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DEVELOPMENT OF BATTERY LIFETIME MODELS FOR ENERGY STORAGE SYSTEMS IN RENEWABLE ENERGY SYSTEMS (RES).

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1 Introduction

This paper presents the ongoing work on battery lifetime modelling in the framework of the EU Project "Benchmarking", ref. 1. The Benchmarking project interacts with the INVESTIRE network, ref 2, which aims at reviewing most existing storage technologies concerning their suitability for solar and wind power systems. Indeed a number of key persons participate in both activities.

The purpose of the work in Benchmarking is to reduce the uncertainties in technical-economical analyses and assessments of renewable energy systems (RES) that include energy storage systems. The application of energy storage can improve the integration of RES significantly. However, batteries constitute a significant source of the uncertainty in both performance and economics. The load patterns that the batteries are subjected to in RES systems depends highly on the particularly system. Some typical patterns can be identified (classification), but there is still no well-documented relationship between load pattern and actual lifetime of the batteries. On this background of a lack of well-defined relationships between the load patterns and the consumption of lifetime, the project aims at developing improved models for battery lifetime assessment.

A battery lifetime model is a model component to be included in a system performance model or to be used as a post-processing routine on e.g. measurements. System performance models will typically include models of the various renewable energy generators, conventional generators, various loads and system controllers. Based on the currently available renewable energy sources, the current consumer demand and the control strategy, the system model will determine the balancing power from the battery. This power is then processed in the battery model that includes both performance (charge transfer, voltages) and ageing (capacity and efficiency degradation). In order to determine the lifetime of the battery the major damage mechanisms for a battery have been identified as well as stress factors that contribute to the damage mechanisms (In the project the term "ageing" is used for the degradation itself while the term "damage mechanism" is used to express the causes for the degradations).

The work in the Benchmarking Project on the lifetime model follows two tracks. The first method is based on cycle counting and is a semi empirical method. The second method is based on a physically based equivalent circuit model of the battery where the components of the model/the model parameters values depend on the load history of the battery as well as the current load. The work on lifetime models is focussed on lead-acid batteries. Some of the methods might be applied to other types of batteries. The battery lifetime model will be applied both in the categorisation procedure and in performance models as part of the Benchmarking project.

2 Battery lifetime, damage mechanisms and stress factors

The definition of battery life is a matter of discretion. The usual definition is that the battery life has expired when the battery capacity is less than 80% of the nominal capacity. However, there may be more to it than that in the present context of battery lifetime modelling.

The performance of a battery deteriorates with time. Several mechanisms are involved. The rate at which the battery deteriorates depends on the load pattern. In order to systematise the ageing of the batteries the most significant damage mechanisms have been identified, and an identification of stress factors that influence the damage mechanisms based on the load pattern to which the batteries are exposed, have been done. The most important damage mechanisms are corrosion and sulphatation followed by shedding and active mass degradation. Loss of water can for some types be significant. A number of stress factors have been identified, which together cause the above mentioned damage mechanisms. Each of these stress factors has an impact on the damage mechanisms. Their relative weights have been found qualitatively. All this has been collected into the table shown in Figure 1.

In the table the significance of the damage mechanisms and the stress factors are colour coded – the darker the more important. The influence of the individual stress factors on the damage mechanisms are also colour coded. The table is then used to prioritise the development of the lifetime models (as well as to develop the categories of the classification system, cf. the paper on the classification system, ref.3 presented by the Benchmarking Project at this conference). The stress factors can be interpreted as derived quantities of the particular load history experienced by the battery.

