electrical connection is due to improper selection of materials during finishing process.

The plates are formed by the application of the paste on the grids lead alloy in the pasting process. The paste of the plates is formed by mixing the lead oxide with water, sulphuric acid and additives. During the curing and drying process, the plates are transported to curing chamber in order to allow the suitable adhesion of the paste on the grid under controlled conditions of temperature, humidity and time. Then, the positive and negative plates with separators between them are assembled and placed in the battery case. The cells are connected with a metal that conducts electricity. The lead terminals or posts are then welded on. During the formation process, the battery case is filled with the electrolyte and connected to the power source in order to convert the cured paste of the plate into active mass. After the formation process, the batteries reach the finishing process where the electrolyte concentration is adjusted and the cover is attached [11,12].

All the types of flooded lead acid batteries suffer from the same damage mechanisms but with different degree depending on the particular conditions for each application. In this section, the critical failure modes for each application with their causes are identified.

In the uninterruptible power supply, the main requirement for the battery is to provide a high current for a short time because the emergency time for UPS systems is usually short. Therefore, a deep discharge of the battery is produced which causes the sulphating phenomenon. The ripples of the DC and AC voltage at the battery terminals also impose negative effects on their performance. The AC ripples are composed two types: discharge and non-discharge. They are of type " no discharge " when their amplitude is small compared to the amplitude of the DC component, otherwise they are of type " discharge ", and the ripples current becomes positive and negative. The ripples of DC and non discharge AC increase the internal temperature of the battery. Since, the discharge AC ripples leads to the battery charge-discharge cycles with a rate determined by the frequency of the AC signal, low frequency of AC ripples is particularly harmful to the battery and causes premature ageing [3]. However, the stationary battery undergoes continuous electrochemical reactions even after it is fully charged due to the float voltage that gives a relatively small charge current and causes mainly grid corrosion. Therefore, the most common failures of stationary lead acid battery are the positive plate corrosion by the overcharge, sulphating of the electrode by the deep discharge and the stratification of electrolyte.

In renewable energy applications, the intermittent nature of energy and non suitable charging cycle create extreme conditions for the state of charge of the battery which causes their failure. The sulphating is occurred when the battery is left in a low state of charge for a long period of time. The low state of charge may be accentuated by high battery usage because of too many amenities, deep and prolonged discharge. The corrosion of the electrode can result from a high ambient temperature and cycles of the order of seconds, minutes or hours depending on the source and used profile. Hence, the reliability problem of lead acid battery in renewable energy systems is the appearance of their overcharging and deep discharge which generates sulphating phenomena, corrosion of electrode and stratification of electrolyte [12].

In the traction applications, the lead acid battery encountered problems related to the negative plates. Under HRPSOC regime, the lead acid battery is infrequent at full charging in regenerative braking during the decelerating or stopping and provides a high rate of discharge in "Zero Emission" mode during starting and acceleration that accumulates a lead sulphate on the negative plate and fails quickly [1,7]. Therefore, the battery fails prematurely due to the sulphating of the negative plates. It was also reported that the negative lugs were corroded severely in these conditions [7]. On the other hand, the traction battery undergoes a lot of charge-discharge cycle that cause the non cohesion of active masse. The particular condition of traction applications generates also the vibration mode of failure due to wear and tear of the road. These vibration causes fatigue failure, particularly between the cast on strap and pillar post leading to loss of electrical connection [9]. Hence, the use of the lead acid battery in traction applications shows the non cohesion of the active mass and the loss of electrical connection; and generates new failure modes like the negative plate sulphating due to HRPSOC.

This qualitative analysis of battery degradation in the different applications allows identifying the critical failure modes according the application. These critical failure modes for each application are summarized in Table I and their causes are described by a causal tree in Fig.1.

IV. Improvement Of Battery Lifetime

The previous section illustrates the causes of lead acid battery degradation for different applications by causal tree. Each of the above causes exerts an influence on the performance of the lead acid battery and their lifetime. In this section, the authors propose corrective actions in order to reduce the degradation phenomenon and extend the battery lifetime.

