A detailed study of Battery Life Cycle

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Abstract

Due to the development of renewable energy and the exploitation of electrified transportation systems, battery life cycle modeling and estimation have become important challenges in modern electric systems. In these fields, batteries have in fact emerged as the most prominent energy storage device, drawing a significant amount of research. Although it is commonly known that a variety of factors, including power density, specific power, energy density, operating environment, and others, affect battery lifetime, it is still necessary—though not easy—to develop precise methods for analyzing this dependence that also take into account the randomness of the aforementioned parameters in actual operating conditions.

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1 Introduction

Batteries, conceived as a proper number of cells connected in series or in parallel, have received since their discovery a great attention by many researchers and recently a further emphasized interest can be registered [1-12], due to the their high potentialities as electrical source for electric vehicles, as storage systems in smart grid environment and naturally as support technology for communication systems. The attractive characteristics of this kind of electric power source has to satisfy the required constraints of reliability, so avoiding premature failure with consequent reduction of the battery cycle-lifetime, which in the paper is also denoted as "life cycle" (LC), as measured by the charge -discharge cycles.

A significant amount of studies have been recently devoted find more and more reliable solution to such problem. In previous papers [9,10] some of the authors proposed a probabilistic approach based upon the Rakhmatov and Virudhula battery model [7-8] with random input for describing the battery behavior under for system operation or forecasting purpose. As for concerns battery design, one of the most crucial challenge is the choice of the most convenient model for solving the problem of the battery size design over a prefixed time horizon of interest. Many approaches have been proposed in the relevant literature, but a lot of difficulties persist, being related to the incidence of many factors which do not allow to derive a quite general modelling able to describe in exhaustive way batteries performances under different operating conditions. It is well known that battery lifetime, or life cycle (LC, as measured by the charge -discharge cycles) depends on many parameters, such as power density, specific power, energy density, operating environment, etc. Accurate methods to analyze this dependence, also taking into account the randomness of the above parameters in real operating conditions, are necessary: it has been indeed shown that parameter uncertainties may lead to significant variations in life cycle estimation, so that large differences are observed between the expected and experienced battery LC. In particular, concerning electric vehicle applications, in a significant number of cases an unexpected degradation of battery performances has been measured with respect to manufacturers claims on battery lifetime. In this framework, in the paper, after a thorough statistical data analysis, a probabilistic method for battery design is proposed which ensures with a high degree of probability that the LC is higher than a prefixed level provided by standards which will be desirably issued in the near future, following studies like the one here proposed.

The method takes properly into account, in particular, the random variations in specific power experienced by a lead-acid battery (with 484 Ah of capacity) during its operation.

The input data came from an experimental campaign done in the Italian Research Centre of Enea Casaccia with an electrical bus (Tecnobus Gulliver U420) with a storage module of 72 V and 484 Ah of capacity serving an on-demand transport service. The bus has been equipped with an automotive on-board device collecting GPS data and vehicle parameters.

The proposed approach combines experimental data and a Monte Carlo procedure, allowing to identify the battery size the minimum cost corresponds to, by keeping into account the replacement cost over a quite extended time interval.

At this aim a first preliminary statistical analysis is performed with respect to the experimental data acquired and elaborated in the *Italian Research Centre of Enea Casaccia*. More specifically, the probability density functions of the maximum power and the energy requested are derived. Hence a cost function is identified, by taking into account the replacement problem, which is strictly related to the lifetime. The lifetime prediction is based upon the accelerated test which without any doubt provide the core of the lifetime model. However, a correction of the interpolation model needs, for taking into account the unavoidable degradation terms related to the ageing effects which cannot be wholly observed in data corresponding to accelerated test. The nonlinearity of the problem does not allow to derive a closed form of the optimum size, but the probabilistic procedure is very feasible to implement and could be employed in a quite general way. It is trivial to observe that for the implementation effectiveness an experimental preliminary campaign is needed, but this allows to guarantee a certain superiority with respect to a wholly theoretical design procedure, involving many parameters which are practically impossible to determine or to estimate.