	Corrosion of the positive grid	Sulphatation	Shedding	Loss of water	(Loss of charged active material surface) AM degradation
Temperature	Strong impact, positive correlation	High temperature has negative impact at low SOC high temperature has positive impact during full charging	No direct impact	Increasing with increasing temperature	Low impact with high temperature on neg. electrode expanders
Depth of discharge	No direct impact	No direct impact	Strong impact	No impact	Direct impact
Acid stratification	Impact through low acid concentration in upper part of electrode	Strong impact through inhomogeneous current distribution and local SOC	Indirect through increase gassing indirect through strong sulphatation in the lower part if the electrode	Indirect through extended charging periods at high voltage	Impact through inhomogeneous current distribution and SOC
Discharge rate	Indirect through positive electrode potential	High discharge rate create many and small sulphate crystals inhomogeneous current distribution causes in. SOC	Probably increased shedding due to high DOD on outer array of active material [pasted plates]	None	Increases inner resistance due to AOS-model (agglomerate of sphere)
Charge rate	Indirect through positive electrode potential	No impact	No impact	Indirect through higher voltage & higher temperature	Positive impact through smaller crystals
Time at low states of charge	Indirect through low acid concentration and low potentials	strong impact	No direct impact	None	None
Cycle duration	No direct impact	Strong impact	No direct impact	No direct impact	None
Voltage	High impact according to corrosion rate as a function of potential	Positive impact at high voltages	No direct impact	No direct impact	Strong impact during voltage reversal (mainly neg. Electrode)
Acid concentration	Strong impact Low concentration --> high corrosion	Strong impact Low concentration --> high solubility of Pb2+	No direct impact	No direct impact	No direct impact
(Overall charge transfer) Ah throughput	No impact	No direct impact	Impact through mechanical stress	No direct impact	Loss of active material structure, larger crystals
Ripple current (f > 1 Hz), without zero-line crossing of current	Impact through potential variations (depends on frequency)	No impact	No direct impact	Some impact at high states of charge	Indirect through higher temperature
Partial cycles (f > 1 Hz)	Impact through potential variations (depends on frequency)	Increase size of sulphate crystals	No direct impact	No impact	Impact
Gas evolution rate	No impact	Indirect through reduced charge efficiency	Strong impact	Strong impact	No direct impact
Reverse charging	No significant impact	Indirect	Very strong mechanical stress	Small impact	Strong loss of negative material structure through loss of expanders
Charge factor	No direct impact	Positive impact through regimes with high charge factor	Strong impact through gassing	Strong impact	No direct impact

Figure 1 Cross matrix with stress factors (rows) and damage mechanisms (columns)

3 Battery lifetime modelling

Battery lifetime modelling has to be seen in the context of its use. This means that the level of details and the resulting accuracy of the model have to correspond with the level of detail in the input and the application of the result. For example the expected accuracy of the results from a screening in a pre-feasibility project will typically be considerably lower than the accuracy of the details in an actual design of a particular system and its controller.

In the context of the Benchmarking project the application of the lifetime models are to be used in the categorisation process to output the expected lifetime of a battery when it is exposed to a given load time series, and the lifetime model will also be included in system models in order to predict expected lifetime of a battery in a potential system. In both cases the input to the lifetime model will be time histories of temperature and power or voltage and current.

In the battery lifetime models the stress factors and/or the damage mechanisms can be modelled explicitly or indirectly. One basic modelling procedure is to quantify the stress factors at the current time in the simulation based on the history. The factors are then used to quantify the damage at the same time instant. This will typically be determined as the incremental damage done since the last time step/main event. Another approach is to determine the damage without first calculating the stress factors.

Different strategies for the modelling have been pursued in the literature. In the Benchmarking project, two tracks are followed, one mainly based on cycle counting (CCM) and another based on more explicit modelling of the battery termed Equivalent Circuit Model (ECM) method. Both approaches are dealt with in the paper.

The CCM models require a performance model and often the modelling of the ageing will be empirical and based on an indirect representation of the damage mechanisms. In the ECM approach as it is pursued in the project, the battery parts (electrodes etc.) are explicitly modelled in the form of an equivalent circuit and the ageing of the battery is modelled as changes in the properties of the individual parts of the battery.

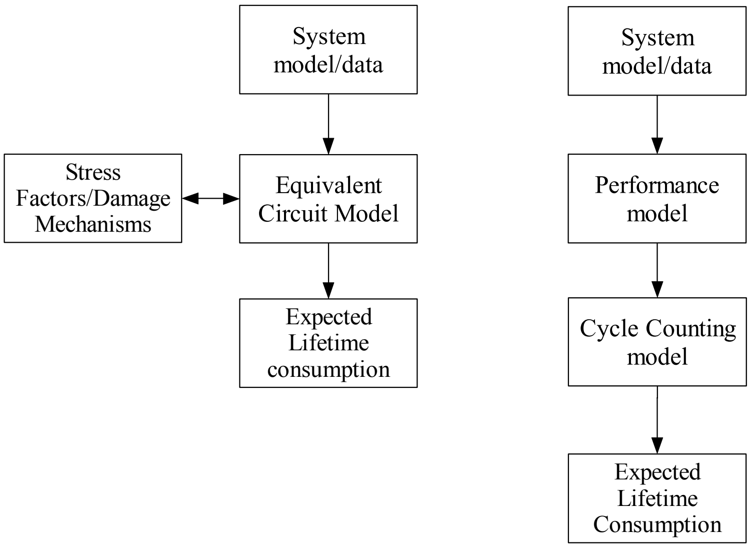

Figure 2 Model flows for the two modelling approaches. For the equivalent circuit model on the left the equivalent circuit model parameter values are updated continuously during simulation to reflect the damage on the battery. For the cycle counting model this is not necessarily the case.