TABLE I
Critical Failure Modes Of Flooded Lead Acid Battery For Different Application

	Traction battery	**Stationary battery**	**Renewable energy storage battery**
Stratification of electrolyte	-	+	+
Non cohesion of active mass	+	-	-
Corrosion of the electrode	-	+	+
Sulphating of the electrode by deep discharge	+	+	-
Sulphating of the electrode by incomplete charge	+	-	+
Loss of electrical connection	+	-	-

A. *Improvement Of Battery Lifetime During The Manufacturing Process*

The capacity and lifetime of the battery depend greatly on the structure of the active mass. Hence, improvement the lead acid battery quality requires applying corrective actions during the various manufacturing processes.

The stationary battery should have thick plates with high paste density where high energy and power are not requested, but the capability of long living on float or moderate overcharge is an important. In fact, the main failure mode of stationary battery is the corrosion of electrode due to the high self-discharge rate. Therefore, several studies have been done to reduce the high self-discharge rate of the negative electrode in batteries with antimony in the positive grid alloys. Since the other metals like tin, antimony, calcium, silver are inserted into the grid composition in order to improve the toughness as well as the resistance against corrosion. Low antimony 0.5-3.5%Sb with Se, Te, S, Cu, As, Sn (Al) are used to decrease of Sb contamination at negative electrode in UPS applications. The use of standard calcium 0.06-0.12%Ca 0-3% Sn, (Al) avoids also the Sb contamination at negative electrode [13].

On the other hand, the low quality of electrolyte facilitates the stratification of the stationary and renewable energy storage battery. In this context, the improvement of the electrolyte quality can be provided by adding boric acid H_3BO_3 (<0.4wt%) in the electrolyte solution prevents hard $PbSO_4$ formation and reduces self-discharge of the positive electrode [5]. The addition of phosphoric acid in combination with 2.2wt% or 4wt% of colloidal silica in the electrolyte decreases the acid stratification on cycling at high discharge rates and prevents softening of the positive active mass. The sulphating of negative electrode can be decreased by improvement the quality of paste where the addition of barium sulphate (0.8-1wt%) and polyaspartate (<0.05wt%) facilitates the formation of small crystals of lead sulphate ($PbSO_4$).