The paper is organized as follows. In section II the experimental set is discussed, putting in evidence the various step for obtaining the measurement data. In the section III, a new battery design methodology is proposed. In the last section the design approach is numerically shown with respect to the measurement data at own disposal.

2 Battery Life cycle

Several tests have been performed in ENEA to calculate the life-cycle of lead-acid batteries [4,4,6], applied to the evaluation of the benefits in the adoption of the supercapacitors in parallel with the batteries.

In [4] a battery pack installed on a city-car prototype, has been tested executing the type approval driving cycle (the ECE14) in order to calculate the number of maximum cycles of the battery. A comparison between a simple battery storage with a hybrid (battery plus supercapacitors) has been made and the results was that with the supercapacitors, capable to limit the maximum current supplied from batteries, the life of the lead-acid batteries increases. The same comparison has been made also for a forklift [6], with the same result. Also the economical evaluation demonstrate that the supercapacitors can decrease the maintenance costs of the vehicles. Such evaluation demonstrates that there is a reduction of costs also taking account for the higher purchase cost due to the Supercapacitors subsystem. In [7], a life-cycle curve has been developed in order to describe the probabilistic laws governing the number of cycles, L, i.e. the battery lifetime, in terms of a design parameters such as “design” specific power, as below described.

Within a project denoted as "QUIBUS", an experimental acquisition campaign has been made in order to characterize the behavior of an electric bus during an on-demand transport service.

The equipment installed on-board was devoted to acquire a series of information needed for our subsequent analysis: the instantaneous speed of the vehicle, the travelled distance, and a set of electrical quantities regarding the actual status of the battery, as the instantaneous ingoing/outgoing motor current, the instantaneous battery voltage and an estimate of its residual capacity. These vehicle parameters were acquired on a time base of two measurements every time second. Also geographical definitions such as instantaneous latitude, longitude and altitude were acquired through a GPS receiver connected to the main hardware; these latter data were acquired on a time base of one measurement every second. All data were organized in a database for further analyses, for a total of 44 days present in it. However, the contents related to 23 days, due to an excessive number of incomplete/missing data, cannot be considered useful for our analysis.

The general arrangement of the acquisition system can be observed in fig. 1.

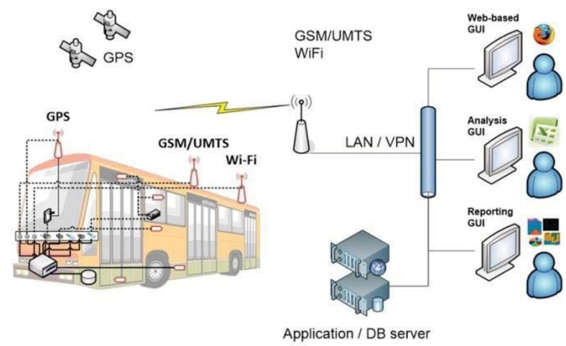

Fig. 1 *A general outline of the data acquisition system*

In fig. 1, we can note the on-board system, able to collect the vehicle instantaneous parameters and to transmit them to a server through a GSM/UMTS channel; moreover, also the geographical data are available through a GPS receiver.

Fig. 2 reports a typical recording, the corresponding instantaneous speed profile (km/h versus time) during a working day. density function of the battery cost is practically impossible to determine.

Samples for P and E are generated according the Weibull distribution, already mentioned, which has been proven the best one in fitting the numerical data.

In the successive section, the proposed approach is explained with respect to the experimental data.

3 Numerical Application

As already outlined in the previous section, a statistical analysis with respect to the measurement data is preliminary performed. The peak power and the requested energy are optimally described by a suitable Weibull distribution.