In both approaches the battery lifetime model determines the (change in) lifetime of the battery during a course of events, based on input in the form of either measured data or simulated results from a system model. In the case of system modelling the power flow to the CCM model comes from a separate battery performance model (PM) that interacts with the system model. The ECM model works directly on the data / system model results through the stress factors (SF's) and damage mechanisms (DM's) of the cross matrix shown in Figure 1, thus alleviating the need for a separate PM. The figure indicates that there is expected to be a strong cross-fertilization between the two approaches with respect to the stress factors / damage mechanisms applied.

4 Ah-throughput and cycle counting methods

In the Benchmarking project two existing cycle counting models form the foundation for the development work. The first is developed by NREL/RERL, UMASS, ref 4. The second is developed by FhG-ISE, ref 5.

The simplest lifetime model is a simple ampere-hour (Ah) throughput model where the lifetime of the battery is modelled as a fixed amount of Ah that can be cycled through the battery. The assumption is that the battery life expires when the Ah throughput has reached the rated amount. More advanced methods still uses the basic concept of Ah throughput but modifies it in different ways. In the project, two such approaches form the basis of the cycle counting method track of the lifetime modelling. It is based on previous work by NREL/UMASS and FhG-ISE. The NREL model (ref 4) introduces a weighting according to the depth of discharge per cycle only, whereas the FhG-ISE model (ref 5) introduces weighting factors based on the time between full charges and the acid stratification that is likely to develop between full charges.

The NREL/RERL model is part of the hybrid system simulation tool HYBRID2. The battery model in the tool consists of two parts: A performance model and a lifetime model. The modelling approach for both models is that the models should be simple with few easily determinable parameters (from datasheets). The lifetime model is based on the assumption that the lifetime consumption mechanism of a battery is similar to fatigue in material e.g. metal subjected to vibrations. The idea is also closely linked to the standard lifetime information provided by manufacturers in the form of a number of cycles with a particular DOD to failure.

The model assumes that the battery last for a particular number of cycles with a given amplitude. It is further assumed that it is the amplitude that determines the lifetime consumption and not the SOC level at which the battery is cycled. This means that the lifetime consumption of a cycle at 80% SOC with amplitude of 10% (80%-70%-80%) is the same as a cycle at 40% with the same amplitude (40%-30%-40%). In order to determine the cycle a so-called rain flow counting method, ref 6, is used. This is again taken from materials fatigue. Rain flow counting is a particular way of counting and collecting cycles. For the collected cycles in bins an associated fractional damage is calculated based on the lifetime information supplied by the manufacturers in the form of a Cycles to failure vs. DOD curve. The lifetime estimation is done after the simulation and there is no performance degradation of the performance model. The model is based on physical insight, but it has not been validated against measurements. The model does not directly relate to the stress factor-damage mechanisms table except that the major stress factor (and the only one considered) is the Ah throughput without a direct relation to a particular damage mechanism. The damage is similar to the combination of sulphatation, shedding and AM degradation.

The FhG-ISE model is more comprehensive than the NREL/RERL model. It is not a cycle counting model although cycles play a role in the determination of one of the stress factors. The FhG-ISE model directly relates to part of the cross matrix (Figure 1). The damage mechanisms modelled are corrosion and the capacity reduction as a result of sulphatation, shedding and AM degradation. The end of life condition is when the battery has a certain amount of capacity left (typically 80% of the original capacity).

Contrary to the NREL/RERL model the battery model integrates performance and lifetime so that the performance of the battery deteriorates due to the load pattern that it is exposed to. The model consists of a voltage model, charge and loss model, and lifetime model with two components: One for corrosion and one for degradation due to Ah throughput.