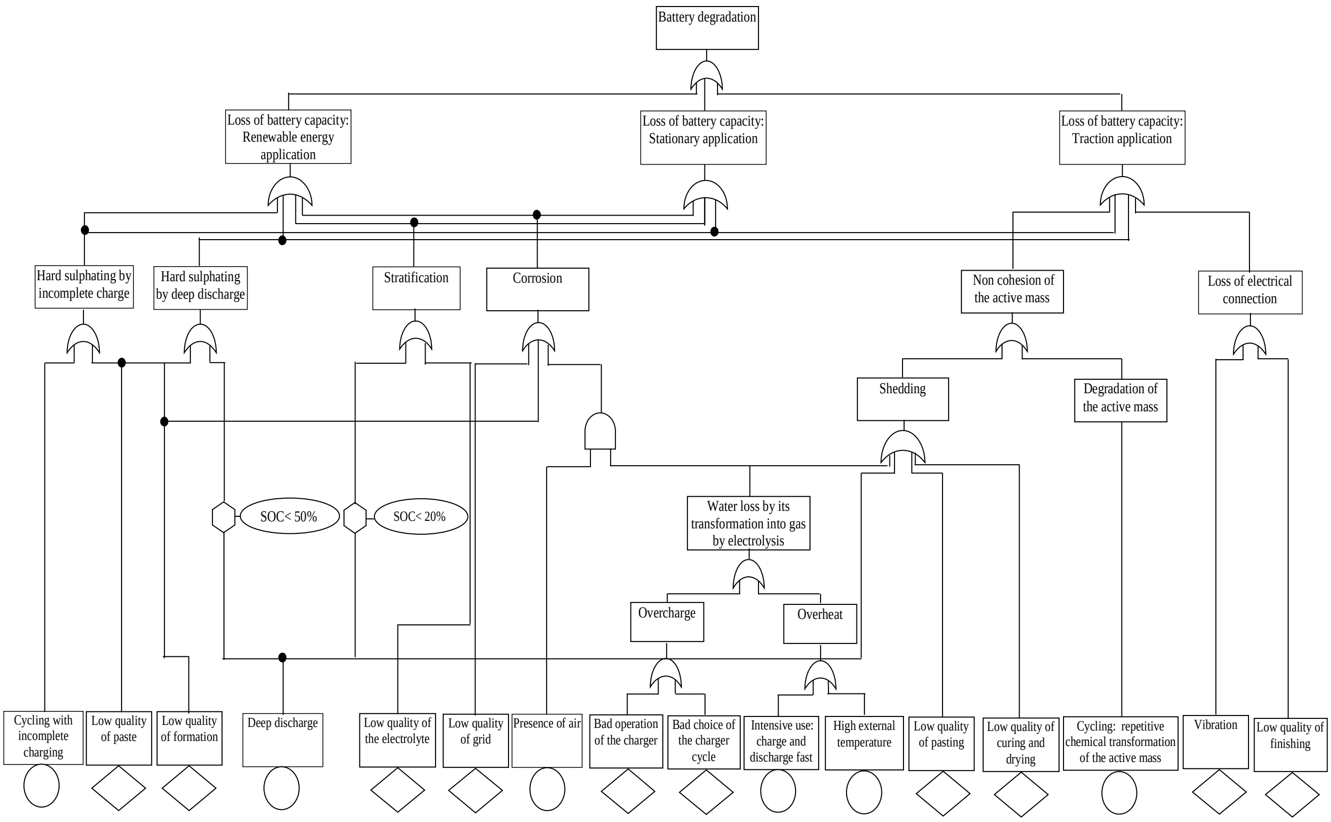

Fig. 1. Causal tree of the critical failure modes of lead acid battery

The lead acid battery used in electrical vehicle must be able to withstand long cycling, while featuring high energy density. They must be constructed with thick plates supporting high-density pastes, electrochemically formed in low-density acid solutions. The main failure mode of traction battery is the non cohesion of the active mass. It must have a good quality of the pasting, curing and drying processes in order to eliminate or reduces the non cohesion of the active mass by controlling the climatic conditions (controlled temperature, etc) that improve the quality of the plate texture. In addition, the battery performances are strongly predetermined by the paste type used for the manufacture of the plate. The better active mass is generally obtained from a cured positive paste 4BS that has a high output power performance with a longer lifetime than that of the plates with a cured positive paste 3BS [12].

The reduction of the non cohesion of the active mass can be take place also by the addition of additives during the mixing process in order to improve the paste quality such as porosity and conductivity. The addition of diatomite (3-5wt%) and glass microspheres (1.1-6.6wt%) ensures the increasing and the maintaining of the porosity during the restructuring of the active materials while the additive acetylene black (0.2-2wt%) backs the conduction system of the active mass. Some manufacturer adds the glass microfibers (0.5-1.5wt%) in the positive paste in order to increase the specific surface of the active mass. Otherwise, the conductivity of the negative active mass is improved by the addition of black carbon (0.1-0.3wt%) and expanded graphite (<1.5wt%), while the surface area of the negative active mass is increased by the lignosulfonate additive (0.2-0.3wt%) [14,15].

In addition, standard antimony 4-11%Sb As, Sn, Cu(Ag) in the grid alloy provides strong grids, stability for active material in positive electrode, improvement of cycle performance [5]. The vibration failure can be avoided by addition of more than 2%wt tin content that increase the amount of eutectic liquid and improves the fluidity of the alloy. The battery degradation by sulphating of the electrode may be reduced by the implementation of corrective action as shown previously for stationary and renewable energy applications.

B. Improvement Of Battery Lifetime During The Operational Phase

In this section, the authors propose corrective actions during the lead acid battery operation in order to reduce the degradation phenomenon and ensure maximum battery reliability. The stratification of electrolyte in UPS and renewable energy applications can be reduces by a proper maintenance and a suitable energy management system of battery. Proper maintenance can extend the battery cycle life by checking periodically the specific gravity of the electrolyte and adjusted to a correct value. The energy management system of battery should prevent the deep discharge that causes the stratification of electrolyte and the sulphating of electrode by fixing the maximum state of discharging of the battery to 50%. The sulphating of the electrode by the incomplete charging can be avoided by charging the battery until the full state of charge 100%.