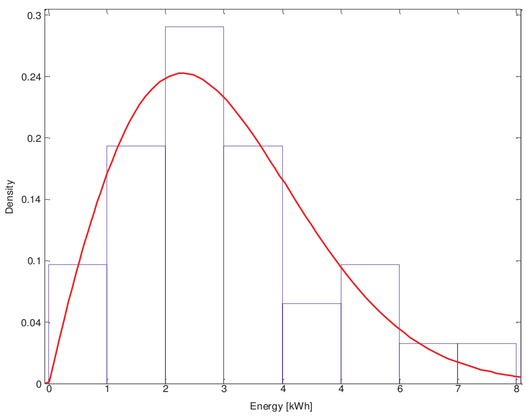

***Fig. 3** the Weibull pdf describing energy distribution*

The correlation coefficient of the above two RV has been estimated equal to 0.3. Thus, in the numerical application, for sake of simplicity, these ones are supposed to be statistically independent.
For sake of battery design the energy demand, by maintaining the same distribution, is doubled for taking into account an expected increased service along the time. N_0 and D have been assumed equal to 440 and 0.8 respectively.
Monte Carlo procedure has been implemented by generating 3000 samples for both the peak power and the energy.
The expected cost versus the battery mass is reported in Fig. 4. The optimal value of battery mass was numerically computed as equal to 1200 kg, as also roughly apparent from Fig. 4.
The corresponding histogram of the lifetime L is shown in Fig. 4, which is optimally fitted by a lognormal distribution. The mean value of the lifetime is equal to 4.82 year which is aligned to the one substantially observed in actual field.

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θ=18362 and γ=30.36.
-The parameters of the energy demand pdf are θ=3.34and γ=29.4, the curve being depicted in Fig.3.

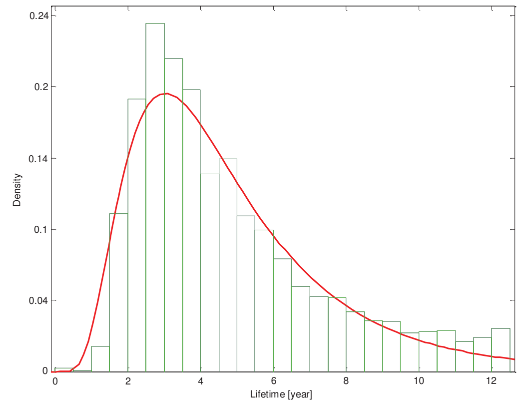

***Fig.4**: Lifetime distribution*

4 Conclusion

In the paper, the battery lifetime prediction in terms of basic design or random parameters, and its proper design are based upon extensive data elaboration and suitable lifetime model, under the so called "*Lauria method*". According to such method: first, battery lifetime prediction is based upon the accelerated test which without any doubt provide the core of the lifetime model. Moreover, a correction of the interpolation model is added for taking into account the unavoidable degradation terms related to ageing effects occurring in real operation, which cannot be wholly observed in data corresponding to accelerated test, not only for the length of such tests but also because it is not possible under such tests to keep all random factors affecting under control. Then, the optimal design of battery is dealt with in such framework, assuming a Weibull model for battery random load and a proper cost function expressed in terms of basic battery features, also taking into account replacement intervals. A numerical application illustrated in the second part of the paper has shown the feasibility of the approach. The method is meant to complete to a general probabilistic methodology for deriving the above lifetime distribution, as illustrated in [9,10] following the Rakhmatov and Virudhula battery model [7-8]. Further steps are worth to be developed towards the aspect of parameter estimation of the model [14-16]. In such field, the opportunity of Bayesian methods comes to mind, for the lack of historical which is typical with high-reliability components, and the efficiency and robustness of the Bayesian method, which are evident in the case of small sample sizes [16-18]. Another possible exploitation of Bayesian methods for battery design is the framework of Multicriteria Analysis with random inputs, as recently illustrated in [19].

References

[1] Agarwal, V., Uthaichana, K. , De Carlo, R.A., Tsoukalas, L.H.: *Development and Validation of a Battery Model Useful for Discharging and Charging Power Control and Lifetime Estimation*, IEEE Tr. on Energy Conversion, Vol. 24, No. 3, September 2010, pp: 821-834.

[2] Lidula, N.W.A.; Rajapakse, A.D.: *Microgrids research: A review of experimental microgrids and test systems*, Renewable and Sustainable Energy Reviews, Vol.14, *Index Terms*— electrical energy storage systems, renewable energy, statistical methods.