The corrosion has an impact both on the voltage and on the capacity due to the corrosion layer that is being built and the resulting non-homogeneous current distribution. This layer increases the internal resistance and reduces the active mass. It is assumed that both the effects are proportional to the corrosion layer. The thickness of the layer is modelled based on the results of Lander on the corrosion speed caused by voltage. The DOD and the current determine the corrosion voltage in the model i.e. DOD and current are the stress factors for corrosion.

The capacity reduction also has contributions from other stress factors in the FhG-ISE model. Three other stress factors are modelled: stratification, time between full charge and maximum DOD (sulphatation effects on capacity). They are modelled as temporal weight factors on the Ah throughput.

The stratification weight factor is modelled as balance between two processes. The first process builds up the stratification and depends on the current stratification factor (it has the shape of a time constant). The other process dissolves the stratification when the battery cell voltage exceeds a certain value. This process models the gassing of the electrolyte at higher voltages.

The second weight factor models the impact of sulphatation. The two stress factors are the maximum DOD and the time between two full charges. The weight factor builds up when the battery is not fully charged. The rate of the build up proportional to time and depends on the maximum DOD since the last full charge. The weight factor is reset when full charge is reached.

The two weight factors are used to modify the Ah throughput i.e. the impact of 1 Ah on the lifetime depends on the condition of the battery and is amplified by the weight factors when the voltage and SOC charge has been low for extended periods. This modified Ah value is used to determine the reduction in capacity.

The capacity loss for corrosion and Ah throughput are both subtracted from the original capacity and the remaining capacity is determined. If the remaining capacity goes below, the limiting value the battery lifetime has expired and the battery is replaced with new battery in the simulation. All battery parameters are then reset to the original values. This implies that the lifetime model is an integrated part of the battery model and has to be solved at each time instant of the simulation.

It is unclear from the references to what extent the model has been validated, but in any case further validation is needed as the project aims at being able to predict lifetime of batteries for new and unknown load profiles.

The two lifetime models are very different in their complexity. The basic idea of the NREL/RERL model is to have a simple model capturing the main effects of the battery using only parameters that can be established from standard datasheets. On the other hand, the FhG-ISE model aims at a better accuracy and is therefore much more involved. The algorithm is much more complex and it also involves parameters that are not derived from datasheets, but have to be established through measurements. Both the models do not directly model the electrochemistry involved, however, the FhG-ISE model is much closer to the real battery than the NREL/RERL model. Both the models have a performance model, but only the FhG-ISE model integrates performance and lifetime models.

The two CCM model are being assessed for future merging. The objective is to try to maintain the simplicity of the NREL/RERL model but improve it by including the effects of the stress factors modelled in the FhG-ISE model.

5 Equivalent circuit model method

Since the damages to the battery are due to changes in particular parts of the battery direct modelling of these individual parts and their degradation as they are subjected to a load pattern is an interesting approach. This is the second approach that is followed in the project. The model of the battery is done through an equivalent circuit and the model includes directly both performance and lifetime of the battery.

The equivalent circuit used to model the battery is shown in Figure 3. In the figure the battery is divided in three layers: top, middle and bottom. These three layers are used to model stratification. For each layer the current conducting elements and voltage sources are modelled explicitly. These are the grid, the corrosion layer, the active mass, the polarisation and the electrolyte. Furthermore, the positive electrode is modelled at three positions: inside, middle and outside. The three positions are used to model the diffusion process of the electrolyte through the electrode and to calculate the voltage at the grid more accurately. For a detailed account of these aspects see ref 7.

The value of each of the elements of the model can be a function of current, temperature and SOC (and their history). This means that their values depend on the current conditions as well as any change that may be the result of the load history. The components will have different values and each of them will change individually over time.

The work on the model in the Benchmarking project is currently focussed on establishing procedures for the determination of the values of the elements and an updating procedure during simulation