In the same way, the energy management system of battery should prevent the overcharge that generates the corrosion of the electrode. The overcharge is observed when battery voltage above the maximum charge voltage that recommended 2.35V per cell [16]. The maximum charge voltage of a battery is determined by the following equation.

$$V_{bat\text{-}max} = \text{Number of cell} \times 2.35\text{V} \qquad (1)$$

Therefore, the authors propose a charging cycle of battery based on multistep current in order to reduce the degradation of battery by sulphating and corrosion of electrode. During the charging cycle, the battery is charged until the voltage reached the floating voltage $V_{floating}$, and then the current decreases over time, until the battery ultimately reaches 100% SOC with the charging rate C/50. The floating voltage of a battery is determined by the following equation:

$$V_{floating} = \text{Number of cell} \times 2.25\text{V} \qquad (2)$$

The multistep current profile is based on the calculation of the voltage variation and the current variation. The voltage variation is determined as follows:

$$\Delta V_{bat-steps} = \frac{V_{bat-\max} - V_{floating}}{n} \qquad (3)$$

With: n is the number of steps;

The current variation can be defined as:

$$\Delta I_{bat-steps} = \frac{I_{C/10} - I_{C/50}}{n} \qquad (4)$$

The current steps can be estimated by the following equation:

$$I_{step\_n+1} = I_{step\_n} - \Delta I_{bat-steps} \qquad (5)$$

With:

$$I_{step\_0} = I_{C/10} \qquad (6)$$

The lead acid battery used in this paper has a nominal voltage of 24V and a nominal capacity of 100Ah with initial state of charge 60%.

According to Eqs, (3)- (6), for n=4, there are 4 steps with $\Delta I_{bat-steps} = 2A$ and $\Delta V_{bat-steps} = 0.3V$.

The used charging current and the corresponding voltages range at 25°C are indicated in Table II. The proposed control strategy that reduces the degradation phenomena and ensures maximum battery reliability is described by Fig. 2. In this control strategy, the battery is charged from an AC source in case of UPS applications or wind applications, otherwise, the battery is charged from a DC source such as PV applications and hybrid electric vehicle applications.

TABLE II
VOLTAGES RANGE AT THE VARIOUS CHARGING CURRENT

Steps	**Voltage range (V)**	**Charging current (A)**
Step 1	27→27.3	8
Step 2	27.3→27.6	6
Step 3	27.6→27.9	4
Step 4	27.9→28.2	2