[3] Conte M., Pede G., Sglavo V,, Macerata D., "Assessment of high power HEV lead-acid battery advancements by comparative benchmarking with a European test procedure" Journal of power sources, Elsevier, Vol.16 No. pp:118-127, 2003

[4] Sglavo,V., Vellucci, F., "Prove Vita di batterie piombo-acido con e senza livellamento del carico", Report RdS/2012/ 121

[5] Ortenzi, F., Pede, G., and Rossi, E., *Cycle Life Cost Assessment of a Hybrid Lead Acid Battery-Supercapacitor Storage for an Electric Microcar* SAE Technical Paper 2014-01-1816, 2014, doi:10.4271/2014-01-1816

[6] Conte M., Genovese A., Ortenzi F., Vellucci F.,*Hybrid battery-supercapacitor storage for an electric forklift: a life-cycle cost assessment*, Journal of Applied ElectrochemistryApril 2014, Volume 44, Issue 4, pp 423-432

[7] E. Chiodo, D. Lauria, M. Pagano, G. Pede, F. Vellucci, *Experimental performances and life cycle estimation of hybrid electric storage systems*, Proc. IEEE International Conference on Clean Electrical Power Renewable Energy Resources Impact (ICCEP 2013) , Alghero, Italy, June 11-13, 2013.

[8] Laldin, O., Moshirvaziri, M., Trescases, O.: *Predictive Algorithm for Optimizing Power Flow in Hybrid Ultracapacitor/Battery Storage Systems for Light Electric Vehicles*, IEEE Transactions on Power Electronics, vol.28,No.8, 2013, pp.3882-3894.

[9] Li W.: *Evaluating Mean Life of Power System Equipment with Limited End-of-Life Failure Data*", *IEEE Transactions on Power Systems,* Vol. 19, No. 1, 2004, pp. 236-242.

[10] Rakhmatov, D., Vrudhula, S.: *An analytical high-level battery model for use in energy management of portable electronic systems*, Proc. of Int. Conf. on Computer Aided Design (IC-CAD01), 2001, pp: 488-493.

[11] Rakhmatov, D., Vrudhula, S., Wallach D.A.: *A Model for Battery Lifetime Analysis for Organizing Applications on a Pocket Computer*, IEEE Tr. on Very Large scale integration (VLSI) Systems, Vol. 11, No. 6, December 2003, pp: 1019-1030.

[12] E. Chiodo , A. Del Pizzo, L. P Di Noia, D. Lauria, Modeling and Bayes Estimation of Battery Lifetime for Smart Grids Under an Inverse Gaussian Model, IREE, International Review of Electrical Engineering, August 2013, pp.1243-1266

[13] A. Papoulis, S. U. Pillai, *Probability, Random Variables and Stochastic Processes,* 4th ed., McGraw-Hill, 2001

[14] N.L. Johnson, S. Kotz, N. Balakrishnan*, Continuous Univariate Distributions*, J. Wiley, Vol. 1 and 2, 1994

[15] W.Q. Meeker, L.A. Escobar, *Statistical Methods for Reliability Data*, J. Wiley & Sons, 1998

[16] H.F. Martz and R.A.Waller, *Bayesian Reliability Analysis*, Malabar, FL: Krieger Publishing, 1991

[17] S. Chen, T. Ho, B.H. Mao, *Component Reliability Estimations without Field Data*, Transactions of Hong Kong Institution of Engineers, vol. 14, n. 3, 2007 pp. 10-17

[18] E. Chiodo, *Model Robustness Analysis of a Bayes Stress-Strength Reliability Estimation with Limited Data*, Proc. of IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2014), Ischia (Italy), 14-16 June 2014

[19] E. Chiodo, L. P. Di Noia, R. Rizzo, *The Application of Bayes Inference in Multicriteria Analysis to Design Energy Storage Systems in Renewable Power Generation*, Proc. IEEE International Conference on Clean Electrical Power Renewable Energy Resources Impact (ICCEP 2013)*,* Alghero, Italy, June 11-13, 2013