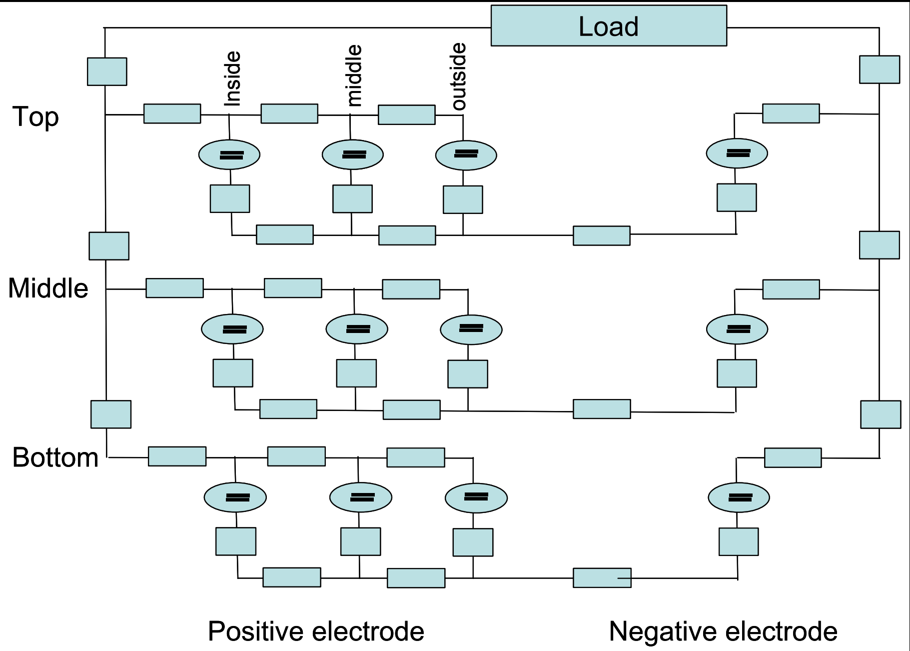

Figure 3 The Equivalent Circuit Model. The battery is modelled as three current paths at three heights (for stratification modelling) and with three positions in the positive electrode (for diffusion modelling). The discrete parts of the battery is modelled explicitly i.e. grid and electrolyte resistances.

6 Integration into system performance models

Each of the battery lifetime models will eventually be included in system performance models. In these models the load pattern of the battery in terms of current, voltage and temperature will be determined as a result of the load balance of the system which depends on the renewable energy input, the consumption and the control strategy.

For the battery it is of major importance that the load pattern is close to the real load pattern. In order to obtain this, it is very important that the system controls are accurately represented in the model and that the time steps are not to long. This is especially the case for systems with high wind energy penetration. In such systems the power will fluctuate fast and with large excursions.

The modelling of the power flow between the components of a system – and hence the power flow in and out of the battery – depends strongly on the realistic representation of both the overall system control (supervisory control) and the controllers of each system component (component control). With very few exceptions the system models available today only have at most a small number of pre-specified control strategies available in the model while real systems exhibit an almost infinite variety of manufacturer's control strategies. For a detailed account of this aspect see for example ref 8.

System performance models are usually run with time steps of the order one hour, in some cases with variations down to 10 minutes or up to several hours. These long time steps – long compared to e.g. the variability in wind speeds and thus wind turbine power output, transitions between various system configurations such as diesel start / stops etc. – are caused by the wish / need to limit the number of time steps in the simulation of a year, not to mention a 20 year lifetime. In each of these time steps the fluctuating behaviour of the system and its components is given an "integrated", stationary representation. However, in order to represent adequately the behaviour of a battery in a hybrid system with high RES proportion, the battery model will be modelled in very short time steps, down to the order one second (just short of system dynamics) in an "incremental" representation. These short time steps may then be combined to form longer time steps in an overall system model.

The battery model will interact with the rest of the system through the battery performance part of the model, taking part in the exchange of power with the rest of the system and influencing the actual system control. The battery lifetime part of the model may in principle be run entirely separated from the system model, maybe even at the end of the run. In reality it should be run "on line" as part of a simulation so that battery lifetime aspects may be fed back to the system controllers.

7 Conclusion

The Benchmarking project will pursue both tracks described in the paper; so that the battery lifetime modelling component will have the following two deliverables:

1. An incremental update of the CCM / weighted Ah throughput model, based on NREL / FhG-ISE software. This is a "firm and safe" deliverable with a large application potential in the sense that the project by definition will have a functional improvement of an existing, if imperfect and holistic, state-of-the-art approach at the end of the project.
2. A 1st pilot version of the ECM framework based on a MATLAB equivalent circuit diagram linked to a programmed version of the cross-matrix. This is a more "speculative but visionary" deliverable with far reaching and innovative perspectives in the sense that it opens the path for development of a comprehensive and systematic quantification of battery ageing under system and site specific conditions, strictly based on the actual physics involved.

There could be a strong cross-fertilisation between the two approaches with respect to the stress factors / damage mechanisms applied. In both tracks the developments will - to the extent possible - be validated with the results from the battery tests performed in the project.

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