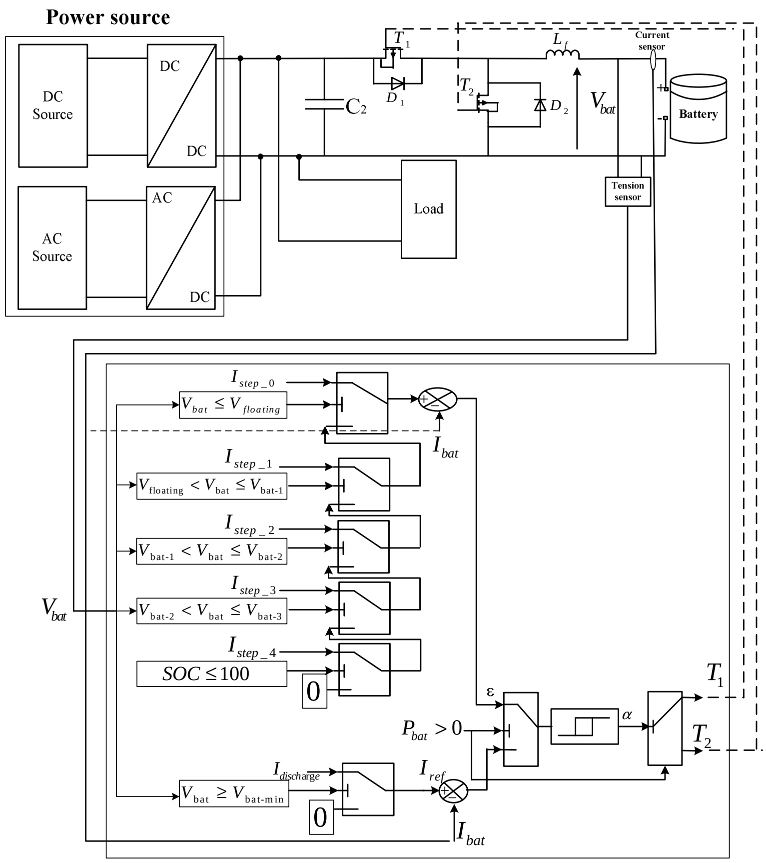

Fig. 2 Proposed control strategy of battery.

The characteristics by Matlab Simulink of current, voltage, state of charge and power of lead acid battery based on multistep current control illustrate in Fig. 3.

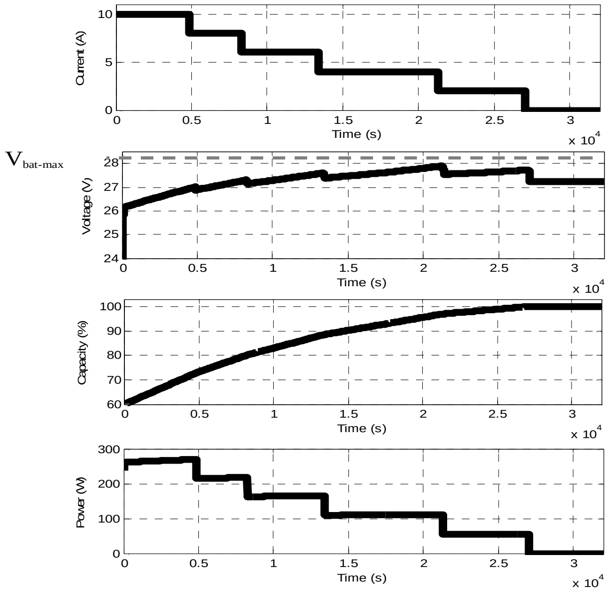

Fig.3. Current, Voltage, State of charge and Power of the battery for charging control based on multistep current.

These results shows that the proposed control strategy avoids the sulphating phenomena by the full state of charge (SOC=100%) with a terminal voltage of the battery lower than the maximum charge voltage ($27.72V<V_{bat-max}=28.2V$) which reduces the corrosion phenomenon. Another benefit of decreasing the current through the battery is reducing the degradation of the active mass. At the same time, the amount of gassing is restricted by the application of constant current C/50 at the end of charge, such that the electrolyte stratification and the excessive gassing problems are avoided. The gas bubbles brew the electrolyte and make it more homogeneous. This method serves to eliminate the stratification of the electrolyte produced during extended periods of discharge of the battery, which allows preserving the capacity and increase the battery lifetime. This charge cycle allows reducing the degradation of the active mass for the traction application and the sulphating, corrosion and the stratification phenomena in the stationary and renewable energy applications. Therefore, the charge control based on multistep current increases the reliability of the battery and extends their lifetime by reducing their degradation.

V. Conclusions

The paper presents an approach using causal tree analysis to describe the various phenomena causing the degradation of flooded lead acid battery in different applications. This study allows identifying the critical failure modes for each application, resulting from either manufacturing inadequacies or service related problem. However, the traction battery is mainly degraded by the non cohesion of active mass, sulfating of electrode and the loss of electrical connection. the main degradation modes of the stationary battery are the sulphating by the deep discharge, corrosion of electrode and stratification of electrolyte, while the renewable energy application shows the failure of battery by the sulfating due to the incomplete charge cycle, the corrosion and stratification phenomenon. Finally, the authors propose corrective actions during the manufacture process and during lead acid battery operation to reduce their degradation and extend their lifetime. In this context, a charging cycle based on multistep current is developed in order to take the best care of the battery to be overcharge and reduce the risk of failure by the incomplete charging.

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